RHIC and EIC Physics Lecture 2

RHIC Spin Physics

June 27, 2018
APCTP, Pohang, South Korea
Lecture 2

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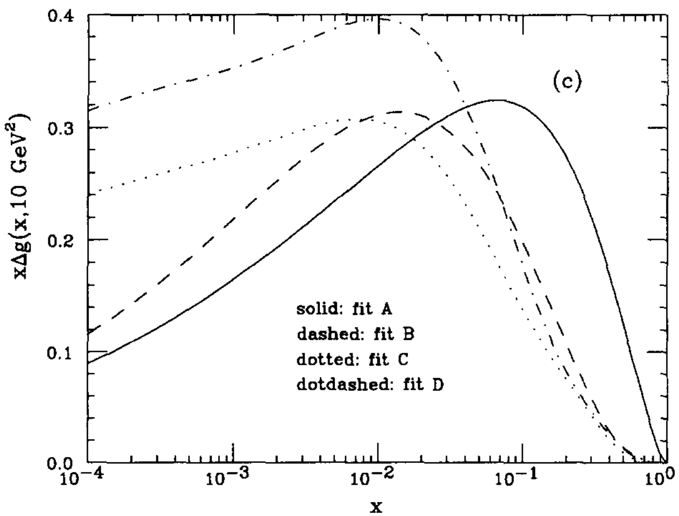
High expectations from ΔG

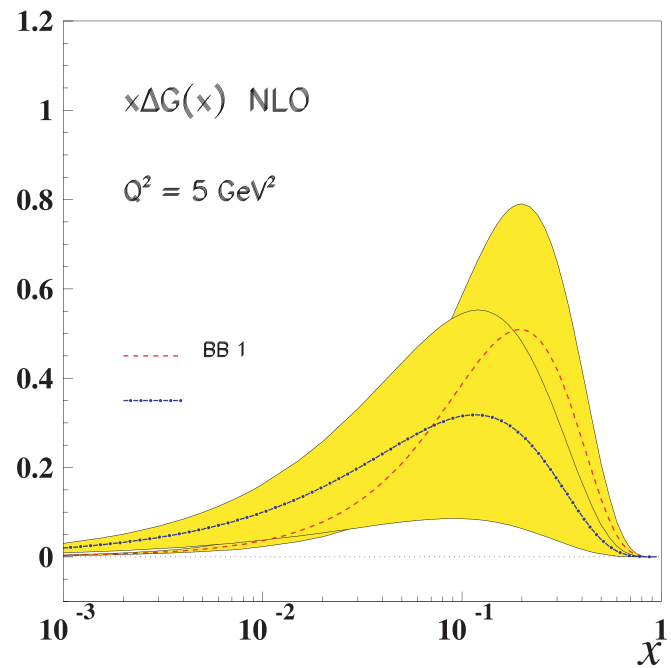
Altarelli et al. NP B 496 (1997) → NLO pQCD analysis of inclusive DIS in AB scheme



$$\Delta\Sigma(1) = 0.45 \pm 0.04\ (\text{exp}) \pm 0.08\ (\text{th}) = 0.45 \pm 0.09,$$

$$\Delta g(1, 1\ \text{GeV}^2) = 1.6 \pm 0.4\ (\text{exp}) \pm 0.8\ (\text{th}) = 1.6 \pm 0.9,$$

$$a_0(\infty) = 0.10 \pm 0.05\ (\text{exp})\ {}^{+0.17}_{-0.10}\ (\text{th}) = 0.10\ {}^{+0.17}_{-0.11},$$



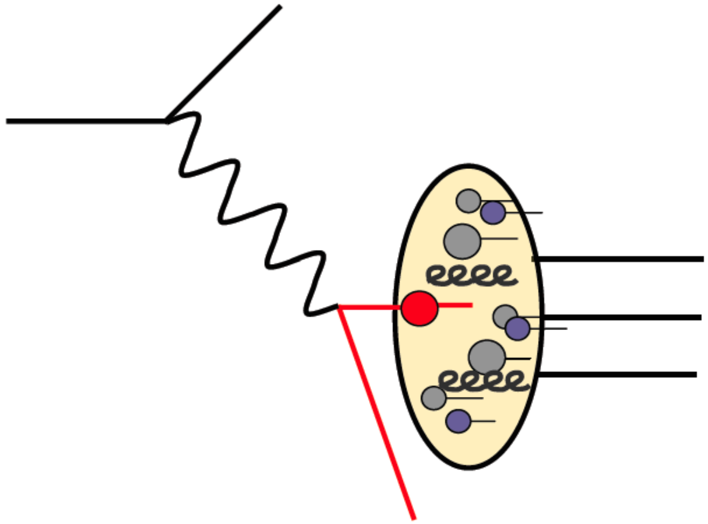
Blumlein et al. NP A721 (2003)
→ NLO pQCD in MSbar Scheme:
ΔG at Q^2=4 GeV^2 ~ 1.0 +/- 0.7

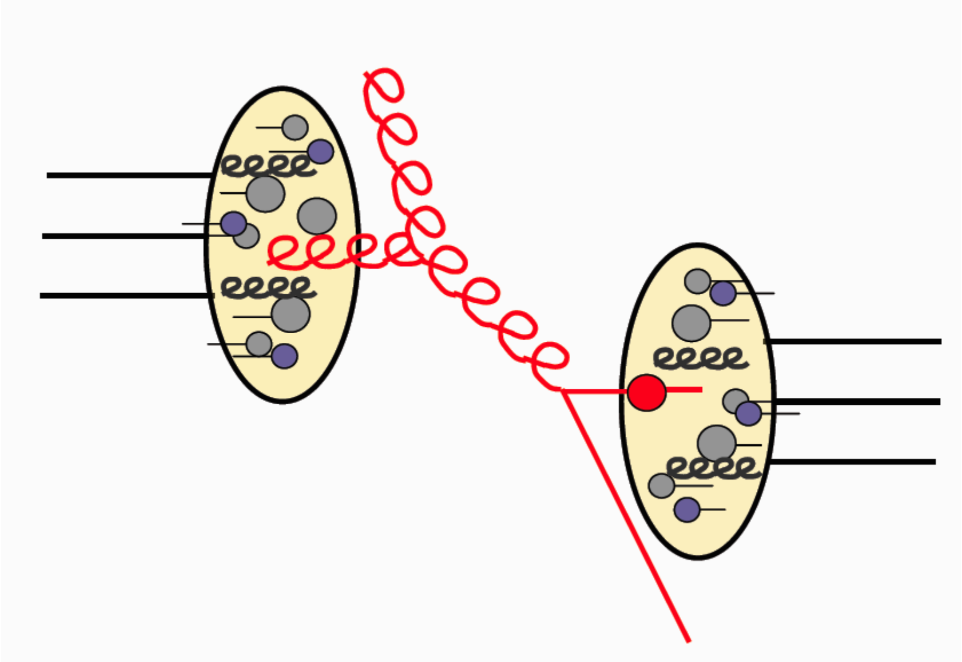
Also see: PRD 58 112002 (1998) for detailed discussion uncertainties

Motivation for RHIC Spin:

- If gluons really carry the bulk of nucleon's spin, why not use polarized proton (known by then to be predominantly made of gluons!)?
  - Technical know-how (Siberian Snakes, Spin Rotators, polarimetry ideas) to do this at high energy evolved around the time (mid/late-1990s)
- Why $\Delta\Sigma$ (quark + anti-quark's spin) small? Are quark and anti-quark spins anti-aligned? Polarized *p*+p at high energy, through W+/- production could address this
- A severe need for investigations of the surprising transverse spin effects was naturally possible and needed with the proposed polarized p+p collider…

Complementary techniques

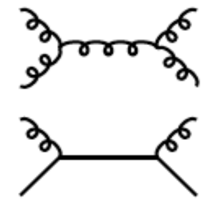
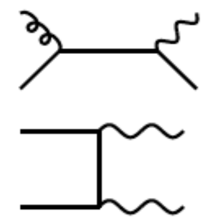
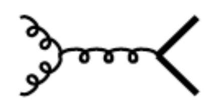
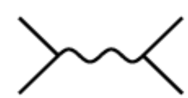
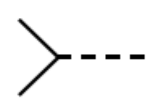




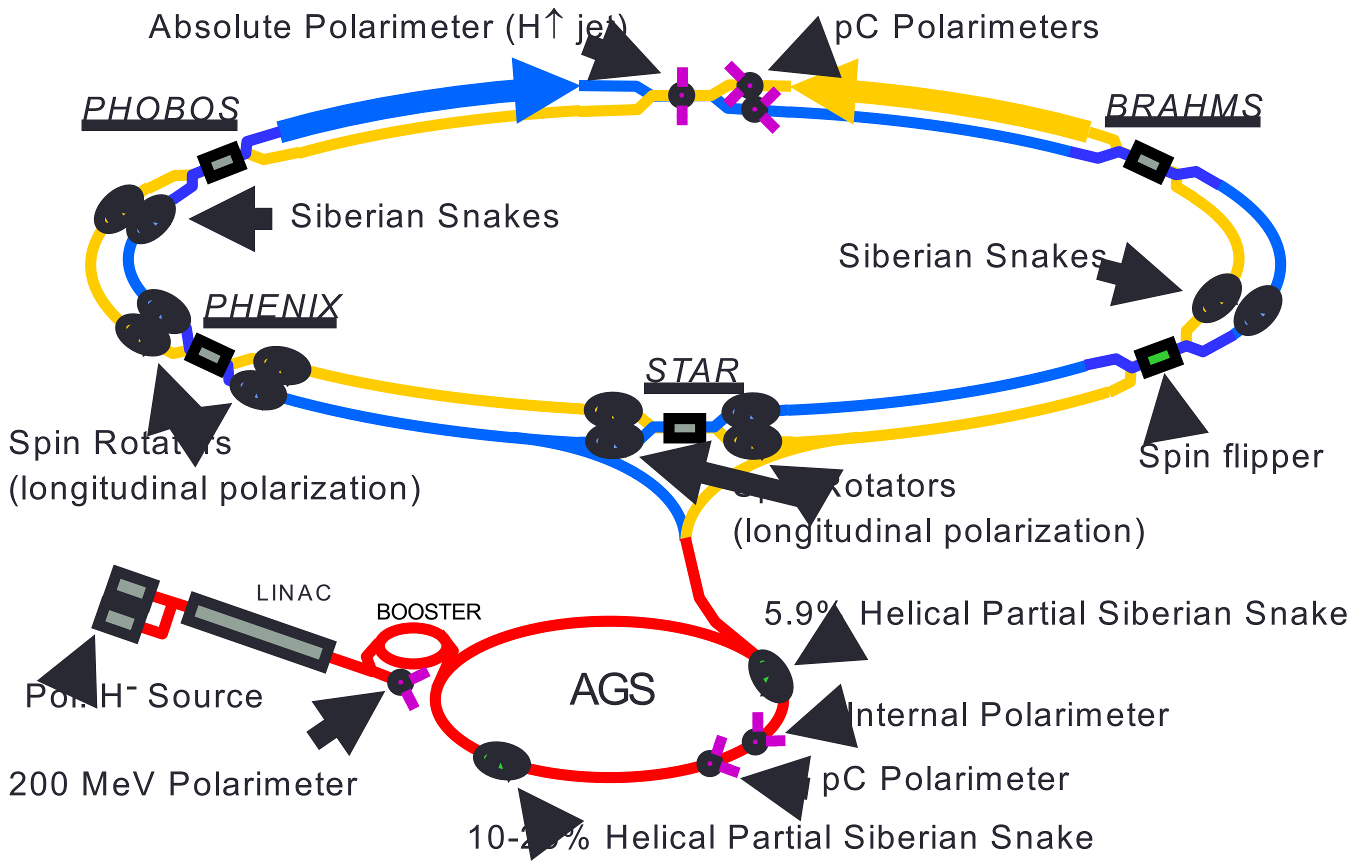
- Photons colorless: forced to interact at NLO with gluons
- Can’t distinguish between quarks and anti-quarks either

- Why not use polarized quarks and gluons abundantly available in protons as probes ?

The probes and techniques at RHIC

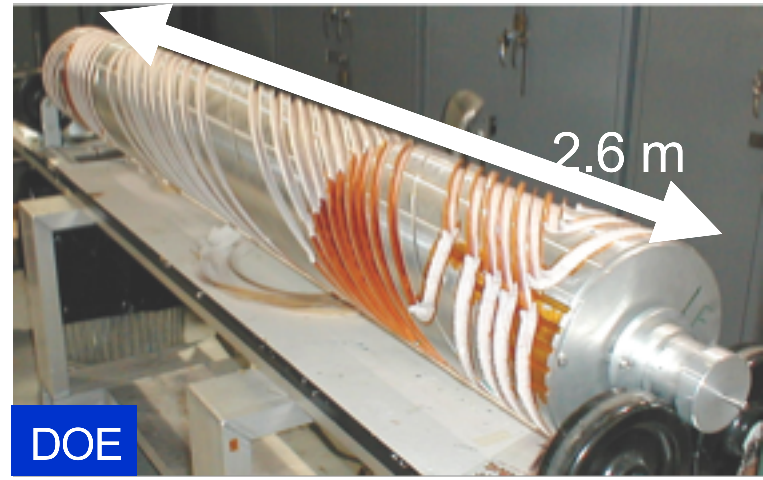
Reaction	Dom. partonic process	probes	LO Feynman diagram
$\vec{p}\vec{p} \to \pi + X$	$\vec{g}\vec{g} \to gg$ $\vec{q}\vec{g} \to qg$	Δg	
$\vec{p}\vec{p} \to \mathrm{jet(s)} + X$	$\vec{g}\vec{g} \to gg$ $\vec{q}\vec{g} \to qg$	Δg	(as above)
$\vec{p}\vec{p} \to \gamma + X$ $\vec{p}\vec{p} \to \gamma +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

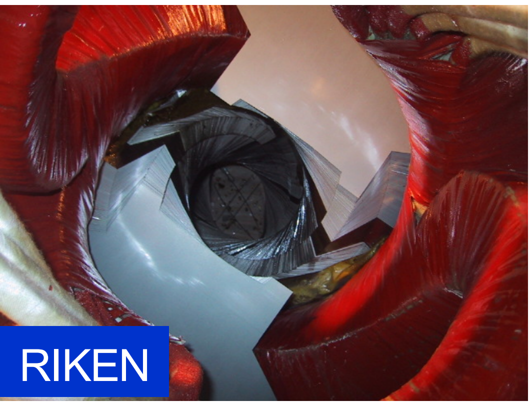
RHIC as a Polarized Proton Collider



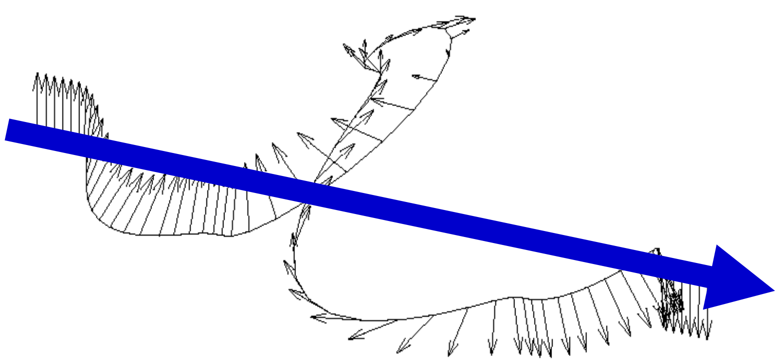
Without Siberian snakes: $\nu_{sp} = G\gamma = 1.79$ E/m → ~1000 depolarizing resonances
With Siberian snakes (local 180° spin rotators): $\nu_{sp} = ½$ → no first order resonances
Two partial Siberian snakes (11° and 27° spin rotators) in AGS

Siberian Snakes

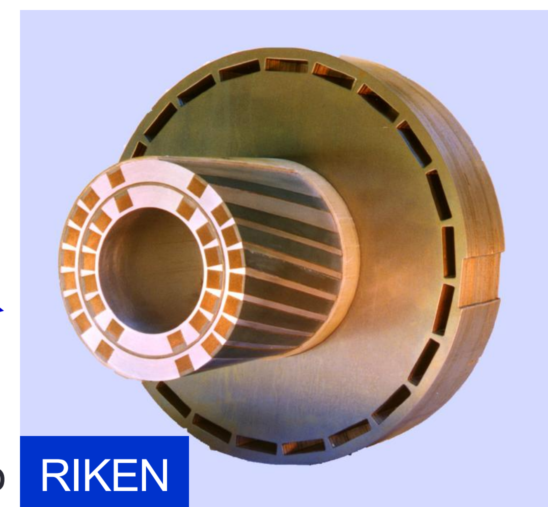




- AGS Siberian Snakes: variable twist helical dipoles, 1.5 T (RT) and 3 T (SC), 2.6 m long
- RHIC Siberian Snakes: 4 SC helical dipoles, 4 T, each 2.4 m long and full 360° twist



Courtesy of A. Luccio



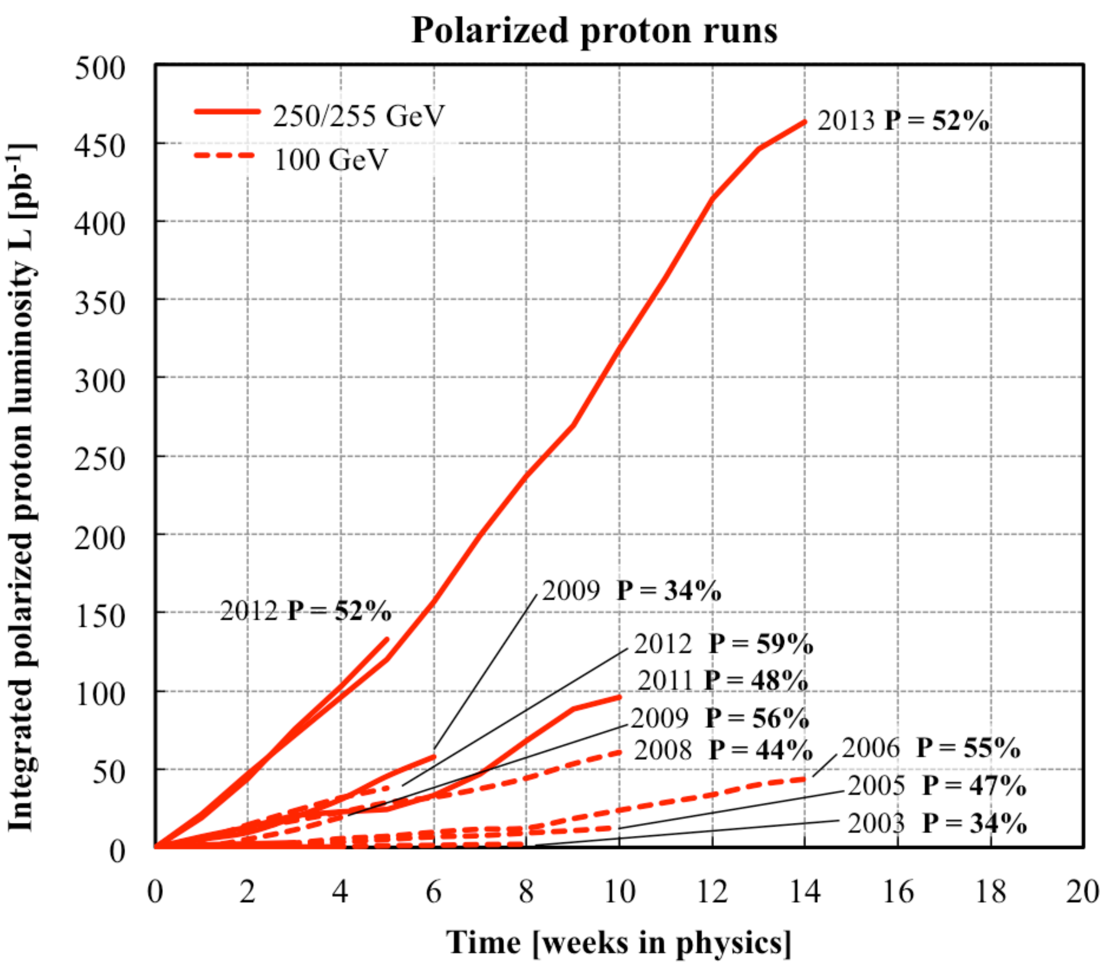
Polarized Collider Development

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	70

Since 2006: more data, 200 and 500 GeV

Run (End Year)	√s (GEV)	L recorded (pb^{-1})	Polarization	FOM (P^4*L)
Run 06	200	7.5	57%	0.79
Run 06	**62.4**	**0.08**	**48%**	**0.0042**
Run 09	200	16	57%	1.5
Run 09	**500**	**14**	**39%**	**0.21**
Run 11	**500**	**25**	**45%**	**1.03**
Run 12	**200**	**40**	**60%**	
Run 12	**500**	**140**	**52%**	

RHIC polarized collider: a success!



Runs 4,5,6 & 9 with 100 GeV beams

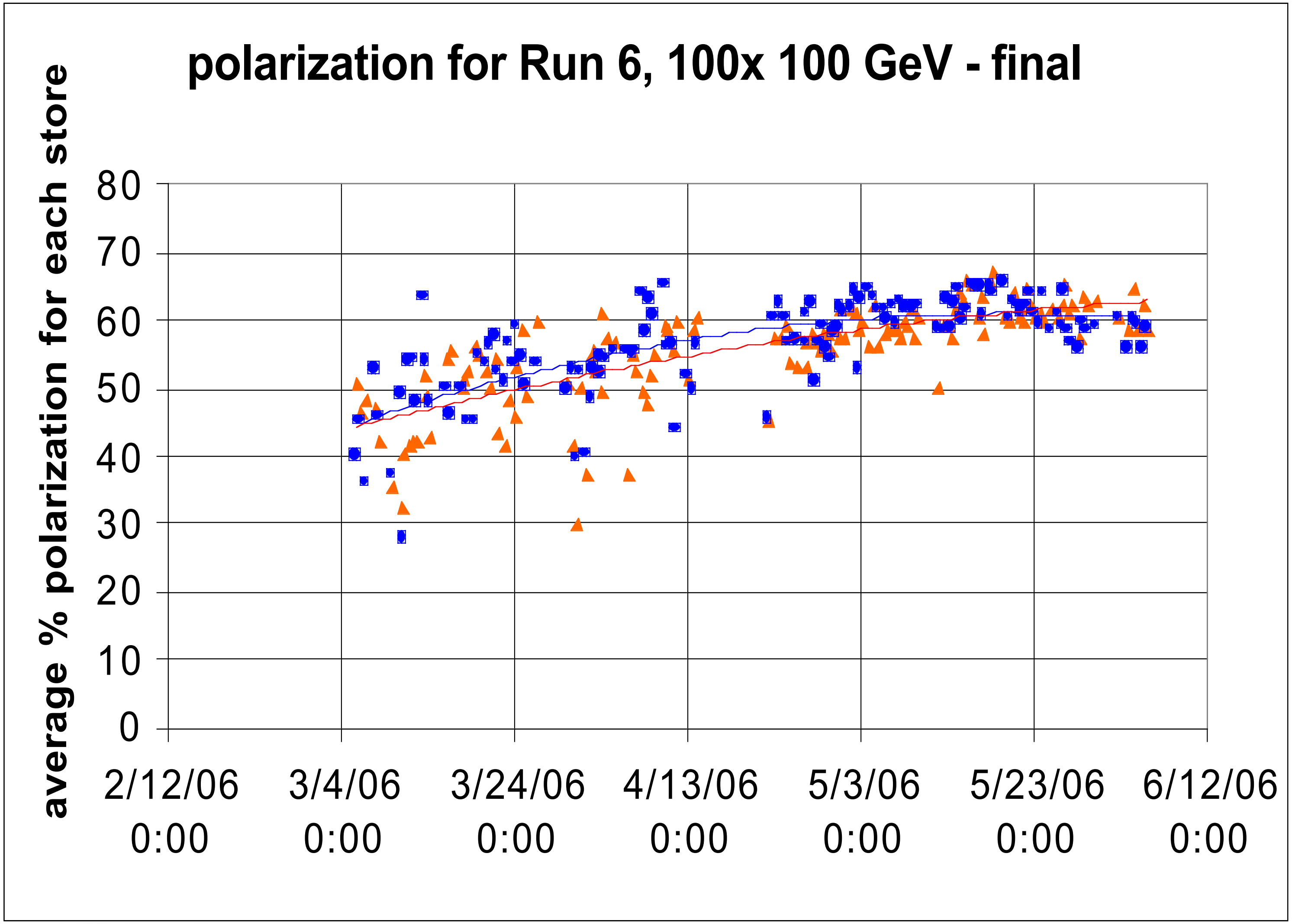
- ΔG, transverse spin

Runs 9,11,12, 13 with 250 GeV beams

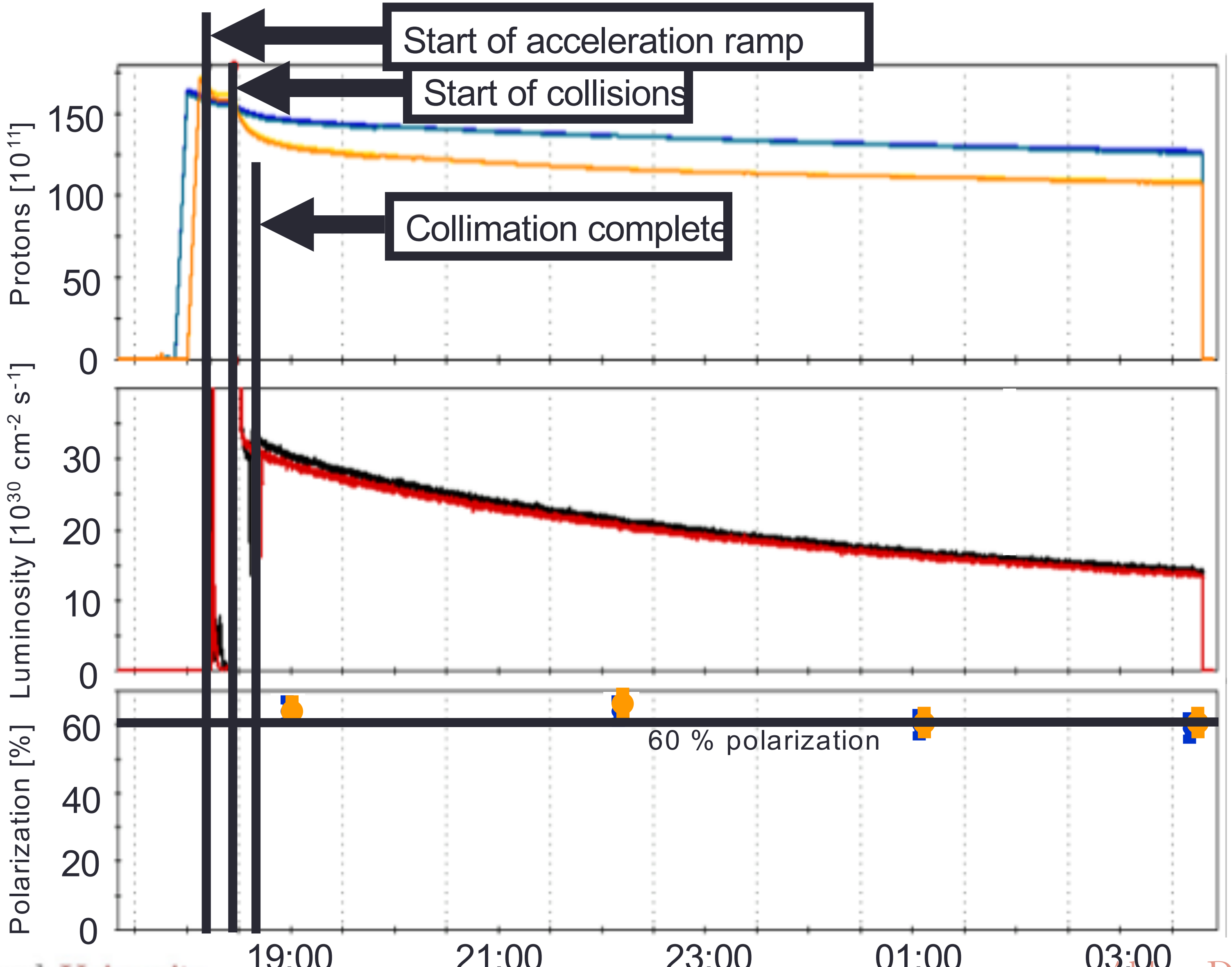
- ΔG, W-Physics

See experimental and theoretical talks in this session for details of various results & their interpretations

Polarization at 100 GeV



A typical store at 100 GeV



RHIC beam polarimetry

How do we know the proton beams are polarized?

Polarimetry had to be developed

How do we know that they are longitudinally polarized?

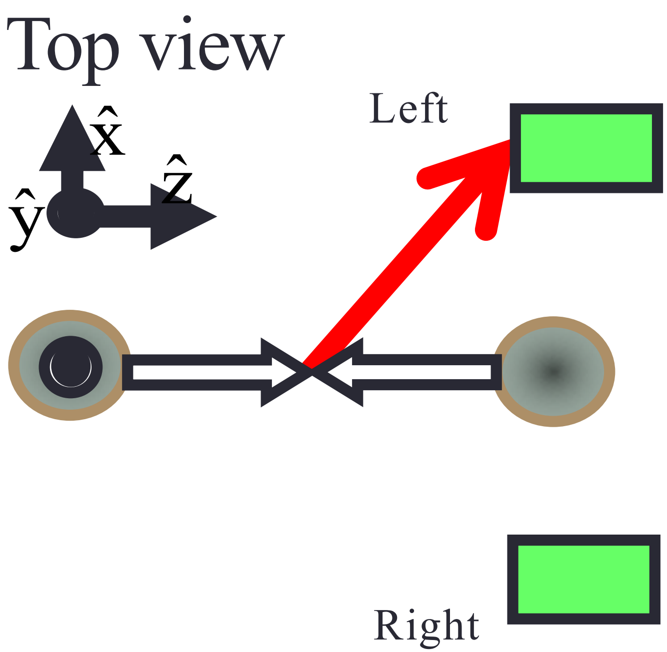
Stable direction of spins in the storage ring is vertical, spin rotator magnets rotate them. How do we know they are doing their job?

RHIC polarimetry (I)

Measurement of degree of polarization

- Elastic p-p Coulomb Nuclear Interference (CNI) measures **absolute polarization** employing a polarized Hydrogen-Jet (as target)
- Elastic p-Carbon CNI polarimeter **monitors the degree of polarization with multiple measurements during fills**
- Both together succeeded in getting an uncertainty in the polarization measurement of +/- 4.7%

Beam polarization measurement (1)



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

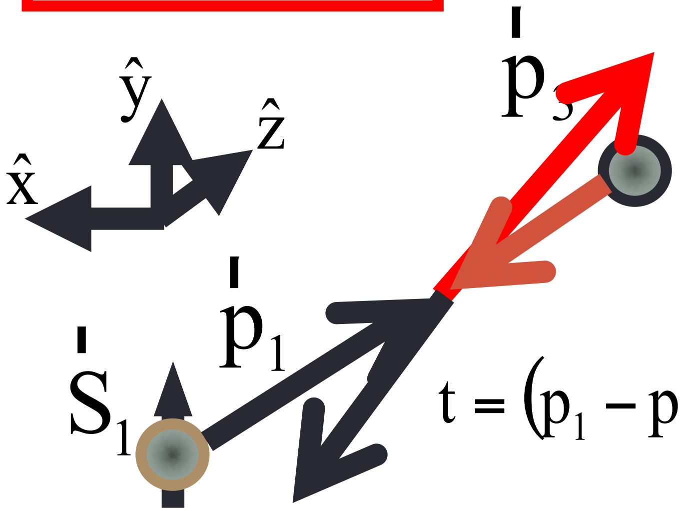
$$SSA = \frac{1}{pol.} \frac{\sqrt{N^L_\uparrow N^R_\downarrow} - \sqrt{N^R_\uparrow N^L_\downarrow}}{\sqrt{N^L_\uparrow N^R_\downarrow} + \sqrt{N^R_\uparrow N^L_\downarrow}}$$

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

RHIC Absolute Polarization

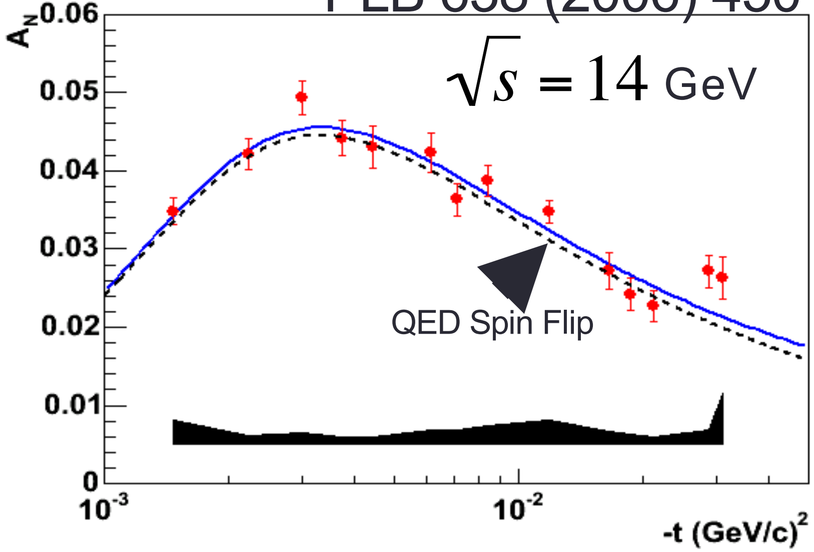
$p^{\uparrow} + p \rightarrow p + p$

Very forward scattering



$t = (p_1 - p_3)^2 < 0$

PLB 638 (2006) 450



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

RHIC-AGS Best Thesis Award 2006, Hiromi Okada

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

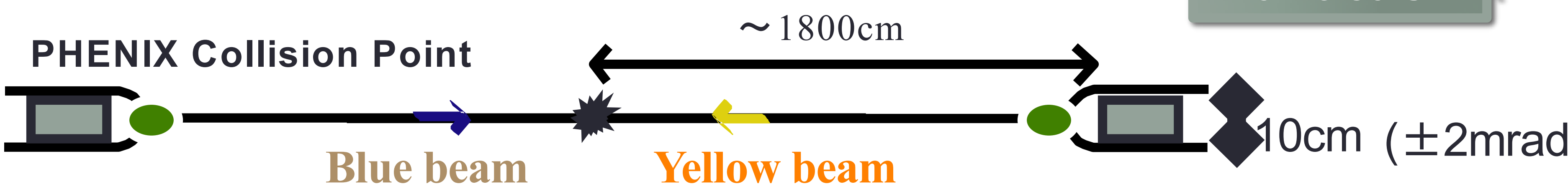
RHIC polarimetry (I)

Determination and monitoring of spin vector direction in the interaction region

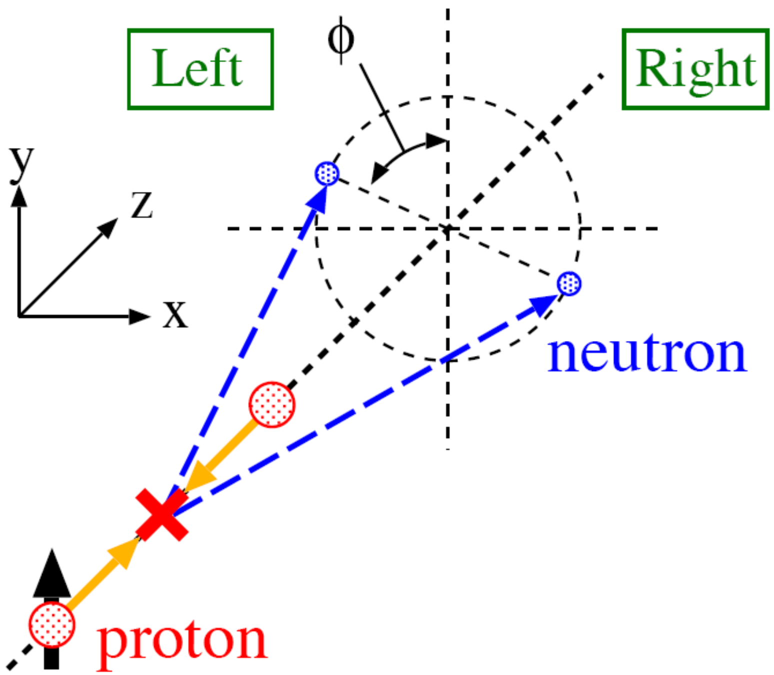
- Employs (accidentally discovered in 2002) single transverse spin asymmetry in “forward” neutron production
- “Local Polarimeters”: at PHENIX, now at STAR as well

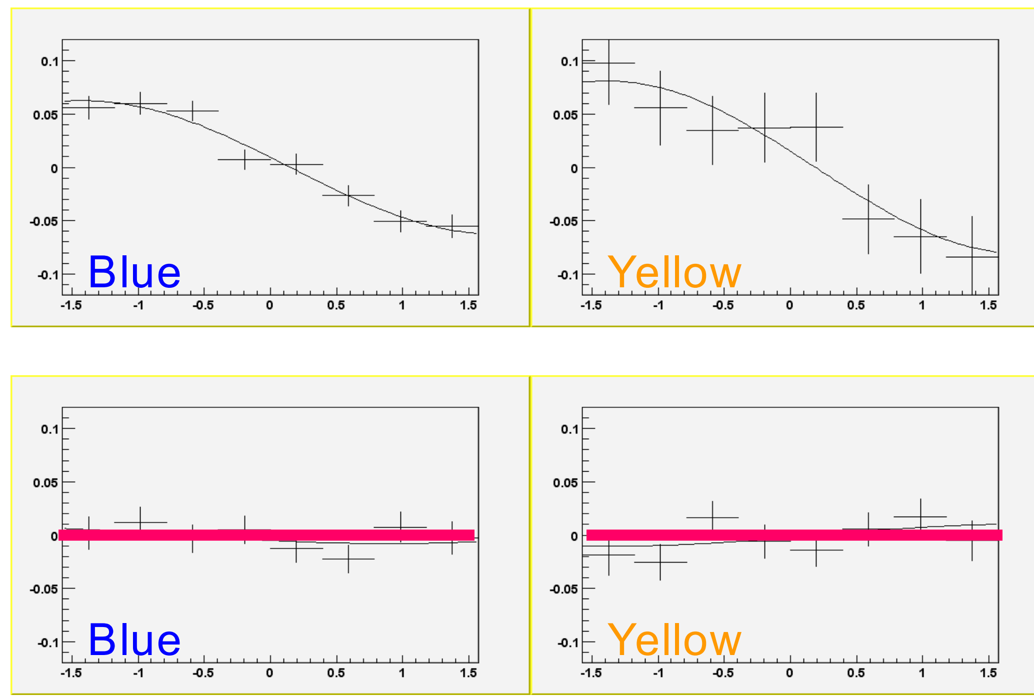
PHENIX* Local Polarimeter

*Now also STAR

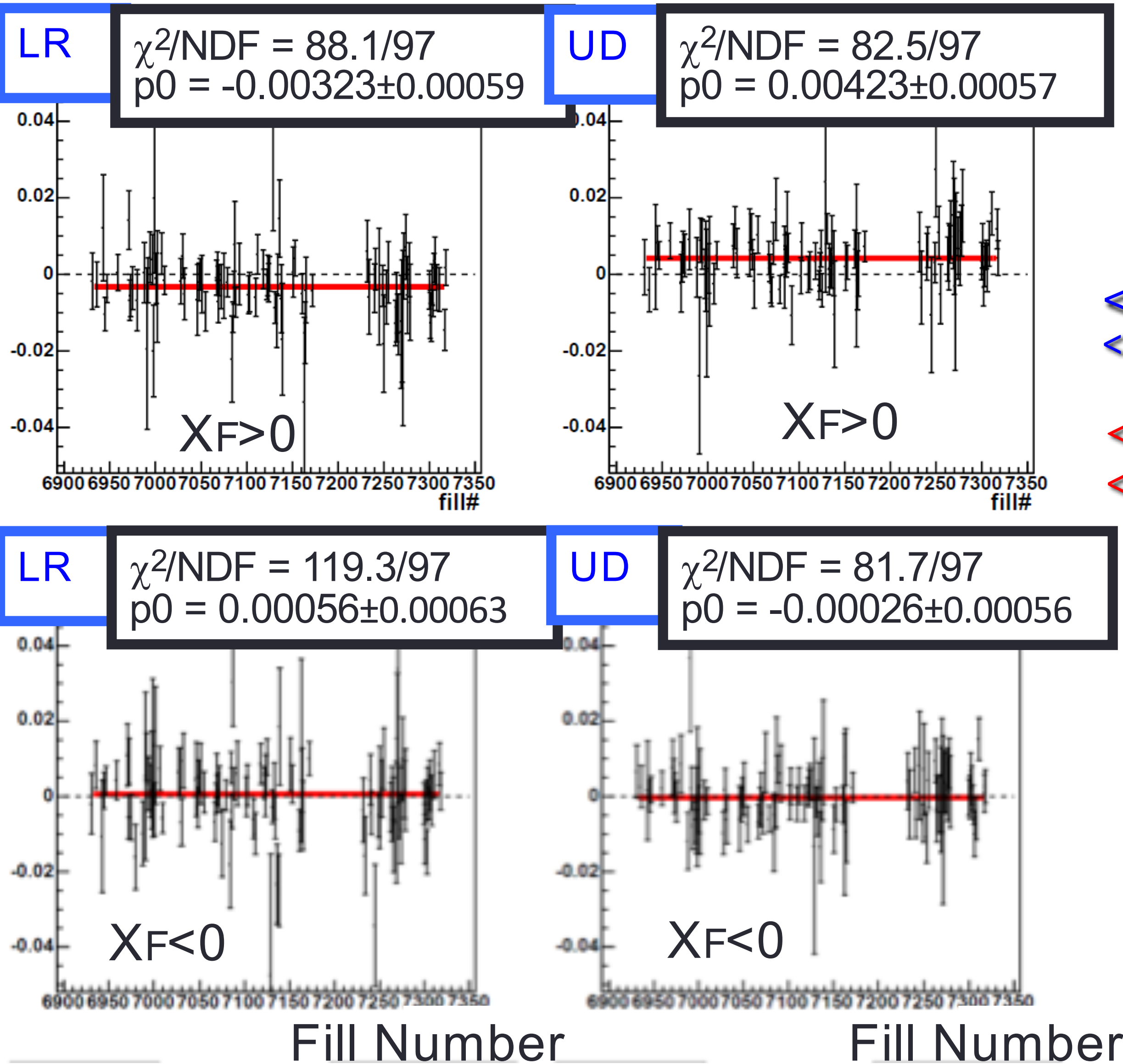


PL/P > 0.99 blue & yellow





Measured Asymmetry During Longitudinal Running



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

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

$\langle P_T/P \rangle$=10±2(%)
$\langle P_L/P \rangle$ =99.48±0.12±0.02(%)

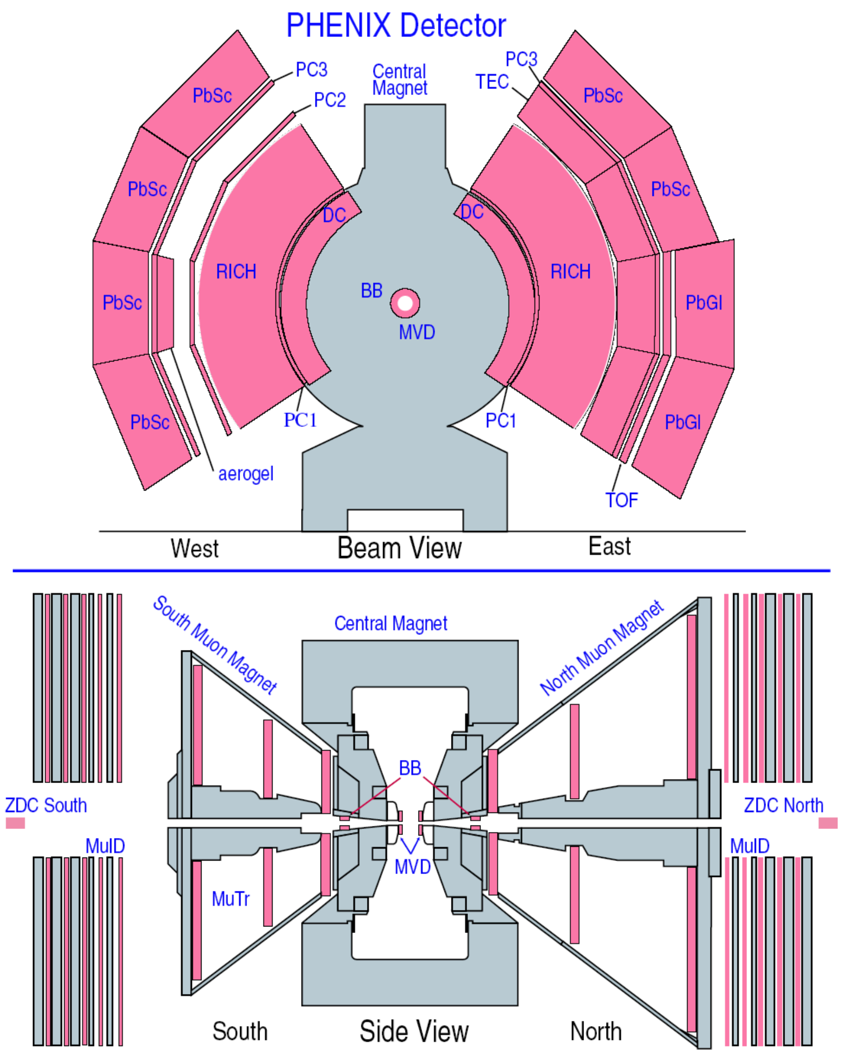
$\langle P_T/P \rangle$=14±2(%)
$\langle P_L/P \rangle$=98.94±0.21±0.04(%)

- Measurement of remaining transverse component → spin pattern is correct

Developed in Run-5, now routine operation

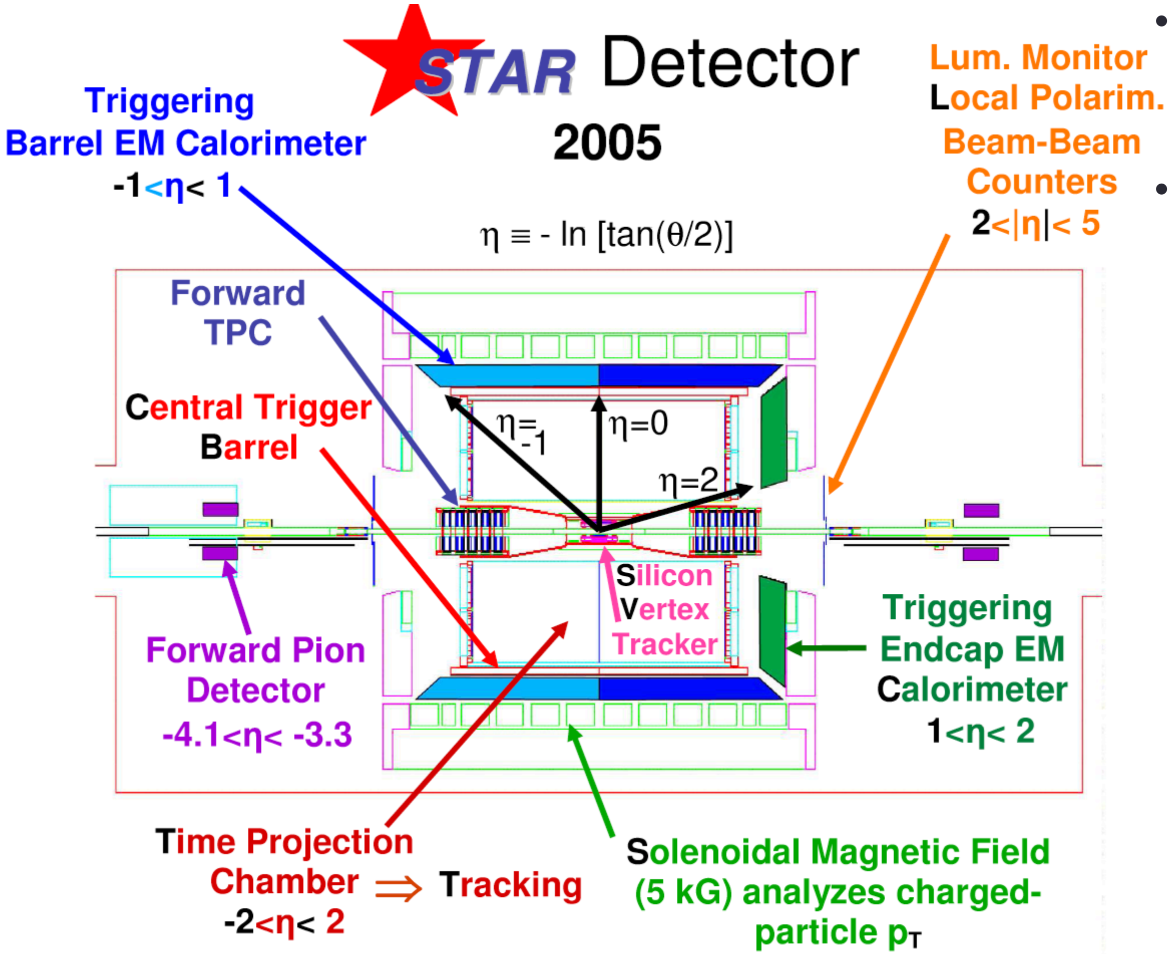
ΔG MEASUREMENTS

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
    $\Delta\phi x \Delta\eta \sim 0.01 \text{ x } 0.01$
    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

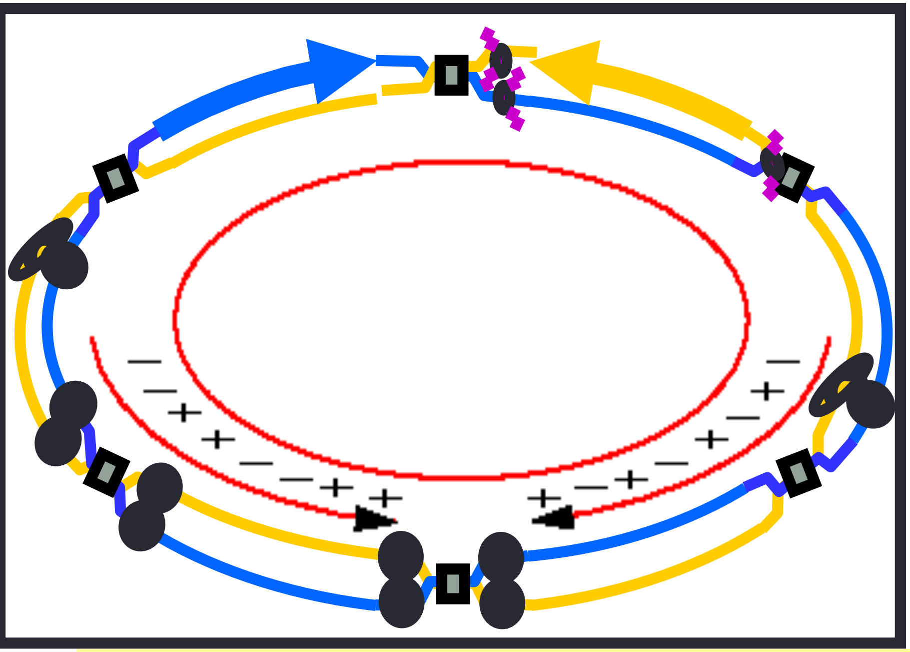
STAR Detector at RHIC



- *Design Philosophy:*
  - *Maximize acceptance*
  - *lower resolution*
- Subsystems:
  - f = 2p 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

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

Exquisite control over false asymmetries due to ultra fast rotations of the target and probe spin.

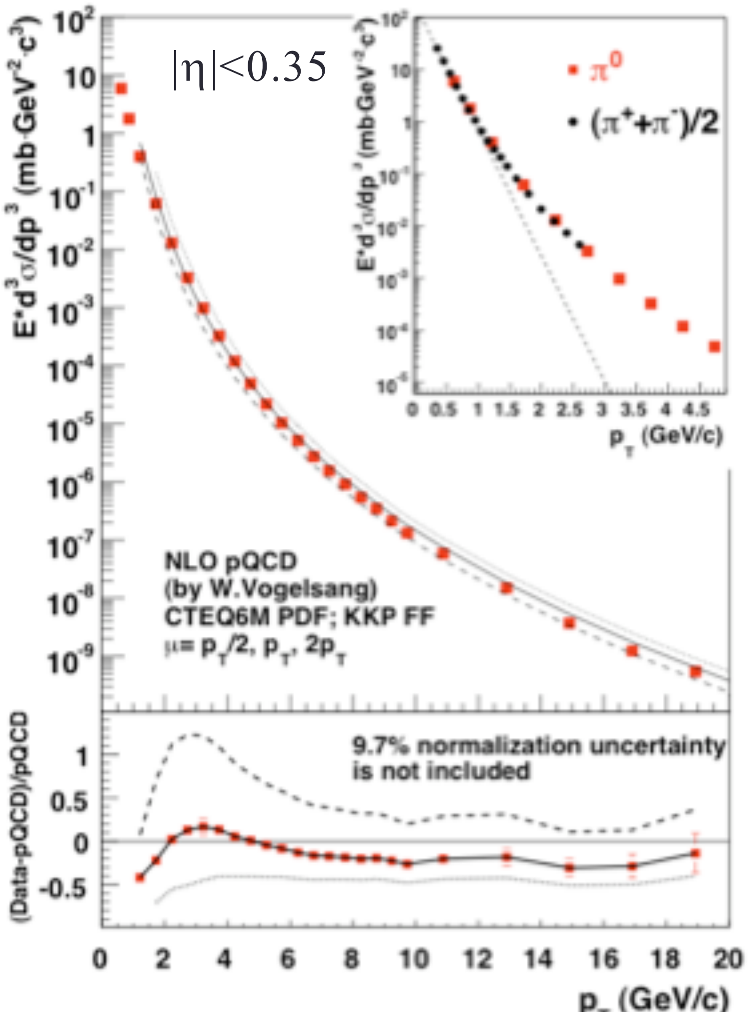
✓ Bunch spin configuration alternates every 106 ns
✓ Data for all bunch spin configurations are collected at the same time
⇒ Possibility for false asymmetries are greatly reduced

Calibration of our probes…

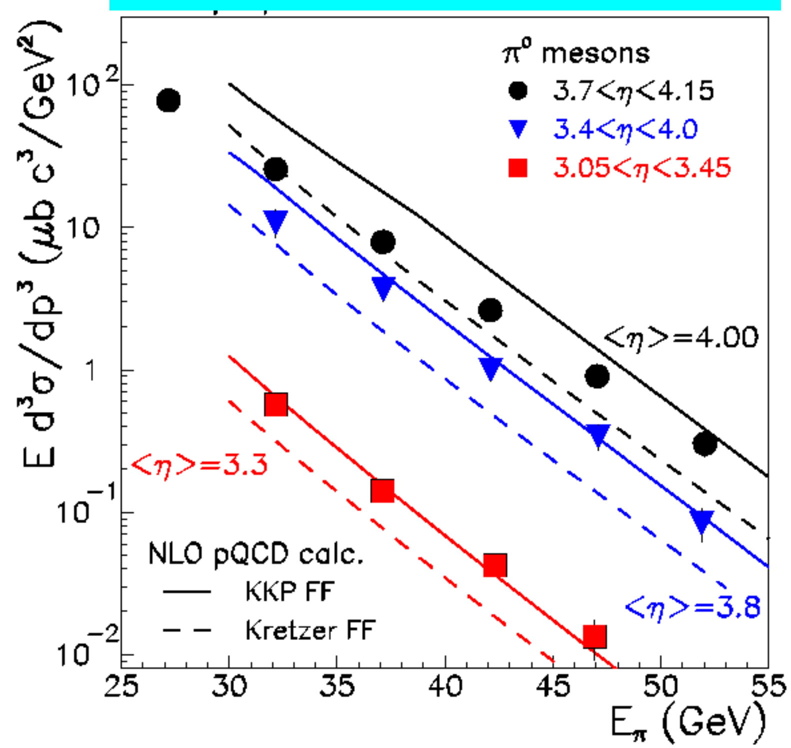
- Measurement of a cross section involves:
  - Detailed understanding of the luminosity
  - Detailed understanding of the detector
- Comparison of the data with theory: if they agree:
  - Theoretical framework applicable in this kinematic regime
  - Double spin asymmetries can be interpreted in terms of polarized gluon distributions
- **An extremely important check: Imperative for all measurements we publish**

Un-polarized π^0 Cross Section: 200 GeV CM

PHENIX: π^0 mid-rapidity (central)
hep-ex-0704.3599



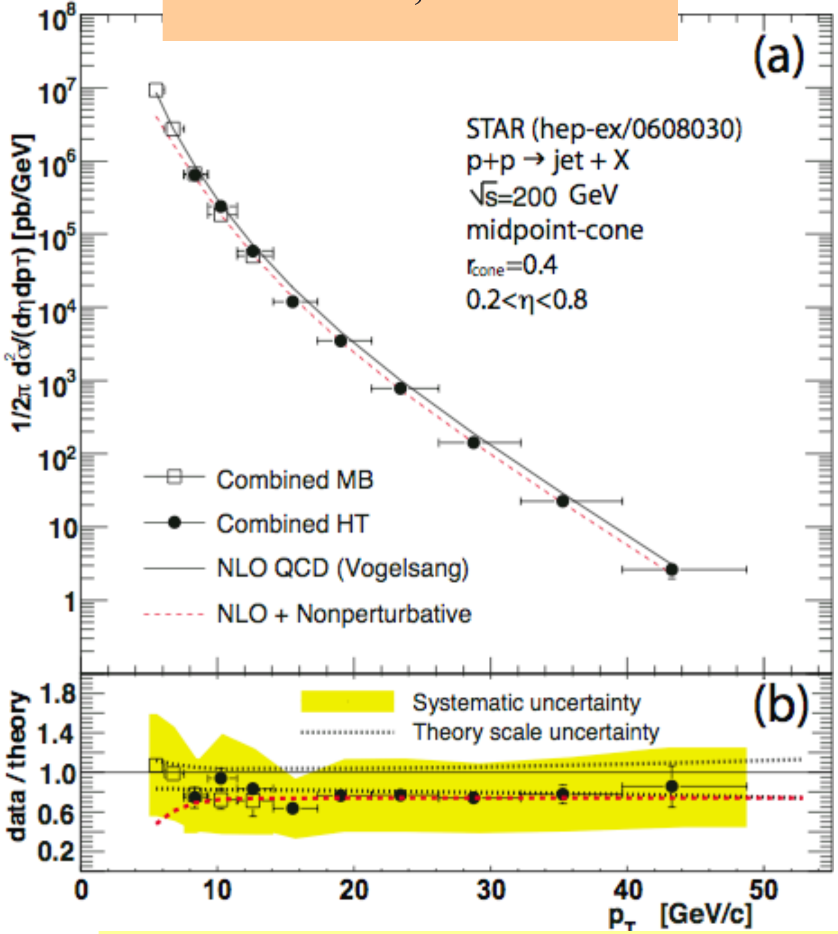
STAR: π^0 high rapidity (forward)
PRL 97, 152302



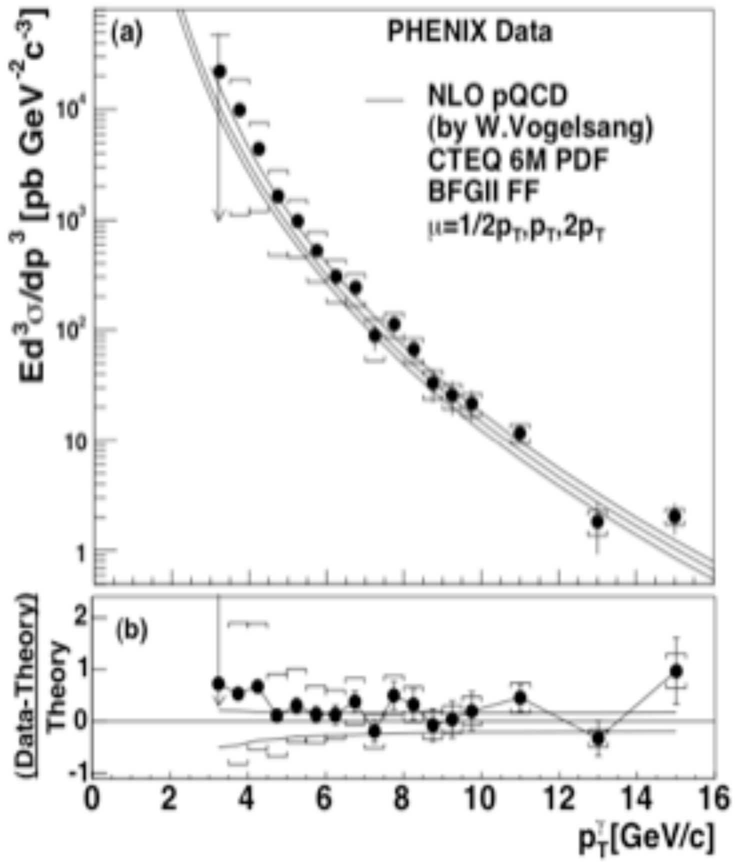
Good agreement between NLO pQCD calculations and data
Comparison fails at lower energies

Unpolarized Cross Section in *pp*

STAR: pp→jet X
PRL 97, 252001



PHENIX: pp→γ X
PRL 98, 012002



Excellent agreement between NLO pQCD calculations and data

Accessing ΔG in p+p Collisions at RHIC

$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{\sum_{a,b,c=q,\bar{q},g} \Delta f_a \otimes \Delta f_b \otimes \Delta\hat{\sigma} \otimes D_{\pi/c}}{\sum_{a,b,c=q,\bar{q},g} f_a \otimes f_b \otimes \hat{\sigma} \otimes D_{\pi/c}}$$

From ep (&pp) (HERA mostly)

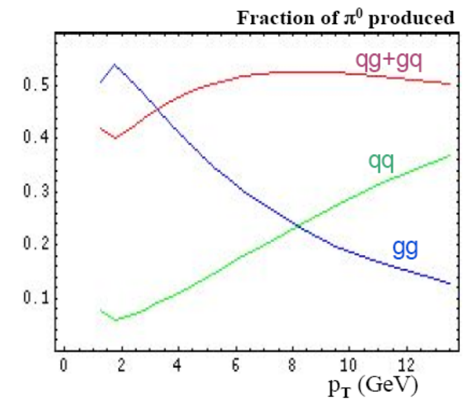
NLO pQCD

From e+e- (& SIDIS,pp)

- If Δf = Δq, then we have this from pDIS
- So roughly, we have

$$A_{LL} \cong a_{gg}\Delta g^2 + b_{gq}\Delta g \Delta q + c_{qq}\Delta q^2$$

where the coefficients a, b and c depend on final state observable and event kinematics (η,p_T).



+- = 

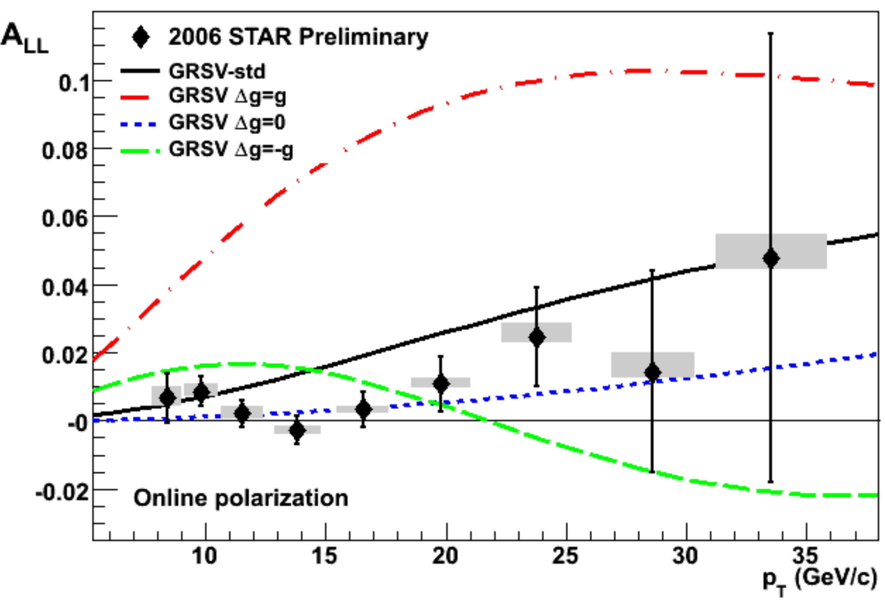
++ = 

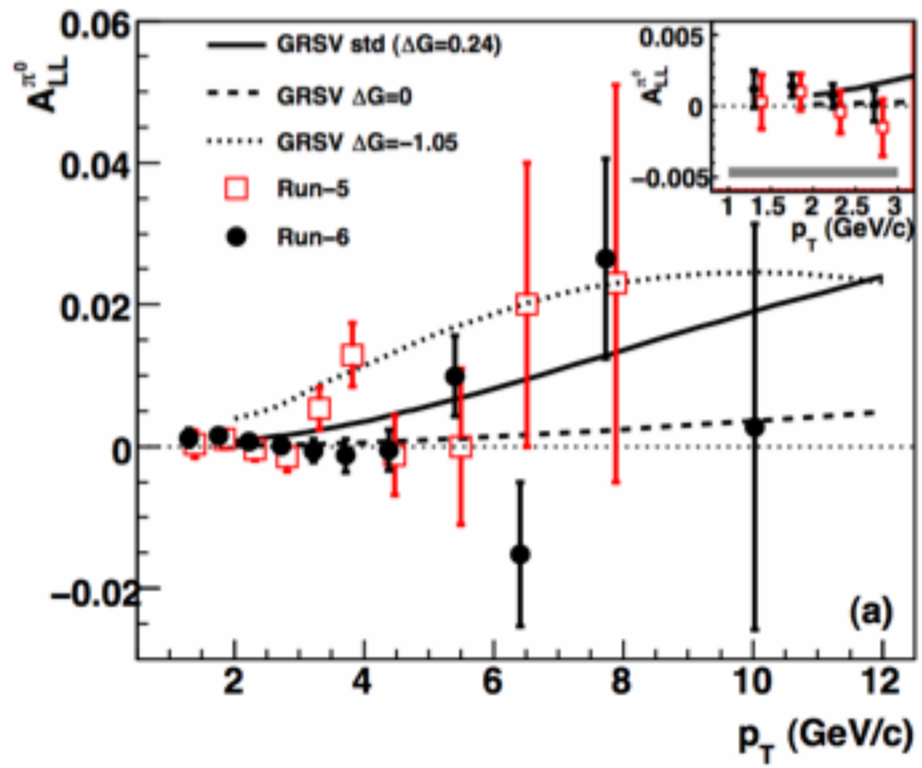
2005, 2006 Run Data Sets Analyzed

GRSV: NLO Fit to the polarized DIS data to extract polarized gluon distribution: PRD63, 094005 (2001)

- 2005
- 2006 Preliminary

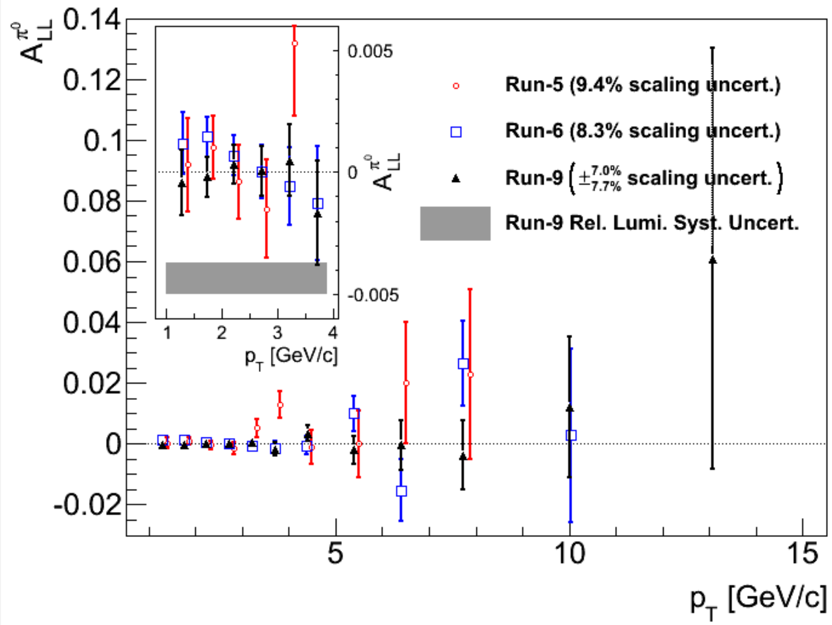
- 2005: PRD76, 05116
- 2006: arXiv:0810.0694 (PRL)



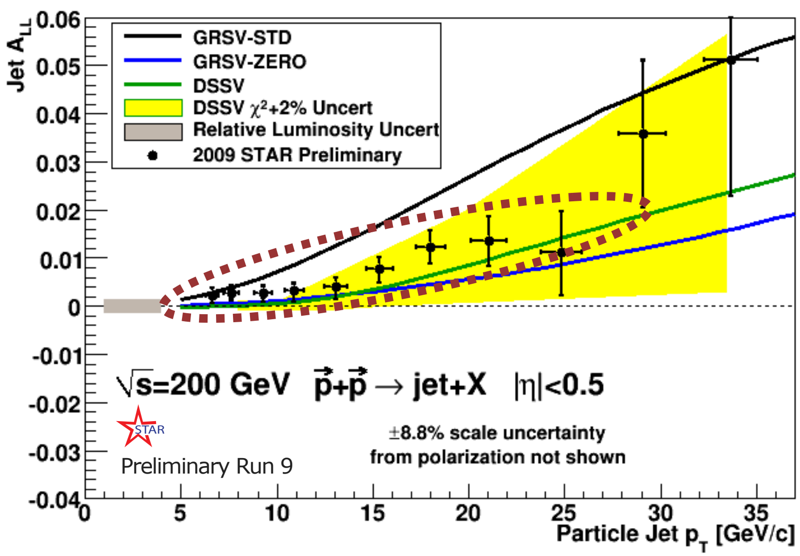


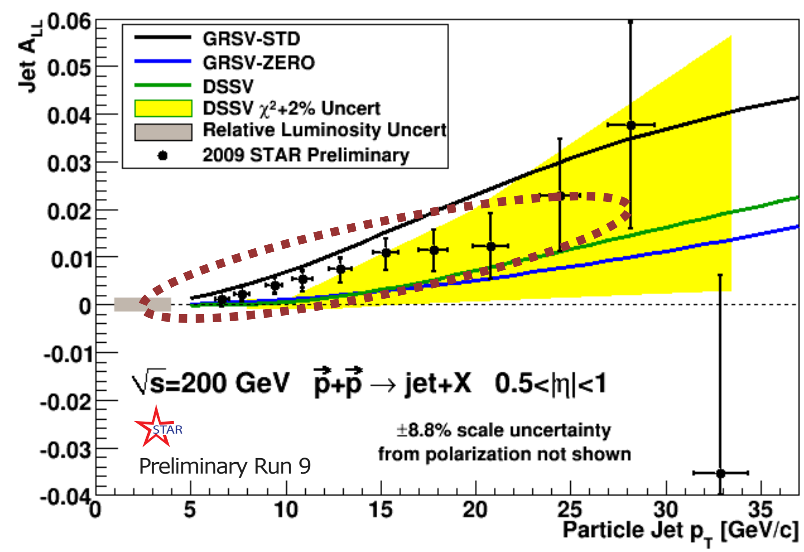
Most impactful results: on ΔG

- Inclusive probes
- Many others but highest impact with π^0 and jets
- Have been used in recent NLO pQCD analyses
- Experimental & theory systematic uncertainties have largely been downplayed.. This is an opportunity for near term improvement (Manion's talk)



A. Manion for PHENIX

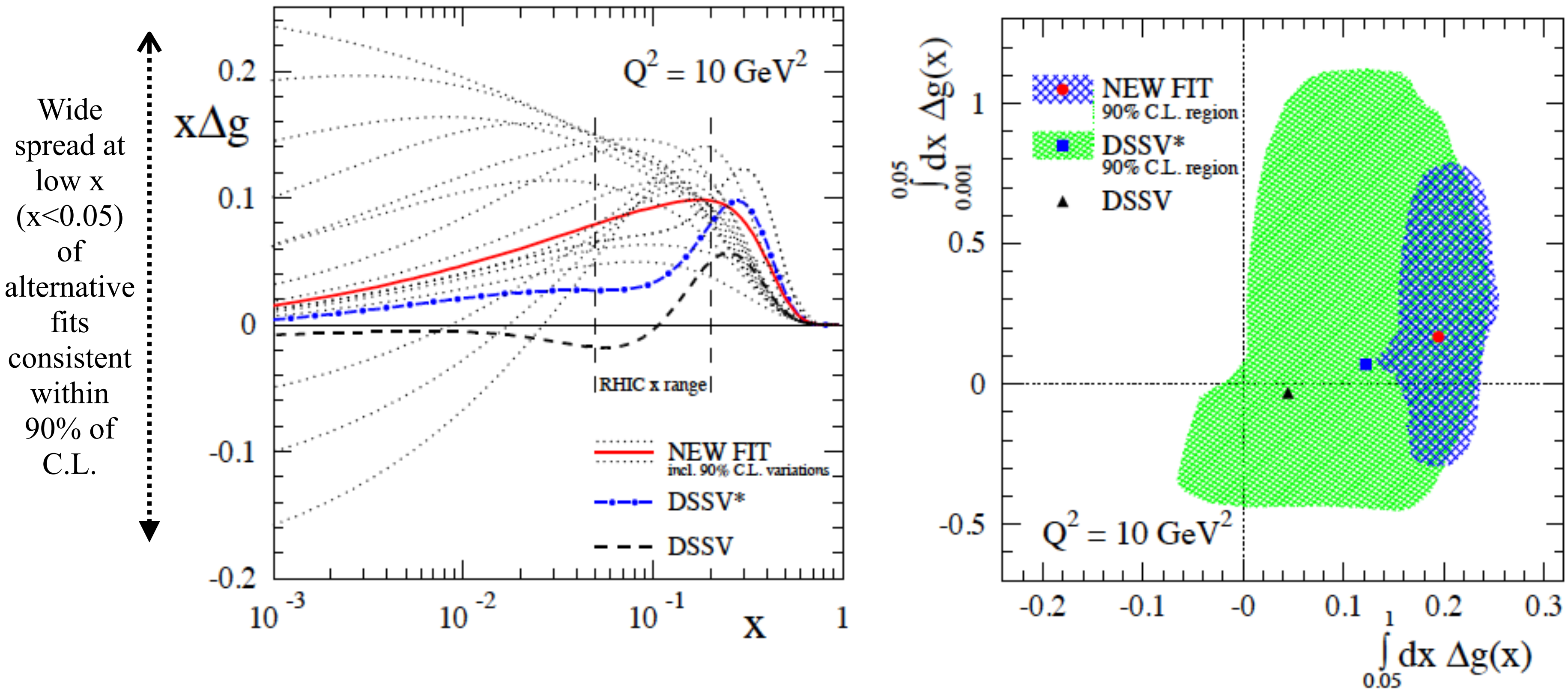




B. Surrow for STAR at DIS2014

Recent global analysis: DSSV

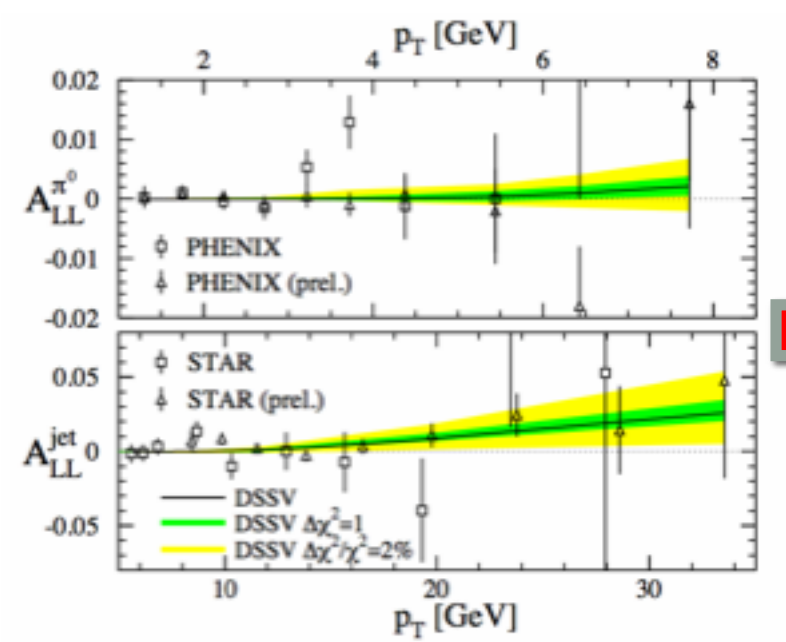
D. deFlorian et al., arXiv:1404.4293

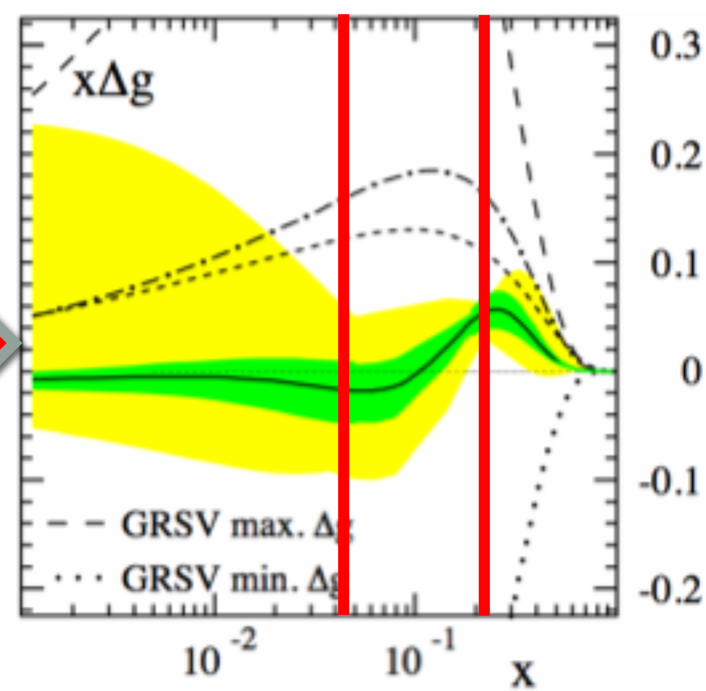


Dramatically makes the statement that, while we have made a huge impact, We are improving ΔG contributions only in a limited x-region, allowing large uncertainties to remain in the low-x unmeasured region!

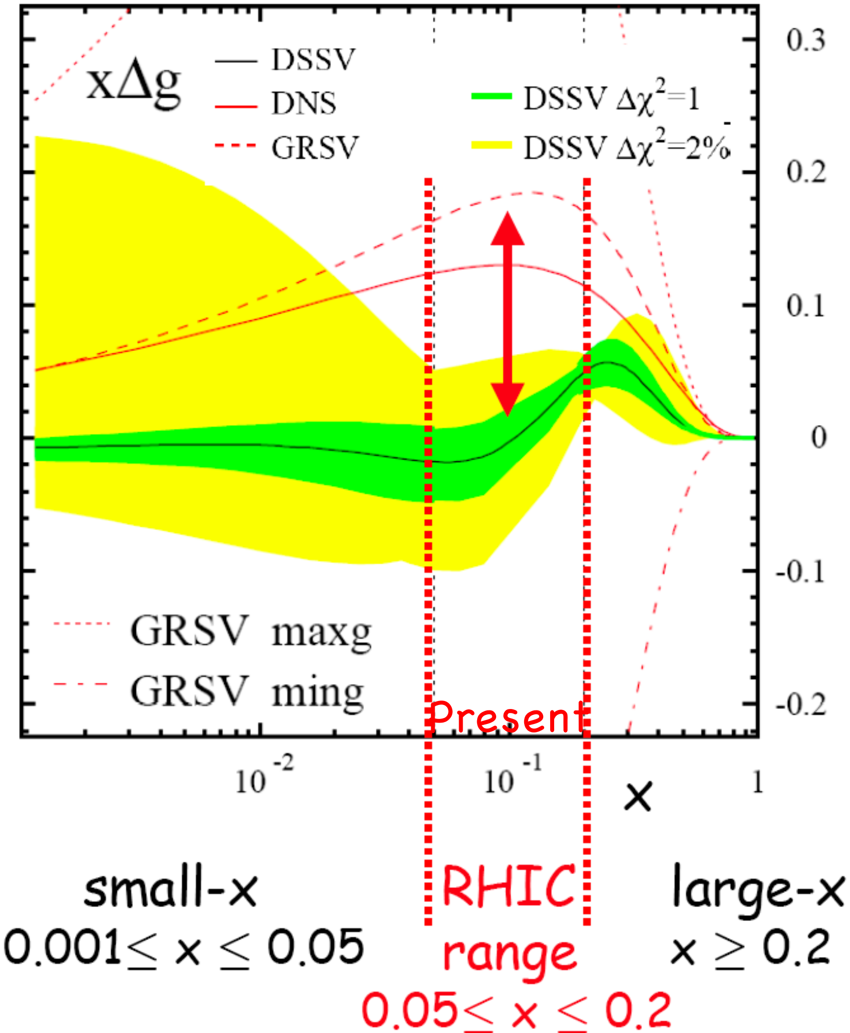
1st step: truly global NLO QCD fit

- D. de Florian et al, PRL 101, 072001 (2008)
- Includes PHENIX Inclusive π^0 at 200 and 62 GeV and STAR inclusive Jets at 200 GeV along with world's polarized DIS data sets → ***Resulting ΔG is small, with large uncertainties***



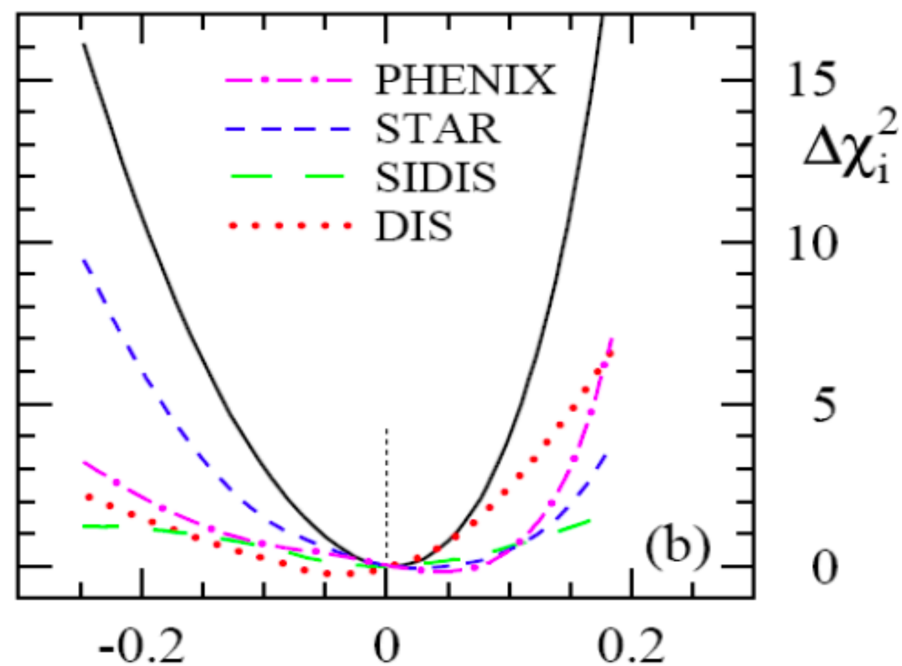


ΔG(x) @ Q²=10 GeV²



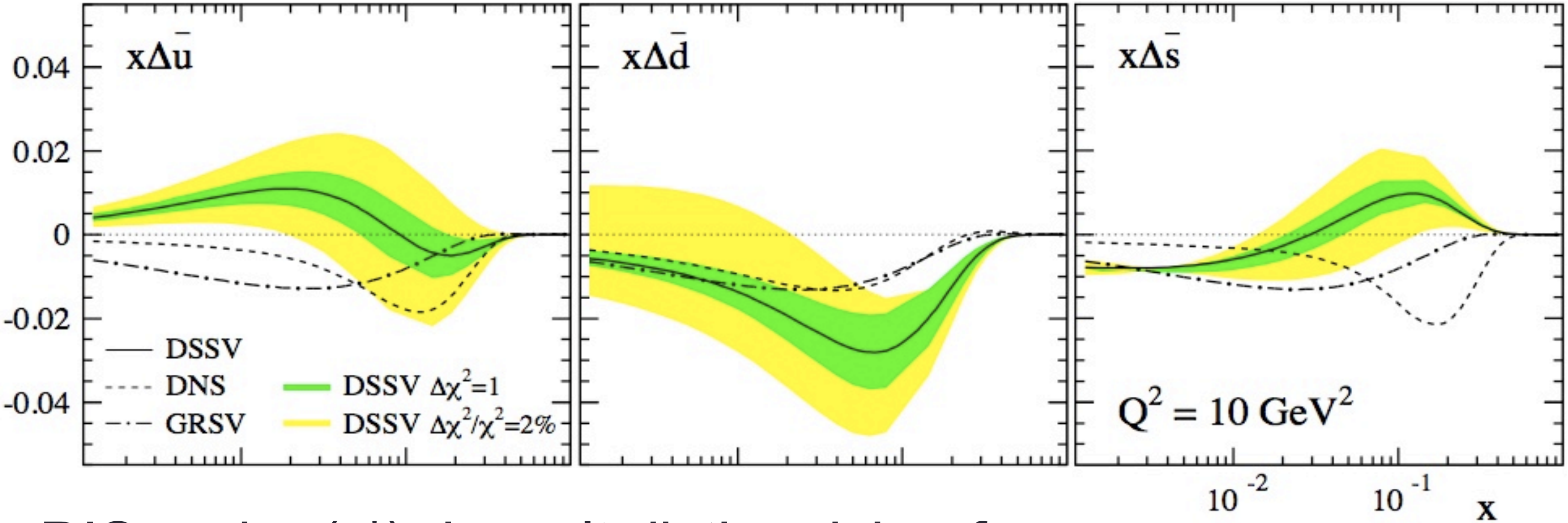
de Florian, Sassot, Stratmann & Vogelsang

- **Global analysis: DIS, SIDIS, RHIC-Spin**
- **Uncertainly on ΔG large: Need more low-x measurements!**



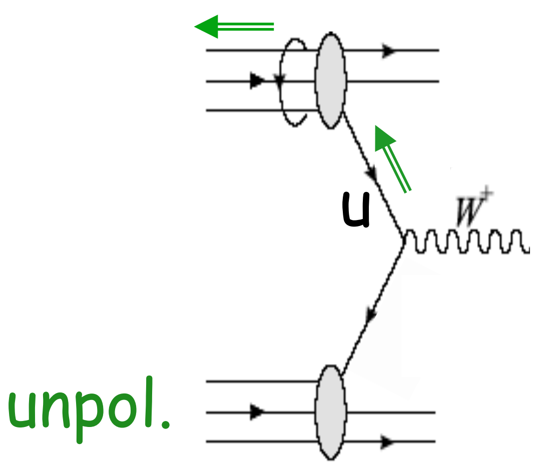
$$\delta g \equiv \int_{0.05}^{0.2} \Delta g(x, 10\ \mathrm{GeV}^2)dx$$

What about the anti-quark polarization?



- DIS probe (γ^*) doesn't distinguish q from qbar
  - Has to take measure semi-inclusive (π, K production)
  - Uncertainties in fragmentation functions
- High energy p-p collisions enable probing q,qbar through $W^{+/-}$ production –> Plan at RHIC

Anti-Quark Polarization measurement via W production and decay



$$\sqrt{s} = 500 \text{ GeV}$$

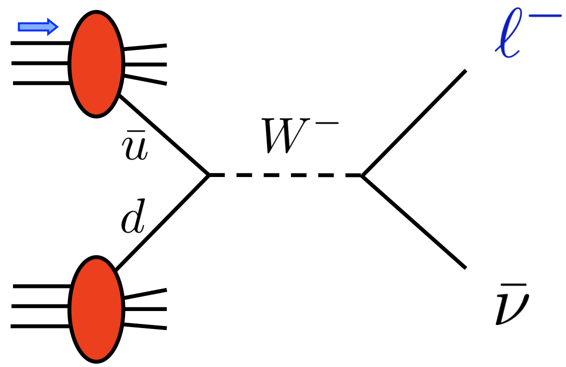
- Large parity violating effect anticipated

$$A_L = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} \neq 0$$

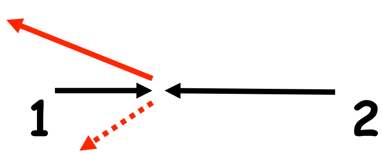
- Measurement complimentary to SIDIS, but devoid of fragmentation function makes it cleaner!

- NLO analyses about now available

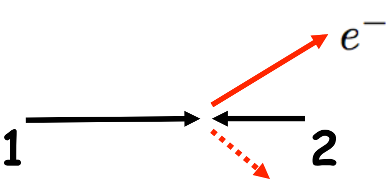
Some insight in to what goes on….



$$\sigma^{W^-} \propto \bar{u}(x_1)\, d(x_2) \qquad + \; d(x_1)\, \bar{u}(x_2)$$

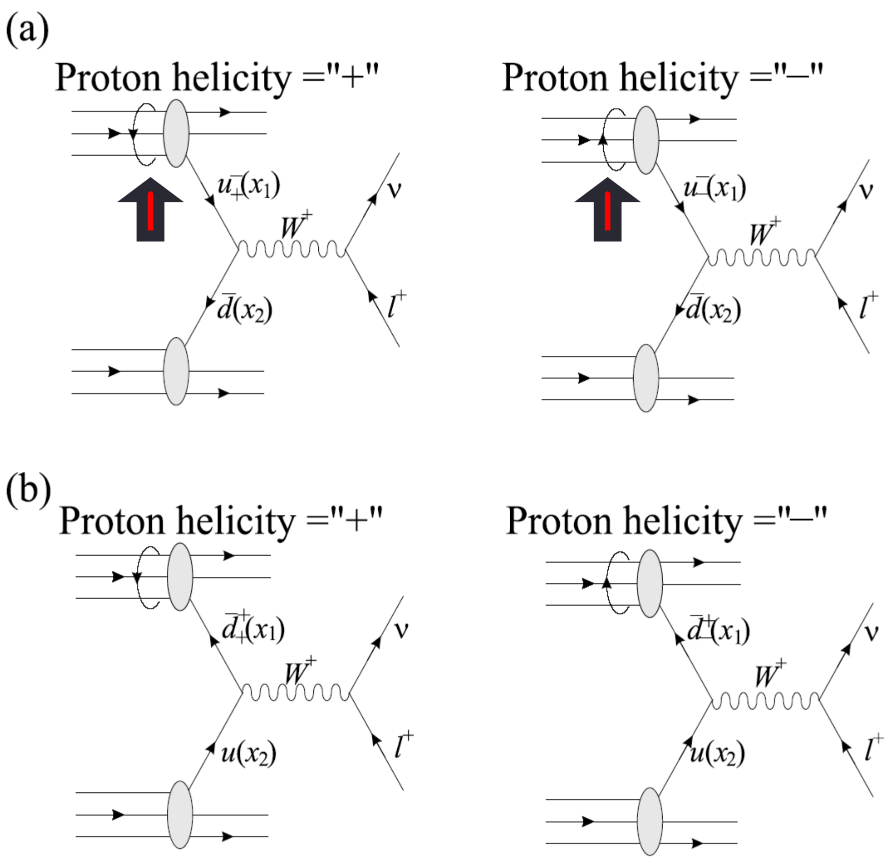


$\bar{u}(x_1)\, d(x_2)$



$d(x_1)\, \bar{u}(x_2)$

W production @ RHIC



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

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

Identify a W event:

W decays in to a charged lepton and a neutrino

Spin and momentum correlations important

→40 GeV charged lepton + 40 GeV neutrino

→Identification of charged lepton?

Isolated charged lepton identification (e or μ)

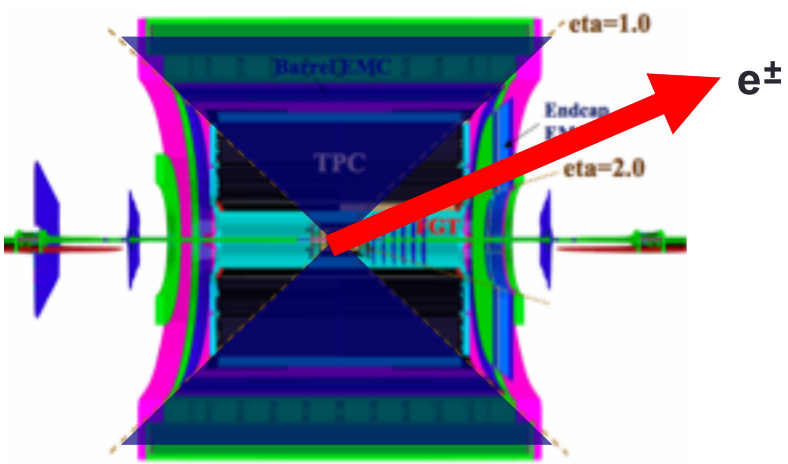
If electron final state is measured: (central arms of PHENIX, every where in STAR), with electromagnetic calorimetry

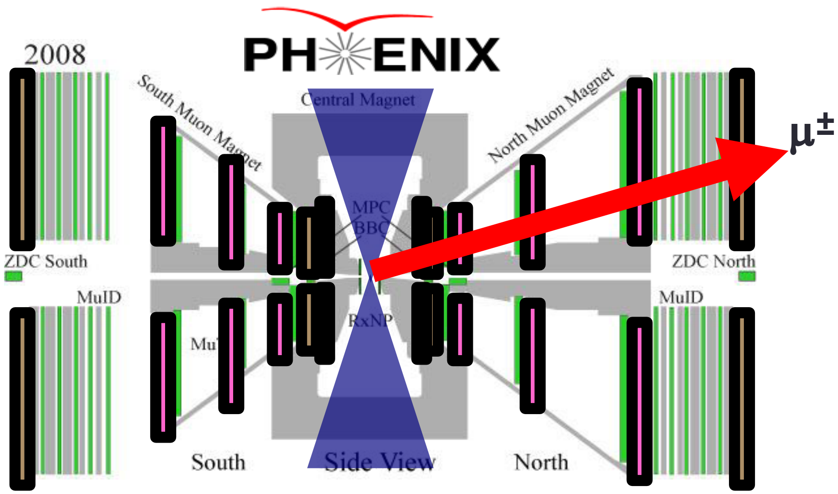
If muon final state, tracking and MuID system is needed:

→MuID : large amount of material followed by tracking

→Every thing else will stop in the material, except muons

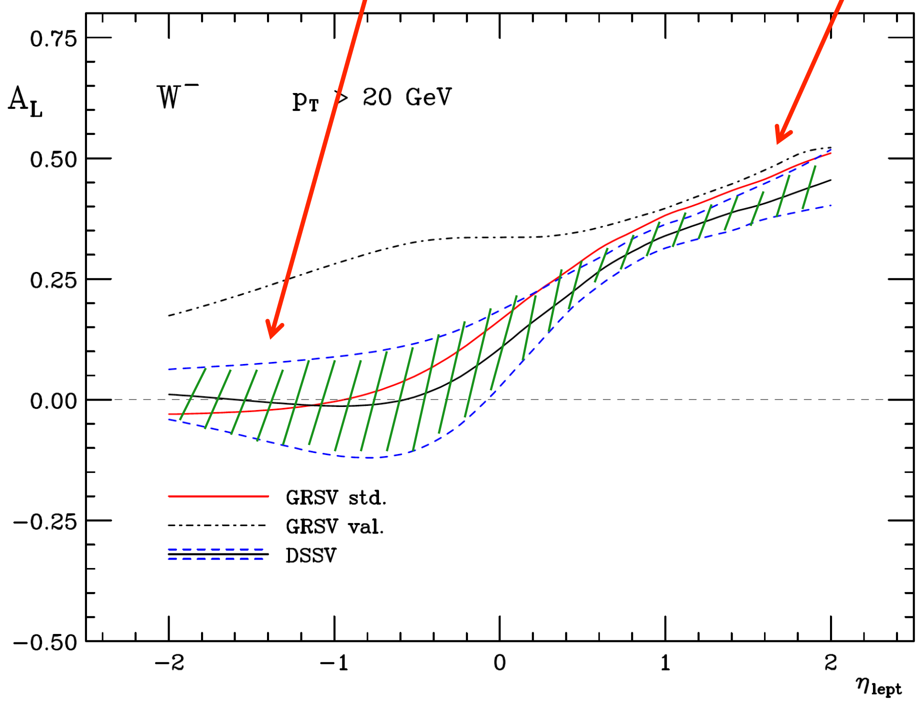
→Background subtraction challenging in both cases since all mesons and unstable hadrons typically have decays resulting finally in electrons or/and muons

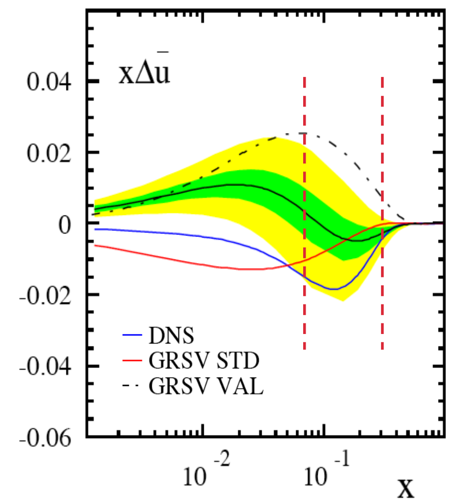

eta=1.0
BarrelEMC
Endcap
TPC
eta=2.0
FGT
e±


2008
PHENIX
South Muon Magnet
Central Magnet
North Muon Magnet
MPC
BBC
RxNP
ZDC South
ZDC North
MuID
MuID
South
Side View
North
μ±

Single spin asymmetry in full detail….

$$A_L^{e^-} \approx \frac{\int_{\otimes(x_1,x_2)} [\Delta\bar{u}(x_1)d(x_2)(1-\cos\theta)^2 - \Delta d(x_1)\bar{u}(x_2)(1+\cos\theta)^2]}{\int_{\otimes(x_1,x_2)} [\bar{u}(x_1)d(x_2)(1-\cos\theta)^2 + d(x_1)\bar{u}(x_2)(1+\cos\theta)^2]}$$





$\theta > \frac{\pi}{2}$ $\theta < \frac{\pi}{2}$

First Observation of W's at RHIC
Exciting few years ahead… STAR

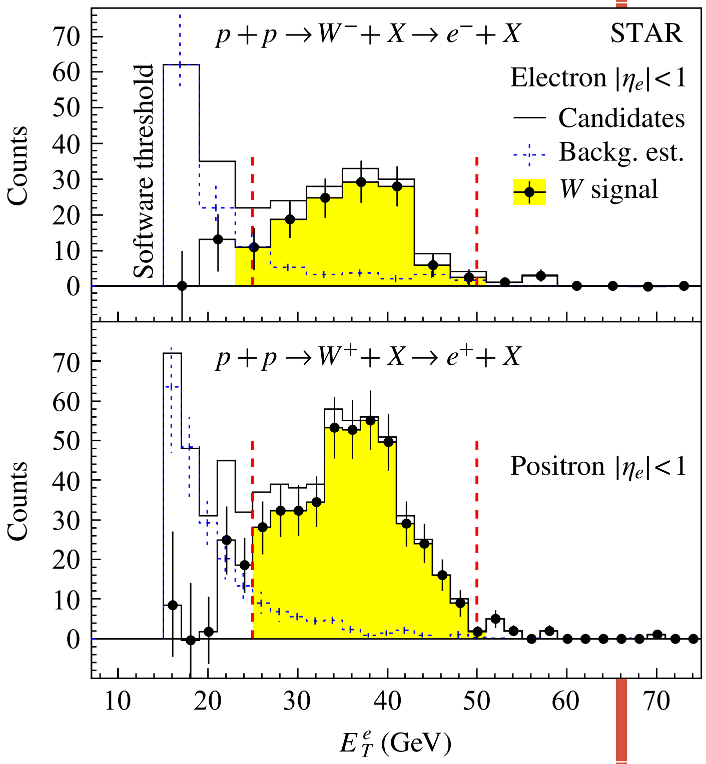
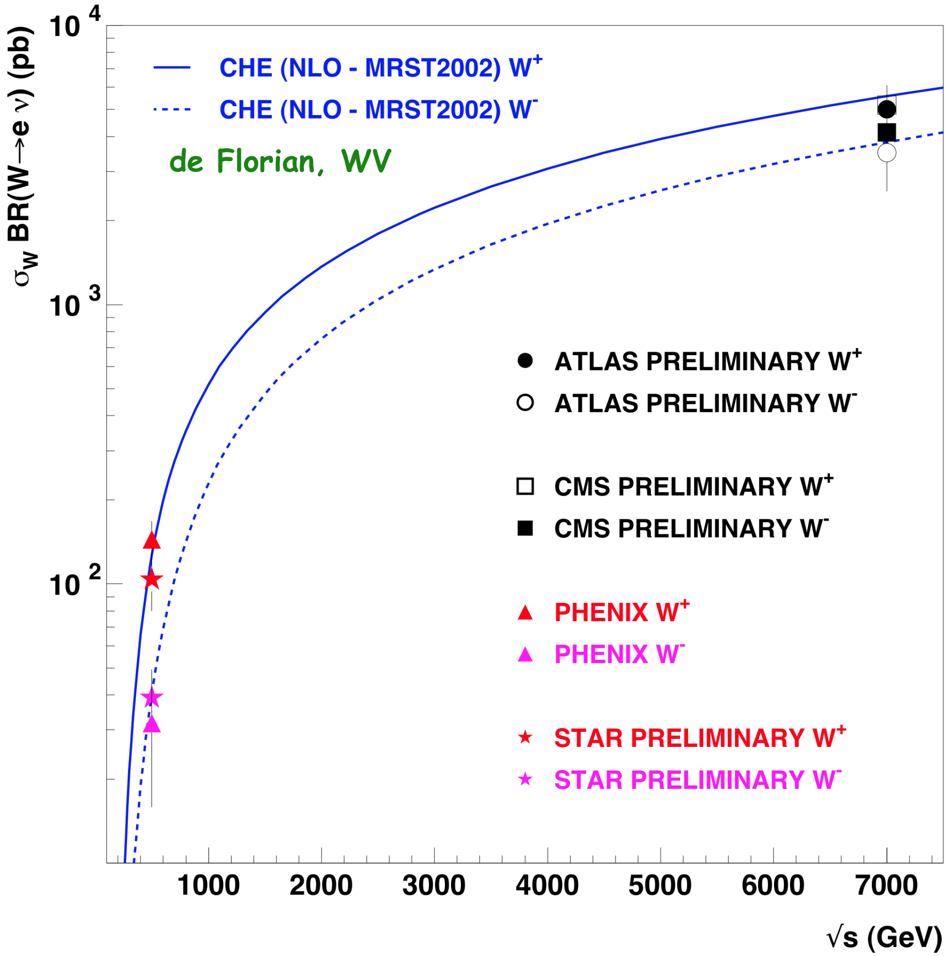


FIG. 3 (color online). E_T^e for W^+ (bottom panel) and W^- (top panel) events showing the candidate events as solid line histograms, the full background estimates as dashed line histograms, and the signal distributions as shaded histograms.

PRL **106,** 062002 (2011)

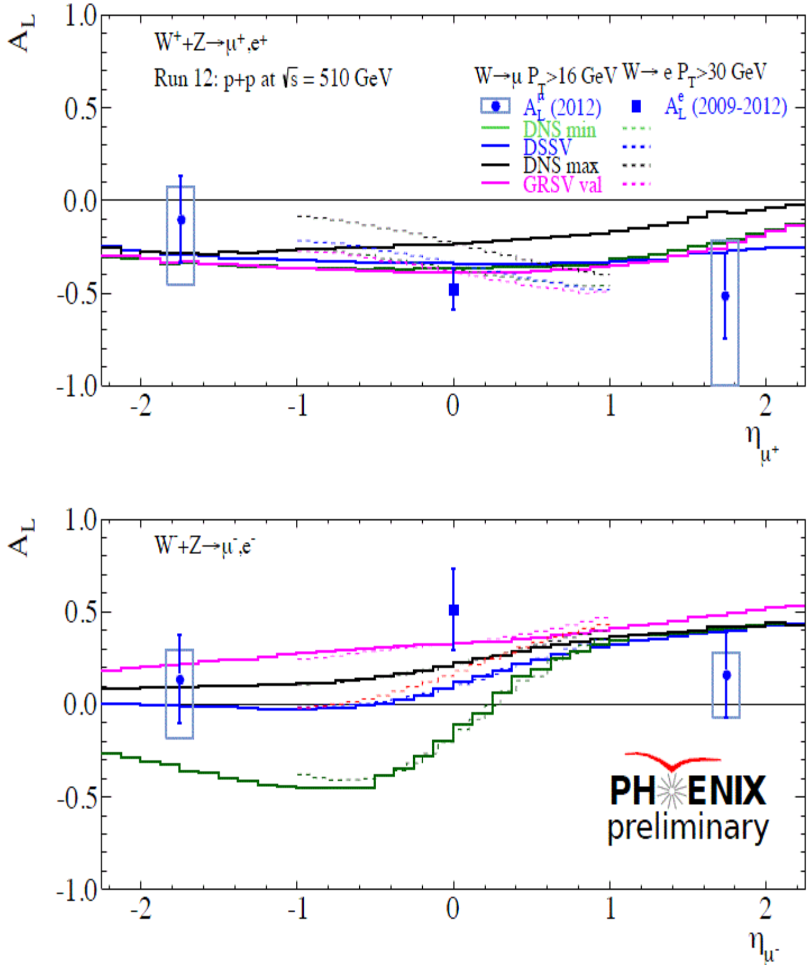
Calibration of probes…. W cross section



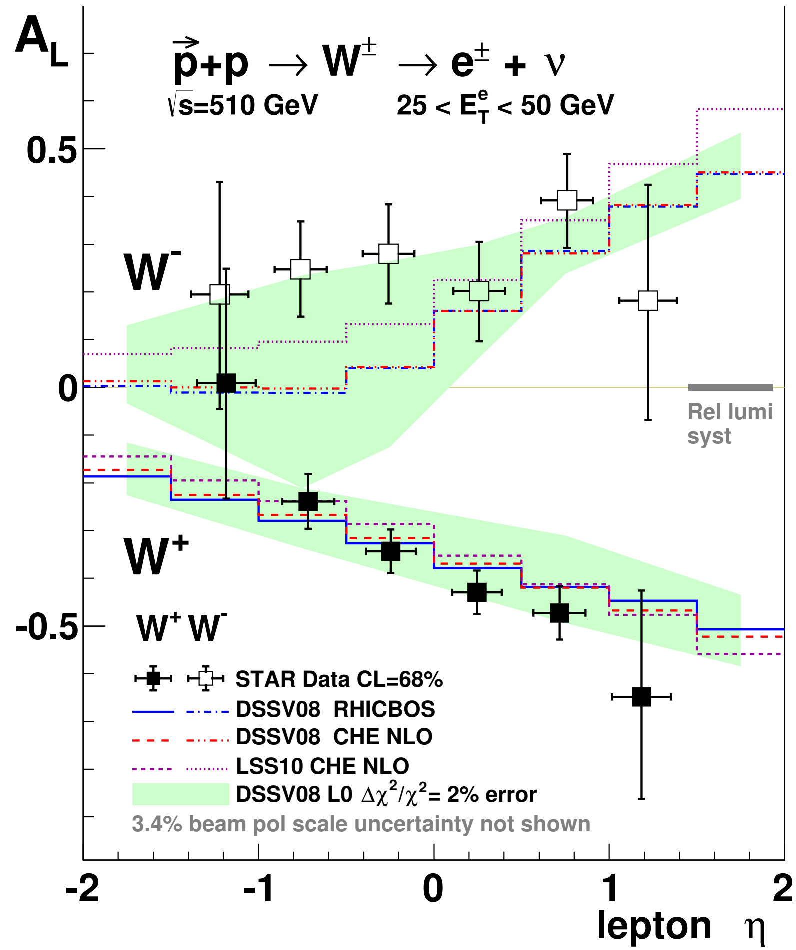
PHENIX and STAR
Data consistent with
Standard model predictions
Of p-p cross section

Recent results from RHIC: W→ $e^{+/-}$,$\mu^{+/-}$

N Bandara for PHENIX

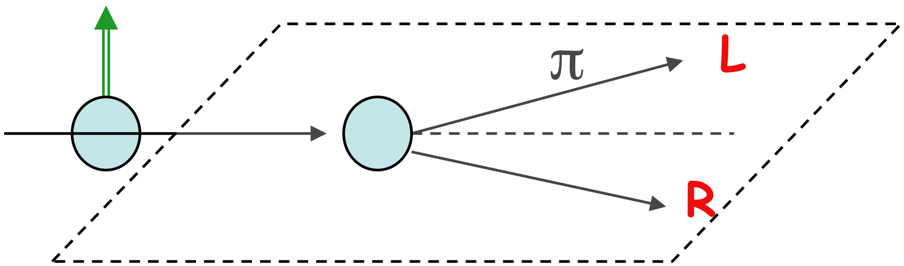


arXiv:1404.6880 STAR



Transverse Spin Physics at RHIC

Transverse spin introduction



$$A_N = \frac{N_L - N_R}{N_L + N_R}$$

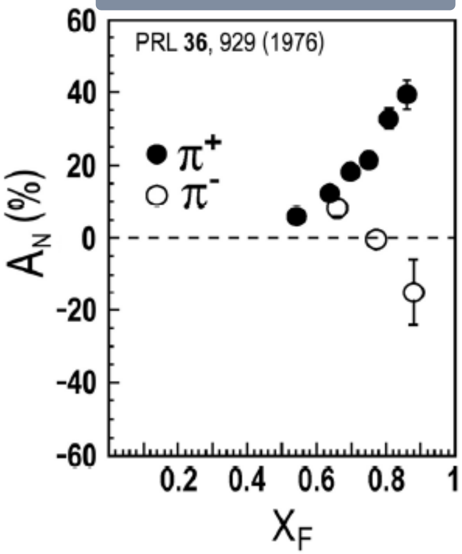
$$A_N \sim \frac{m_q}{p_T} \alpha_S$$

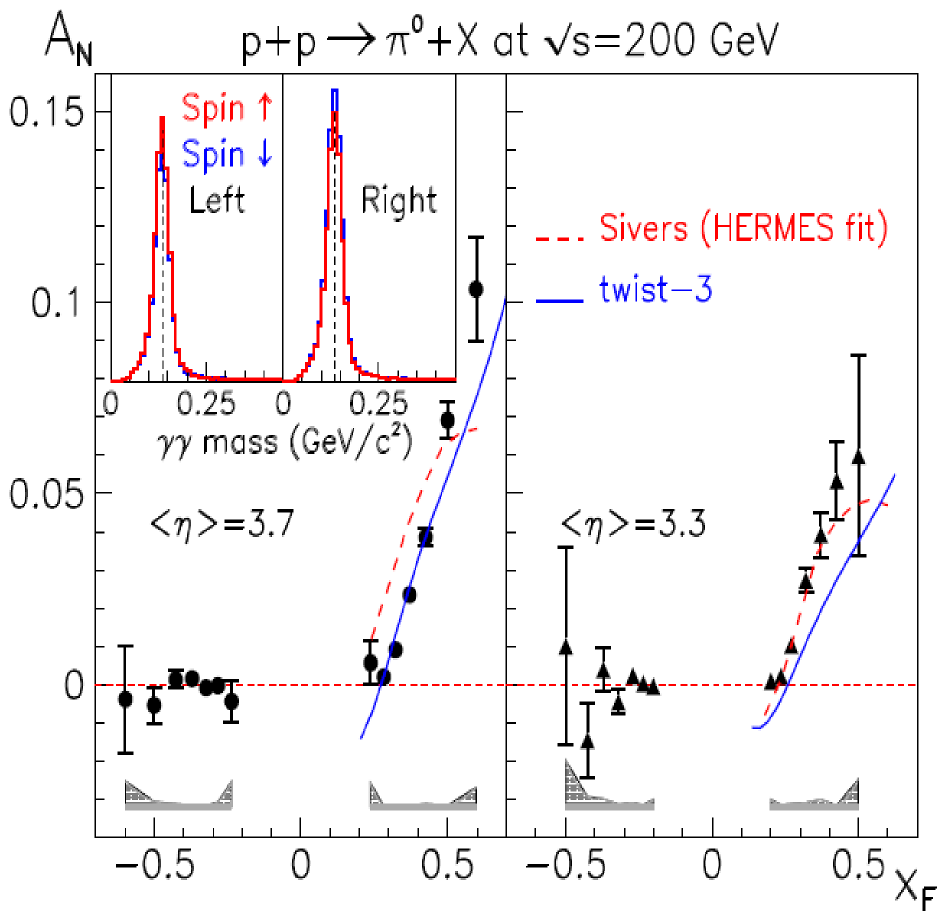
Kane, Pumplin, Repko 1978

- Since people starved to measure effects at high p_T to interpret them in pQCD frameworks, this was "neglected" as it was expected to be small….. However….
- Pion production in single transverse spin collisions showed us something different….

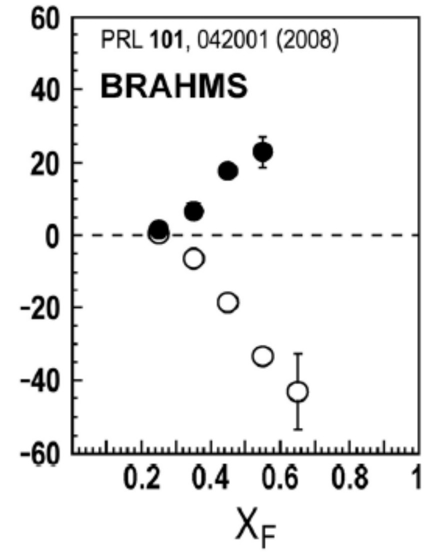
Pion asymmetries: at most CM energies!

ZGS/ANL
$\sqrt{s}$=4.9 GeV





RHIC
$\sqrt{s}$=62.4 GeV

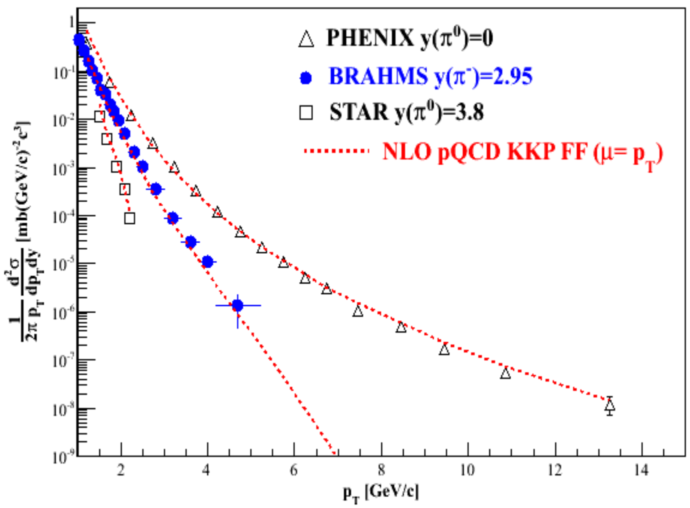


Suspect soft QCD effects at low scales, but they seem to remain relevant to perturbative regimes as well

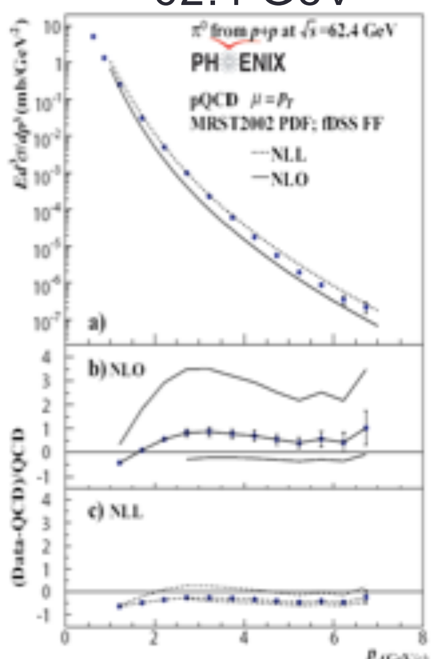
New at RHIC: pQCD Framework

- At 200 GeV Pion cross sections at both mid and forward rapidities described by NLO pQCD calculation.
- At 62.4 GeV pions are reasonably well described at both mid and forward rapidities NLL may be important

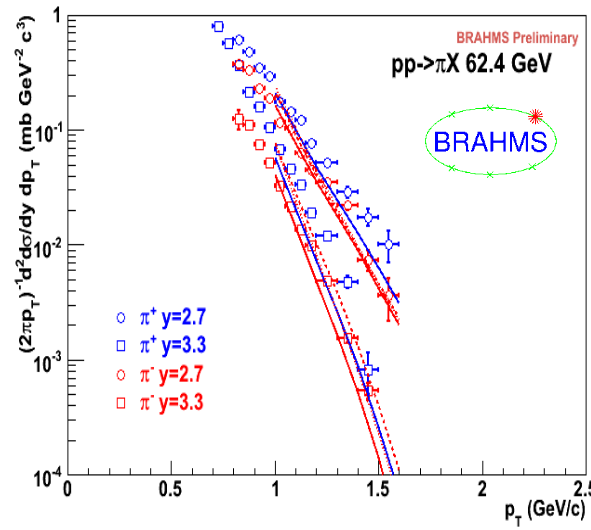
200 GeV



62.4 GeV



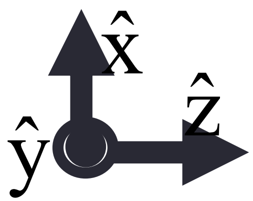
62.4 GeV



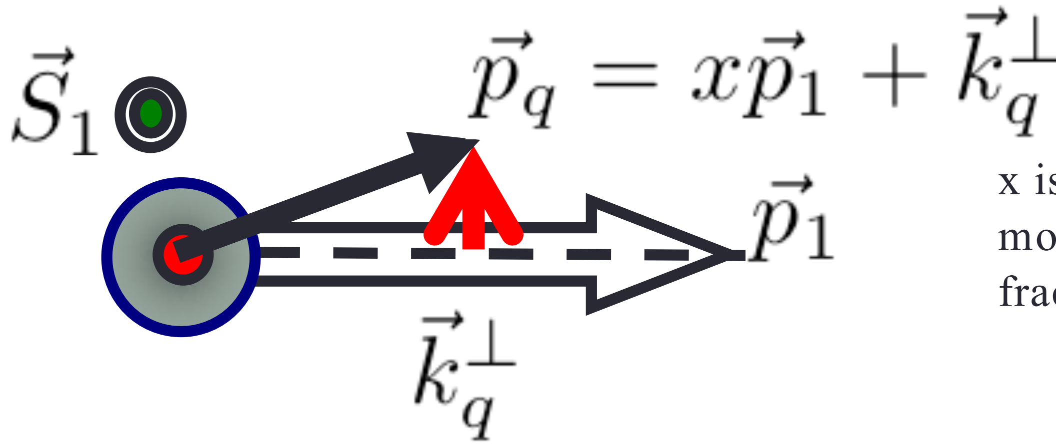
Sivers effect: due to transverse motion of quarks in the nucleon: initial state effect

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

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

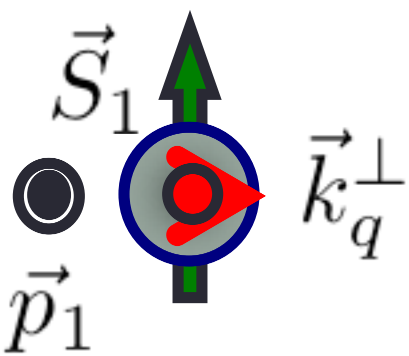


Top view



x is longitudinal momentum fraction.

Front view

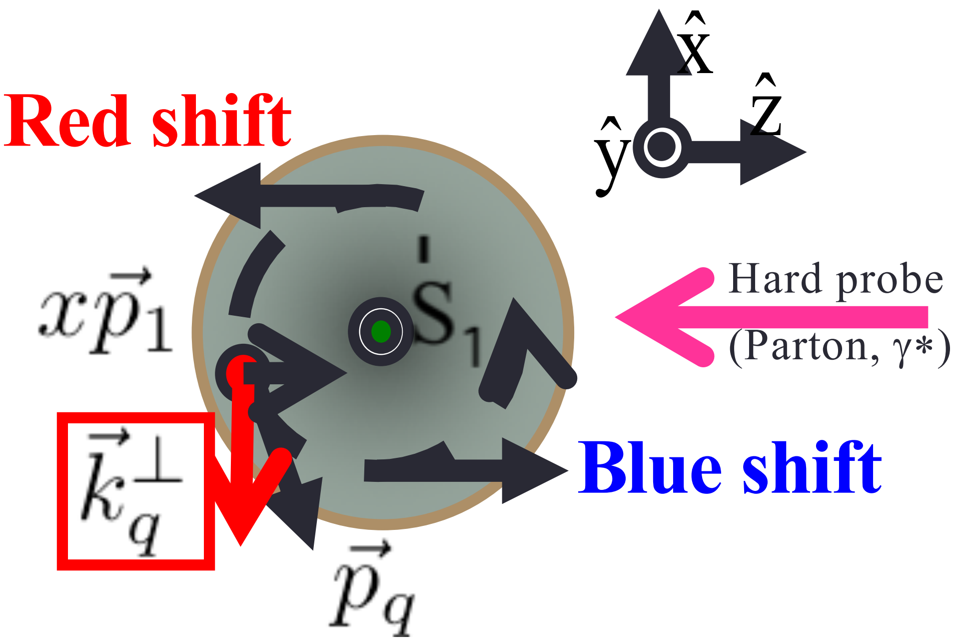


Quark transverse momentum in transversely polarized proton.

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

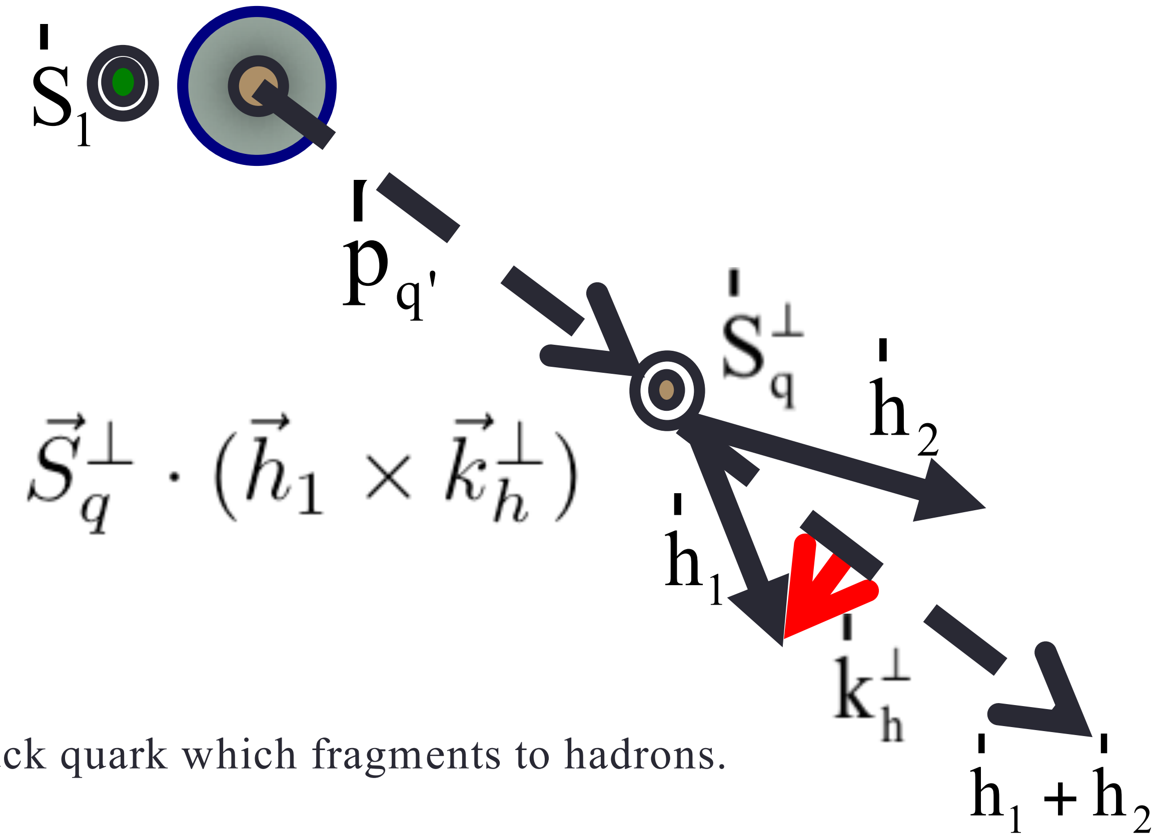
Generalized **P**arton **D**istribution Functions

PRD59 (1999) 014013

Collins (Heppelmann) effect: Asymmetry in the fragmentation hadrons

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

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

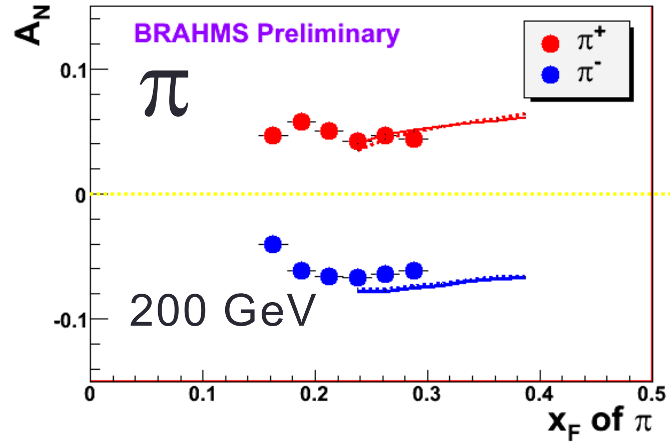


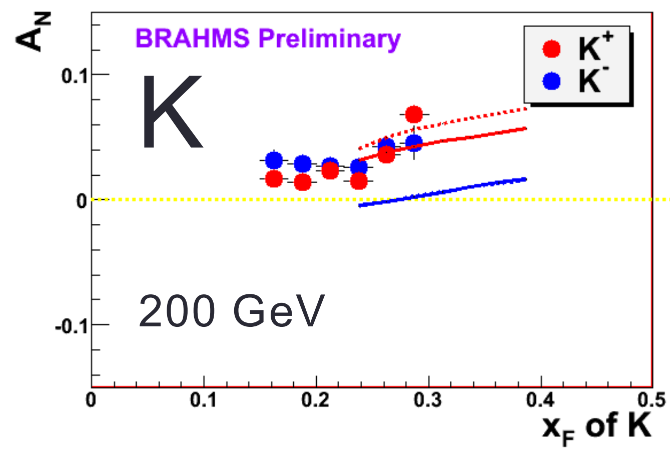
$$SSA_{Collins} \propto \vec{S}_q^{\perp} \cdot (\vec{h}_1 \times \vec{k}_h^{\perp})$$

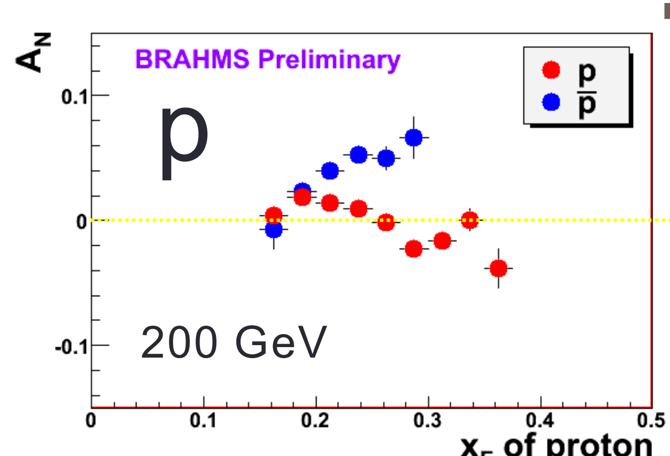
Polarization of struck quark which fragments to hadrons.

π,K,p 200 & 62.4 GeV

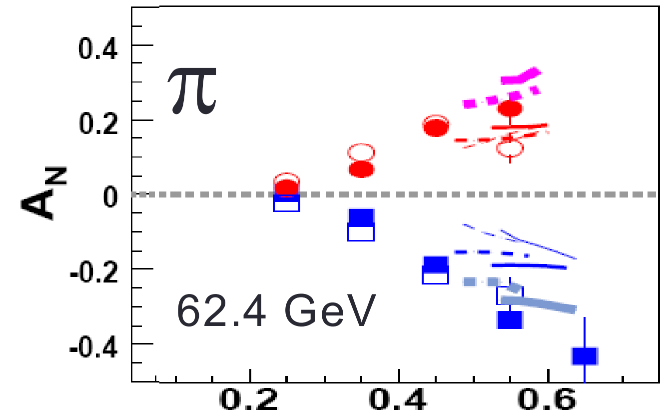
BRAHMS

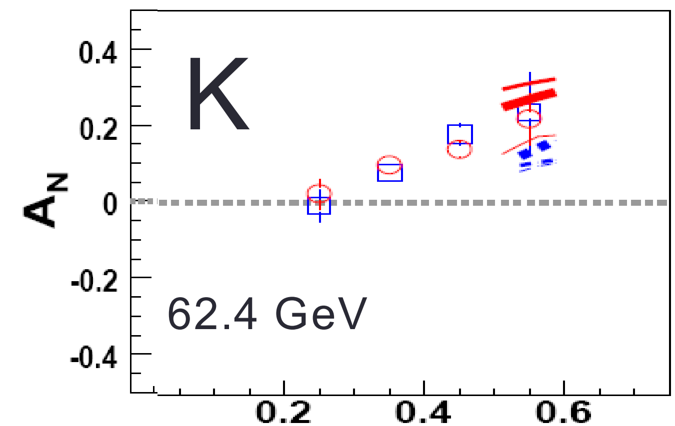


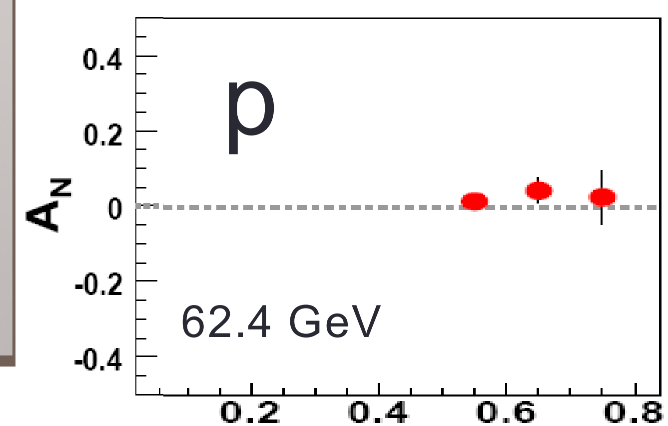




- Scales on plots different
- Kaon asymmetries not predicted
- Unfortunately no anti-proton measurement







Although not expected, at any observable level, 400+ times the expected values of asymmetries have been routinely seen experimentally: both in ep and pp systems.

Much work is now under progress to systematically study and understand them.

- Transverse motion/momentum of partons or
- Asymmetry in fragmentation process (final state) or
- Both …. May be responsible.

If it is the transvers momentum of quarks… then it may have direct connection to orbital motion of partons, and hence connected to the total angular momentum contributing to the nucleon spin!

- Much more on this in lectures by others…

Emergent picture of the nucleon:

RHIC has definitively shown that in x > 0.05, the GLUON's spin contribution to nucleon is small. Future facility should aim to make precise measurements at lower x.

RHIC seems to shown that quark anti-quark polarized PDFs are broadly consistent with expectations from SIDIS (not in violent disagreement!), early concerns about not knowing the fragmentation functions, possible higher twist and other complications of SIDIS: not a big concern.

Transverse spin in RHIC is quite possibly the best laboratory to test our understanding of QCD: Needing data and their understanding from e-p, e-e and theory to test if they can predict or explain the p-p:

A future Electron Ion Collider can certainly address these very precisely and conclusively