Spin Physics at RHIC

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– Spin Crisis and Polarized PDF
– Test of (p)QCD with Spin

Curiosity & Fascination of Spin is Universal!

1955 Bohr & Pauli trying to understand the dynamics of a tippy-top toy

Why spin physics?

- Spin is a fundamental degree of freedom originated from the space-time symmetry.
- Spin plays a critical role in determining the basic structure of fundamental interactions.
- Test of a theory is not complete without a full test of spin-dependent decays and scattering.
- Spin provides a unique opportunity to probe the inner structure of a composite system (such as the proton) and hence testing our ability to understand the working of non-perturbative QCD.

Part I: Spin Crisis and Polarized PDF

- Key measurements from RHIC:
  - Gluon polarization

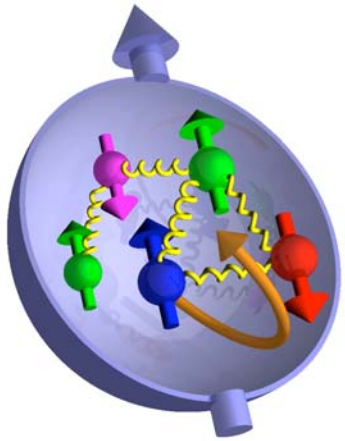
$$\Delta G(x)$$

  - Flavor identified quark polarization

$$\Delta u(x), \Delta d(x)$$

$$\Delta \bar{u}(x), \Delta \bar{d}(x)$$

The 20-year Old Proton Spin Puzzle



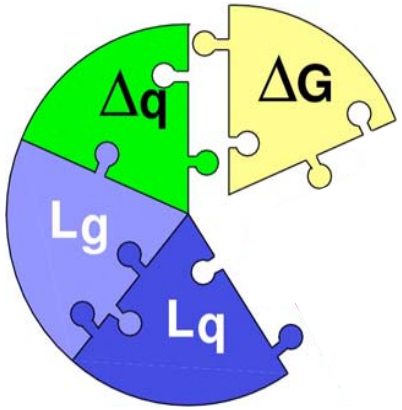
The proton is viewed as being a "bag" of bound quarks and gluons interacting via QCD

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

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

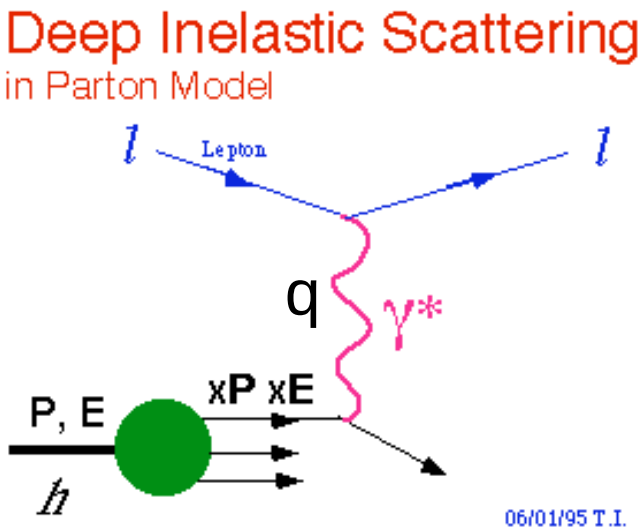
Fairly well measured only ~30% of spin

Beginning to be measured at RHIC



A future challenge

A little Bit of History



- DIS cross section

$$d\sigma \propto \frac{\alpha^2}{Q^4} L_{\mu\nu}(k,q,s) W^{\mu\nu}(P,q,S)$$

$$W^{\mu\nu}(P,q,S) = -(g^{\mu\nu} - \frac{q^\mu q^\nu}{q^2})F_1(x,Q^2) + (p^\mu - \frac{P\cdot q}{q^2}q^\mu)(p^\nu - \frac{P\cdot q}{q^2}q^\nu)\frac{1}{P\cdot q}F_2(x,Q^2)$$

$$-i\varepsilon^{\mu\nu\lambda\sigma}q_\lambda[\frac{M\cdot S_\sigma}{P\cdot q}\{g_1(x,Q^2)+g_2(x,Q^2)\} - \frac{M\cdot S\cdot qP_\sigma}{P\cdot q}g_2(x,Q^2)]$$

- @Bjorken limit in parton model:

$$Q^2 \to \infty$$

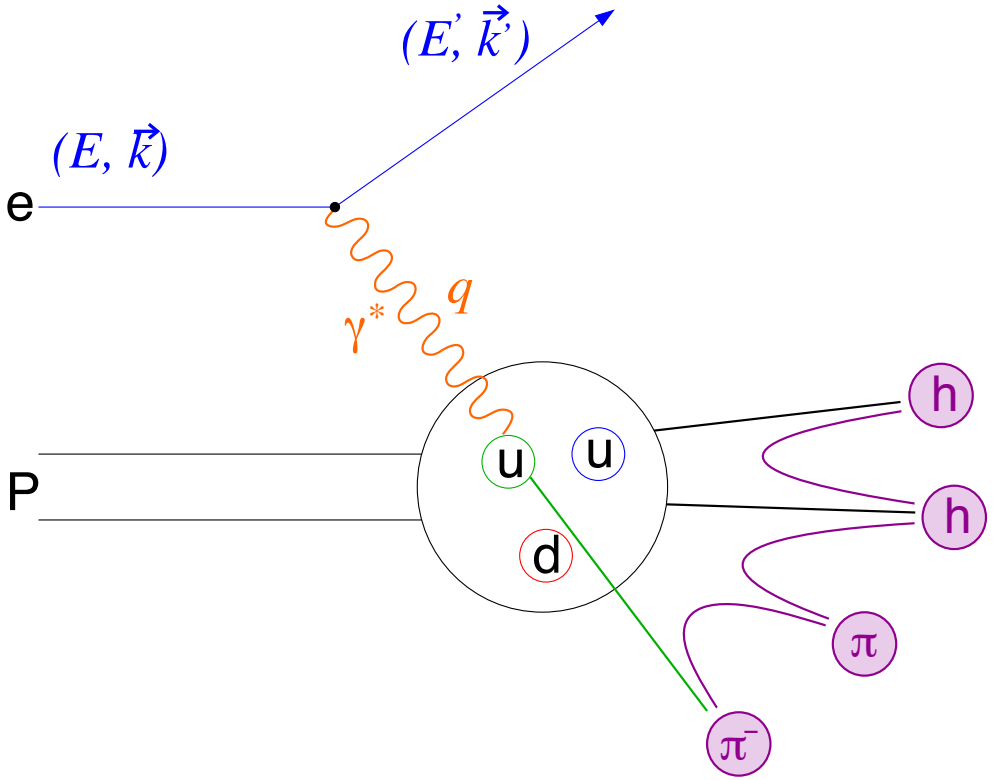
$$F_2(x) = 2xF_1(x)$$

$$g_2(x) = 0$$

$$F_1(x) = \frac{1}{2}\sum_f e_f^2[q_f^+(x) + q_f^-(x)] = \frac{1}{2}\sum_f e_f^2 q_f(x)$$

$$g_1(x) = \frac{1}{2}\sum_f e_f^2[q_f^+(x) - q_f^-(x)] = \frac{1}{2}\sum_f e_f^2 \Delta q_f(x)$$

Semi-Inclusive Deep Inelastic Scattering



$$Q^2 = -q^2 = -(k - k')^2$$

$$\nu \overset{\text{lab}}{=} E - E'$$

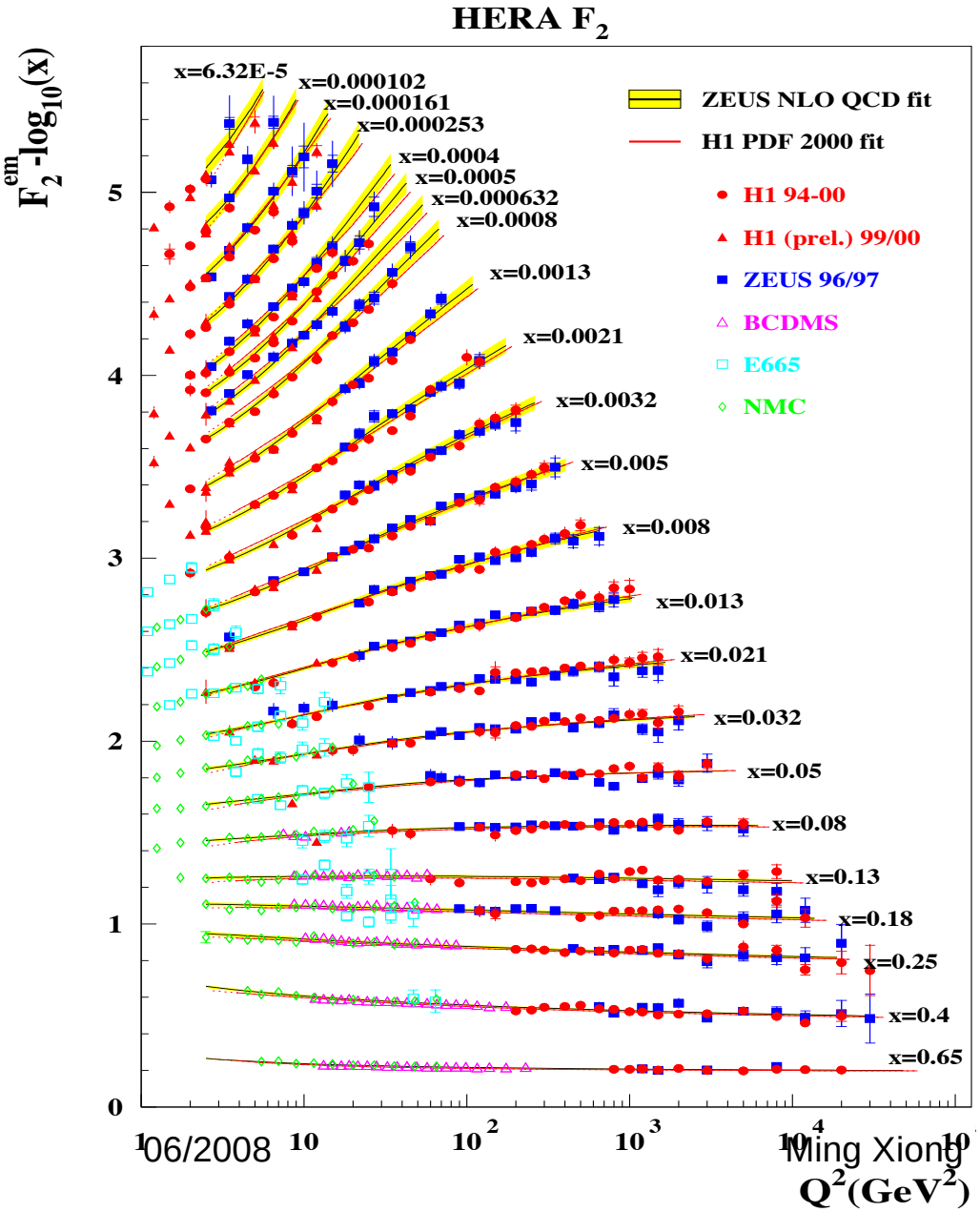
$$x = \frac{Q^2}{2M\nu}$$

$$z \overset{\text{lab}}{=} \frac{E_{had}}{\nu}$$

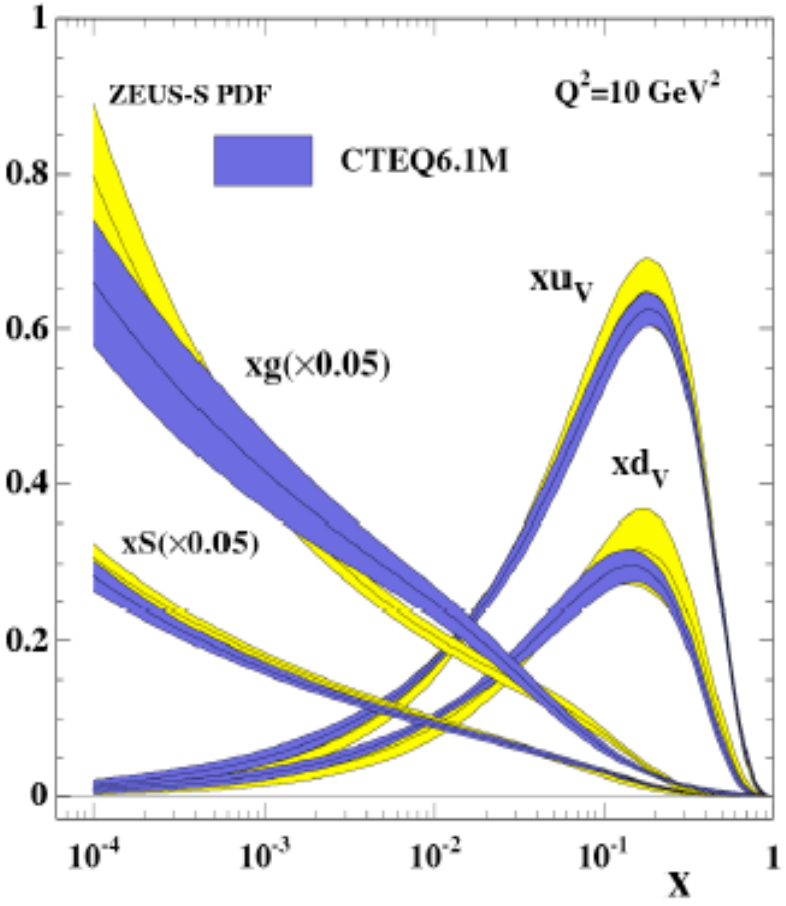
The cross section can be expressed as a convolution of a distribution function and a fragmentation function.

$$\sigma^{ep\to eh} \sim \sum_q DF^{p\to q} \otimes \sigma^{eq\to eq} \otimes FF^{q\to h}$$

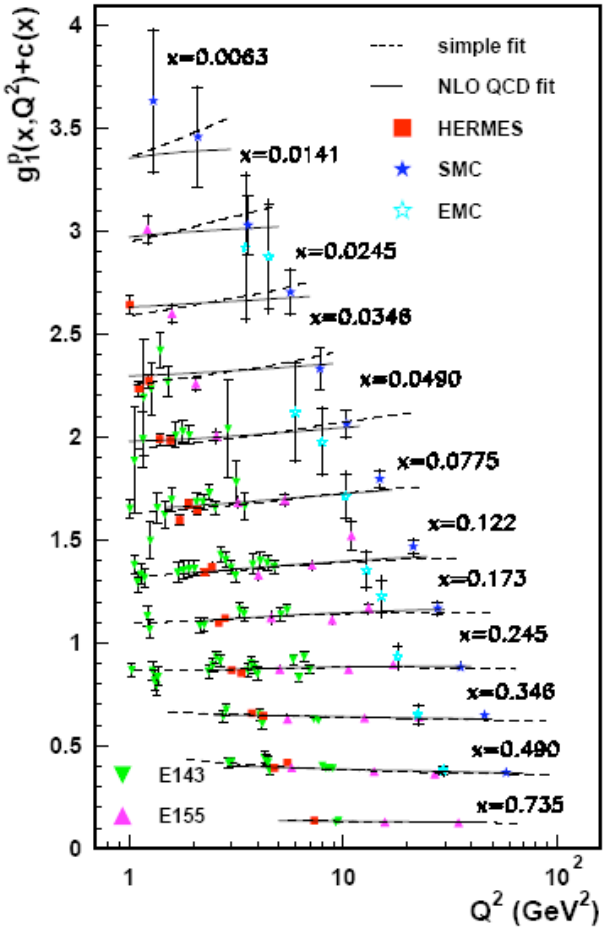
World Data on F_2^p Structure Function

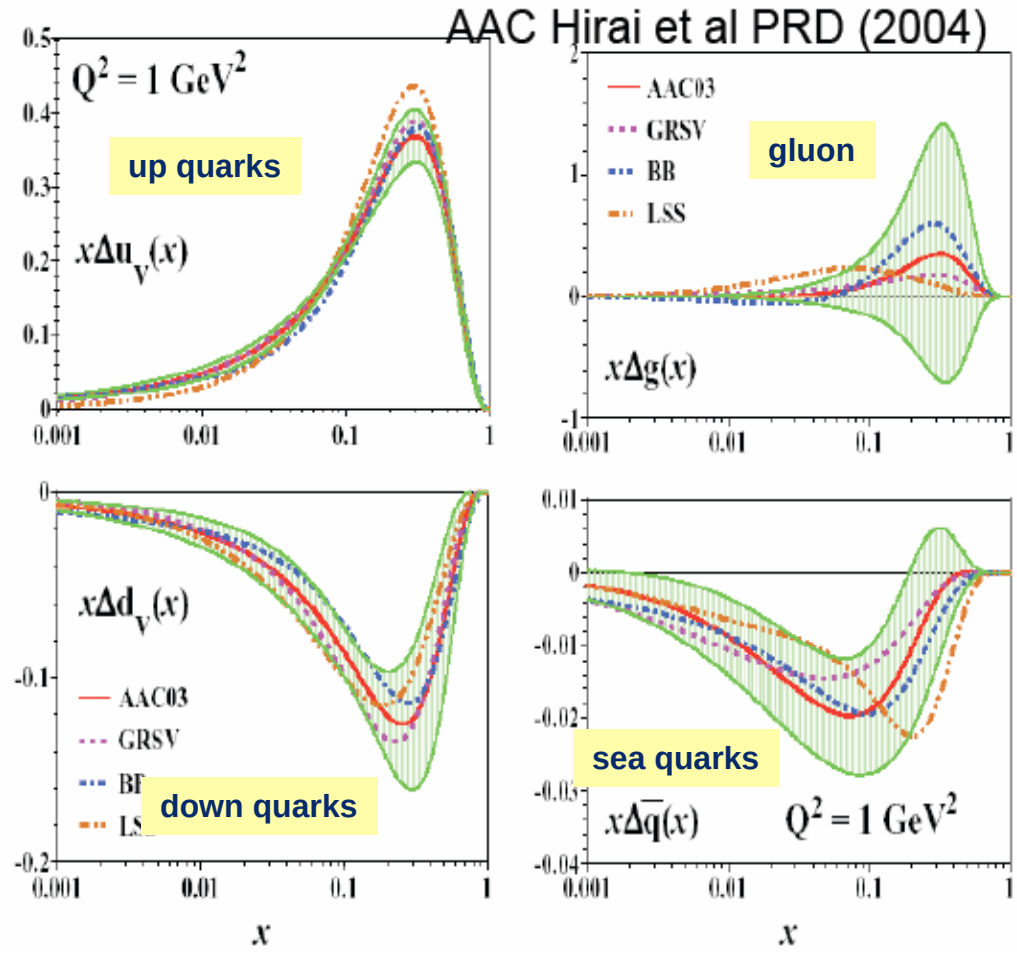


Next-to-Leading-Order (NLO) perturbative QCD (DGLAP) fits



Polarized Quark and Gluon Distributions

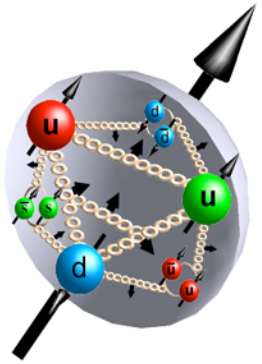




Spin Crisis and Gluon Polarization

- Proton Spin Puzzle:

$$\frac{1}{2} = \frac{1}{2}\Delta q + \Delta G + \Delta L_{G+q}$$
$$= J_q + J_G$$



$$\Delta q \approx 0.3 \; vs \; \Delta q^{QCD} \approx 0.6$$

- Asymptotic limit: $Q^2 \to \infty$

Ji:

$$J_q(Q^2) = \frac{1}{2}\Delta q + \Delta L_q \to \frac{1}{2}\frac{3n_f}{16+3n_f}$$
$$J_G(Q^2) = \Delta G + \Delta L_G \to \frac{1}{2}\frac{16}{16+3n_f}$$

- PCAC

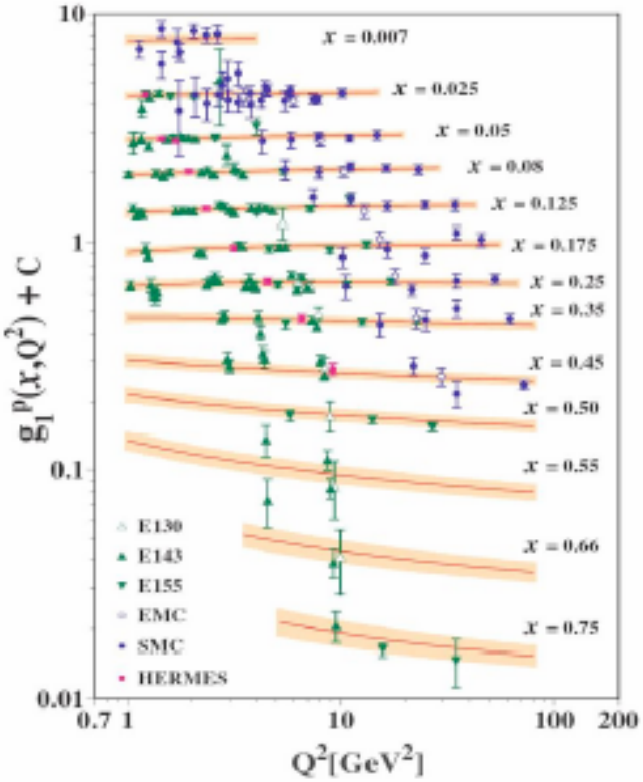
$$\Delta\tilde{q}^{\exp} = \Delta q - N_f \frac{\alpha_s}{2\pi}\Delta G$$
$$\Delta q = 0.6 \to \Delta G \sim 3$$

Gluons may play a significant role !

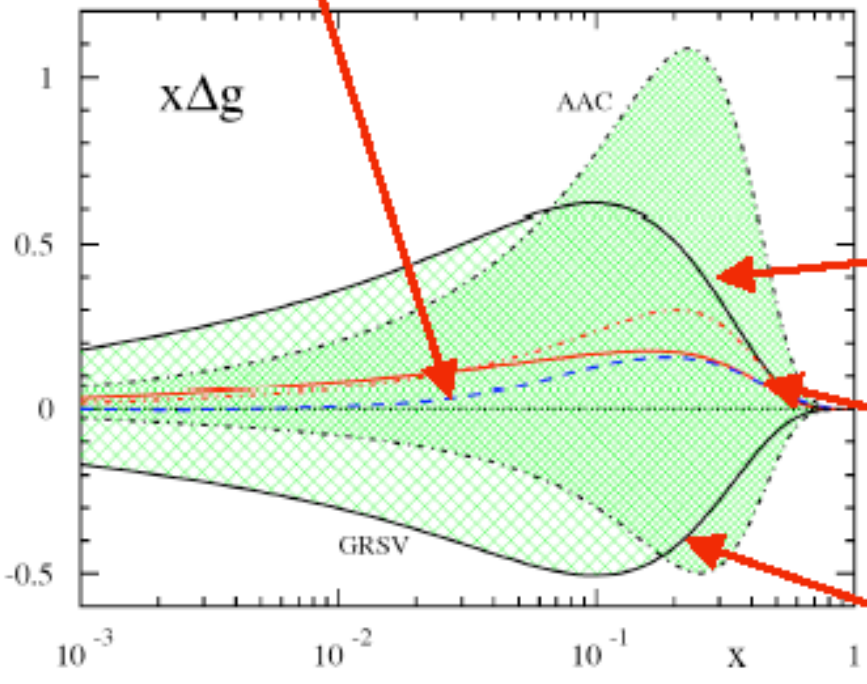
The gluon spin distribution Δg

Not much information until recently:

$$\frac{d\,g_1}{d\log(Q^2)} \propto \frac{\alpha_s}{2\pi} P_{qg} \otimes \Delta g(x,Q^2) \; + \; \text{quark contrib.}$$



Bag model Chen, Ji $\Delta G \approx 0.3$



$\Delta G \approx 1.8$ (@ 1GeV^2)

"axial anomaly" Altarelli et al.

$\Delta G \approx 0.4$

$\Delta G \approx -1.7$

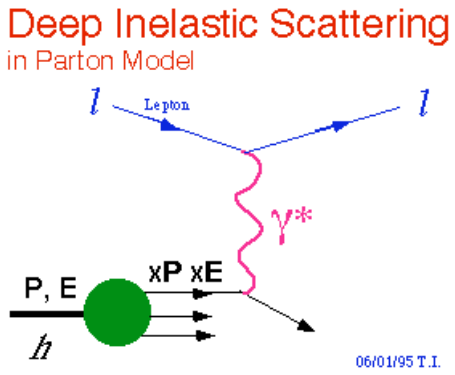
RHIC-Spin Physics

New Frontier of Nucleon Structure Research

- Proton Spin - **a major puzzle from polarized DIS experiments**
  - Proton Spin Decomposition

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \Delta L_{q+g}$$

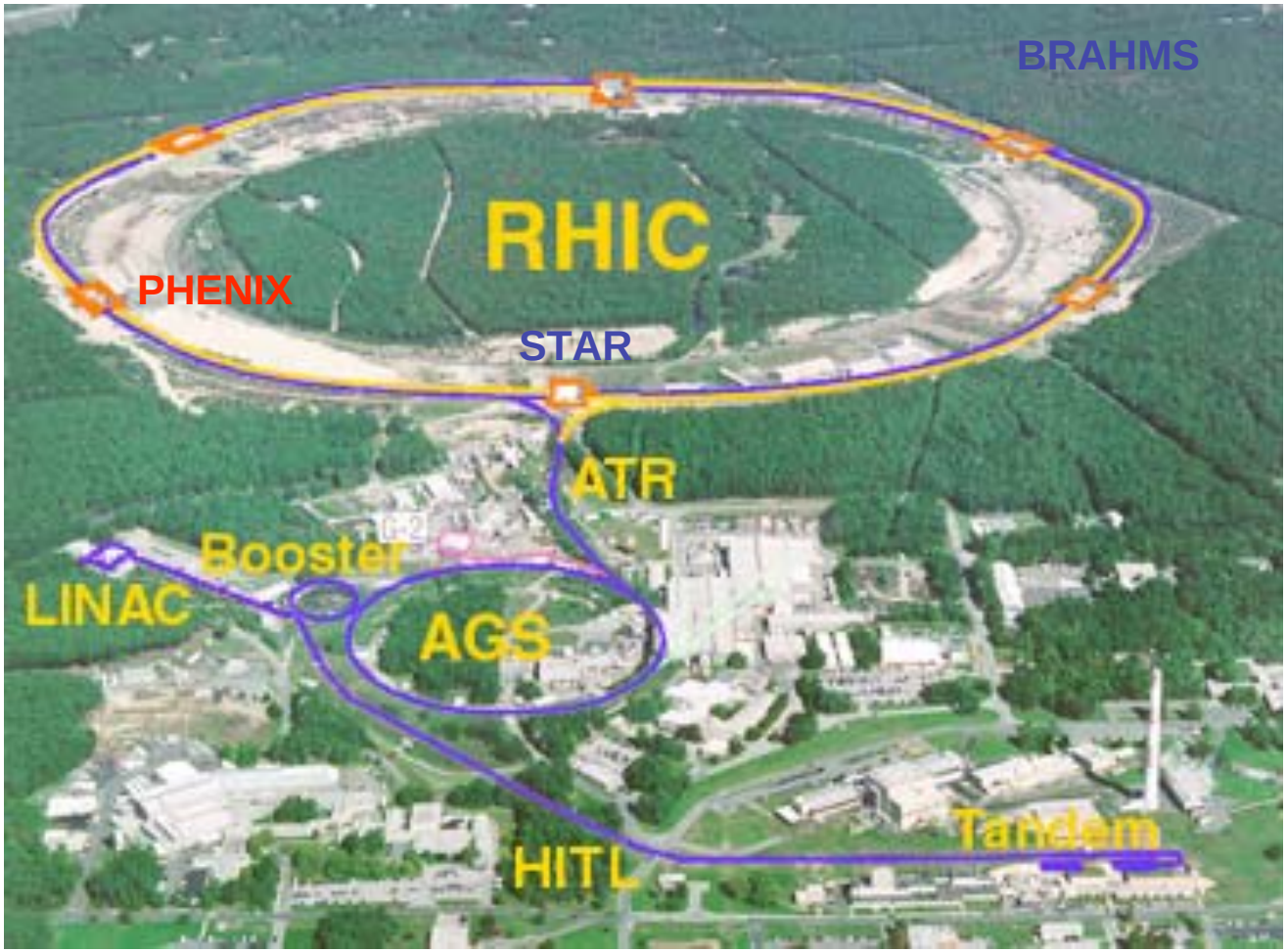
$$\textit{Experimentally} \Longrightarrow \quad \Delta\Sigma = 0.31 \pm 0.04$$



- Origin of Proton Spin:
  - ***gluon, sea quarks, orbital angular momentum ?***
  - **DIS can't directly probe gluons and anti-quarks @LO**

- a new tool : RHIC-SPIN
  - **a polarized proton collider**
  - **quark-gluon, quark-quark and gluon-gluon interactions**
  - **directly explore gluon and sea quark distributions**

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

…

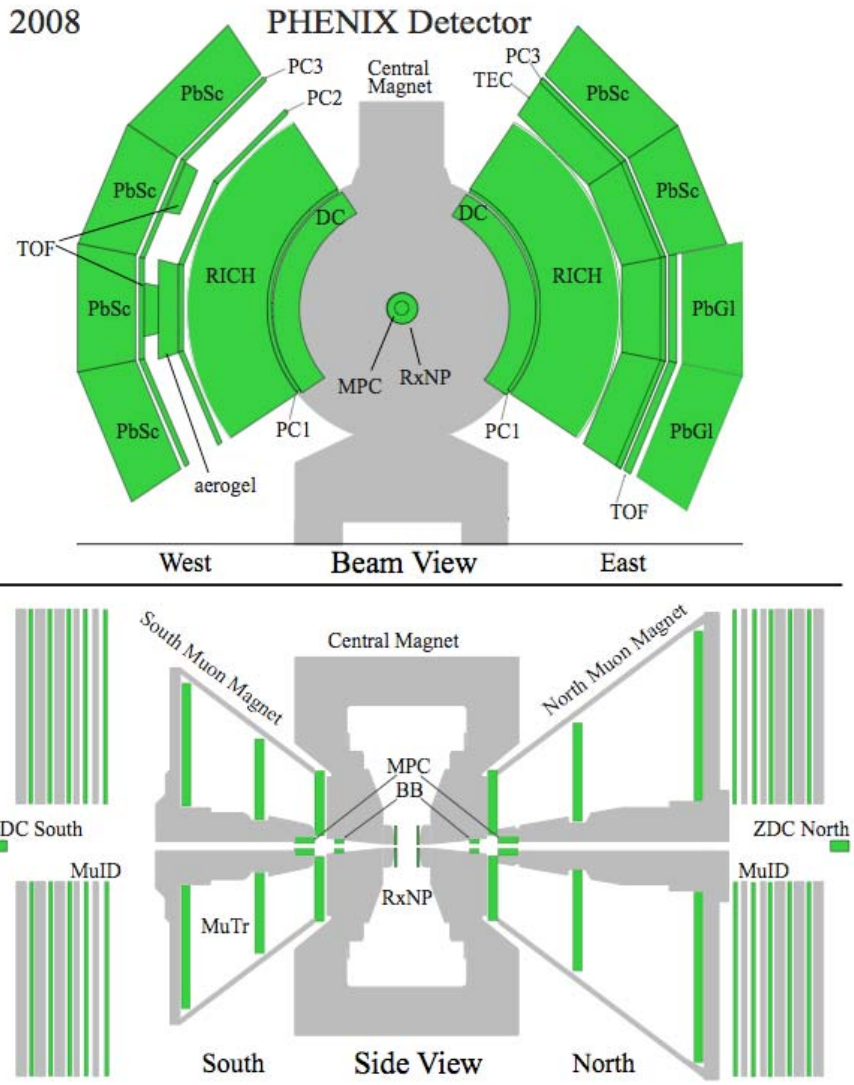
RHIC is a QCD lab

The PHENIX detector

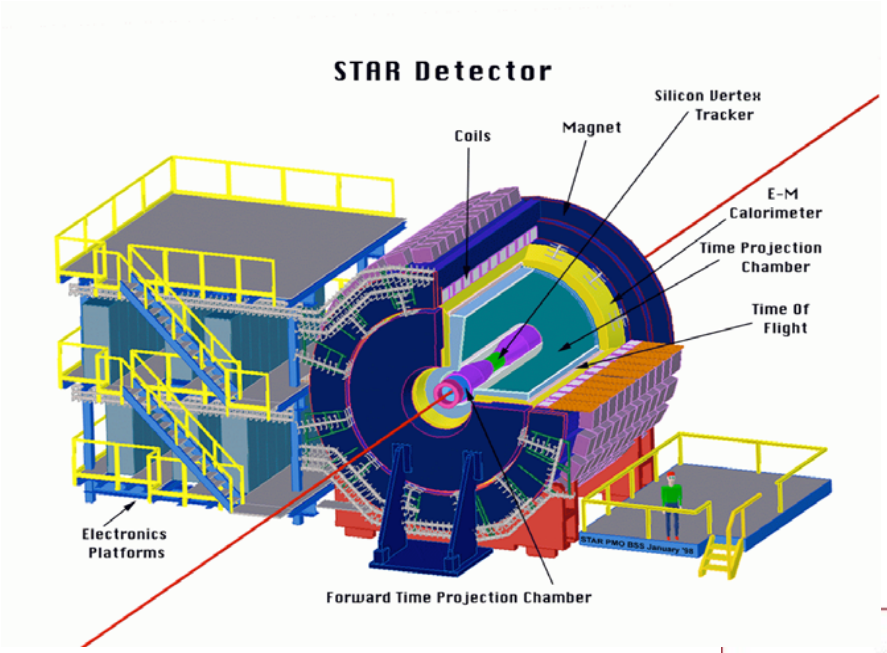
Philosophy:

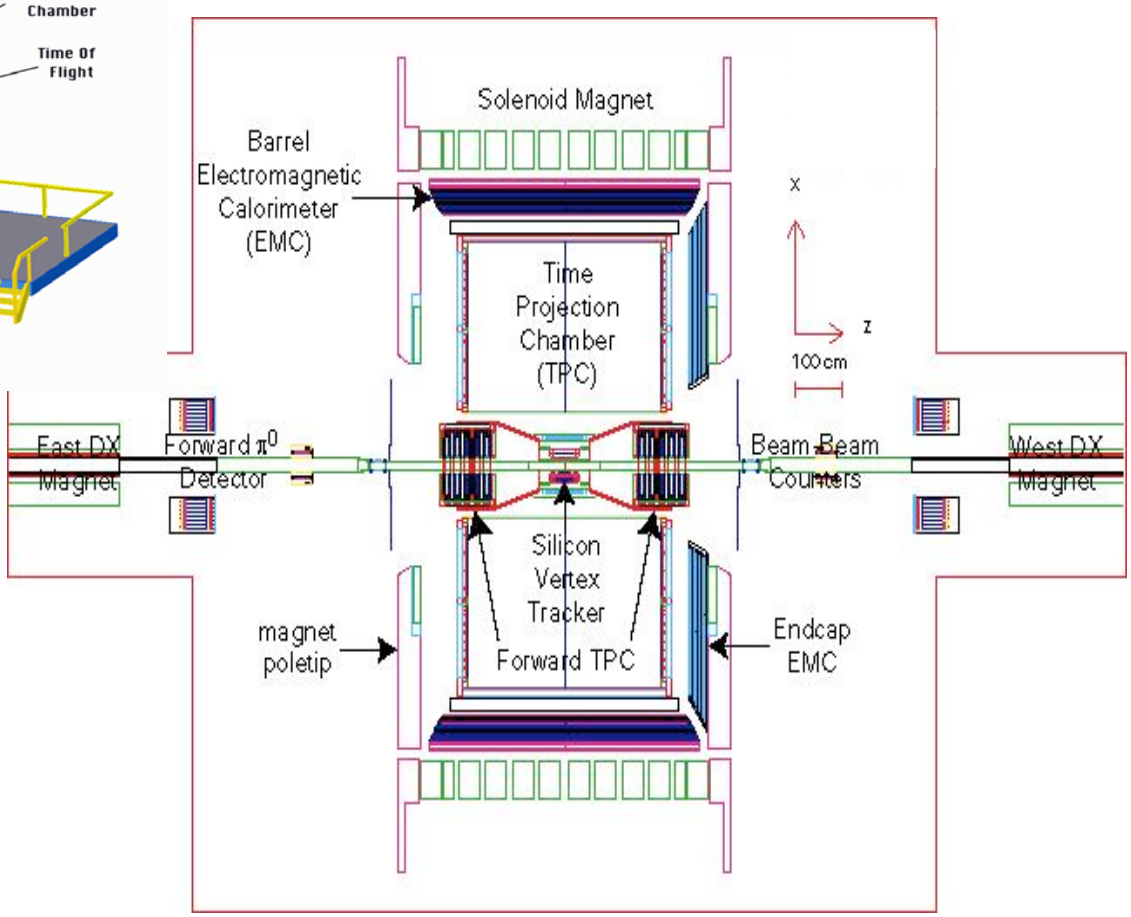
High rate capability to measure rare probes, limited acceptance.

- 2 central spectrometers
  - Track charged particles and detect electromagnetic processes
- 2 forward muon spectrometers
  - Identify and track muons
- 2 forward calorimeters (as of 2007!)
  - Measure forward pions
- Relative Luminosity
  - Beam-Beam Counter (BBC)
  - Zero-Degree Calorimeter (ZDC)



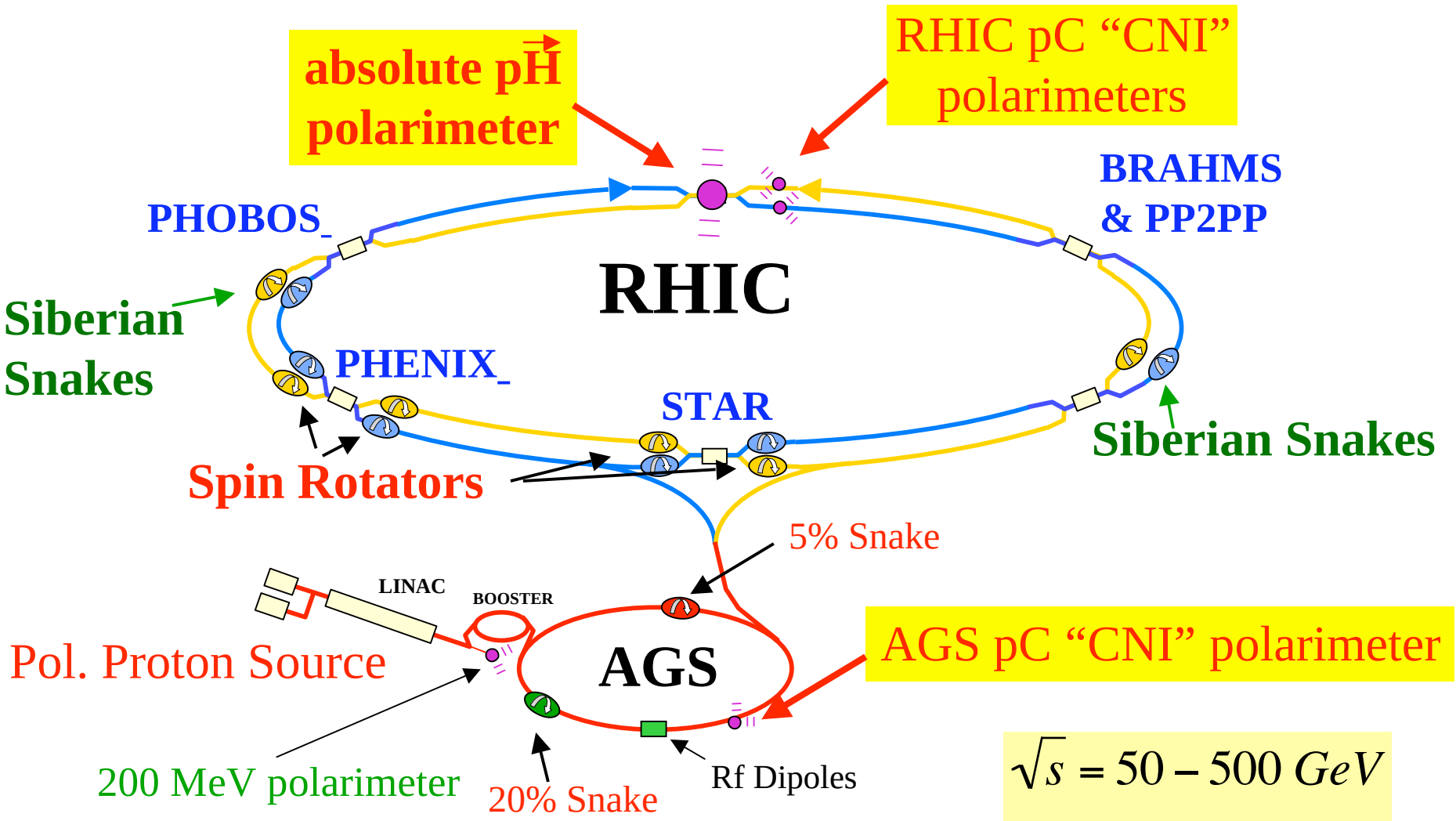
The STAR Detectors





- 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 $3.3<|\eta|<4.1$

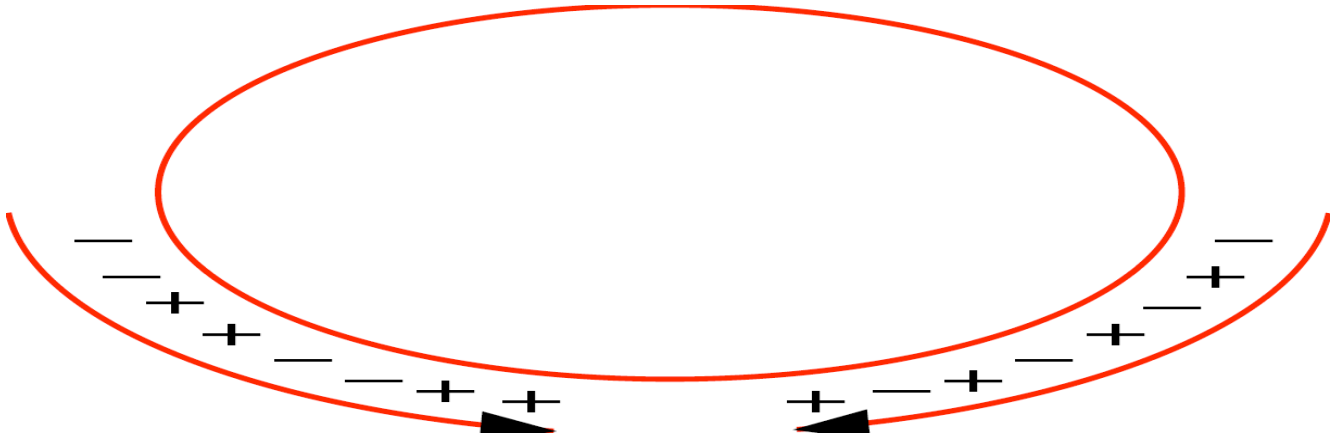
RHIC *pp* Accelerator Complex



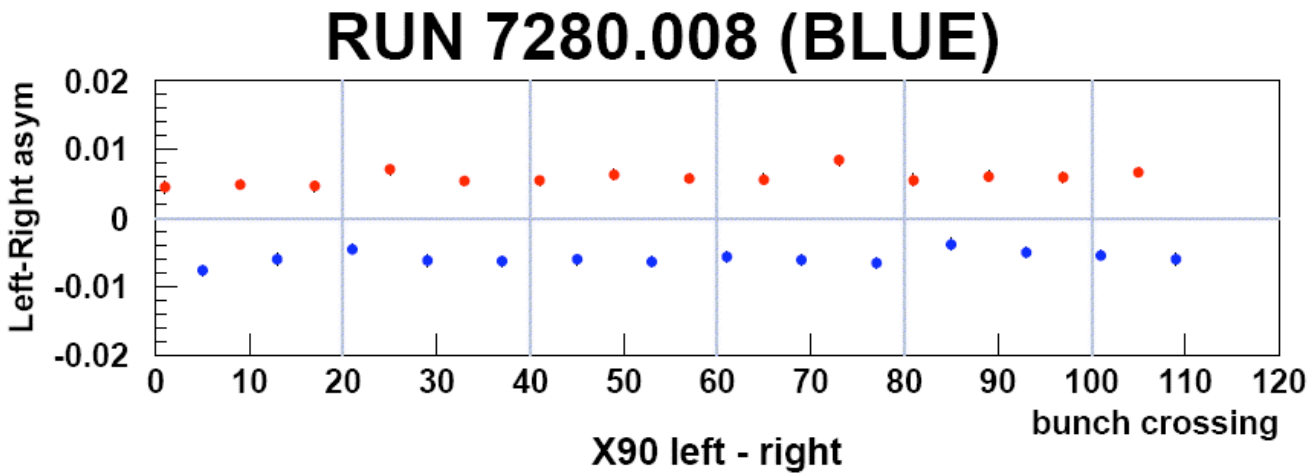
$\sqrt{s} = 50 - 500\ GeV$

$Pol. = 70\%$

Exquisite Control of Systematics



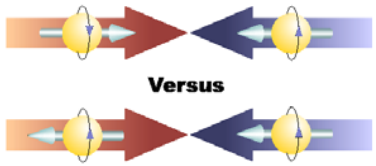
Raw asymmetries from carbon polarimeter by bunch:



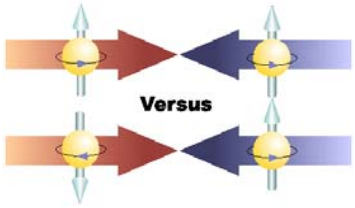
Experimental Observables

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

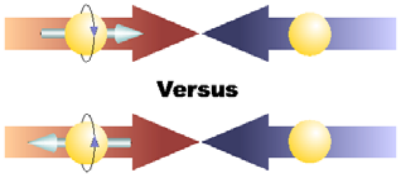
$$A_{LL} = \frac{\sigma(++)-\sigma(+-)}{\sigma(++)+\sigma(+-)}$$



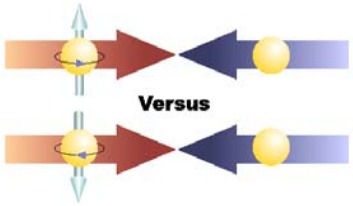
$$A_{TT} = \frac{\sigma(\uparrow\uparrow)-\sigma(\uparrow\downarrow)}{\sigma(\uparrow\uparrow)+\sigma(\uparrow\downarrow)}$$



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



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



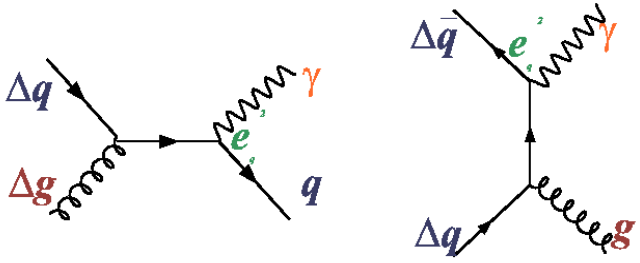
RHIC Spin Run History

	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%		(short) run

What Can We Learn?

- Asymmetries

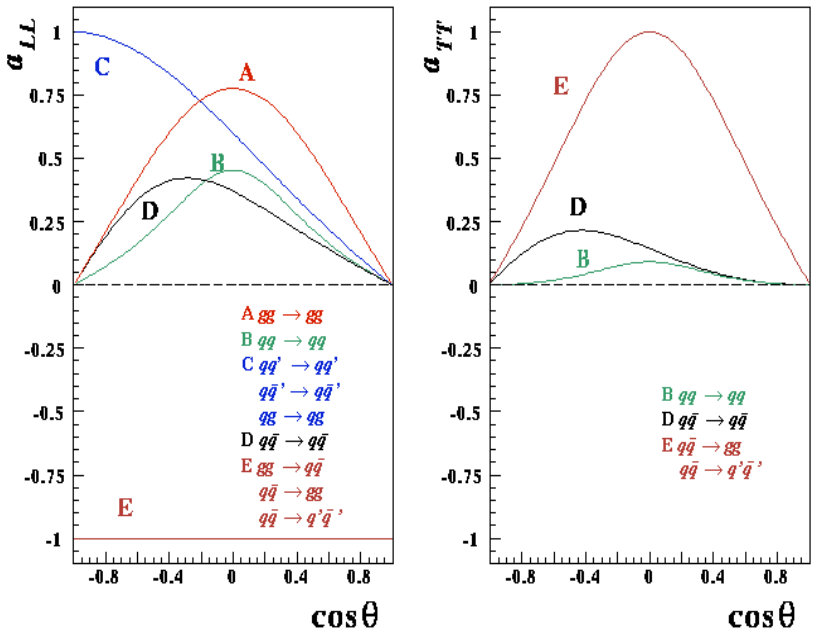
$$E\frac{d^3\Delta\sigma}{dp^3} \propto \Delta f_A^a(x_a,Q^2)\otimes\Delta f_B^b(x_b,Q^2)\otimes\frac{d\Delta\sigma_{ab}^{cd}}{dt}$$



- Polarized Quark and Gluon Distributions - LO

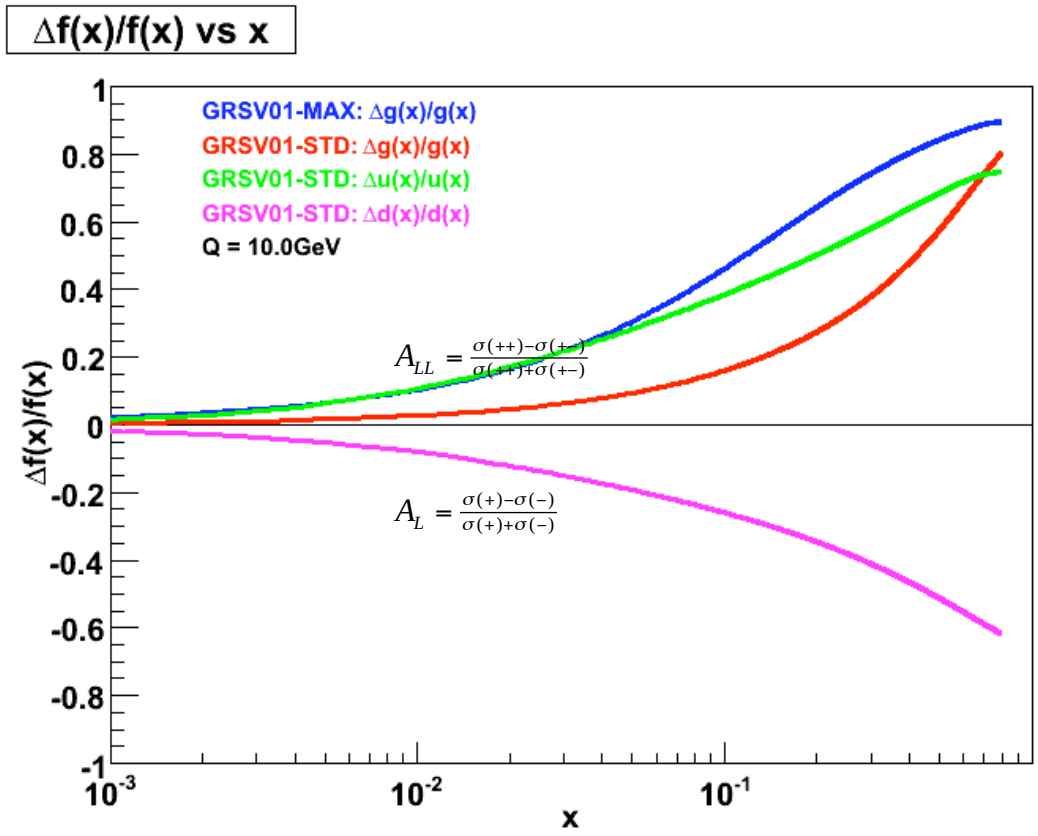
$$\Delta f(x) = f_{\uparrow}(x) - f_{\downarrow}(x)$$

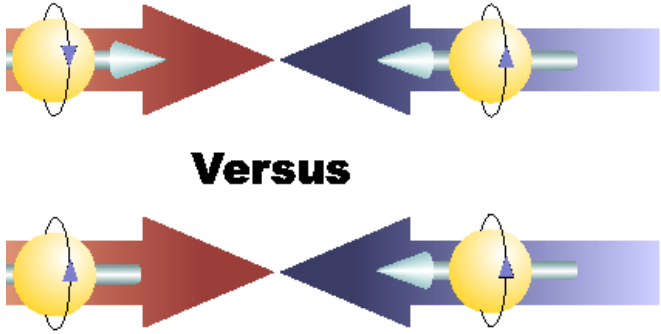
$$\Delta f \equiv \int_0^1 \Delta f(x)dx$$



- Proton Structure
  - QCD dynamics

An Example: GRSV Pol PDF

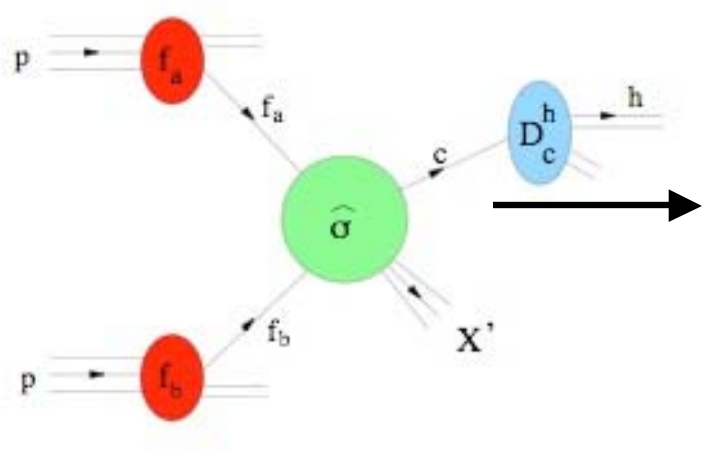


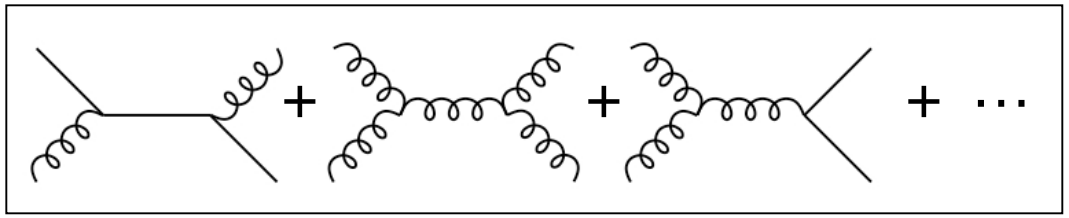


$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}}$$

$$\propto \frac{\Delta f(x_1)}{f(x_1)} \otimes \frac{\Delta f(x_2)}{f(x_2)} \cdot \hat{a}_{LL}$$

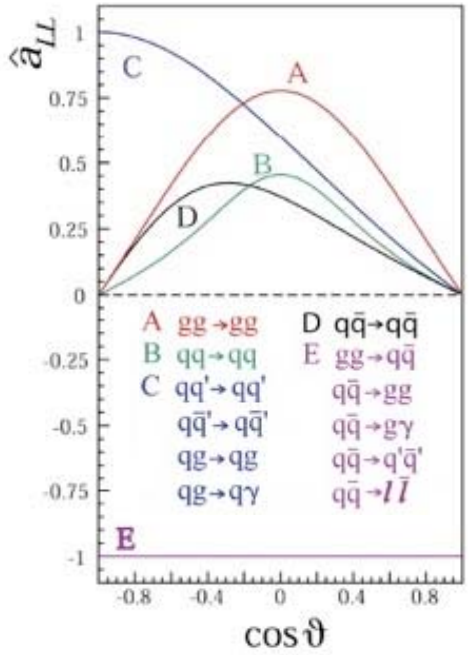
Δ G in Polarized p+p Collisions





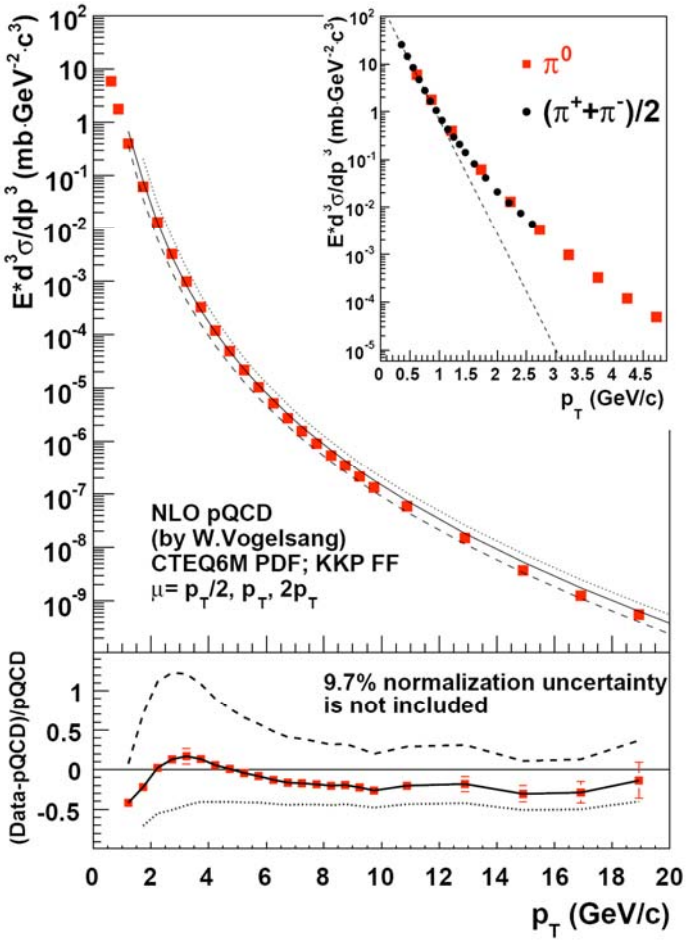
$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} = \frac{\sum_{a,b,c} \Delta f_a \otimes \Delta f_b \otimes d\hat{\sigma}^{f_a f_b \to f_c X} \cdot \hat{a}_{LL}^{f_a f_b \to f_c X} \otimes D_{f_c}^h}{\sum_{a,b,c} f_a \otimes f_b \otimes d\hat{\sigma}^{f_a f_b \to f_c X} \otimes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

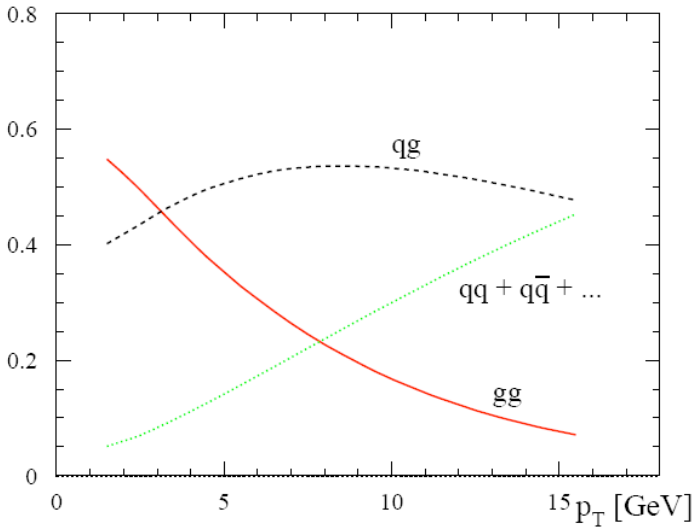
$$A_{LL} \approx a_{gg}\Delta G^2 + a_{qg}\Delta q \Delta G + a_{qq}\Delta q \Delta q'$$



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

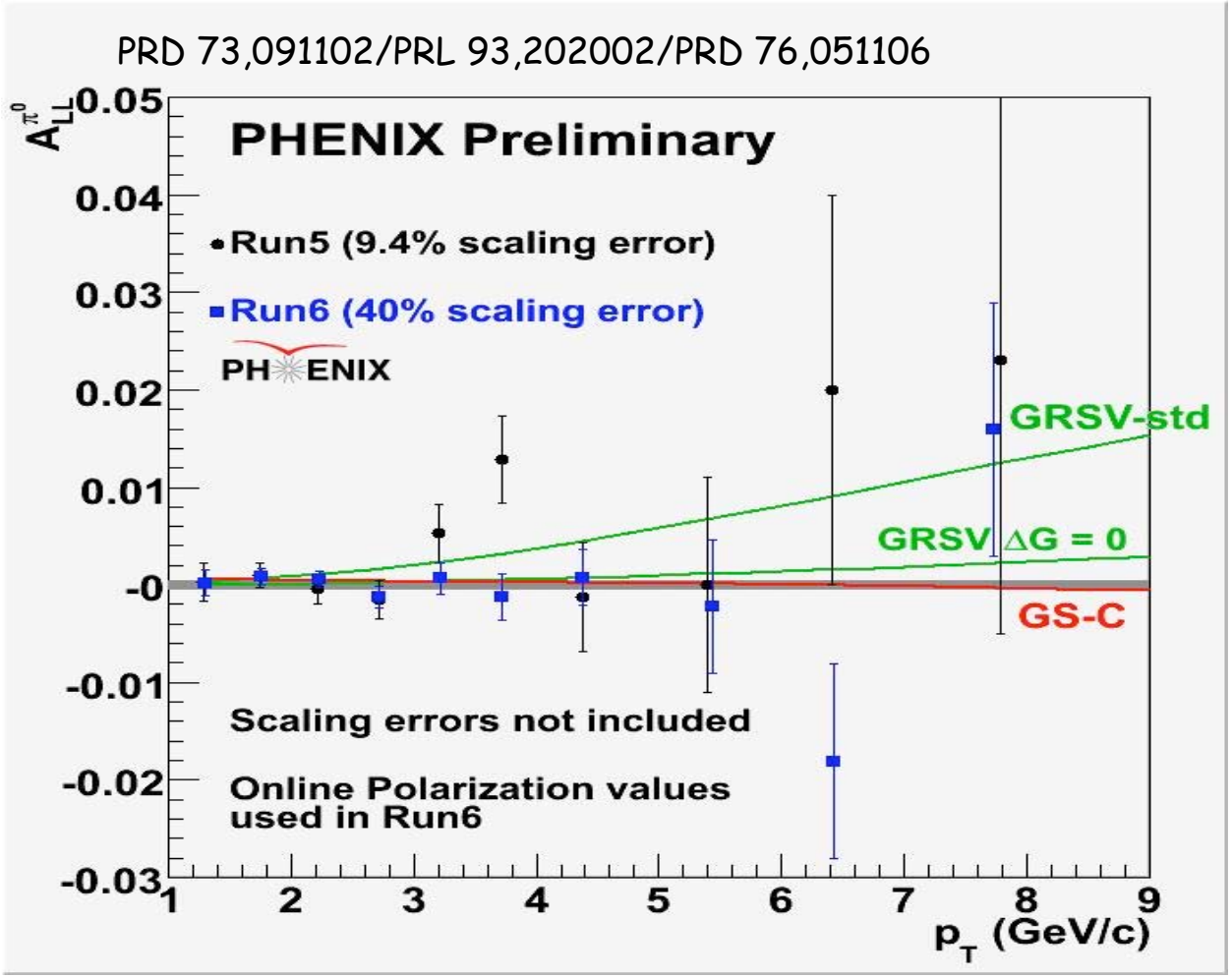
Pion production and pQCD





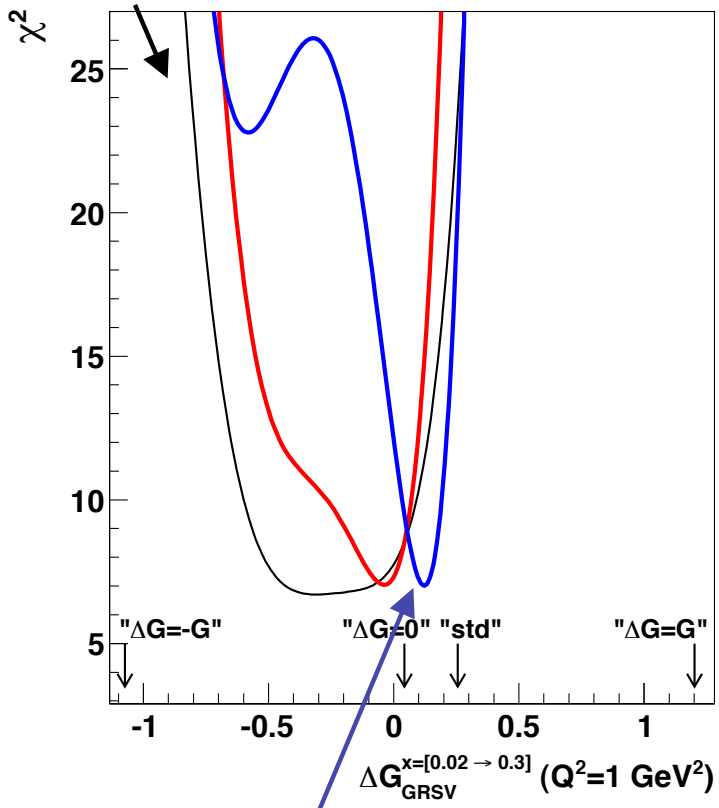
* NLO QCD Calculation Cross-sections consistent with Data
  - --- CTEQ6M pdf
  - --- KKP and Kretzer Fragmentation Fcns
* Necessary Confirmation that pQCD can be used successfully at RHIC to extract spin dependent pdf's

π^0 A_{LL} and ΔG at 200 GeV



200 GeV polarized protons - the elusive ΔG

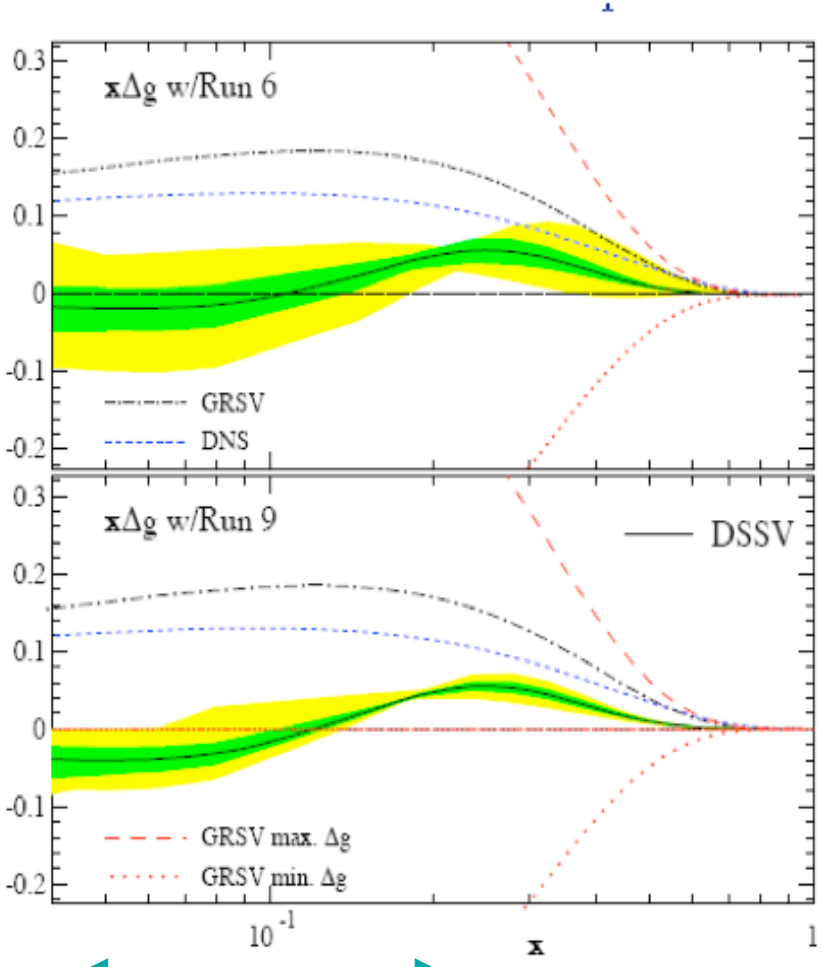
Run-6 result



Run-9 sensitivity for $\Delta G_{GRSV\text{-}std}(x)/2$ (i.e. total=0.2, or 0.1 in measured region)

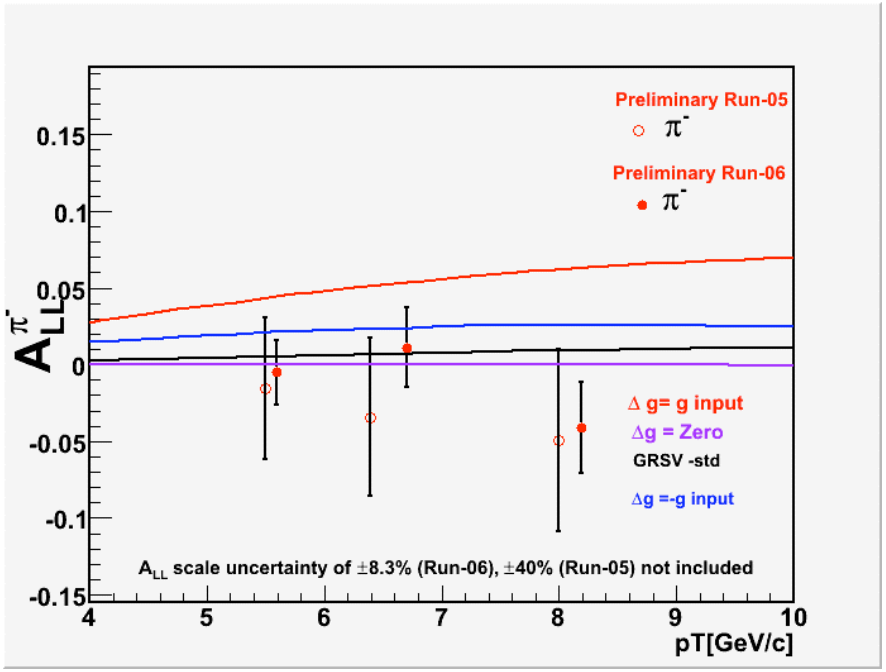
Sensitivity if ΔG=0

Global fits, DSSV arXiv:0804.0422



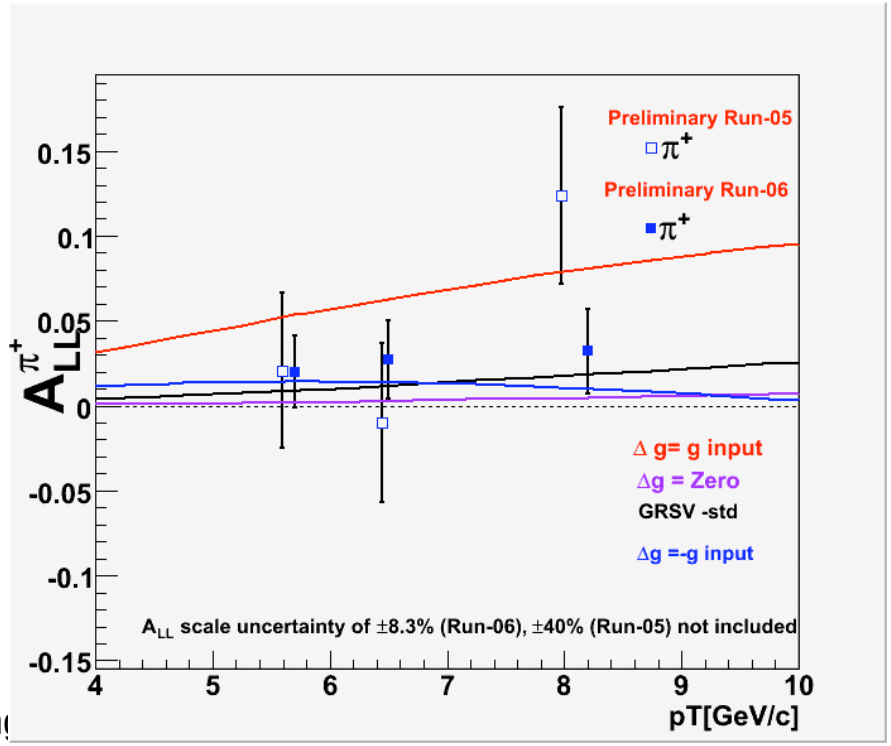
RHIC Constraint

π^+/π^- A_{LL} and and ΔG at 200 GeV



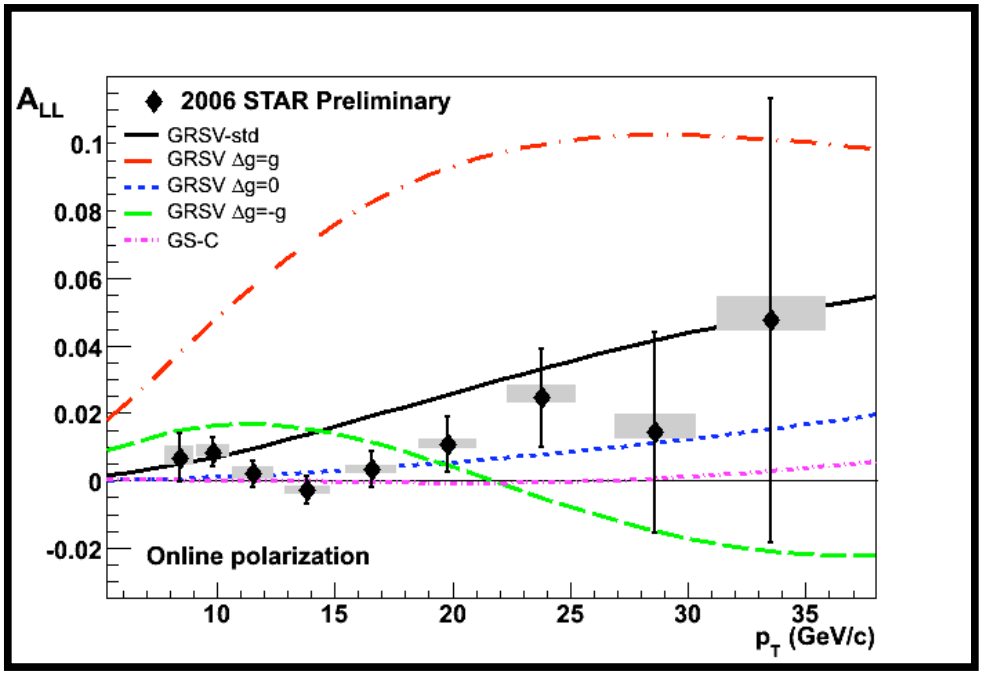
- Produced in large quantities
- No trigger at PHENIX
- Cross section being calculated for these p_Ts

- FFs should pick out different flavor mixtures -> good for consistency
- Sensitive to the sign of gluon polarization



Webb AGS/RHIC 2008

Inclusive Jet Asymmetries (2006)



A_{LL} systematics	(x 10^{-3})
Reconstruction + Trigger Bias	[-1,+3] (p_T dep)
Non-longitudinal Polarization	~ 0.03 (p_T dep)
Relative Luminosity	0.94
Backgrounds	1st bin ~ 0.5 all others ~ 0.1

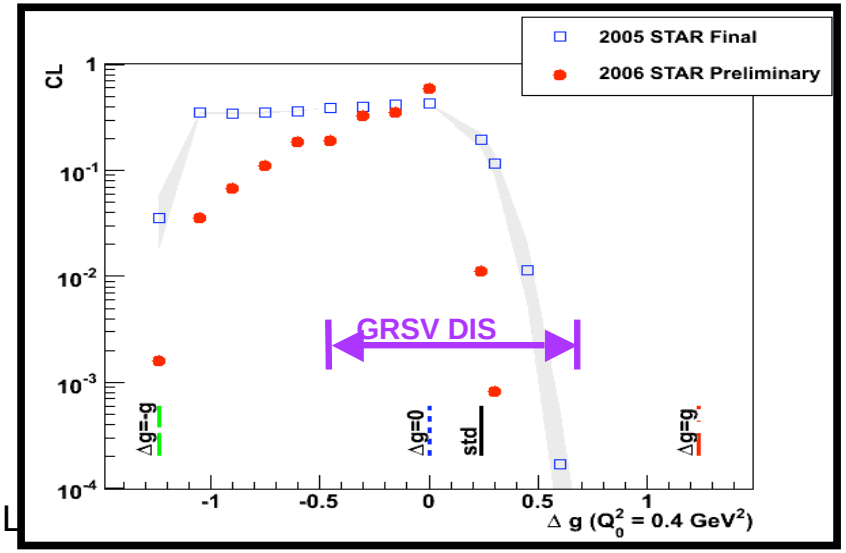
p_T systematic	±6.7%

The *2006* results are a significant improvement over the 2005 measurement:

- Full BEMC
- Jet finder extends into EEMC
- Cone radius enlarged to 0.7
- Increases in luminosity and polarization

Statistical uncertainties are 3x-4x smaller for high pT (pT > 13 GeV).

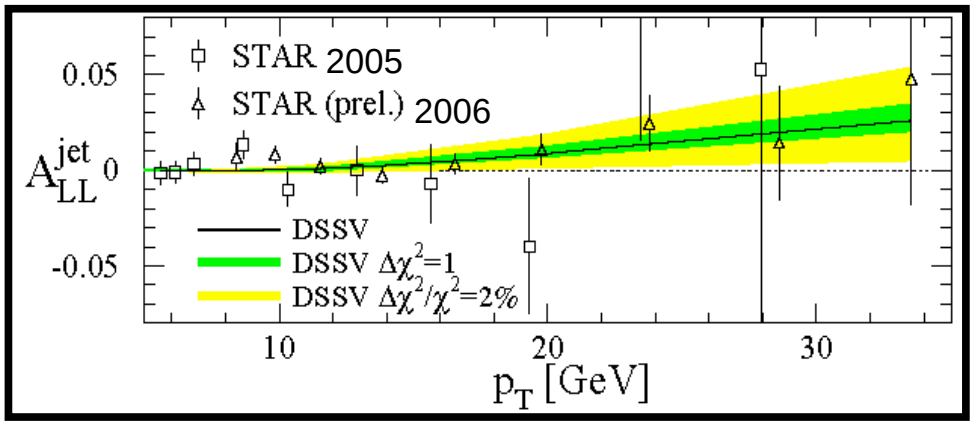
The 2006 jet asymmetries provide significant new constraints on Δg.

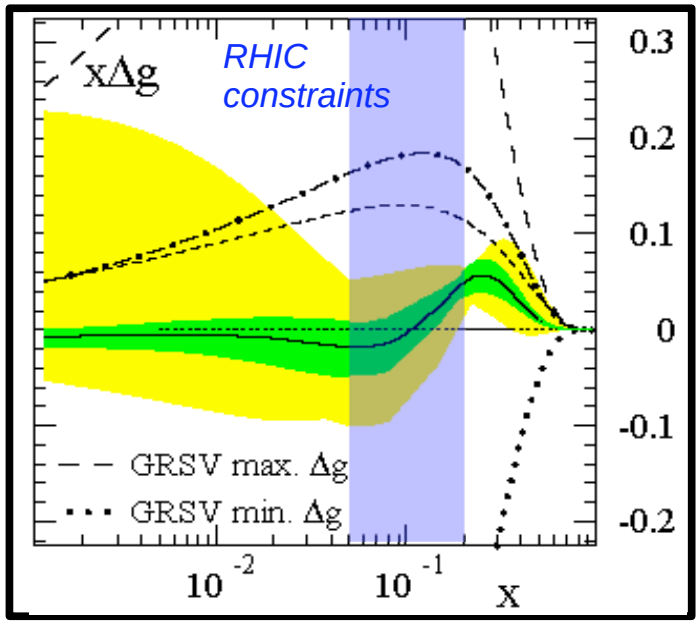


Global Analysis -- DSSV

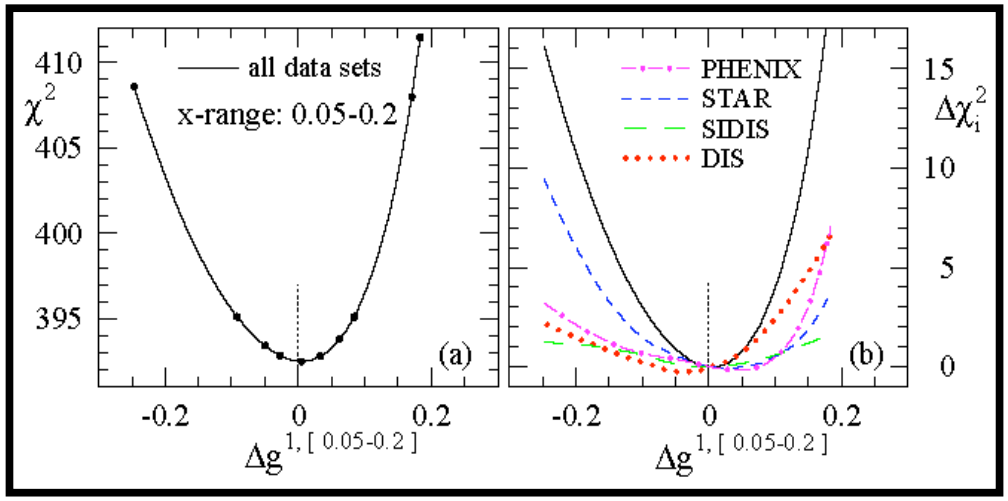
RHIC pp data have recently been included, along with polarized DIS and semi-inclusive DIS data, in a global fit to the polarized pdfs.

D. de Florian, et al., ARXIV:0804.0422





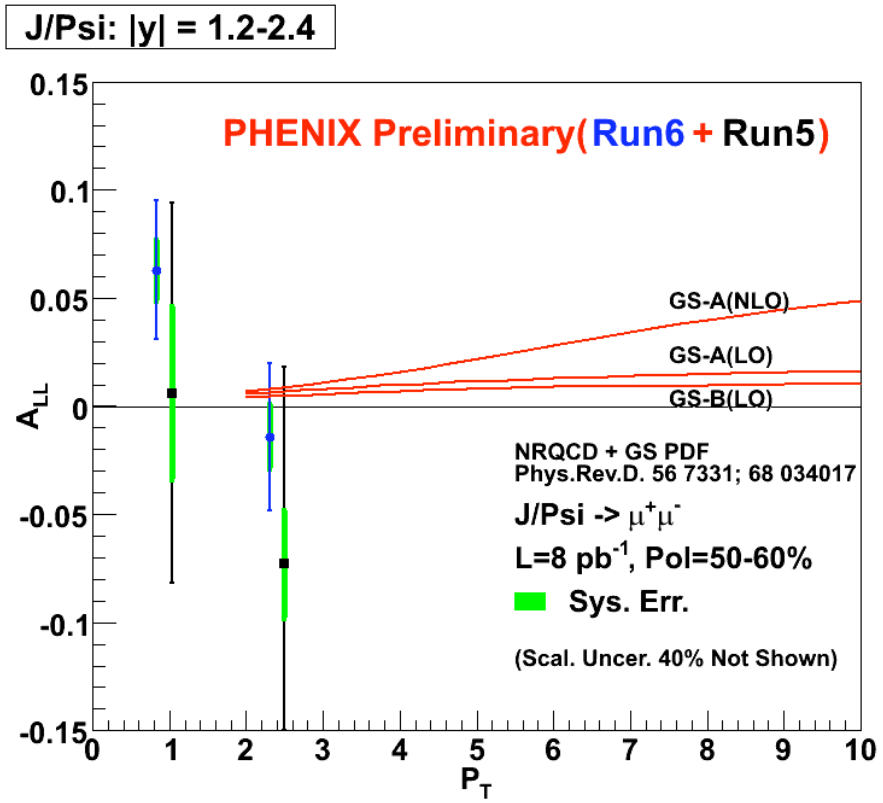
χ^2 distribution as Δg is varied w/in x-range constrained by the RHIC data. The STAR inclusive jet results provide significant constraints on Δg.



It is interesting to note that the best fit has a zero-crossing at x ≈ 0.1. Over the next few years, STAR's emphasis will shift to dijet and gamma+jet measurements, which will map out the x-dependence of Δg.

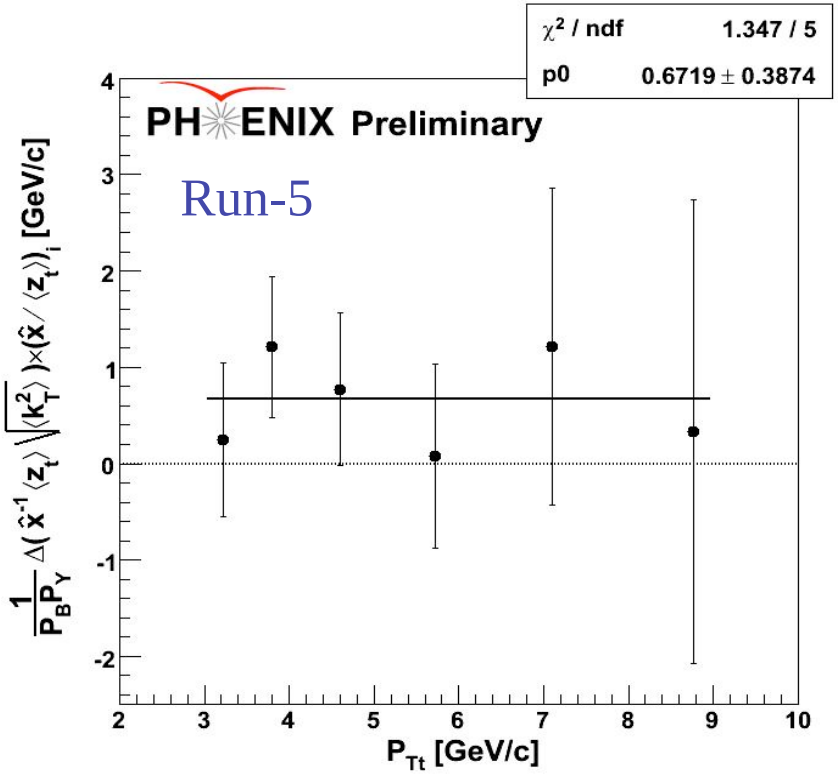
Advertisement for Other Long.

Seele AGS/RHIC 2008



- J/Ψ production connected to heavy flavor production

- Spin correlated transverse momentum (OAM) may contribute to jet k_T (Meng Ta-chung et al., Phys. Rev. D40, 1989)
- Calculate helicity asymmetry of k_T in di-hadron correlations

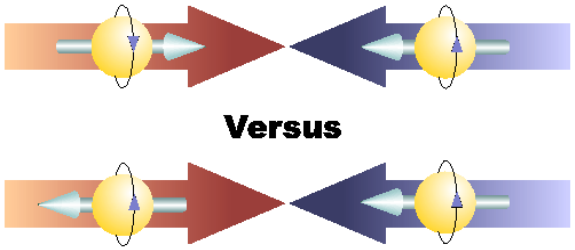


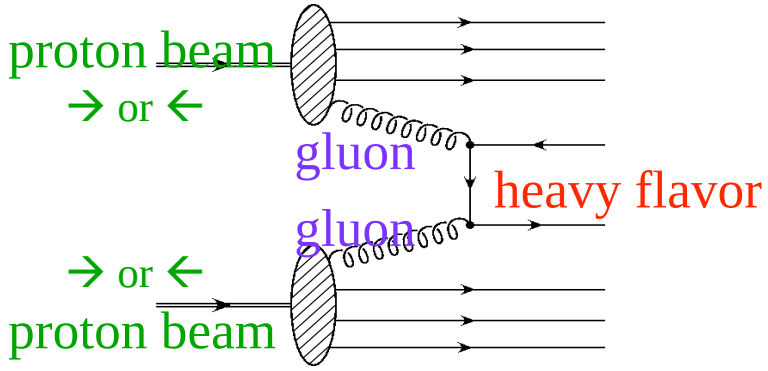
New Probes @RHIC: ΔG

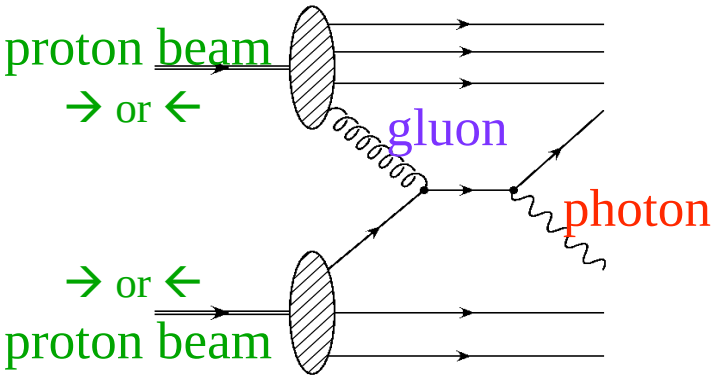
- Polarized hadron collisions
  - double longitudinal spin asymmetry

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

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







Heavy Quark Production @RHIC

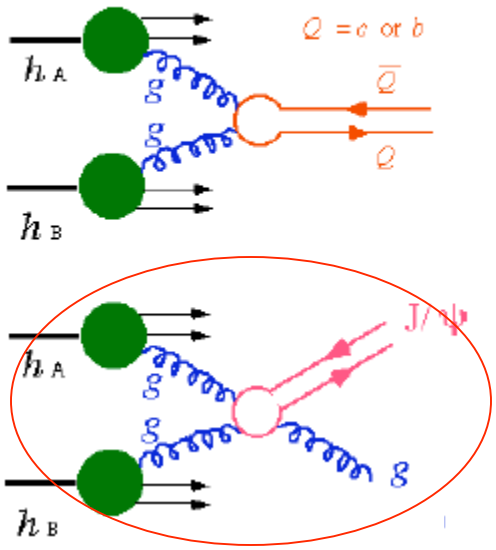
- Sensitive to gluon polarization: $\Delta G(x)$
- Gluon Fusion dominates at LO

PYTHIA estimate:

GeV	Charm	Beauty
200	95:5	85:15
500	97:3	92:8

$$\sigma(gg \to Q\bar{Q}) : \sigma(q\bar{q} \to Q\bar{Q})$$

Gluon Fusion

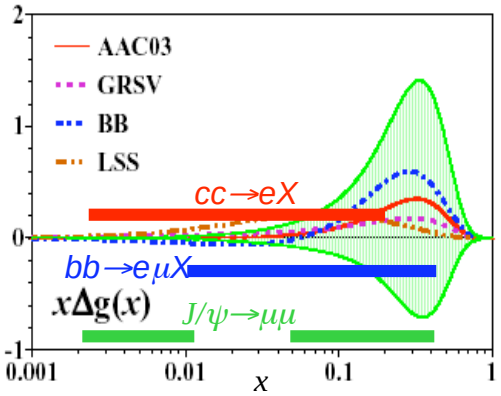


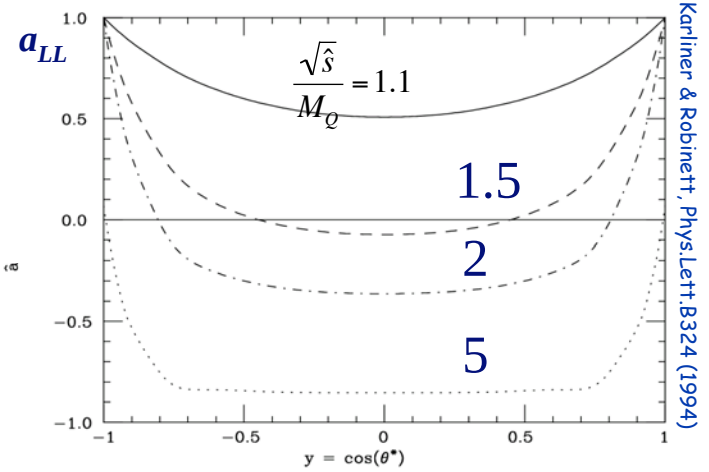
Double spin asymmetry:

$$A_{LL} \approx \frac{\Delta G(x_1)}{G(x_1)} \frac{\Delta G(x_2)}{G(x_2)} a_{LL}^{gg \to Q\bar{Q}}$$

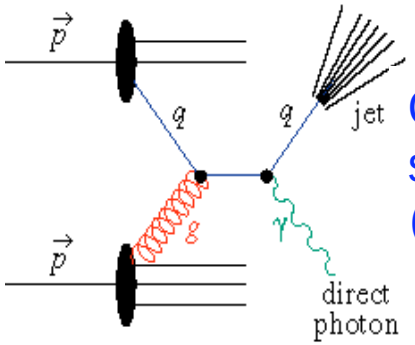
Decay modes:

e^+e^-, $\mu^+\mu^-$, $e\mu$, eX, μX

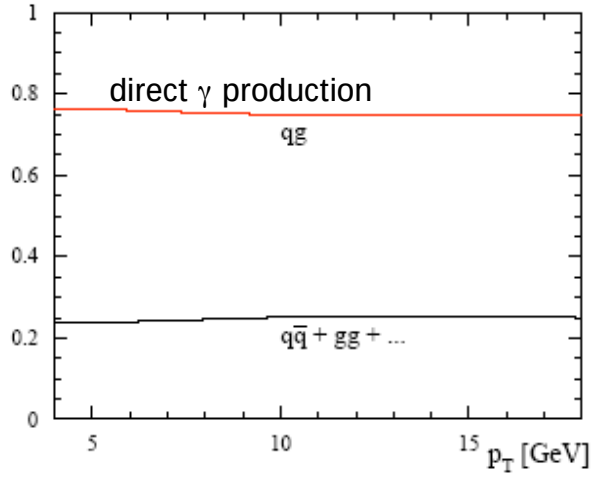




Prompt Photon Production



Quark-Gluon Compton scattering dominates (~75%) direct γ production



The cross section asymmetry A_{LL} for $\vec{p} + \vec{p} \rightarrow \gamma + \text{jet} + X$ (at Leading Order):

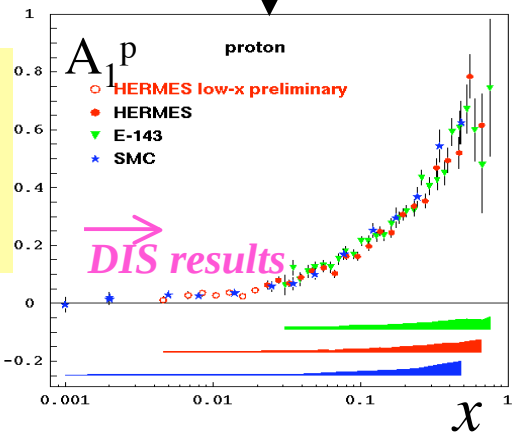
$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} \approx \boxed{\frac{\Delta g(x_g)}{g(x_g)}} \times \underbrace{\frac{\sum e_i^2 \Delta q_i(x_q)}{\sum e_i^2 q_i(x_q)}}_{=A_1^p} \times \underbrace{\hat{a}_{LL}(gq \rightarrow q\gamma)}$$

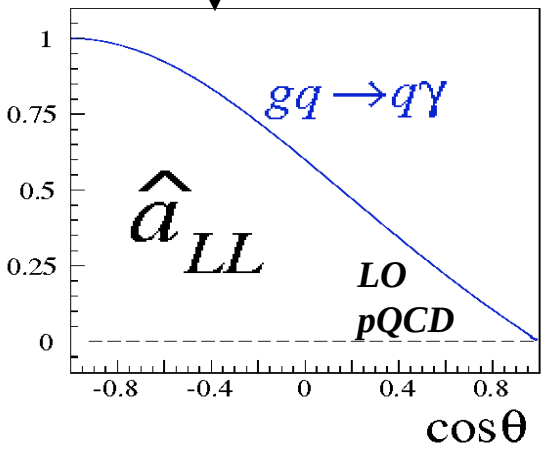
Direct measurement of gluon polarization

known from pol. DIS

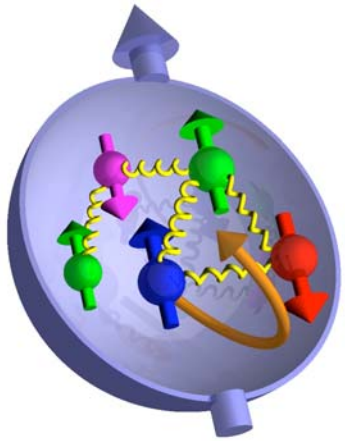
calculable in pQCD, scale ~ p_T^2 of γ

A golden channel:
parton kinematics reconstructed from photon and jet measurements:





The 20-year Old Proton Spin Puzzle



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

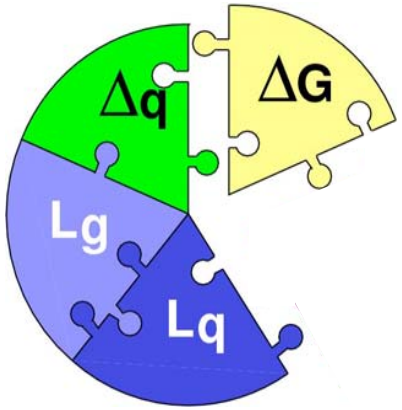
Spins + orbital angular momentum need to give the observed spin 1/2 of proton

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

Fairly well measured only ~30% of spin

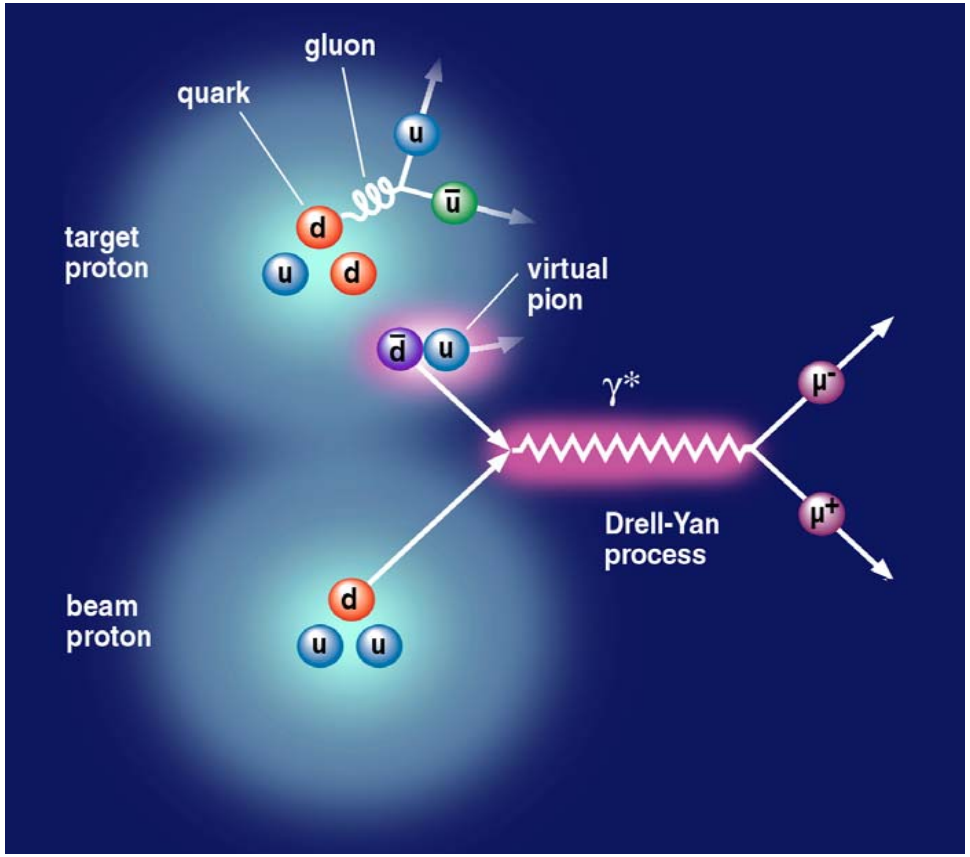
Beginning to be measured at RHIC

A future challenge



Flavor Identified Quark Polarization & Asymmetry

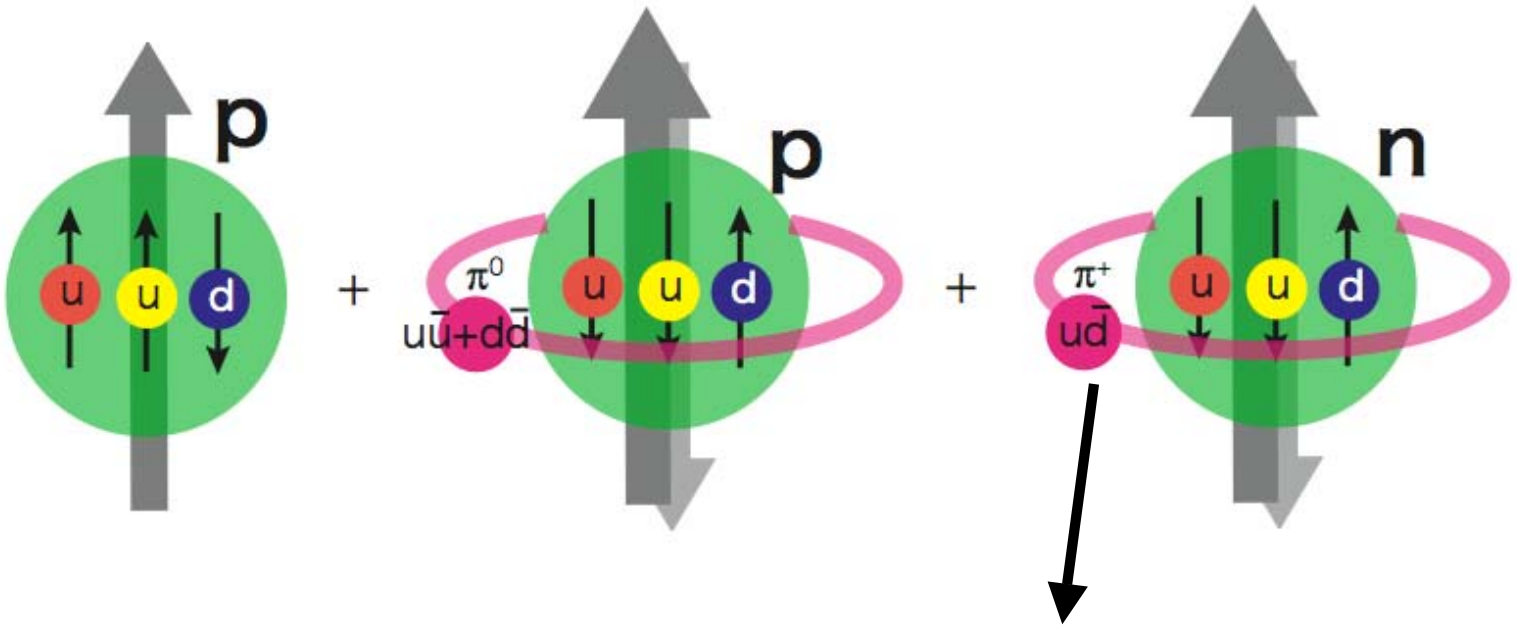
- Nucleon is a complex system
- Sea quarks and gluons correlated



$$\Delta u(x), \Delta d(x)...$$

$$\Delta \bar{u}(x), \Delta \bar{d}(x)...$$

Pion Cloud Model and the Orbital Angular Momentum?!

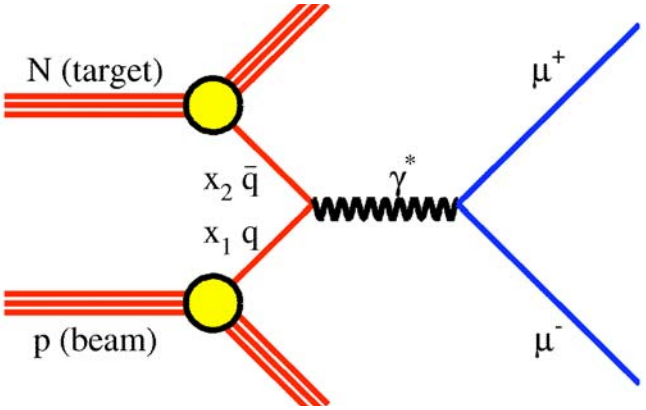


Extra dbar in proton g.s.

Sea Quarks Carry Major Orbital Angular Momentum Component?

Evidence of Pion Cloud?

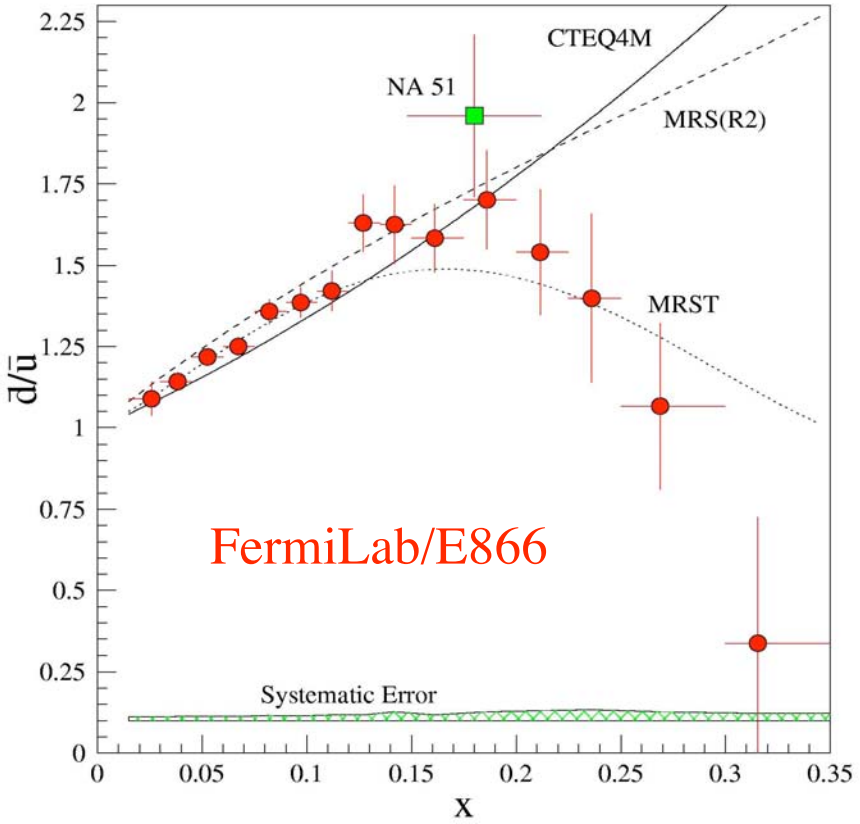
$$pN \to \mu^+\mu^- X$$



Towell et al., Phys.Rev. D64 (2001) 052002

$$\sigma_{DY} \propto \sum_i e_i^2 \left[q_i(x_b)\bar{q}_i(x_t) + \bar{q}_i(x_b)q_i(x_t) \right]$$

$$\left. \frac{\sigma^{pd}}{2\sigma^{pp}} \right|_{x_b \gg x_t} \approx \frac{1}{2}\left[1 + \frac{\bar{d}(x_t)}{\bar{u}(x_t)} \right]$$



Sea Asymmetry from Drell-Yan Processes

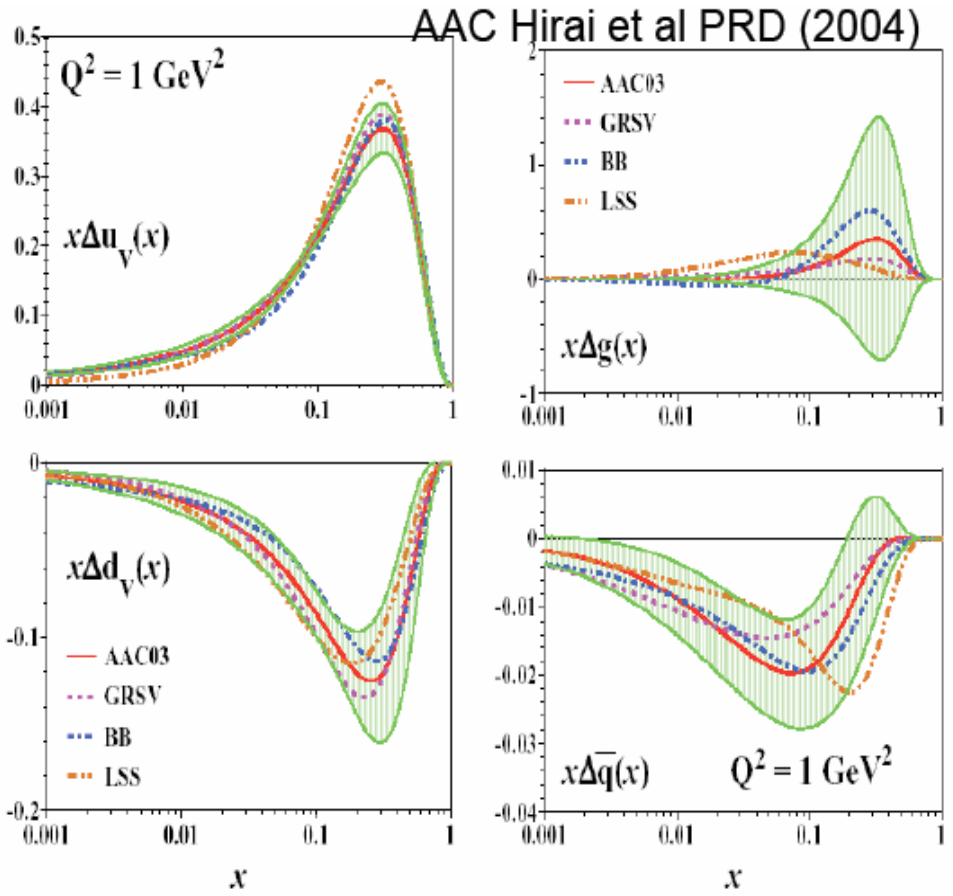
Sea Quark Polarization and Nucleon Structure

- Pion cloud model:

$$\Delta\bar{u} - \Delta\bar{d} = 0$$

- Chiral soliton model:

$$\Delta\bar{u} - \Delta\bar{d} \sim N_C(\bar{u} - \bar{d})$$

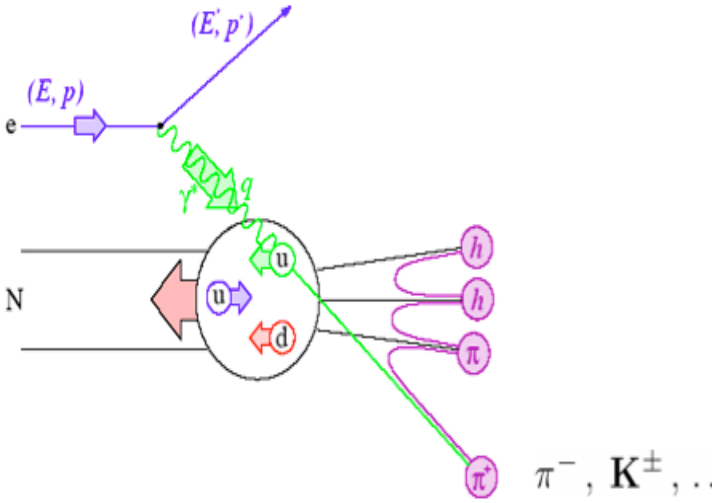


"OLD" - Flavor Decomposition @SIDIS

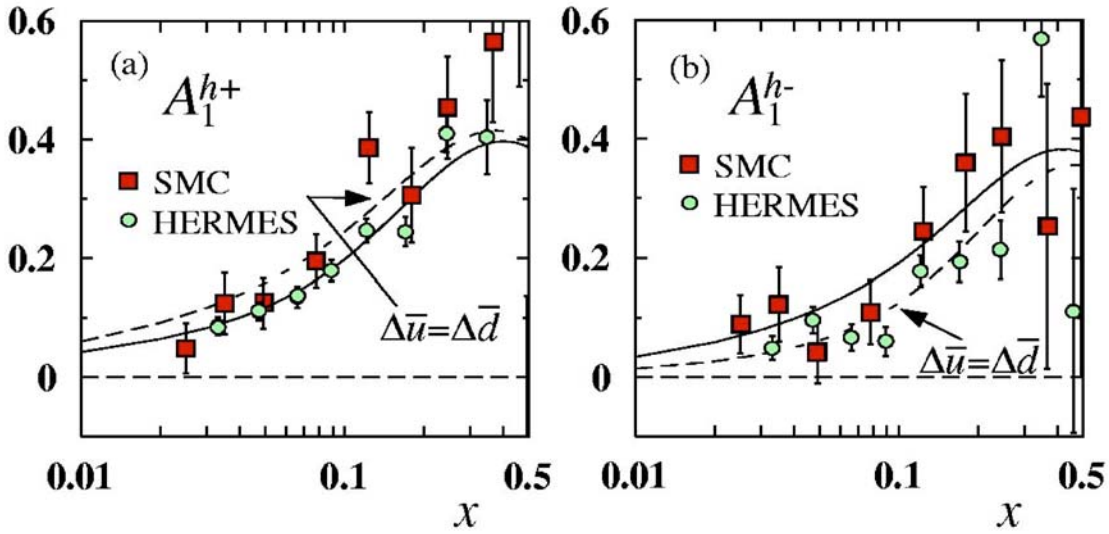
Are the light-quark polarizations in the proton sea large and asymmetric?

Unpolarized experiments, like e.g. NMC, E866/NuSea, have shown a strong breaking of SU(2) symmetry in the antiquark sea, with: $\bar{d}(x)/\bar{u}(x) \neq 1$

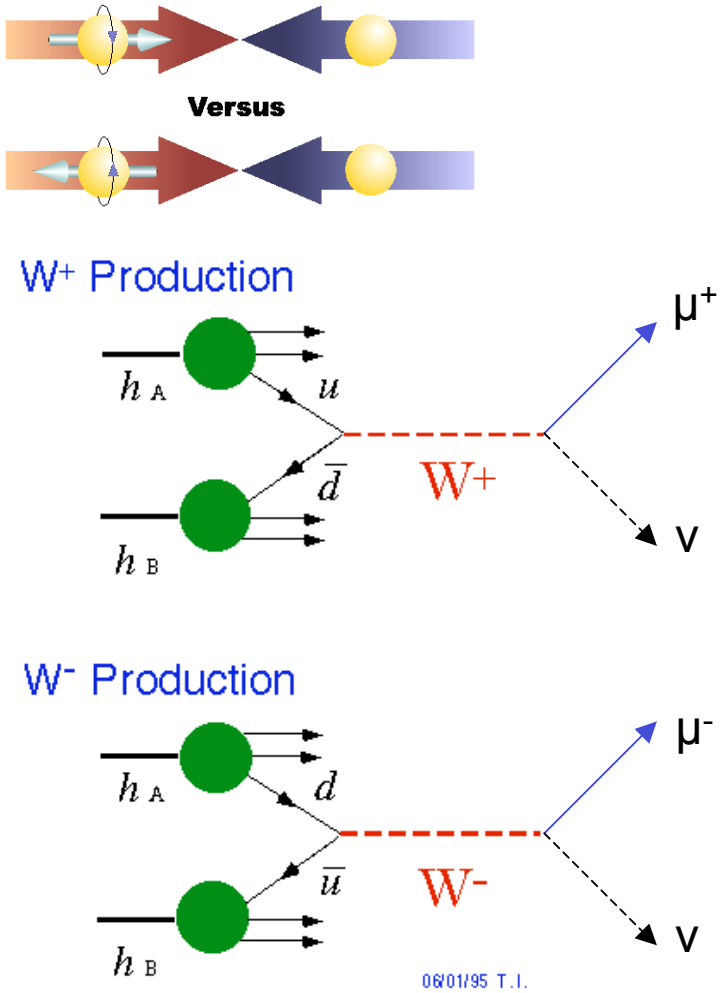
- Semi-inclusive polarized DIS – sensitivity reduced by fragmentation functions and e_q^2 weighting



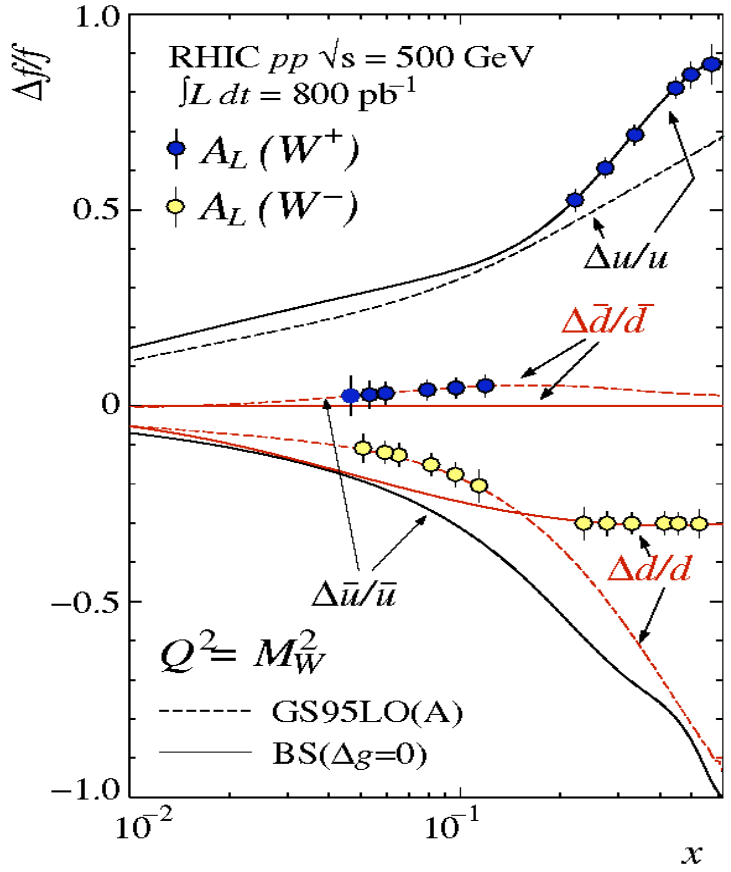
B. Dressler et al. Predictions



"New"- W± Production and A_L @500GeV



Bunce G. et al, hep-ph/0007218

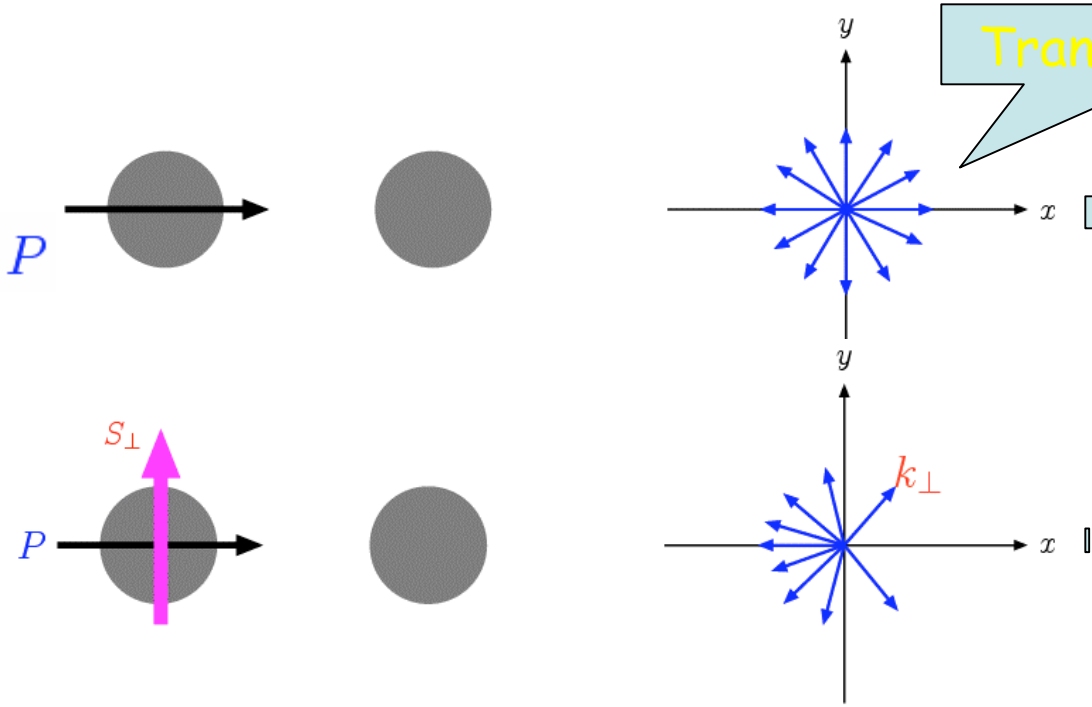


Part II: Test QCD Based Models with Single Spin Asymmetry

- SSA
  - Collins function
  - Sivers function
  - High twist
- Particle production mechanism
  - J/Psi and open heavy quarks

Thanks to F. Yuan

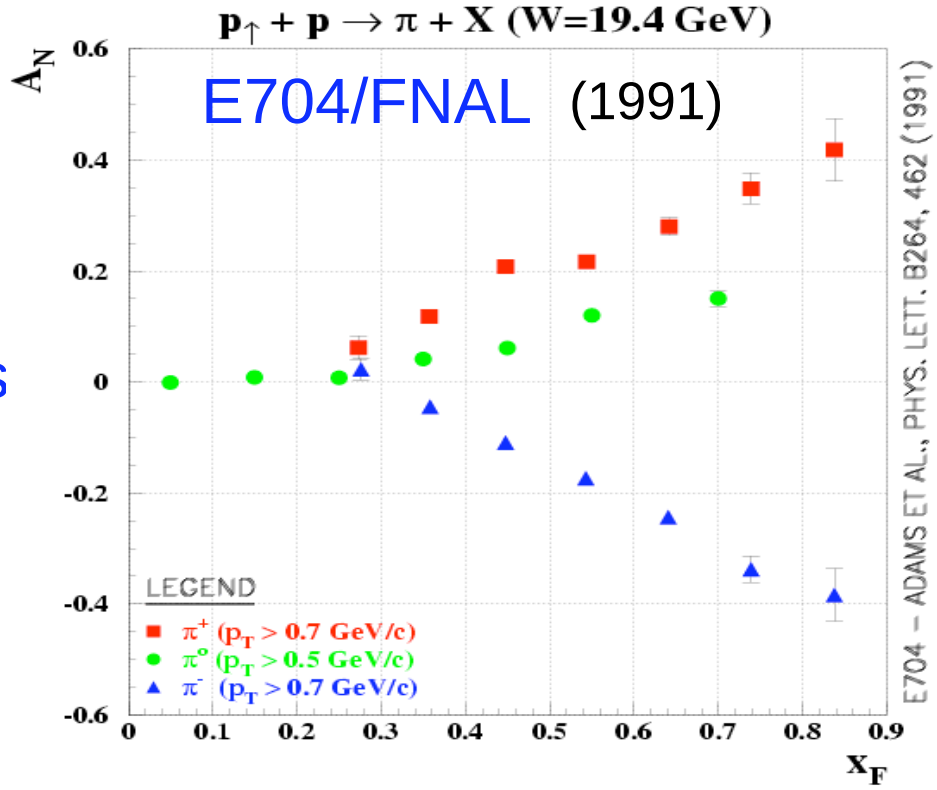
What's Single Spin Asymmetry?



$$A_N = \frac{L - R}{L + R}$$

Single Transverse Spin Asymmetry

- SSA is suppressed in naïve parton models (~$\alpha_s m_q/Q$)
- Large SSAs have been observed at forward rapidities in hadronic reactions



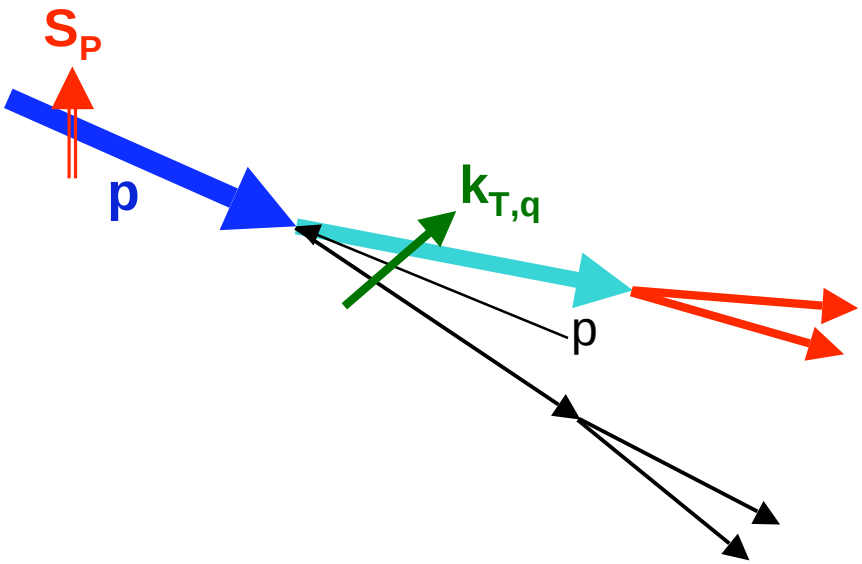
Transverse Momentum Dependent PDFs and A_N

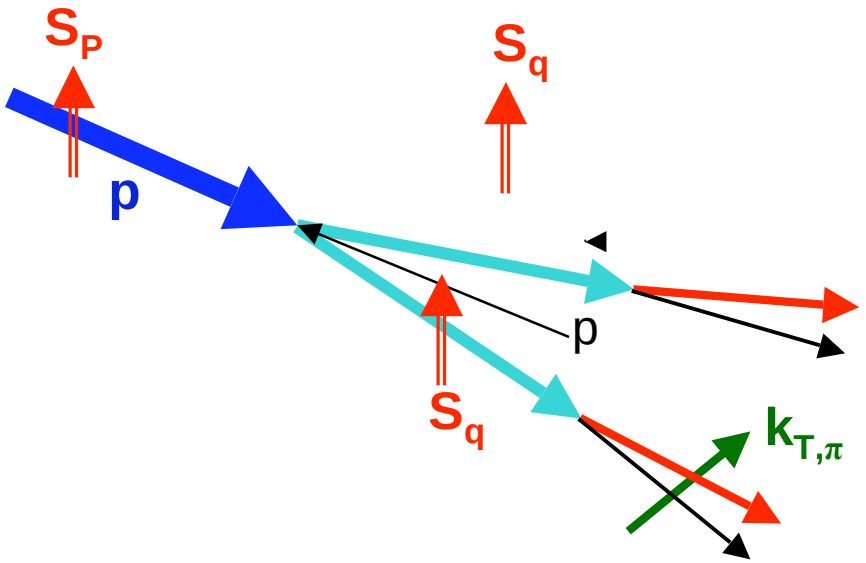
Sivers mechanism: Correlation between nucleon spin and parton k_T

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

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

Nucl Phys B396 (1993) 161





Orbital Angular Momentun?

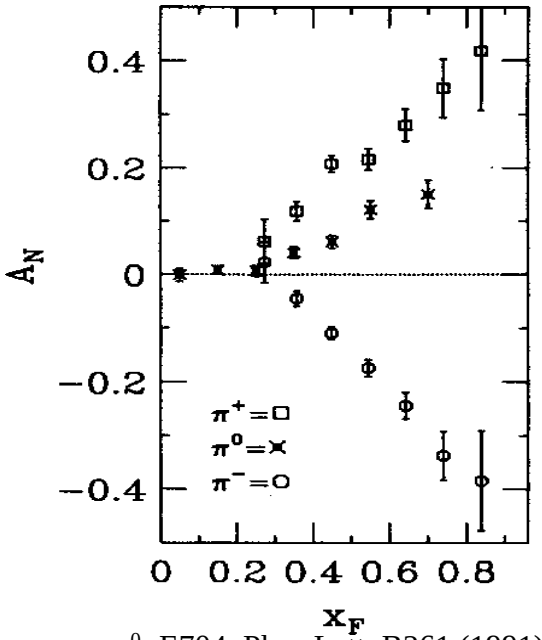
Large asymmetries persist at high √s

Gordon AGS/RHIC 2008

Examples:

√s = 20 GeV

$p_\uparrow + p \rightarrow \pi + X$, √s = 20 GeV
p_T=0.5-2.0 GeV/c

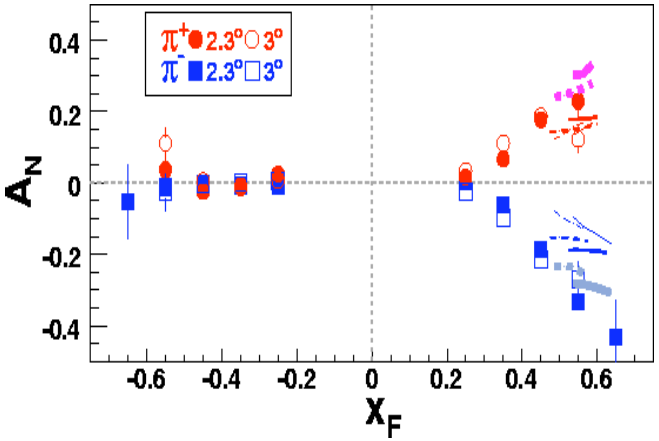


π^0: E704, Phys.Lett. B261 (1991) 201.
$\pi^{+/-}$: E704, Phys.Lett. B264 (1991) 462.

Fermilab, Fixed target, E704, 1991

√s = 62 GeV

$p_\uparrow + p \rightarrow \pi^\pm + X$, √s = 62 GeV

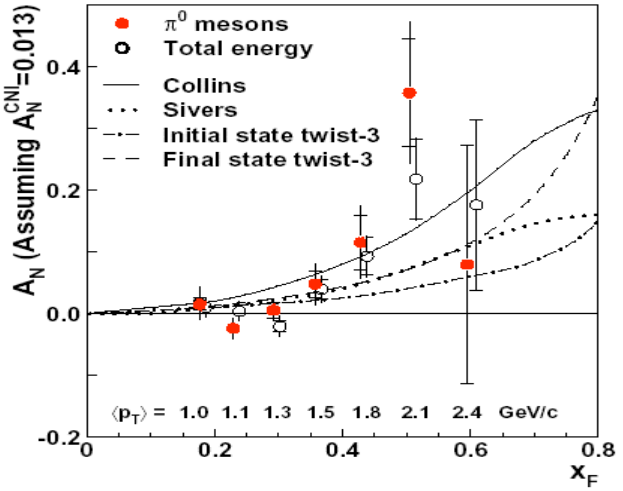


Arsene et al. (BRAHMS), submitted to Phys. Rev. Lett. [arXiv:nucl-ex/0801.1078]

RHIC, Brahms, 2007

√s = 200 GeV

$p_\uparrow + p \rightarrow \pi^0 + X$, √s = 200 GeV

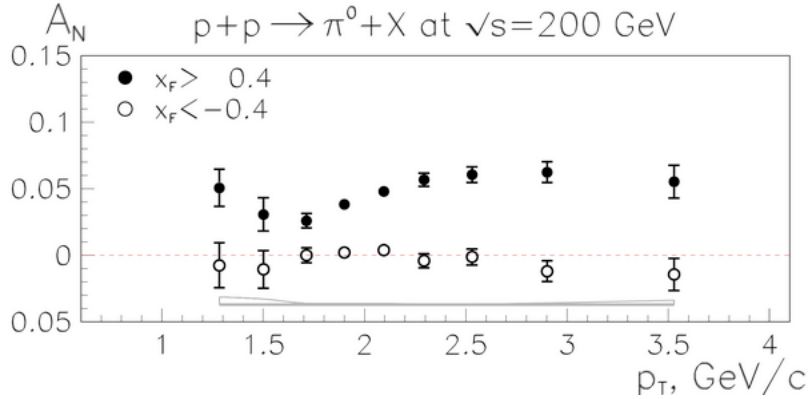


(STAR) Phys. Rev. Lett. **92** (2004) 171801

RHIC, STAR, 2004

Non-Perturbative cross section → Perturbative cross section

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



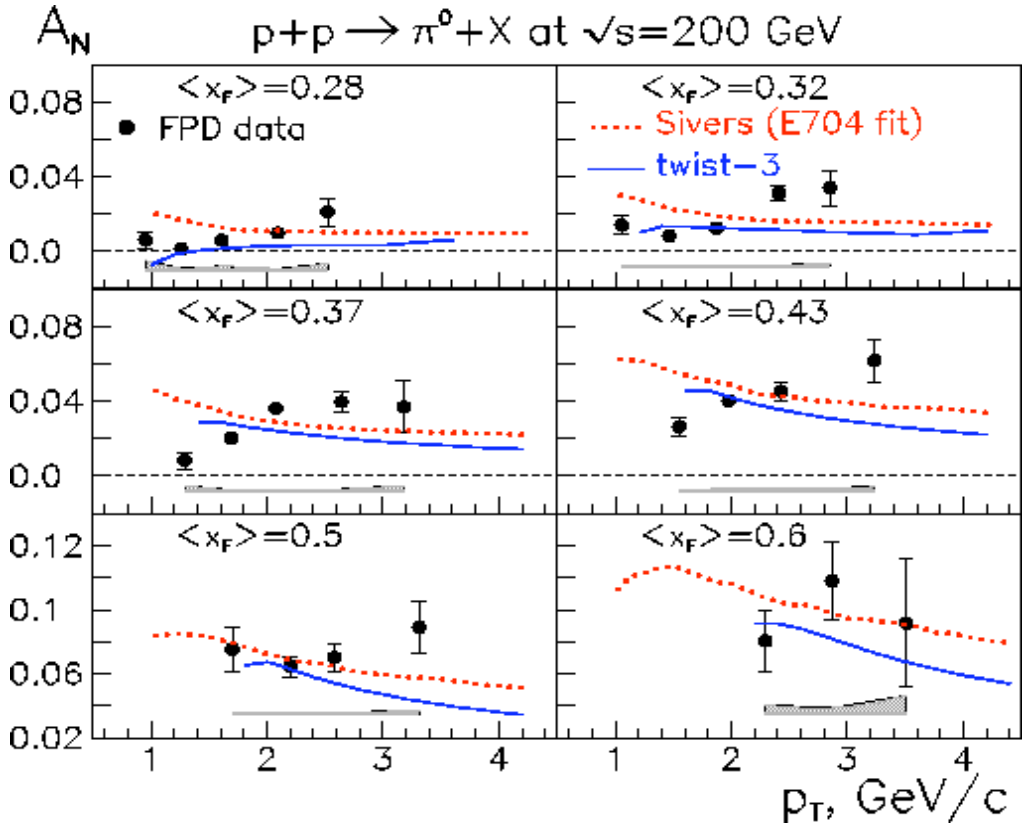
← X_F>0.4

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 →



PHENIX

New Probes at RHIC

Heavy flavor A_N at forward rapidity with muon spectrometers

Why heavy flavor?

- Eliminate Collins' effects
  * heavy flavor production dominated by gluon gluon fusion at RHIC energy

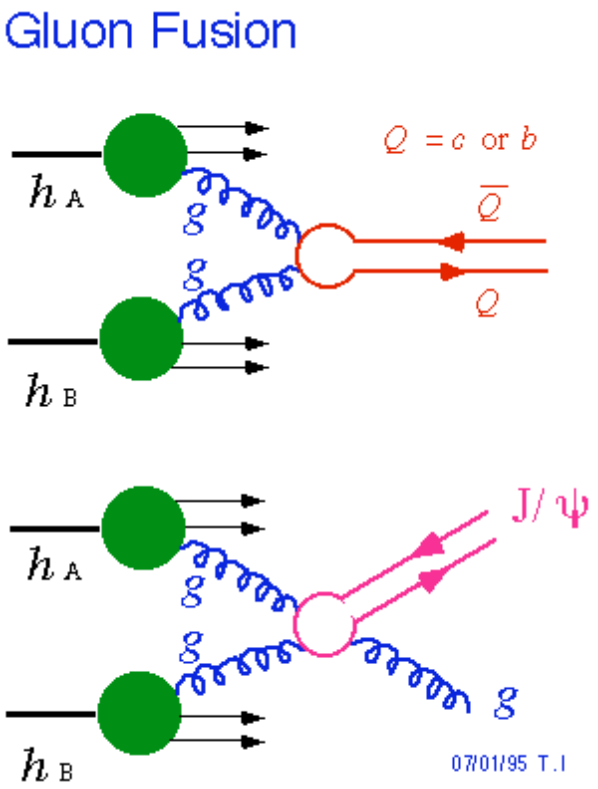
    Pythia 6.1 simulation

$$c\bar{c}: \; gg \rightarrow c\bar{c} \quad 95\%$$
$$b\bar{b}: \; gg \rightarrow b\bar{b} \quad 85\%$$

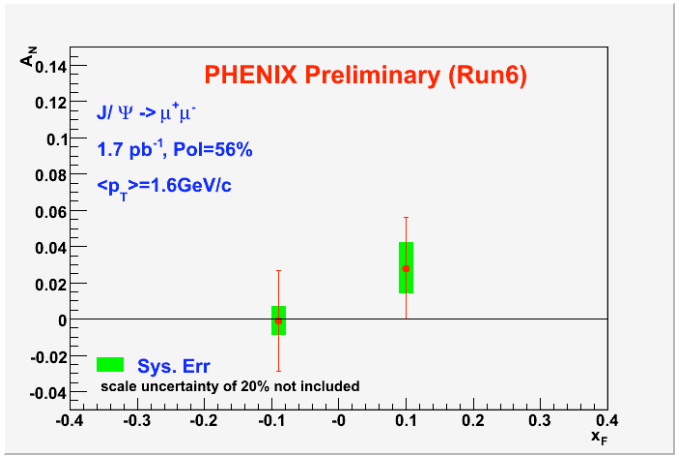
  * gluon has zero transversity

- A perfect channel for gluon Sivers function

- Important to understand the origin of observed large A_N at large x_F



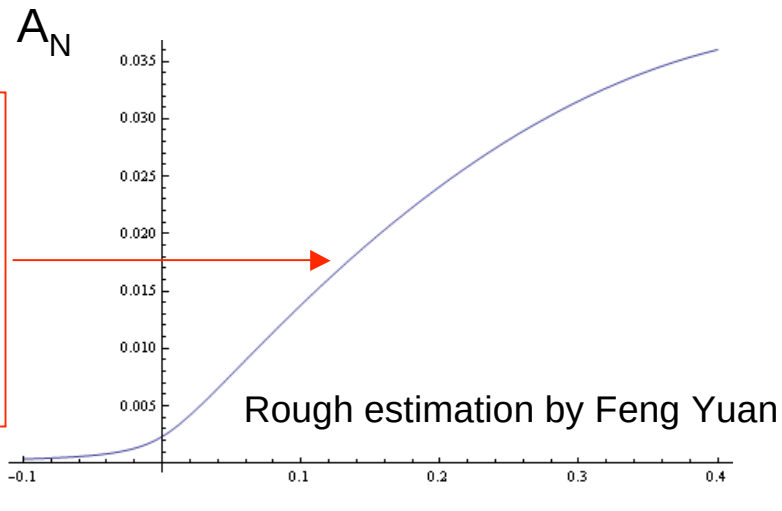
Rough estimate at RHIC



- At RHIC, color-octet dominate the production cross section
- 30%-40% J/Ψ comes from Ψ' and χ_c feeddown

Assume:
--Gluon Sivers function ~ 0.5 x(1-x) times unpolarized gluon distribution (expect large-x and small-x suppression of the Sivers function as compared to the unpolarized one)

-- 30% J/Ψ comes fromχ_c feeddown

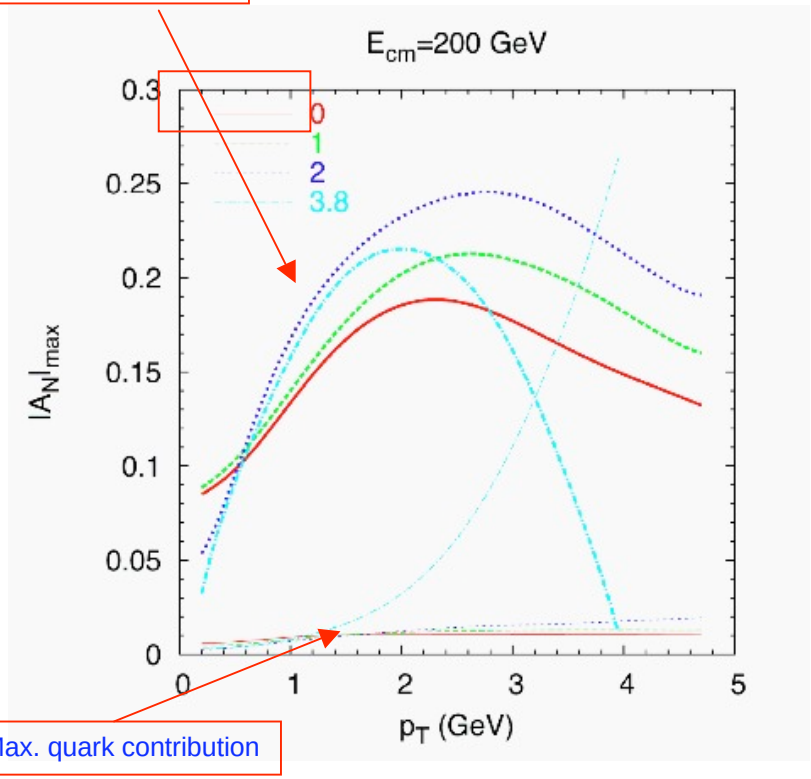


H.Liu AGS/RHIC 2008

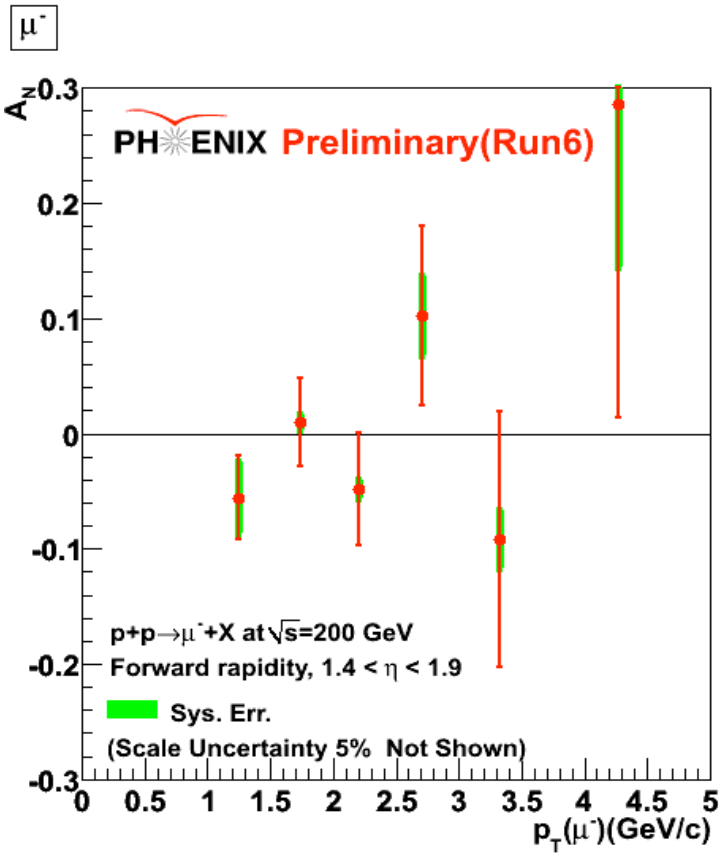
Anselmino's prediction on open charm A_N

Inclusive D meson production at RHIC energy

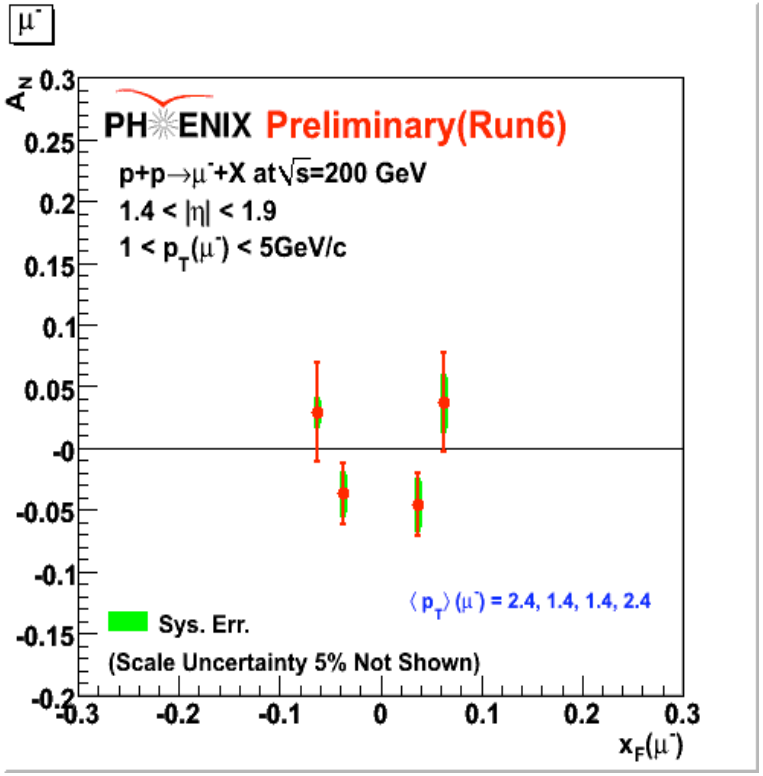
Max. gluon contribution

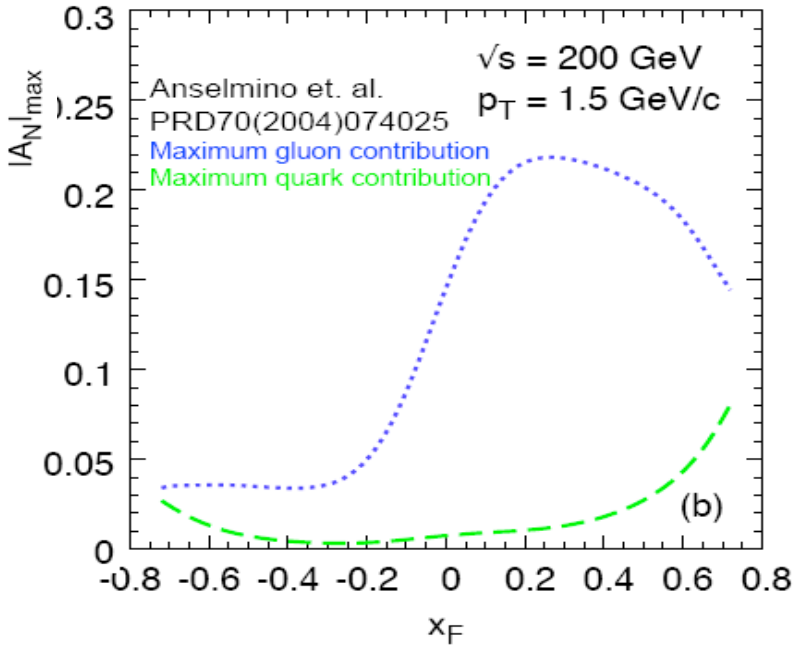


Max. quark contribution



A_N vs. x_F





-- Qualitative conclusion: Data constrain the gluon Sivers function to be significantly smaller than the maximal allowed
-- Translation between D meson and muon kinematics and estimate of charm vs. bottom components underway (next slide)

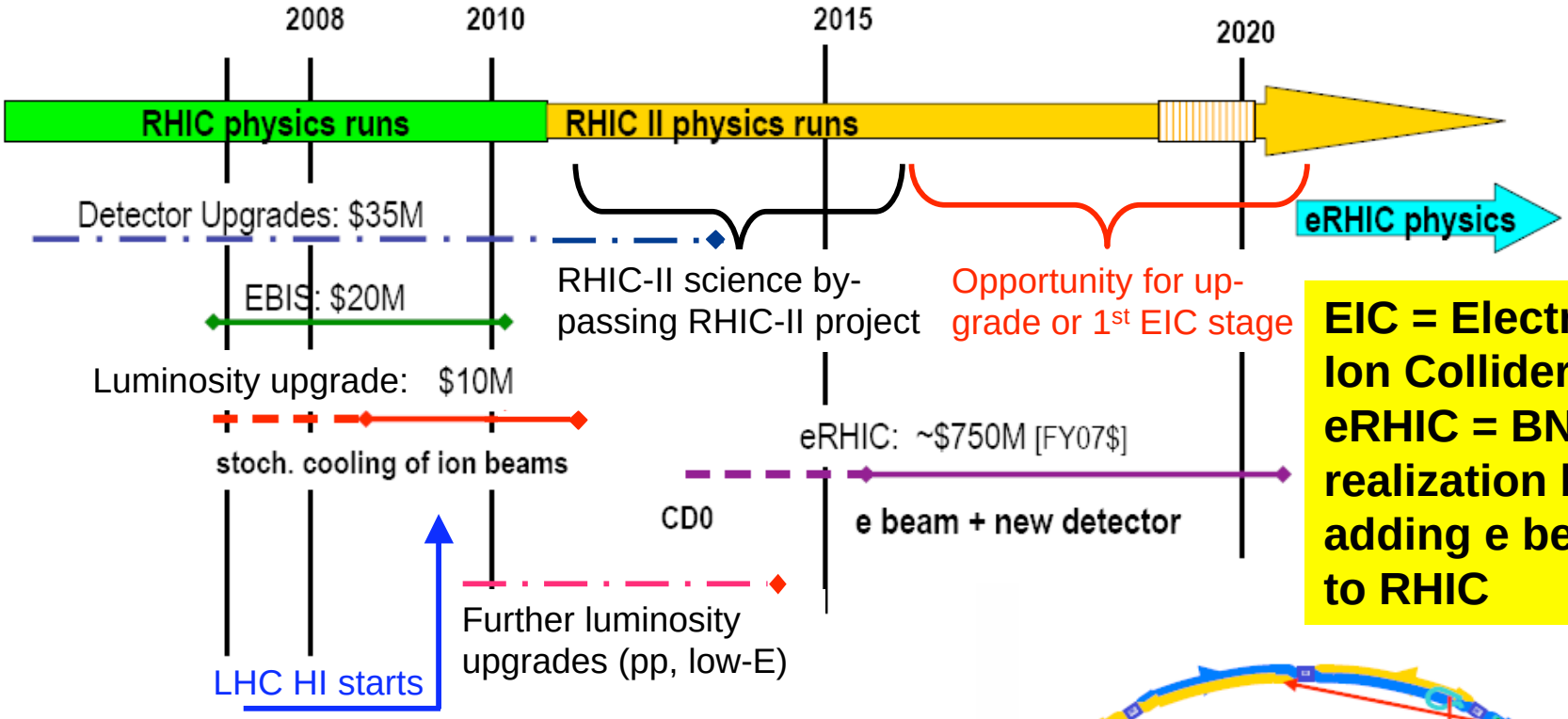
Remarkable experimental progress in QCD spin physics in the last 20 years, and more years to come!

- Inclusive spin-dependent DIS
  - EMC, SMC, COMPASS
  - E142,E143,E154,E156
  - HERMES
  - Jlab-Hall A, B(CLAS)
- Semi-inclusive DIS
  - SMC, COMPASS
  - HERMES
- Polarized pp collisions
  - RHIC
    - PHENIX & STAR

Outlook of RHIC-SPIN

- Gluon polarization @200GeV
  - $50pb^{-1}$ 2009
- W-program @500GeV
  - $100pb^{-1}$ ~2012
  - $300pb^{-1}$
- Future DY @200GeV
  - $250pb^{-1}$ ~2014

A Long Term (Evolving) Strategic View for RHIC



EIC = Electron-Ion Collider; eRHIC = BNL realization by adding e beam to RHIC

RHIC, RHIC-II, LHC-HI and EIC science share a common theme…

Summary and Outlook

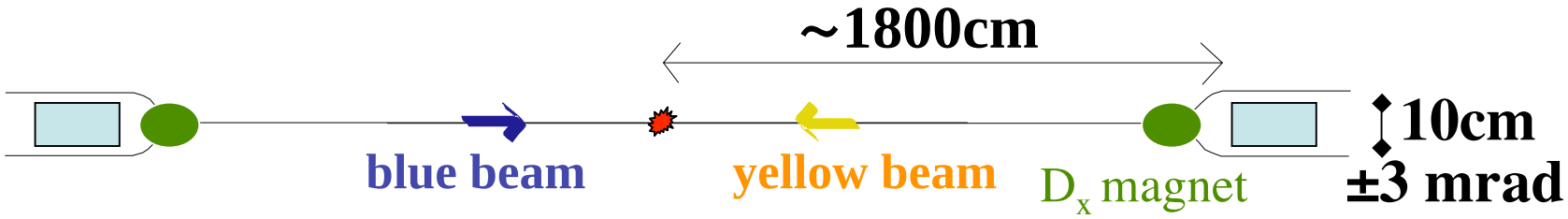
- Very rich physics program with polarized beams at RHIC
  - Spin Puzzle
    - Polarized gluon distribution
    - Flavor-identified polarized quark distributions
  - Excellent QCD test ground with polarized partons

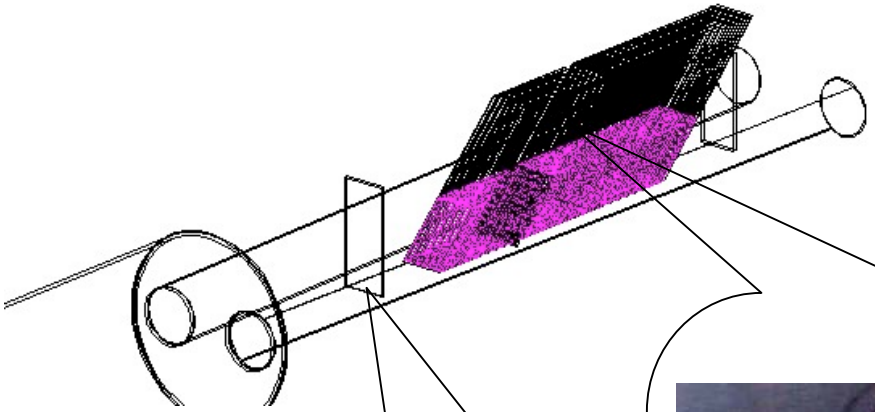
- Latest news from RHIC-Spin:
  - Light hadrons: π, K, η, Λ, ...
  - Heavy quarks: J/Psi, open charm …
  - Explore orbital angular momentum: di-jet correlation etc.

- Where does the nucleon get its spin?
  - Still don't know … but RHIC-SPIN will help us to find the answer
  - and we will learn a lot more about the nature of strong interactions

Backup

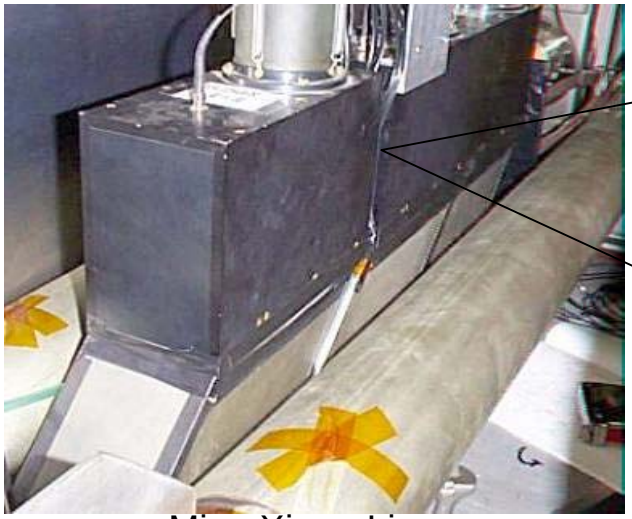
Very Forward Neutron @PHENIX





Forward counter

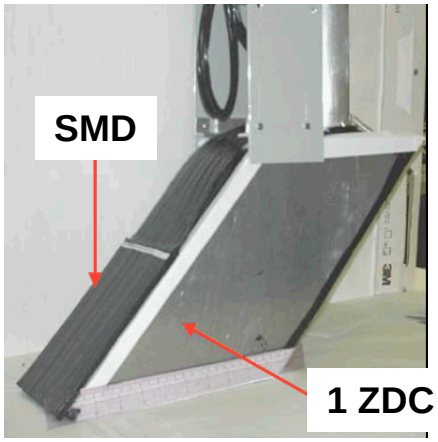
ZDC



Ming Xiong Liu

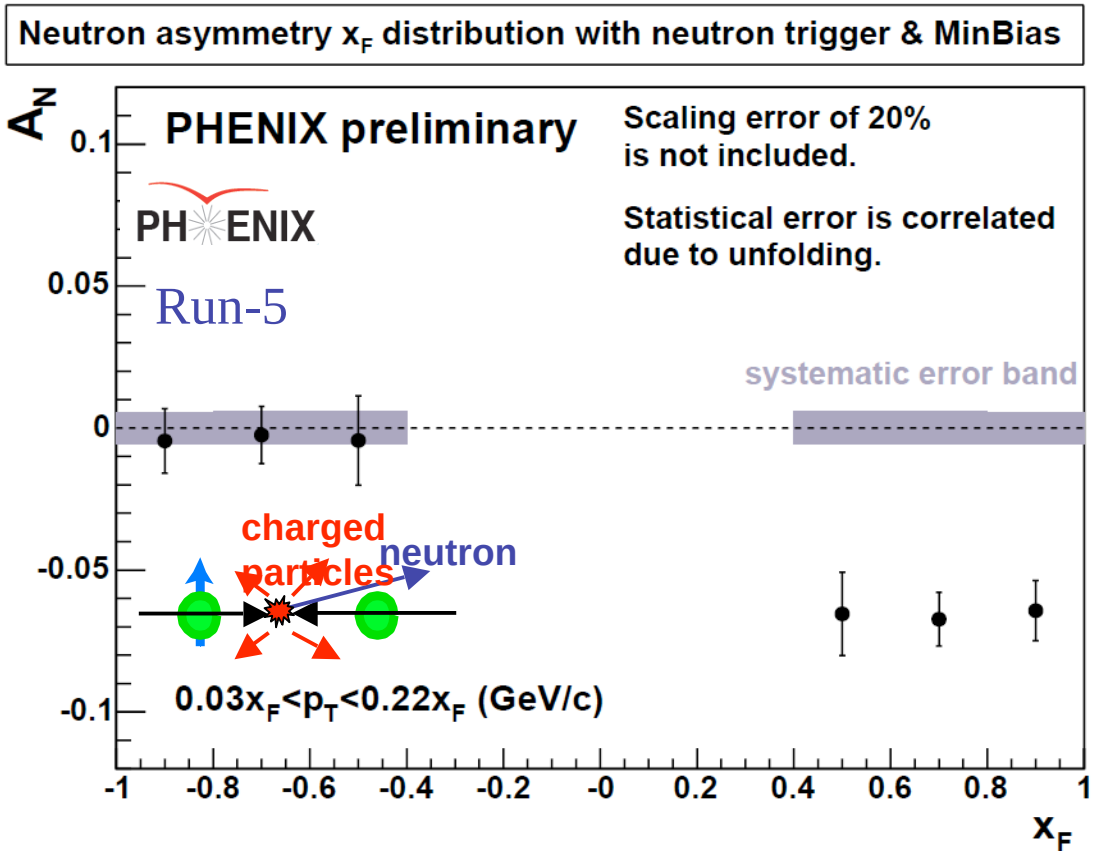
3 modules: $150X_0$ $5.1\lambda_I$

SMD



position measurement with scintillators

Run5: Forward Neutrons Asymmetry



Weak x_F dependence observed

Why such large neutron asymmetries?

- A_N is produced via interference of spin non-flip and spin-flip amplitudes
- In Regge theory

  -- A spin non-flip amplitude contribution can be described due to Reggeon and Pomeron exchange

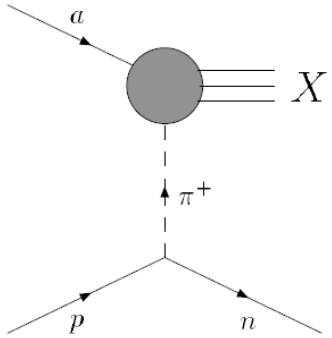
  -- We need spin-flip amplitude –> one pion exchange amplitude

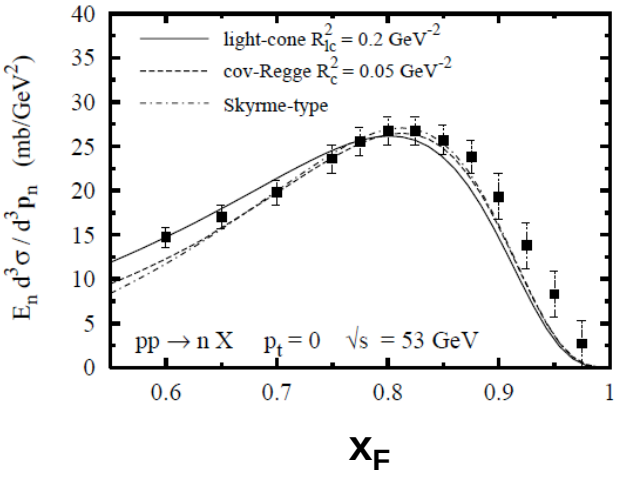
- One pion exchange model (OPE) may explain the result

  -- OPE has been used to describe exclusive diffractive neutron production

  -- The cross-section at ISR is well described by spin-flip OPE

Eur.Phys.J.A7:109-119,2000



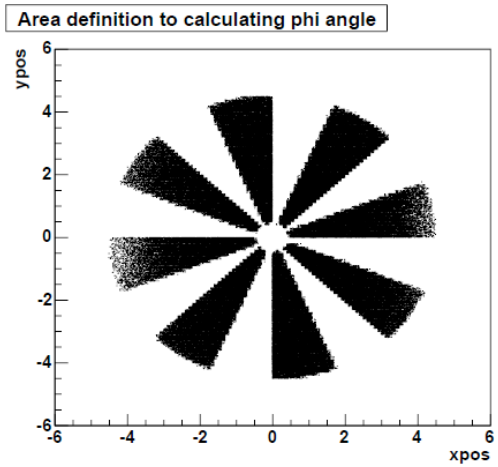


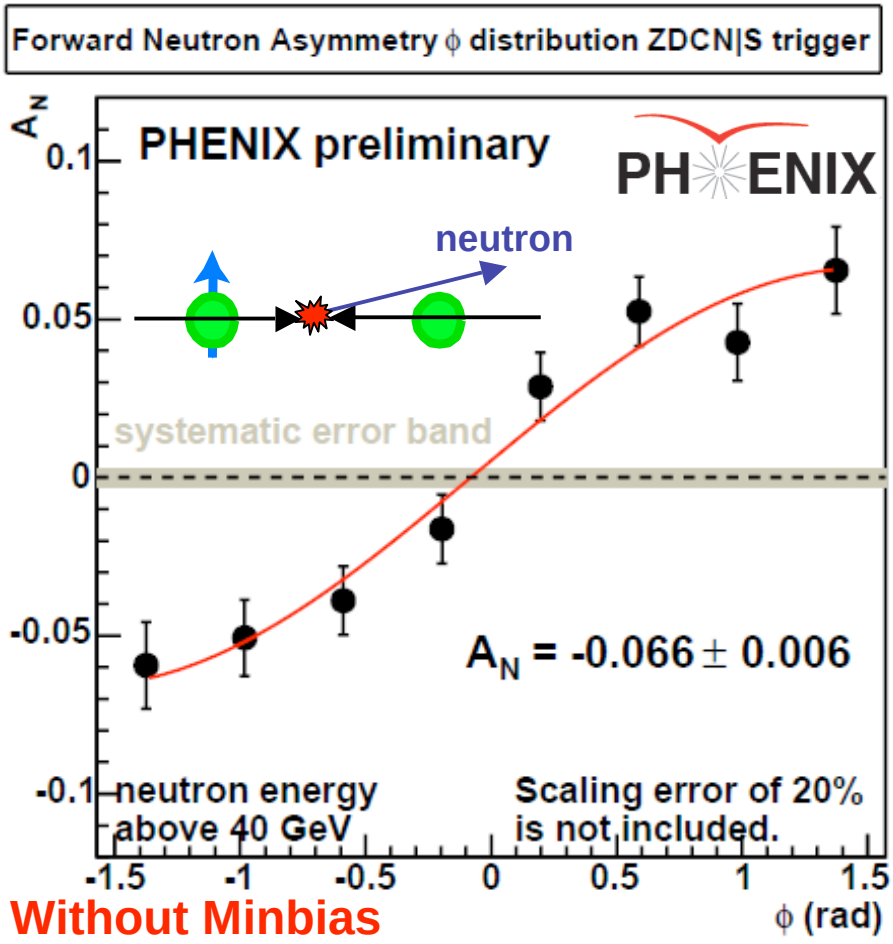
Neutron A_N

- Square-root formula

$$A_N \equiv \frac{1}{P}\frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} \approx \frac{1}{P}\frac{\sqrt{N_L^\uparrow N_R^\downarrow} - \sqrt{N_L^\downarrow N_R^\uparrow}}{\sqrt{N_L^\uparrow N_R^\downarrow} + \sqrt{N_L^\downarrow N_R^\uparrow}}$$

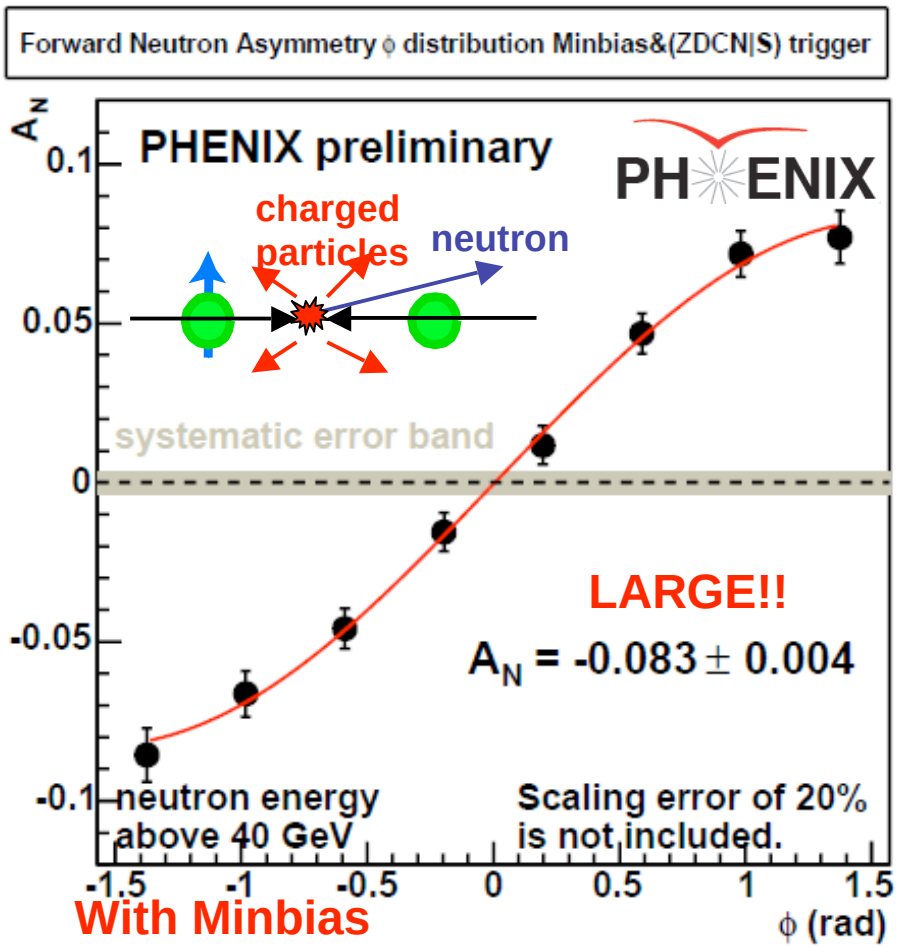
P~48%





Without Minbias

Xion



With Minbias

Theoretical effort on open charm single spin asymmetries

G.D. Zacarias et. al., EPJC 51(2007)619

- Two component model (has been used to describe the production asymmetry of charm productions successfully)

$$\frac{d\sigma^{D}}{dx_F dp_T} = \frac{d\sigma^{D}_{rec}}{dx_F dp_T} + \frac{d\sigma^{D}_{frag}}{dx_F dp_T}$$

-- Recombination process: a quark from the sea joins a valence quark in the initial state

$$\overline{D}^{0} : u\bar{c} \qquad D^{-} : d\bar{c}$$

-- Fragmentation process: assume particles created by the fragmentation process lose information about the spin polarization of the proton in the initial state

$$\frac{d\sigma^{\uparrow}_{frag}}{dx_F dp_T} = \frac{d\sigma^{\downarrow}_{frag}}{dx_F dp_T}$$

Anselmino's prediction

Prediction of two component model

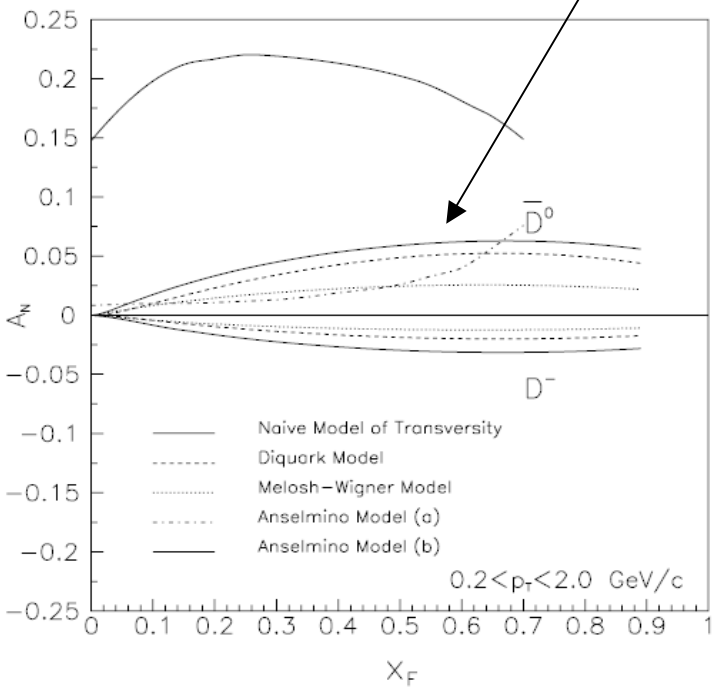


Fig. 6. Comparison of the single spin asymmetries obtained with the model presented here (*solid*, *dash* and *dotted curves*) with those obtained by Anselmino et al. [19] (*solid* in the upper part and *dot dashed curve*)

Prediction:

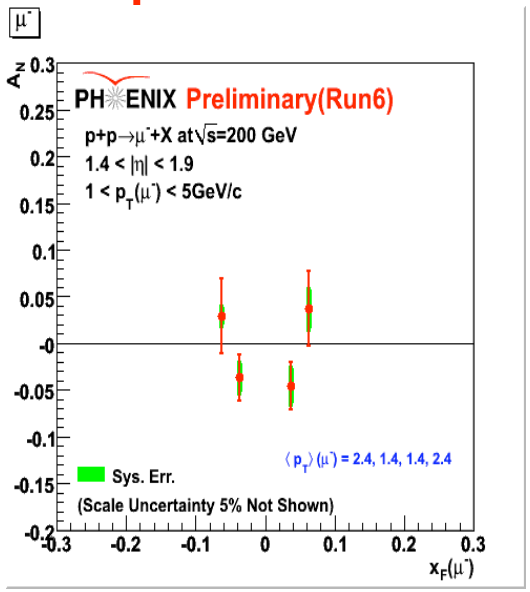
$\bar{D}^0(u\bar{c}), D^-(d\bar{c})$

$D^0(\bar{u}c), D^+(\bar{d}c)$

→ Sizable A_N

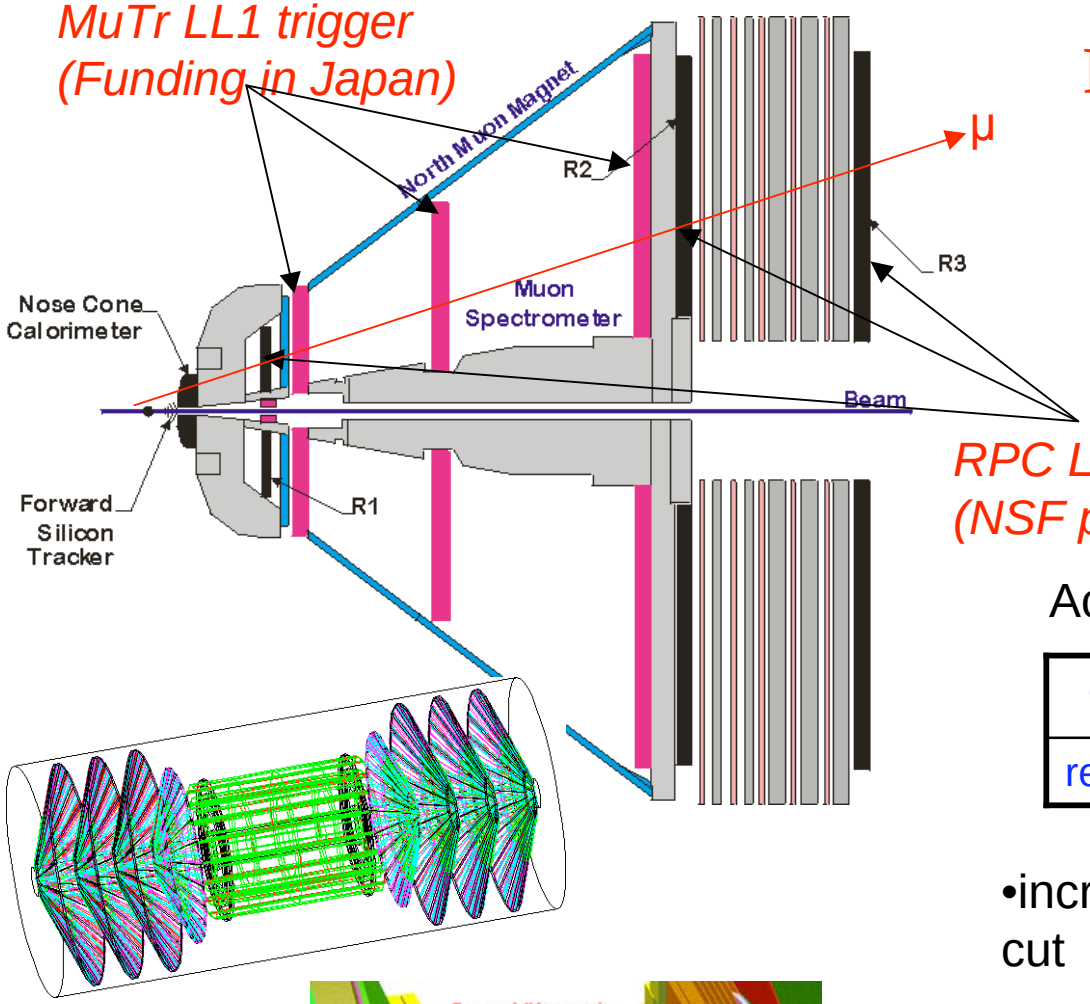
→ A_N=0

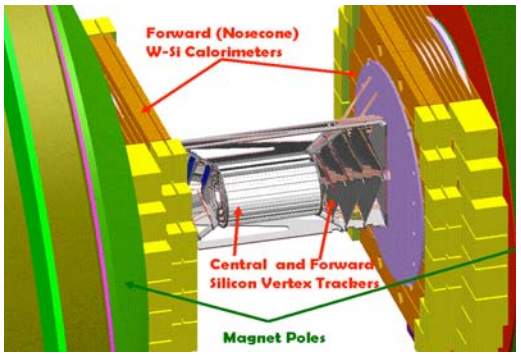
Signal: μ^-



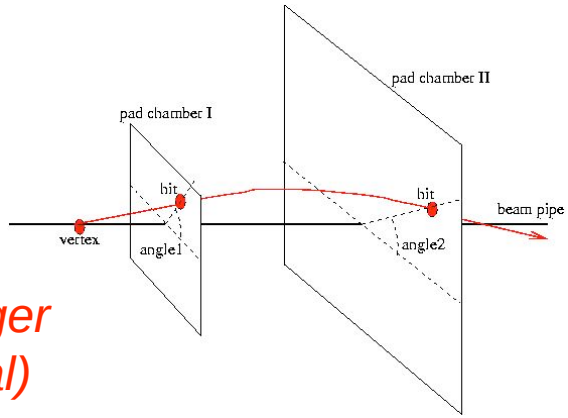
PHENIX forward upgrade

MuTr LL1 trigger (Funding in Japan)





RPC LL1 trigger (NSF proposal)



Achieved enough trigger rejection

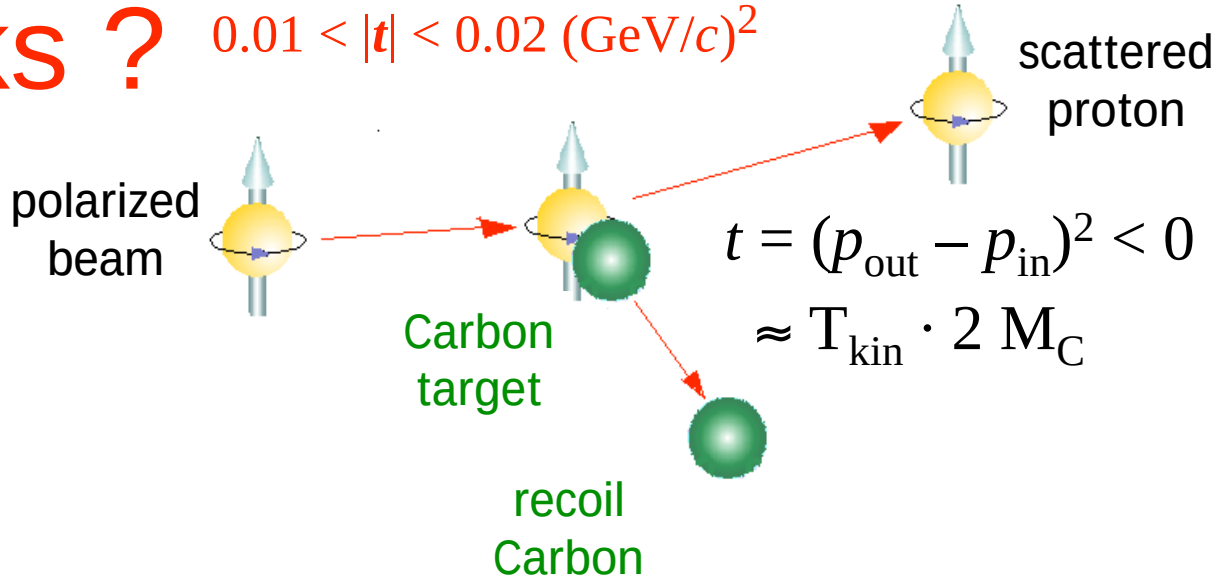
$\delta(\phi)$ deg	<0.7	<1.0	<2.0
rejection	36000	19980	10090

- increase of pion rejection via isolation cut
- possible background rejection via reconstructing W transverse mass.
- possible improve of momentum resolution with well defined determined vertex.

How It Works ?

$0.01 < |t| < 0.02\ (\mathrm{GeV}/c)^2$

$$P_B = -\frac{1}{A_N} \cdot \frac{N_{left} - N_{right}}{N_{left} + N_{right}}$$



$$t = (p_{out} - p_{in})^2 < 0$$
$$\approx T_{kin} \cdot 2\, M_C$$

Polarimetry:

Requires large F.o.M: A_N^2 x *rate* for fast measurement

(not at any price however, i.e. by increasing the rates)

small A_N ~ 1 % (far from ideal !)

⇒ requires large statistics > 10^7, for d P_B ~ few %

however too large rates (i.e. thick target, detector area, etc.)

⇒ occupancy and pileup

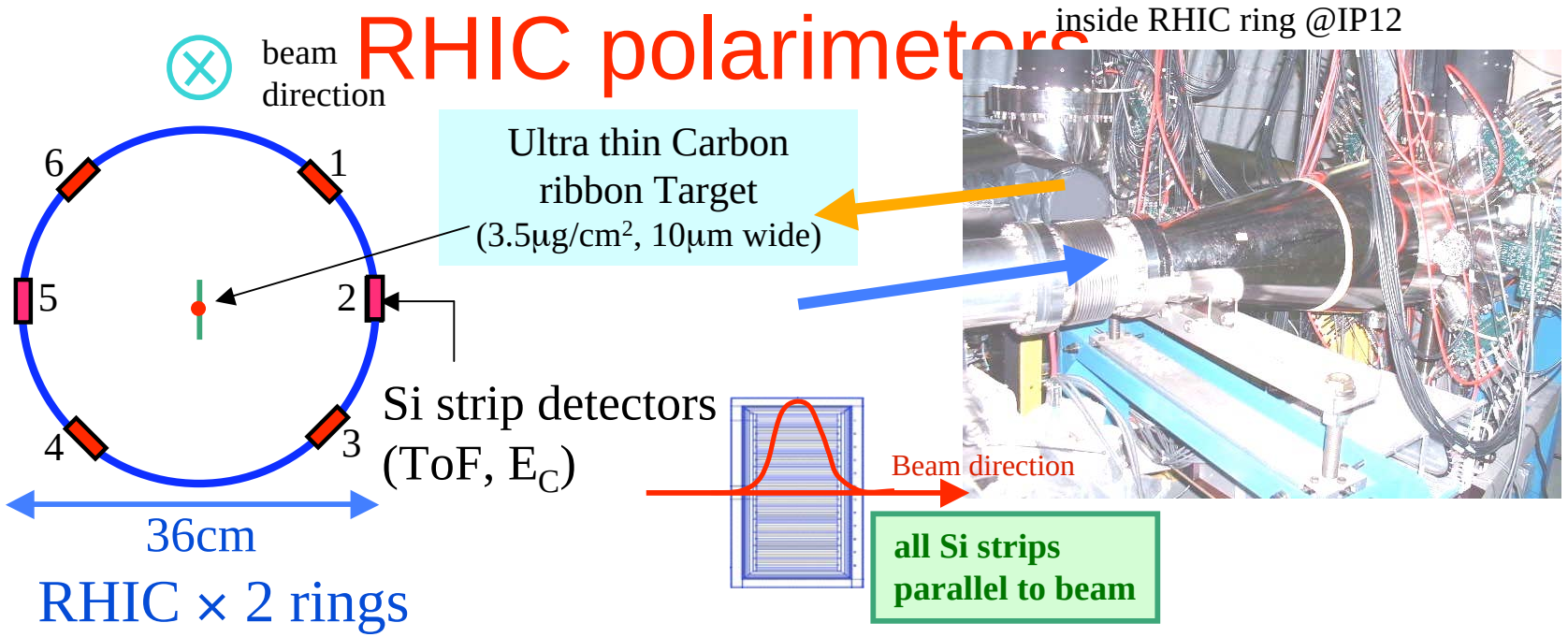
⇒ very difficult operation

⇒ corrections to measured asymmetries

⇒ larger systematic uncertainty

Absolute calibration ⇒ Polarized Gas Jet target

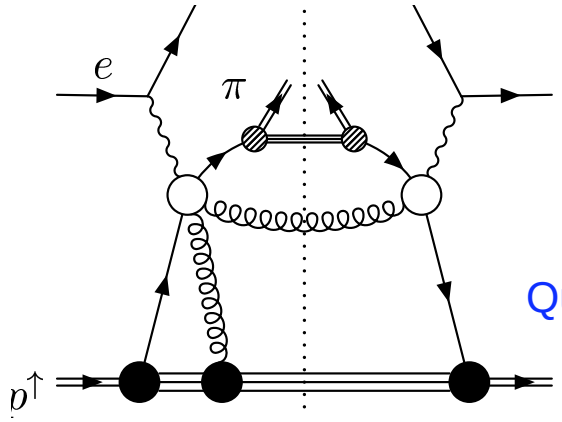
Setup for *p*C scattering – the RHIC polarimeters



- recoil carbon ions detected with Silicon strip detectors
- 2 × 72 channels read out with WFD (increased acceptance by 2)
- very large statistics per measurement (~ 20 × 10^6 events) allows detailed analysis
  - bunch by bunch analysis
  - channel by channel (each channel is an "independent polarimeter")
  - 45° detectors: sensitive to vertical and radial components of $\vec{P}_{beam}$
    → unphysical asymmetries

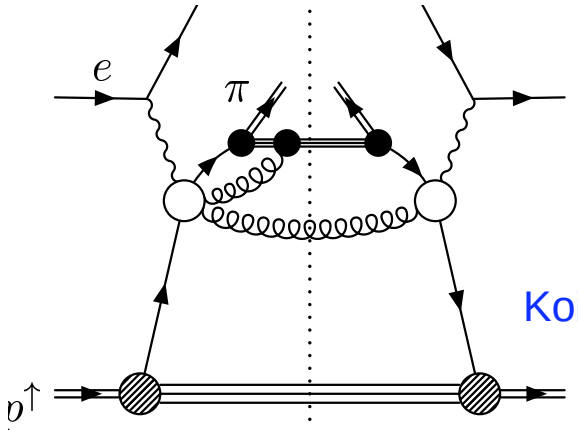
Twist-3 correlation functions and A_N

$G(x_1,x_2)$: quark-gluon correlation at initial state



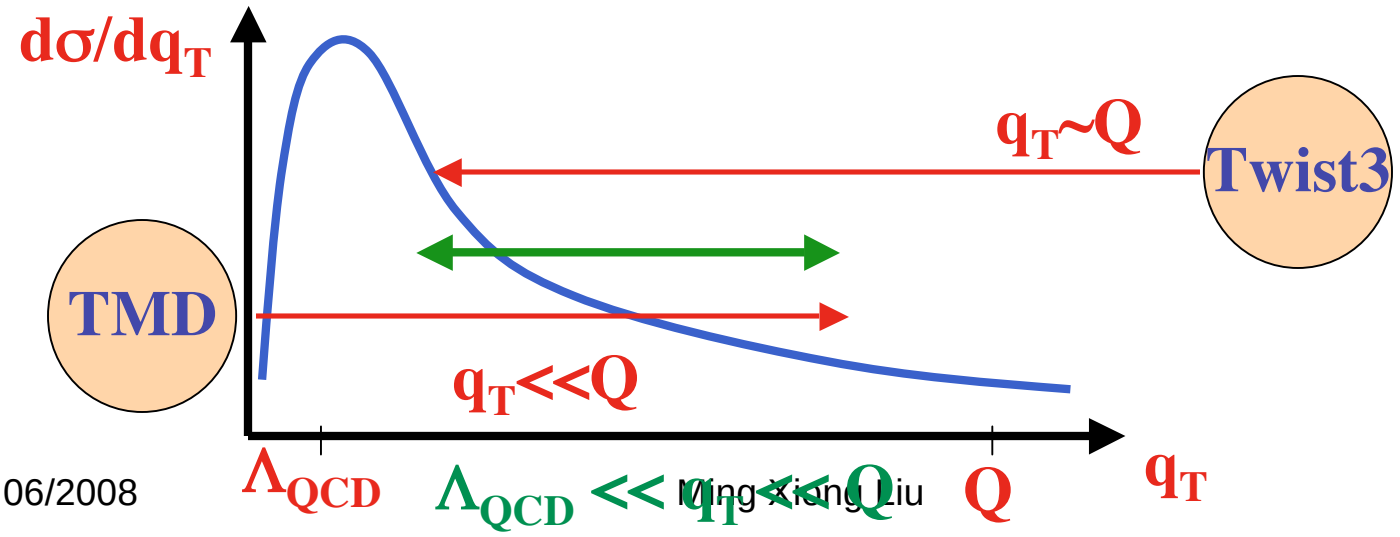
Qui, Starman

$\hat{E}(z_1,z_2)$: quark-gluon correlation at final state



Koike

How those two mechanisms connected ?



Gluon Polarization Measurements: (SI)DIS

- Semi-inclusive DIS
  - HERMES @ DESY
    - high-p_T hadron pairs
  - SMC @ CERN
    - high-p_T hadron pairs
  - COMPASS @ CERN
    - high-p_T hadron pairs
    - open charm