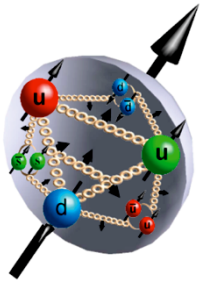
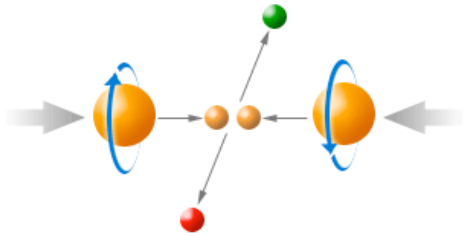


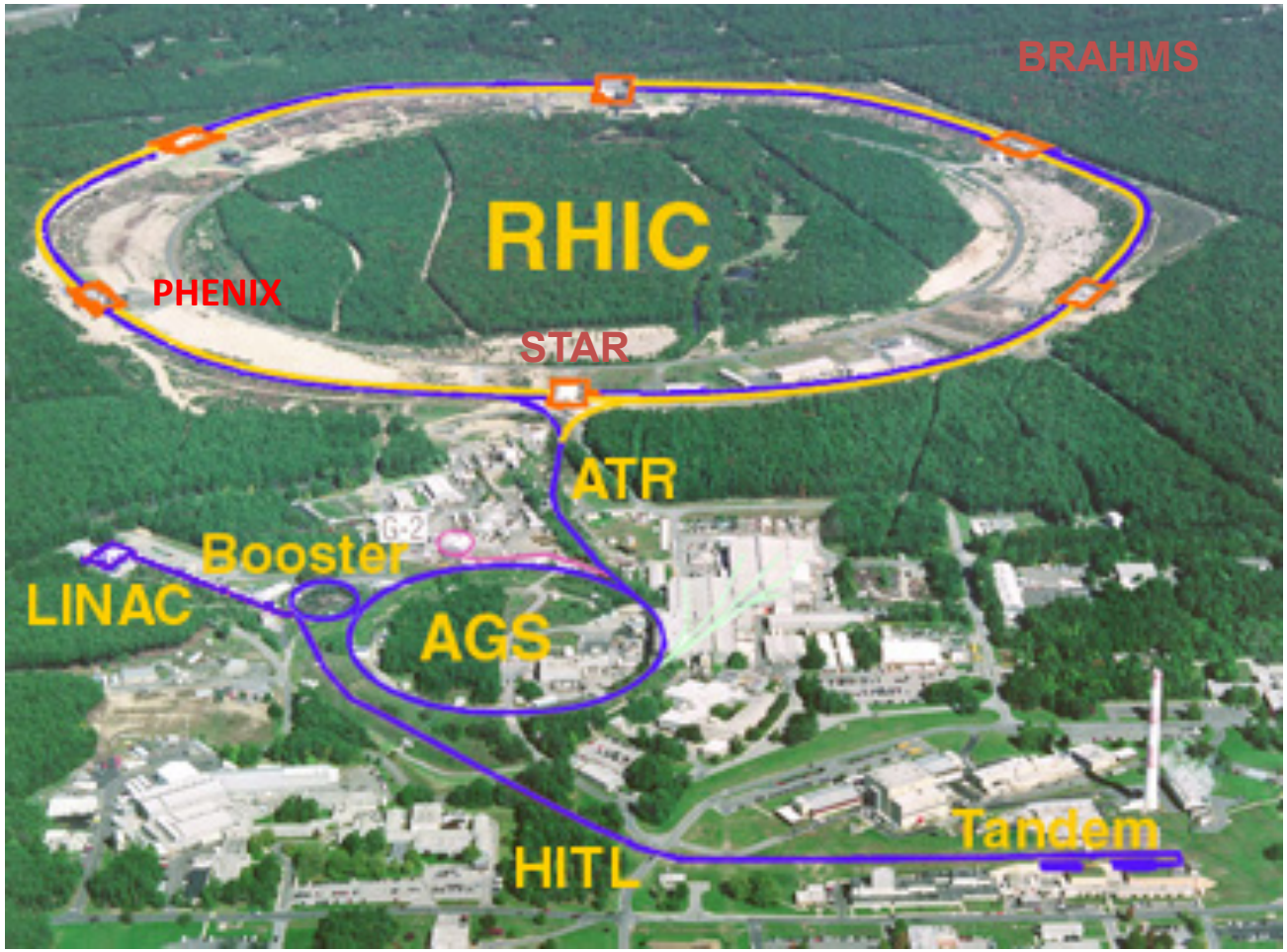


Highlights from RHIC Spin Program

Ming Xiong Liu
Los Alamos National Lab

- Longitudinal spin program
- Transverse spin program

The **R**elativistic **H**eavy **I**on **C**ollider at Brookhaven National Laboratory

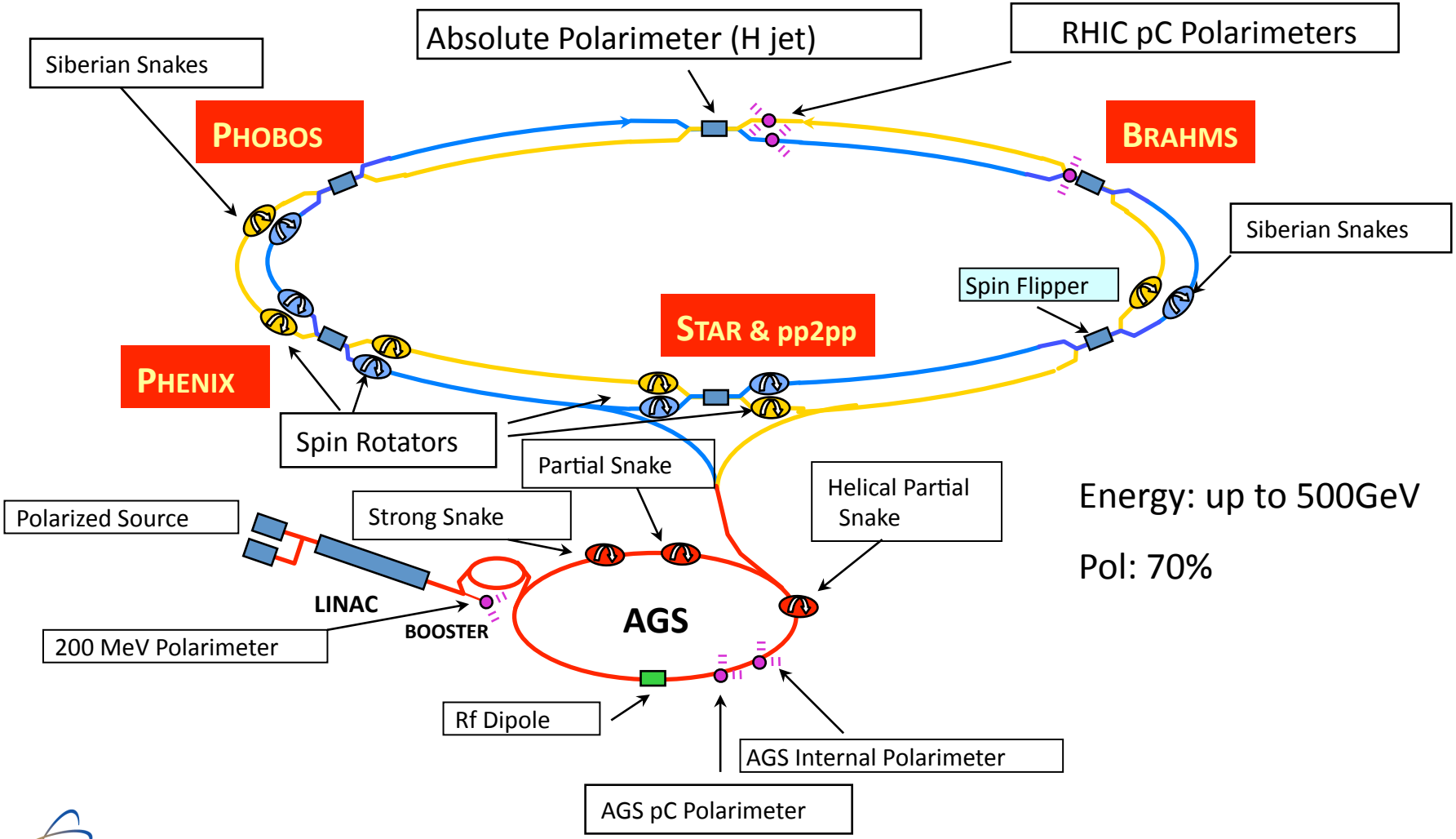


R-HI
New state of matter
QGP
De-confinement
…

polarized proton
Nucleon Spin Structure
Spin Fragmentation
pQCD
…

RHIC is a QCD lab

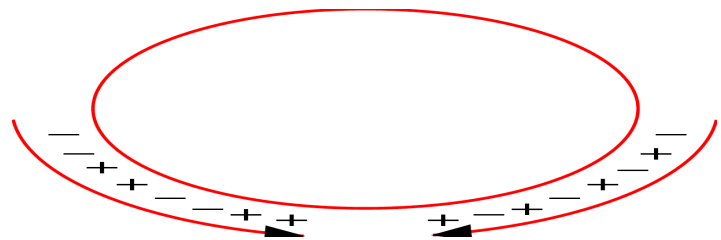
Highest Energy Polarized Proton Collider @RHIC



Energy: up to 500GeV

Pol: 70%

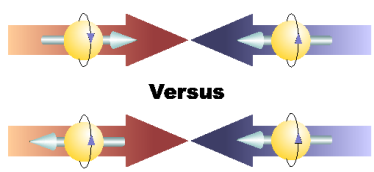
Experimental Observables



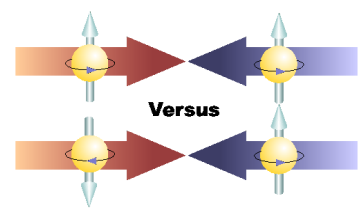
Asymmetries

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

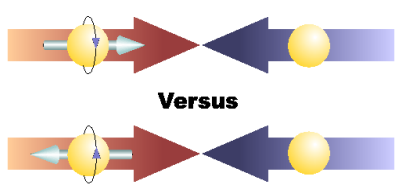
$$A_{LL} = \frac{\sigma(++)-\sigma(+-)}{\sigma(++)+\sigma(+-)}$$



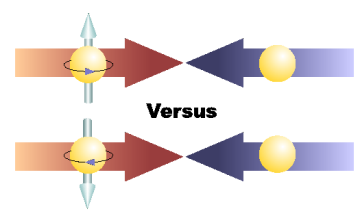
$$A_{TT} = \frac{\sigma(\uparrow\uparrow)-\sigma(\uparrow\downarrow)}{\sigma(\uparrow\uparrow)+\sigma(\uparrow\downarrow)}$$



$$A_L = \frac{\sigma(+)-\sigma(-)}{\sigma(+)+\sigma(-)}$$



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



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

$1.2 < |\eta| < 2.4$

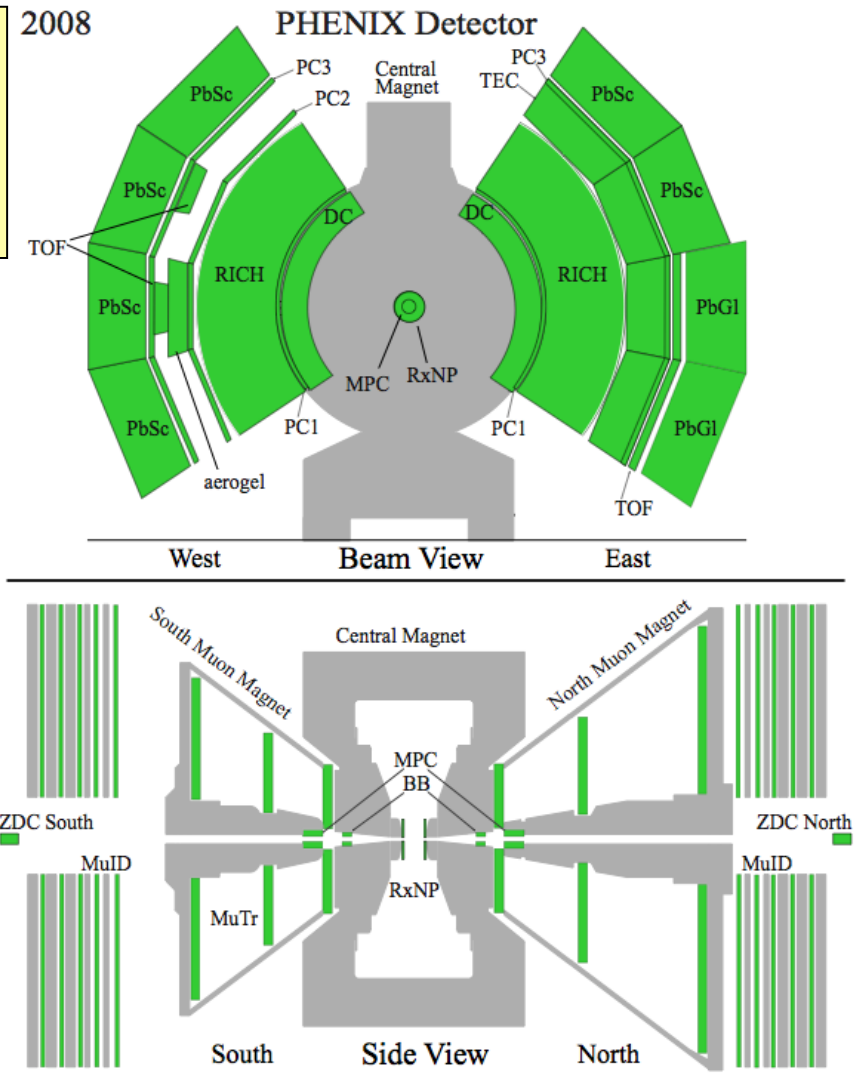
2π azimuth

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

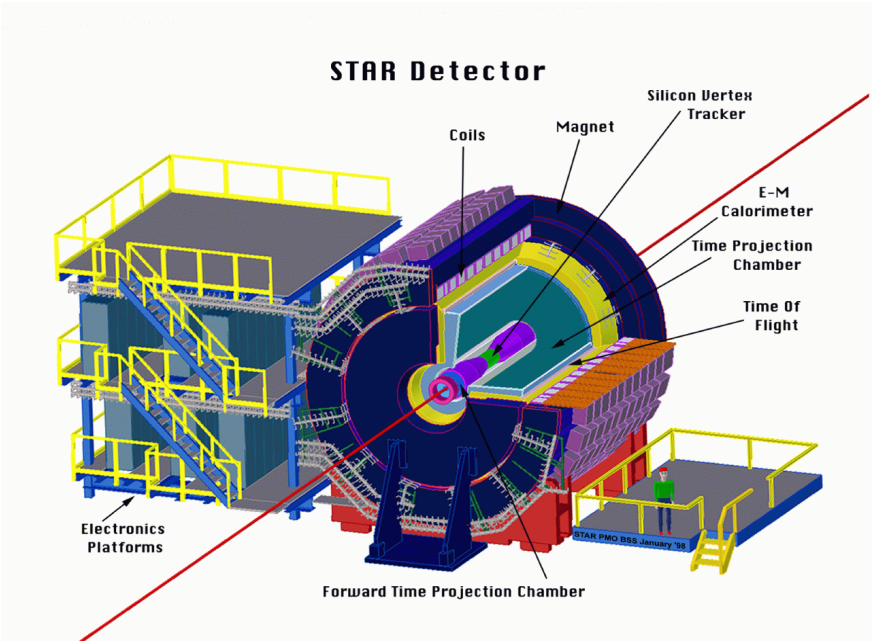
$3.1 < |\eta| < 3.7$

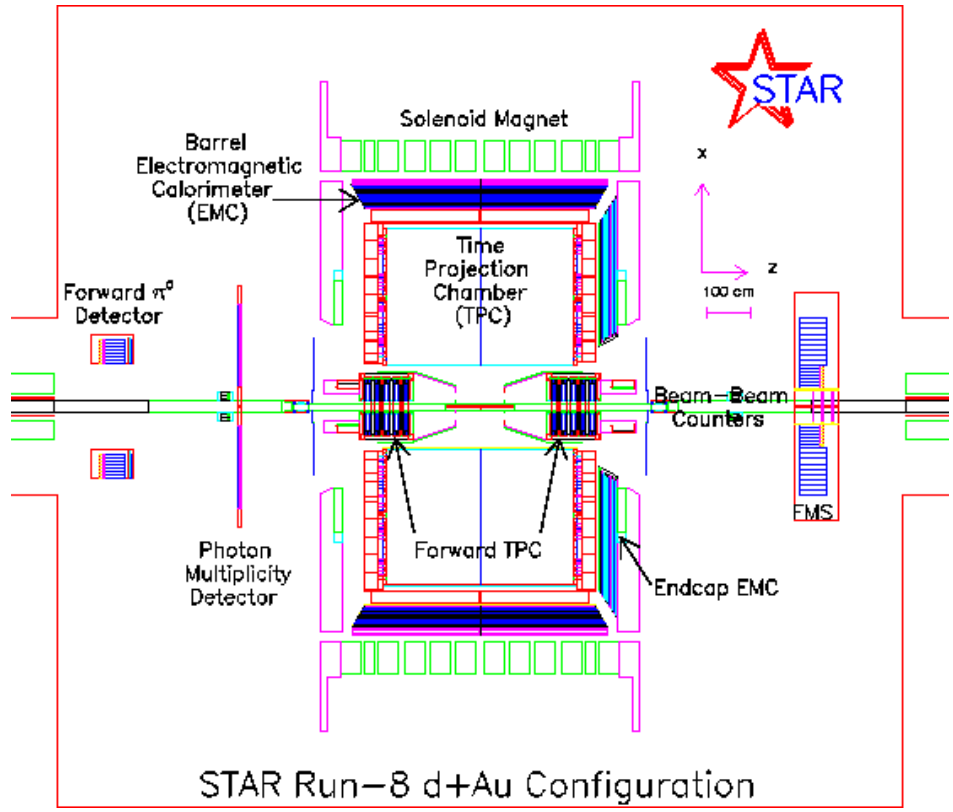
2π azimuth

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



The STAR Detectors



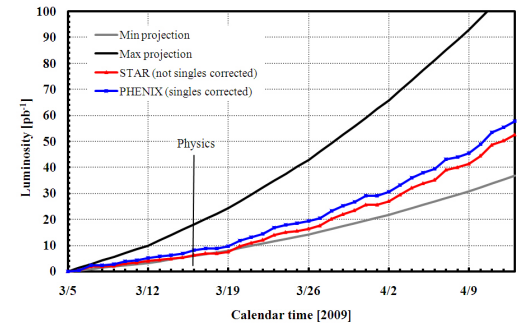


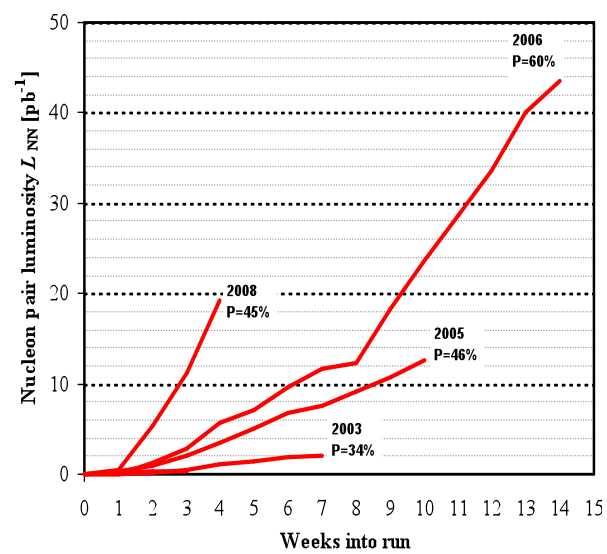
- Time Projection Chamber $|\eta|<1.6$
- Forward TPC $2.5<|\eta|<4.0$
- Silicon Vertex Tracker $|\eta|<1$
- Barrel EMC $|\eta|<1$
- Endcap EMC $1.0< \eta <2.0$
- Forward Pion Detector $3.3<|\eta|<4.1$
- Forward Meson Spectr. $2.5 < \eta < 4$

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

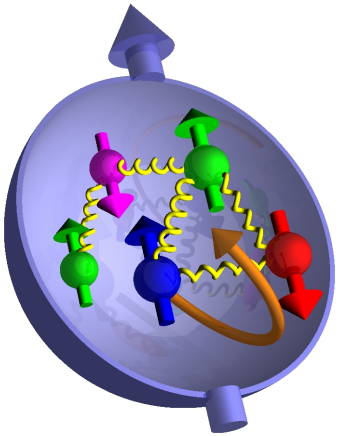
Run9 500 GeV





Los Alamos NATIONAL LABORATORY EST.1943

Part I: Longitudinal Spin Physics Program



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

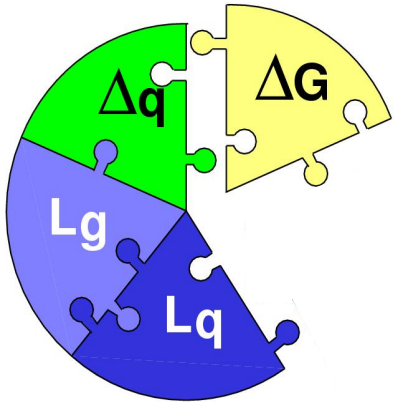
Spins + orbital angular momentum need to give the observed spin 1/2 of proton

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

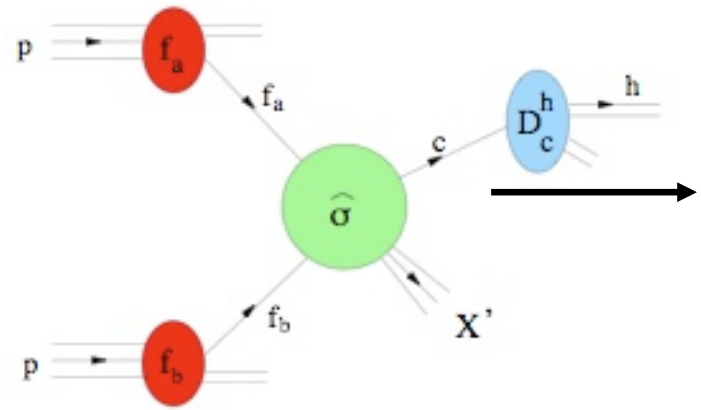
Fairly well measured only ~30% of spin

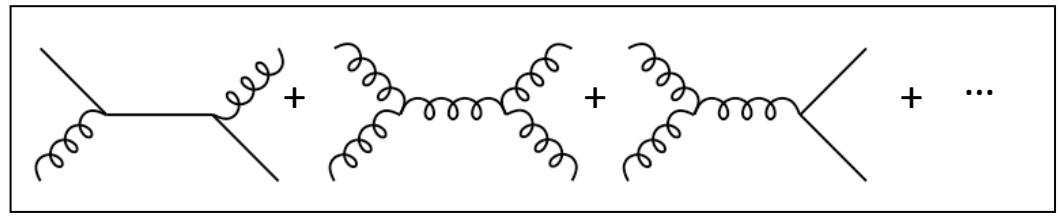
Beginning to be measured at RHIC

A future challenge



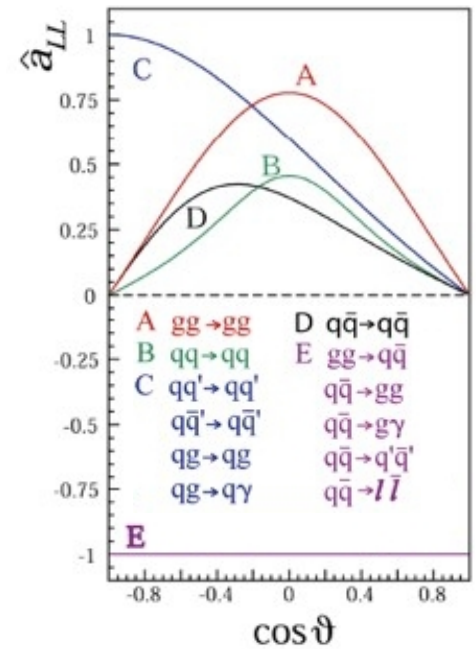
Δg and Polarized p+p Collisions





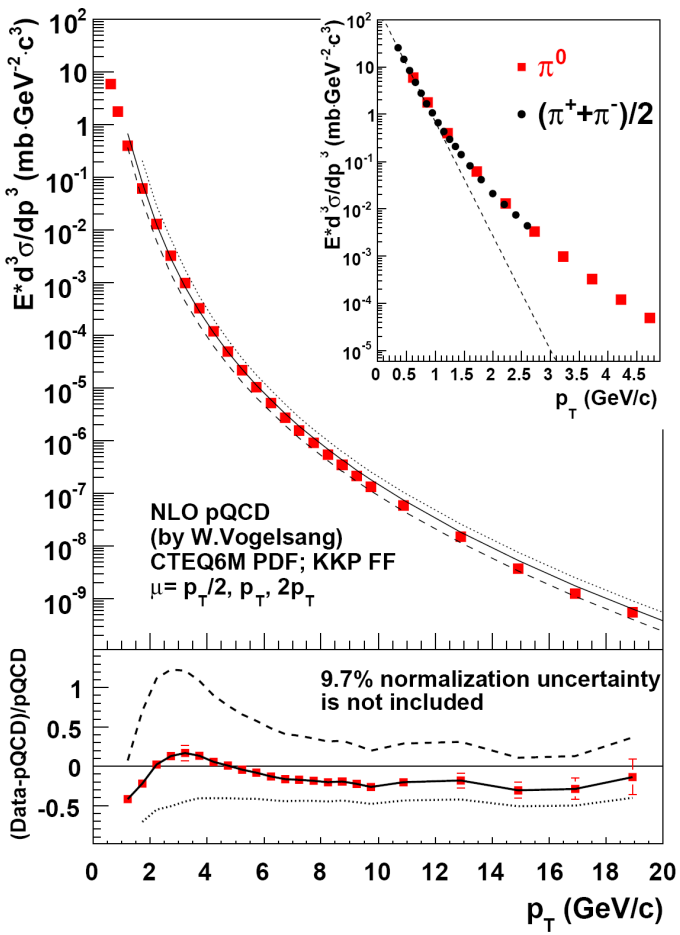
$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} = \frac{\sum_{a,b,c} \Delta f_a \otimes \Delta f_b \otimes d\hat{\sigma}^{f_a f_b \to f_c X} \cdot \hat{a}_{LL}^{f_a f_b \to f_c X} \otimes D_{f_c}^h}{\sum_{a,b,c} f_a \otimes f_b \otimes d\hat{\sigma}^{f_a f_b \to f_c X} \otimes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

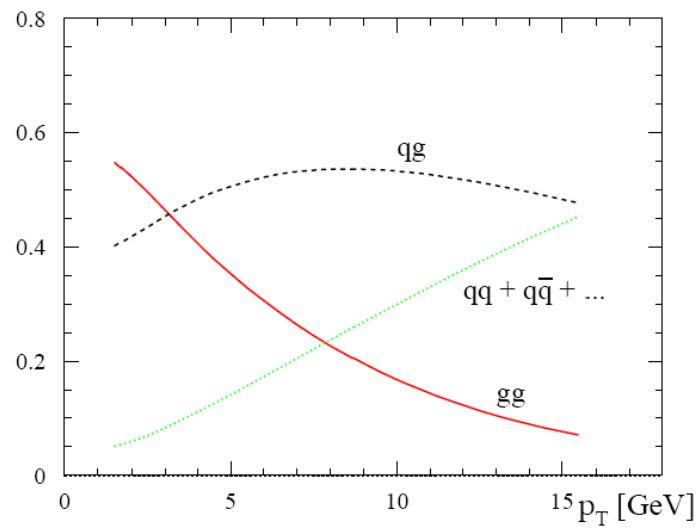
$$A_{LL} \approx a_{gg} \Delta g^2 + a_{qg} \Delta q \Delta g + a_{qq} \Delta q \Delta q'$$



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

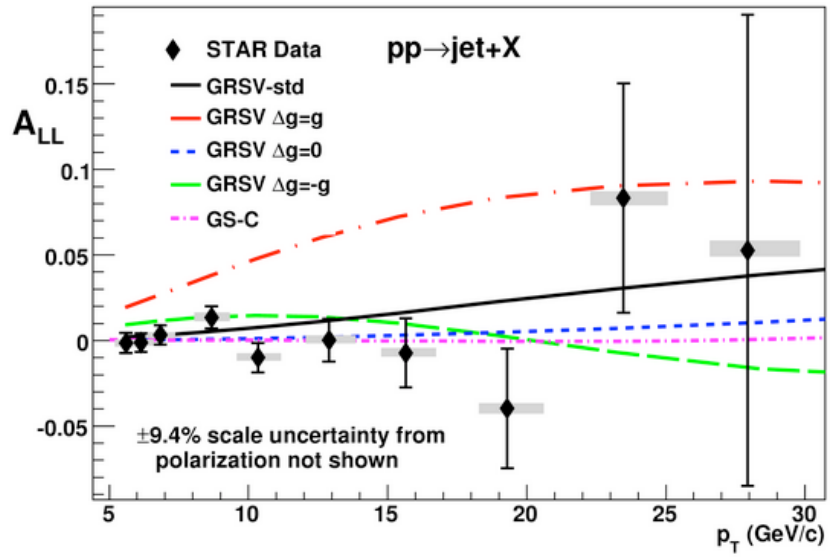
--- KKP and Kretzer Fragmentation Fcns

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

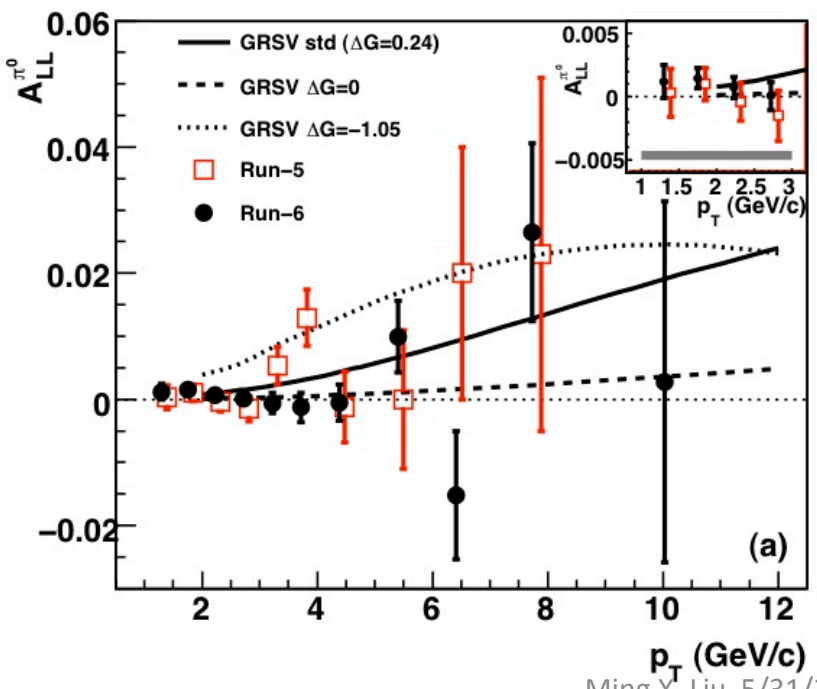
RHIC data and Δg

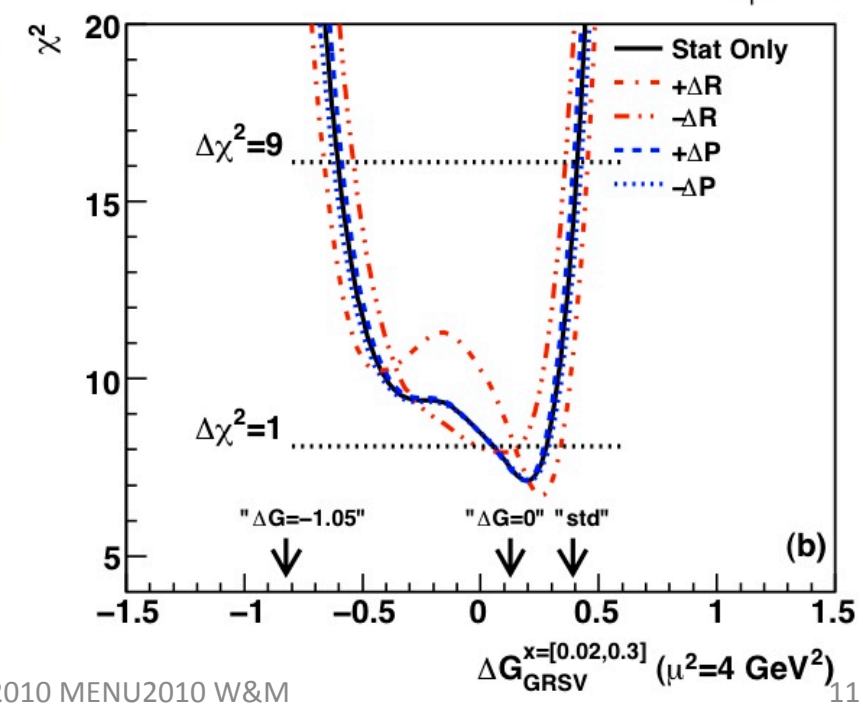
- PHENIX pi0
- STAR inclusive jets

STAR, PRL 100 232003 (2008)



PHENIX, PRL 103 012003 (2009)

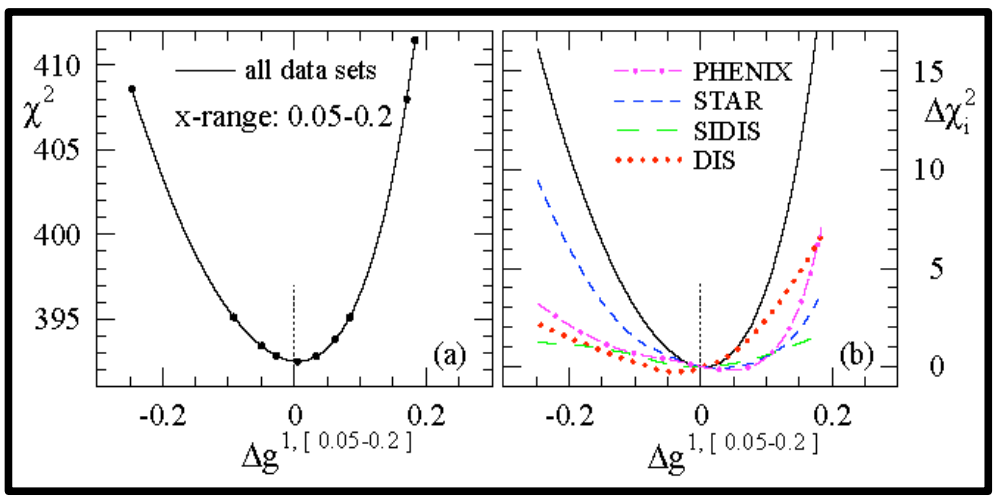




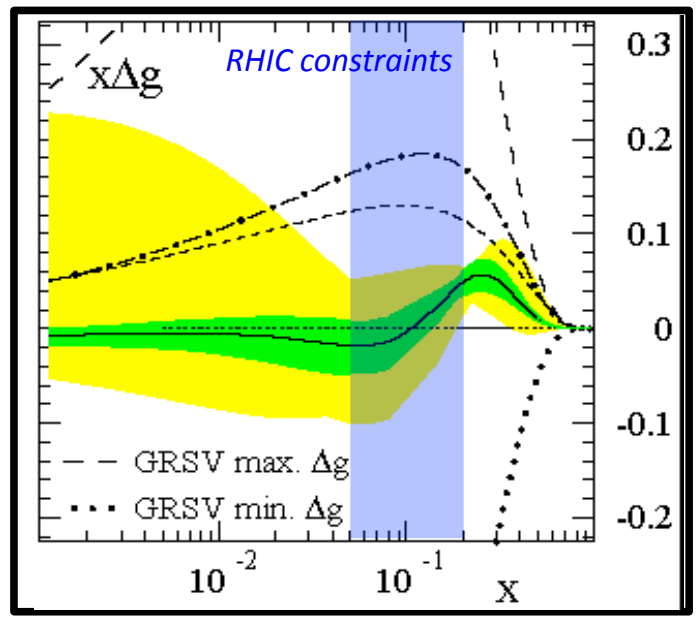
Impact of RHIC-Spin Program on Δg

- 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



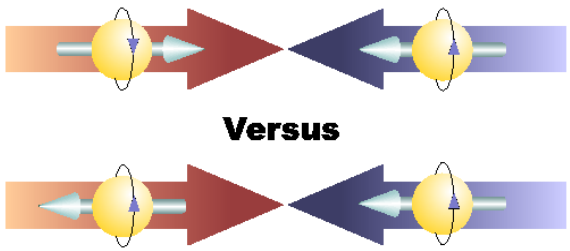
It is interesting to note that the best fit has a zero-crossing at x ≈ 0.1.

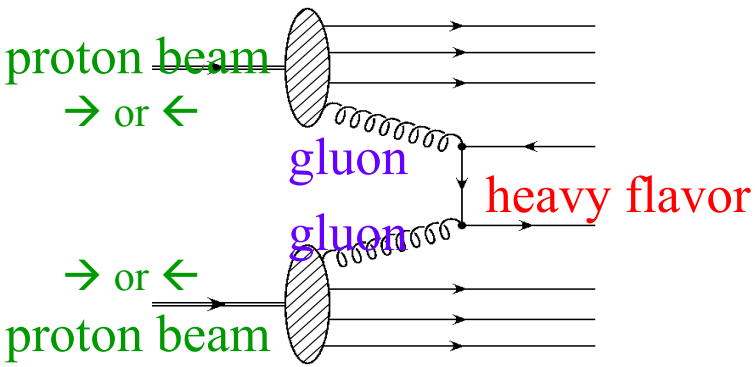
Future New Probes @RHIC: Δg

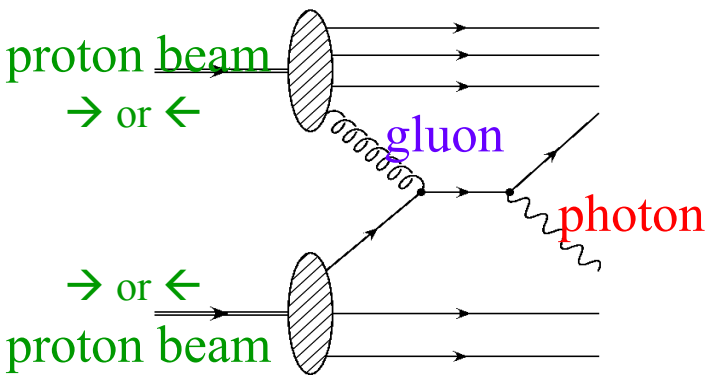
- Polarized hadron collisions
  - double longitudinal spin asymmetry

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

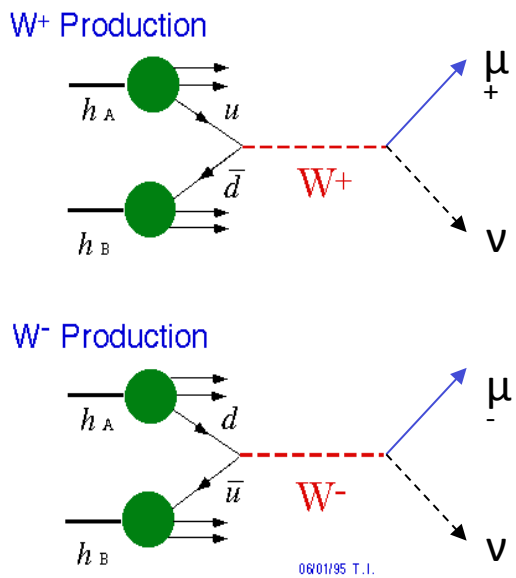
  - leading-order gluon interactions
    - direct-photon production
    - heavy-flavor production
    - Other channels (light hadrons etc.)

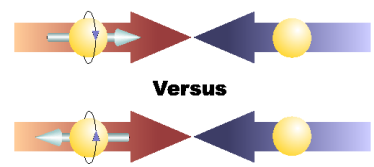






$W^{\pm}$ Production and A_L @500GeV

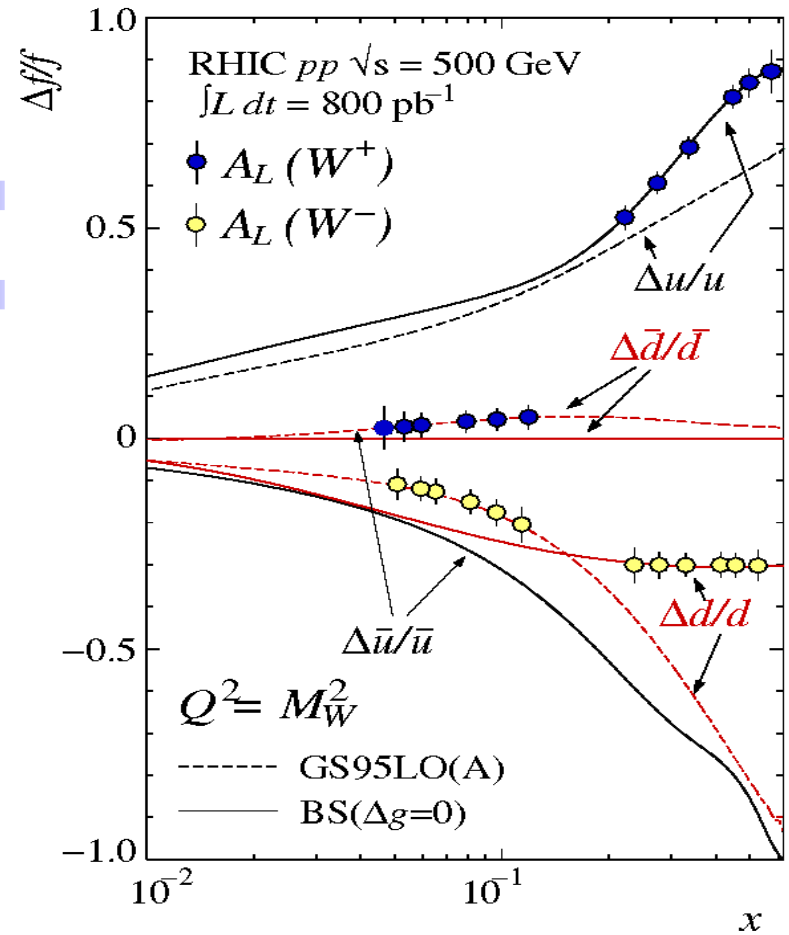




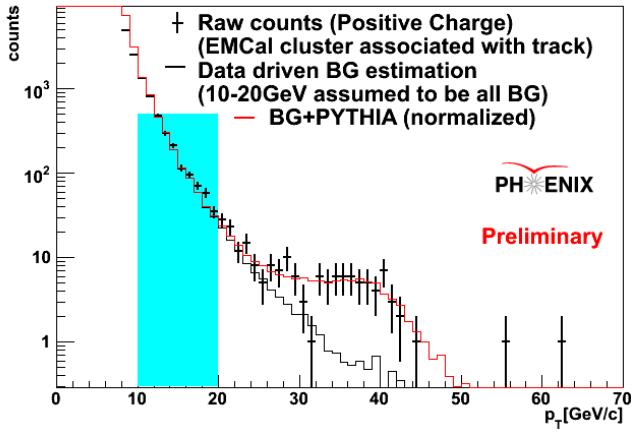
$$A_L^{W+} = \frac{\sigma^{\rightarrow} - \sigma^{\leftarrow}}{\sigma^{\rightarrow} + \sigma^{\leftarrow}} \propto \frac{\Delta\bar{d}(x_1)u(x_2) - \Delta u(x_1)\bar{d}(x_2)}{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)}$$

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

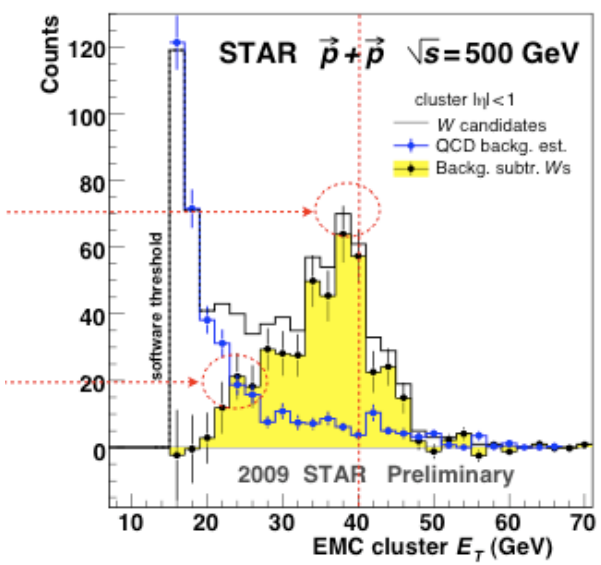
Bunce G. et al, hep-ph/0007218

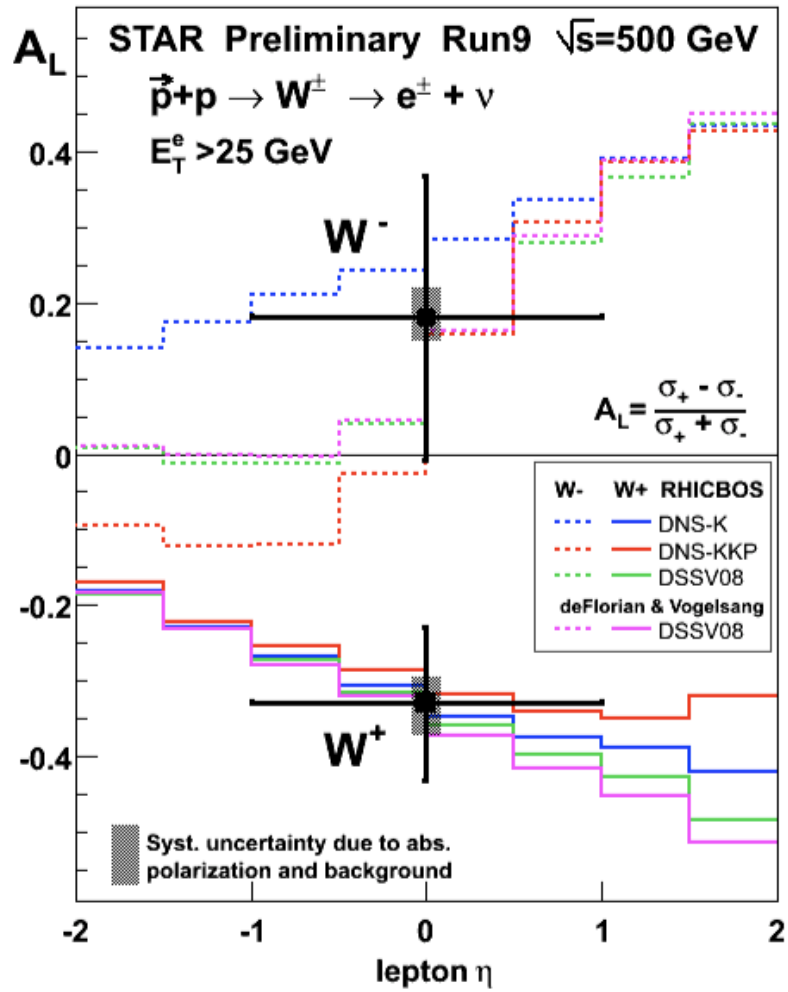


First $W^{\pm}$ Measurements from Run9 500 pp!



J. Seele (MIT): DNP 2009

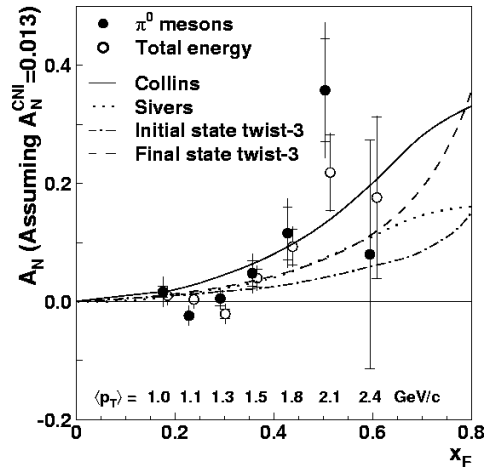




Part II: Transverse Spin Physics Program

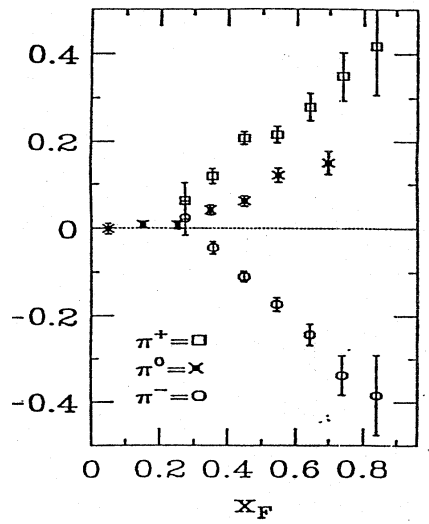
Large Transverse Single Spin Asymmetry (SSA) in forward meson production persists up to RHIC energy.

RHIC 20,000 GeV beam



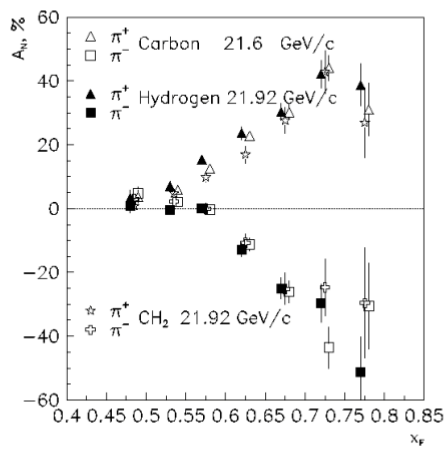
PRL (2004)

FNAL 200 GeV beam



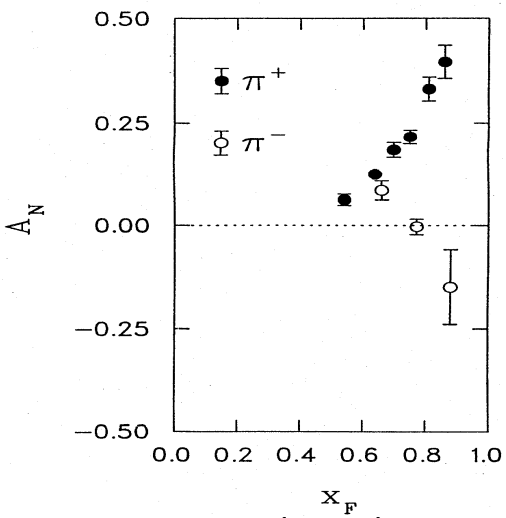
PLB261, 201 (1991)
PLB264, 462 (1991)

AGS 22 GeV beam

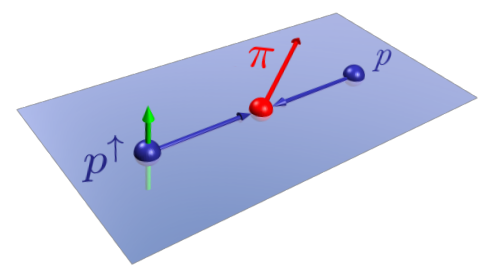


PRD65, 092008 (2002)

ZGS 12 GeV beam



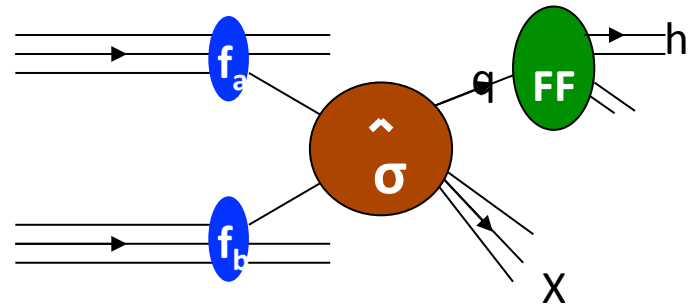
PRL36, 929 (1976)



Non-Perturbative cross section → Perturbative cross section

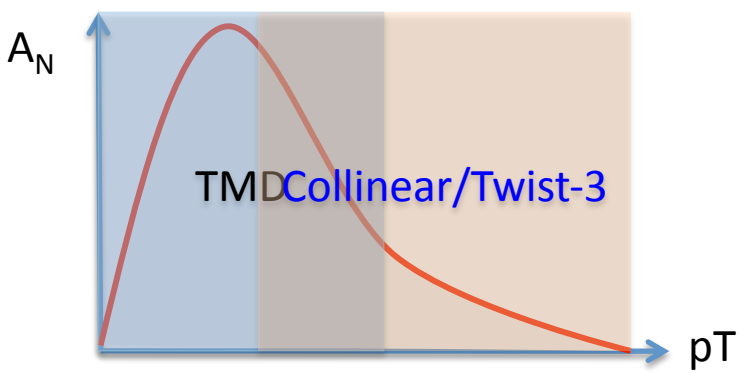
Theory: K_T vs Collinear Factorization

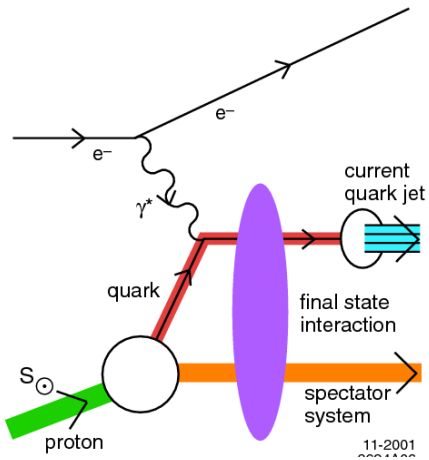
- Tran. Mom. Dep. Funs
  - Sivers Fun
  - Collins Fun

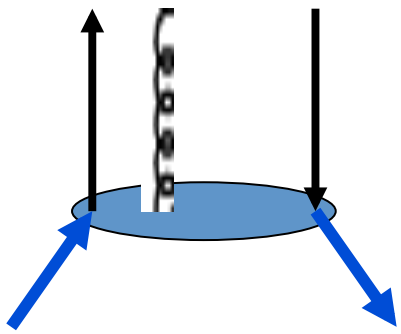


$$\frac{d^3\sigma^{\uparrow}\left(pp^{\uparrow} \to h + X\right)}{dx_1 dx_2 dz} \propto q_i^{\uparrow}(x_1, k_{q,T}) \cdot q_j(x_2) \times \frac{d^3\hat{\sigma}^{\uparrow}(q_i q_j \to q_k q_l)}{dx_1 dx_2} \times FF_{q_{k,l}}(z, p_{h,T})$$

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

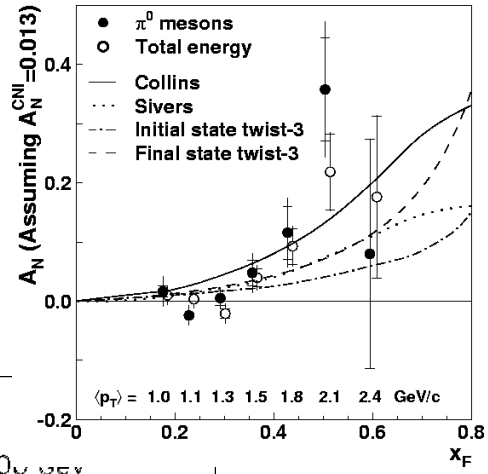


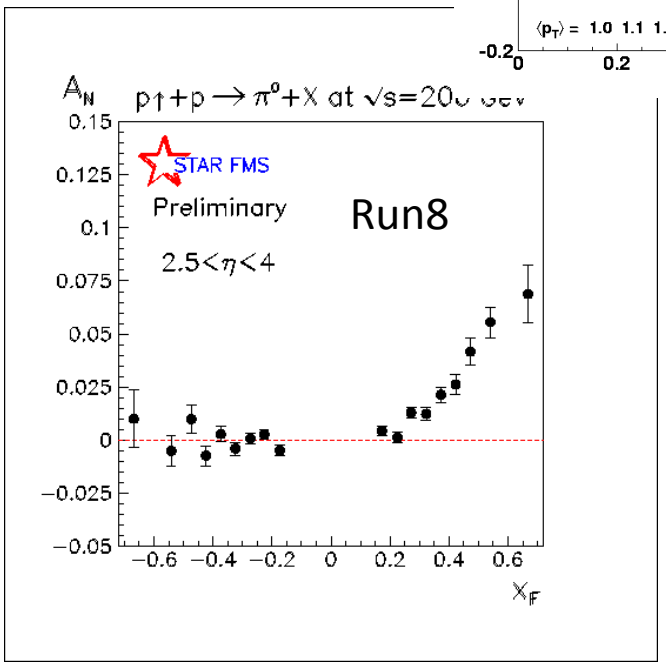




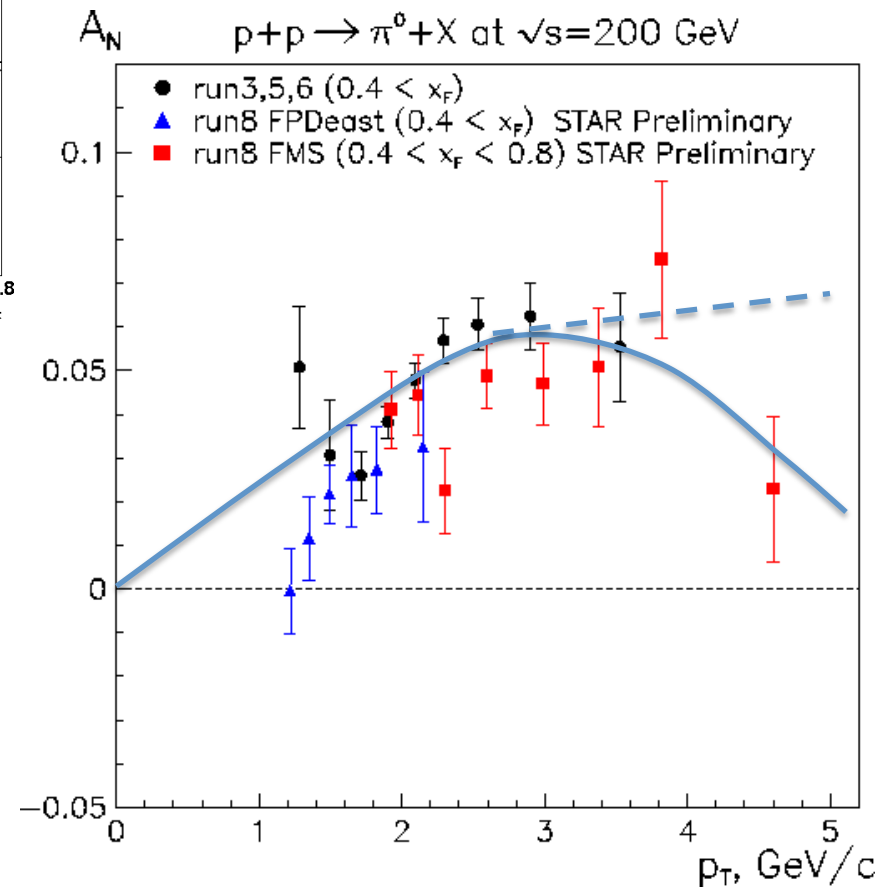
A_N P_T Dependence Remains as a Challenge

A_N vs x_F





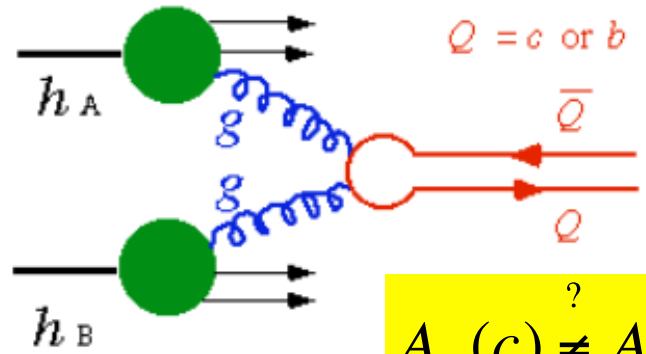
A_N vs p_T



Charm SSA to Probe Gluon Sivers Distribution

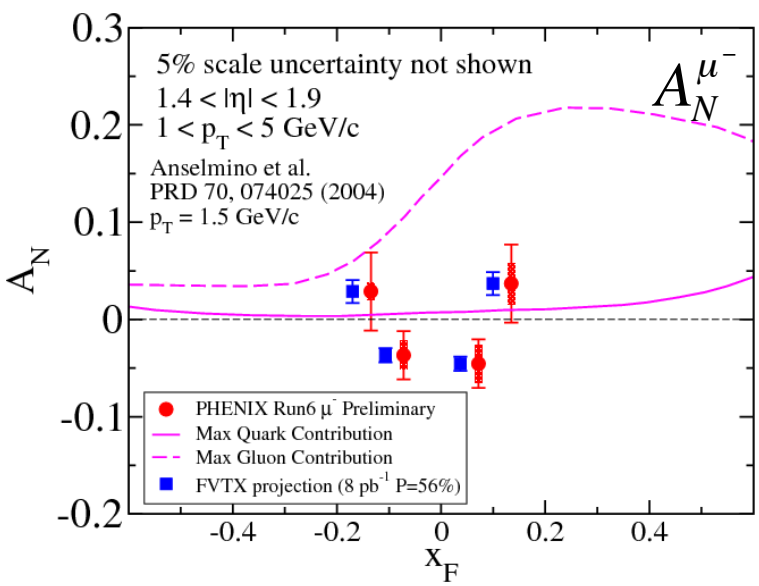
D meson Single-Spin Asymmetry:

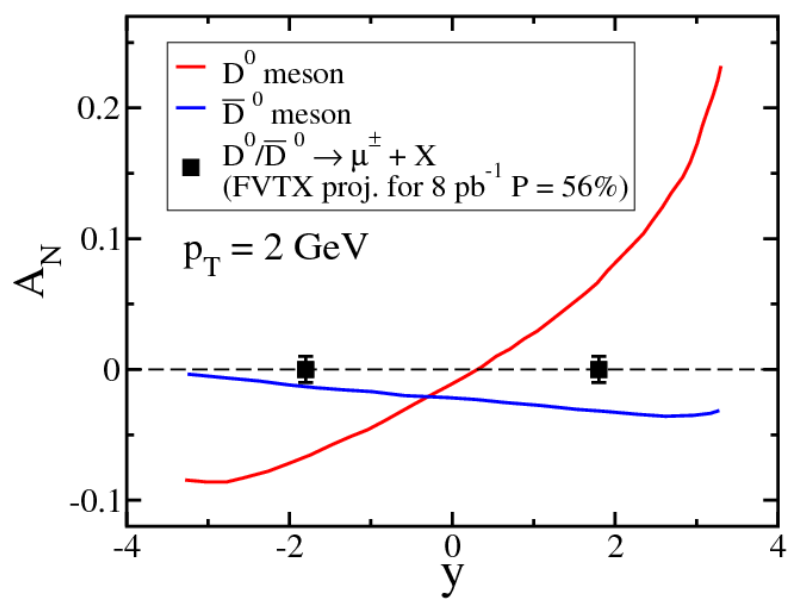
- Production dominated by gluon-gluon fusion
- Sensitive to gluon Sivers distribution
  - PHENIX-2006 data ruled out the max. gluon Sivers
  - Much improved results expected (Run2006+2008)



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

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

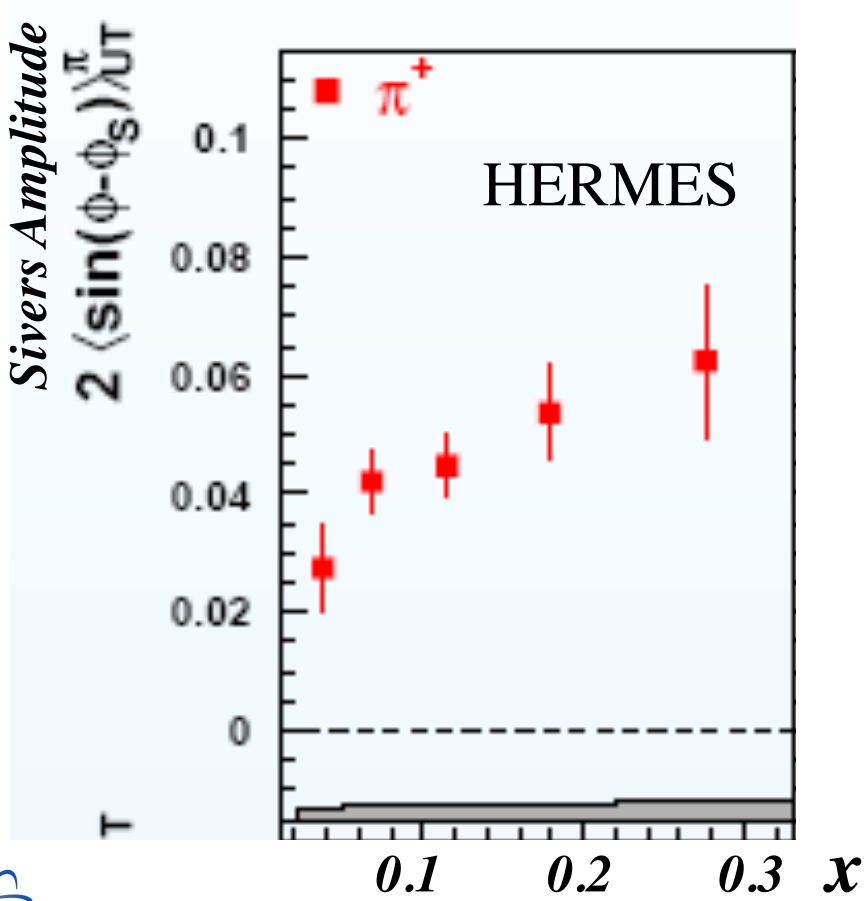


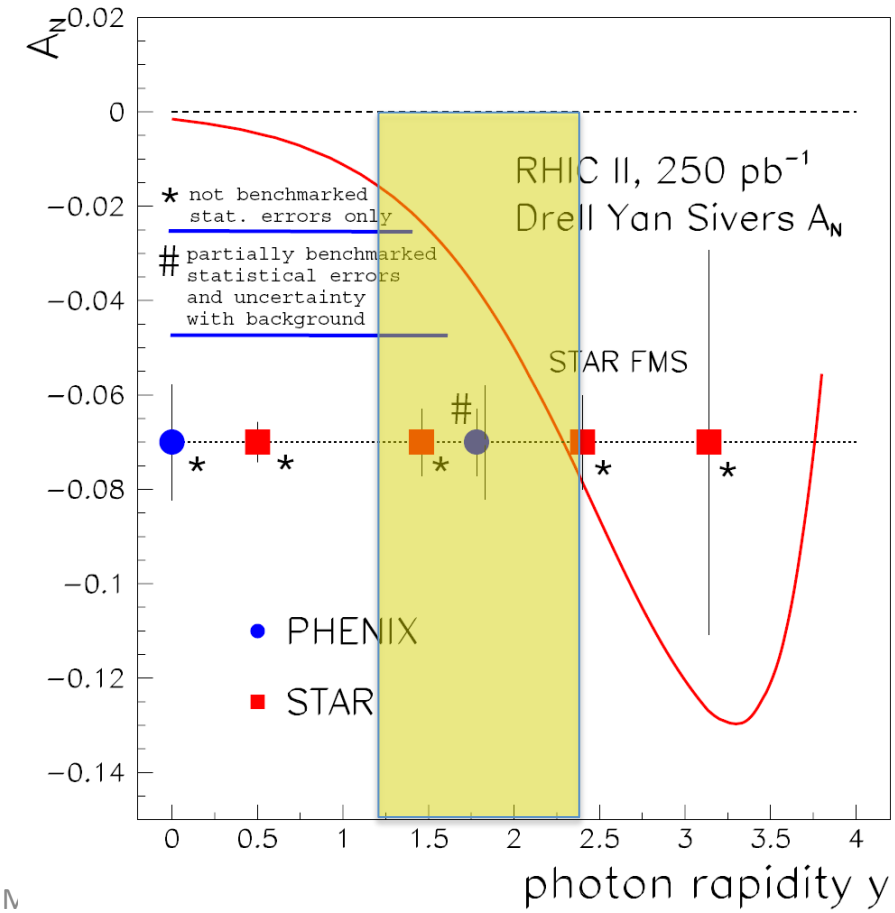


Future Transverse Spin Physics: A_N (Drell-Yan ->$\mu^+\mu^-$)

"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**





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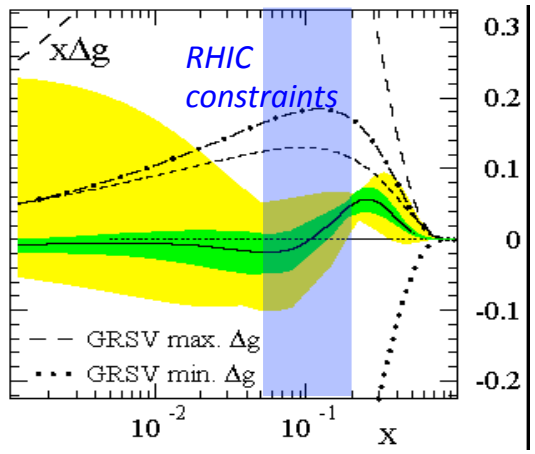
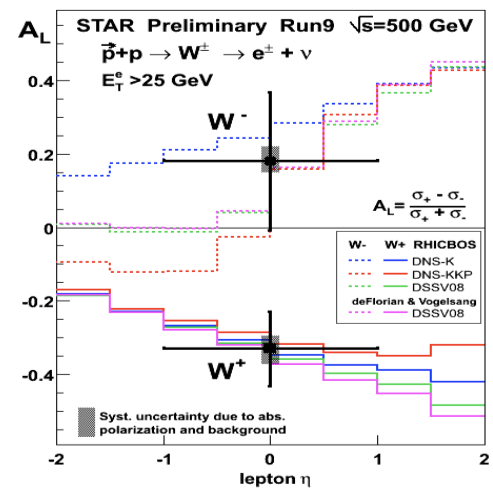
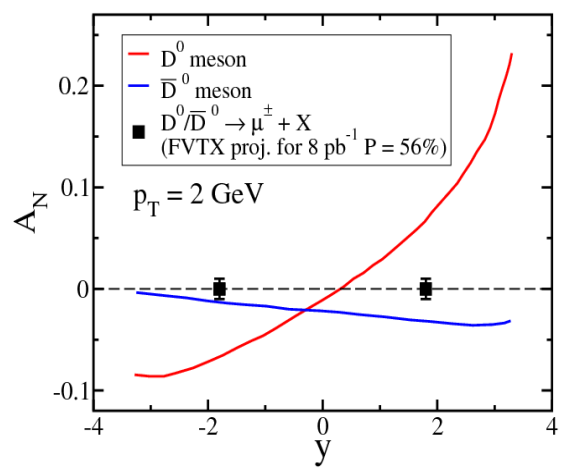
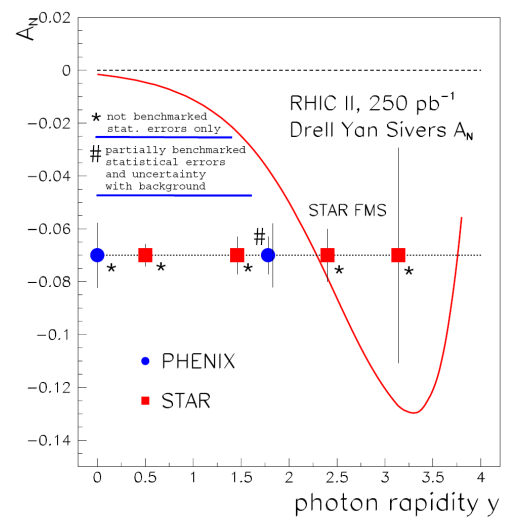
Summary and Outlook

- 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



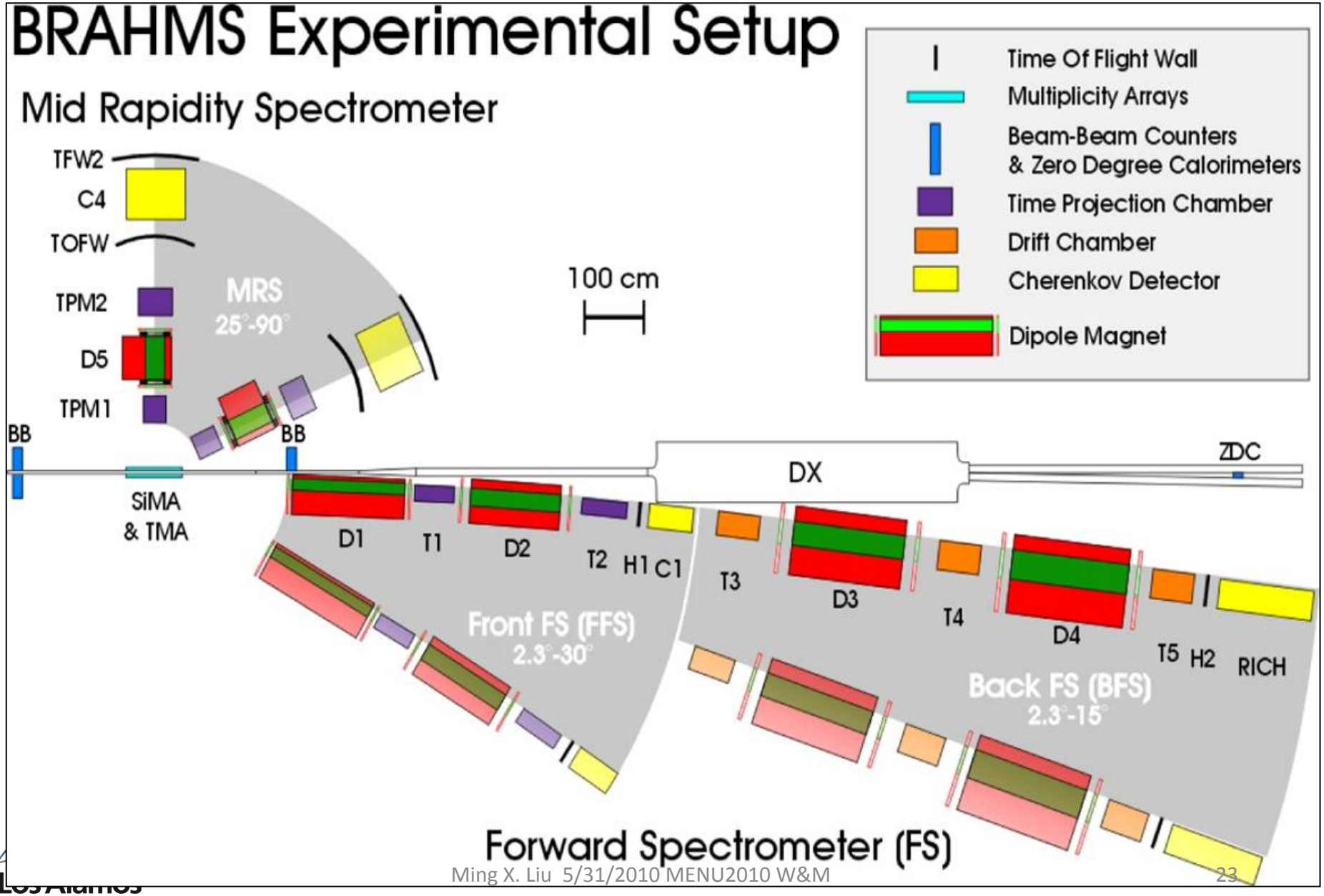






backup

BRAHMS Experimental Setup



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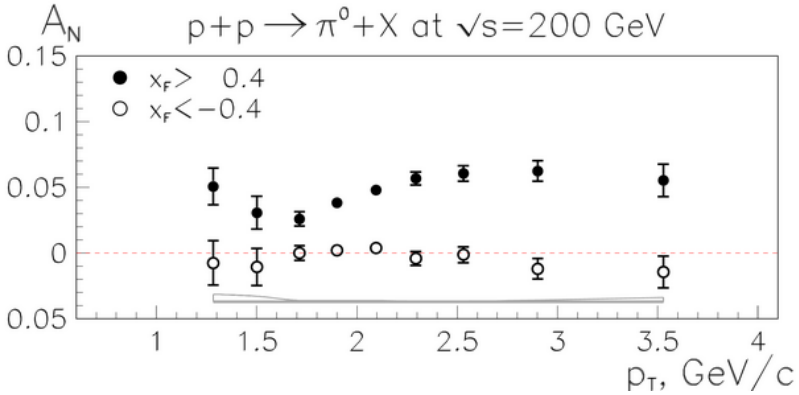
…but rising P_T dependence is not predicted by the same fits

Gordon AGS/RHIC 2008



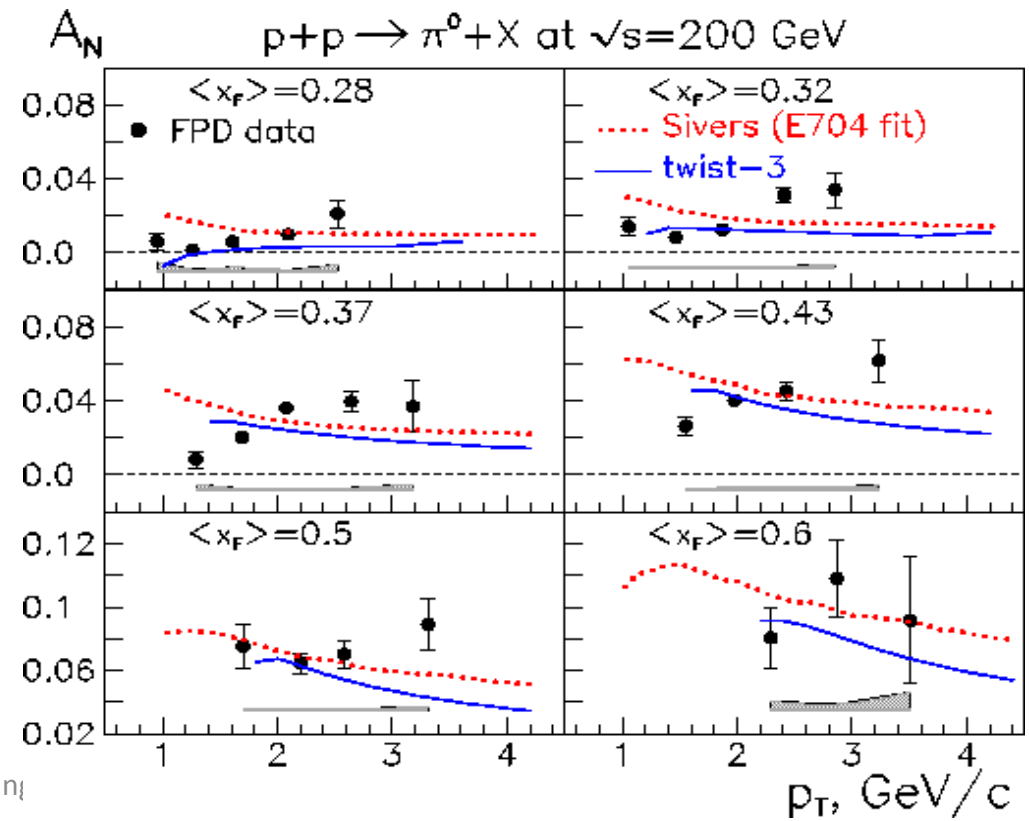
← X_F>0.4

Admixture of Collins and Sivers?

Current data can extend P_T reach of measurements

B.I. Abelev et al. (STAR) [arXiv:hep-ex/0801.2990v1],), submitted to PRL

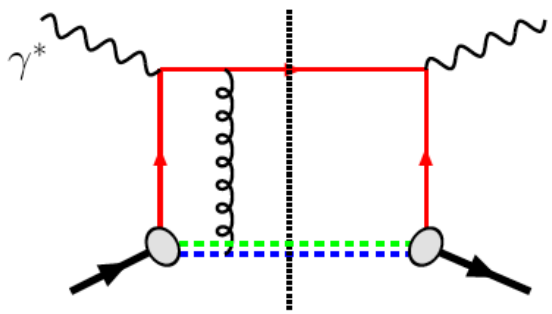
Data broken out in X_F bins →



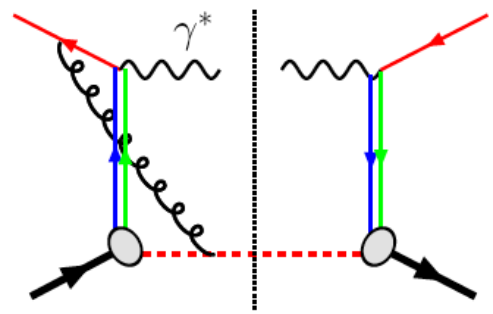
Attractive vs Repulsive "Sivers" Effects

Unique Prediction of Gauge Theory !

DIS: attractive



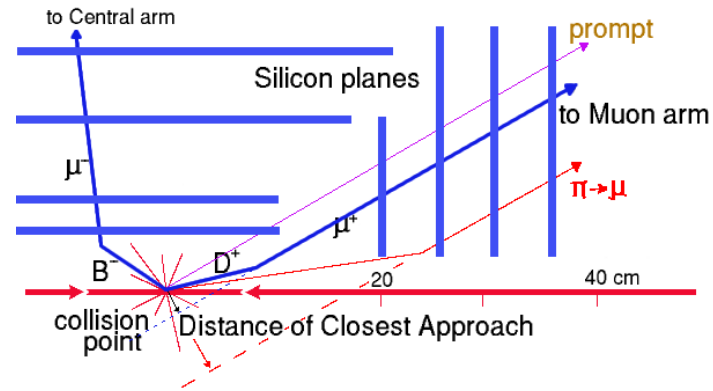
Drell-Yan: repulsive

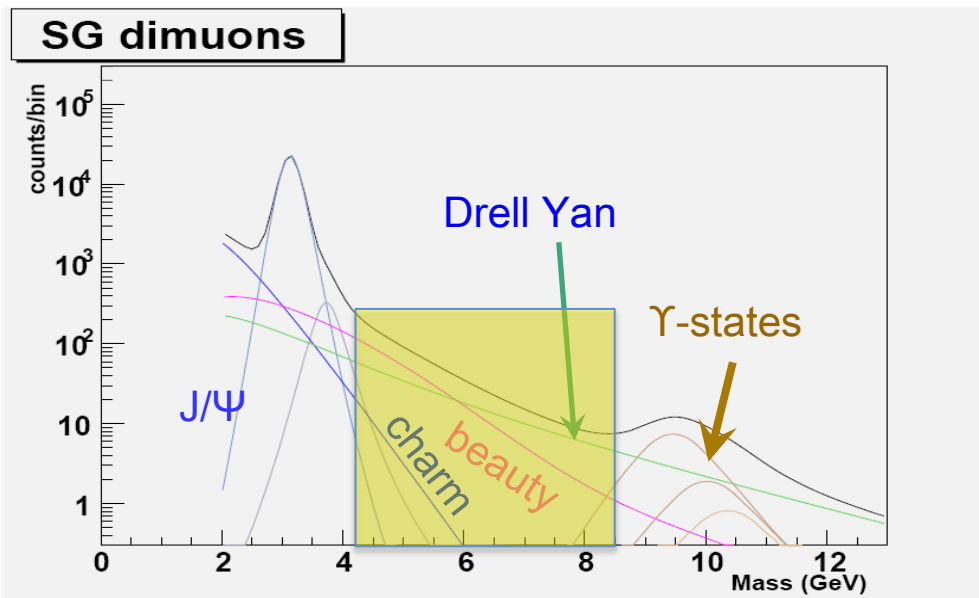


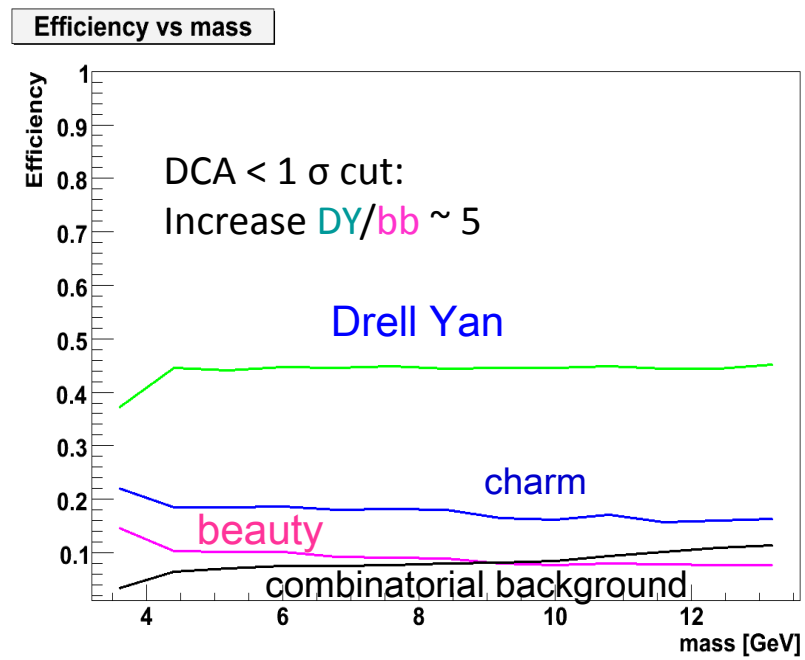
$$\text{Sivers}|_{\text{DIS}} = -\text{Sivers}|_{\text{DY}}$$

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

Transverse Physics

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

- 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

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

$$Z^0: \quad \delta A_N \approx \frac{1}{\sqrt{P^2 \cdot 2 \cdot N}}; \quad P = 0.6, \quad N = 380$$
$$\approx 6.0\%$$

Kang & Qiu PRL 103, 172001 (2009)

$W^{+/-}$

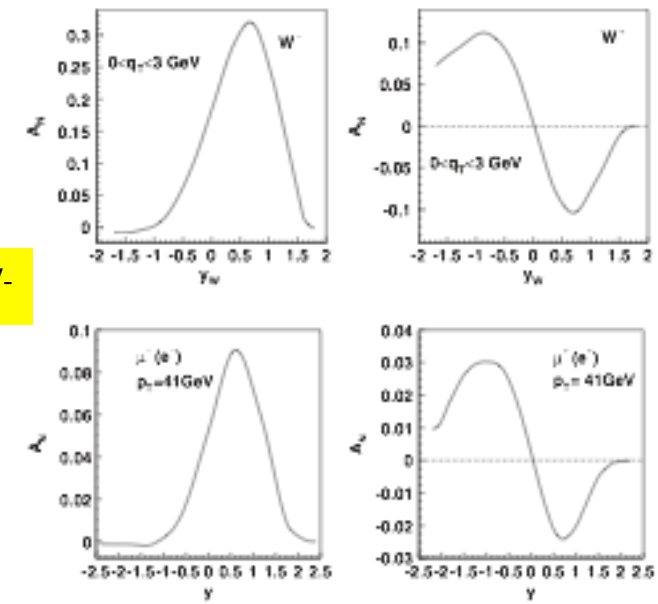


FIG. 3. A_N as a function of lepton rapidity.

Z^0

Kang & Qiu arX 0912.1319

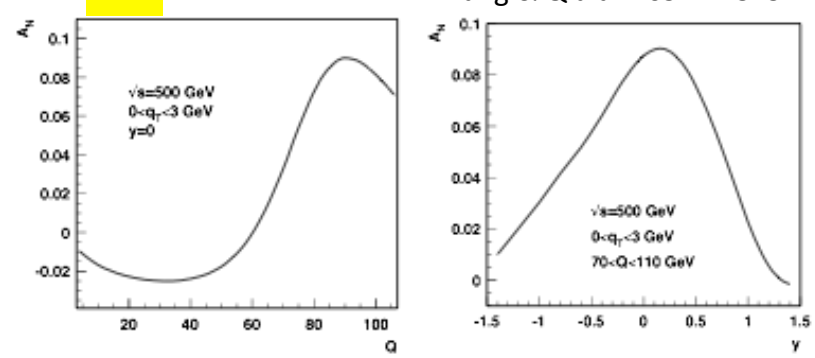


FIG. 3: Left: SSA of lepton pair production as a function of the pair's invariant mass Q. Right: SSA of lepton pair accumulated around Z^0 mass as a function of rapidity y.

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 ≈ 7.5 pb^{-1}/week) at $\sqrt{s} = 200$ GeV

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

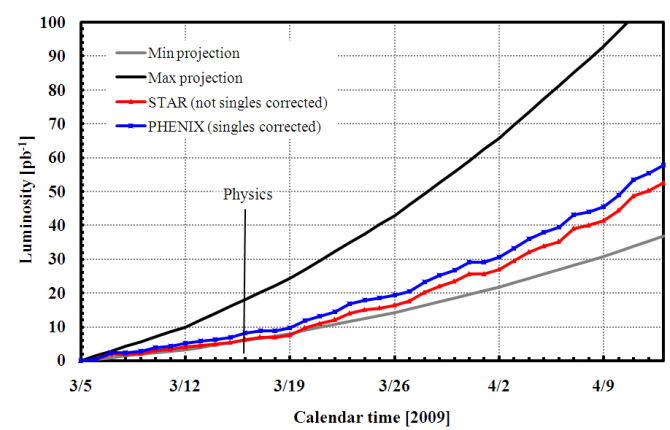
PHENIX(ε=1/3) = 30pb^{-1}

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}

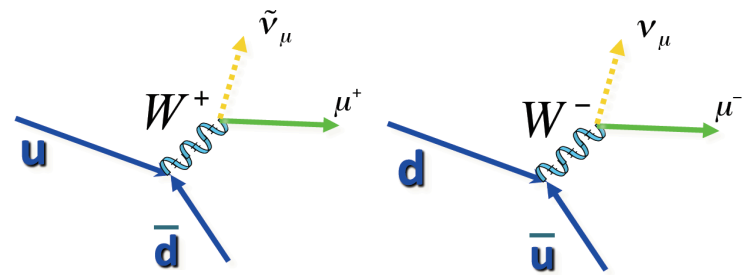
CAD Delivered Run9@500GeV



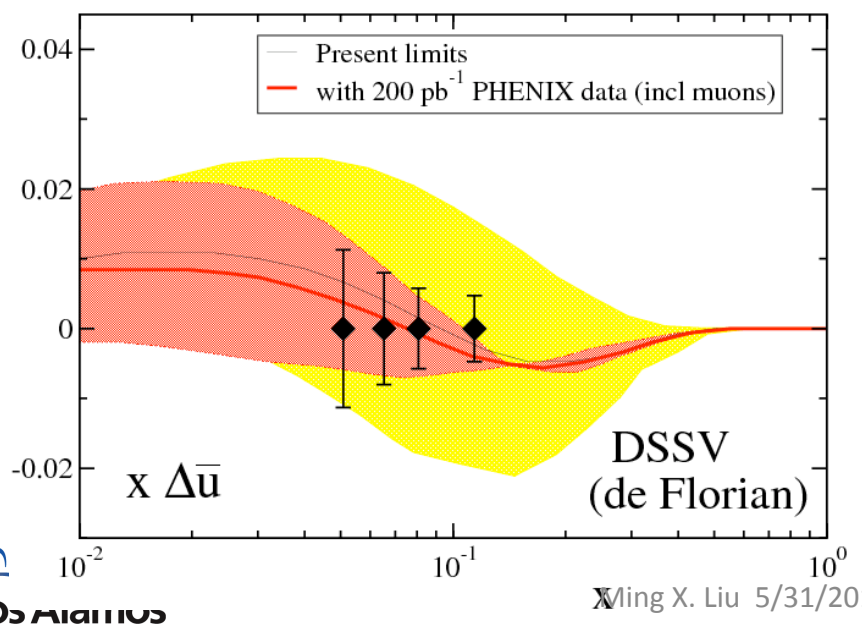
Δq and $\Delta\bar{q}$ through $W^{\pm}$ decay

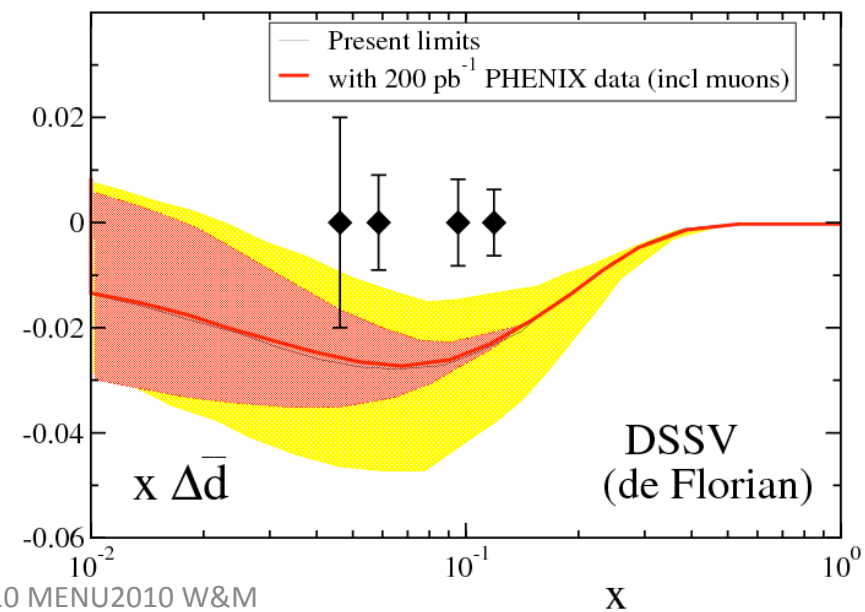
(DOE Milestone HP8, 2013)

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



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





Effect of uncertainties on antiquark distributions over asymmetries

already pretty tight bands! (partly from SIDIS)

Daniel de Florian, RSC'09