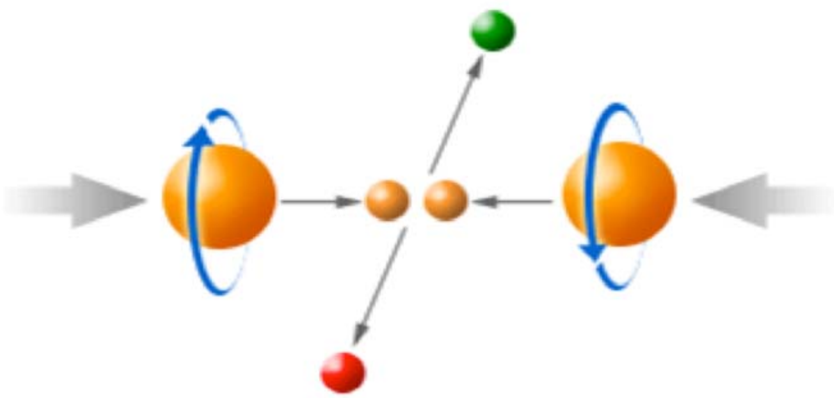
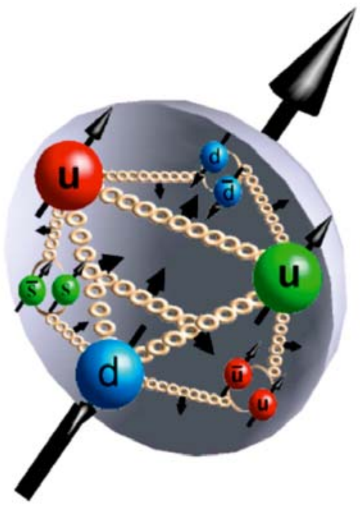


Spin Physics at RHIC

Ming Xiong Liu
Los Alamos National Lab

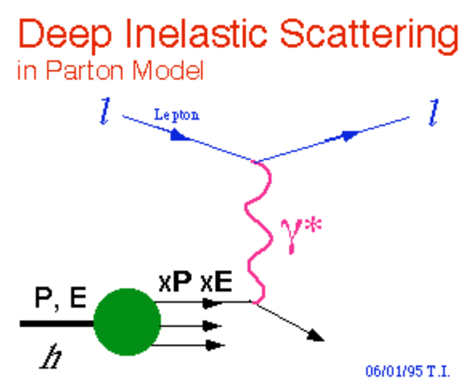


RHIC-Spin Program

New Frontier of Nucleon Structure Research

- Proton Spin Problem- **an outstanding puzzle from polarized DIS experiments**
  - Proton Spin Decomposition

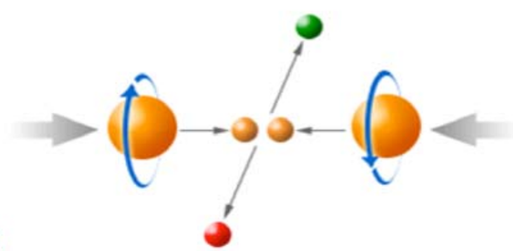
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \Delta L_{q+g}$$



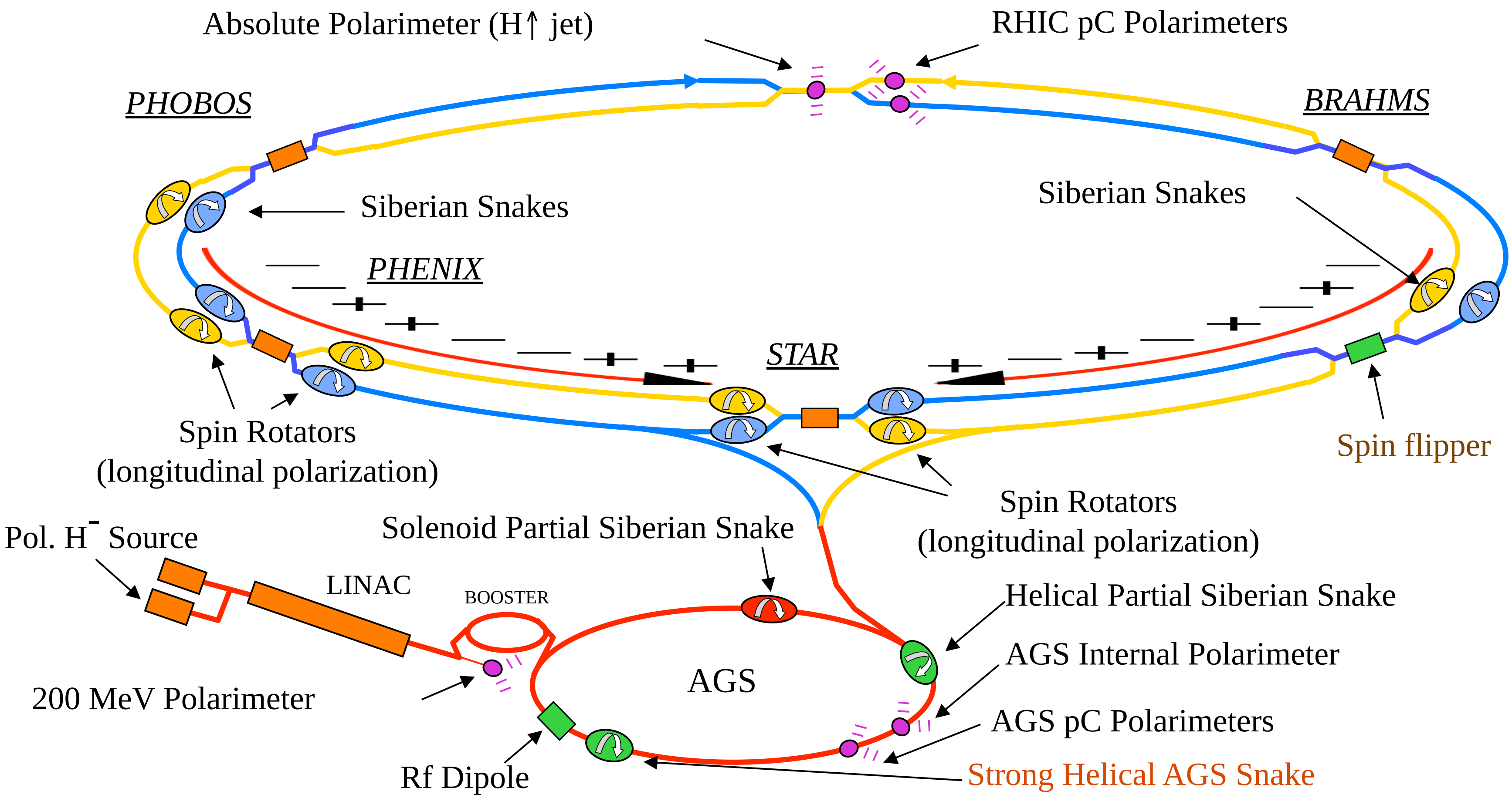
Experimentally ⇒ $\Delta\Sigma = 0.31 \pm 0.04$

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

- a new tool : the 1st polarized proton collider
  - **polarized PDF**
    - **quark-gluon, quark-quark and gluon-gluon interactions**
    - **directly explore gluon and sea quark distributions**
  - **study the role of spin in QCD strong interaction via A_N**



RHIC: the world's first polarized hadron collider

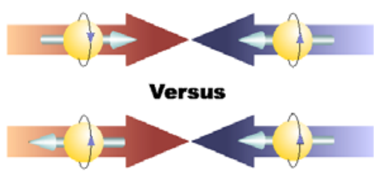


- Spin varies from rf bucket to rf bucket (9.4 MHz)
- Spin pattern changes from fill to fill
- Spin rotators provide choice of spin orientation
- "Billions" of spin reversals during a fill with little if any depolarization

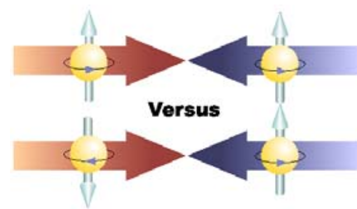
Experimental Observables

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

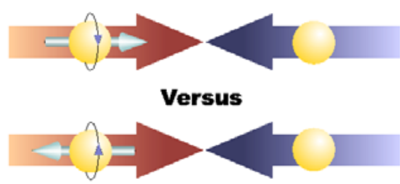
$$A_{LL} = \frac{\sigma(++)-\sigma(+-)}{\sigma(++)+\sigma(+-)}$$



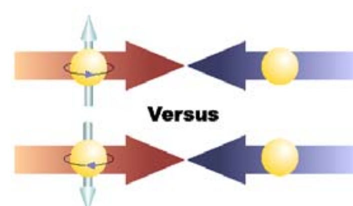
$$A_{TT} = \frac{\sigma(\uparrow\uparrow)-\sigma(\uparrow\downarrow)}{\sigma(\uparrow\uparrow)+\sigma(\uparrow\downarrow)}$$



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



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



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
2009	500GeV/200GeV		just ended 06/2009

The PHENIX detector

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

$1.2 < |\eta| < 2.4$

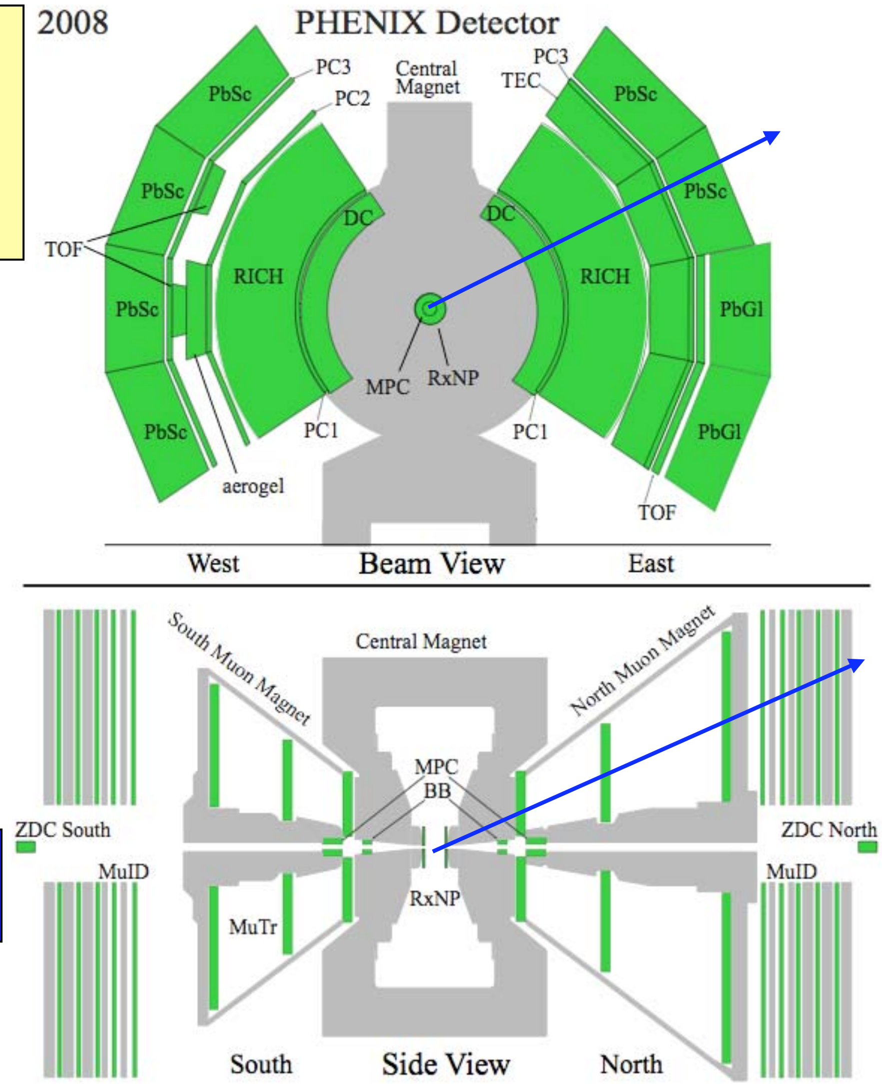
2π azimuth

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

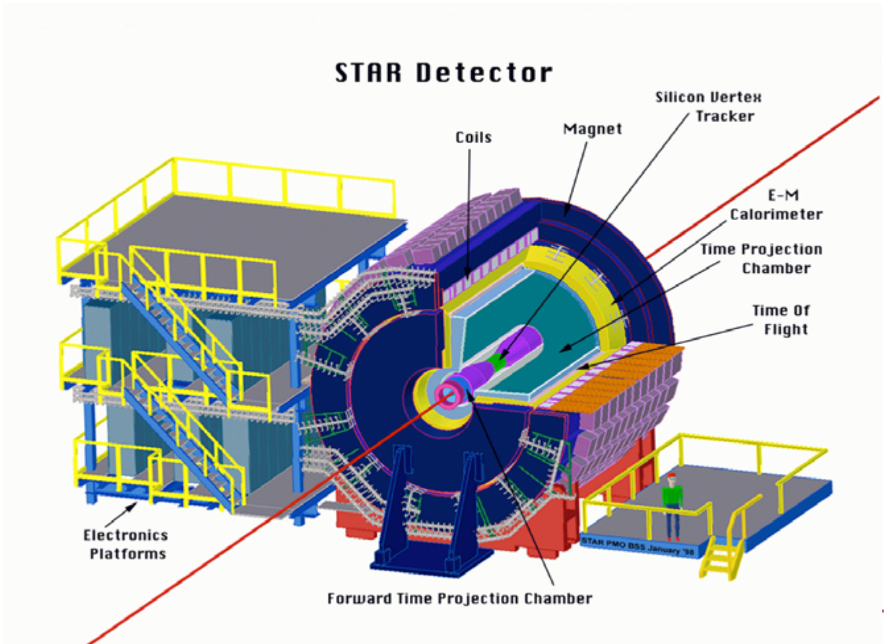
$3.1 < |\eta| < 3.7$

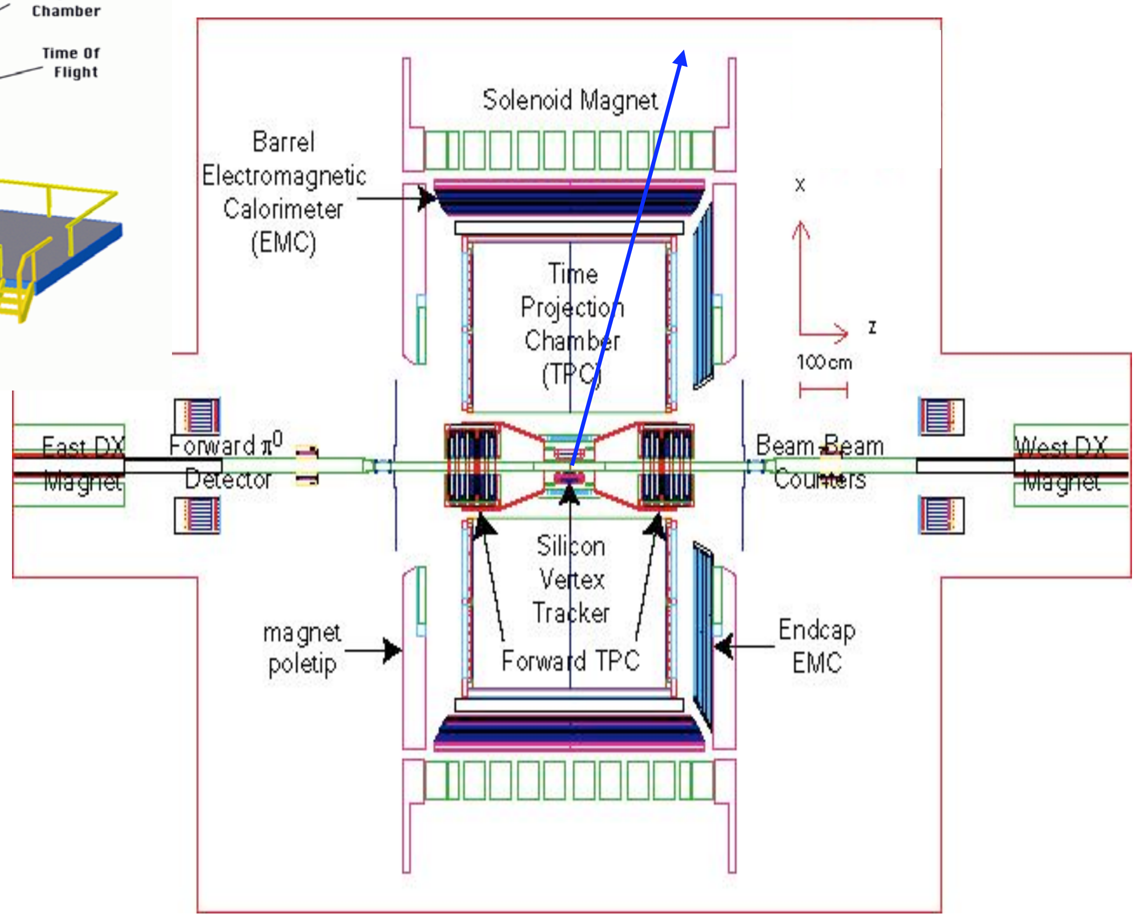
2π azimuth

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



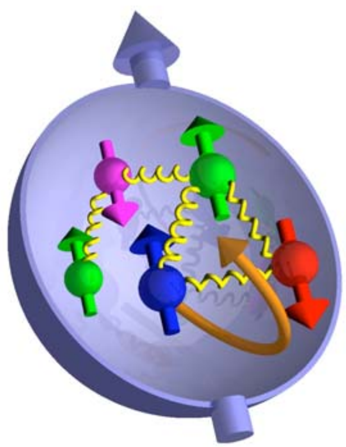
The STAR Detectors





- 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 $3.3<|\eta|<4.1$

Part I: The 20-year Old Proton Spin Puzzle



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

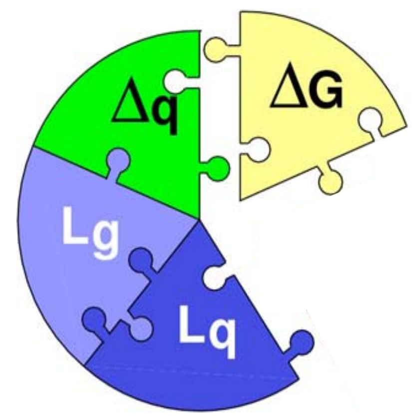
Spins + orbital angular momentum need to give the observed spin 1/2 of proton

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

Fairly well measured only ~30% of spin

Beginning to be measured at RHIC

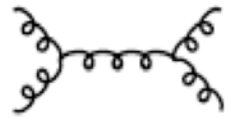
A future challenge



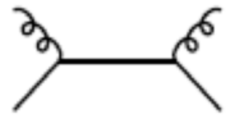
Physics Channels Sensitive to $\Delta g(x,Q^2)$

$$\vec{p}+\vec{p}\rightarrow\pi+X$$
$$\vec{p}+\vec{p}\rightarrow \text{jet}+X$$

$$\vec{g}\vec{g}\rightarrow gg$$



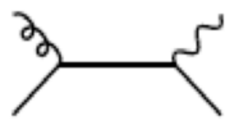
$$\vec{q}\vec{g}\rightarrow qg$$



Pion or jet production; high rates; complex calculation required to extract physics; broad x_g range needed to properly test models

$$\vec{p}+\vec{p}\rightarrow\gamma+X$$
$$\vec{p}+\vec{p}\rightarrow\gamma+\text{jet}+X$$

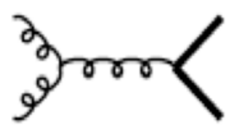
$$\vec{q}\vec{g}\rightarrow\gamma q$$



Photon production; low rates; simpler physics channels promise cleaner result

$$\vec{p}+\vec{p}\rightarrow D+X$$
$$\vec{p}+\vec{p}\rightarrow B+X$$

$$\vec{g}\vec{g}\rightarrow c\bar{c}$$
$$\vec{g}\vec{g}\rightarrow b\bar{b}$$



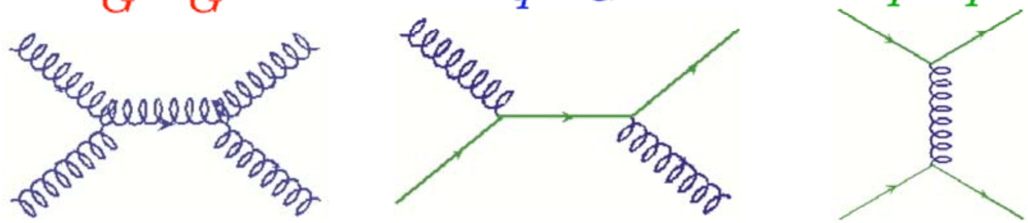
Heavy-flavour production; separated vertex detection required for clean observation, independent channels

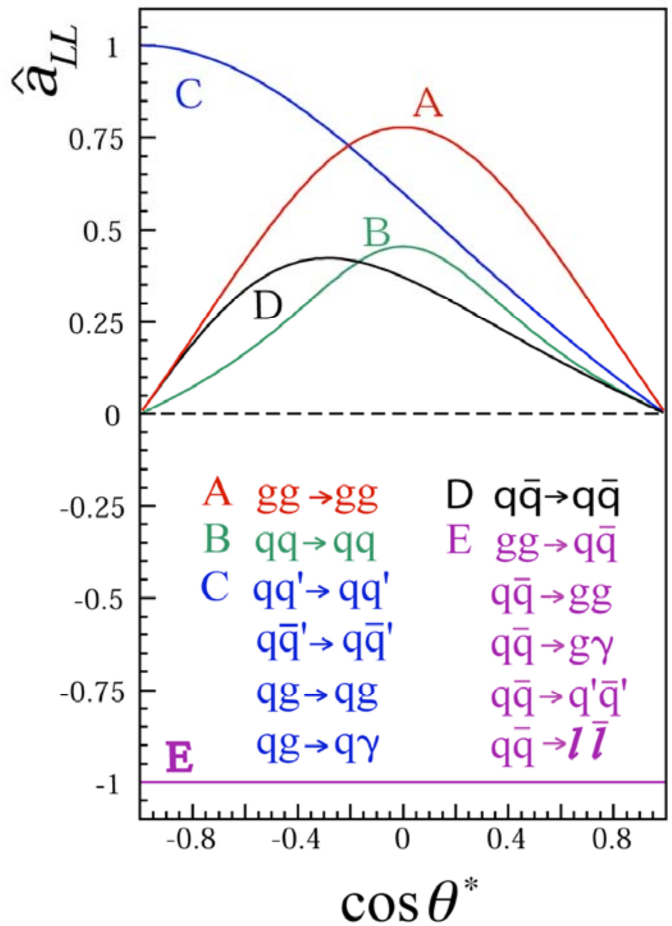
Longitudinally polarized pp collisions at RHIC

$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} \propto \frac{\Delta f_a \Delta f_b}{f_a f_b} \hat{a}_{LL}$$

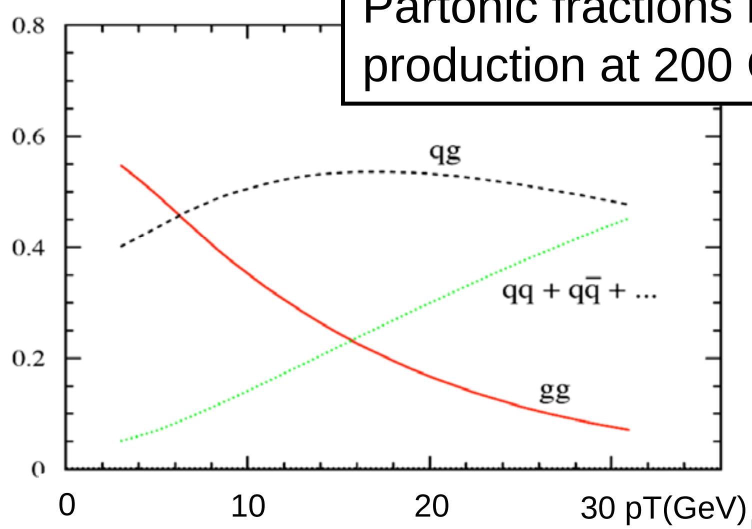
Δf: polarized parton distribution functions

$\frac{\Delta G}{G}\frac{\Delta G}{G}$ $\quad$ $\frac{\Delta q}{q}\frac{\Delta G}{G}$ $\quad$ $\frac{\Delta q}{q}\frac{\Delta q}{q}$



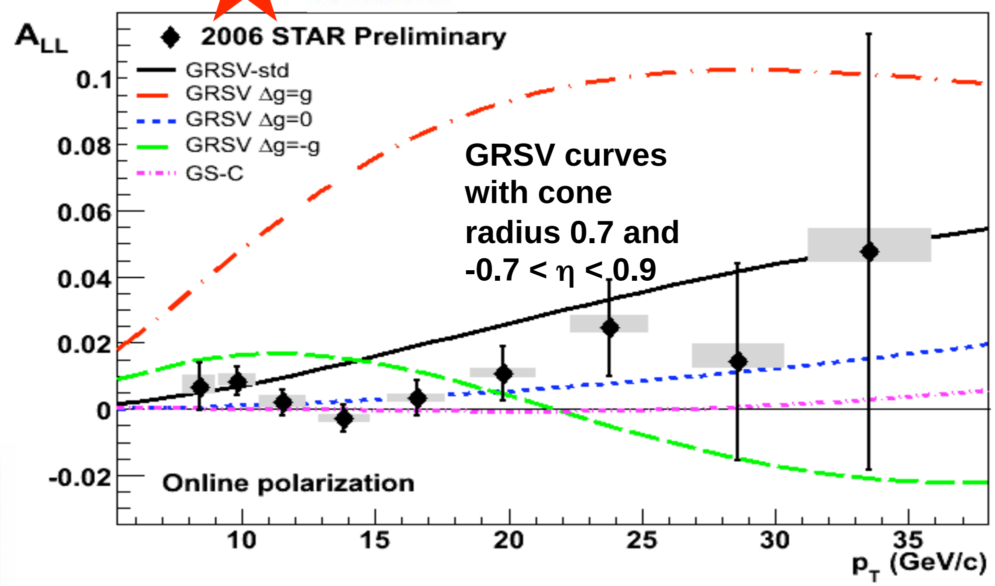


Partonic fractions in jet production at 200 GeV



For most RHIC kinematics, *gg* and *qg* dominate, making A_{LL} for inclusive jets and hadrons sensitive to gluon polarization.

RHIC Data

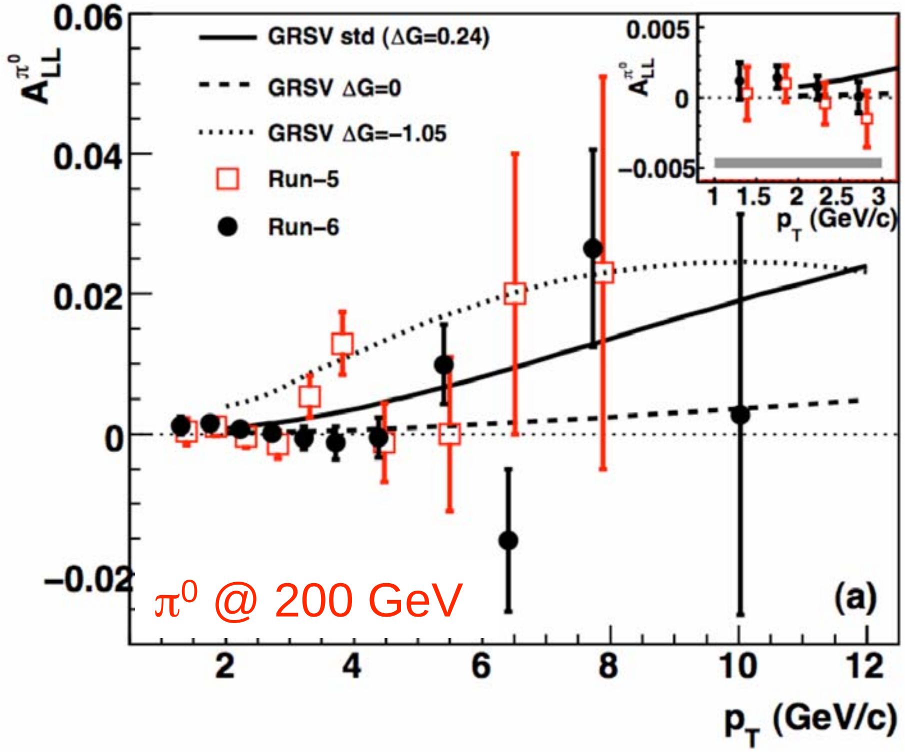


2005 jet data: PRL 100, 232003 (2008)

PHENIX

2005: PRD 76, 051106

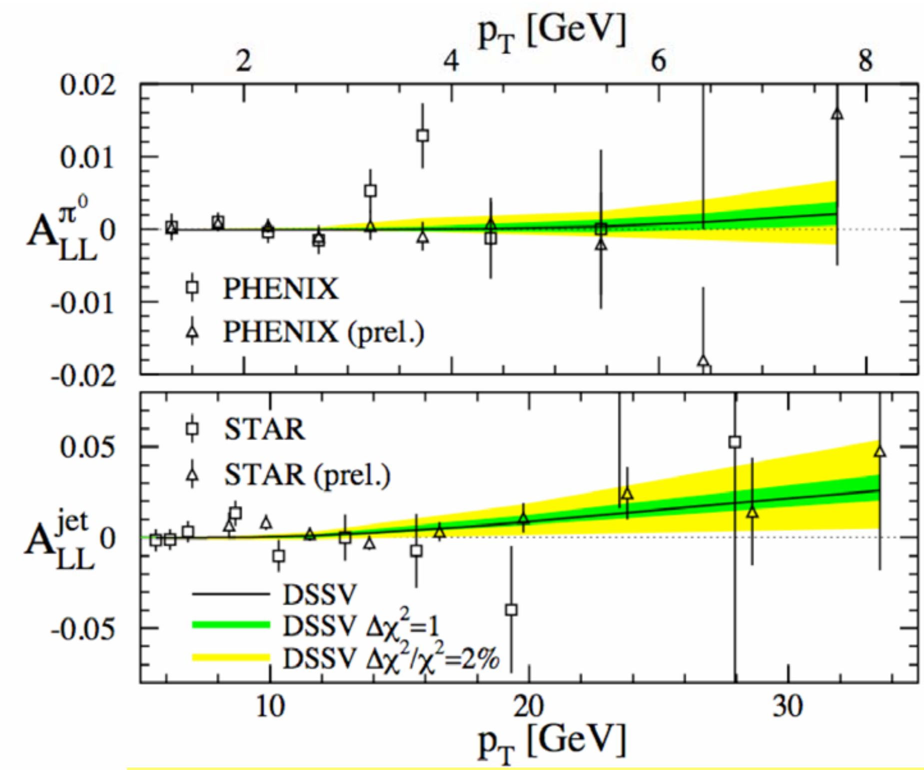
2006: arXiv:0810.0694

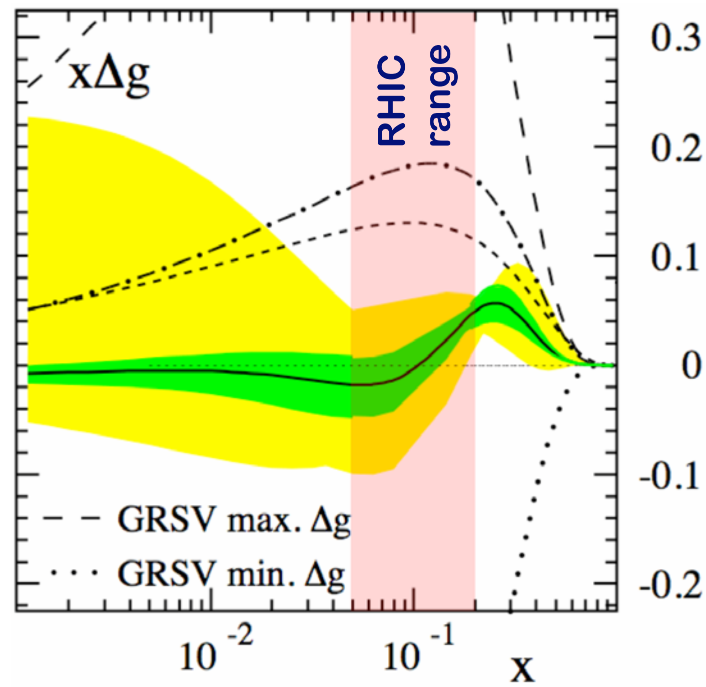


Recent Global Fit: DSSV

- » First truly global analysis of polarized DIS, SIDIS and pp results
- » PHENIX & STAR $\sqrt{s}$ = 200 and 62 GeV data used
- » RHIC data significantly constrain ΔG in range $0.05<x<0.3$

de Florian, Sassot, Stratmann, Vogelsang PRL 101, 072001(2008)



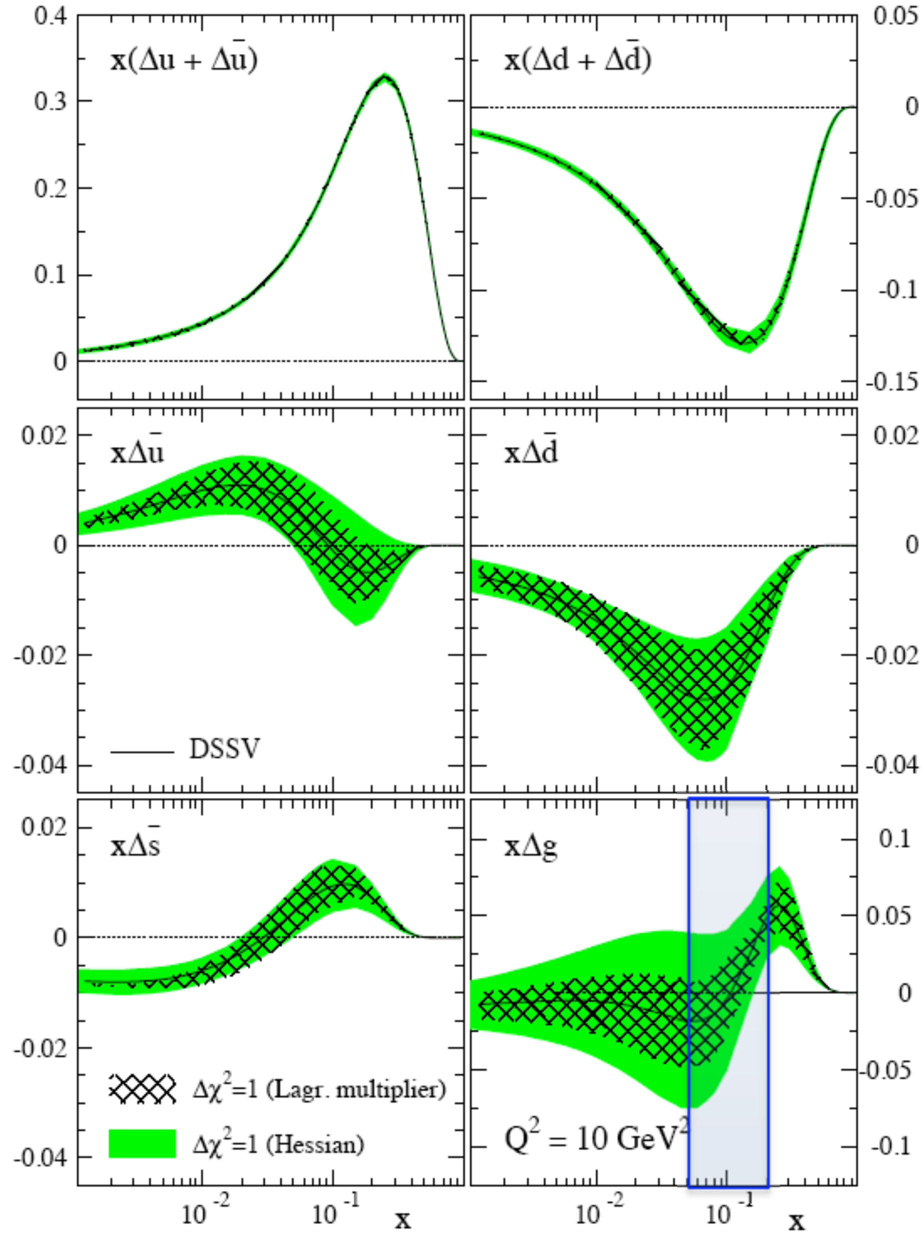


- ➢ **$\Delta g(x)$ small in current RHIC measured range**
- ➢ **Best fit has a node at x~0.1**
- ➢ **Low-x unconstrained**

Updated DSSV Global Fit [arXiv:0904.3821]

TABLE III: Truncated first moments $\Delta f_j^{1,[0.001\to1]}$ at $Q^2 = 10\,\mathrm{GeV}^2$ and their uncertainties for $\Delta\chi^2 = 1$ obtained with the Lagrange multiplier and the Hessian method. In the last line, Δg^{RHIC} represents the first moment but truncated to $[0.05 \to 0.2]$.

	Lagrange mult.	Hessian method
$\Delta u + \Delta\bar{u}$	$0.793^{+0.011}_{-0.012}$	0.793 ± 0.012
$\Delta d + \Delta\bar{d}$	$-0.416^{+0.011}_{-0.009}$	-0.416 ± 0.011
$\Delta\bar{u}$	$0.028^{+0.021}_{-0.020}$	0.028 ± 0.022
$\Delta\bar{d}$	$-0.089^{+0.029}_{-0.029}$	-0.089 ± 0.029
$\Delta\bar{s}$	$-0.006^{+0.010}_{-0.012}$	-0.006 ± 0.012
$\Delta\Sigma$	$0.366^{+0.015}_{-0.018}$	0.366 ± 0.017
Δg	$0.013^{+0.106}_{-0.120}$	0.013 ± 0.182
Δg^{RHIC}	$0.005^{+0.051}_{-0.058}$	0.005 ± 0.056



In the context of this fit, RHIC Spin is straddling a node in $\Delta g(x)$, such that the contribution to our observable integral is nearly zero.

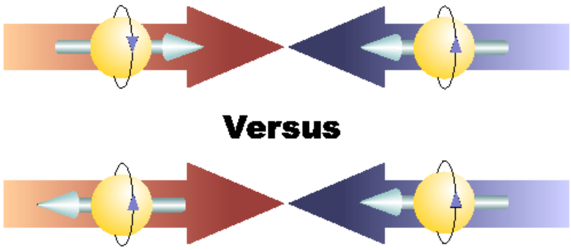
We need to change our √s so that we can observe a different *x*-range.

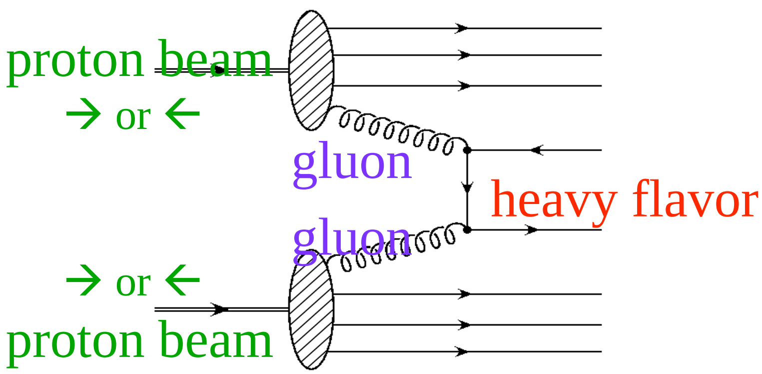
Future New Probes @RHIC: ΔG

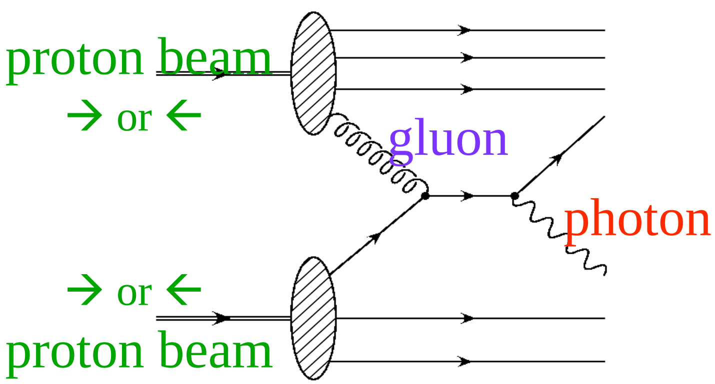
- Polarized hadron collisions
  - double longitudinal spin asymmetry

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

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

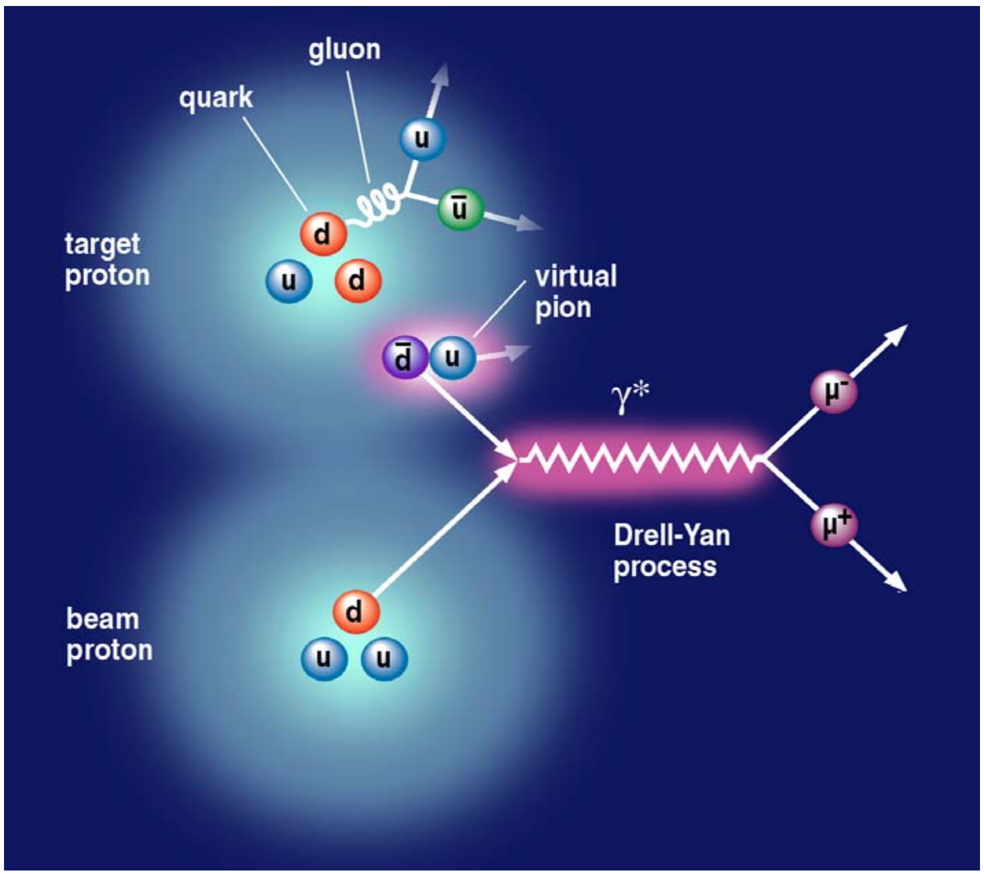






Part II: Sea Quark Polarization & Asymmetry

Nucleon is a complex system
Sea quarks and gluons correlated

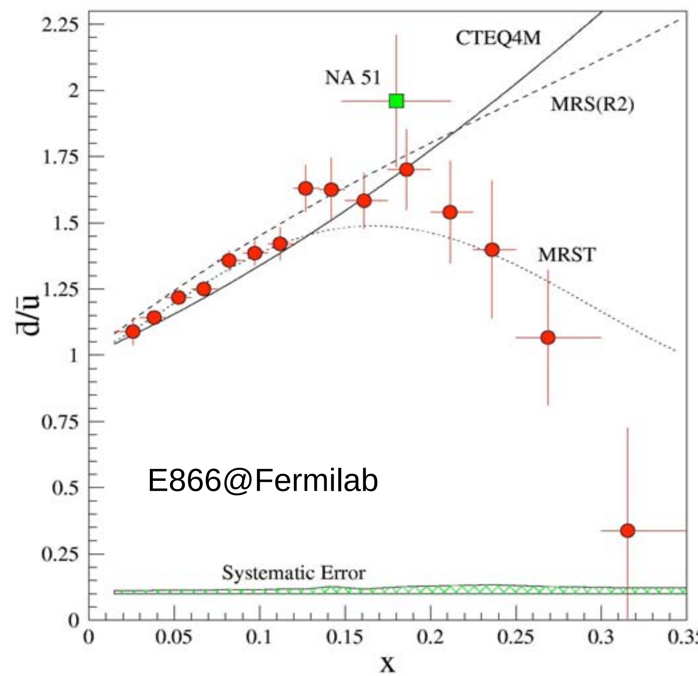


- Pion cloud model:

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

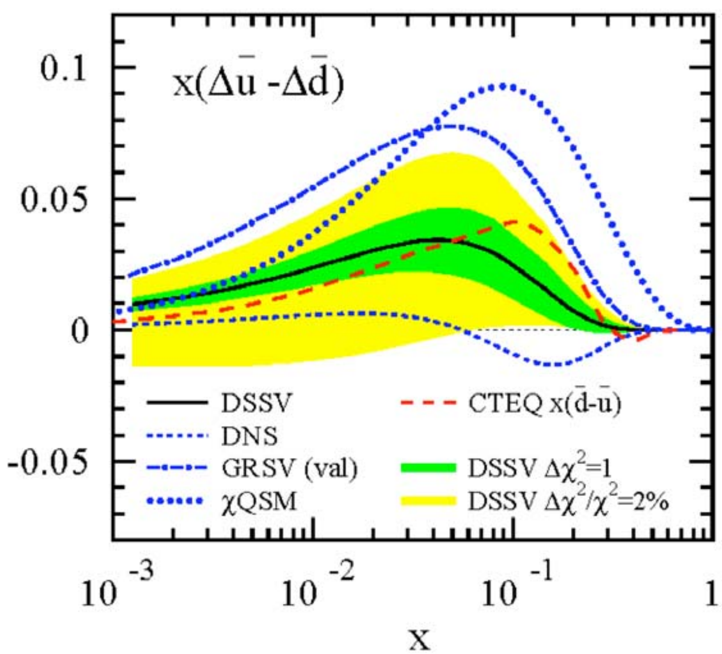
- Chiral soliton model:

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

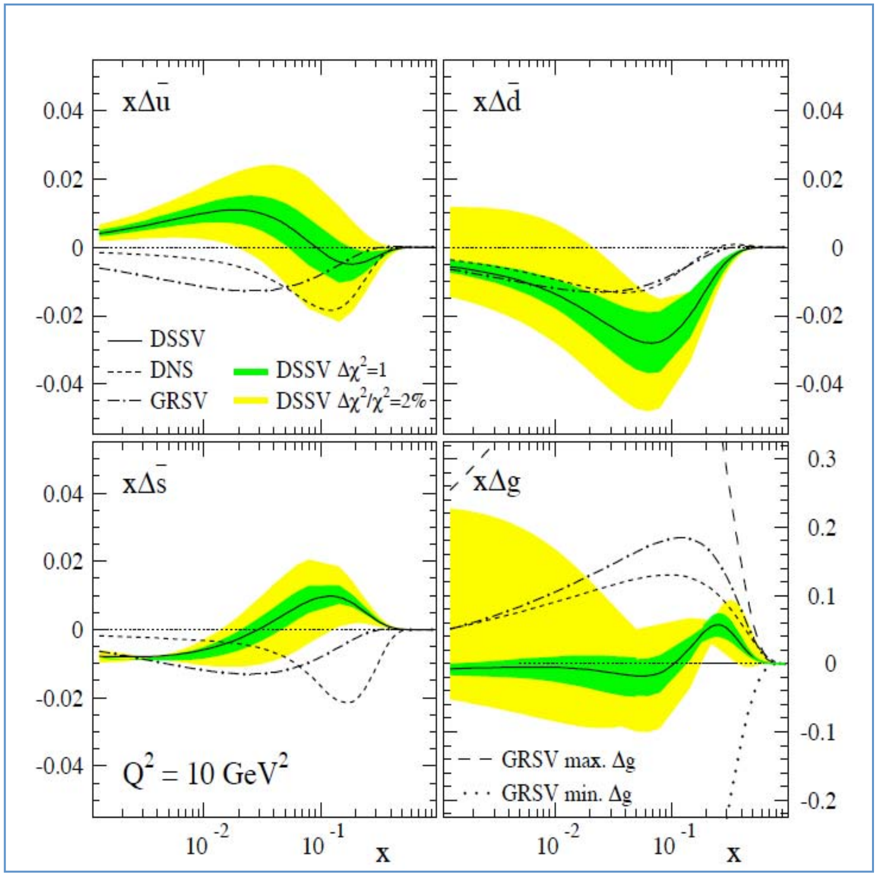


Polarized Sea Quark Distributions

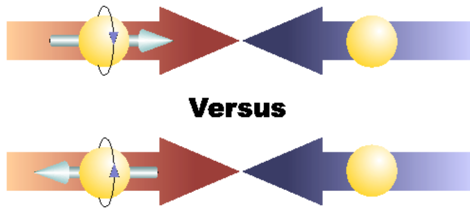
RHIC has an opportunity to provide strong constraints on the *u* and *d* sea distributions via the observation of the parity-violating single-spin asymmetry A_L in *W* production. This requires running at 500 GeV with good polarization.



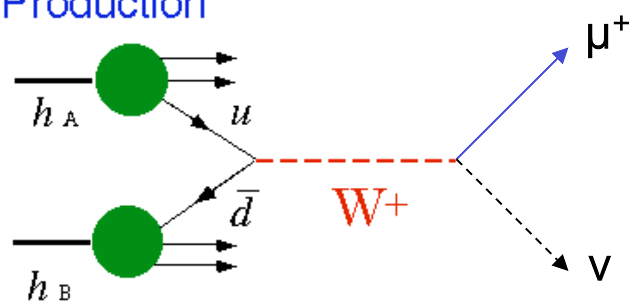
de Florian, Sassot, Stratmann, Vogelsang PRL 101, 072001(2008)



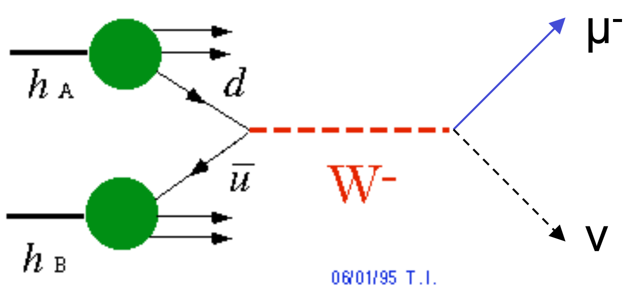
“New Probe”- $W^{\pm}$ Production and A_L @500GeV



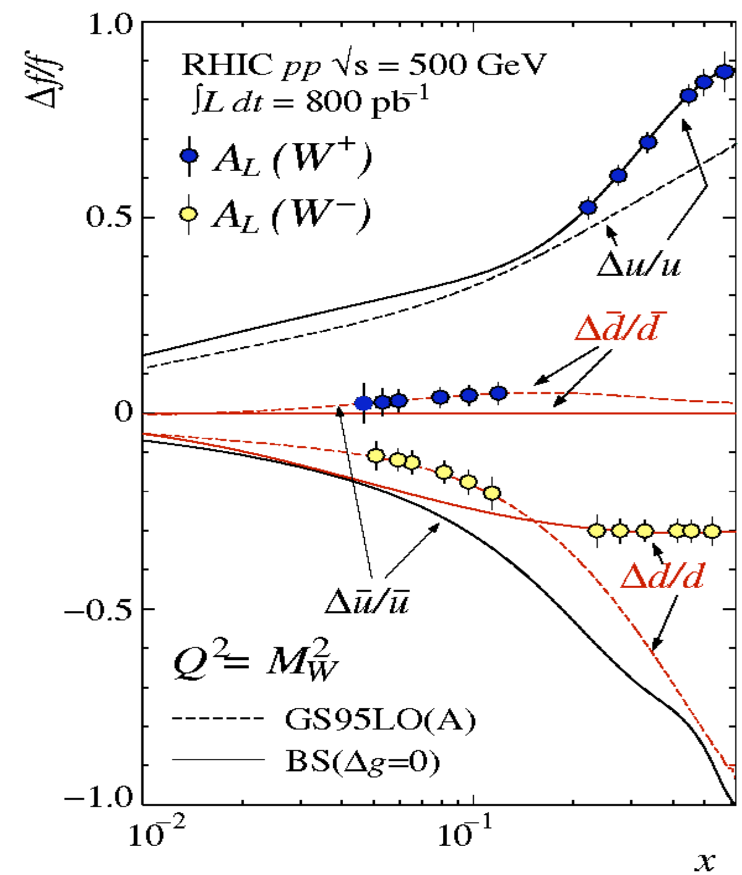
W+ Production



W- Production



Bunce G. et al, hep-ph/0007218

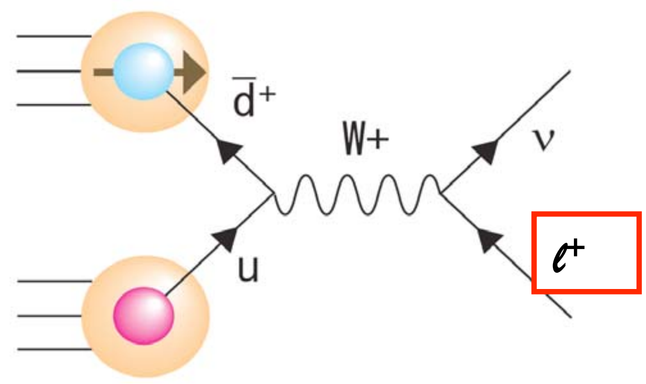


$$A_L^{l^\pm}(W^\pm \to l^\pm \nu)$$

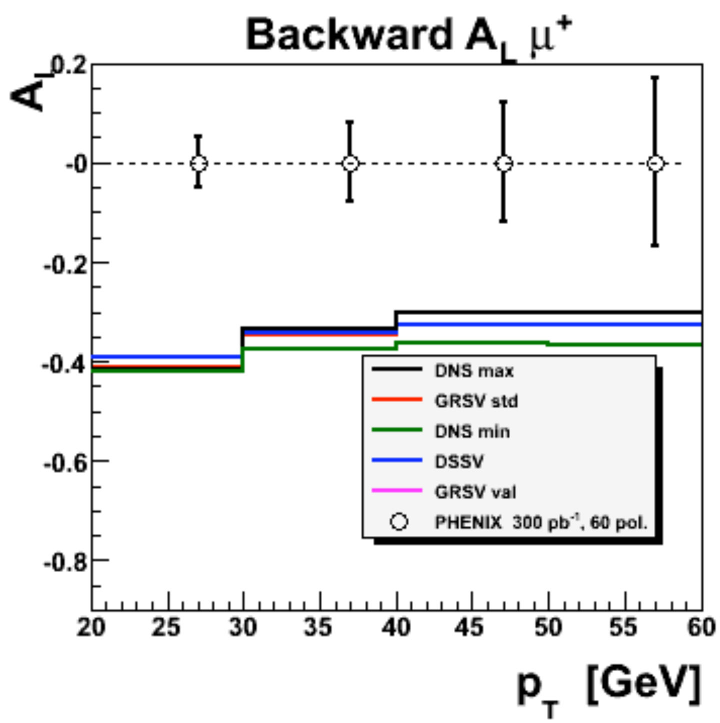
$$A_L^{l^-} = \frac{\Delta\bar{u}(x_1)d(x_2)(1-\cos\theta)^2 - \Delta d(x_1)\bar{u}(x_2)(1+\cos\theta)^2}{\bar{u}(x_1)d(x_2)(1-\cos\theta)^2 + d(x_1)\bar{u}(x_2)(1+\cos\theta)^2}$$

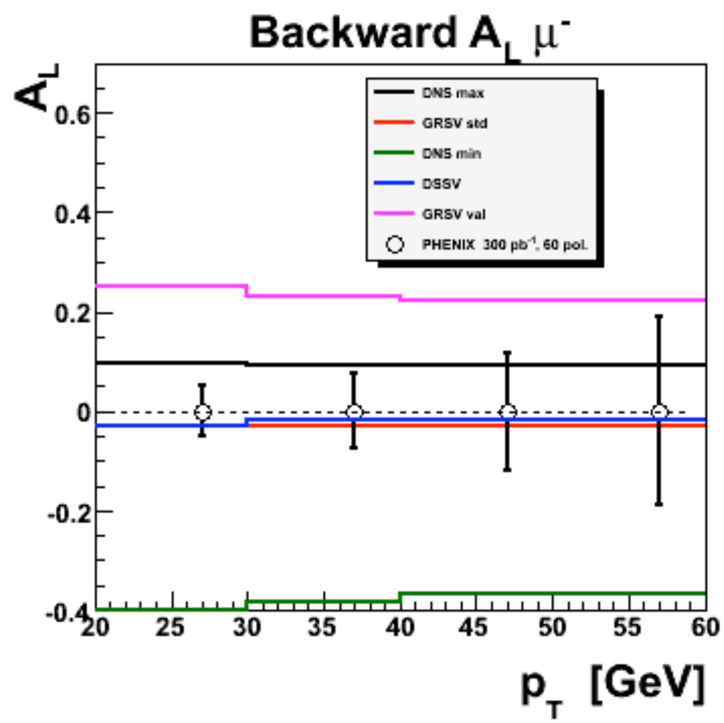
$$A_L^{l^+} = \frac{\Delta\bar{d}(x_1)u(x_2)(1+\cos\theta)^2 - \Delta u(x_1)\bar{d}(x_2)(1-\cos\theta)^2}{\bar{d}(x_1)u(x_2)(1+\cos\theta)^2 + u(x_1)\bar{d}(x_2)(1-\cos\theta)^2}$$

θ = lepton angle in partonic c.m.s.



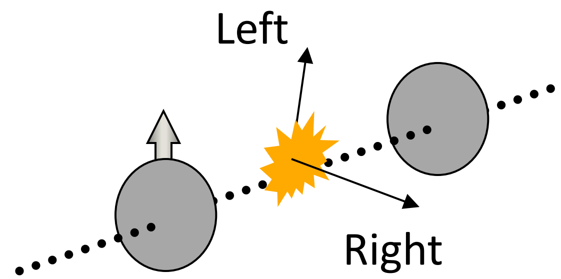
PHENIX can make observations in forward, central, and backward rapidity.





Part III: Transverse Spin Physics

Spin structure of transversely polarized proton



Define left-right asymetry
$$A_N = \frac{1}{P}\frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$$

Theory Expectation:
Small asymmetries at high energies
(Kane, Pumplin, Repko, PRL 41, 1689–1692 (1978))

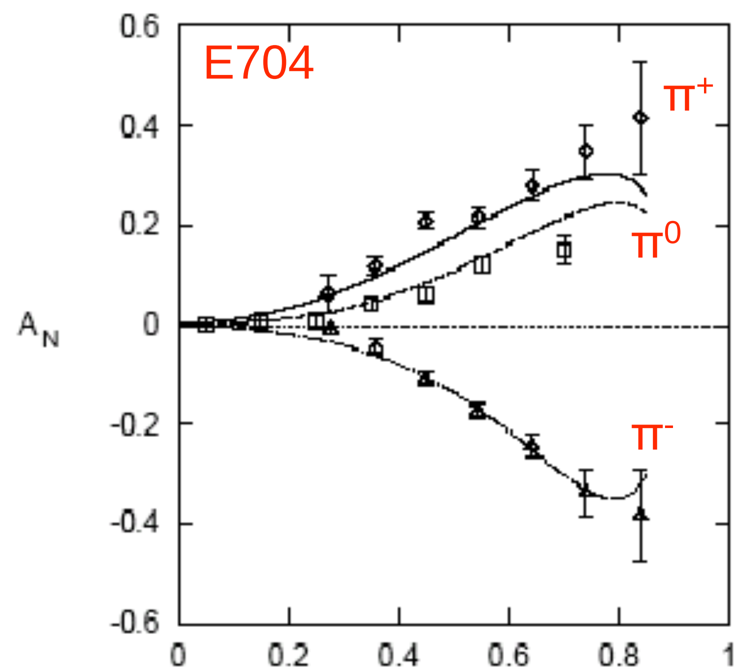
$$A_N \propto \frac{m_q}{\sqrt{s}}$$

A_N ~10^{-4} from theory

Experiment:
E704, Fermilab, 1991

$$pp^{\uparrow} \rightarrow \pi + X$$
$$\sqrt{s} = 20\,\text{GeV}$$

A_N ~10^{-1} measured



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

Possible origins of large A_N

Proton Structure | pQCD | Quark Fragmentation

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

Sivers Effect:

Correlation between proton spin and quark transverse momentum

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

D. Sivers, Phys. Rev. D 41, 83 (1990)

Collins Effect:

Correlation between proton & quark spin + spin dependent fragmentation function

$$\propto \underbrace{\delta q(x)}_{\text{Quark transversity}} \cdot \underbrace{H_1^\perp(z_2, \bar{k}_\perp^2)}_{\text{Collins FF}}$$

J. C. Collins, Nucl. Phys. B396, 161 (1993)

Gordon AGS/RHIC 2008

Large asymmetries persist at high √s

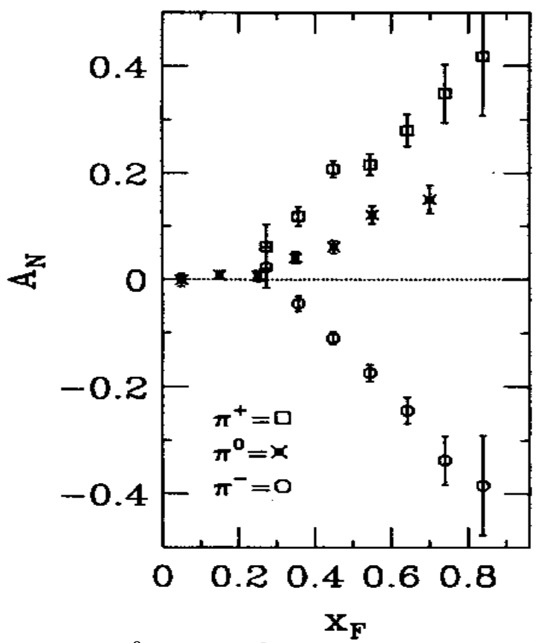
Examples:

√s = 20 GeV

√s = 62 GeV

√s = 200 GeV

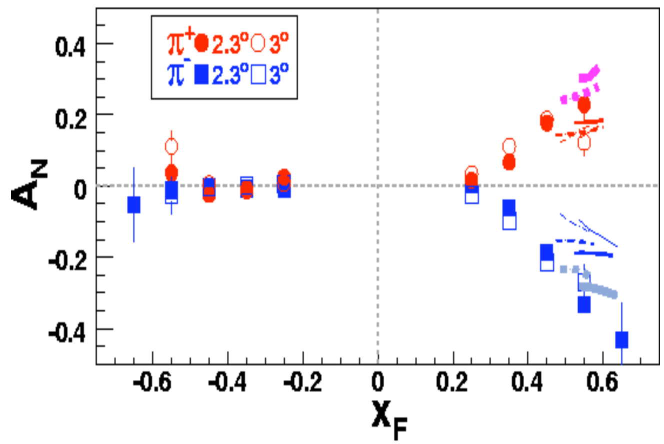
$p_\uparrow + p \rightarrow \pi + X$, √s = 20 GeV
p_T=0.5-2.0 GeV/c



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

Fermilab, Fixed target, E704, 1991

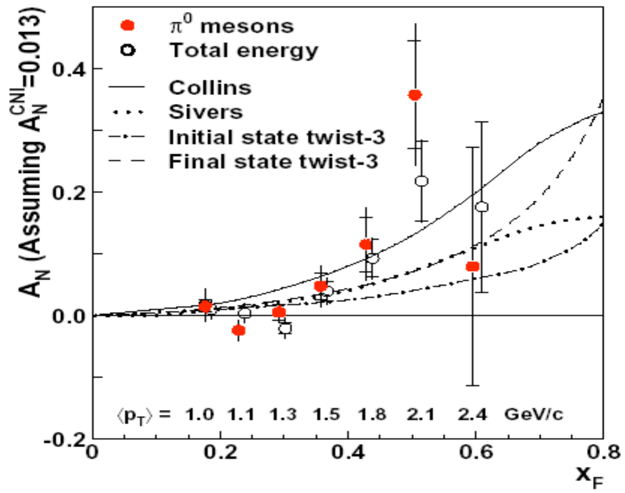
$p_\uparrow + p \rightarrow \pi^\pm + X$, √s = 62 GeV



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

RHIC, Brahms, 2007

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



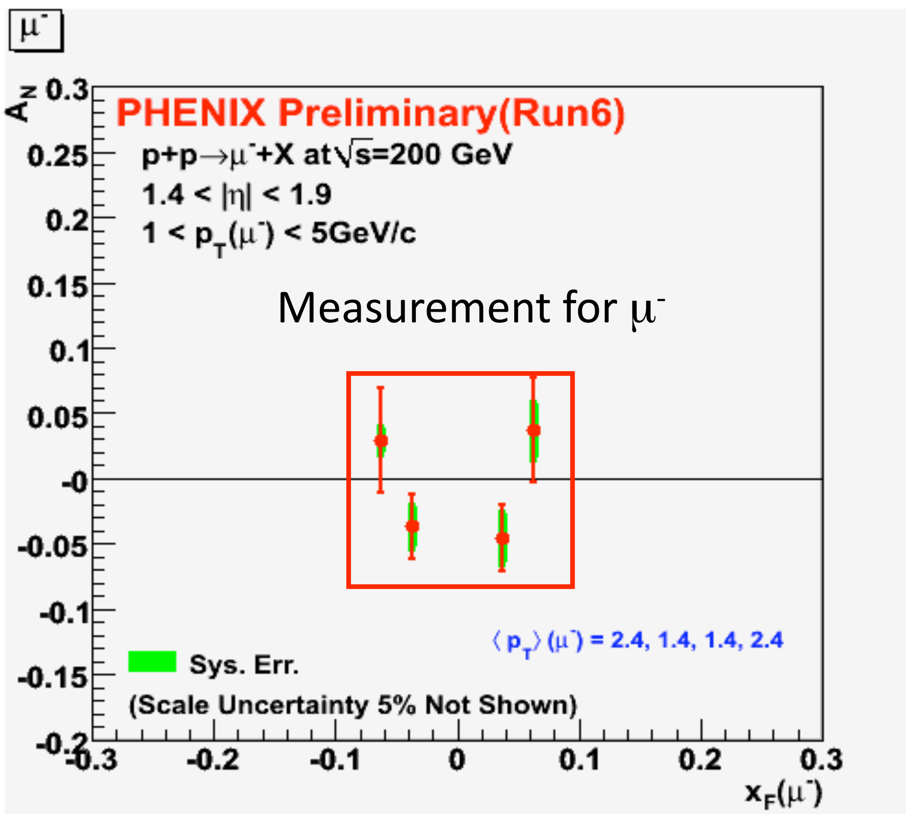
(STAR) Phys. Rev. Lett. **92** (2004) 171801

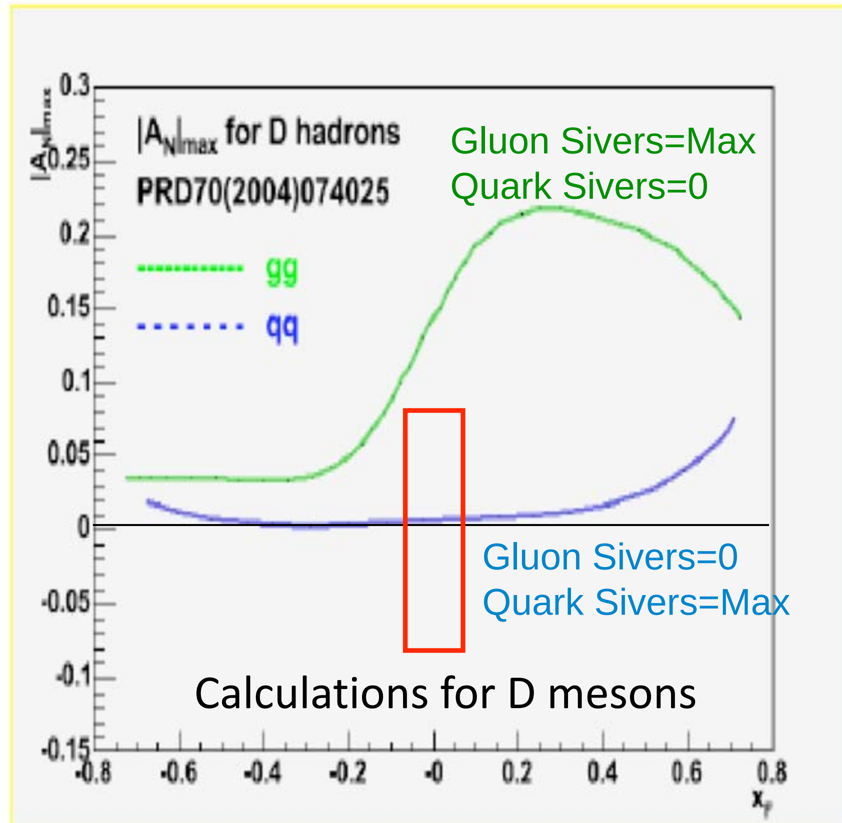
RHIC, STAR, 2004

Non-Perturbative cross section → Perturbative cross section

Sivers effect in heavy flavor production

- D meson production dominated by gluon-gluon fusion at RHIC energy
- Sensitive to gluon Sivers effect
- A_N measured for muons from D decay ("prompt muons")
  - Smear by decay kinematics

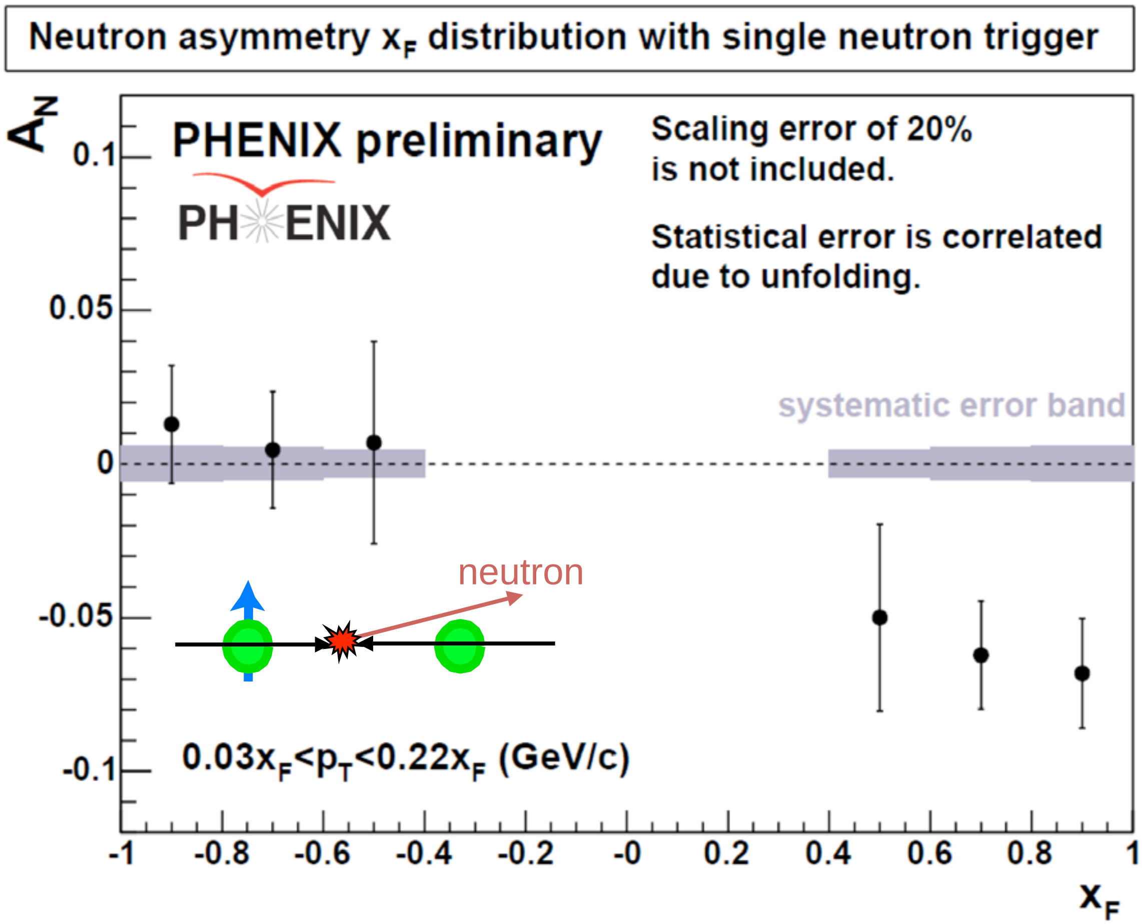


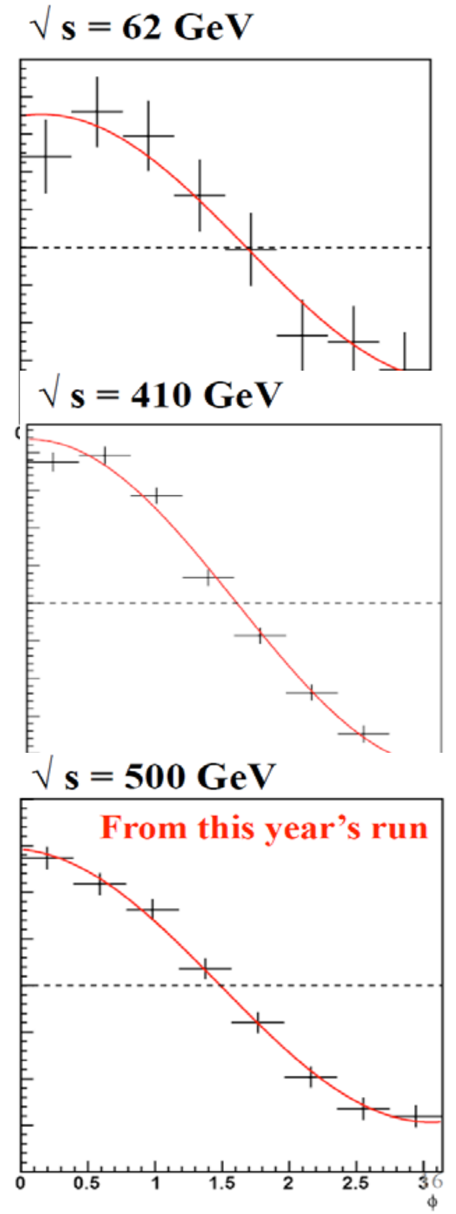


Anselmino et al, PRD 70, 074025 (2004)

Neutron production at very forward region

- Large negative SSA discovered for $x_F>0$
- Diffractive physics
- Used for local polarimetry at PHENIX/STAR

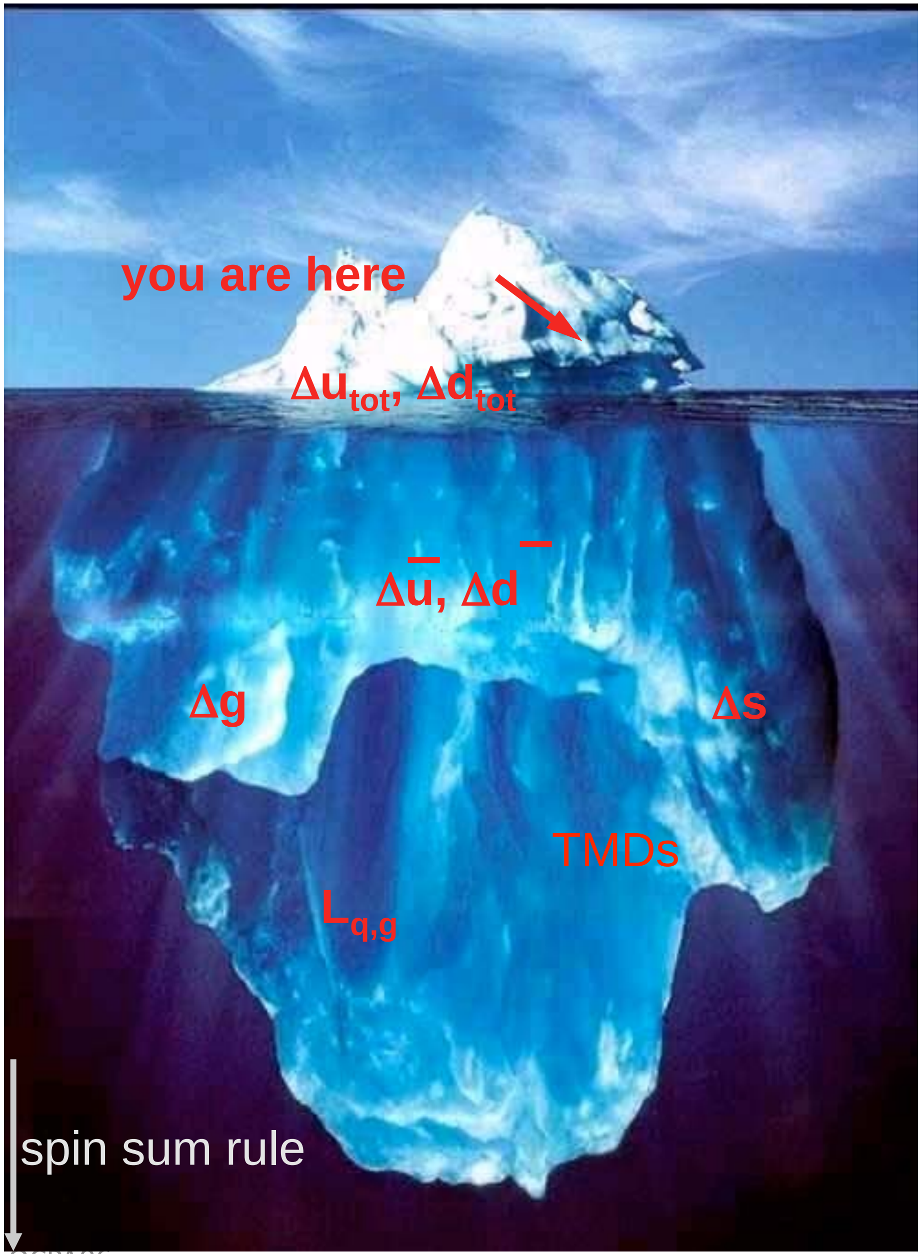




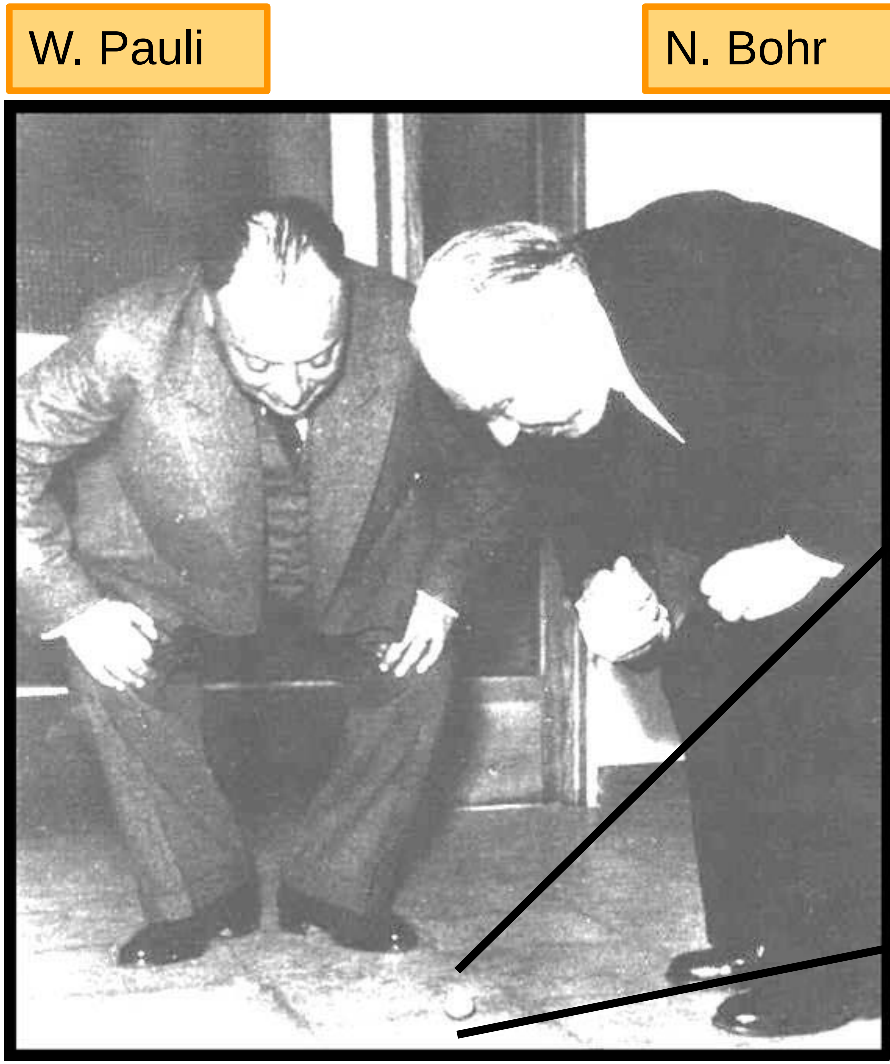
Conclusions

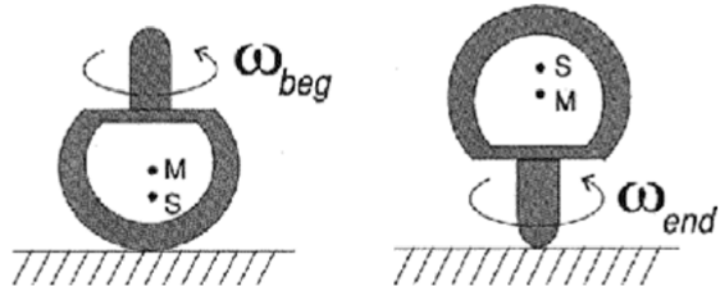
we have just explored the tip of the iceberg

What are the **avenues for further important measurements and theoretical developments?**



Spin is fascinating

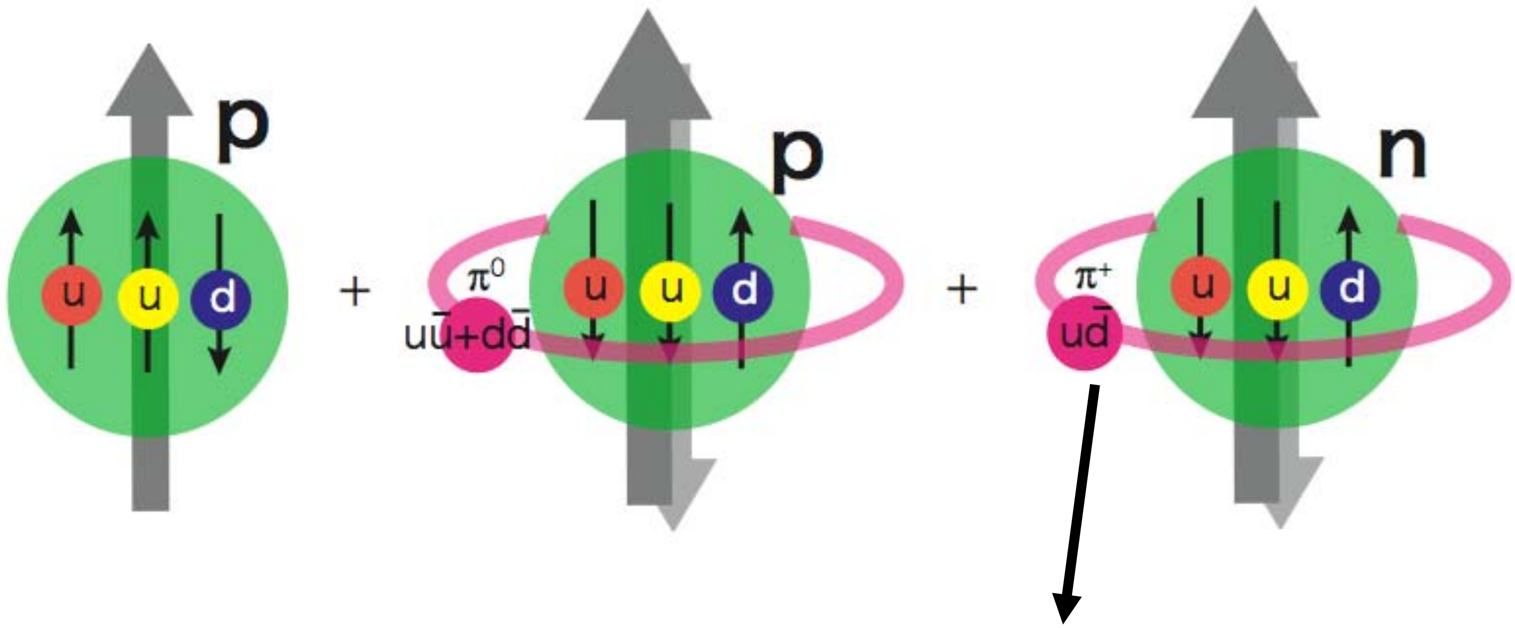




Thank you for your attention

Backup slides

Pion Cloud Model and the Orbital Angular Momentum?!

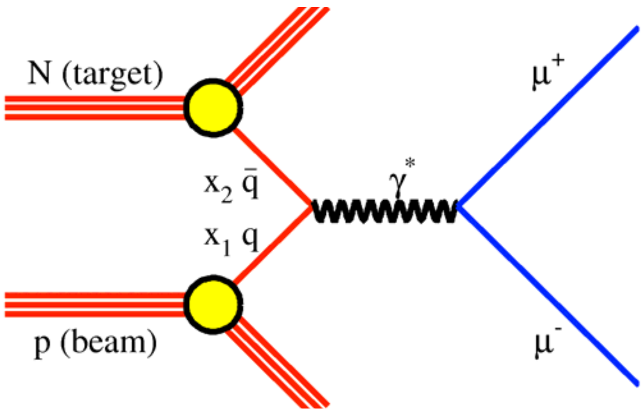


Extra dbar in proton g.s.

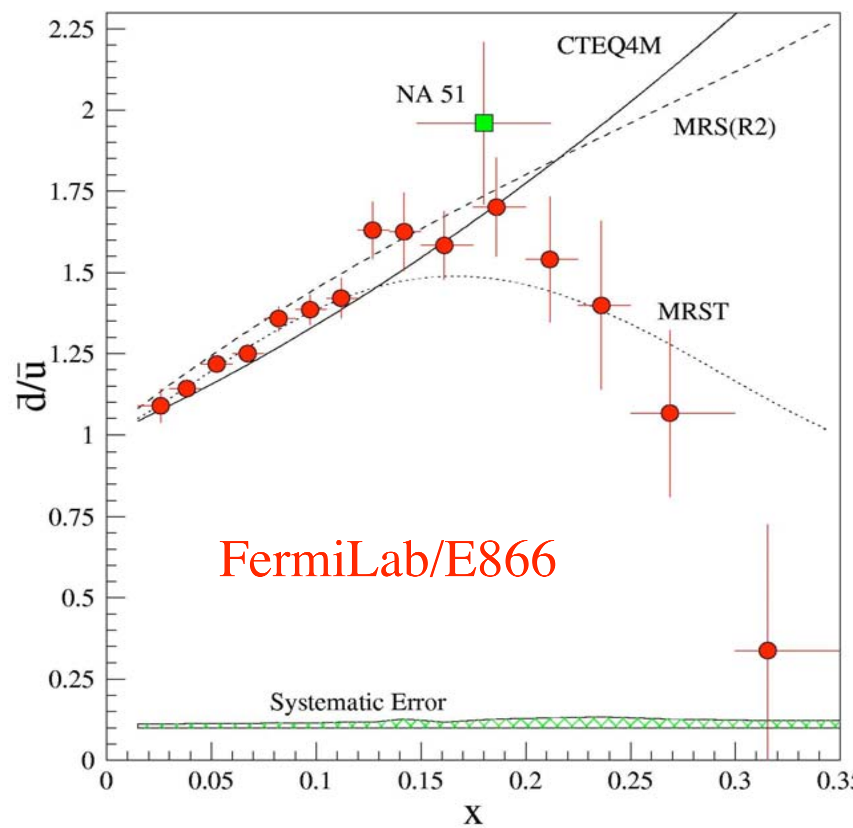
Sea Quarks Carry Major Orbital Angular Momentum Component?

Evidence of Pion Cloud?

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



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



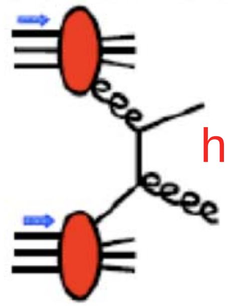
$$\sigma_{DY} \propto \sum_i e_i^2 \left[q_i(x_b)\bar{q}_i(x_t) + \bar{q}_i(x_b)q_i(x_t)\right]$$

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

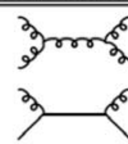
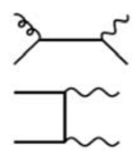
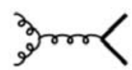
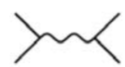
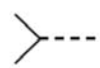
Sea Asymmetry from Drell-Yan Processes

The Gluon Polarization

RHIC: many sub-processes with a dominant gluon contribution

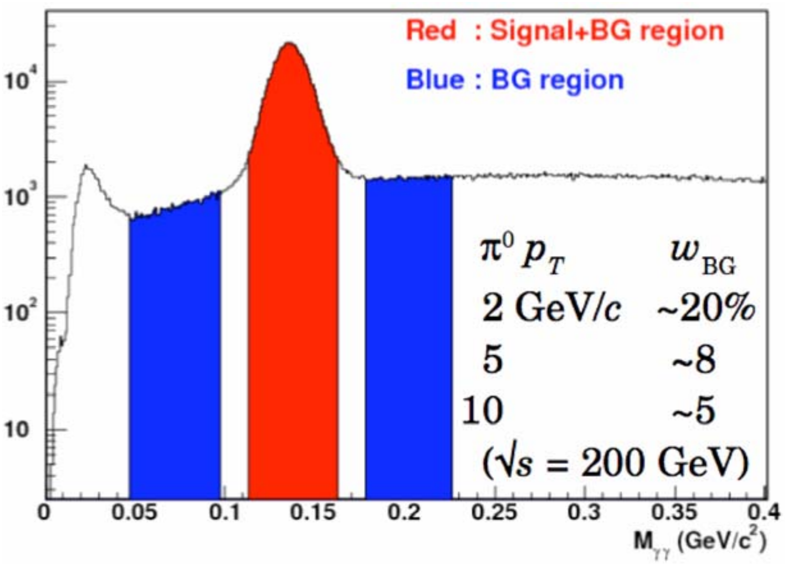


high-p_T jet, pion, heavy quark, …

	Reaction	Dom. partonic process	probes	LO Feynman diagram	in NLO
Δg	$\vec{p}\vec{p} \to \pi + X$	$\vec{g}\vec{g} \to gg$ $\vec{q}\vec{g} \to qg$	Δg		Jäger, Schäfer, Stratmann, WV
	$\vec{p}\vec{p} \to \text{jet(s)} + X$	$\vec{g}\vec{g} \to gg$ $\vec{q}\vec{g} \to qg$	Δg	(as above)	Jäger, Stratmann, WV; Signer et al.
	$\vec{p}\vec{p} \to \gamma + X$ $\vec{p}\vec{p} \to \gamma + \text{jet} + X$ $\vec{p}\vec{p} \to \gamma\gamma + X$	$\vec{q}\vec{g} \to \gamma q$ $\vec{q}\vec{g} \to \gamma q$ $\vec{q}\vec{\bar{q}} \to \gamma\gamma$	Δg Δg $\Delta q, \Delta\bar{q}$		Gordon, WV; Contogouris et al.; Gordon, Coriano
	$\vec{p}\vec{p} \to DX, BX$	$\vec{g}\vec{g} \to c\bar{c}, b\bar{b}$	Δg		Stratmann, Bojak
$\Delta\bar{q}$	$\vec{p}\vec{p} \to \mu^+\mu^- X$ (Drell-Yan)	$\vec{q}\vec{\bar{q}} \to \gamma^* \to \mu^+\mu^-$	$\Delta q, \Delta\bar{q}$		Weber; Gehrmann; Kamal;
	$\vec{p}\vec{p} \to (Z^0, W^\pm)X$ $p\vec{p} \to (Z^0, W^\pm)X$	$\vec{q}\vec{\bar{q}} \to Z^0$, $\vec{q}'\vec{\bar{q}} \to W^\pm$ $\vec{q}'\bar{q} \to W^\pm$, $q'\vec{\bar{q}} \to W^\pm$	$\Delta q, \Delta\bar{q}$		Smith, van Neerven, Ravindran

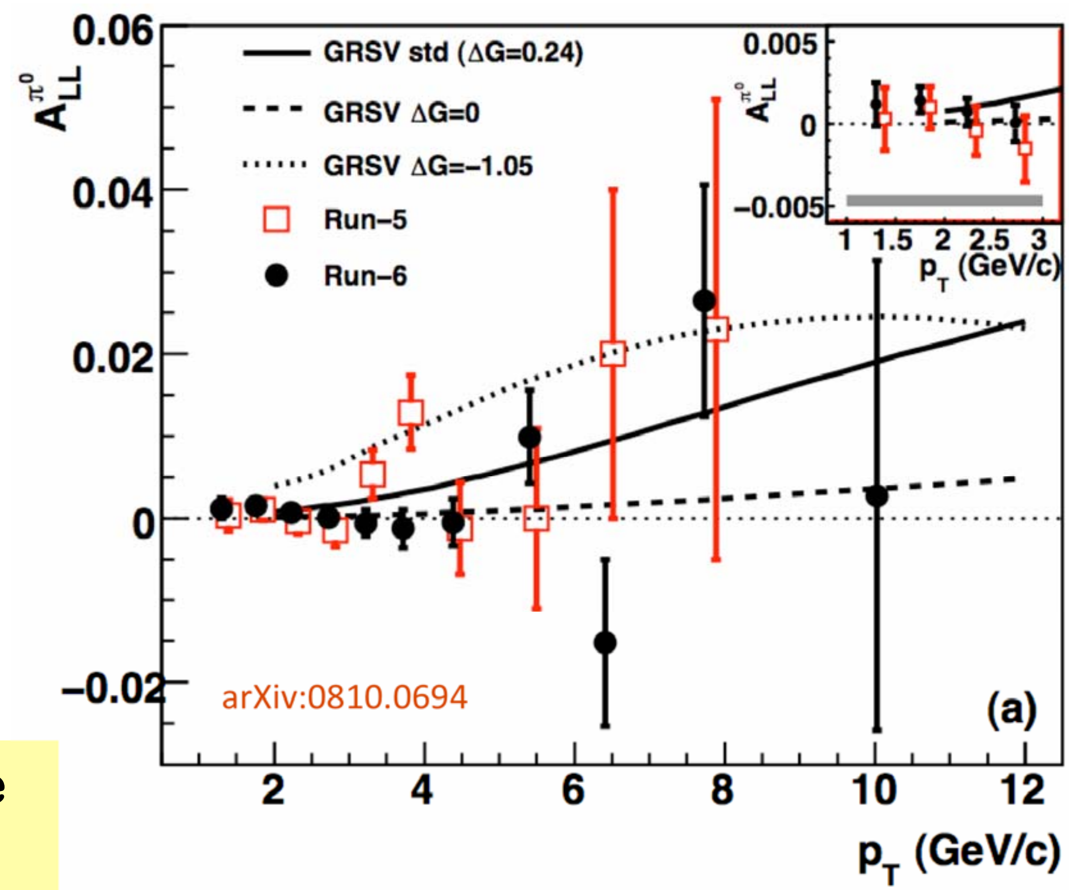
unpolarised cross sections nicely reproduced in NLO pQCD

π^0 A_{LL}



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

PHENIX Run6 ($\sqrt{s}$=200 GeV)



Statistical uncertainties are on level to distinguish "std" and "0" scenarios

GRSV model:

"ΔG = 0": $\Delta G(Q^2=1\text{GeV}^2)=0.1$

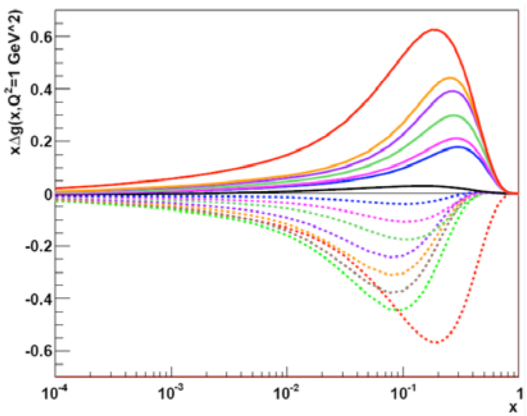
"ΔG = std": $\Delta G(Q^2=1\text{GeV}^2)=0.4$

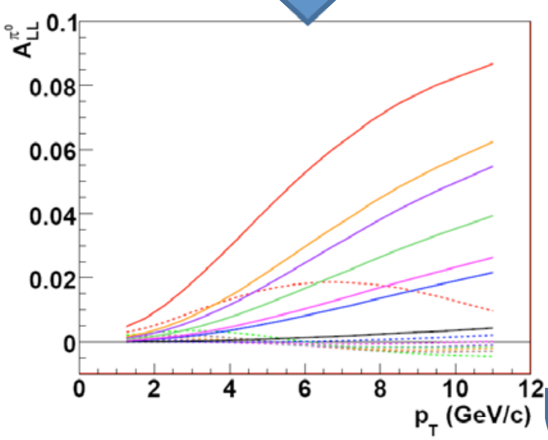
Sensitivity of π^0 A_{LL} to ΔG (with GRSV)

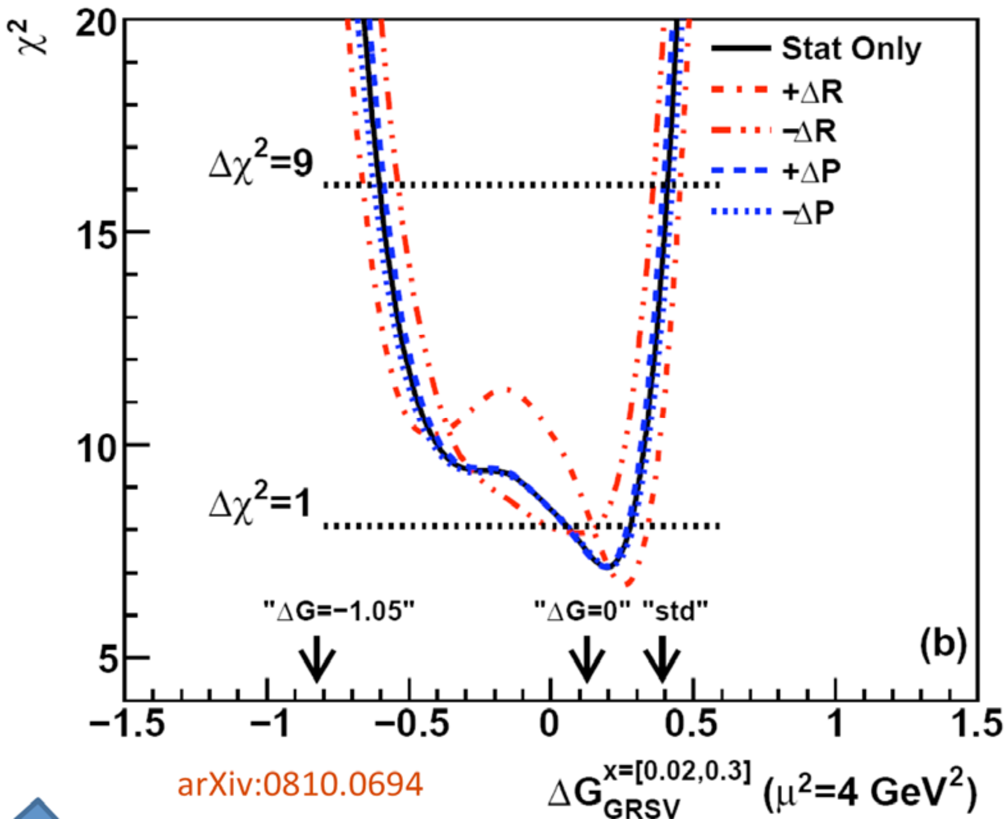
Generate $\Delta g(x)$ curves for different $\Delta G = \int_0^1 \Delta g(x)dx$

Calculate A_{LL} for each ΔG

Compare A_{LL} data to curves (produce χ^2 vs ΔG)







Stat. error : $\Delta G^{x=[0.02,0.3]}_{GRSV}\left(\mu^2 = 4\,\mathrm{GeV}^2\right) = 0.2 \pm 0.1\ (1\sigma)$ and $0.2^{+0.2}_{-0.8}\ (3\sigma)$

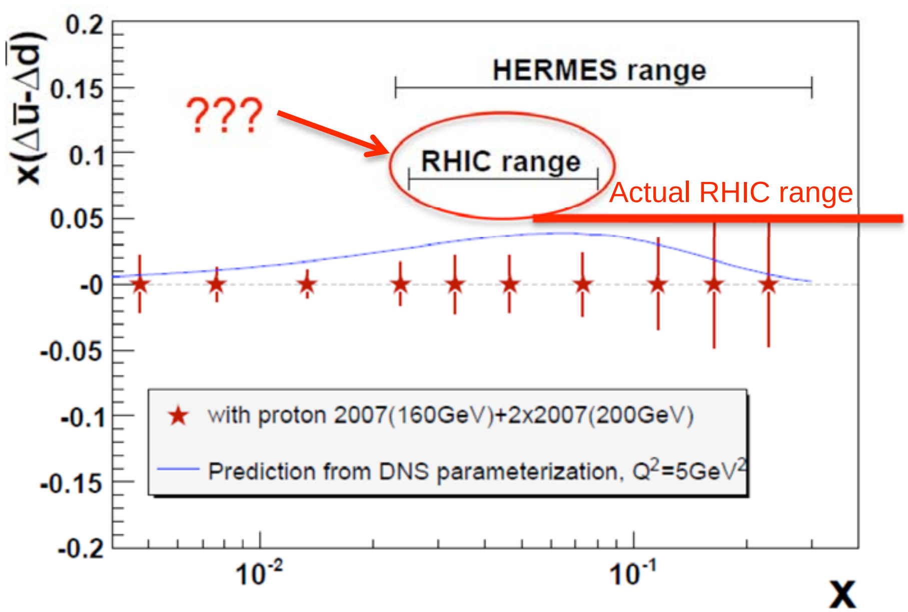
Syst. exp. error : ± 0.1

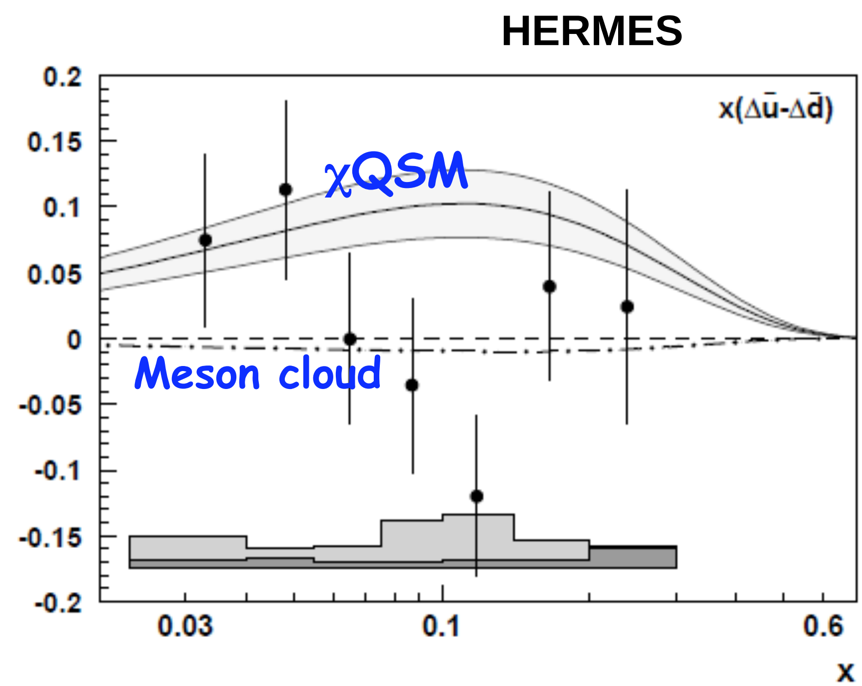
From Nicole D'Hose (CEA/IRFU Saclay) at CERN "New Opportunities" Workshop

Flavor asymmetry of the polarised light sea $\Delta\bar{u} - \Delta\bar{d}$

With Semi-Inclusive Hadron Asymmetries

COMPASS Projection
with 1 additional year of proton





→Separation between extreme models

→enters in NLO global fits

They can do this in the next few years if approved!