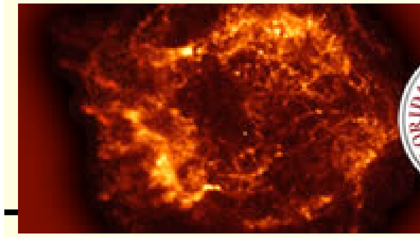


National Nuclear Physics Summer School 2007
The Florida State University
July 8th - 21st

The Physics with Polarized Protons at RHIC

(The RHIC Spin Program)

Abhay Deshpande
Stony Brook University
RIKEN BNL Research Center

NNPSS 2007, July 12, 2007

The plan of this talk….

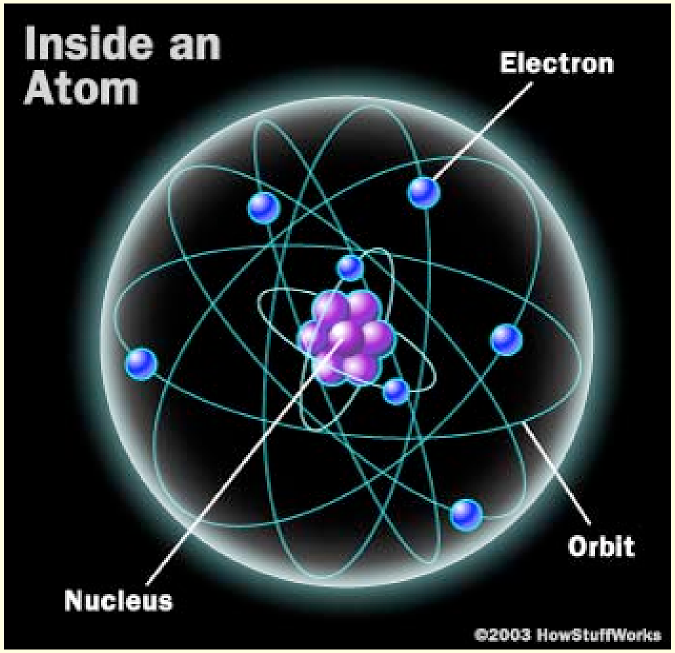
- Nucleon structure including its' spin in the last century
  - Special requirements in "spin" related experiments
- RHIC spin program: this decade
  - Motivation, the technique, advantages and disadvantages
  - Accelerator status and progress
  - Brief overview of Experiments
  - Where we are in terms of the program: Recent results
- A few concluding remarks:
  - Outlook: short and long term…

Nucleon Structure & Spin
1901 - 2000

What did we know?
When did we know it?
How did we know it?

The early years…

- Geiger, Marsden and Rutherford 1909
  - Demonstrate the existence of the Nucleus inside the atom
  - Later found to be composed of neutrons and protons!

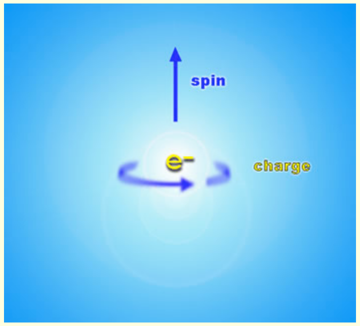


- Do neutrons and protons also have a sub-structure? What binds stuff together?

Spin: the golden years!

- 1925, the spinning electron (Goudsmit and Uhlenbeck)
  - Intrinsic angular momentum: ħ/2
    - Magnetic Moment:

$$\bar{\mu} = -\frac{2e\hbar}{mc}\vec{s}$$



- 1927 proton has spin 1/2 (Dennison and Heisenberg)
- 1933 the magnetic moment of the proton measured (Stern)

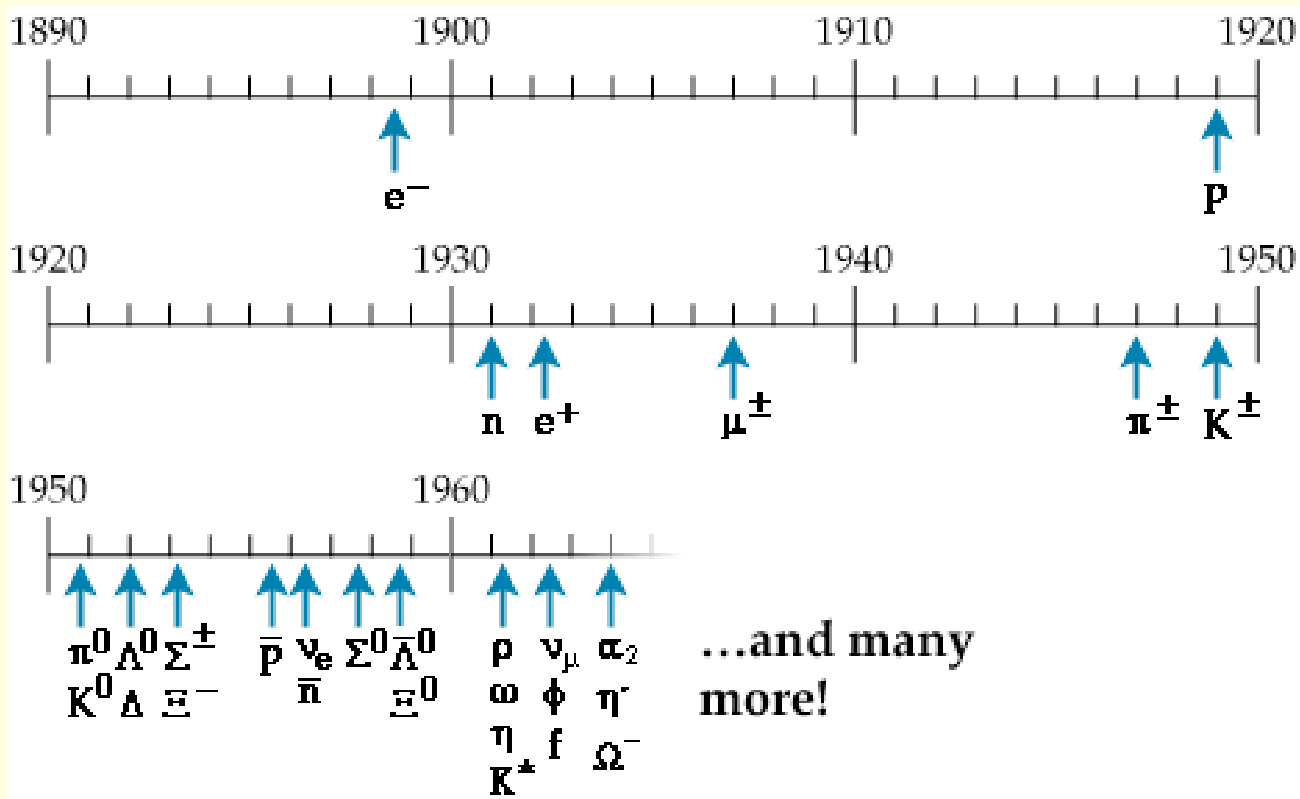
$$\bar{\mu} = -\frac{2e\hbar}{mc}\vec{s} \times 2.79$$

  - The protons must have an internal structure…. NOT POINT LIKE!

A simple Standard Model to a Particle Zoo!

New experiments being performed, higher and higher energies reached, detector technologies being developed….

THE RESULT:



*"When the Nobel prizes were first awarded in 1901, physicists know something of just two objects which are now called "elementary particles": the electrons and the proton. A deluge of other "elementary" particles appeared after 1930s; neutron, neutrino, μ meson, π meson, heavier mesons, and various hyperons. I have heard it said that the finder of a new elementary particle used to be awarded with a Nobel Prize, but such a discovery **now** ought to be punishable by a $10,000 fine"*

Lamb, Nobel lecture 1955

Was there a method behind this madness?

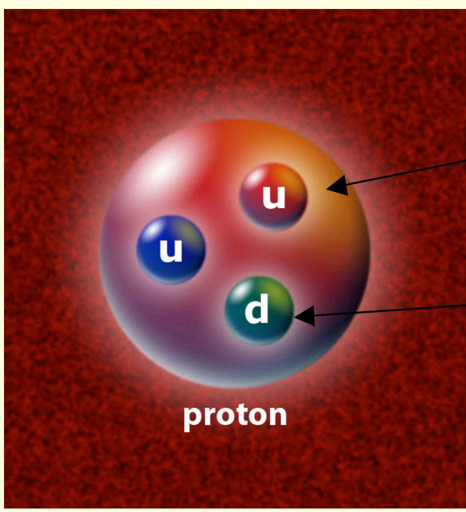
A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

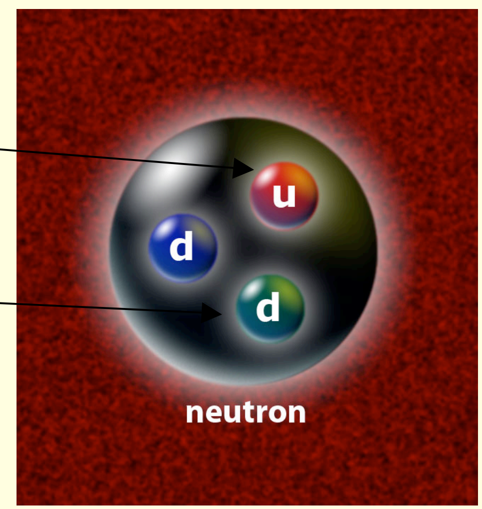
It is fun to speculate about the way quarks would behave if they were physical particles of finite mass instead of purely mathematical entities

- SU(3) Representations of u,d,s quarks (Gell-Mann, Zweig)



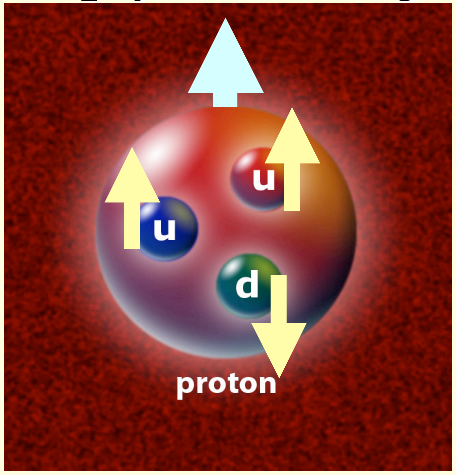
Charge 2/3

Charge -1/3



Success?

- Explains the large anomalous magnetic moment!
- Explained the spin of the proton simply to be originating from the quark's spin….



$$+1e = \frac{2}{3}e + \frac{2}{3}e + \frac{-1}{3}e$$

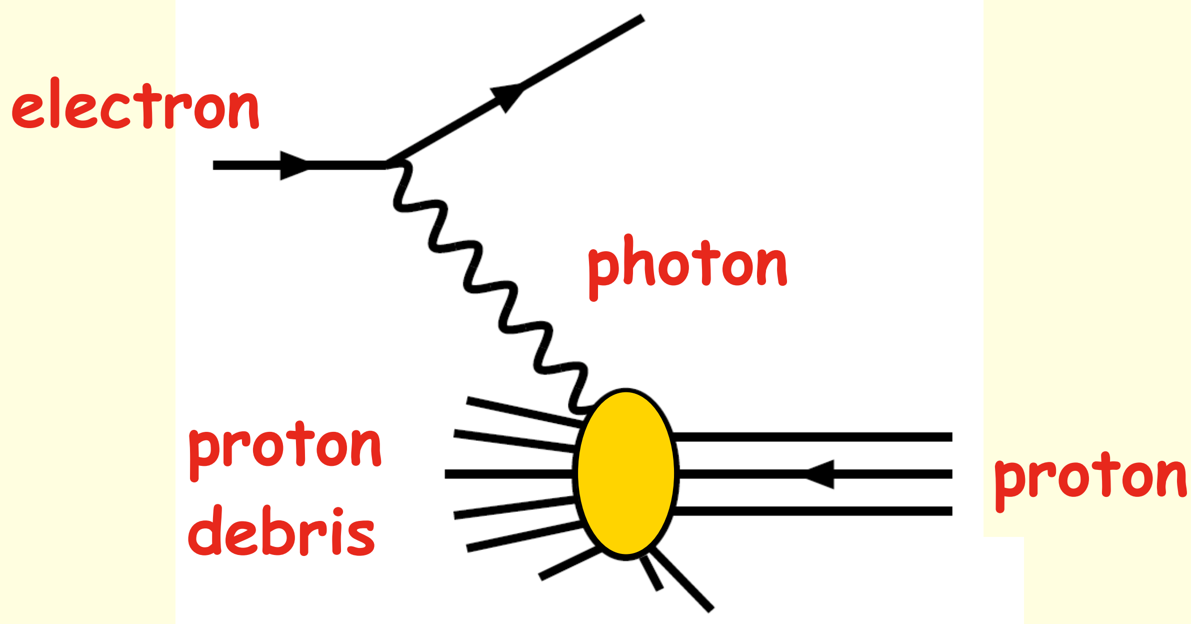
PROTON CHARGE

$$\frac{1}{2} = +\frac{1}{2} + \frac{1}{2} + \frac{-1}{2}$$

PROTON SPIN!

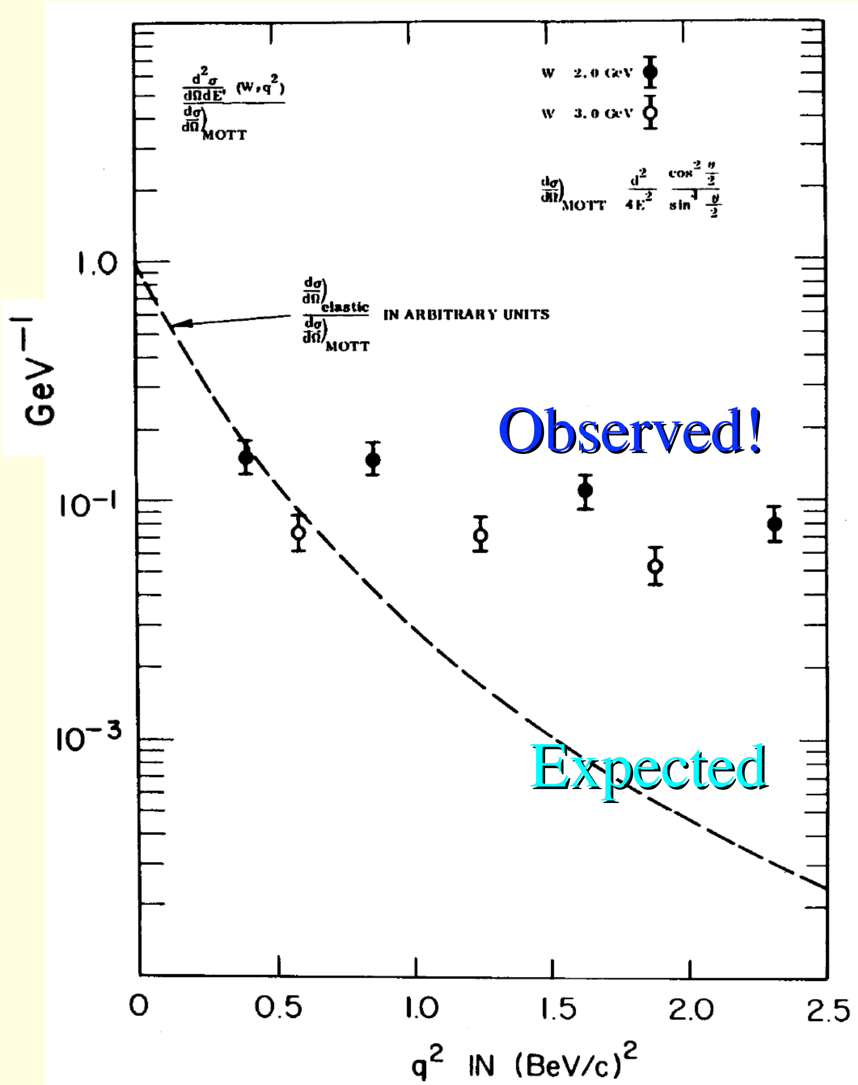
Similarly for Neutrons!

Deep Inelastic Scattering…



- Electron a “point” structure-less particle
- Exchanges a virtual photon … momentum transferred Q^2 (GeV^2)
  - Resolution scale: $\lambda \approx \frac{\hbar}{Q^2}$ Resolves the structure of the proton!
- First tried at SLAC and revealed the internal structure of protons! (Taylor et al.)

Amazing revelation…



- Rutherford's experiment at a very high energy scale reveals the internal structure of the proton!
- No wonder then that the magnetic moment of the proton was 2.79 times higher than a point like fermion!

What about the spin?

For this we need to perform an experiment with spin polarized target and beams!

Polarized **Deep Inelastic Scattering**

First at SLAC, then at CERN, DESY and now also at Jefferson Laboratory

Polarized Cross Section & Spin SFs

- Lepton Nucleon Cross Section:

$$\frac{d^3\sigma}{dx\,dy\,d\phi} = \frac{\alpha^2 y}{2Q^4} L_{\mu\nu}(k, q, s,) W^{\mu\nu}(P, q, S)$$

Nucleon spin

Lepton spin

- Lepton tensor $L_{\mu\nu}$ controls the kinematics (QED)

- Hadronic tensor $W^{\mu\nu}$ nucleon structure

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

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

Structure Functions & PDFs

- The F_1 and F_2 are unpolarized structure functions or momentum distributions
- The g_1 and g_2 are polarized structure functions or spin distributions
- In QPM
  - $F_2(x) = 2xF_1$ (Calan-Gross relation)
  - $g_2 = 0$ (Twist 3 quark gluon correlations)

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

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

Nucleon spin & Quark Probabilities

- Define $$\Delta q = q^{+} - q^{-}$$
  - With q^+ and q^- probabilities of quark & anti-quark with spin parallel and anti-parallel to the nucleon spin

- Total quark contribution then can be written as:

$$\Delta\Sigma = \Delta u + \Delta d + \Delta s$$

- And the proton spin then becomes:

$$\boxed{\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_G}$$

First Moments of SPIN SFs

- With $\Delta q = \int \Delta q(x) dx$

$$\Gamma_1^p = \frac{1}{2}\left[\frac{4}{9}\Delta u + \frac{1}{9}\Delta d + \frac{1}{9}\Delta s\right]$$

$$= \frac{1}{12}\underbrace{(\Delta u - \Delta d)}_{a_3 = g_a} + \frac{1}{36}\underbrace{(\Delta u + \Delta d - 2\Delta s)}_{a_8} + \frac{1}{9}\underbrace{(\Delta u + \Delta d + \Delta s)}_{a_0}$$

a_3=g_a — Neutron decay

a_8 — (3F-D)/3 Hyperon Decay

a_0 — $\Delta\Sigma$

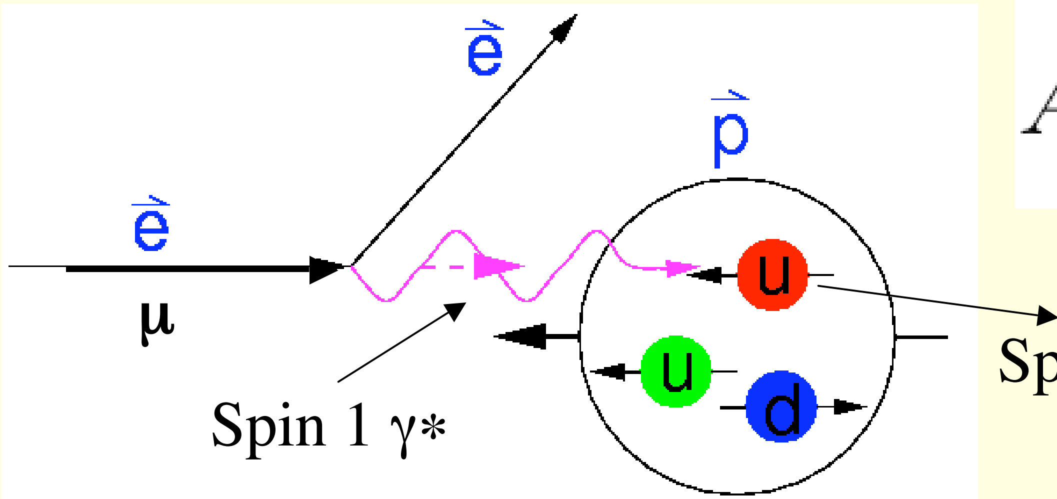
$$\Gamma_1^{p,n} = \frac{1}{12}\left[\pm a_3 + \frac{1}{\sqrt{3}} a_8\right] + \frac{1}{9} a_0$$

The experimental method and …….
surprises!

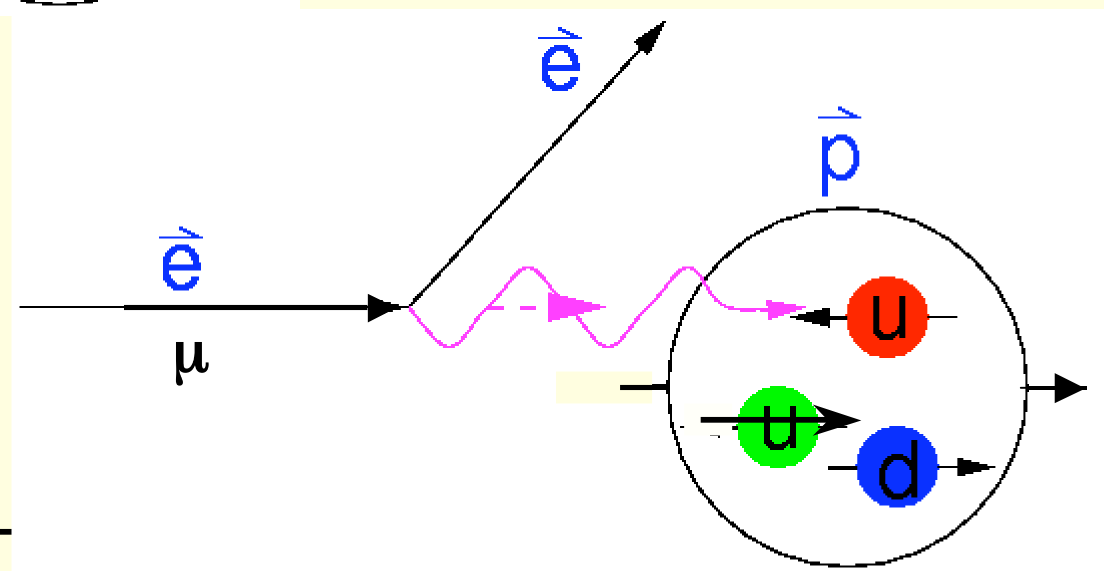
How is Quark Spin measured?

- Deep Inelastic polarized electron or muon scattering

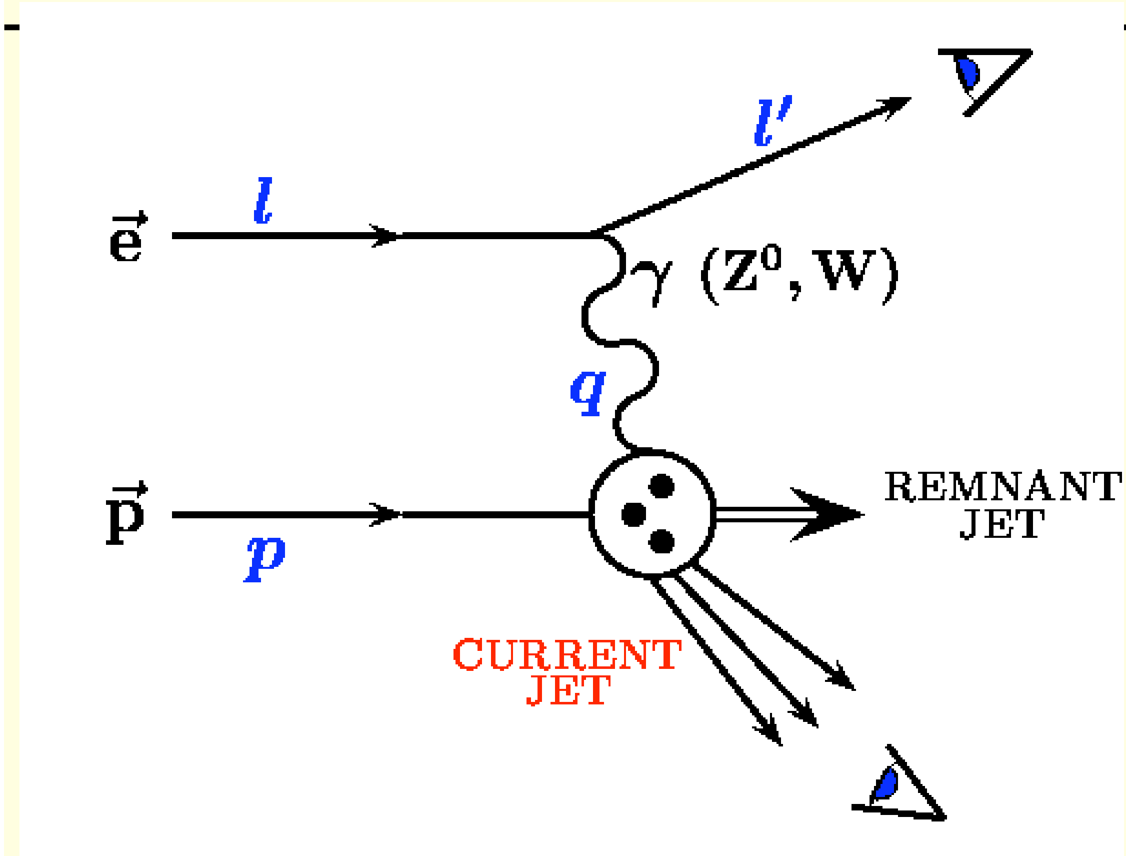
$$A_{\gamma^* p} = \frac{N^{\uparrow\downarrow} - N^{\uparrow\uparrow}}{N^{\uparrow\downarrow} + N^{\uparrow\uparrow}}$$



$$\lambda = \frac{\text{Constant}}{p}$$



Deep Inelastic Scattering



$$Q^2 = -q^2 = sxy$$

$$x = \frac{Q^2}{2p \cdot q}$$

$$y = \frac{p \cdot q}{p \cdot l}$$

$$s = 4E_e E_p$$

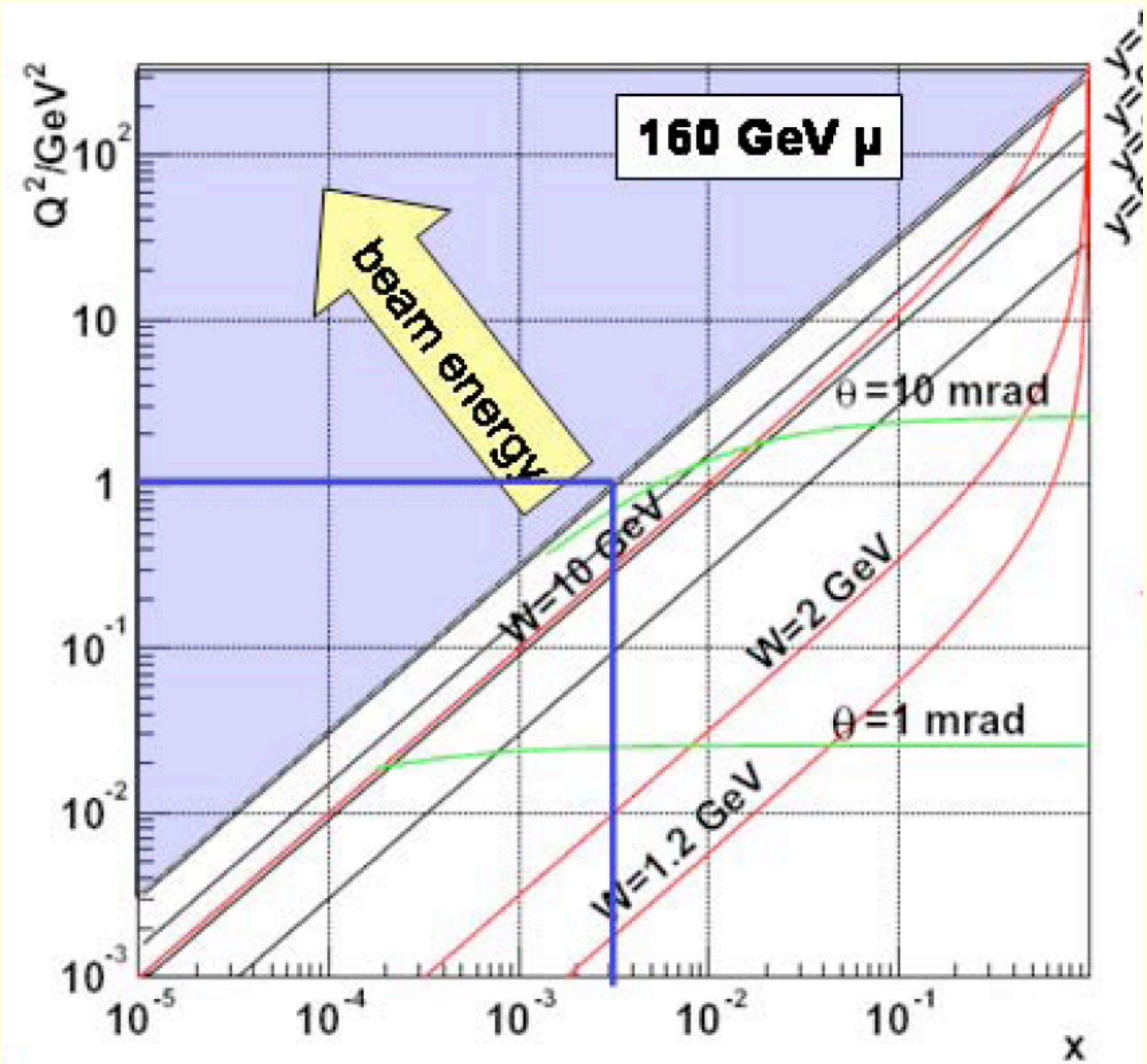
$$W = (q + p)^2$$

Inclusive DIS: only measure the scattered electron

Semi-Inclusive DIS: Inclusive + Current Jet remnants

Exclusive DIS: Semi-Inclusive + Target Jet remnants

Example of DIS kinematic Reach



- CERN experiment with muon beam 160 GeV/c
- Plot of Q^2 vs. x
- Lines of constant y and W shown
- Blue line indicates an "adhoc" limit of $Q^2 > 1$ GeV^2 or DIS
- *For Spin Sum Rule Verification: measurements over a large x range and constant and high Q^2 value*

Experimental Needs

Polarized target, polarized beam

- Up to very recent times only fixed target polarized DIS experiments
- Polarized target: hydrogen(proton), deuteron (proton+neutron), Helium (2 protons + neutron)
- Polarized beams: electron, positron, muon used in DIS experiments

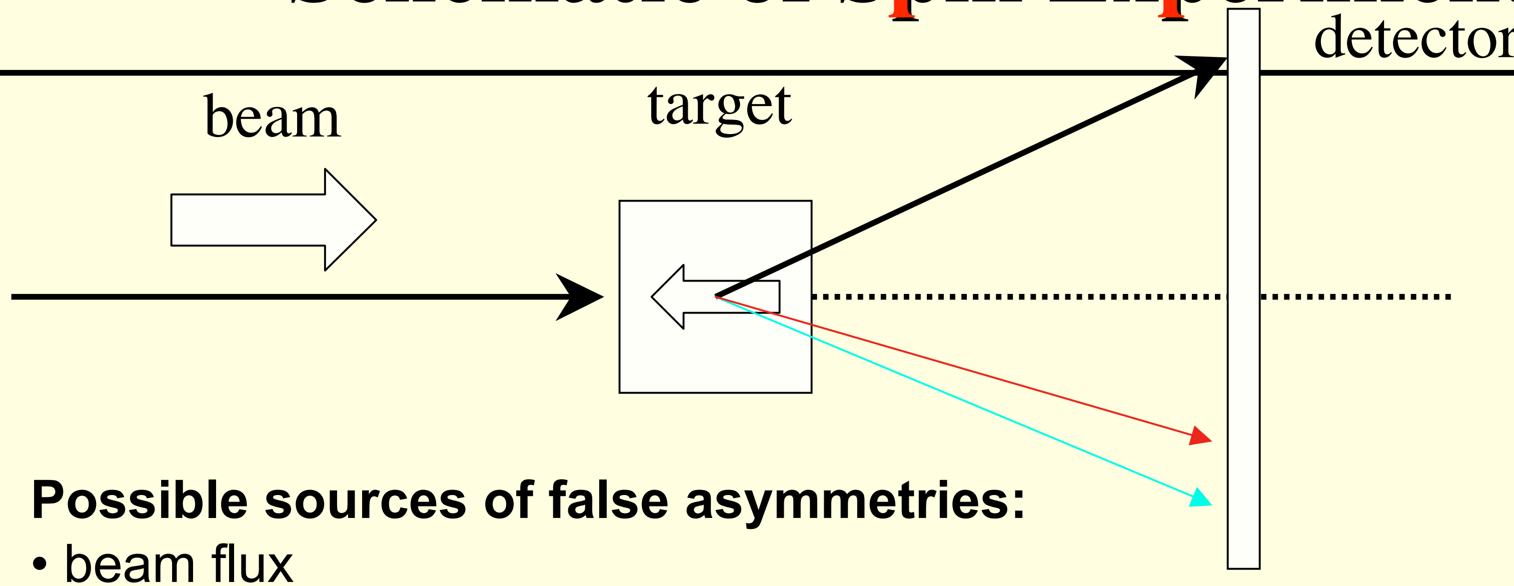
Determine the kinematics: measure with high accuracy:

- Energy of **incoming lepton**
- Energy, direction of **scattered lepton**: energy, direction
- Good identification of **scattered lepton**
- *In case of semi-inclusive and exclusive extend this to current and jet fragments including particle identification*

Control of false asymmetries:

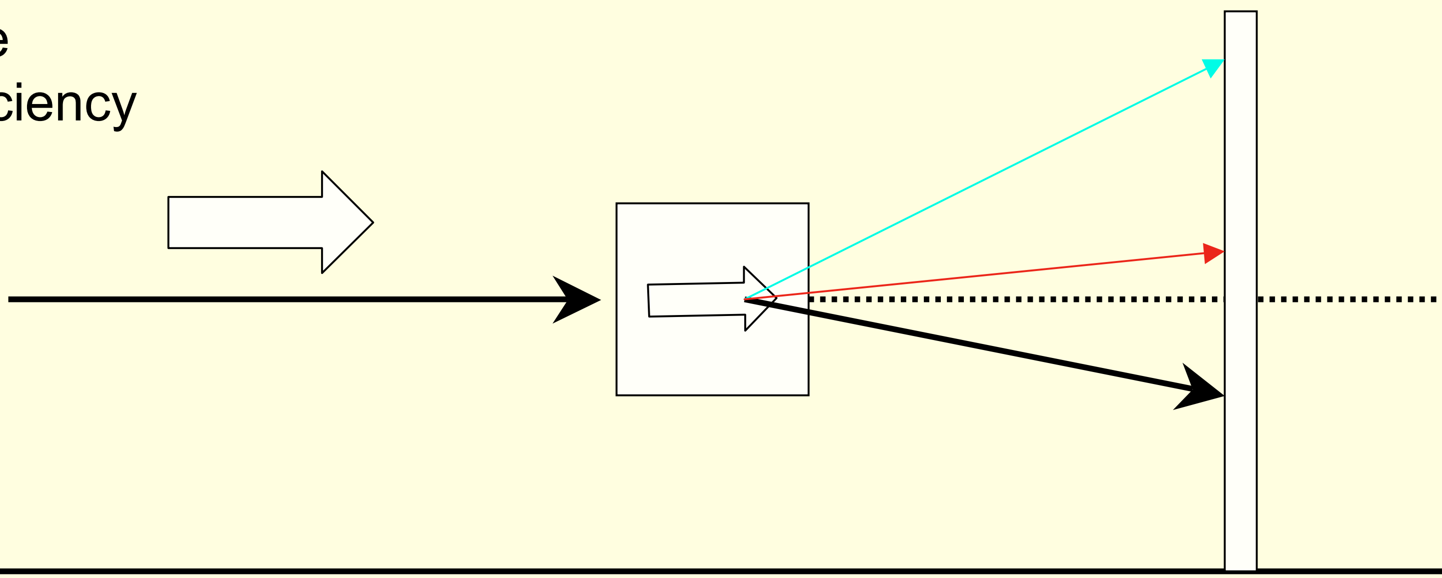
- Need excellent understanding and control of **false asymmetries** (time variation of the detector efficiency etc.)

Schematic of Spin Experiment



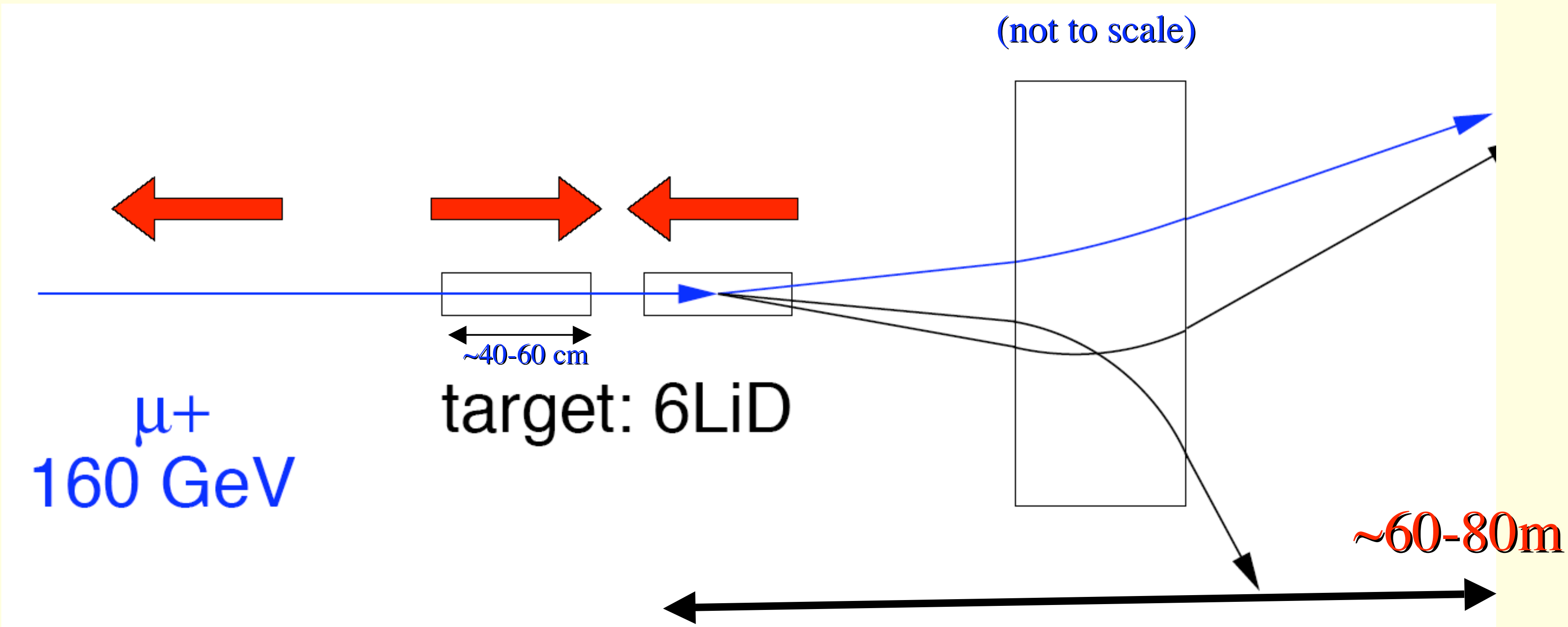
Possible sources of false asymmetries:

- beam flux
- target size
- detector size
- detector efficiency



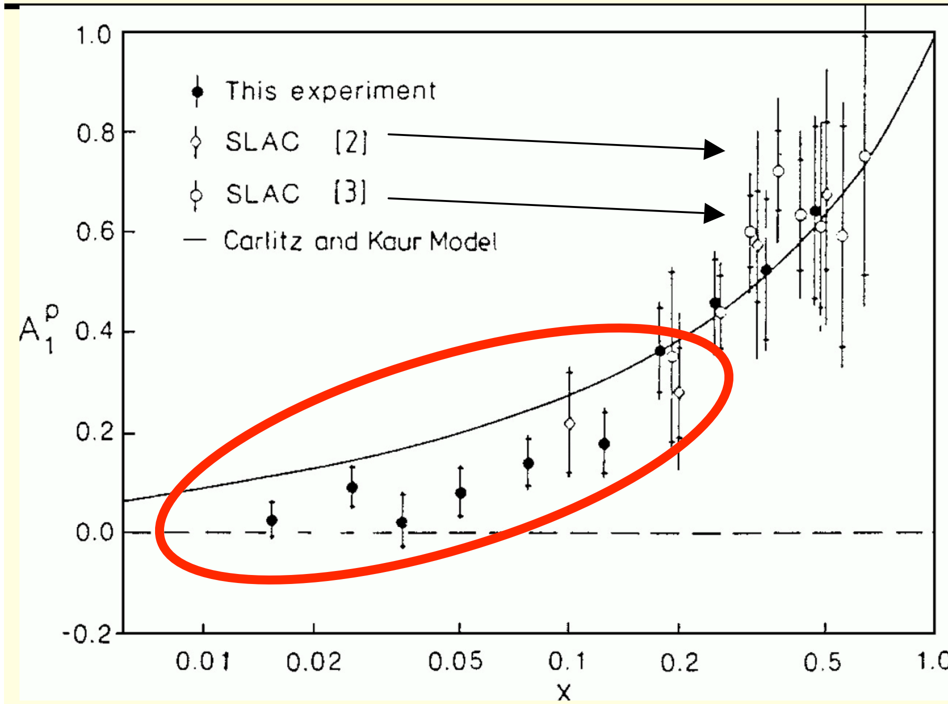
A better polarized DIS experiment setup

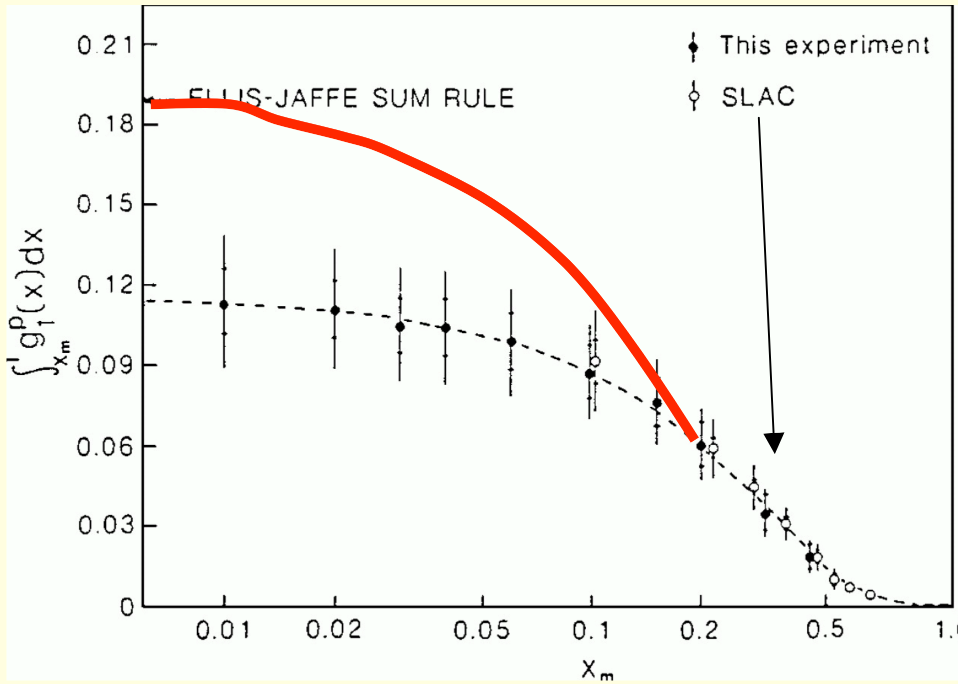
- Typical Fixed target experiment setup (EMC, SMC, *COMPASS*)



- Target polarization direction reversed every 6-8 hrs
- Typically experiments try to limit false asymmetries to be about 10 times smaller than the physics asymmetry of interest

Proton Spin Crisis (1989)!

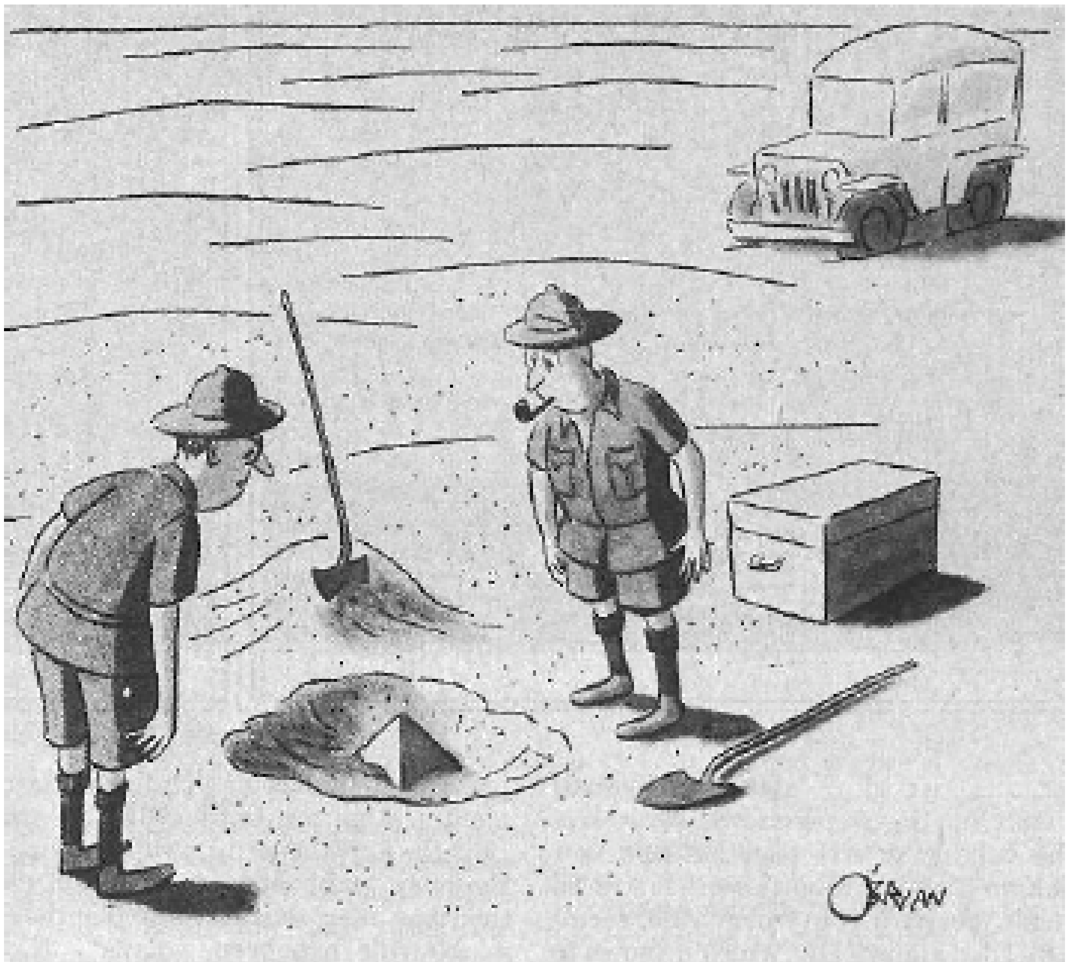




Quarks Don't Carry the Proton the Spin "1/2"

$\Delta\Sigma$ = (0.12) +/- (0.17) (EMC, 1989)

How significant is this?

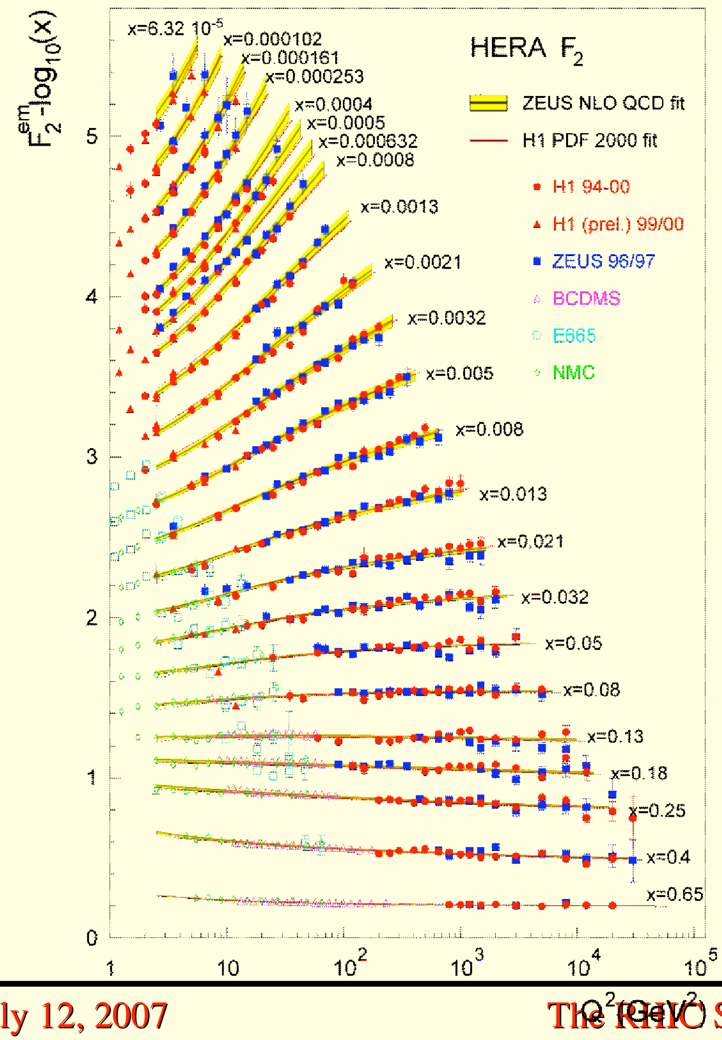


"This could be the discovery of the century. Depending, of course, on how far down it goes."

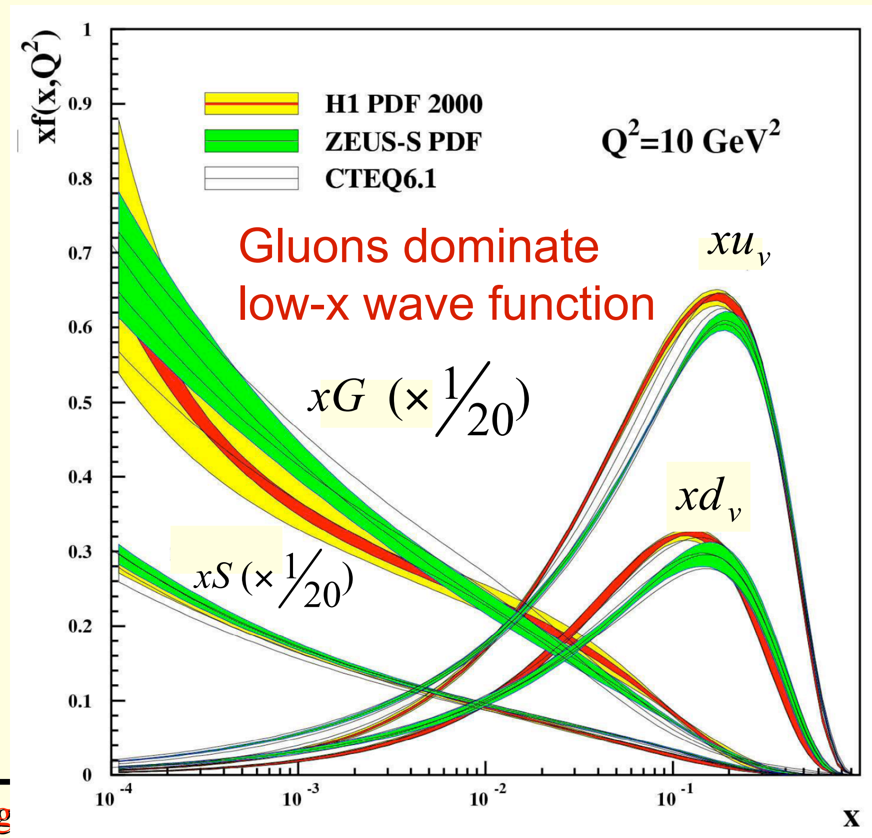
This could be the discovery of the century! Depending of course, on how far down it goes.

F_2 and un-polarized gluon distribution G from HERA

Deep Inelastic Scattering: $$\frac{d^2\sigma^{ep\rightarrow eX}}{dxdQ^2} = \frac{4\pi\alpha_{e.m.}^2}{xQ^4}\left[\left(1 - y + \frac{y^2}{2}\right)F_2(x,Q^2) - \frac{y^2}{2}F_L(x,Q^2)\right]$$



- Scaling violation: $dF_2/d\ln Q^2$ and linear DGLAP Evolution ⇒ $G(x,Q^2)$



CERN established the existence of gluons, HERA measured them with precision…. And established unequivocally that they play a central role in the proton's internal dynamics…..

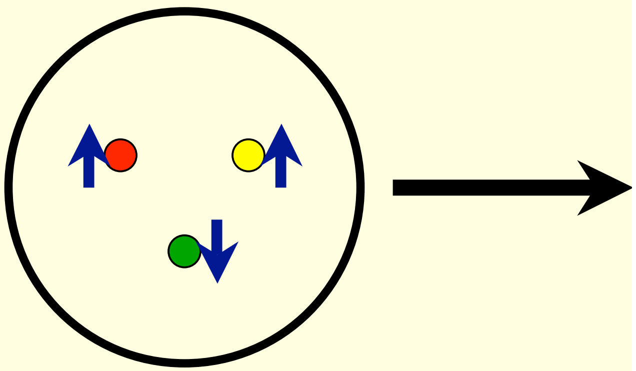
And we (the spinners) had completely ignored gluon's contribution to the spin!

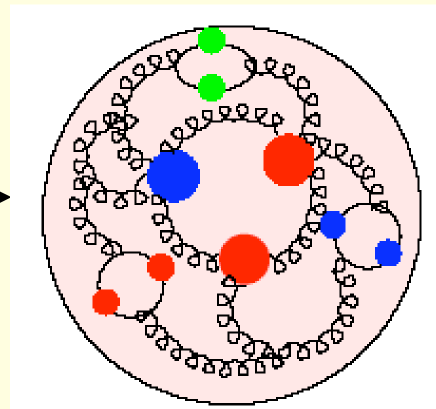
Nucleon Spin

- Proton Spin: contributions from quark-anti-quarks ($\Delta\Sigma$), ***polarized glue(ΔG)*** and possibly from the orbital angular momentum (L)

Quark Model

QCD + Orbital motion





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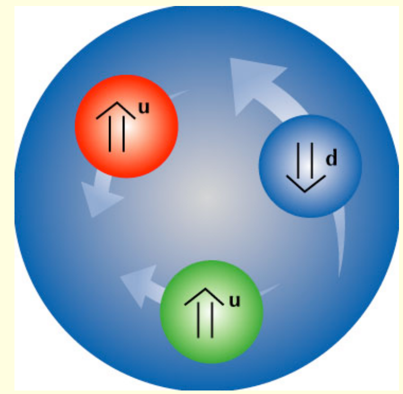
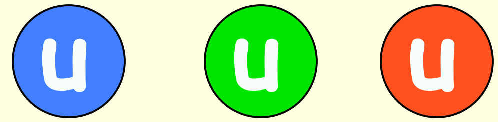


$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_{Q+G}$$

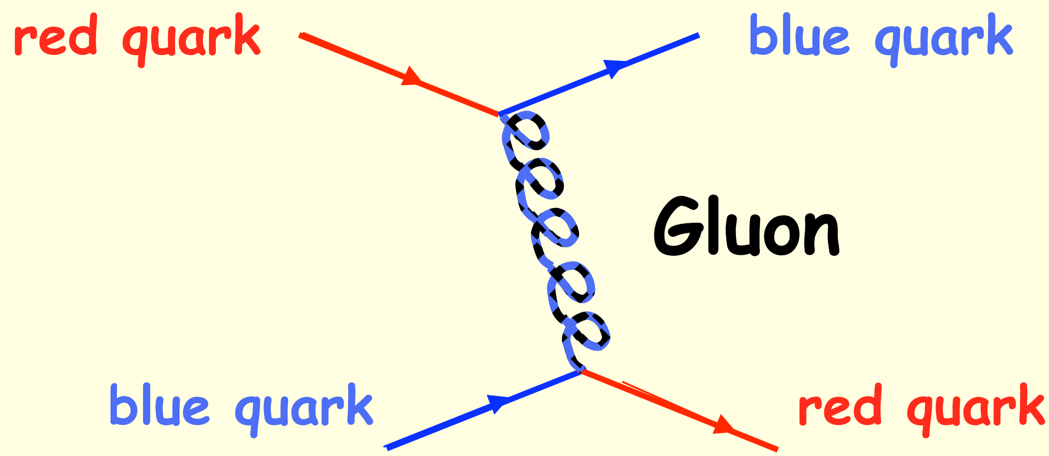
0.12 Significant(?) ???

Quantum Chromo-Dynamics (QCD)

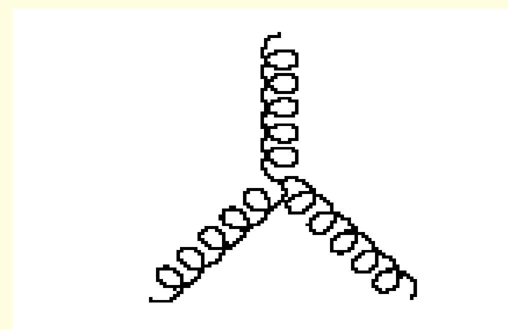
- Quarks come in three colors!



- Interact via **gluons!**



- **Gluons are unique!**
  - They are colored…
  - … they can interact with each other!
  - Spin 1 particles…



Note however some unique consequences….

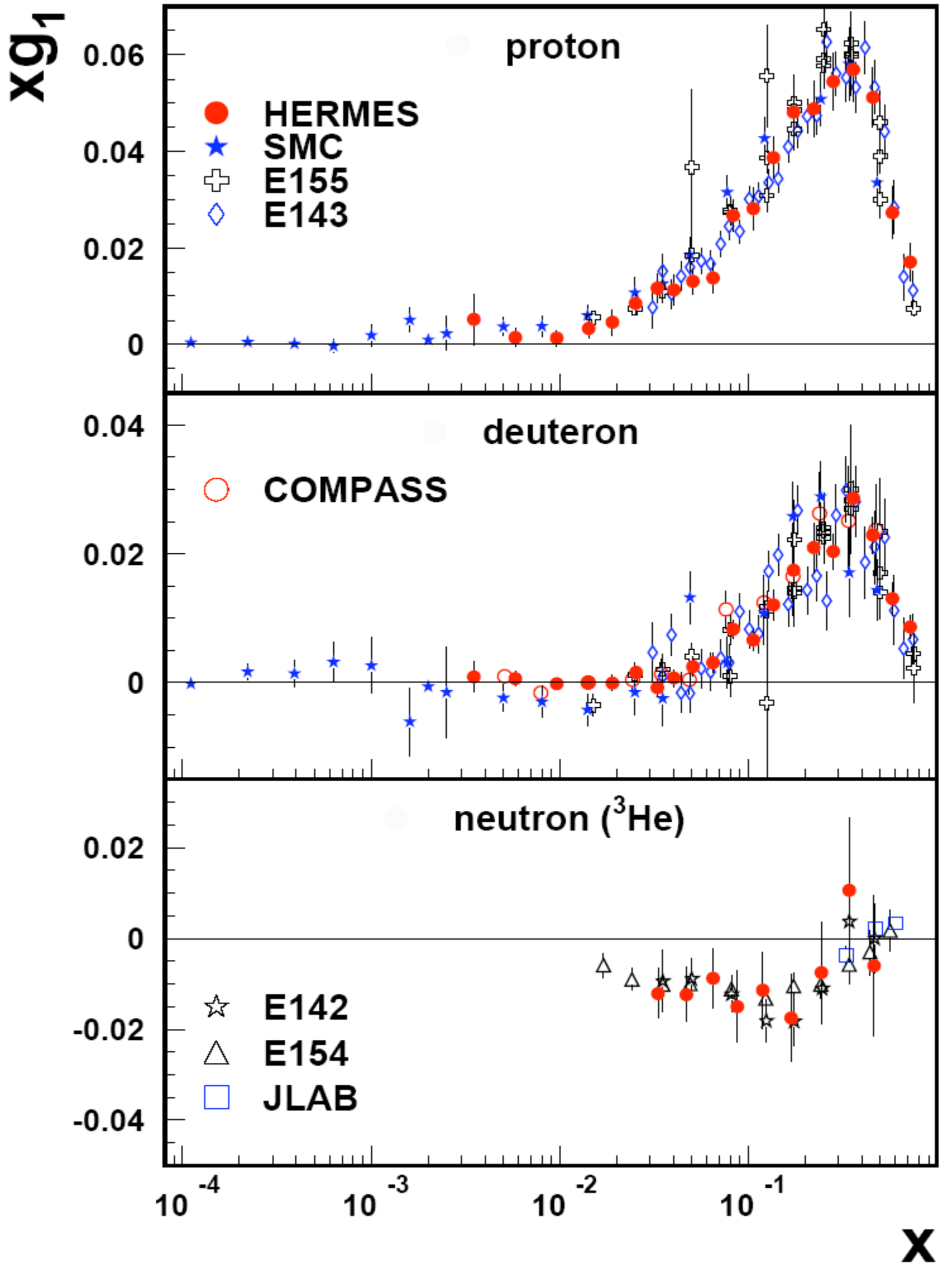
- Gluons are charge-less
  - So the photons can not directly interact with them!

- Photons are colorless
  - So the gluons can not interact with them either!

So lets do the same type of QCD evolution analysis with the polarized DIS data, as we did with the HERA data…..

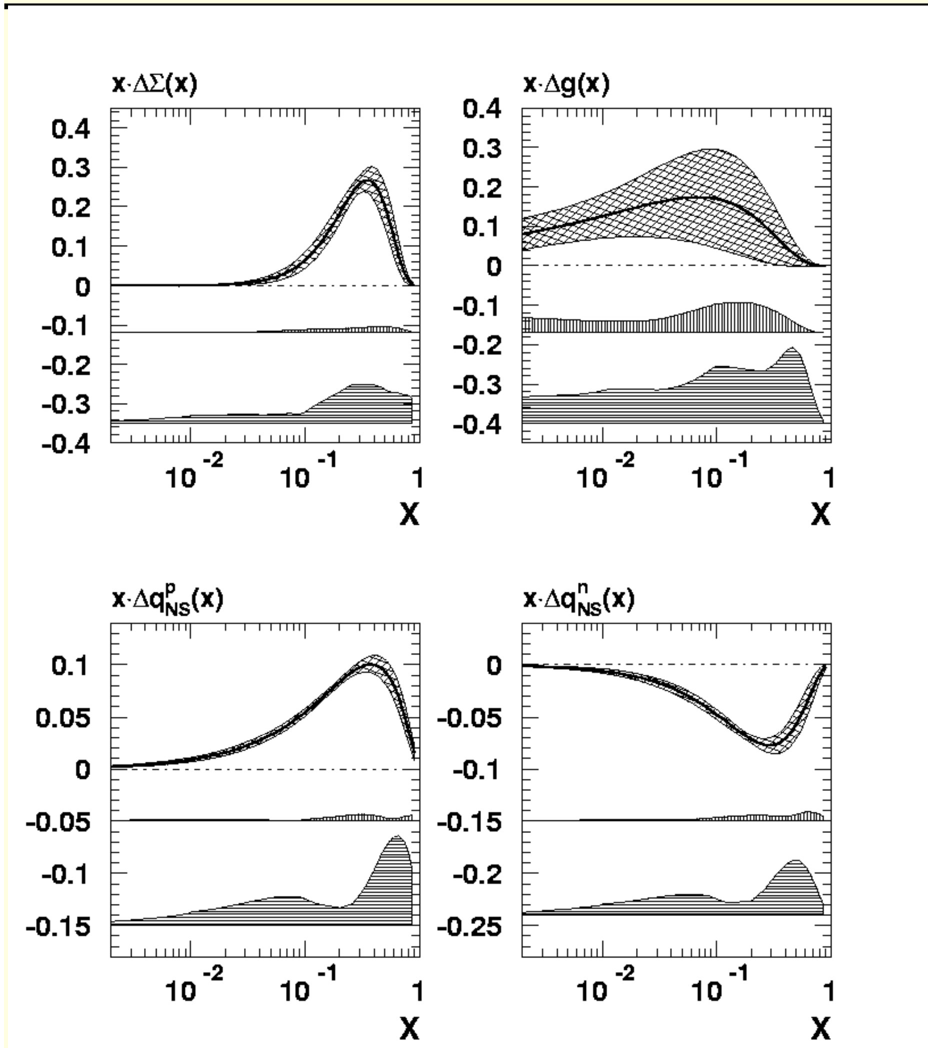
--DOES NOT WORK!

Spin structure Functions



- Measurements over the last twenty odd years
- SMC measure lowest x
- SLAC/Jlab measure highest x
- Data consistent amongst all experiments over a large range of Q^2
- *But there should be differences if gluon polarization is sizable, the the spin structure functions should evolve with Q^2*

Scaling Violations of Spin SF



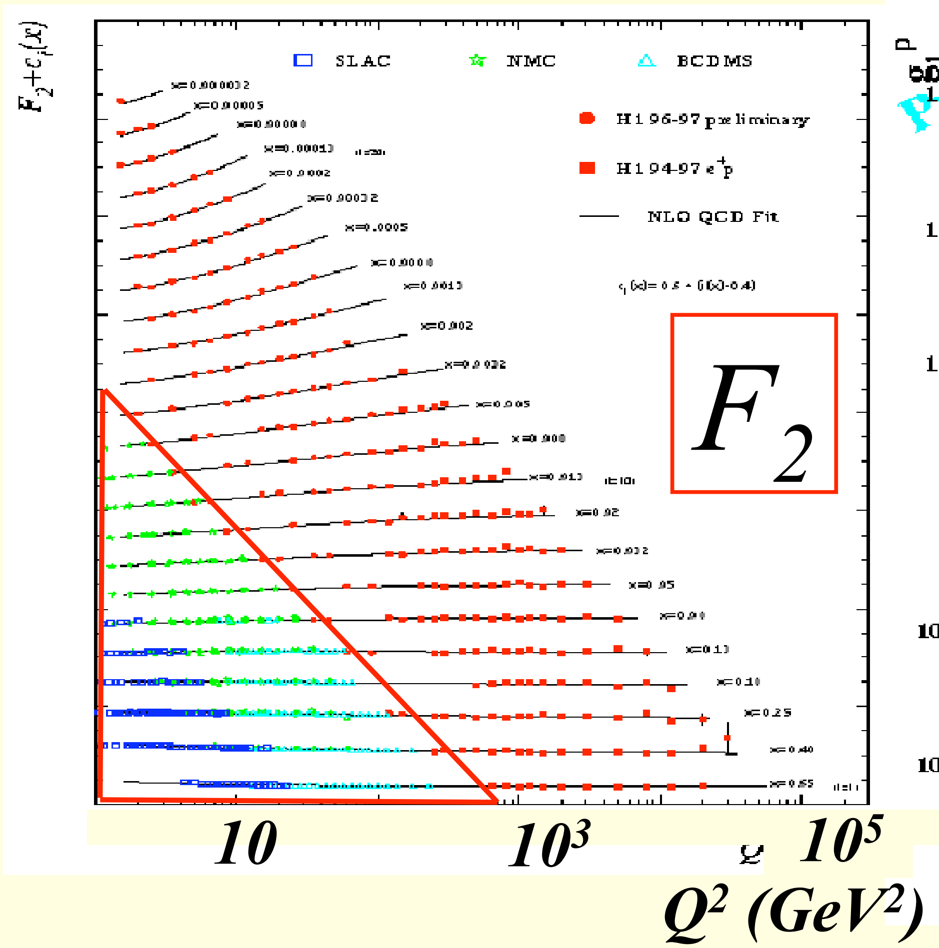
- World's all available g_1 data
- Coefficient and splitting functions in QCD at NLO
- Evolution equations: DGLAP

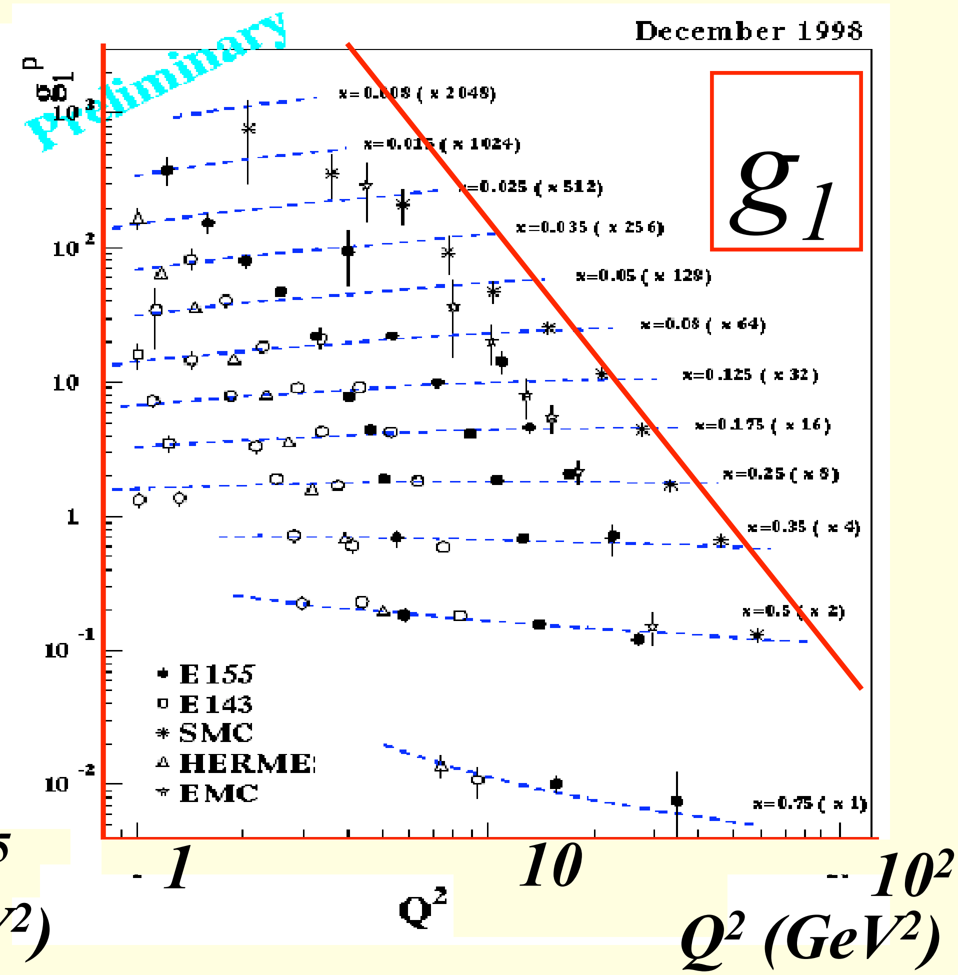
$$f(x) = x^{\alpha}(1-x)^{\beta}(1+ax+bx^2)$$

- Quark distributions fairly well determined, with small uncertainty
  - $\Delta\Sigma = 0.23$ +/- 0.04
- **Polarized Gluon distribution has largest uncertainties**
  - **$\Delta G = 1$ +/- 1.5**

A LARGE UNCERTAINTY!
Why?

Not enough x-Q^2 range in polarized DIS





Large amount of polarized data since 1998… but not in NEW kinematic region!

Is there another way?

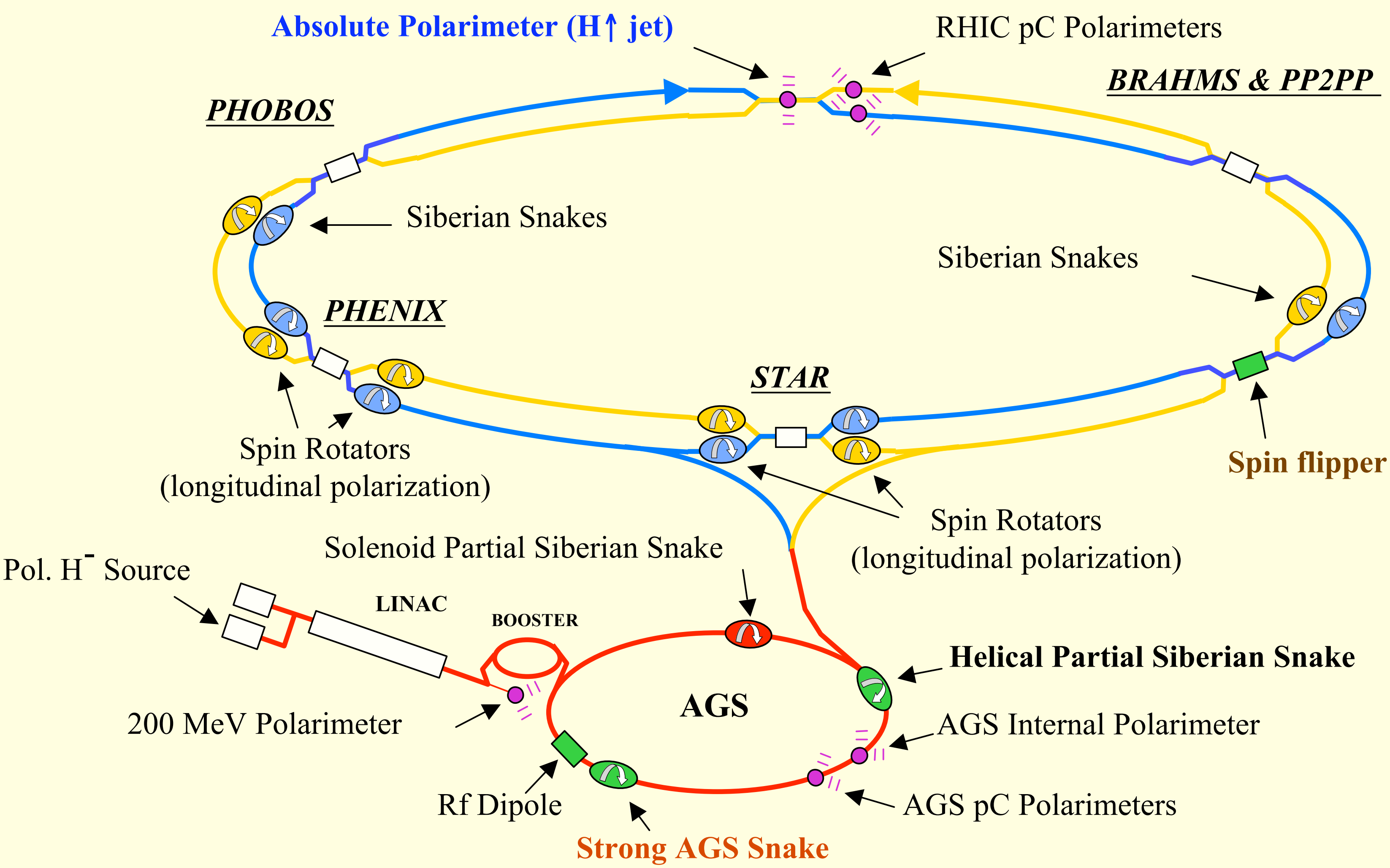
- *How about direct measurement of gluons?*
  - Protons are full of gluons as we have learnt from HERA… in fact they carry 50% of the proton's momentum….
  - Why not collide polarized protons on polarized protons….
    - Gluon-gluon scattering
    - Gluon-quark scattering
    - Quark-quark scattering
  - The first two g-g and g-q scattering clearly of interest
  - How can we use this effectively?

WHY NOT COLLIDE POLARIZED PROTONS ON POLARIZED PROTONS? GLUE-GLUE AND GLUE-QUARK COLLISIONS MIGHT BE OF USE! ==> **RHIC SPIN PROGRAM AT BNL!**

RHIC at BNL

The ONLY polarized collider in the WORLD!

RHIC Polarized Collider



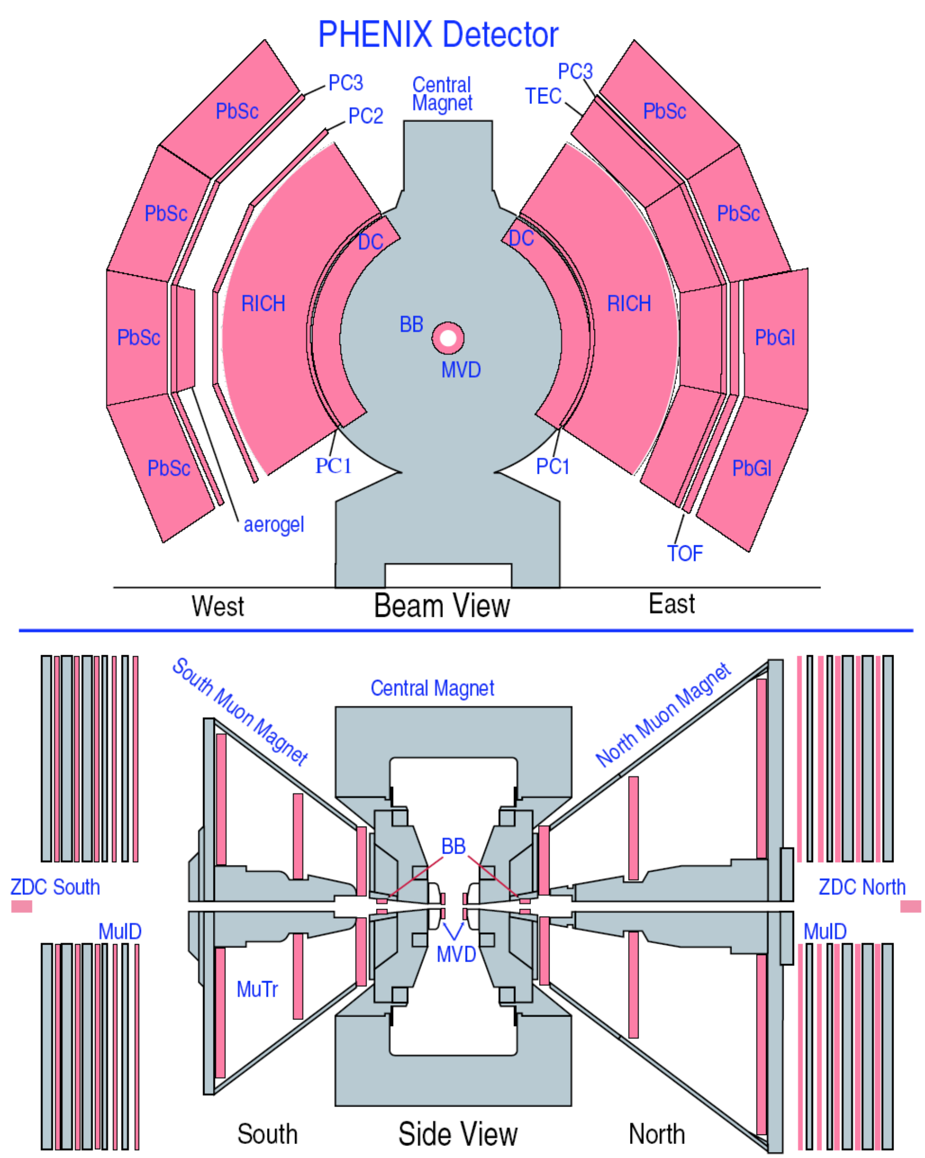
RHIC Spin Physics Program

- *Direct measurement* of polarized gluon distribution *using multiple probes: Measure* *double spin asymmetry A_{LL} in*
  - *gg,qg* $\longrightarrow \pi^{0,+,-}$ *+ X*
  - *gg* $\rightarrow$ *c-cbar, b-bbar + X*
  - *gq* $\rightarrow \gamma$*+X*

- Direct measurement of *anti-quark polarization* using parity violating production of $W^{+/-}$ in single spin A_L
  - u + dbar $\rightarrow W^{+} + \nu_{l}$ and ubar + d $\rightarrow W^{-} + \nu_{l}$

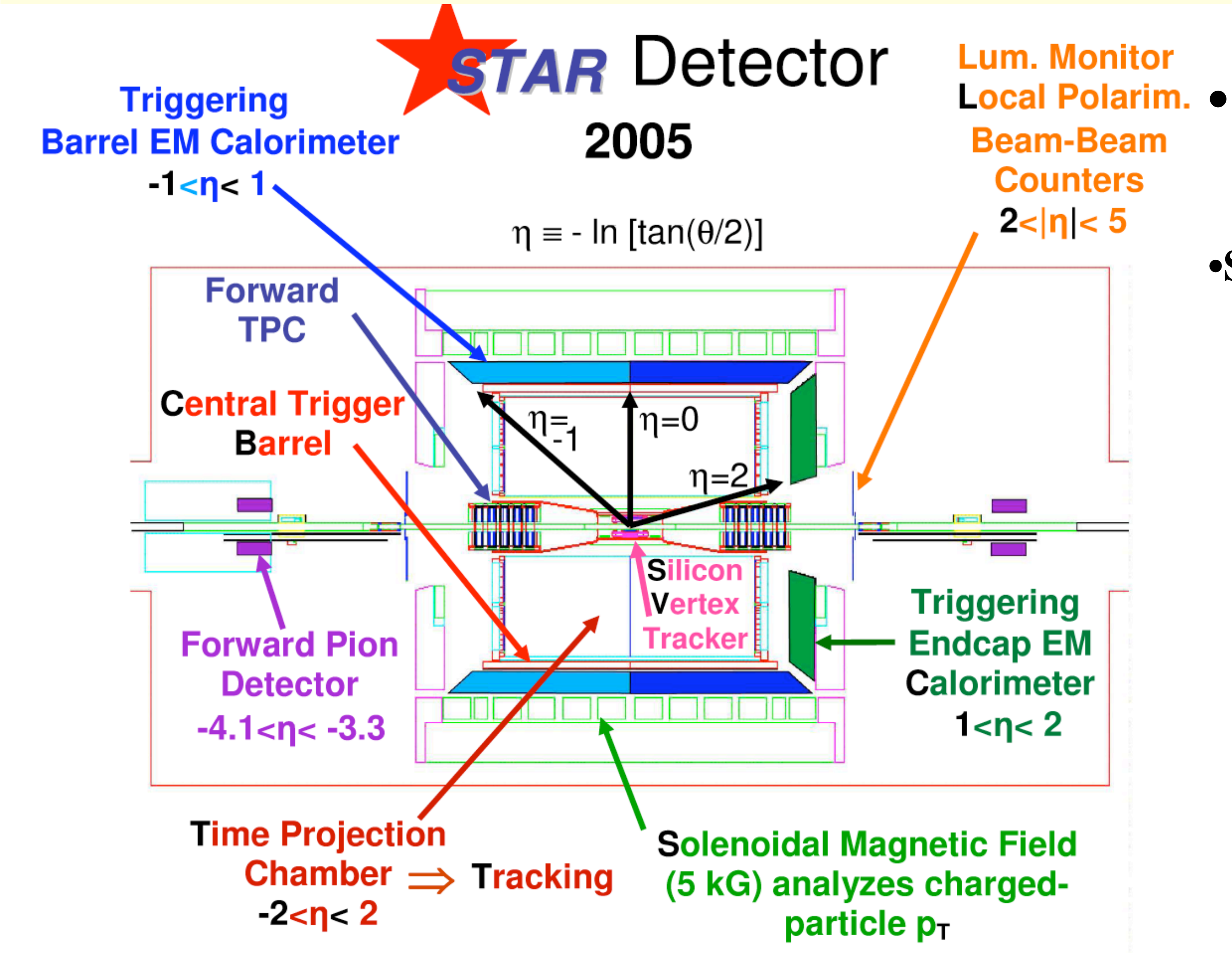
- Transverse spin: Transversity & transverse spin effects: possible connections to orbital angular momentum?

PHENIX Detector at RHIC



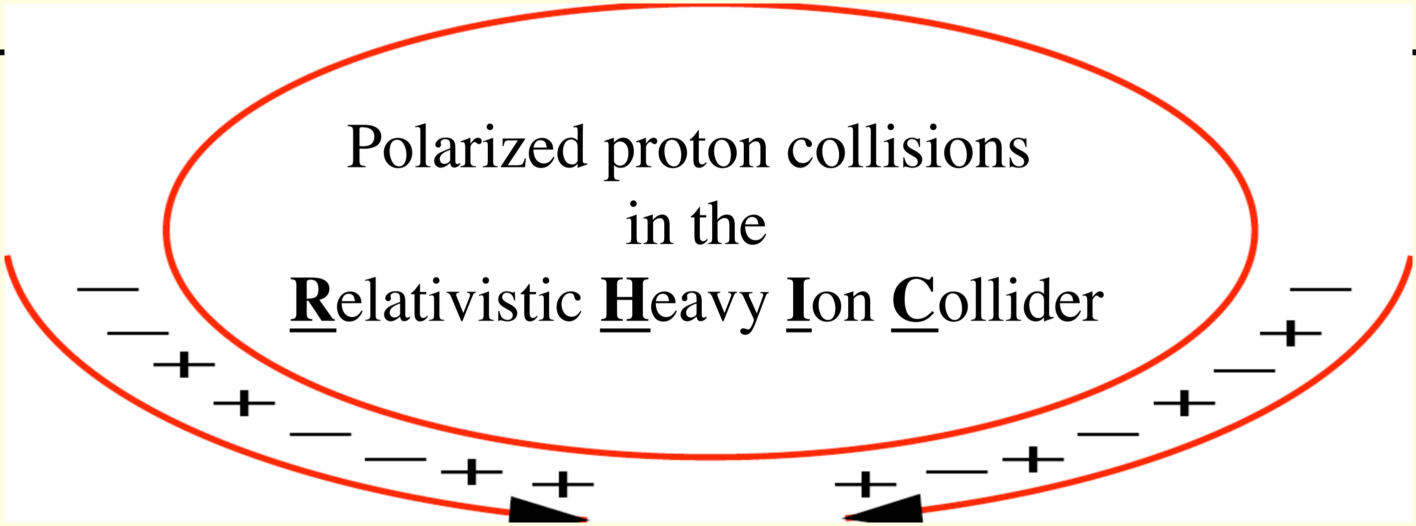
- *Design philosophy:*
  - ***High resolution limited acceptance***
  - ***High rate capability DAQ***
  - ***Excellent triggers for rare events***
- Central arm
  - Tracking: Drift chambers, pad chambers, time expansion chamber
  - Superb EM Calorimetry PbGl, PbSc
    $\Delta\phi x \Delta\eta \sim 0.01 \times 0.01$
    π^0 to 2γ resolved up to 25 GeV pT
  - Particle Identification: RICH, TOF
- Forward Muon Arms:
  - Muon tracker, muon identifiers
- Global detectors:
  - Beam beam collision (BBC) counter, Zero Degree Calorimeters (ZDCs)
- Online monitoring, calibration and production

STAR Detector at RHIC

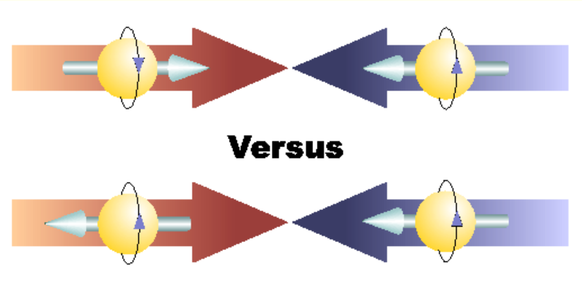


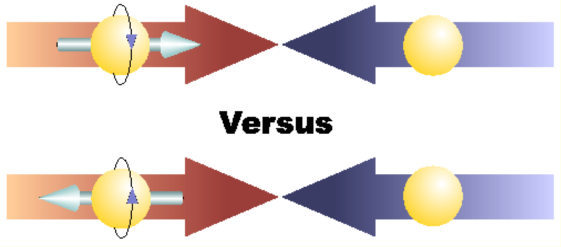
- ***Design Philosophy:***
  - *Maximize acceptance at the cost of resolution*
- **Subsystems:**
  - f = 2π acceptance in EM calorimetry
    - Barrel and EndCap
    - Total: -1 < h < 2
  - Time Projection Chamber
  - Separate Forward pion detector
  - Silicon vertex tracker
  - Beam-Beam Counters
  - Zero Degree Calorimeter

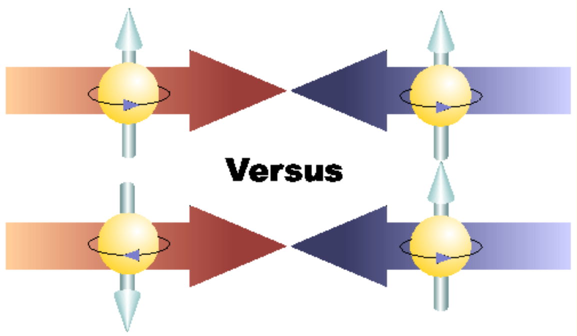
Exquisite Control of Systematics



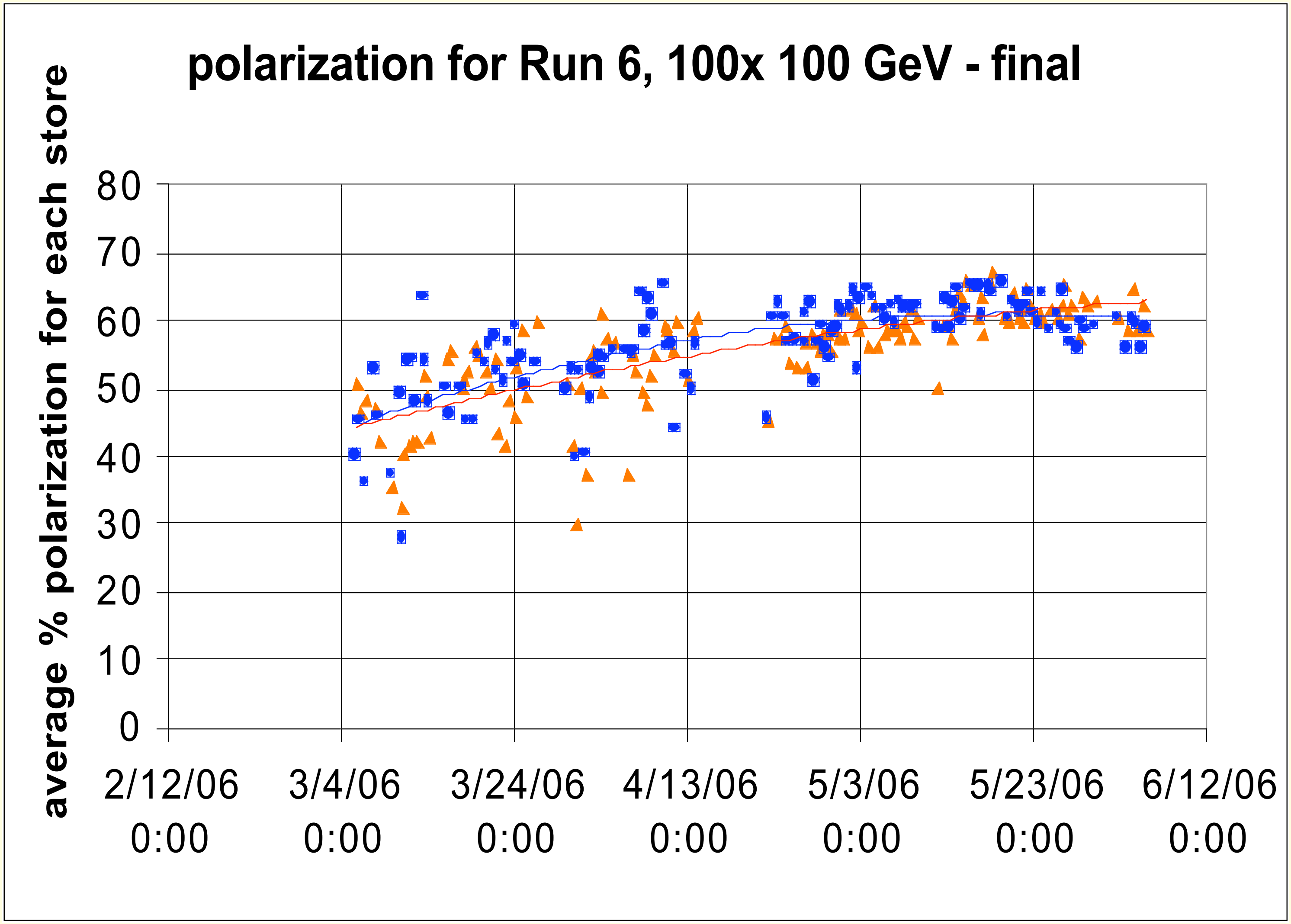
Flexibility & Spin Manipulation at RHIC:
Access to different physics



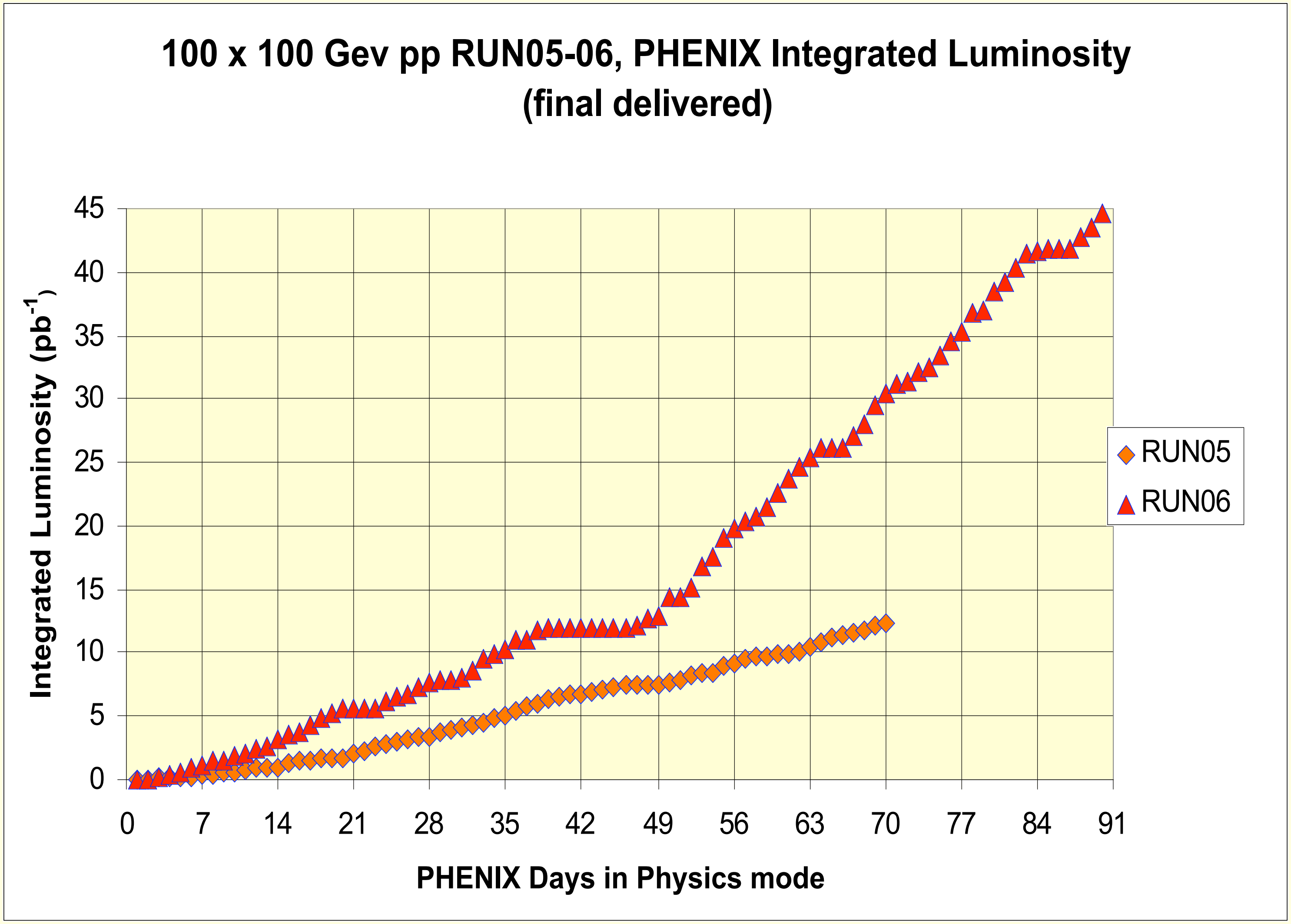




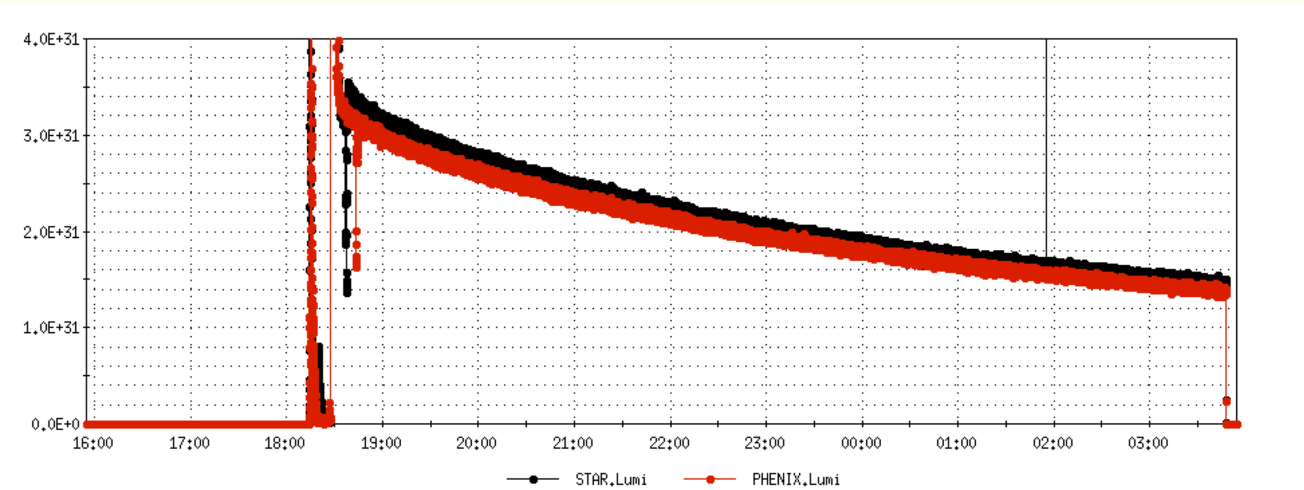
Polarizations Achieved

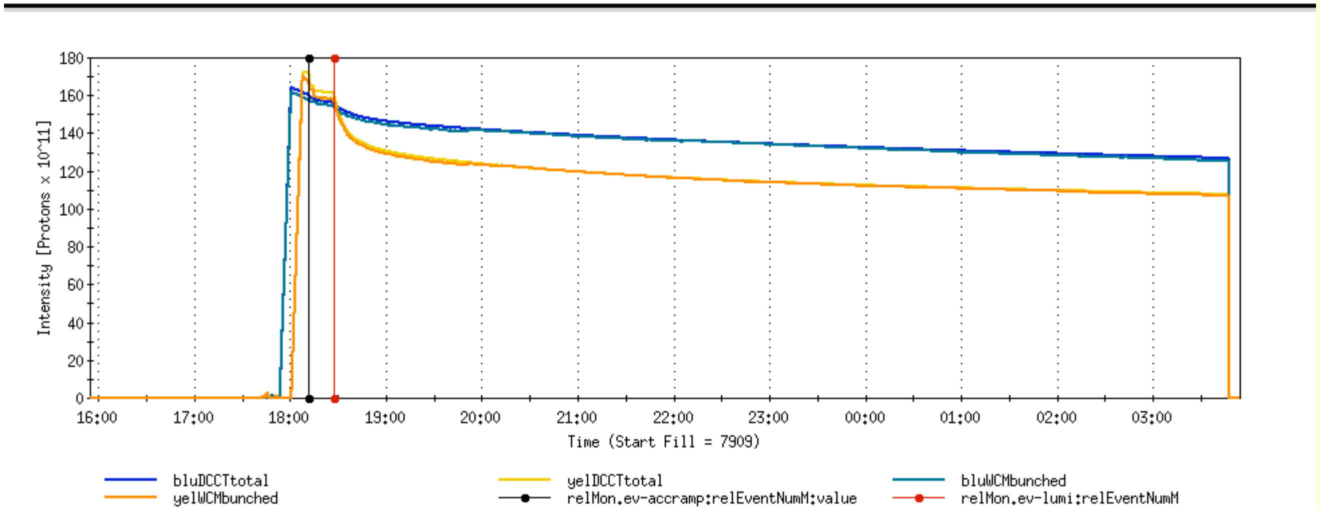


Luminosity Delivered



A typical "good" store (Run-6)





Typically:

8-10 hr stores
Average polarization 60%

No evidence of beam polarization loss
Measurements every 2 hrs

Average time between stores ~ 2.5 hrs in run6
Could be as short as 1 hr

About 3-4 times this is the average goal, and 65-70% beam polarization

Polarized Collider Development

Parameter	Unit	2002	2003	2004	2005	**2006**	Design
No. of bunches	--	55	55	56	106	**111**	**111**
bunch intensity	10^{11}	0.7	0.7	0.7	0.9	**1.4**	**2.0**
store energy	GeV	100	100	100	100	**100**	**100** **250**
β^*	m	3	1	1	1	**1**	**1**
peak luminosity	$10^{30}cm^{-2}s^{-1}$	2	6	6	10	**35**	**80**
average luminosity	$10^{30}cm^{-2}s^{-1}$	1	4	4	6	**20**	**60**
Collision points	--	4	4	4	3	**2**	**2**
average polarization, store	%	15	35	46	47	**60-65**	**70**

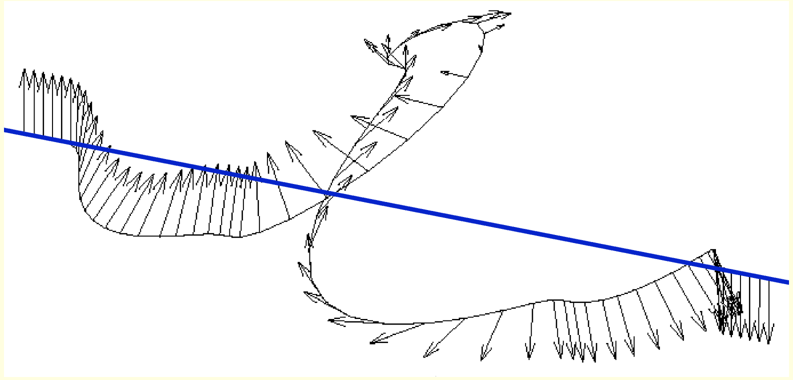
Each milestone below was developed in the last 10 years!

- Production of polarized protons
- Acceleration of polarized protons from low energies (100s of MeV/c) to high energies(100-250 GeV/c)
  - Measurements of polarization on the way
- Measurement of beam polarization
  - Initial diagnostics, in each energy step on the way
  - Finally only initial and final
- For experiments, confirm the orientation of the polarized protons in collisions (Local Polarimetry)
  - Transverse, natural, easy
  - Longitudinal, with spin rotators, required new physics ideas to be developed

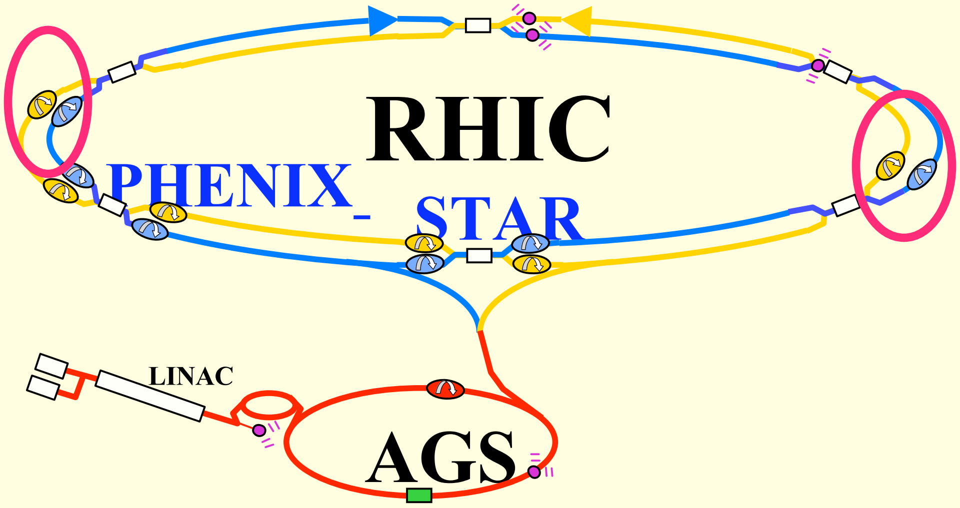
Siberian Snakes at RHIC

(Funded by RIKEN Institute in Japan)

Depolarizing Resonance:
Spin tune = no. of spin kicks
Imperfection resonances:
--magnet errors & mis-alignements
Intrinsic resonances:
--vertical focusing fields



Effect of depolarizing resonances averaged out by rotating spin by large angles on each turn



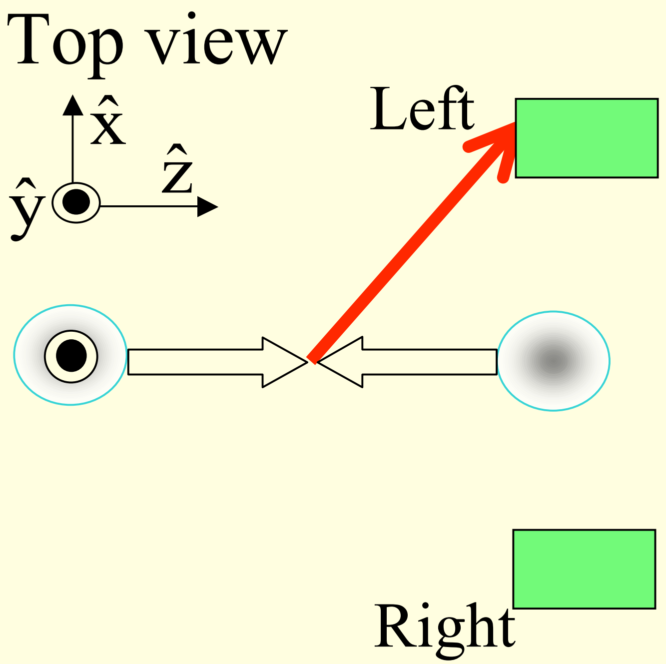
RIKEN/BNL

4 helical dipoles ➔ S. snake
2 snakes in each ring
-- axes orthogonal to each other

Proton Beam Polarimetry at high energy

How do we know our protons are polarized when they collide?

Beam polarization measurement (1)



- Use single spin asymmetry in elastic scattering of p-p and p-Carbon
  - Coulomb Nuclear Interference (CNI) kinematics

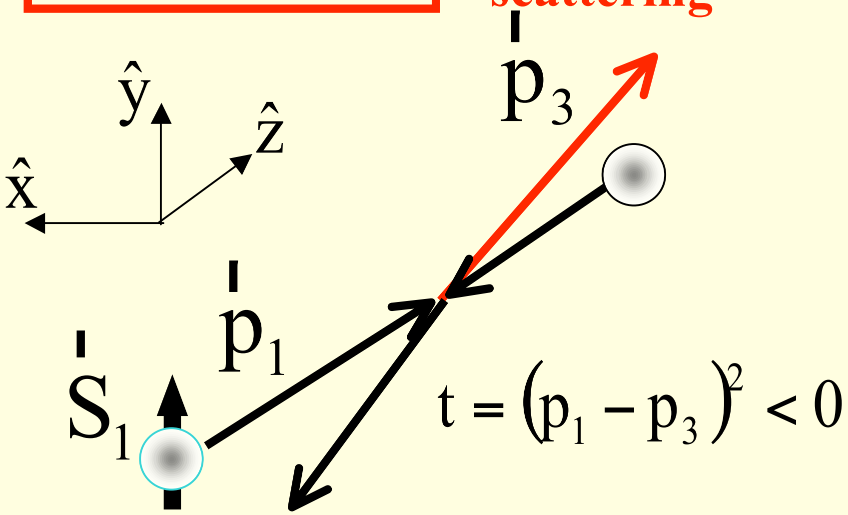
$$\text{SSA} = \frac{1}{\text{pol.}} \frac{\sqrt{N_{\uparrow}^{L} N_{\downarrow}^{R}} - \sqrt{N_{\uparrow}^{R} N_{\downarrow}^{L}}}{\sqrt{N_{\uparrow}^{L} N_{\downarrow}^{R}} + \sqrt{N_{\uparrow}^{R} N_{\downarrow}^{L}}}$$

For a known/understood scattering process, measure the single spin asymmetry and calculate the beam polarization.

RHIC Absolute polarization

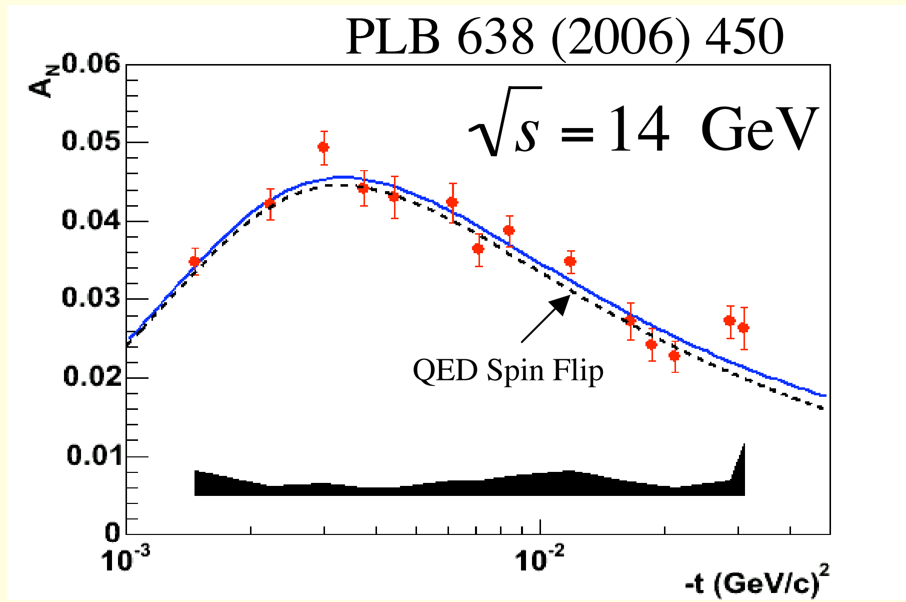
$p^{\uparrow} + p \rightarrow p + p$

Very forward scattering



Elastic p-p scattering single spin asymmetry as a function of momentum transfer t

Best Thesis Award 2006, Hiromi Okada



- Calculation by Shwinger 1946
- Unknown spin-flip amplitude
- Now found to be zero

Beam polarization monitor…

- Use p-Carbon CNI scattering, similar in every thing except, the calculation uncertainty large
- The event rate is however very large: ~1 Mevents/seconds
  - Asymmetry measured for 20 sec to confirm that beam is polarized
  - Measurements performed every ~2 hrs

- No sign of beam depolarization has ever been observed in RHIC when things are going well
- Other systematic effects such as possibilities of beam profile in transverse direction, are now being studied.
  - Methods to correct the beam polarization known and understood

“Local Polarimeter”

Experiments: Local Polarization Vector study/confirmation

- Stable vector beam polarization direction in RHIC is transverse (vertical) along the direction of the accelerator's holding field

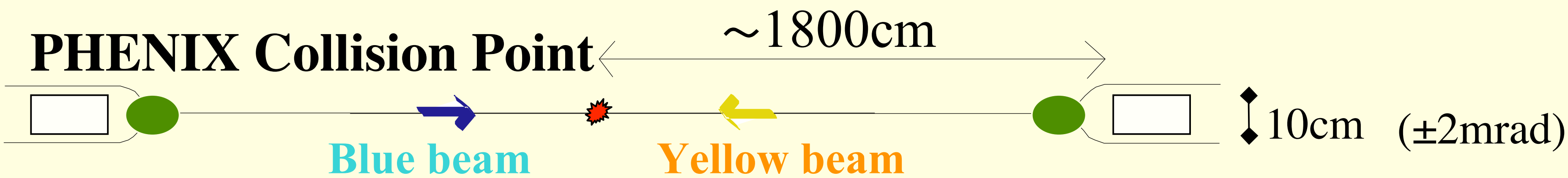
- For longitudinal double and single spin asymmetries A_{LL} and A_L , longitudinal orientation at the experiment is achieved using SPIN ROTATOR MAGNETS (SRM)

- Direction of spin orientation being nearly longitudinal is confirmed using physics measurements, often called "Local Polarimeters"
  - They simply confirm experimentally, that the SRMs are doing their job

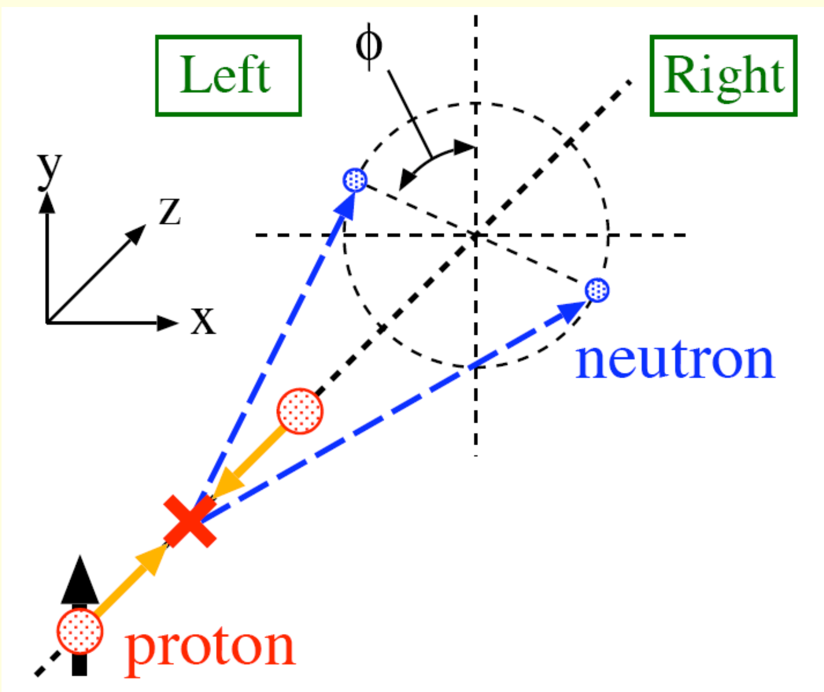
Local Polarimetry

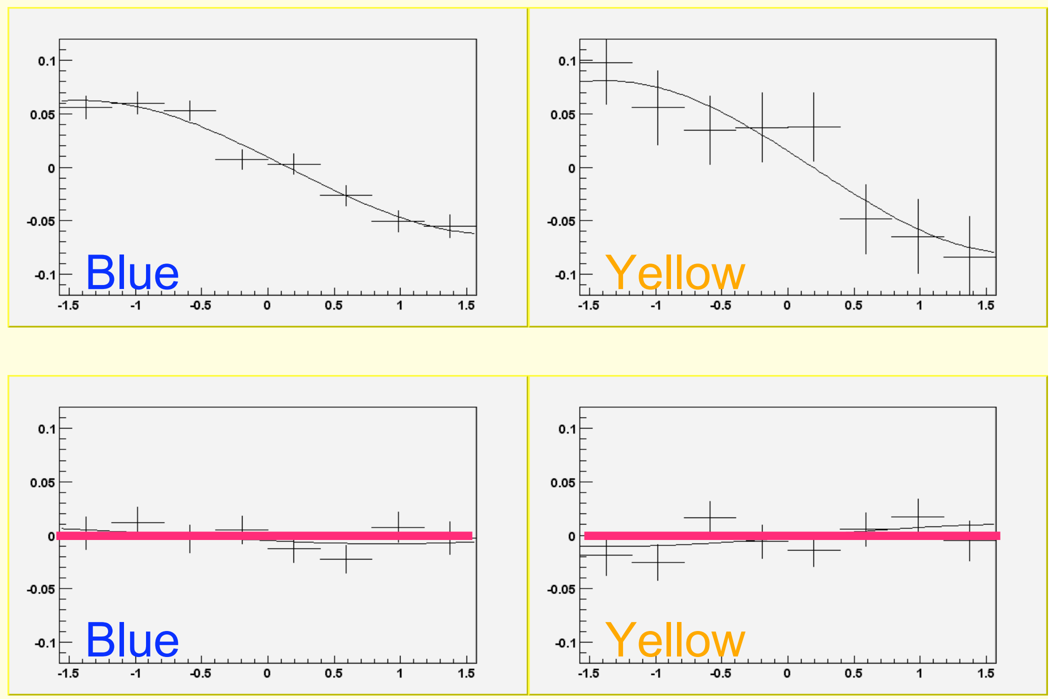
- PHENIX
  - FIRST Observation of forward neutron production single spin left-right asymmetry
  - Zero Degree Calorimeter: detects a neutron
  - Shower Max detector: detects the position of the neutron (left/right)
  - Lack of residual beam left-right or up-down asymmetry signals proper rotation of spin vector from vertical to longitudinal
- STAR
  - Uses a similar asymmetry in particle production in the forward region using their Beam-Beam Collisions Counters

PHENIX Local Polarimeter

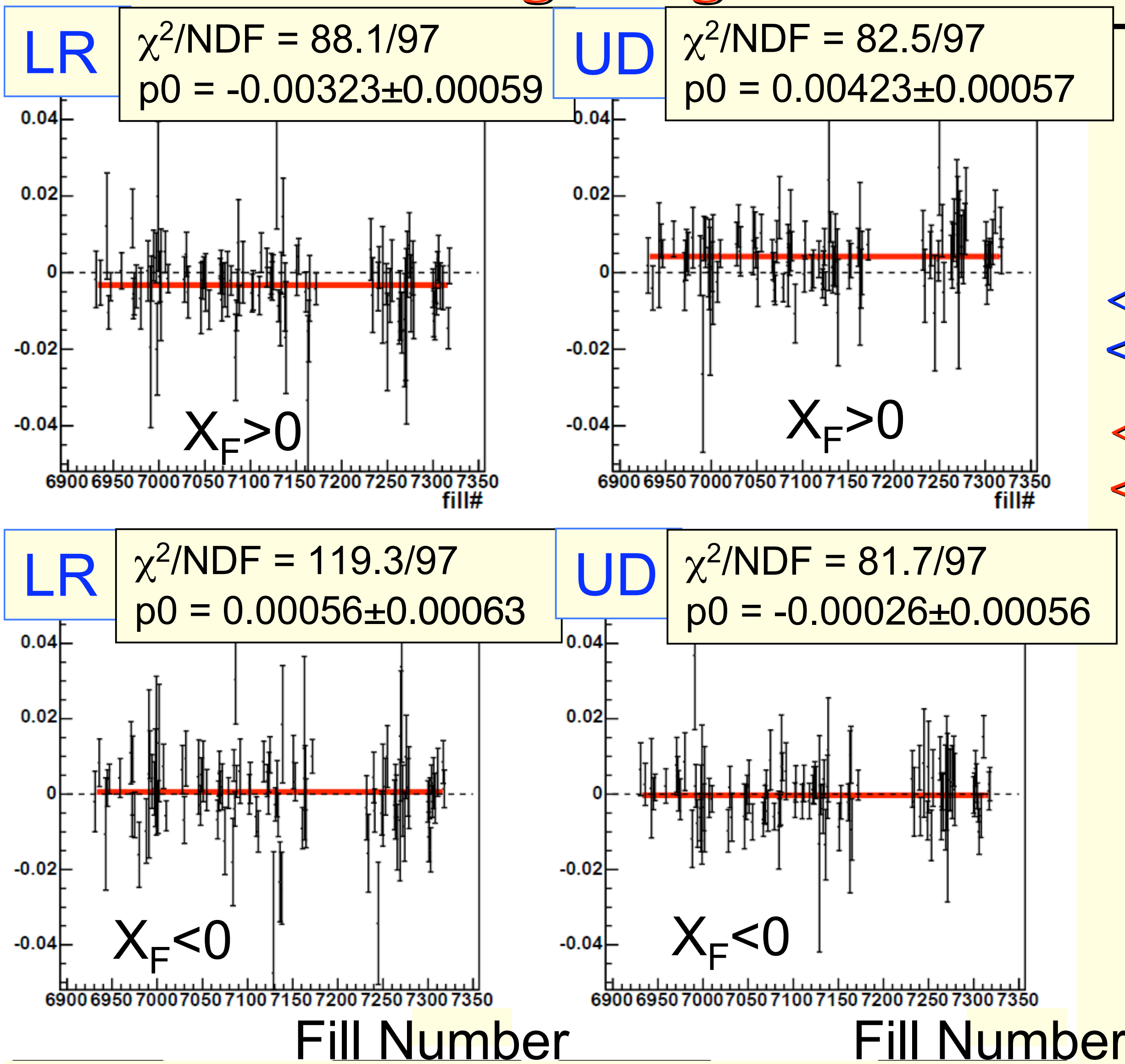


$P_L/P > 0.99$ blue & yellow





Measured Asymmetry During Longitudinal Running (2005)



$$S_L = \sqrt{1 - S_T^2}$$

$$S_T = \sqrt{S_X^2 + S_Y^2}$$

$\langle P_T/P \rangle = 10 \pm 2 (\%)$

$\langle P_L/P \rangle = 99.48 \pm 0.12 \pm 0.02 (\%)$

$\langle P_T/P \rangle = 14 \pm 2 (\%)$

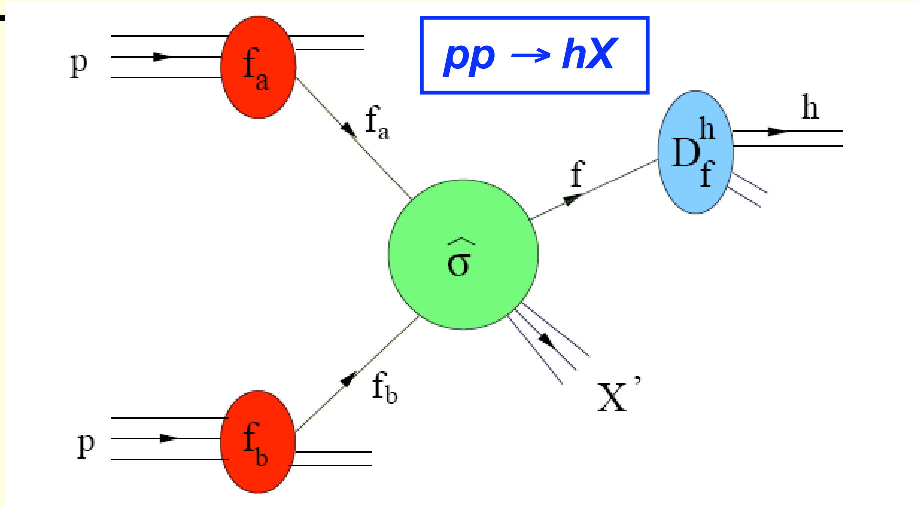
$\langle P_L/P \rangle = 98.94 \pm 0.21 \pm 0.04 (\%)$

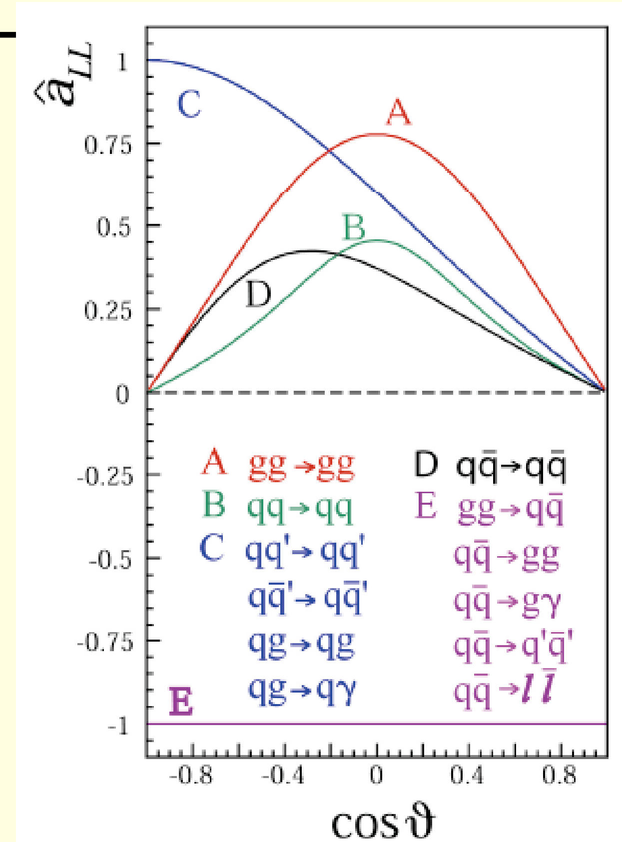
- Measurement of remaining transverse component → spin pattern is correct

Also confirmed in Run6 analysis

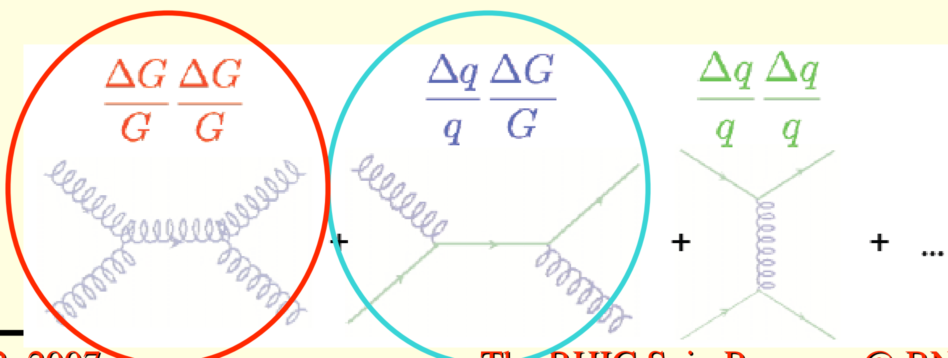
ΔG at RHIC Spin

Probing ΔG in pol. pp collisions



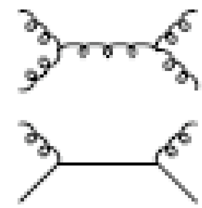
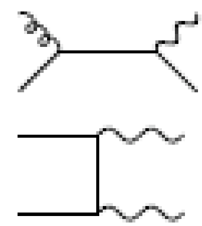
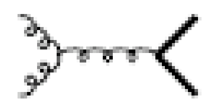
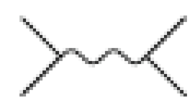
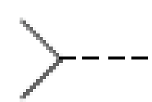


$$A_{LL} = \frac{d\sigma^{++} - d\sigma^{+-}}{d\sigma^{++} + d\sigma^{+-}} = \frac{\sum_{a,b} \Delta f_a \otimes \Delta f_b \otimes d\hat{\sigma}^{f_a f_b \to fX} \cdot \hat{a}_{LL}^{f_a f_b \to fX} \otimes D_f^h}{\sum_{a,b} f_a \otimes f_b \otimes d\hat{\sigma}^{f_a f_b \to fX} \otimes D_f^h}$$



Double longitudinal spin asymmetry A_{LL} is sensitive to ΔG

RHIC Spin Physics

Reaction	Dom. partonic process	probes	LO Feynman diagram
$\vec{p}\vec{p} \to \pi + X$	$\vec{g}\vec{g} \to gg$ $\vec{q}\vec{g} \to qg$	Δg	
$\vec{p}\vec{p} \to \text{jet(s)} + X$	$\vec{g}\vec{g} \to gg$ $\vec{q}\vec{g} \to qg$	Δg	(as above)
$\vec{p}\vec{p} \to \gamma + X$ $\vec{p}\vec{p} \to \gamma + \text{jet} + X$ $\vec{p}\vec{p} \to \gamma\gamma + X$	$\vec{q}\vec{g} \to \gamma q$ $\vec{q}\vec{g} \to \gamma q$ $\vec{q}\vec{\bar{q}} \to \gamma\gamma$	Δg Δg $\Delta q, \Delta\bar{q}$	
$\vec{p}\vec{p} \to DX, BX$	$\vec{g}\vec{g} \to c\bar{c}, b\bar{b}$	Δg	
$\vec{p}\vec{p} \to \mu^+\mu^- X$ (Drell-Yan)	$\vec{q}\vec{\bar{q}} \to \gamma^* \to \mu^+\mu^-$	$\Delta q, \Delta\bar{q}$	
$\vec{p}\vec{p} \to (Z^0, W^\pm)X$ $p\vec{p} \to (Z^0, W^\pm)X$	$\vec{q}\vec{\bar{q}} \to Z^0,\ \vec{q}'\vec{\bar{q}} \to W^\pm$ $\vec{\bar{q}}'q \to W^\pm,\ q'\vec{\bar{q}} \to W^\pm$	$\Delta q, \Delta\bar{q}$	

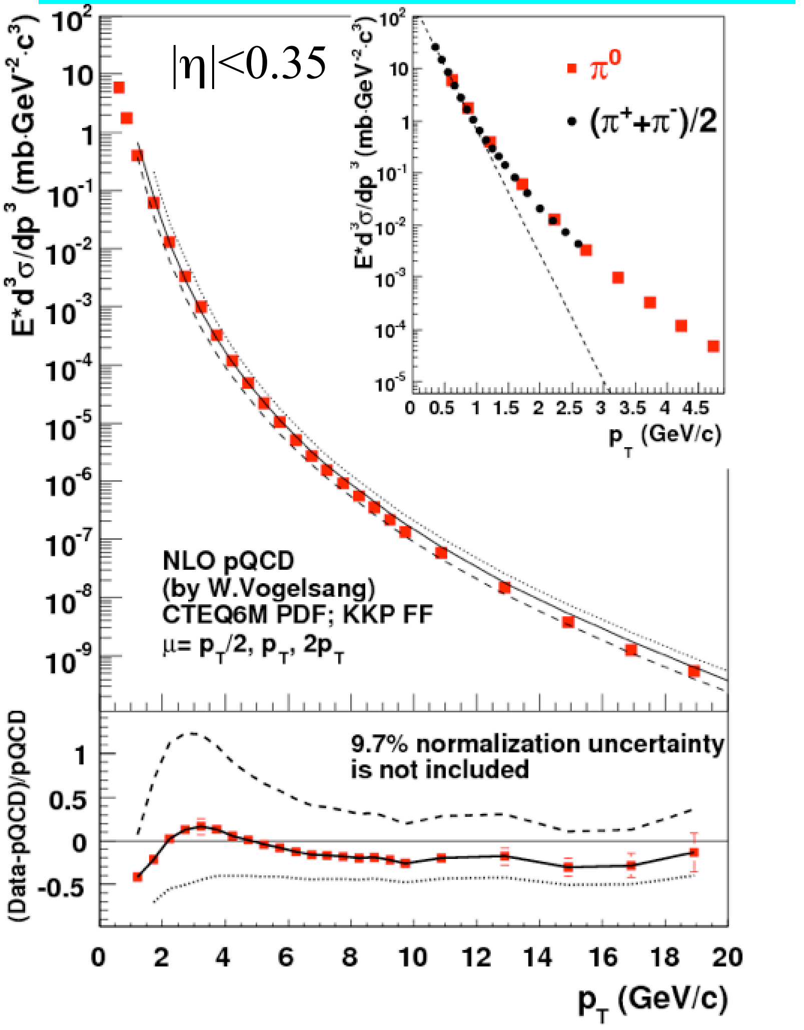
Calibration of our probes…

- Measurement of a cross section involves:
  - Detailed understanding of the luminosity
  - Detailed understanding of the detector
- Comparison of the data (above) with theory, if it is good:
  - Theoretical framework used for the calculation seems to be applicable in this kinematic regime
  - Gives us confidence that the double spin asymmetries measured, could be interpreted in terms of polarized gluon distributions using the same theoretical tools…
- An extremely important check, which we make a "MUST" for any measurement we want to publish.

Un-polarized Cross Section in *pp*

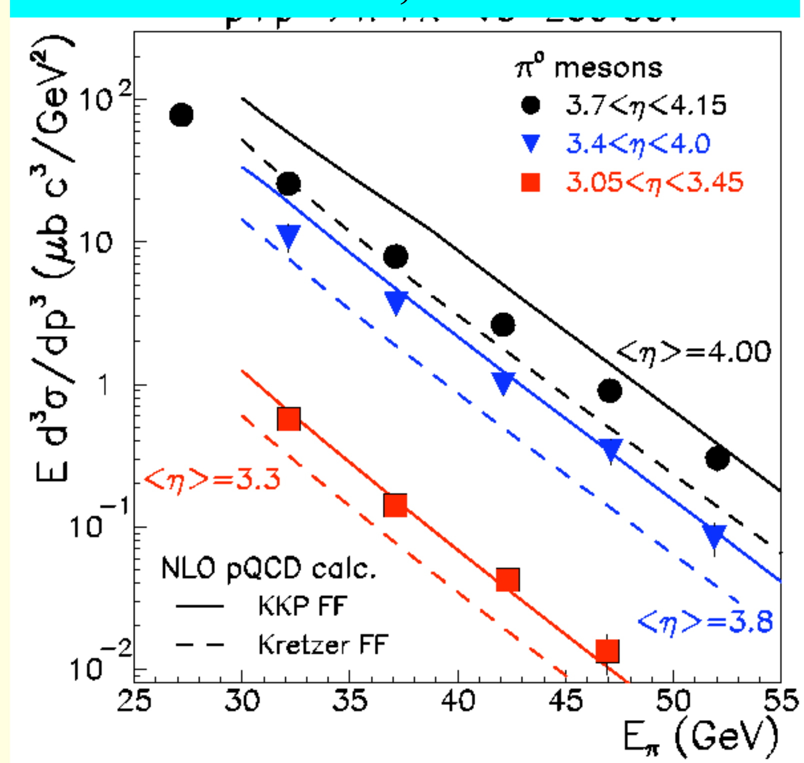
PHENIX: π0 mid-rapidity

hep-ex-0704.3599



STAR: π0 forward rapidity

PRL 97, 152302

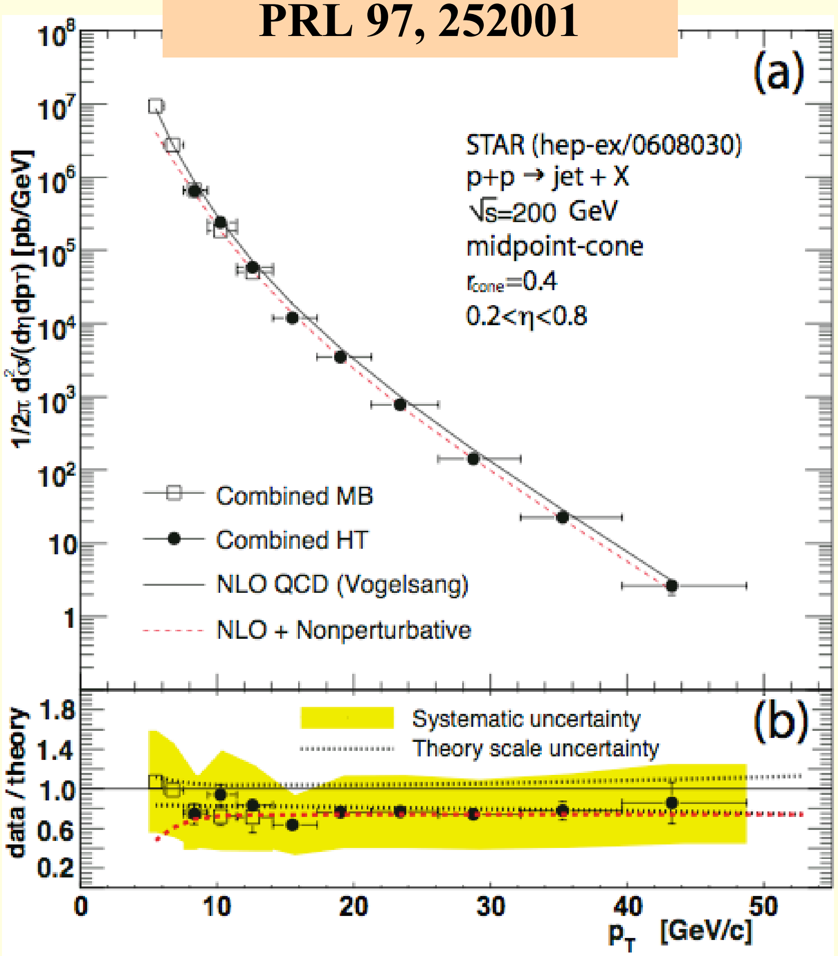


Good agreement between NLO pQCD calculations and data ⇒ confirmation that pQCD can be used to extract spin dependent pdf's from RHIC data.

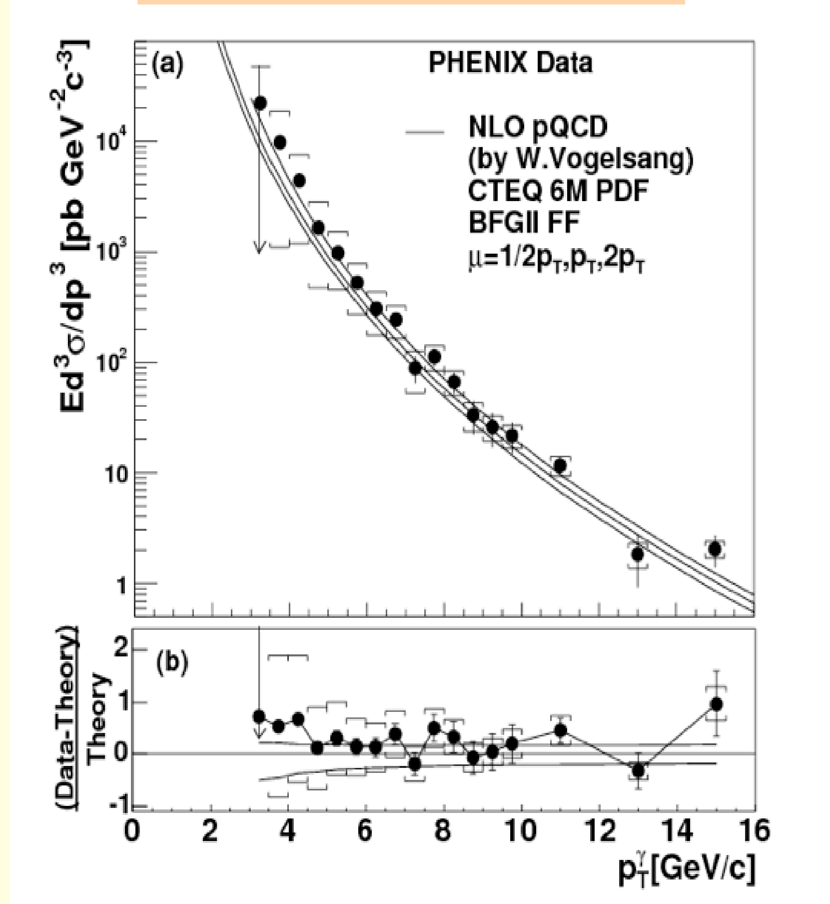
- Same comparison fails at lower energies

Unpol. Cross Section in *pp*

STAR: pp→jet X
PRL 97, 252001



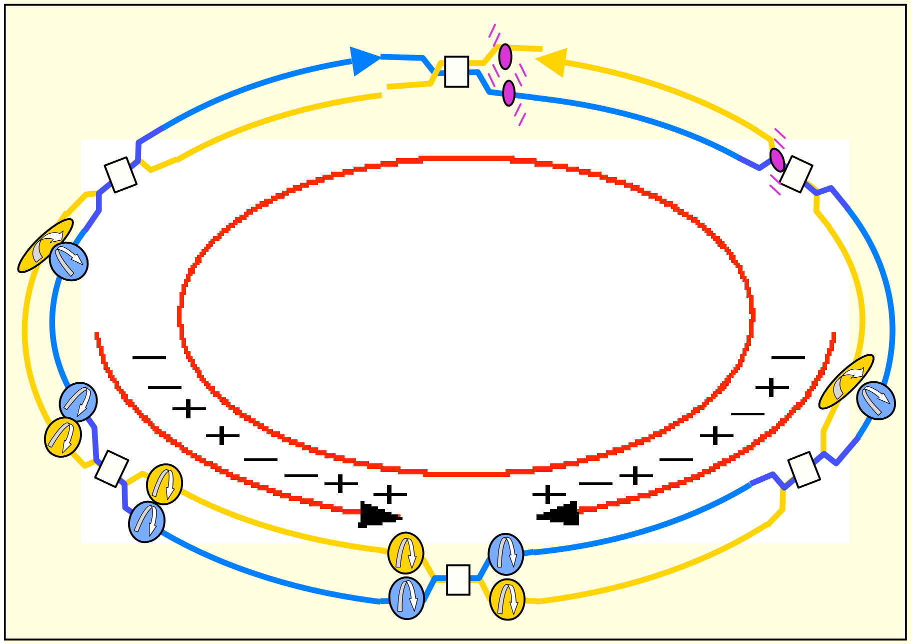
PHENIX: pp→γ X
PRL 98, 012002



Again, good agreement between NLO pQCD calculations and data

Measuring A_{LL}

$$A_{LL} = \frac{d\sigma_{++} - d\sigma_{+-}}{d\sigma_{++} + d\sigma_{+-}} = \frac{1}{|P_1 P_2|} \frac{N_{++} - RN_{+-}}{N_{++} - RN_{+-}}; \qquad R = \frac{L_{++}}{L_{+-}}$$



(N) Yield

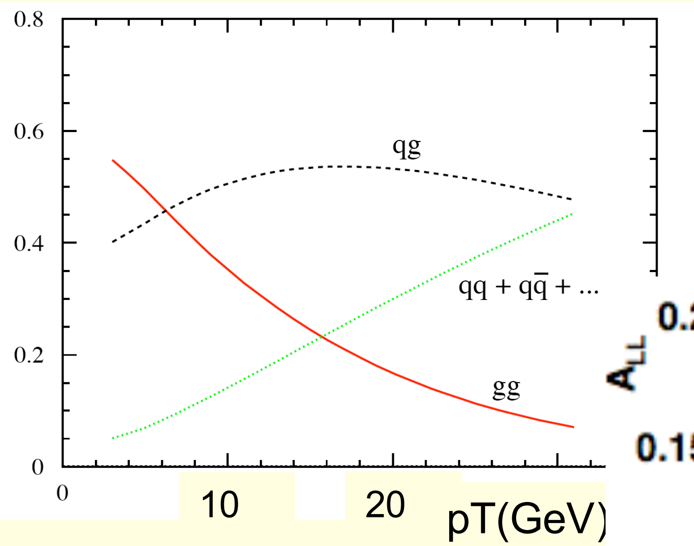
(R) Relative Luminosity

(P) Polarization

✓ Bunch spin configuration alternates every 106 ns

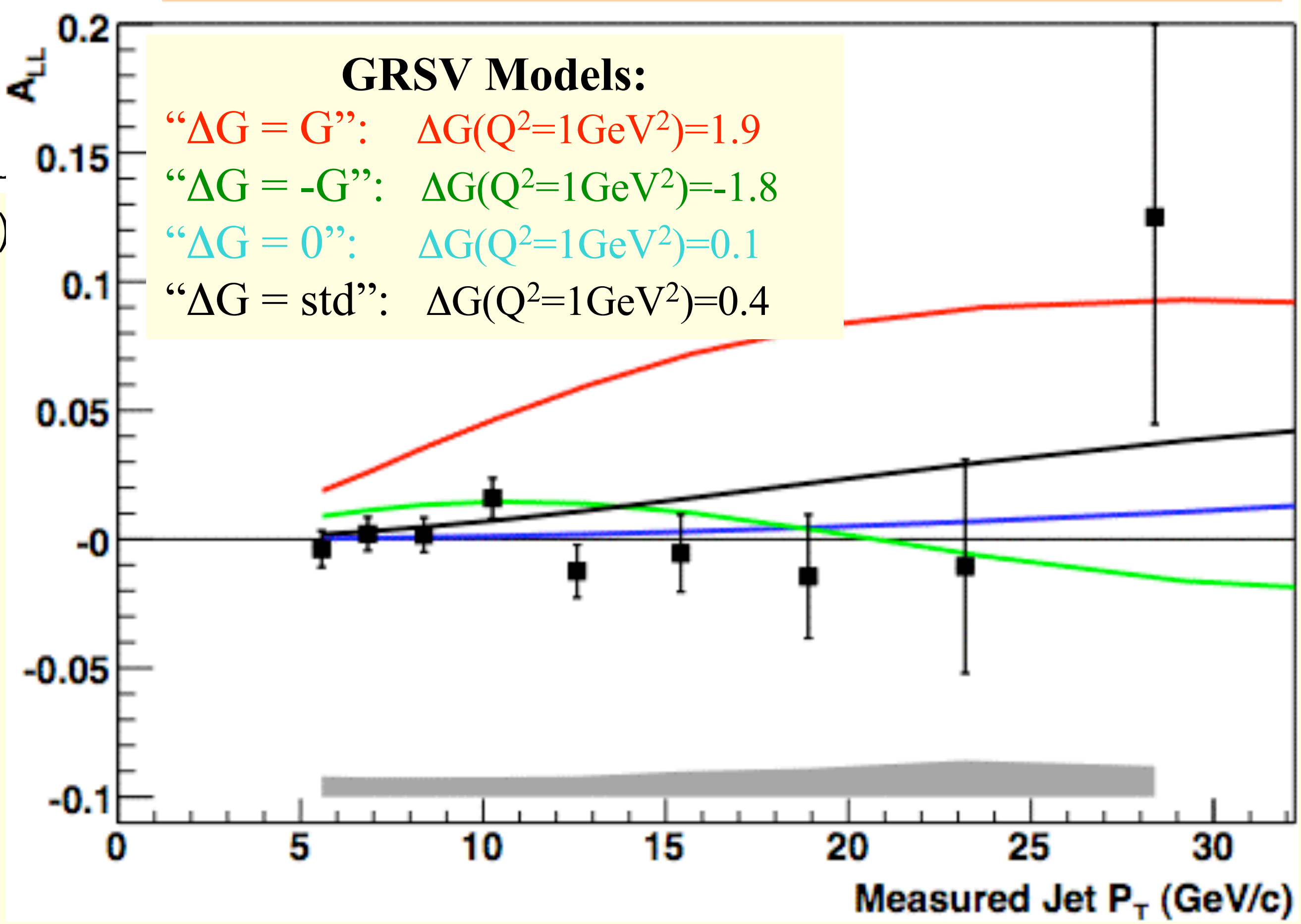
✓ Data for all bunch spin configurations are collected at the same time

⇒ Possibility for false asymmetries are greatly reduced



A_{LL}: jets

STAR Preliminary Run5 (√s=200 GeV)



Large gluon polarization scenario is not consistent with data

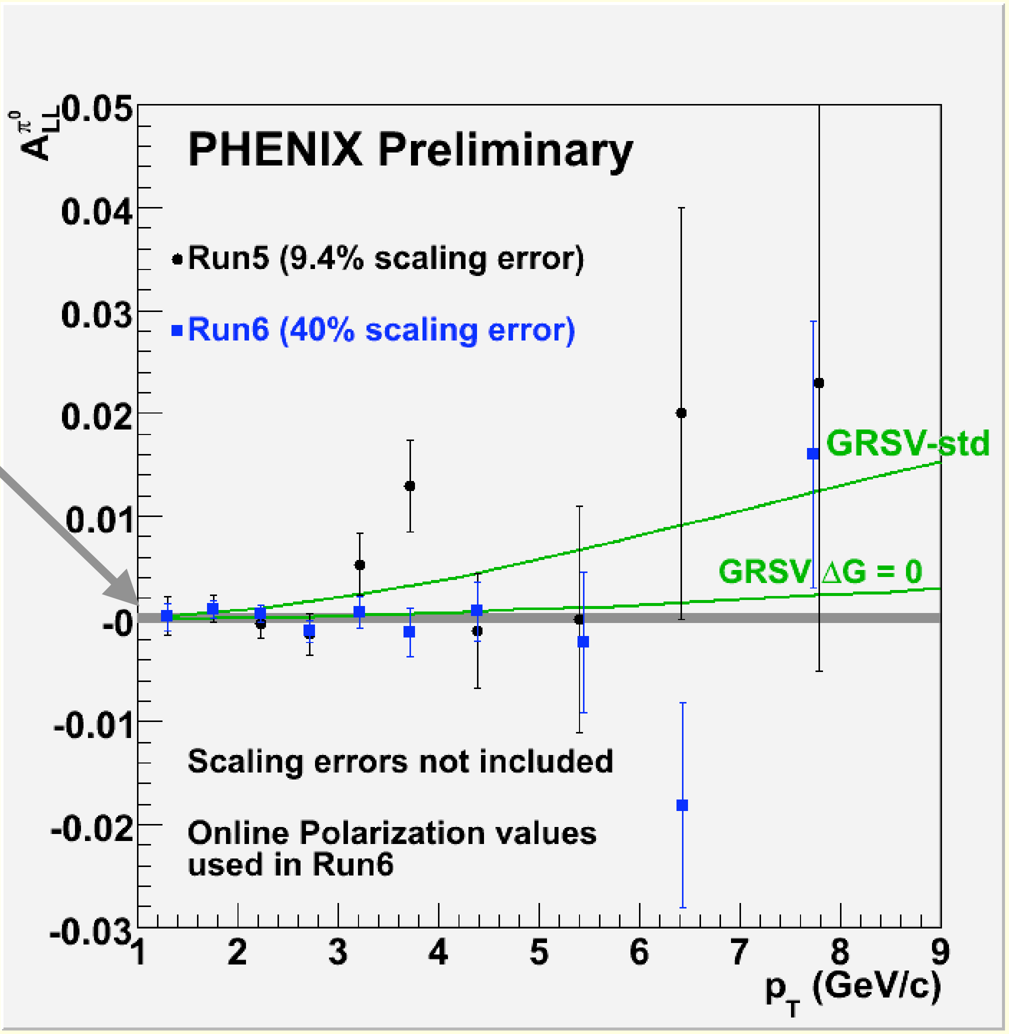
Run3&4: PRL 97, 252001

Run6 π^0 A_{LL}

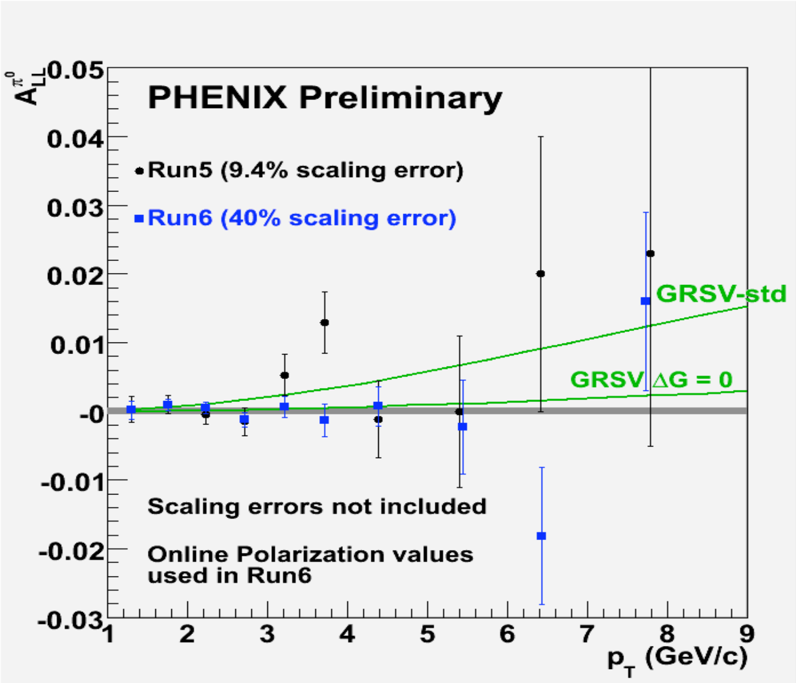
- Run6 scaling error based on online polarization values. Final scaling error expected to be ~10%
- Grey band is systematic uncertainty due to Relative Luminosity, and is p_T independent.
- Run6 Data favor "GRSV ΔG=0" over GRSV-std

Theory	χ^2/NDF	CL(%)
GRSV-std	23.8/8*	0.25
GRSV ΔG=0	7.9/8*	44

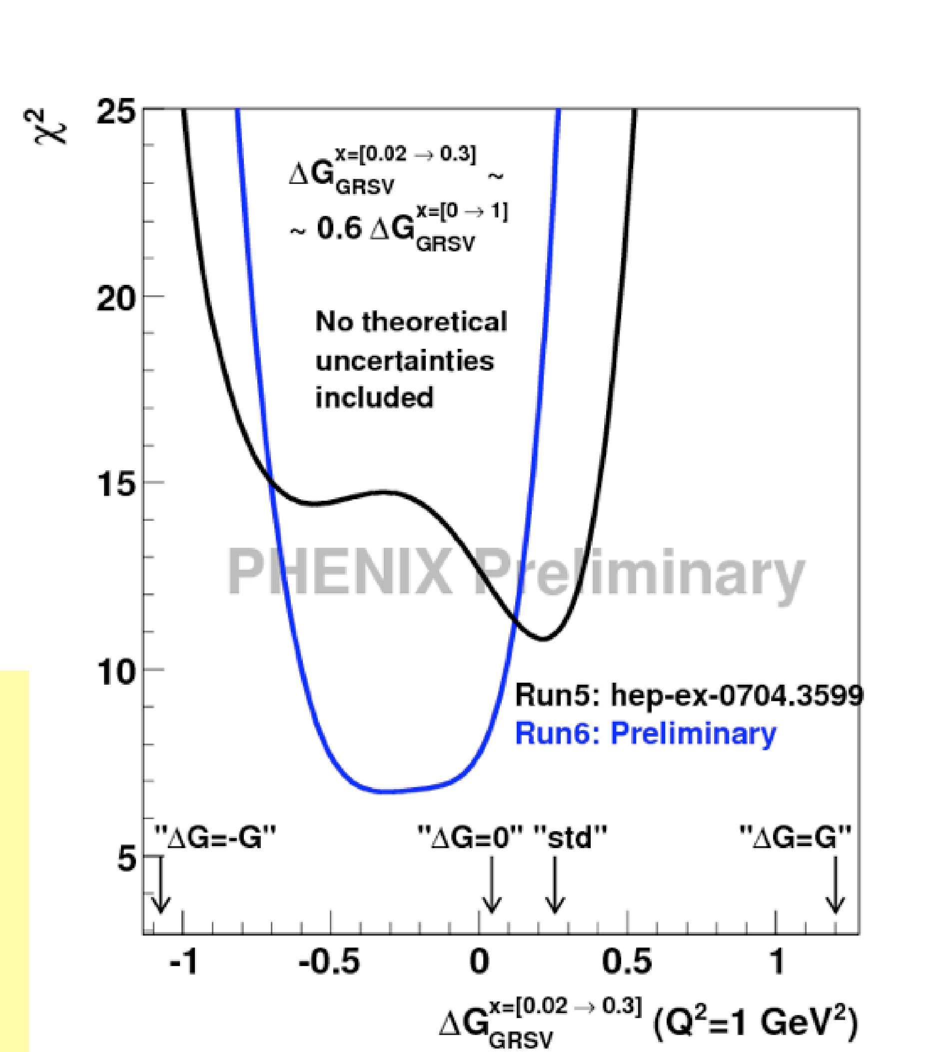
*Theoretical uncertainties not included



From A_{LL} to ΔG (with GRSV)



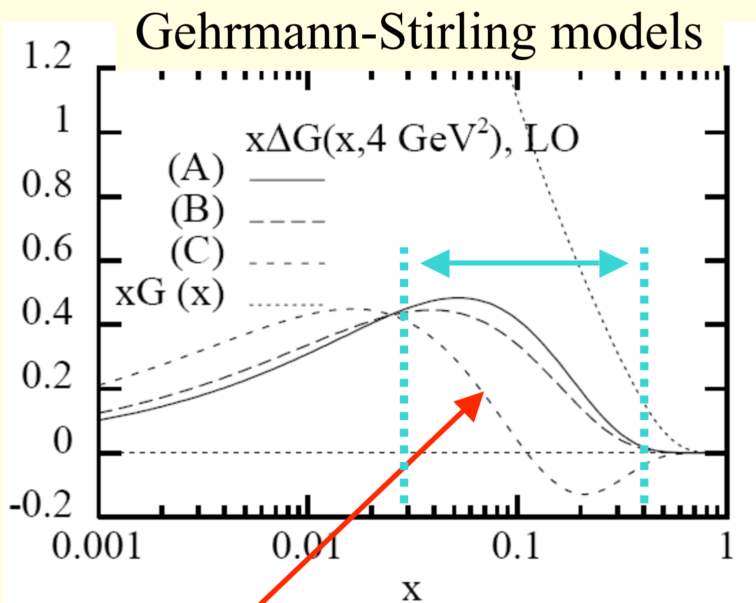
⇒

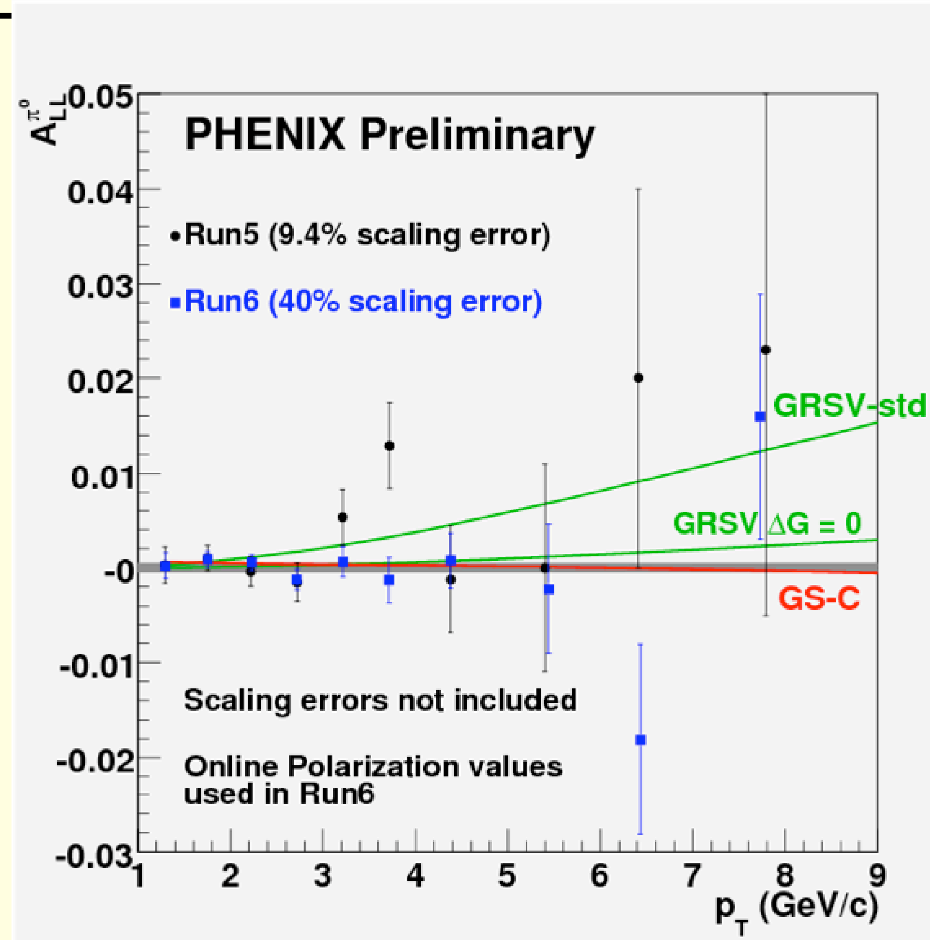


"std" scenario, $\Delta G(Q^2=1GeV^2)=0.4$, is excluded by data on >3 sigma level: $\chi^2(\text{std})-\chi^2_{min}>9$

- ✓ Only exp. stat. uncertainties are included (the effect of syst. uncertainties is expected to be small in the final results)
- ✓ Theoretical uncertainties are not included

Extending x range is crucial!





GSC: $\Delta G(x_{gluon} = 0 \rightarrow 1) = 1$

$\Delta G(x_{gluon} = 0.02 \rightarrow 0.3) \sim 0$

GRSV-0: $\Delta G(x_{gluon} = 0 \rightarrow 1) = 0$

$\Delta G(x_{gluon} = 0.02 \rightarrow 0.3) \sim 0$

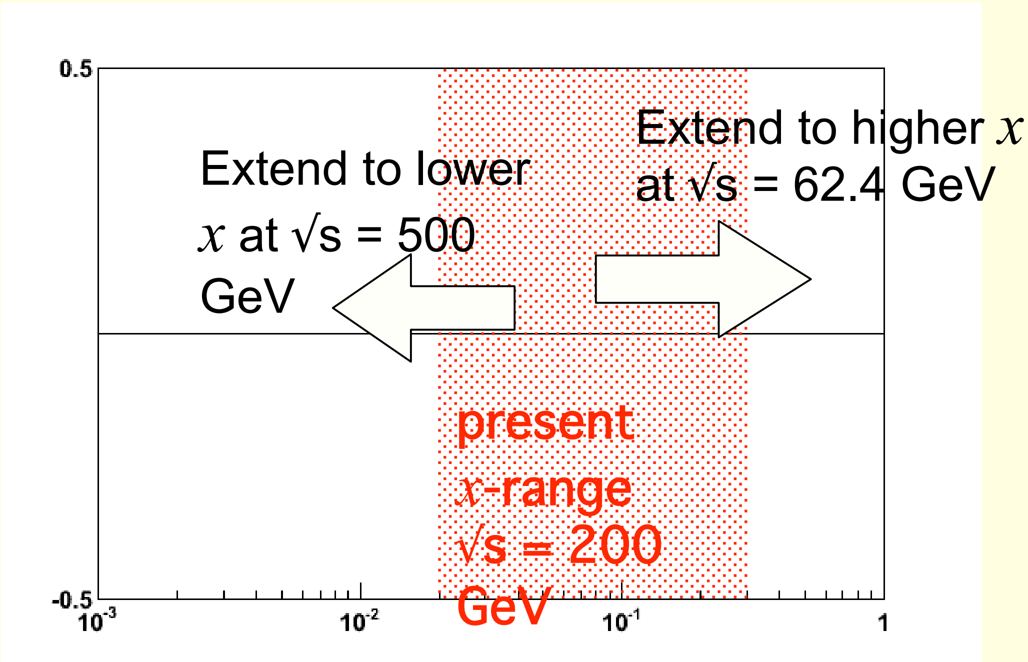
GRSV-std: $\Delta G(x_{gluon} = 0 \rightarrow 1) = 0.4$

$\Delta G(x_{gluon} = 0.02 \rightarrow 0.3) \sim 0.25$

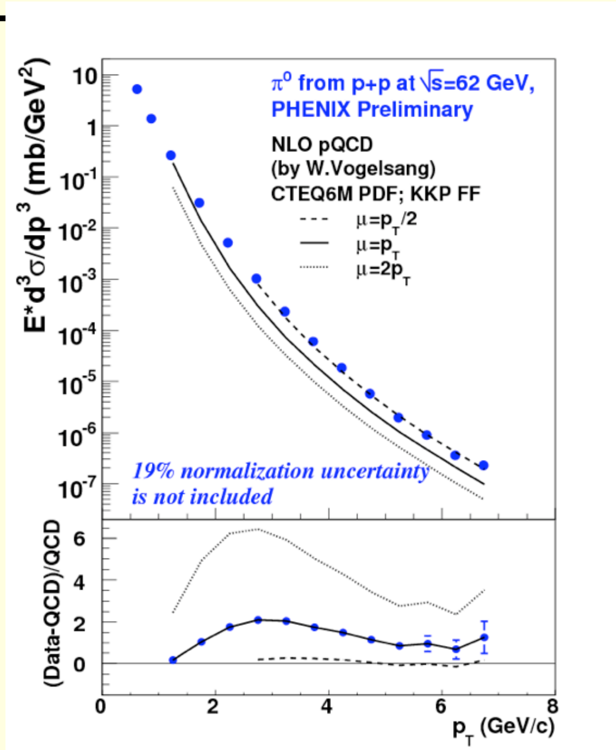
Current data is sensitive to ΔG for $x_{gluon} = 0.02 \rightarrow 0.3$

Need to Extend x Range and the shape!

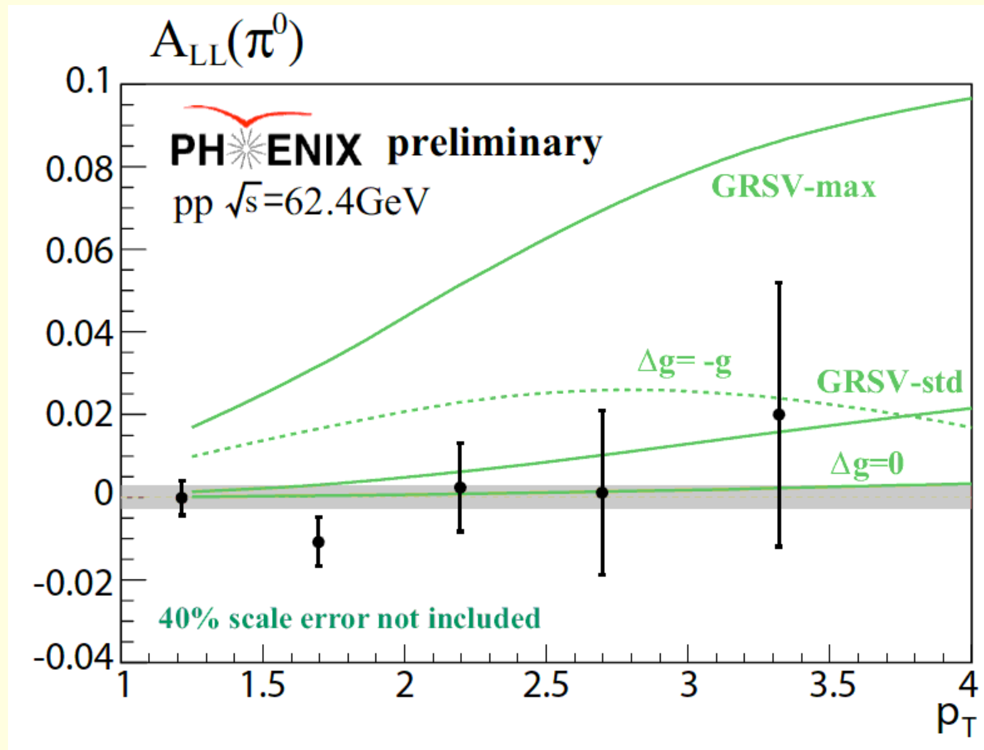
- By measuring at different center of mass energies, we can reach different *x* ranges.
- We can extend our *x* coverage towards lower *x* at √s = 500 GeV. Expected to start in 2009.
- We can extend our *x* coverage towards higher *x* at √s = 62.4 GeV. → Run6



Different √s



√s=62 GeV π0 cross section described by NLO pQCD within theoretical uncertainties



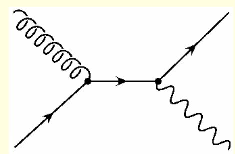
Sensitivity of Run6 √s=62 GeV data collected in one week is comparable to Run5 √s=200 GeV data collected in two months, for the same $x_T=2p_T/\sqrt{s}$

√s=500 GeV will give access to lower x; starts in 2009

ΔG: what's next

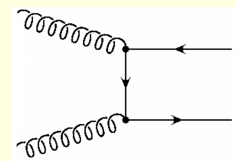
- ❑ Improve exp. (stat.) uncertainties and move to higher pT

- ❑ Different channels
  - ✓ Different systematics
  - ✓ Different x
  - ✓ $gq \to g\gamma$ sensitive to ΔG sign



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

$gg \to Q\overline{Q}$



$$\propto \frac{\Delta G}{G}\frac{\Delta G}{G}$$

- ❑ $pp \to \gamma + jet$ and $pp \to jet + jet$
  - ✓ Map ΔG vs x

- ❑ Different √s
  - ✓ Different x

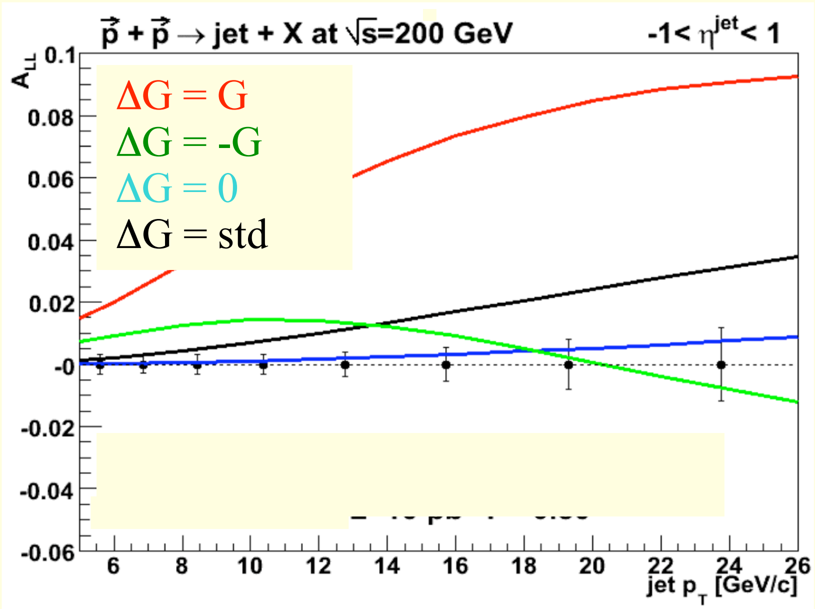
- θ Global analysis
  - ✓ Within pQCD framework

These might be of interest to many in this audience for potential theses and post doctoral work projects!

Improve exp. uncertainties

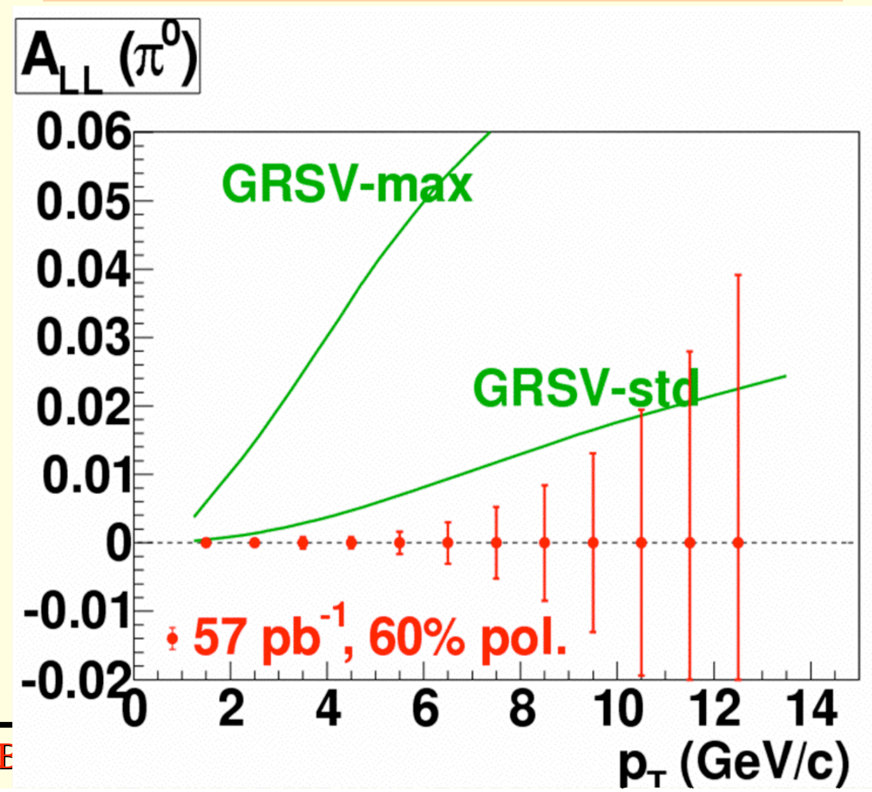
Need more FOM=$P^4 \cdot L$ (stat. uncertainty ~ √FOM)

STAR Jets: expectations from Run6 (√s=200 GeV)

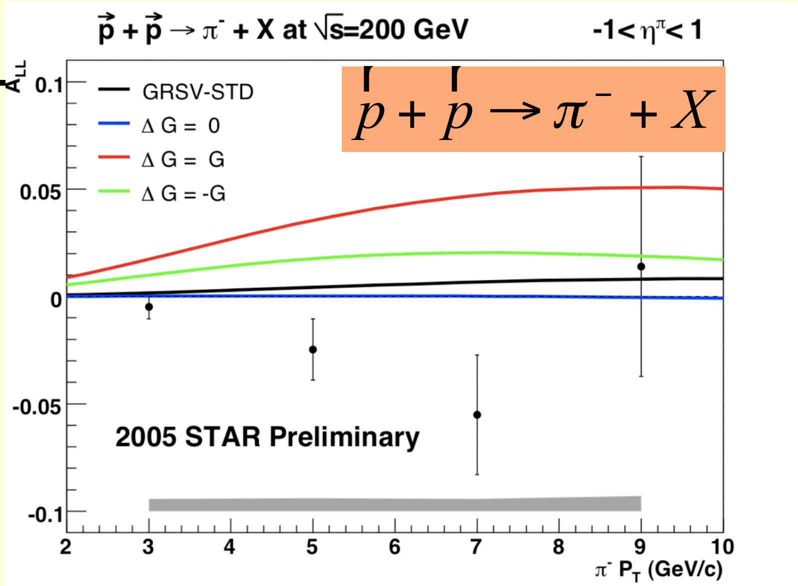


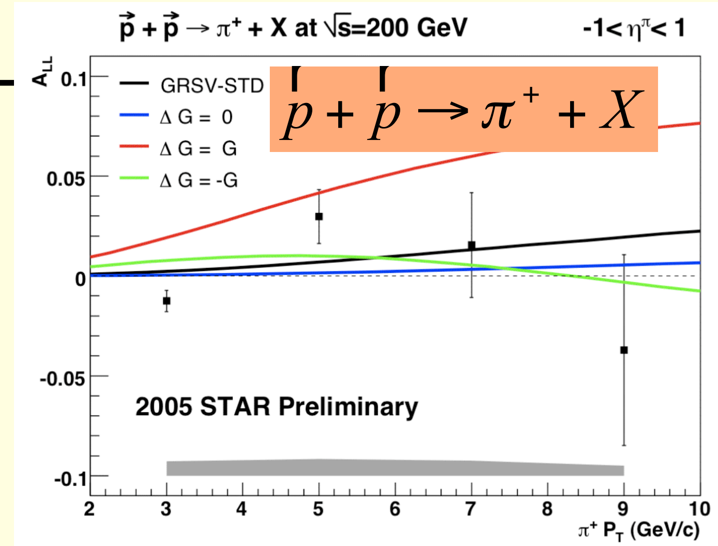
Data already available!
Results expected soon.

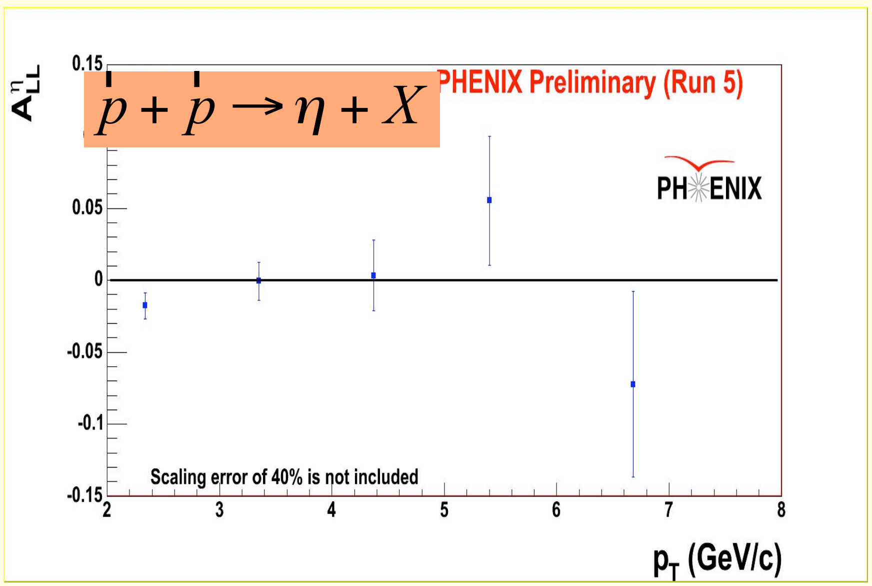
PHENIX π0: expectations from Run-8

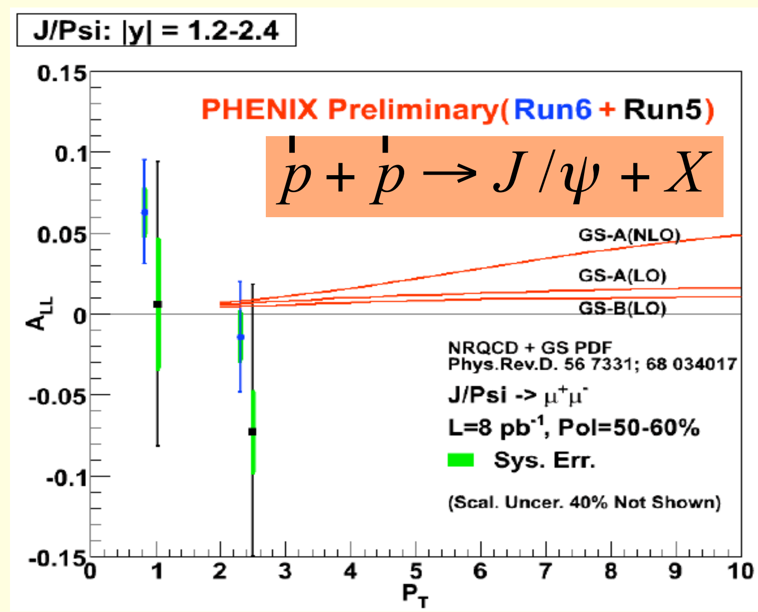


Different channels



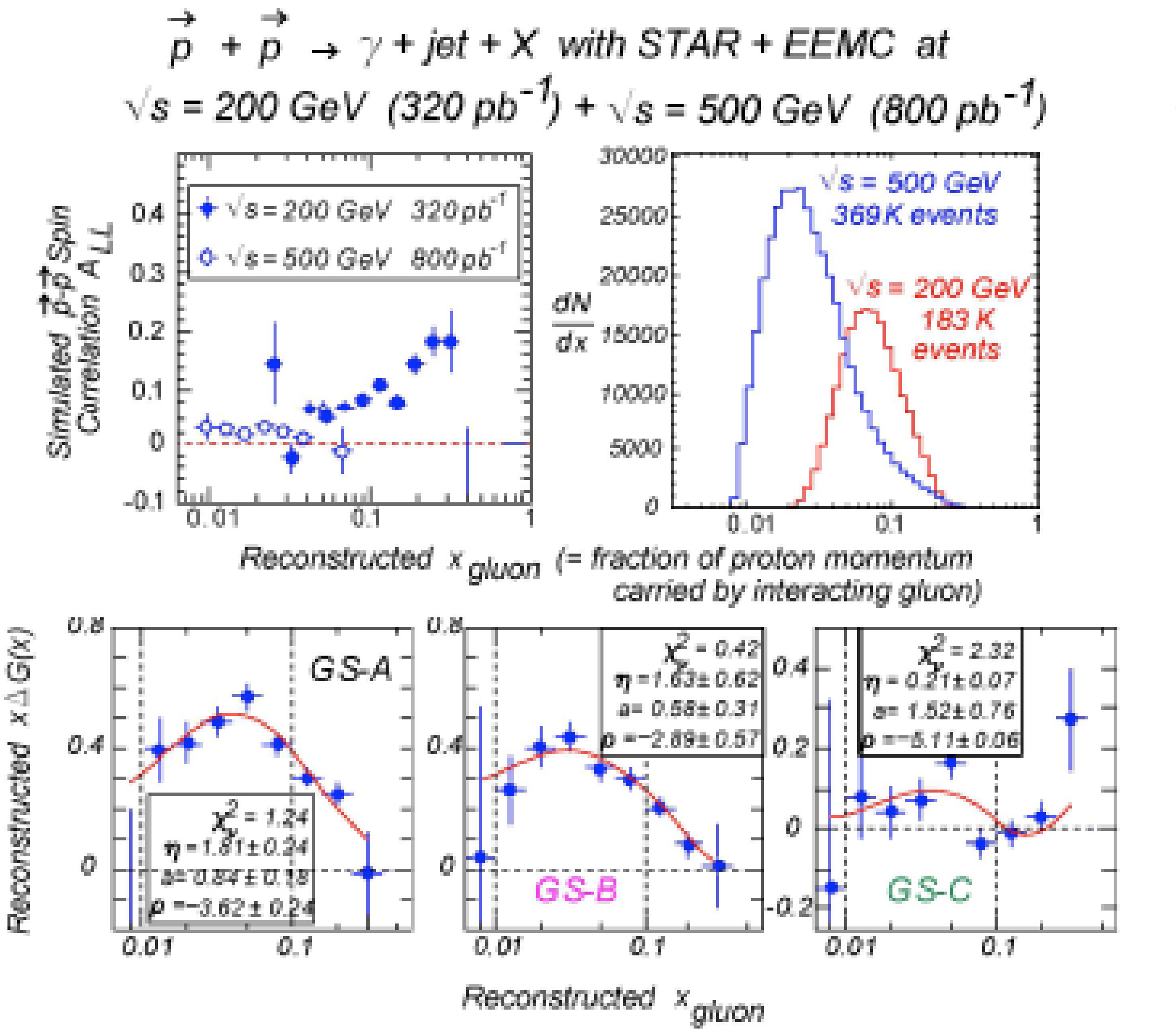


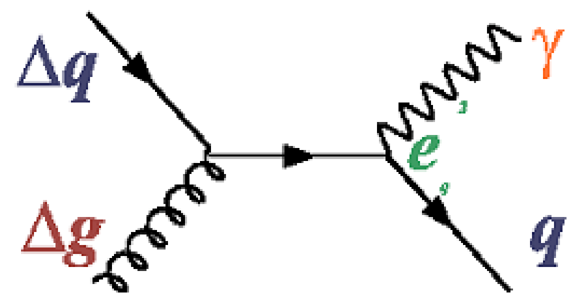




Need more FOM=P⁴·L (stat. uncertainty ~ √FOM)

$pp \rightarrow \gamma$ + jet, needed to constrain the shape of ΔG distribution…





Parton kinematics is well constrained, event-by-event

Lower x data provided by $\sqrt{s}$=500 GeV data is essential for reducing extrapolation (to lower x) errors

Summary of ΔG Measurement so far

- First measurements in a limited x range indicate, NO contribution to the ΔG integral from this measured region.
- Low x region needs to be explored
  - Will need operation at higher energy: I.e. Center of Mass energy of 500 GeV instead of 200 GeV of present operation: expected in 2009
- Precision measurement will also require measurement of the shape of the distribution in x
  - Semi-inclusive measurements will explore this
  - These might be rate-limited…

Study of transverse spin phenomena in the RHIC spin program

Transverse spin effects in proton

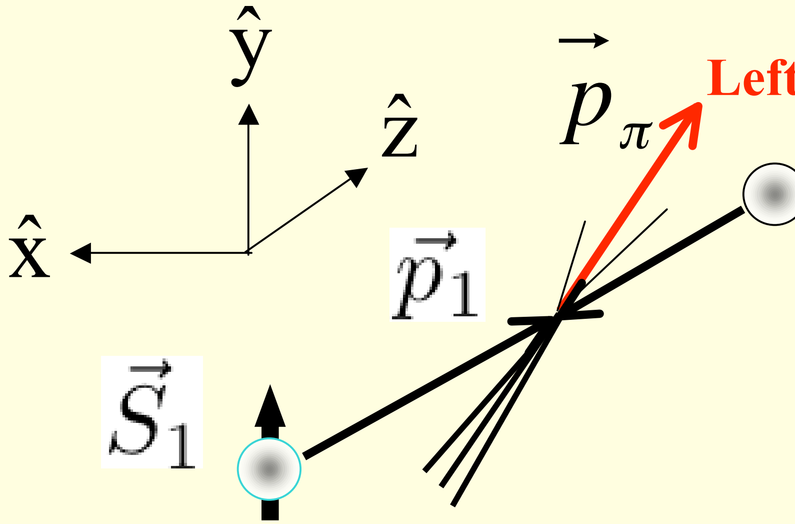
- An emergent science, driven mainly by experiments

- The story is both, intriguing and mysterious… with lots of complicated convolutions…
  - Compare & Contrast with Longitudinal Physics:
  - Quark spin (1989) and Gluon Spin (now) seem to be small when we expected large contributions…
    - Gluon spin is still unknown, but small in the region already measured…
  - Transverse spin not expected, and observed every where we look!

- A high level preview follows.

Early expectations… Sing Spin Asymmetries

For example: $p^{\uparrow} + p \rightarrow \pi + X$ **Azimuthal asymmetry in singly polarized *pp* collisions**



$$SSA \propto \vec{S}_1 \cdot (\vec{p}_1 \times \vec{p}_\pi)$$

Prediction: $SSA \sim \frac{m_q \alpha_s}{p_T} \sim 0.001$

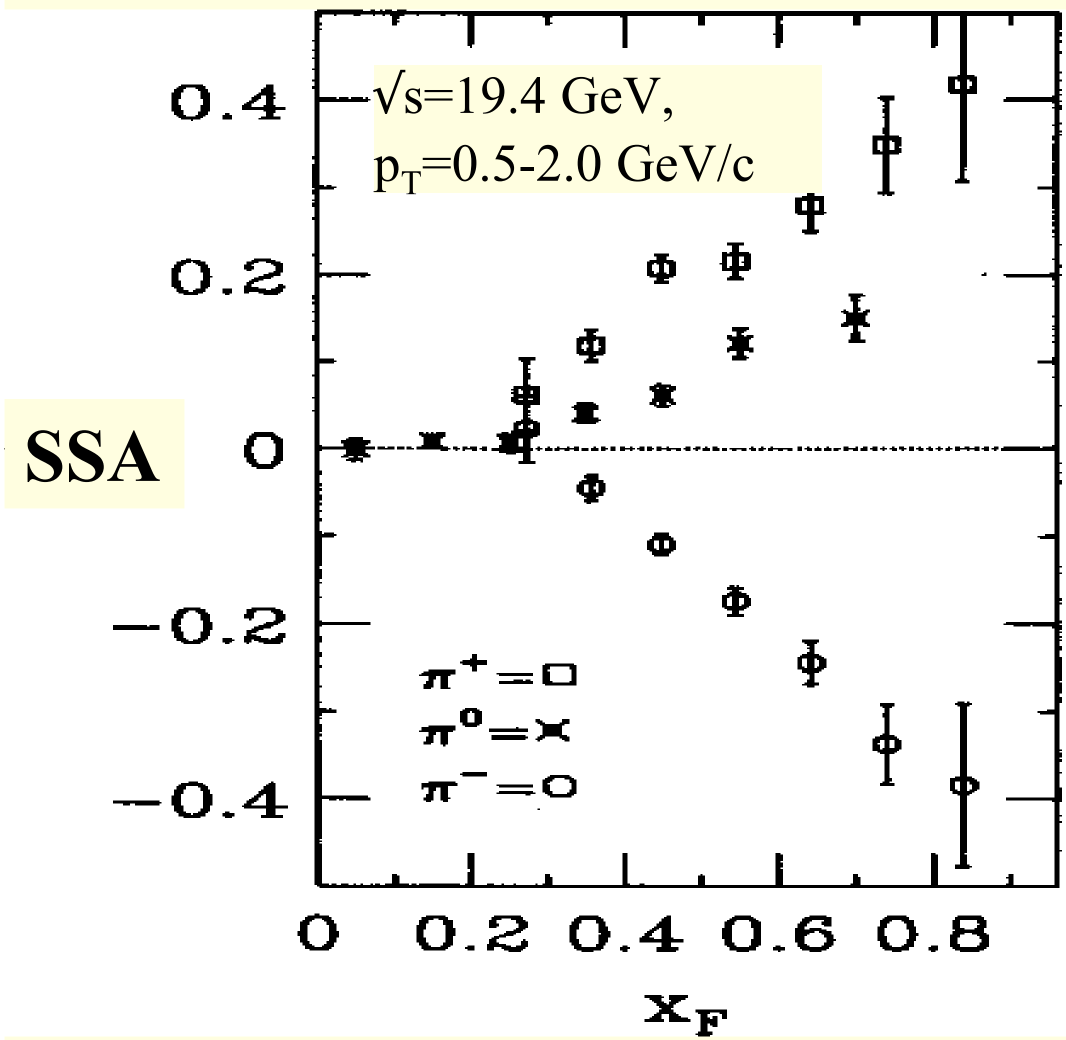
Kane, Pumplin and Repko
PRL 41 1689 (1978)

SSAs in hard scattering are expected to be very **small**: **(leading twist effects)**.

Measurements?

Huge SSAs have been measured at E704-FNAL!

$$p^{\uparrow} + p \rightarrow \pi^{0,\pm} + X$$



π^0 – E704, PLB261 (1991) 201.
$\pi^{+/-}$ - E704, PLB264 (1991) 462.

- Increase linearly with Feynman x (x_F).
- ~400 times bigger than expectation!
- What is the p_T dependence?

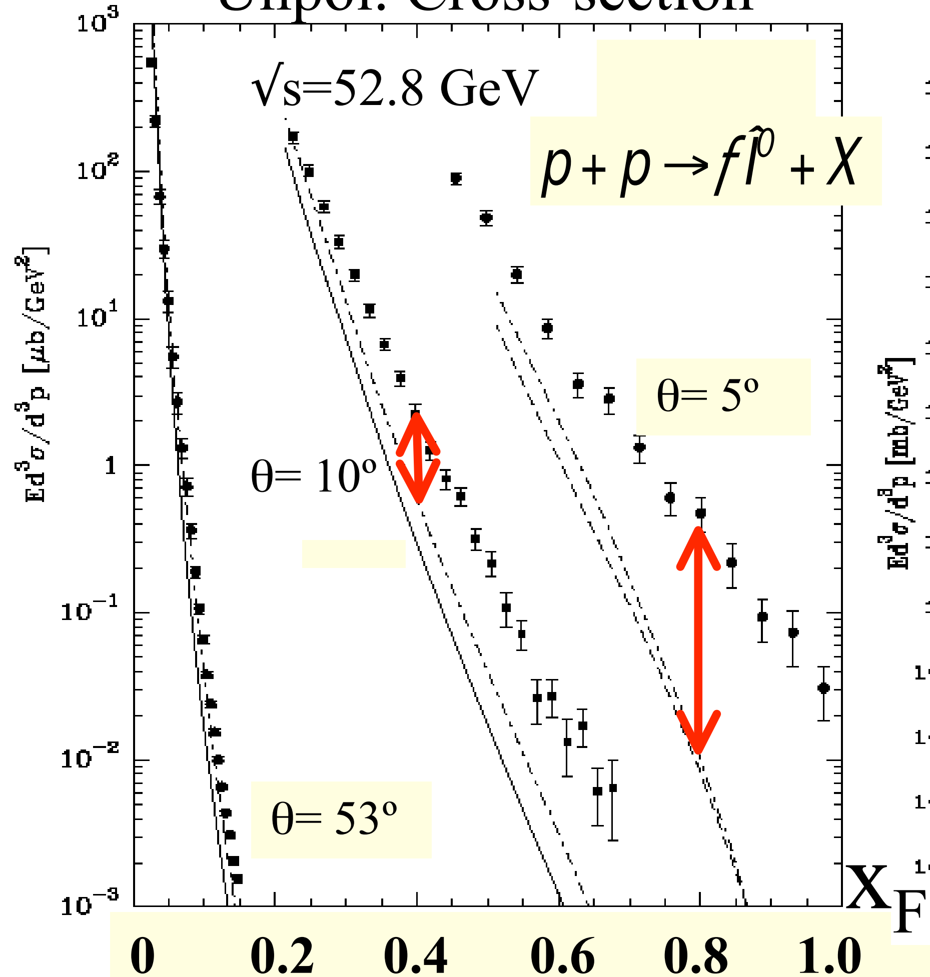
$$x_F = \frac{p_{z,\pi}}{p_{z,1}} \approx \frac{2E_\pi}{\sqrt{s}}$$

Is pQCD applicable for √s ≤ 50 GeV ?

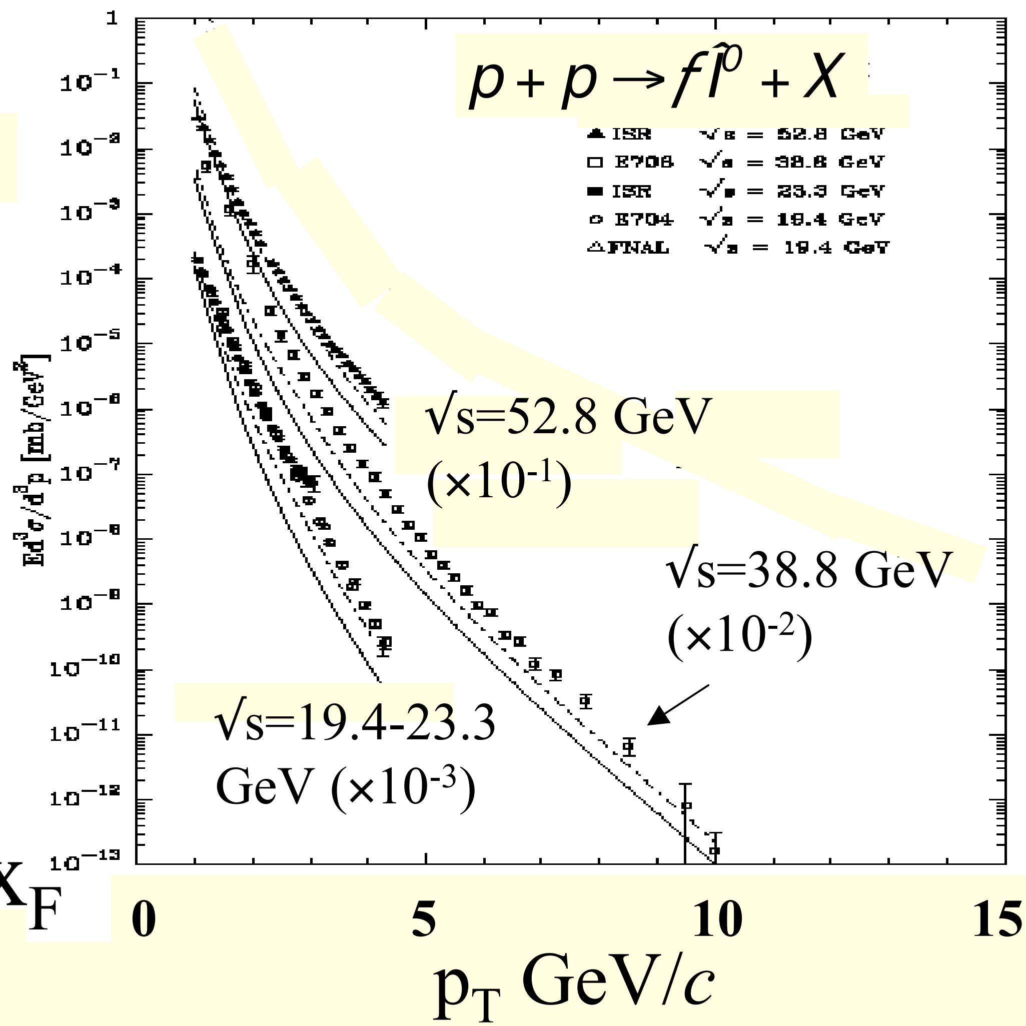
Eur.Phys.J.C36:371-374,2004. ,
Data references therein.

2 NLO calculations with different scales p_T and $p_T/2$

Unpol. Cross-section



Unpol. Cross-sections at θ=90°



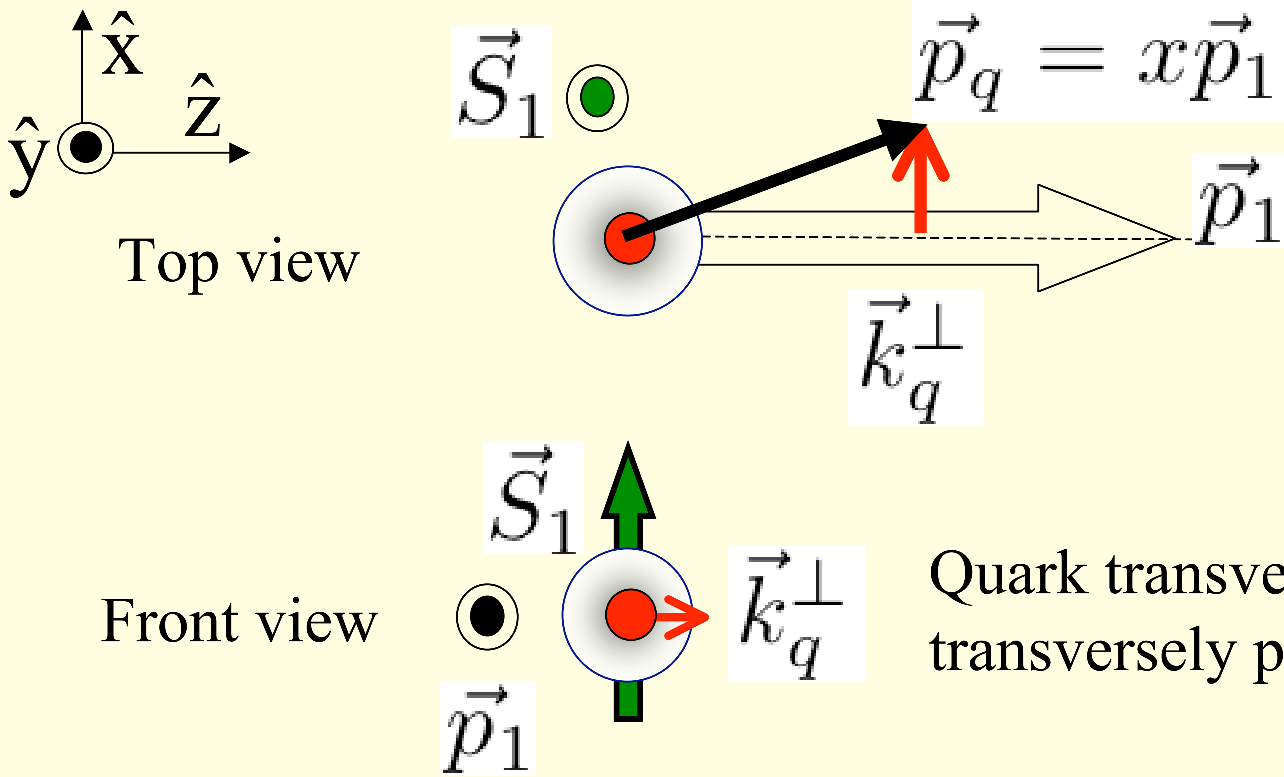
Require more than NLO pQCD…blame on soft physics

Sivers effect: due to transverse motion of quarks in the nucleon: initial state effect

Phys Rev D41 (1990) 83; Phys Rev D43 (1991) 261

$$SSA_{Sivers} \propto \vec{S}_1 \cdot (\vec{p}_1 \times \vec{k}_q)$$

$$\vec{p}_q = x\vec{p}_1 + \vec{k}_q^{\perp}$$



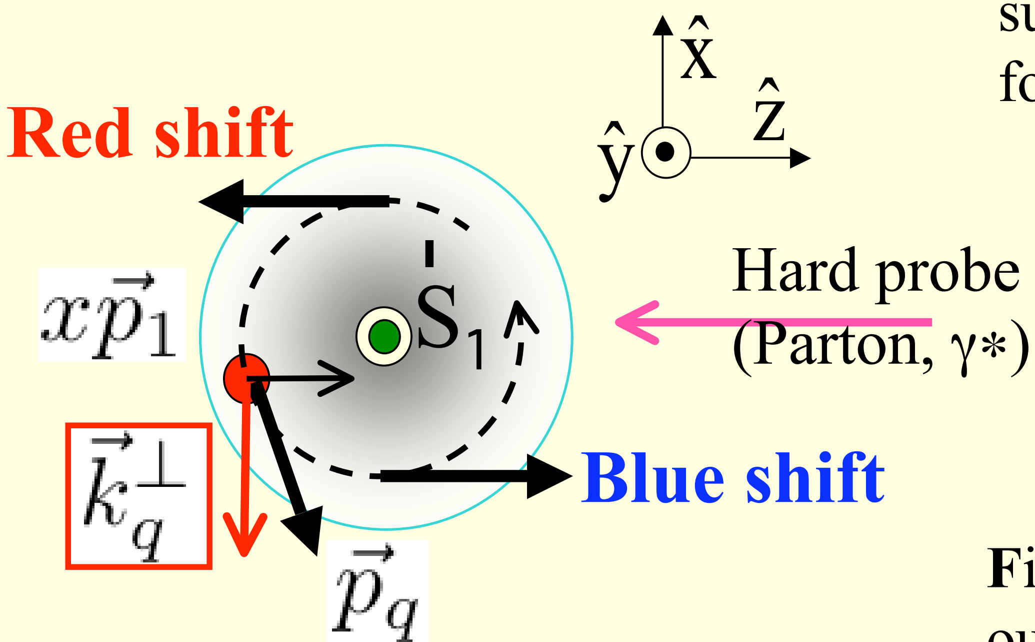
x is longitudinal momentum fraction.

Quark transverse momentum in transversely polarized proton.

INITIAL STATE EFFECT: Orbital angular momentum?

What does "Sivers effect" probe?

Top view, Breit frame



Quarks orbital motion adds/ subtracts longitudinal momentum for negative/positive $\hat{x}$.

PRD66 (2002) 114005

Parton **D**istribution **F**unctions rapidly fall in longitudinal momentum fraction x.

Final **S**tate **I**nteraction between outgoing quark and target spectator.

Sivers function

$$f_{1T}^\perp(x, \vec{k}_q^\perp)$$

hep-ph/ 0703176

⟹

Quark Orbital angular momentum

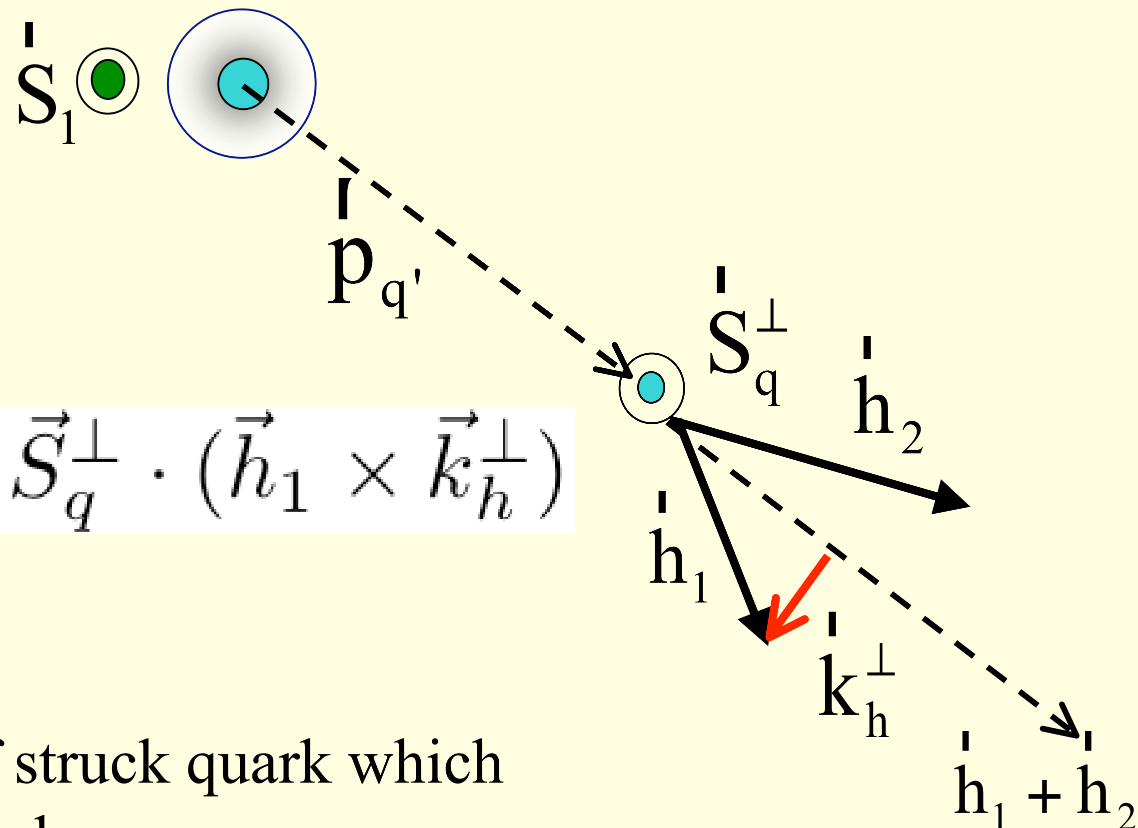
Generalized **P**arton **D**istribution Functions

PRD59 (1999) 014013

Collins (Heppelmann) effect: Final state of fragmentation hadrons

Nucl Phys B396 (1993) 161,
Nucl Phys B420 (1994) 565

Example: $p^{\uparrow} + p \rightarrow h_1 + h_2 + X$

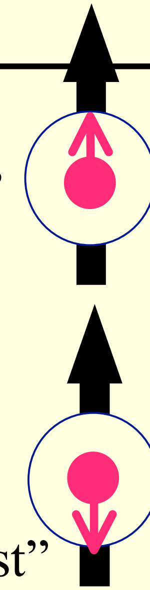


$$SSA_{Collins} \propto \vec{S}_q^{\perp} \cdot (\vec{h}_1 \times \vec{k}_h^{\perp})$$

Polarization of struck quark which fragments to hadrons.

Collins function: analyzer of **"Transversity"**

$$\delta q(x,\mu) = q_{\uparrow}^{\uparrow}(x,\mu) - q_{\uparrow}^{\downarrow}(x,\mu)$$



"with"

"against"

$q_{\uparrow}^{(\uparrow\downarrow)}(x,\mu)$: Probability to observe **parton** whose pol. vector is "with" or "against" the proton pol. vector with the renormalization scale μ.

δq(x,μ) has not been measured experimentally.

Lattice QCD calculates the first moments of δq(x,μ) for u,d, s quarks and the sum at μ^2=2 GeV^2.

$$\delta q(\mu) = \int_0^1 dx\left[\delta q(x,\mu) - \delta\bar{q}(x,\mu)\right]$$

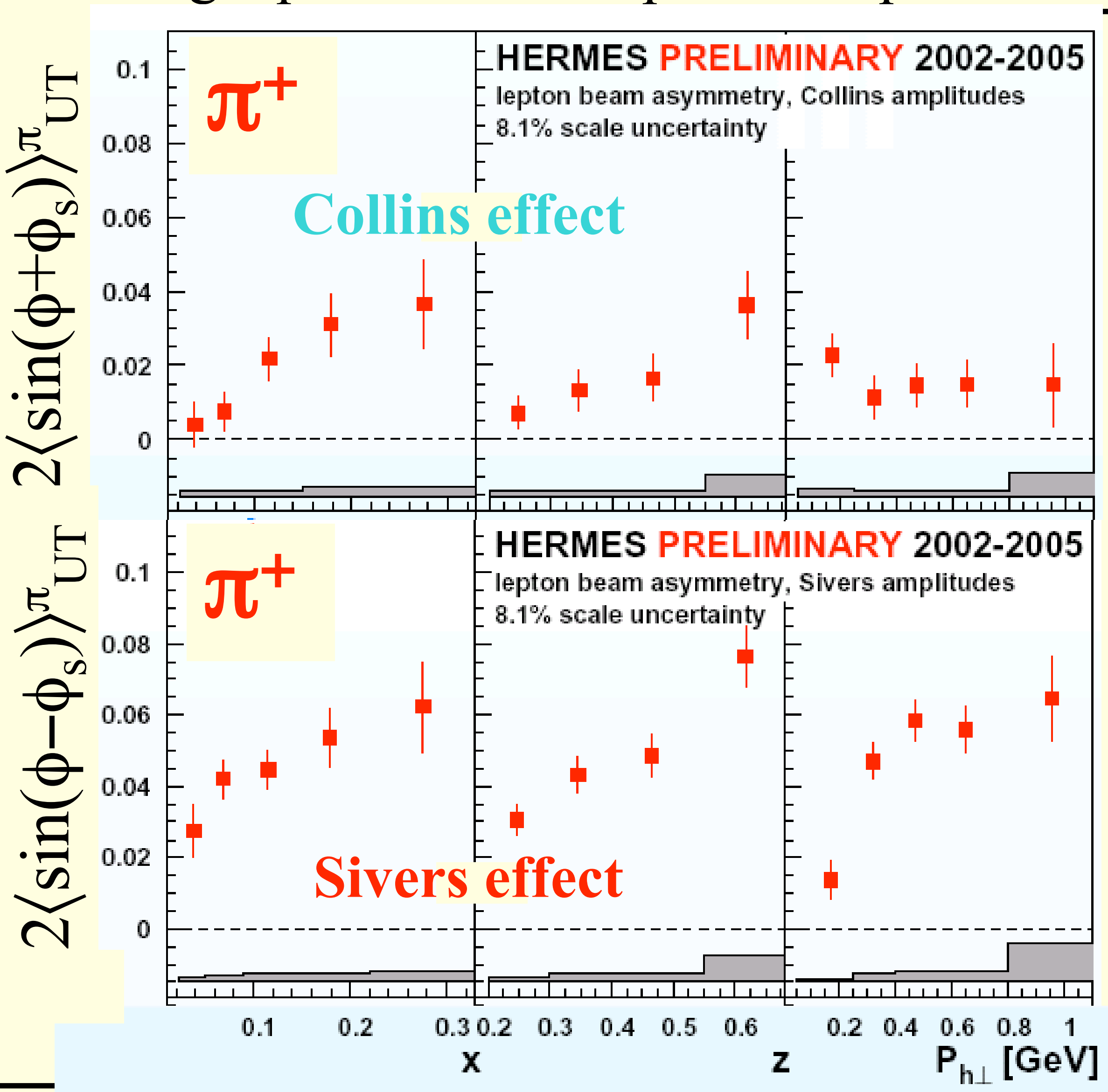
$$\delta\Sigma(\mu) = \delta u(\mu) + \delta d(\mu) + \delta s(\mu)$$

- Each of these possibilities has
  - Different pT dependences
  - Different signs for different particle species
  - Different Center of Mass dependences

- A systematic study of the transverse spin physics is hence necessary, and just beginning.

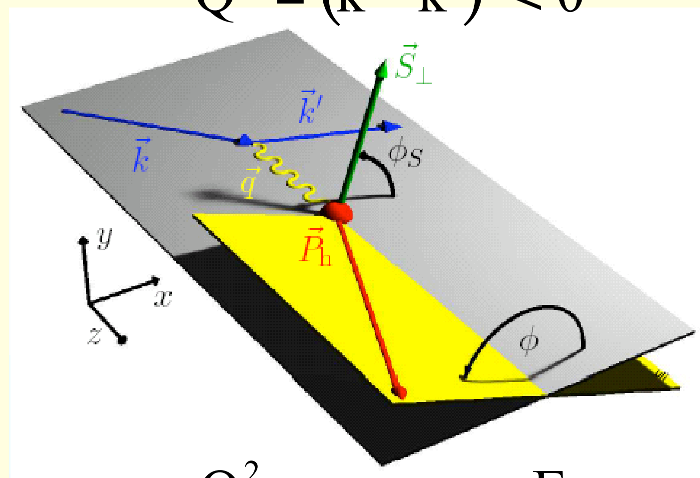
SSAs have been measured in Deep Inelastic Scattering.

Using lepton beam and polarized proton target.



$$k = \left(E, \vec{k}\right) \quad k' = \left(E', \vec{k}'\right)$$

$$-Q^2 = \left(k - k'\right)^2 < 0$$



$$x = \frac{Q^2}{2M\left(E - E'\right)}, \quad z = \frac{E_h}{E - E'}$$

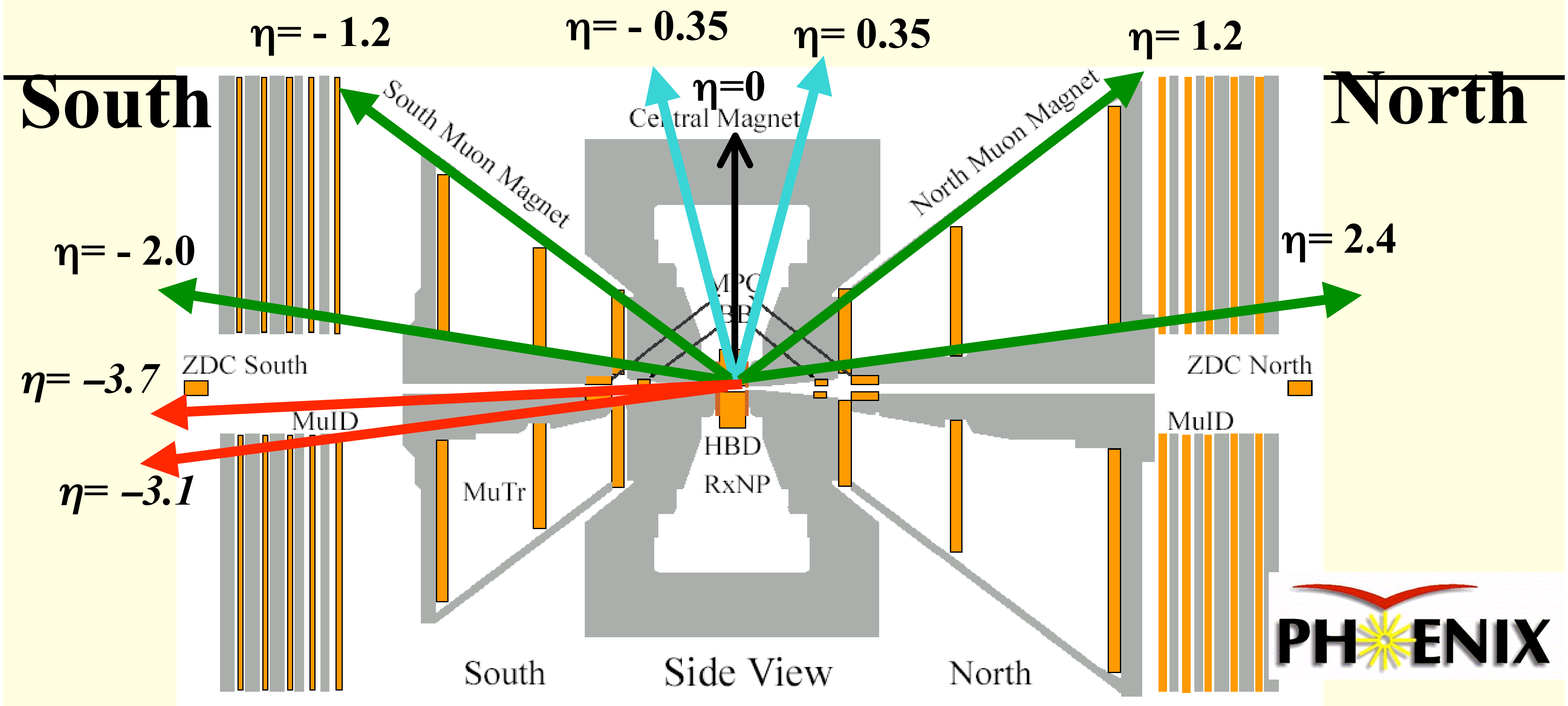
$P_{h\perp}$: Transverse momentum of π^+

Ongoing experiments at **DESY**, **CERN etc.**
New program at **JLAB** 12GeV upgrade.

What about RHIC?

We know this is definitely perturbative regime…
if the transverse spin effects are purely non-perturbative, they should **NOT** exist!

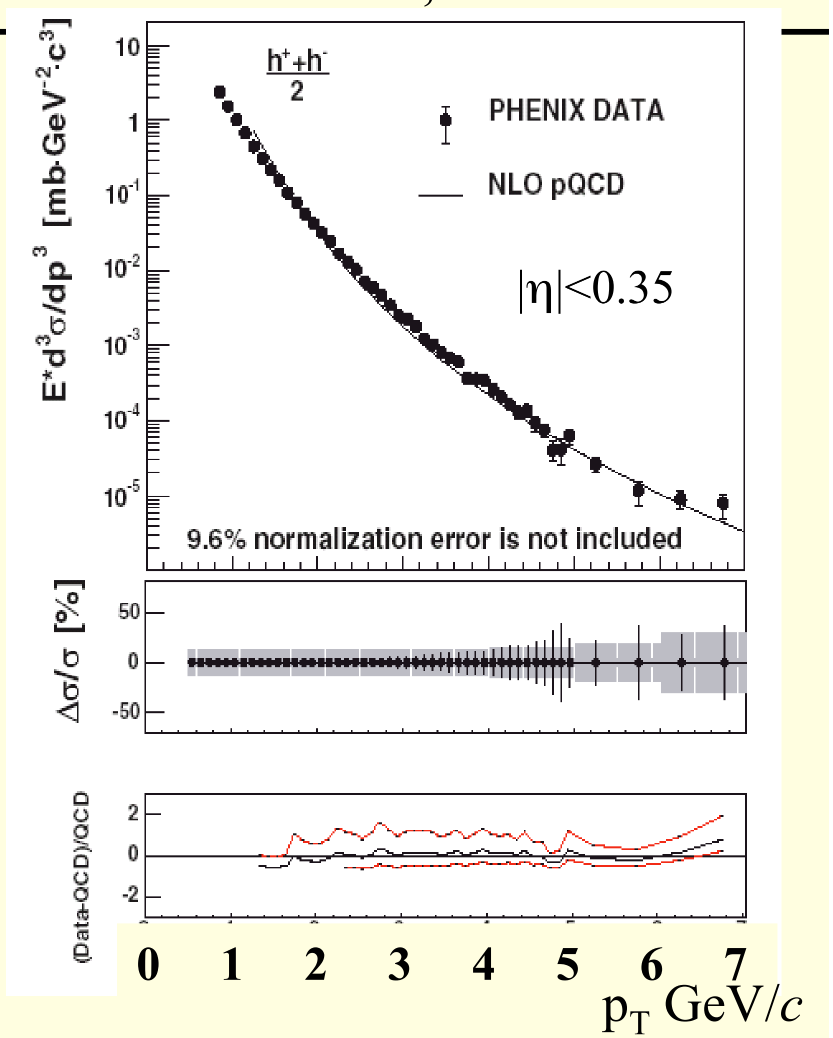
Kinematical coverage at PHENIX (Side View)



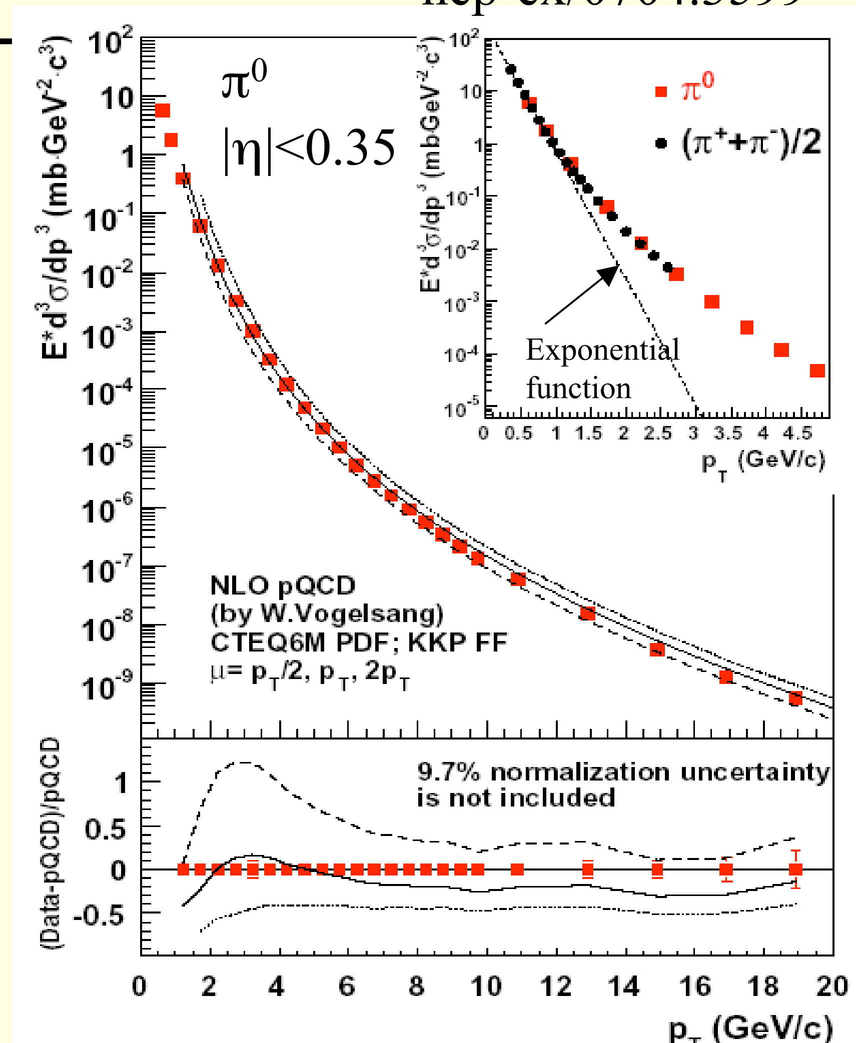
- Central-Arms: $\pi^0/h^\pm$ at $\sqrt{s}$=200GeV, $|\eta|<0.35$
- μ-Arms: J/ψ at $\sqrt{s}$=200GeV, $-2.0<\eta<-1.2$ & $1.2<\eta<2.4$
- *MPC: Inclusive π^0 at $\sqrt{s}$= 62GeV, $-3.7<\eta<-3.1$*

pp collision at √s=200GeV (1)

PRL95:202001,2005.



hep-ex/0704.3599



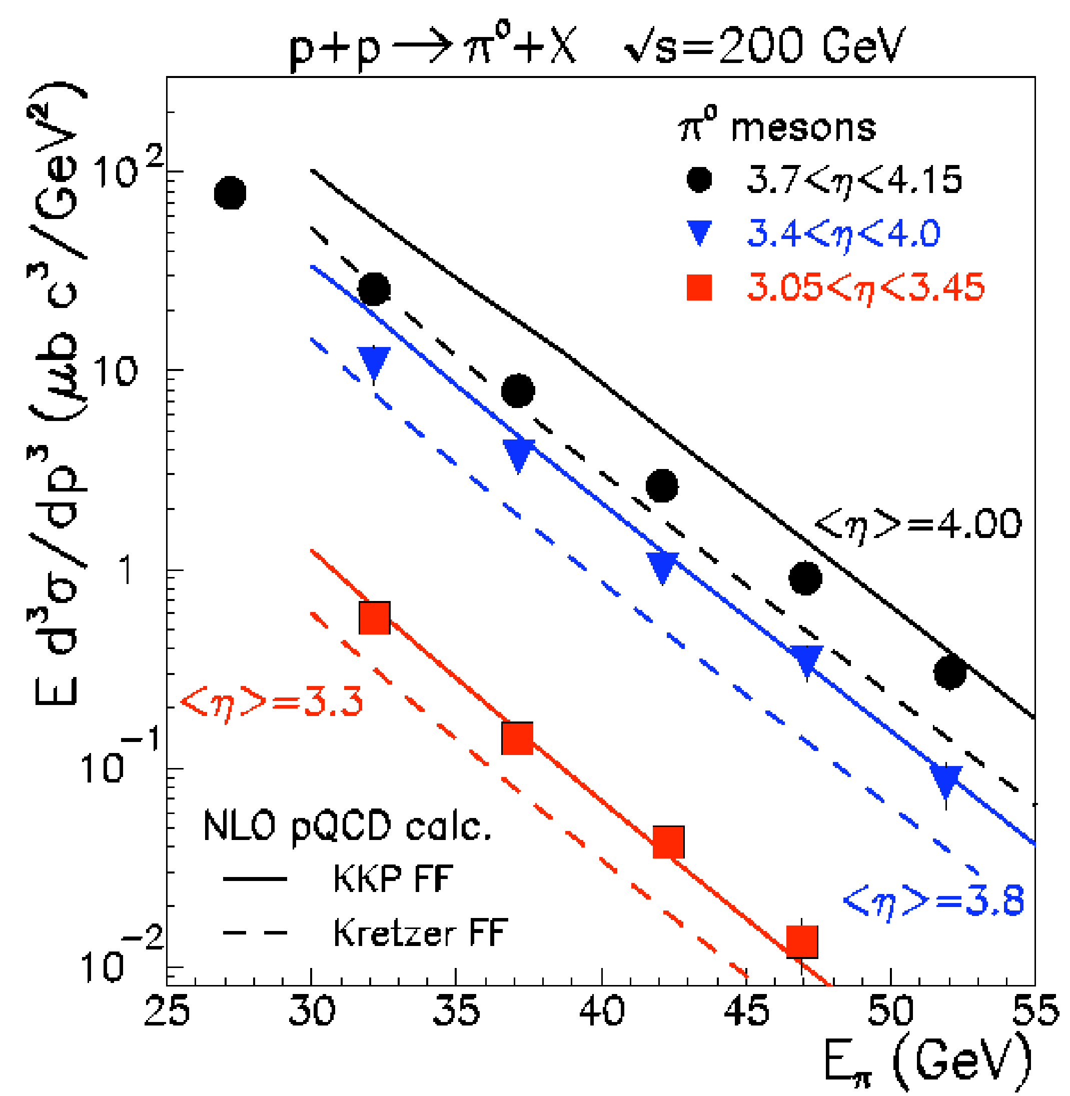
Cross-sections at |η|<0.35 are consistent with NLO pQCD.

W. Vogelsang, M. Stratmann *et al.*

pp collision at √s=200GeV (2)

STAR

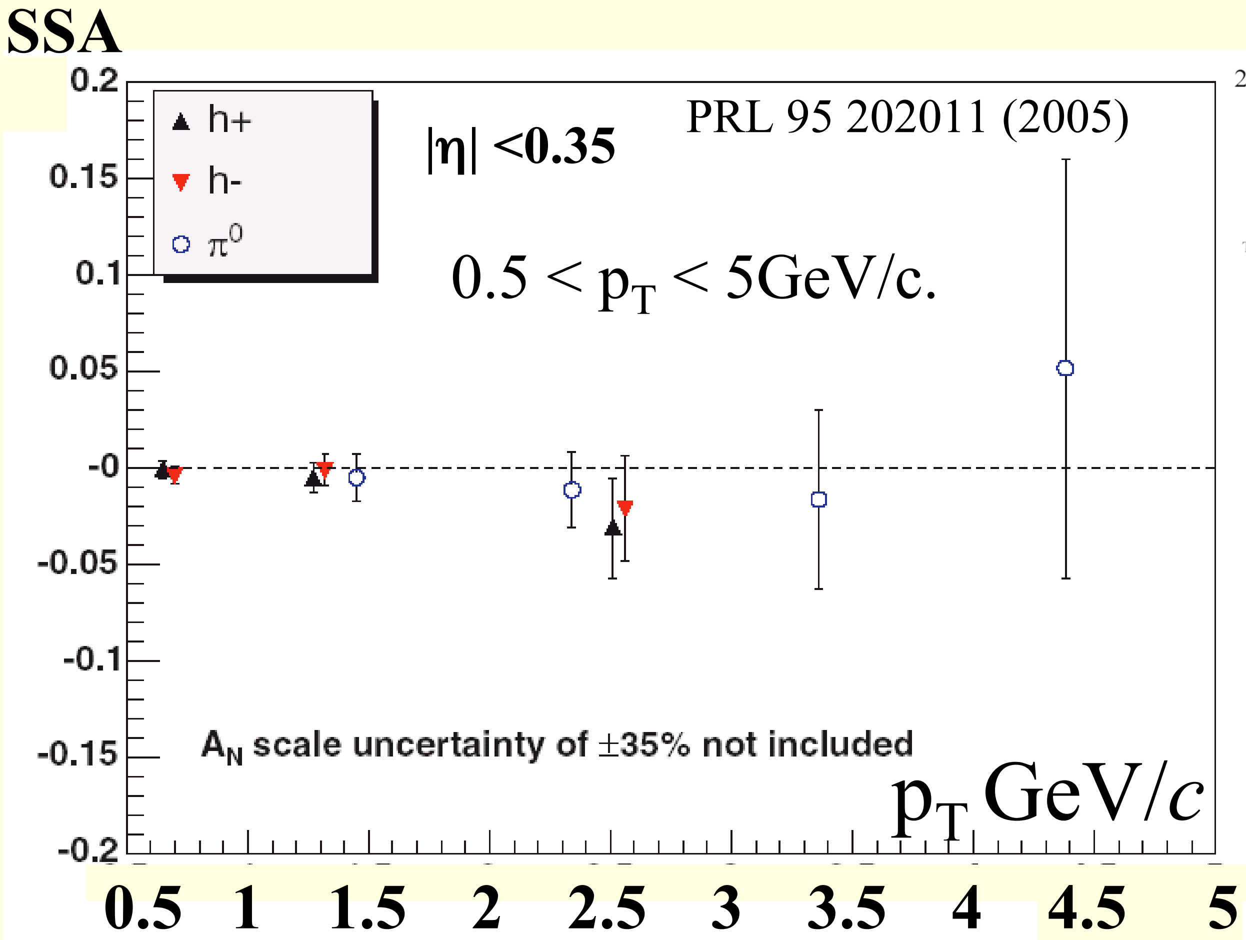
PRL97:152302, 2006.

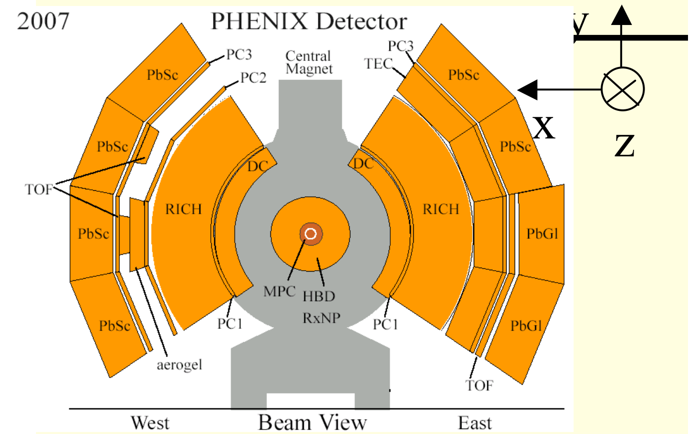


Cross-sections at the forward region, <η>=3.3, 3.8 and 4.0 are mostly consistent with NLO pQCD calculations.

KKP FF : Nucl. Phys. B597, 337 (2001)
Kretzer FF: Phys. Rev. D62, 054001 (2000).

SSA of π^0 and $h^\pm$ from central-arms at $\sqrt{s}$=200GeV





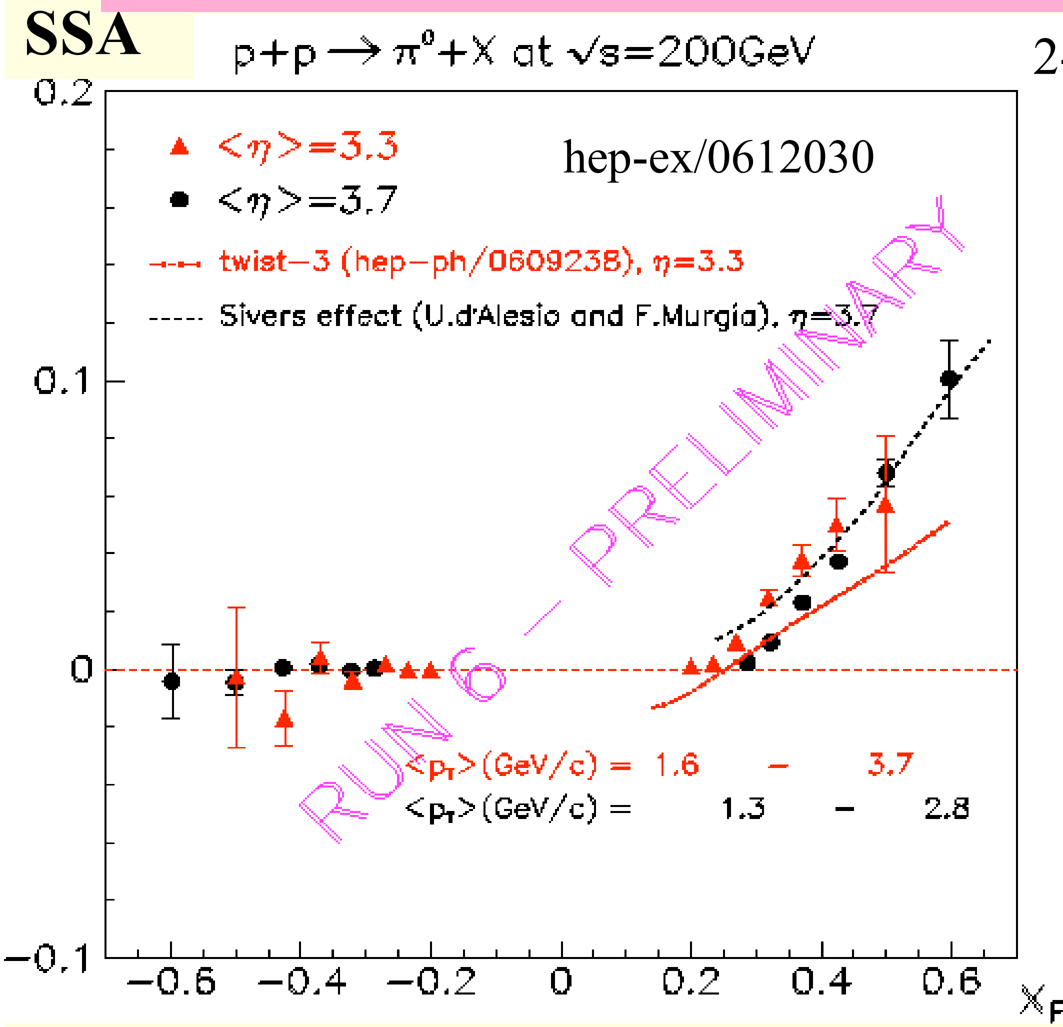
Left-arm Right-arm

SSAs are measured by square-root-formula with two-arms (left-right) detector for either beam polarization.

- ✓ Mid-rapidity $<x_F>\sim 0$ → See "pure" p_T dependence of SSAs.
- ✓ **SSAs for mid-rapidity production of both π^0 and $h^\pm$ are consistent with zero.**

However… at large rapidities…

SSA (π^0) at $\sqrt{s}$=200 GeV SURVIVES !



Inclusive π^0

STAR

2-γ inv.-mass spectra

$47 <= E_\pi < 56$ GeV

- SSA is measured by square-root formula with double-arms (left-right) detector:
- SSAs at different <η> do not change much.

$$x_F = \frac{p_{z,\pi}}{p_{z,1}^{pol.}} > 0$$

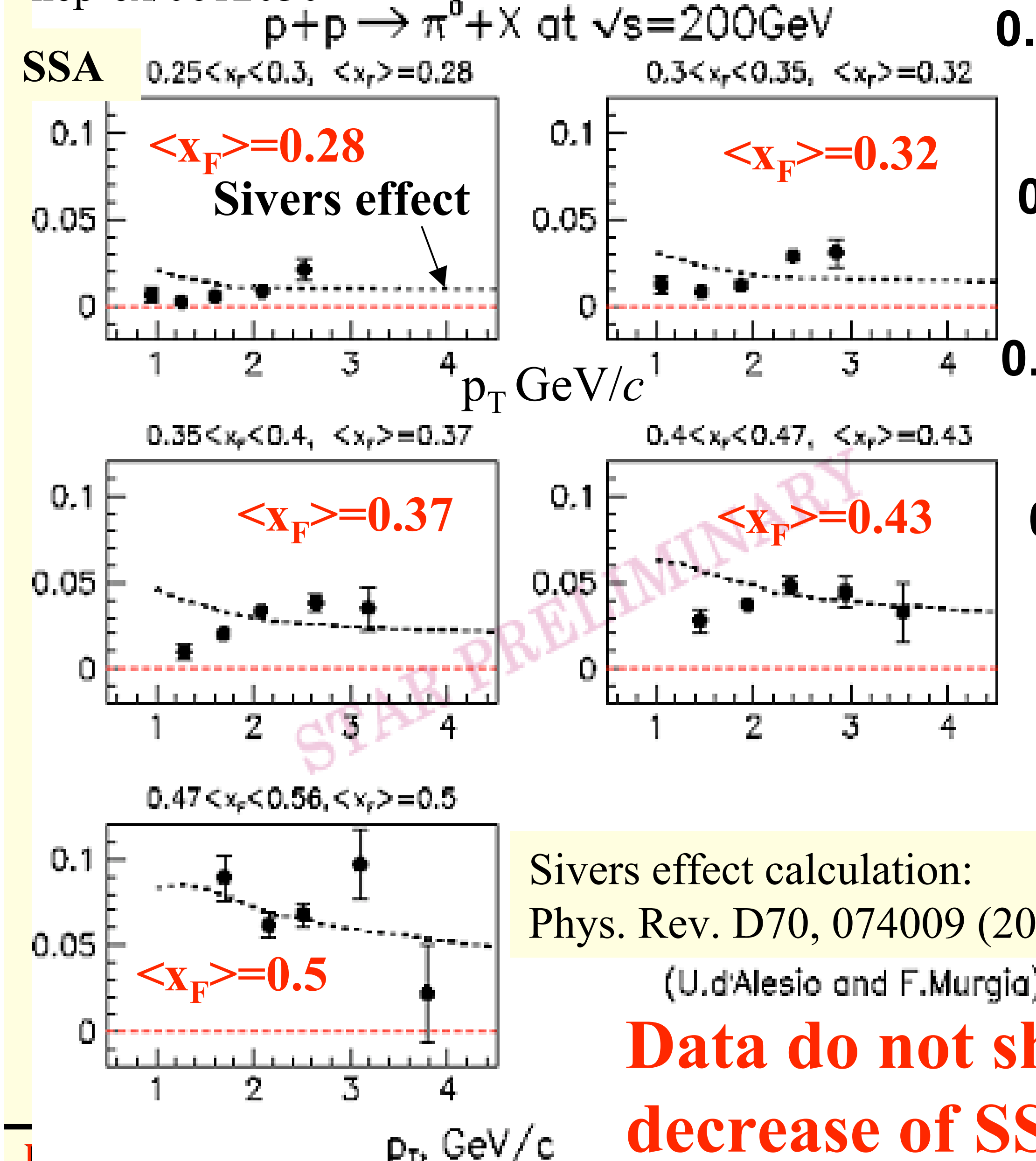
$$x_F = \frac{p_{z,\pi}}{p_{z,1}^{unpol.}} < 0,$$

SSA as a function of p_T in x_F slice

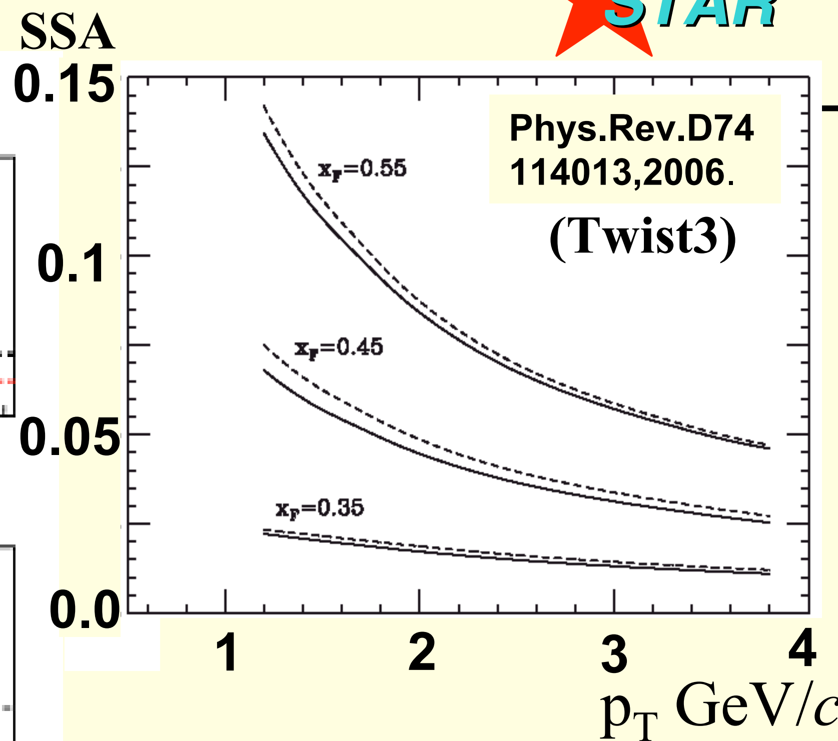
Inclusive π^0

STAR

hep-ex/0612030



Sivers effect calculation:
Phys. Rev. D70, 074009 (2004)



- Combined data from three runs at <_>=3.3, 3.7 and 4.0.
- Within each x_F bin, $\langle x_F \rangle$ does not significantly change with p_T.

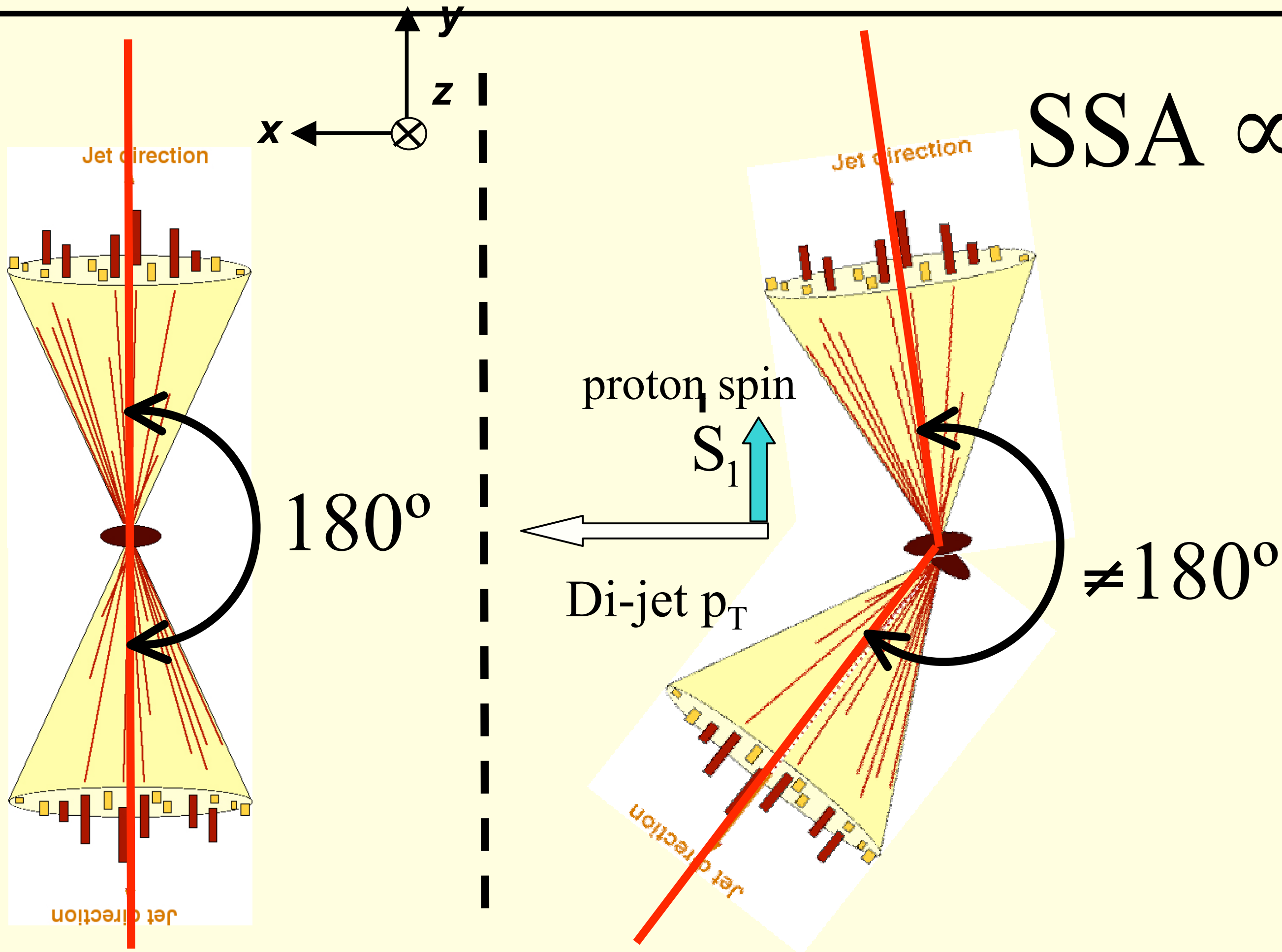
Data do not show a simply monotonic decrease of SSA with increasing p_T.

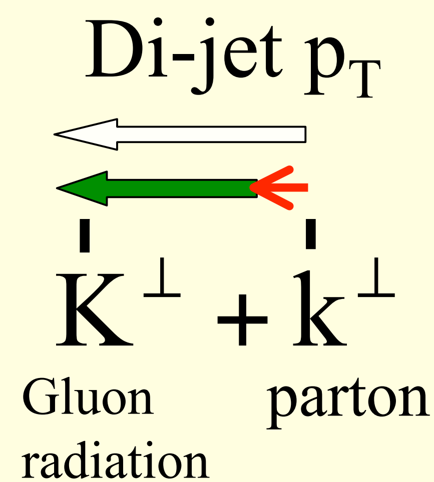
SSA in di-jet production

Boer & Vogelsang, PRD 69, 094025 (2004)

Di-jet STAR

$$SSA \propto \vec{S}_1 \cdot \left(\vec{p}_1 \times \vec{k}^{\perp}\right)$$

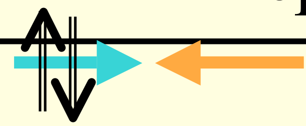




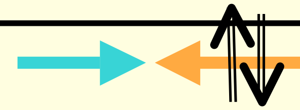
What is dominance of di-jet p_T ?

STAR Results vs. Di-jet Pseudorapidity Sum

hep-ex/0705.4629, submitted to PRL.

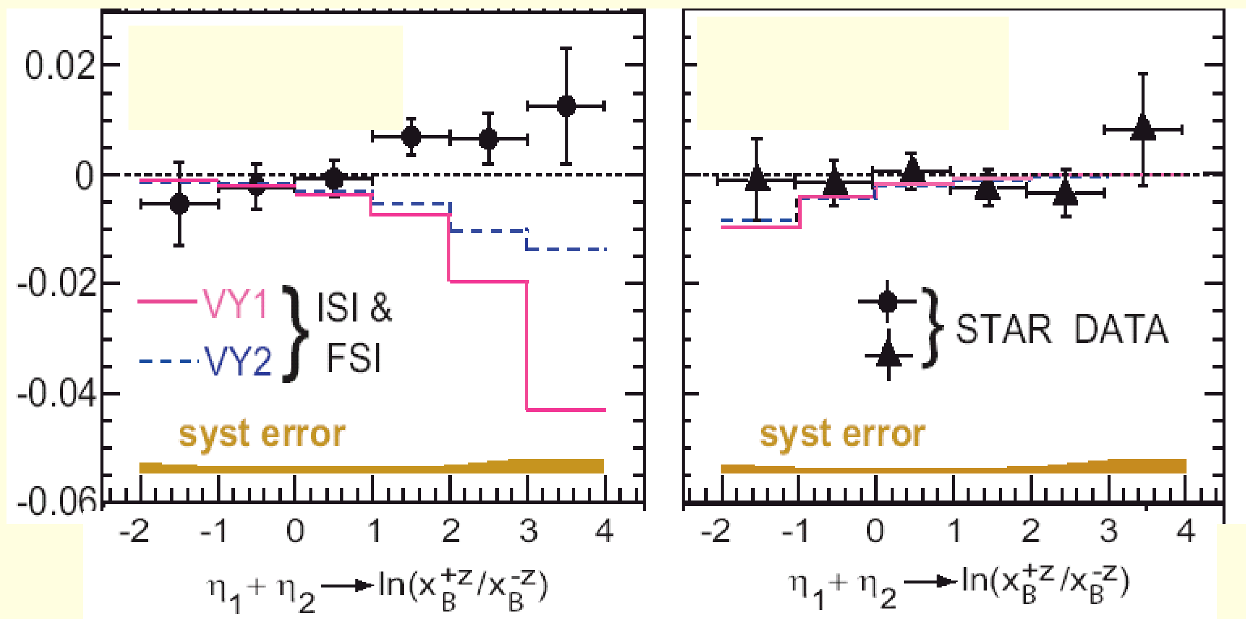
+z 

Quark from +z beam contributes

 −z

Gluon from -z beam contributes

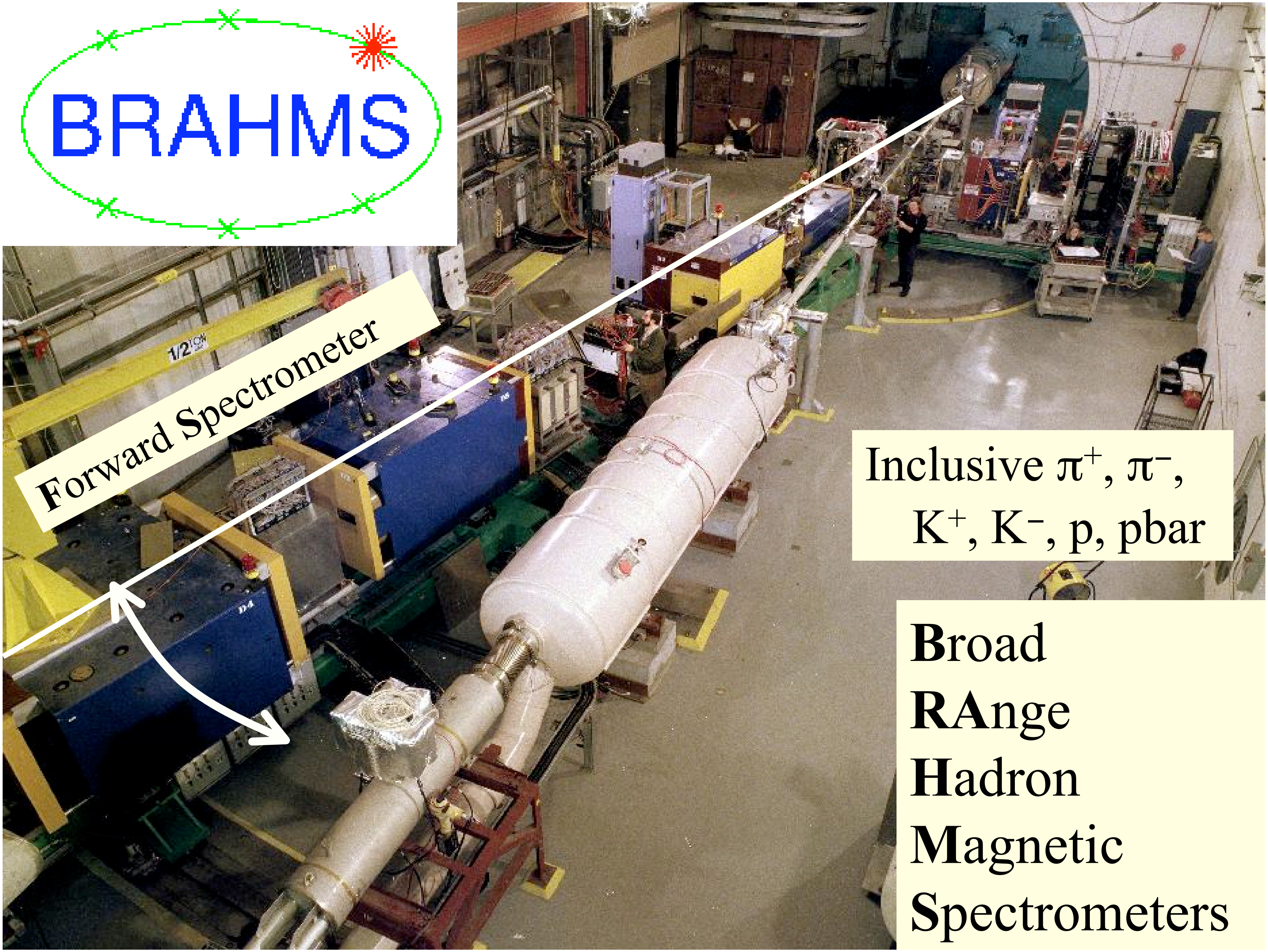
SSA



Measured di-jet SSAs are consistent with zero.

VY 1, VY 2 are calculations by Vogelsang & Yuan using HERMES-fitted quark Sivers function. PRD **72** (2005) 054028.

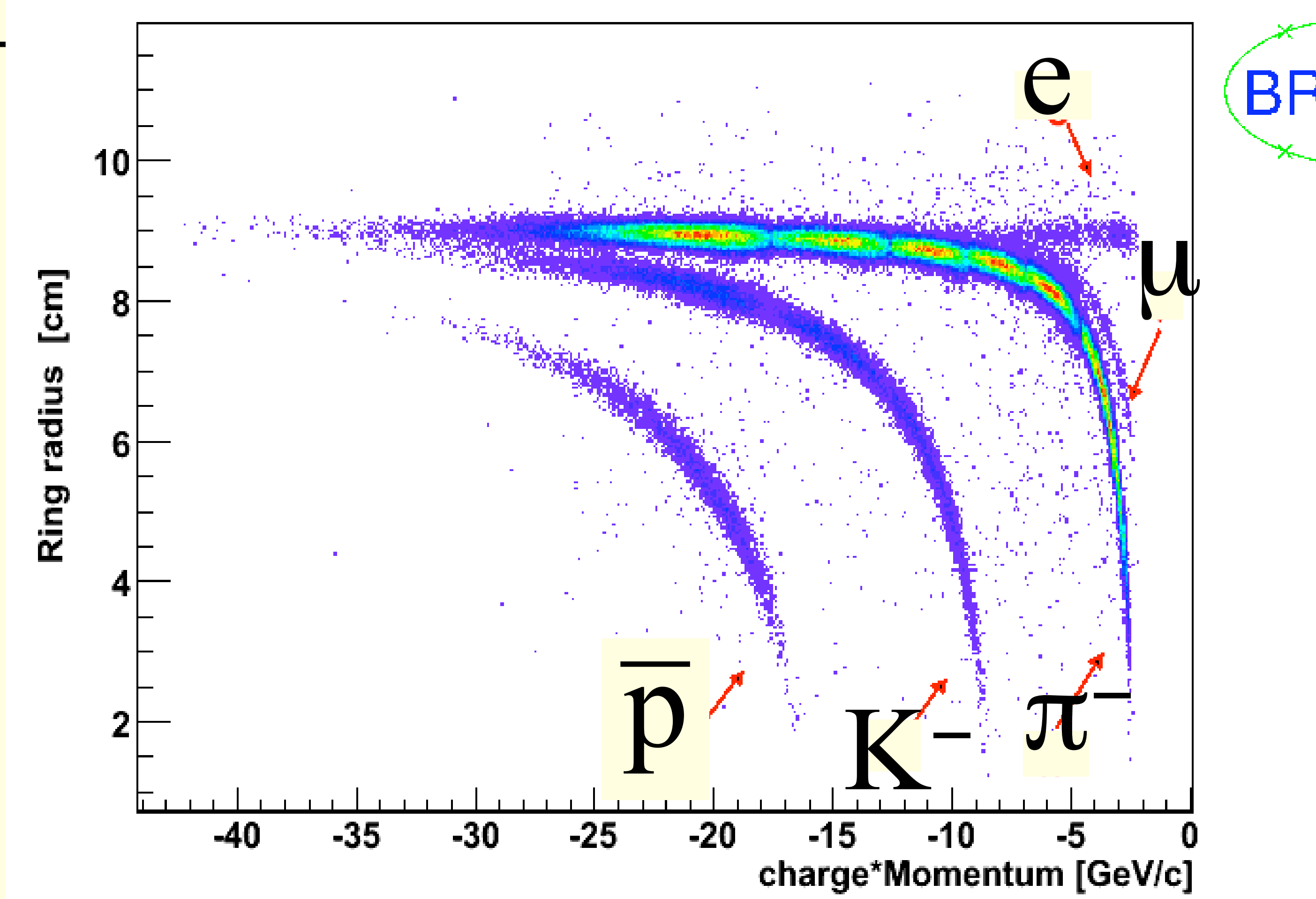
BRAHMS



Inclusive π^+, π^-, K^+, K^-, p, pbar

Broad
RAnge
Hadron
Magnetic
Spectrometers

Particle Identification using RICH

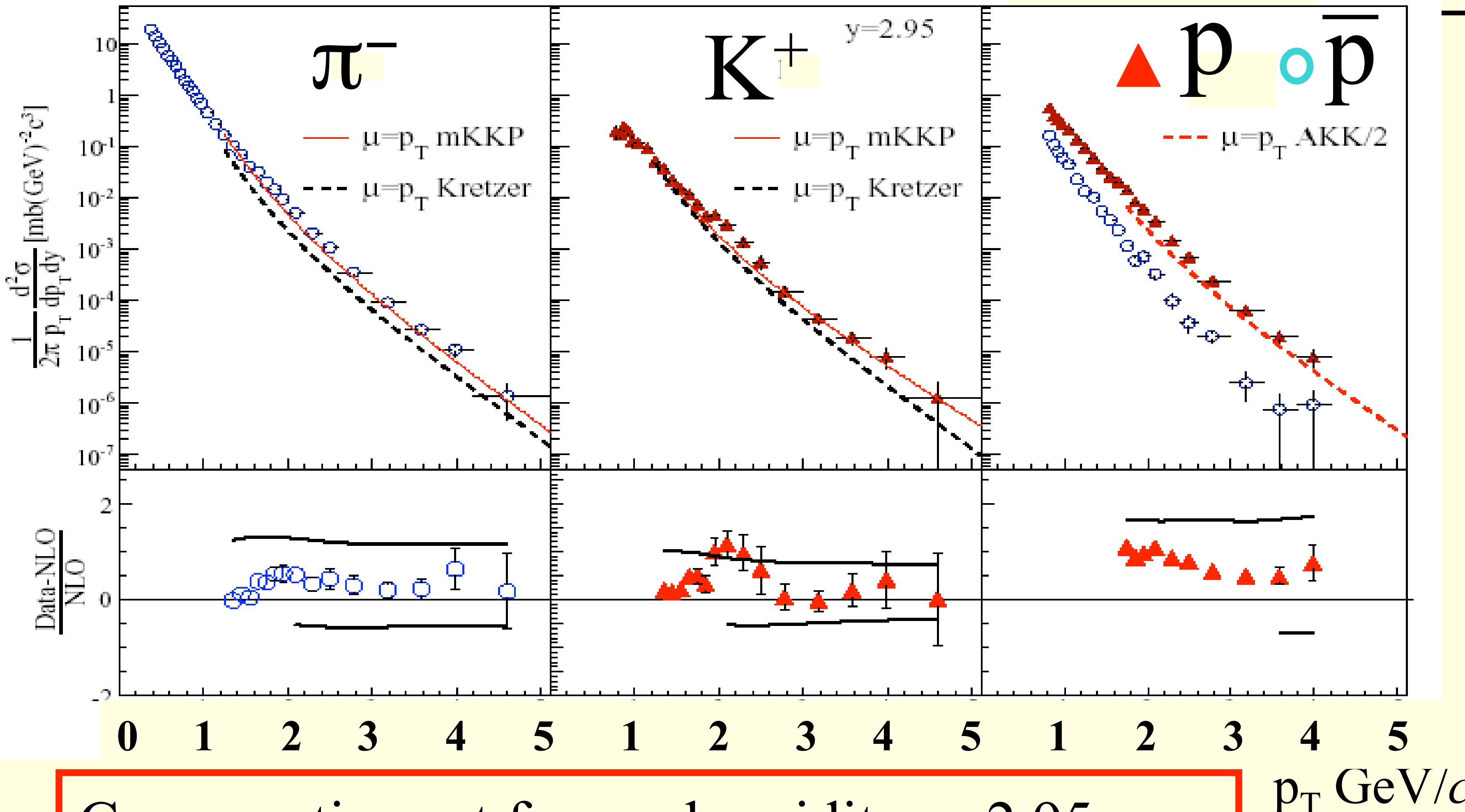


p,K identification < 30 GeV/*c*, > 17 Ge p̄ *c* with efficiency ~ 97%

pp collision at √s=200GeV (3)

BRAHMS

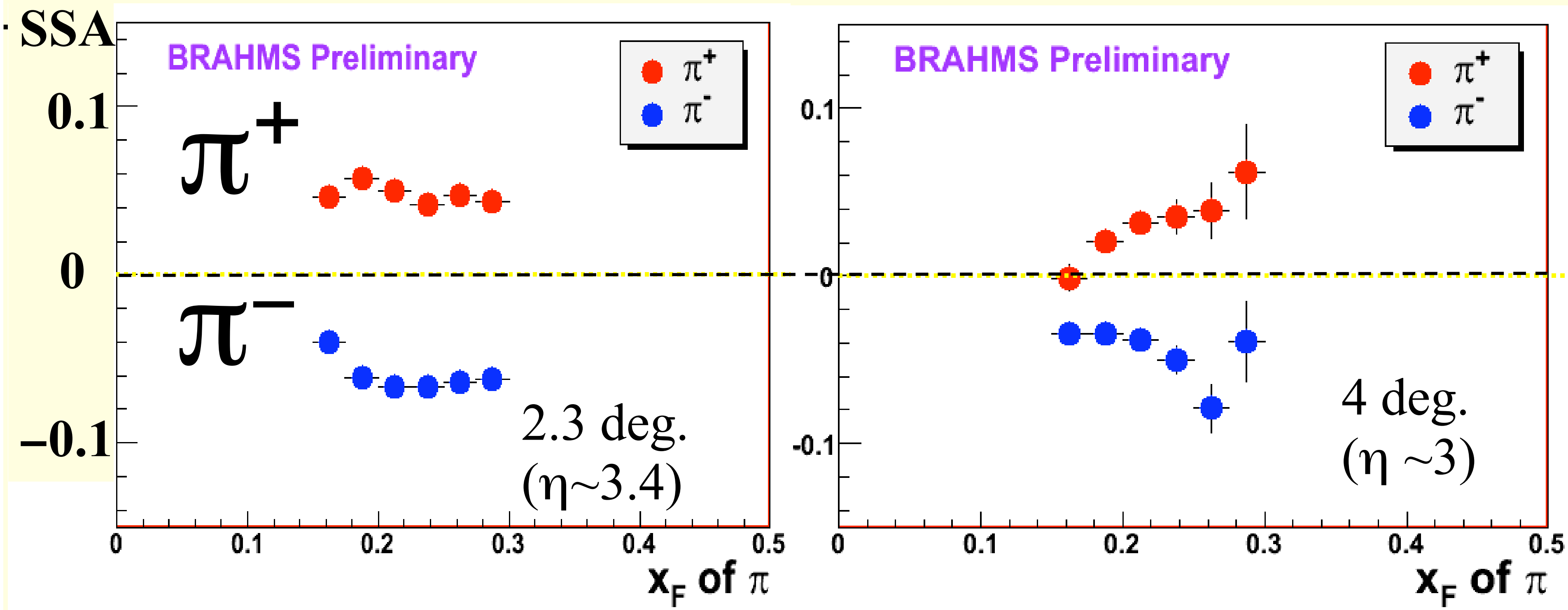
Accepted for publication in Phys. Rev. Lett. **hep-ex/0701041**



Cross sections at forward rapidity y=2.95 are consistent with NLO pQCD.

mKKP: Nucl. Phys. B597, 337 (2001); Kretzer: Eur. Phys. J.C22, 269 (2001); AKK: Nucl. Phys. B725, 181 (2005)

$\pi^{\pm}$ SSAs at 2.3 and 4 deg. at $\sqrt{s}$ = 200 GeV

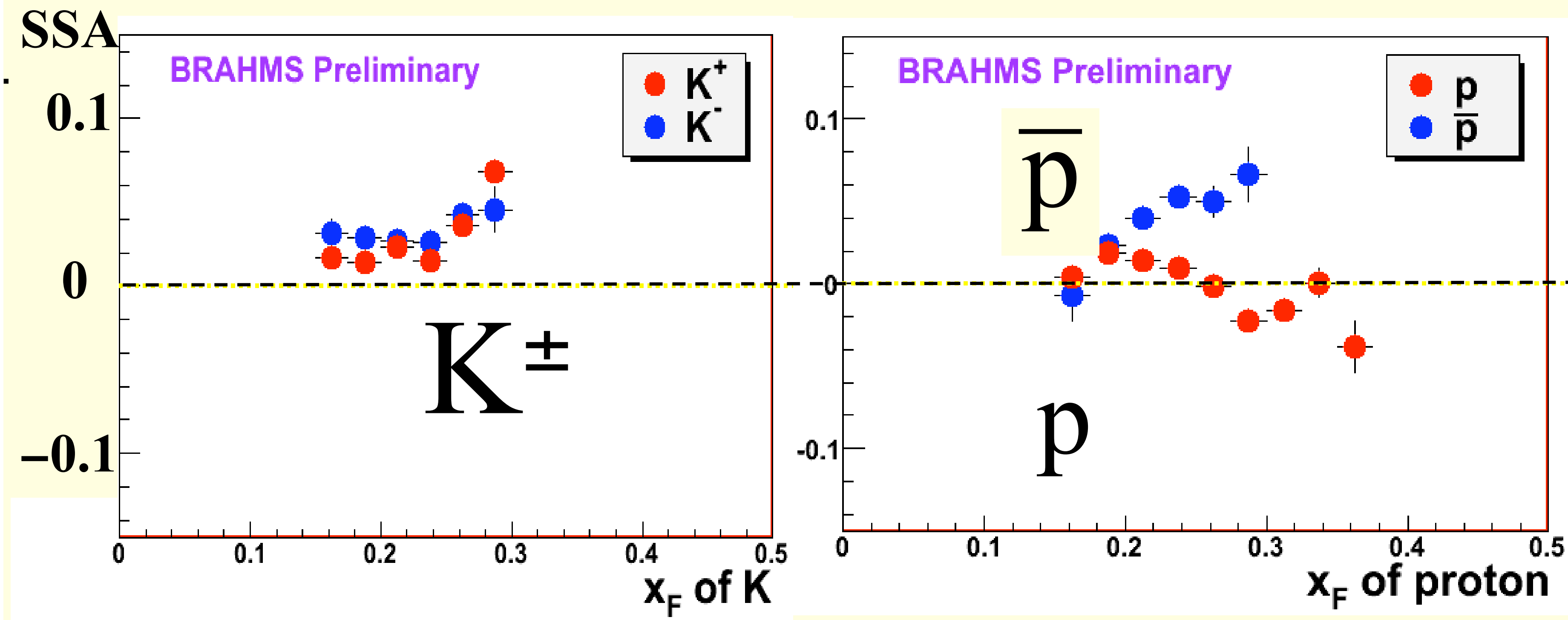


- SSA(π^+): positive SSA(π^-): negative

 4-6% in 0.15 <x_F< 0.3.

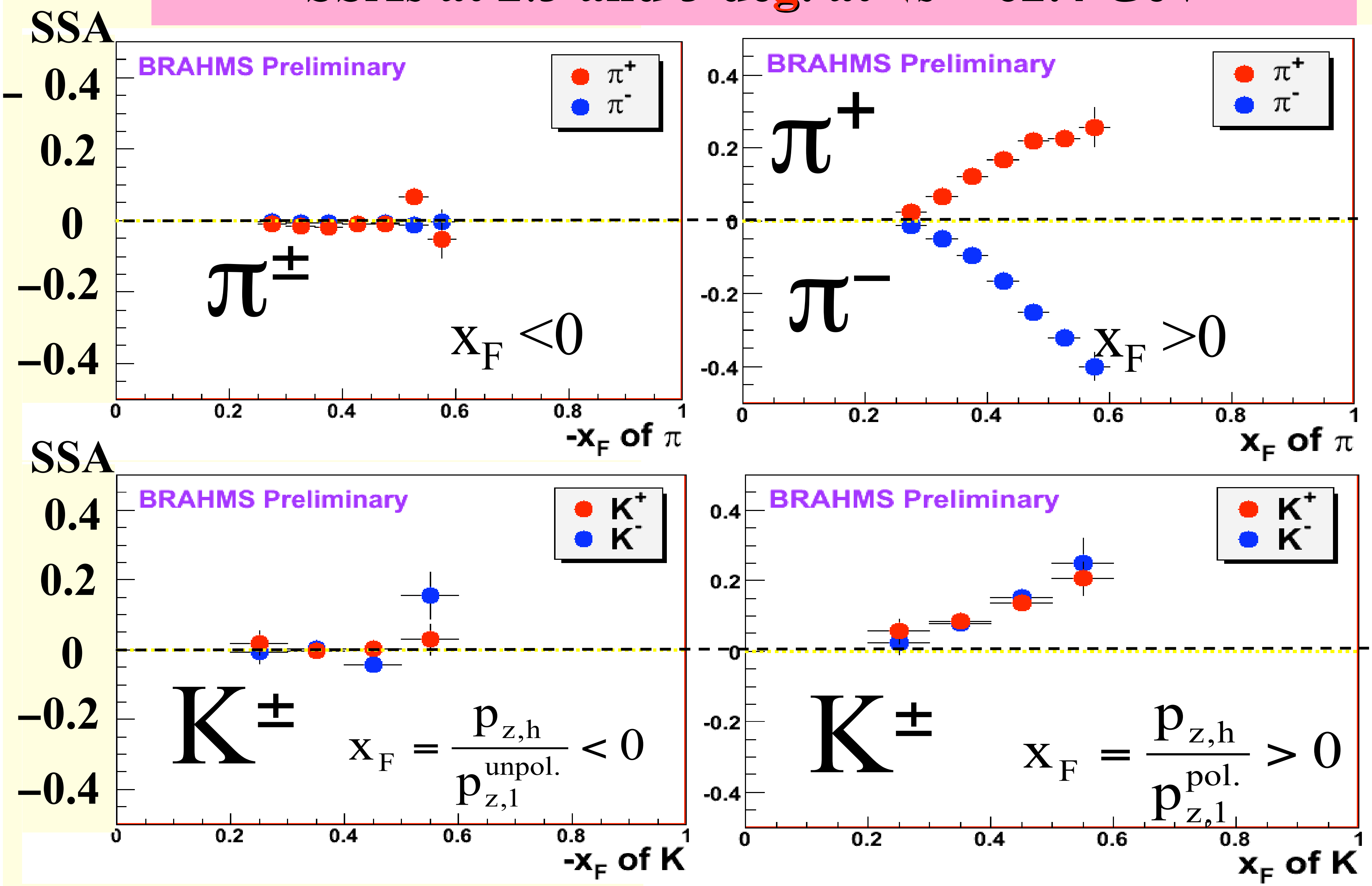
- SSA ($\pi^{\pm}$) survive.

SSAs at 2.3 deg. at $\sqrt{s}$ = 200 GeV



- SSA(K^+), SSA(K^-): positive 2-5% for 0.15 <x_F <0.3.

SSAs at 2.3 and 3 deg. at √s = 62.4 GeV



Summary of transverse physics @ RHIC

- It is just a beginning…..
  - To understand the complete structure of the nucleon spin, it is inevitable that we understand these unexpectedly large single spin transverse spin effects
  - Systematic studies only possible now with different sets of data, available for different species of particles, in different kinematic regions….
    - Enough fodder to thought for theorists to put these things together to start forming a coherent picture
- Connections to Generalized Parton Distributions?
  - Christian Weiss's talk tomorrow…

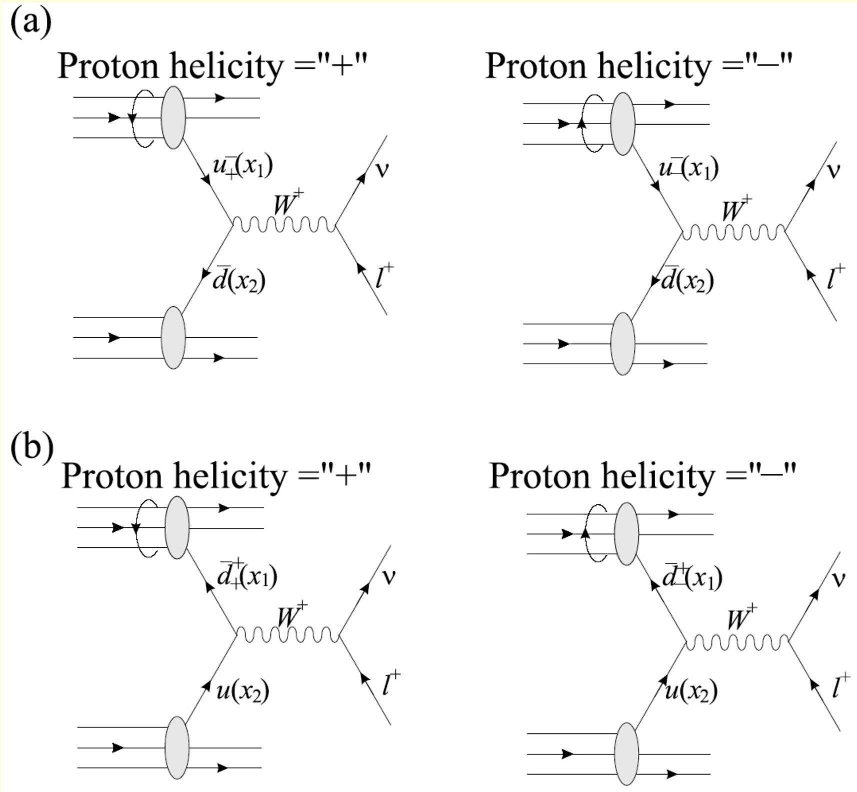
What's in it for me?
This audience may ask….

Large data sets anticipated in near future…

Detector upgrades associated with various physics measurements being approved…

OPPORUNITY!

Δq-Δqbar at RHIC via W production

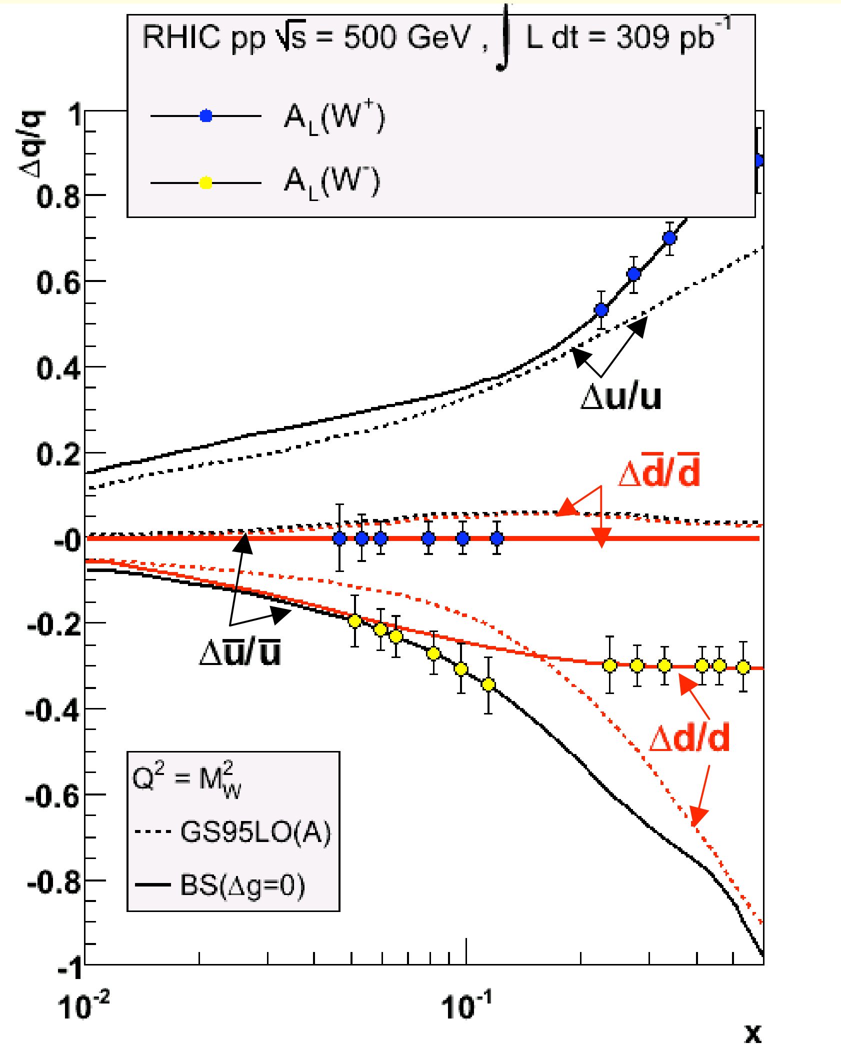


- Single longitudinal scattering asymmetry A_L
- No uncertainties from fragmentation functions as in DIS, and complementary kinematics
- Requires identification of charge of lepton in final state : need upgraded detector

$$A_L^{W^-} = \frac{\bar{d}_-^+(x_1)u(x_2) - \bar{d}_+^+(x_1)u(x_2)}{\bar{d}_-^+(x_1)u(x_2) - \bar{d}_+^+(x_1)u(x_2)} = -\frac{\Delta\bar{d}(x_1)}{\bar{d}(x_1)}$$

$$A_L^{W^+} = \frac{u_-(x_1)d(x_2) - u_+^-(x_1)d(x_2)}{u_-^-(x_1)\bar{d}(x_2) + u_+^-(x_1)\bar{d}(x_2)} = \frac{\Delta u(x_1)}{u(x_1)}$$

Flavor separation of u,d,ubar,dbar



- With 500 GeV Center of Mass
- Blue for W+, Yellow for W-
- Various theoretical expectations shown as curves
  - GS95LO is Gehrmann & Stirling, D53, PRD 1995
  - BS is Bourley and Soffer, B445, NP 1996

PHENIX Upgrades

Silicon Tracking

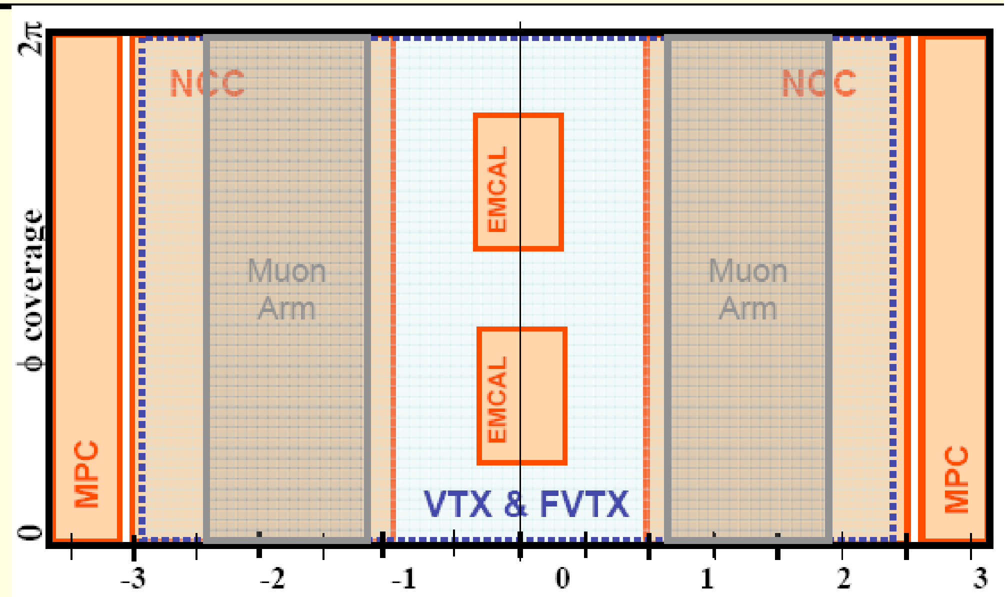
- VTX (barrel) by 2009
- FVTX (forward) by 2011

Electromagnetic Calorimetry

- NCC by 2011
- MPC, already installed!

Muon trigger upgrade

- By 2009
- Momentum selectivity in the LVL-1 trigger



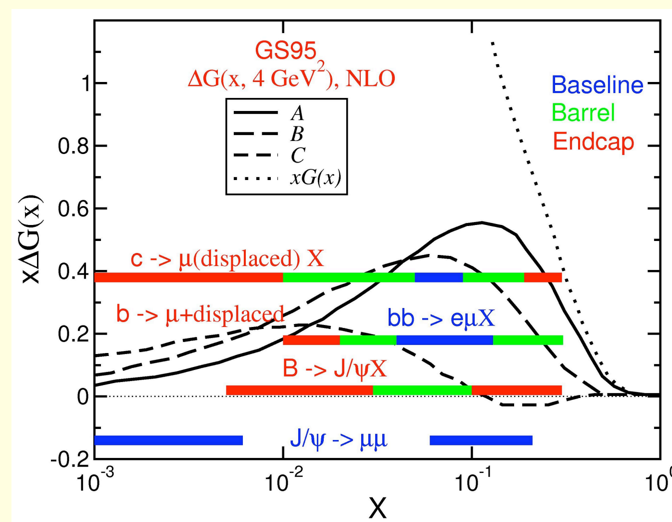
ΔG from heavy flavor, photon-tagged jets

- Expanded reach in x

Flavor separation of spin asymmetries

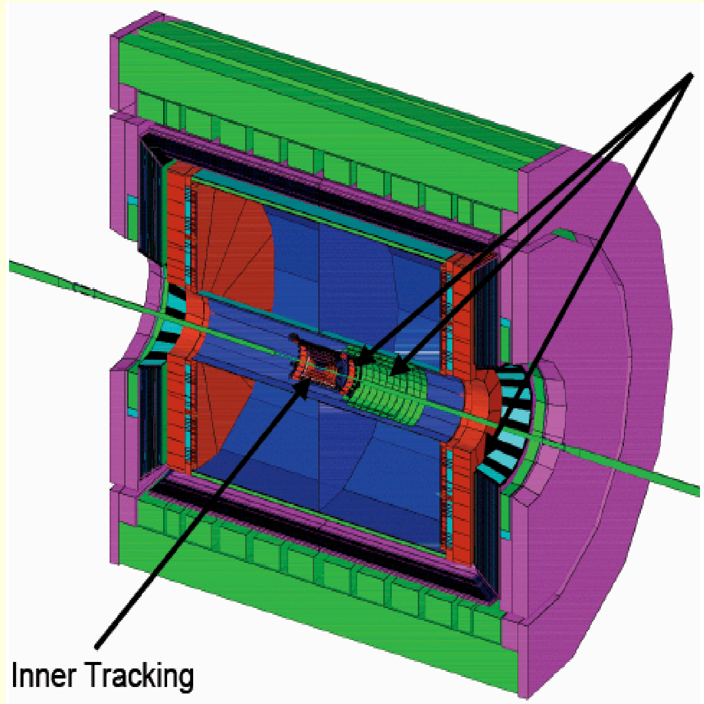
- *W* physics at 500GeV

Transverse Spin Physics



STAR Upgrade

- Inner Tracking
  - Precision vertex
  - By 2010
- Forward Tracking
  - $1<\eta<2$
  - Charge sign for high momentum e±
  - By 2011
- Forward Meson Spectrometer
  - $2.5<\eta<4$, $\Delta\varphi=2\pi$
  - Ready for Run8!
- DAQ (×10 faster)
  - By 2008



- ΔG from heavy flavor, jets
  - Expanded reach in x
- Flavor separation of spin asymmetries
  - *W* physics at 500GeV
- Transverse Spin Physics

Summary

- RHIC is the world's first polarized collider
  - Technology has been developed as needed, and has worked superbly in every aspect
- Over all project goal to study aspects of nucleon spin have begun
  - Early results on gluon's role in determining nucleon spin now emerging
  - Transverse spin phenomena being discovered, and understood in the framework of perturbative and non-perturbative models
- Only the beginning of the program:
  - Only about 1% of the luminosity delivered so far,
  - Ideal challenge for the experimentally & theoretically minded people in this audience to consider

Thanks…

- To many of my RHIC spin colleagues and collaborators. Many of the slides and figures used in this lecture were taken from their presentations, often without their knowledge….