G. Bunce
RHIC PAC, 29 March 2007

RHIC Spin: from now to eRHIC

I would like to thank Les Bland, Werner Vogelsang, Abhay Deshpande, Sasha Bazilevsky, Matthias Grosse Perdekamp, Ernst Sichtermann, Bernd Surrow for their advice and many plots.

RHIC Spin Summary—LRP

The key points for RHIC Spin are:

- **Spin structure of proton**
- **Strongly interacting probes**
- **P=60%, L=2x10^31, root(s)=200 GeV in 2006**
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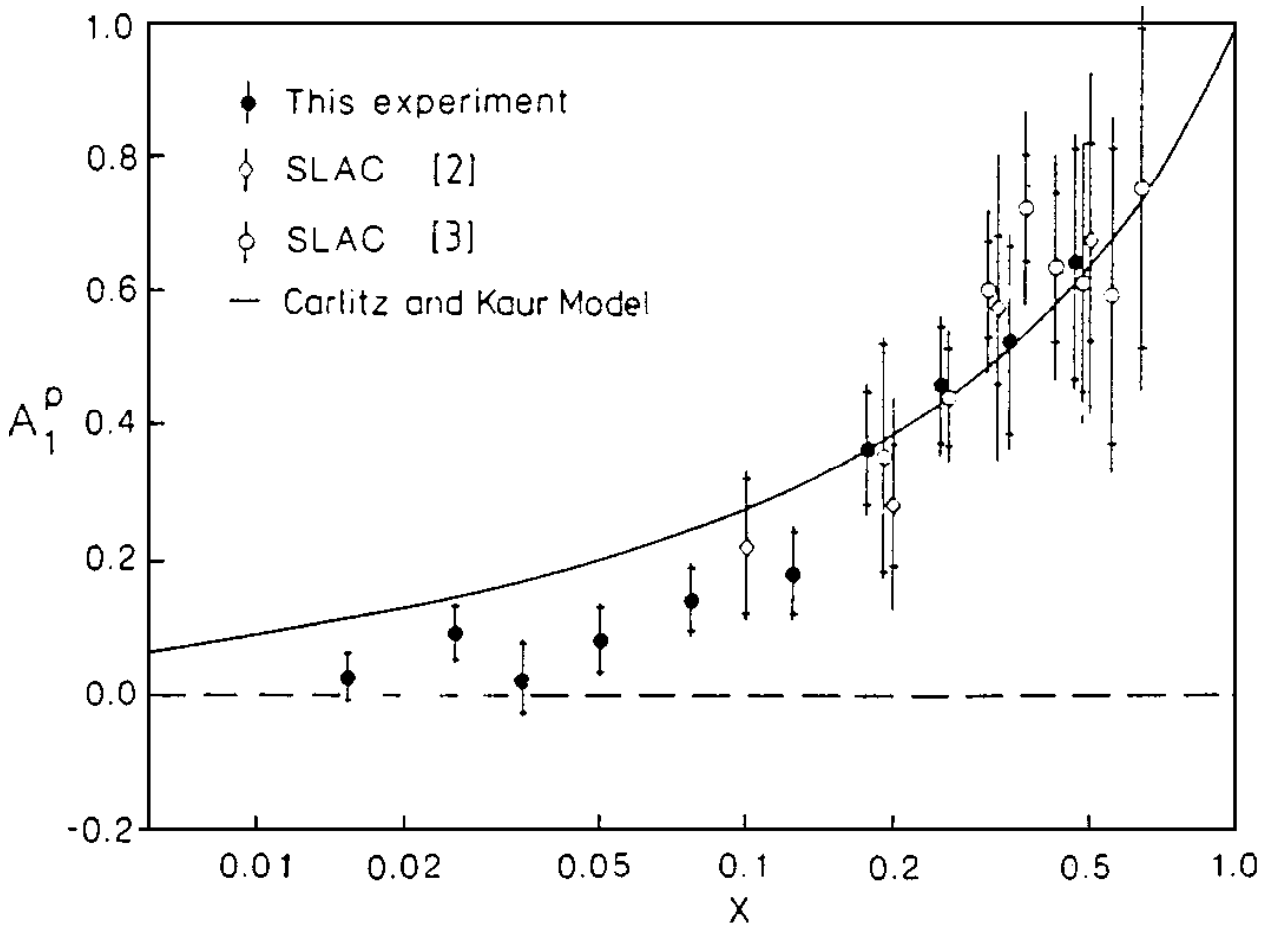
- **W boson parity violating production: ubar and dbar polarizations in proton**
- **Very large transverse spin asymmetries in pQCD region**
- **Theoretical advances on cross section, helicity, and transverse spin**
- **The RHIC Spin Plan and three goals for "RHIC II"**

EMC at CERN: J. Ashman et al., NPB 328, 1 (1989):
polarized muons probing polarized protons



$$\Delta\Sigma = \Delta u + \Delta d + \Delta s = 12 \pm 9(\text{stat}) \pm 14(\text{syst})\%$$

"proton spin crisis"

- **What else carries the proton spin ?**

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

  → **How are gluons polarized ?**
  → **How large are parton orbital angular mom. ?**

- **What are the detailed patterns of quark & antiquark polarizations ?**
  → **Flavor asymmetries in sea ? Strangeness ?**

- **What are the origins of large observed single-transverse-spin asymmetries ?**
  What do they tell us about the nucleon ?
  → **Transverse quark pol.? Correlations spin / parton k_T ?**
  Orbital angular momentum? Spatial distributions?

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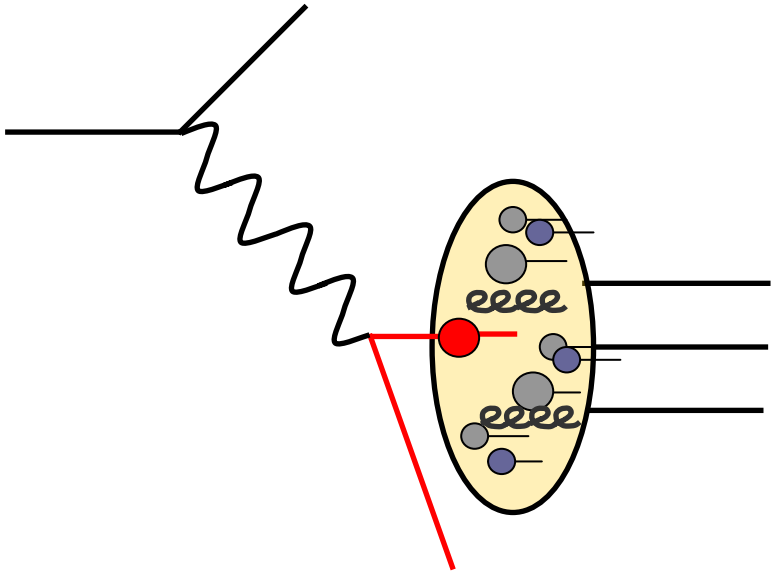
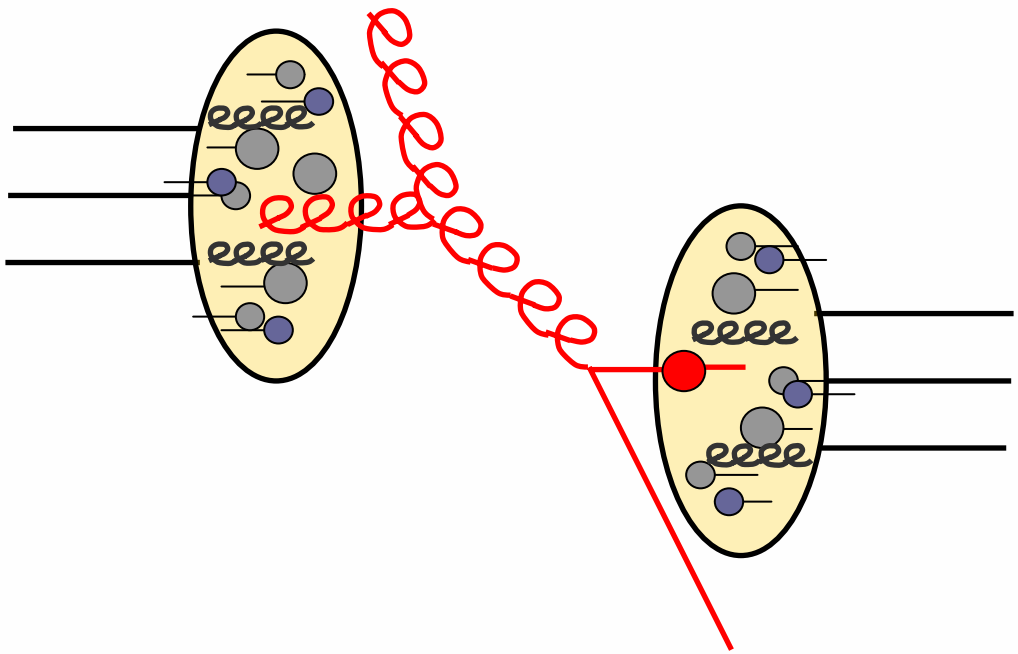
DIS



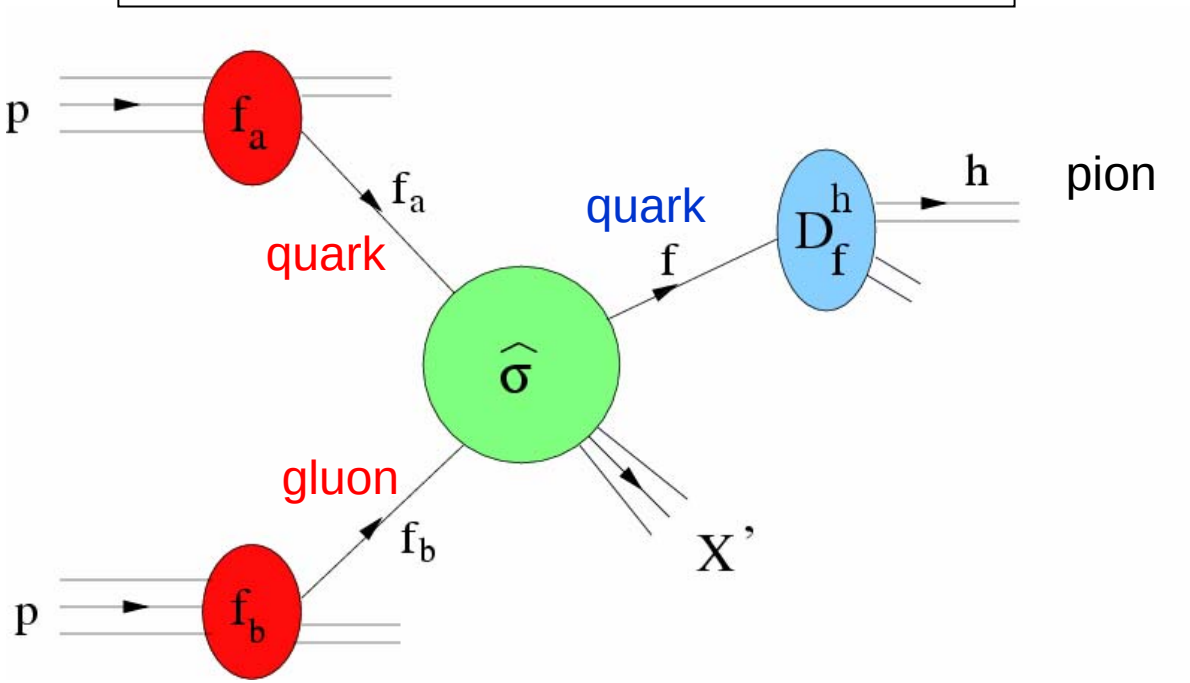
pp



Measuring the proton spin structure with polarized proton probes

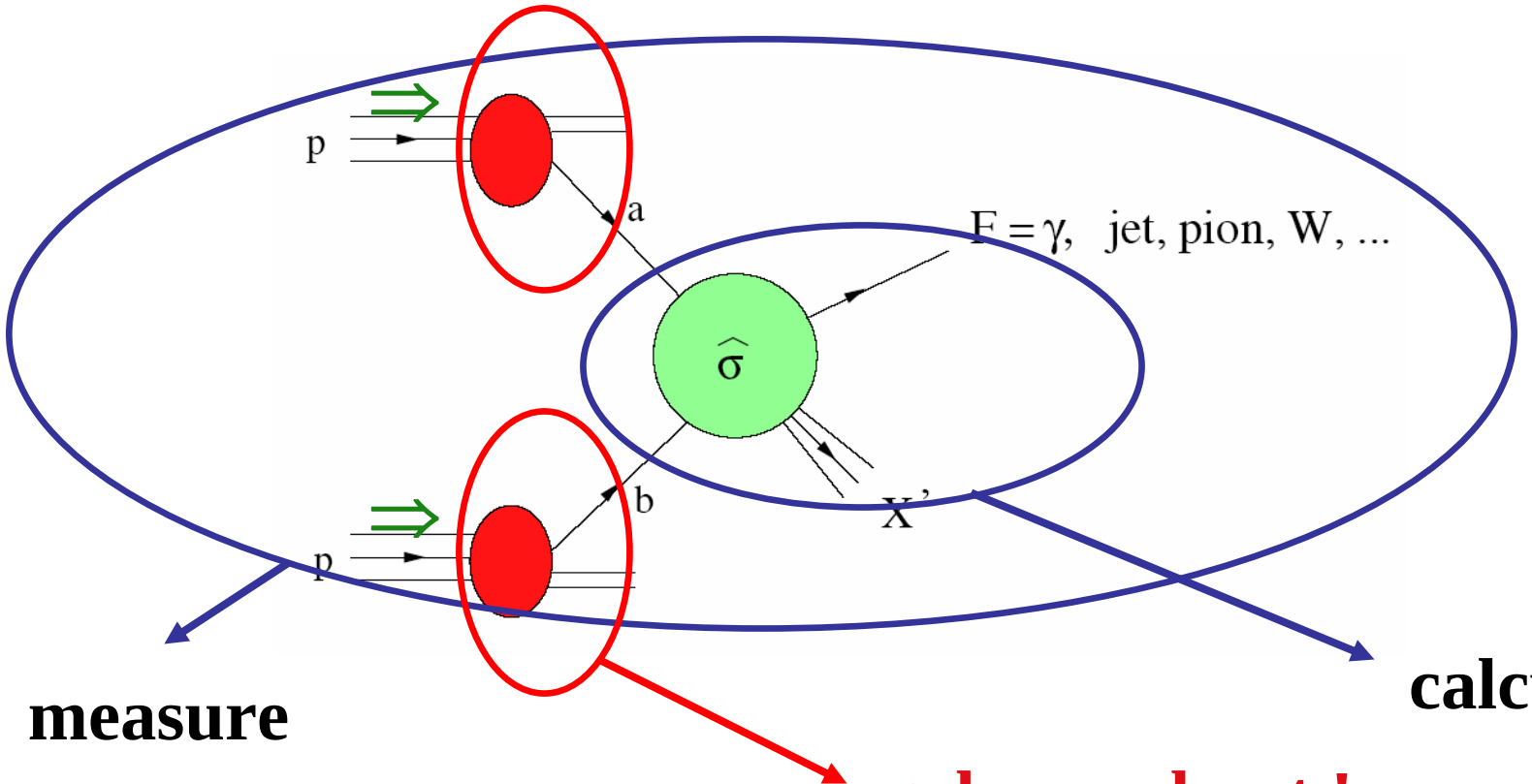
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

Quarks contribute only 20%!



- this is formalized through “factorization theorems”

Sterman,Libby; Ellis et al.; Collins,Soper,Sterman



measure

calculate

→ learn about !

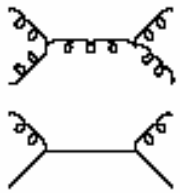
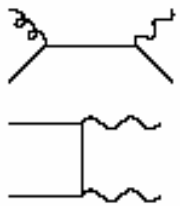
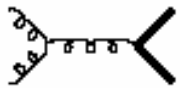
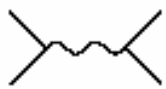
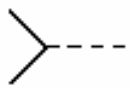
$$\frac{d\sigma^{\Rightarrow\Leftarrow} - d\sigma^{\Rightarrow\Rightarrow}}{dp_T d\eta} = \sum_{ab} \int dx_a \int dx_b \, \Delta f_a(x_a, p_T) \, \Delta f_b(x_b, p_T) \, \frac{d\hat{\sigma}_{ab}^{\Rightarrow\Leftarrow} - d\hat{\sigma}_{ab}^{\Rightarrow\Rightarrow}}{dp_T d\eta}$$

sigma x A_LL

universal

parton scatt.
perturbative QCD

Probing the spin structure of the nucleon in polarized pp collisions

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)	$\vec{q}\,\vec{\bar{q}} \to \gamma^* \to \mu^+\mu^-$	$\Delta q, \Delta\bar{q}$	
$\vec{p}\vec{p} \to (Z^0, W^\pm)X$ $p\vec{p} \to (Z^0, W^\pm)X$	$\vec{q}\,\vec{\bar{q}} \to Z^0,\ \vec{q}'\,\vec{\bar{q}} \to W^\pm$ $\vec{q}'\,\bar{q} \to W^\pm,\ q'\,\vec{\bar{q}} \to W^\pm$	$\Delta q, \Delta\bar{q}$	

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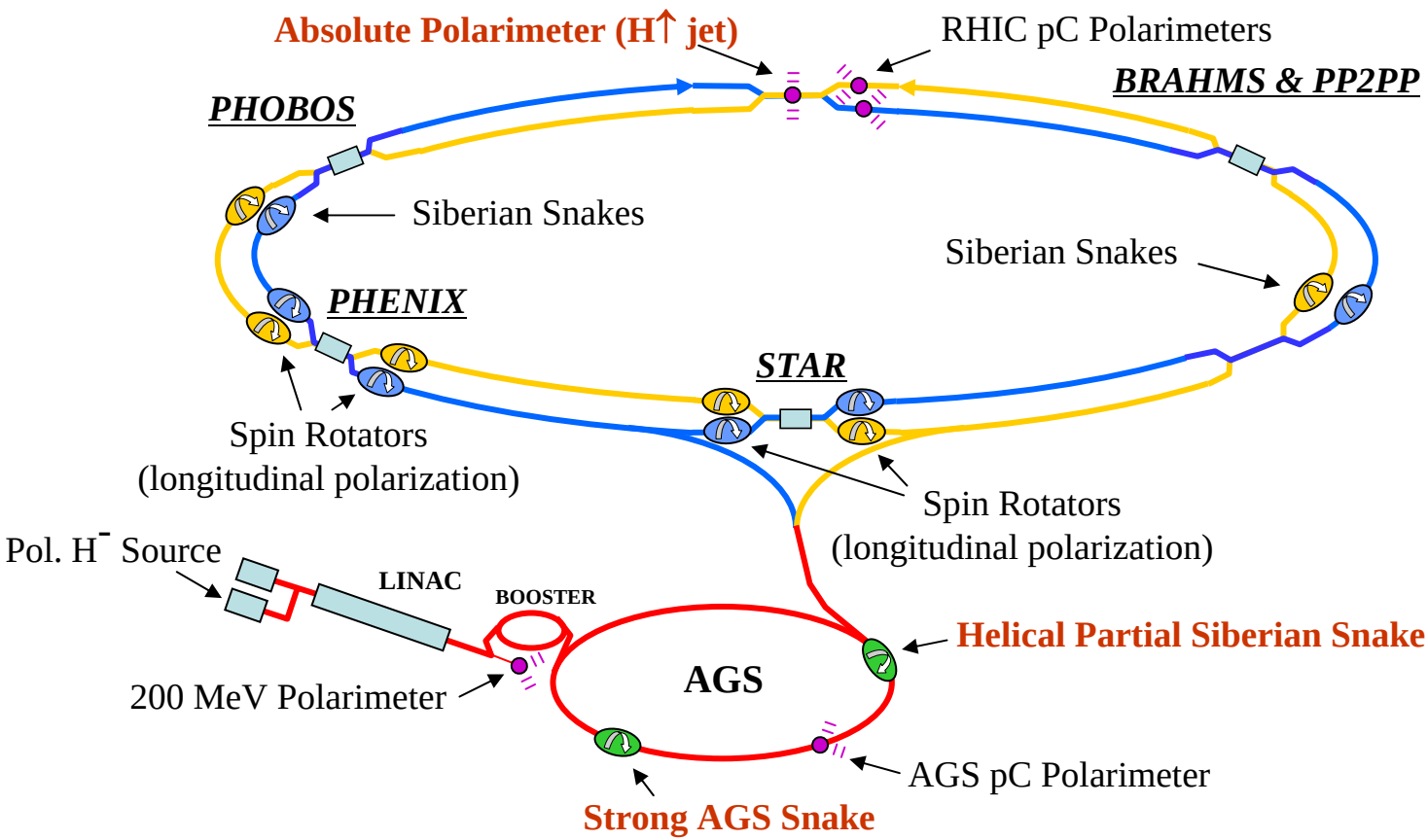
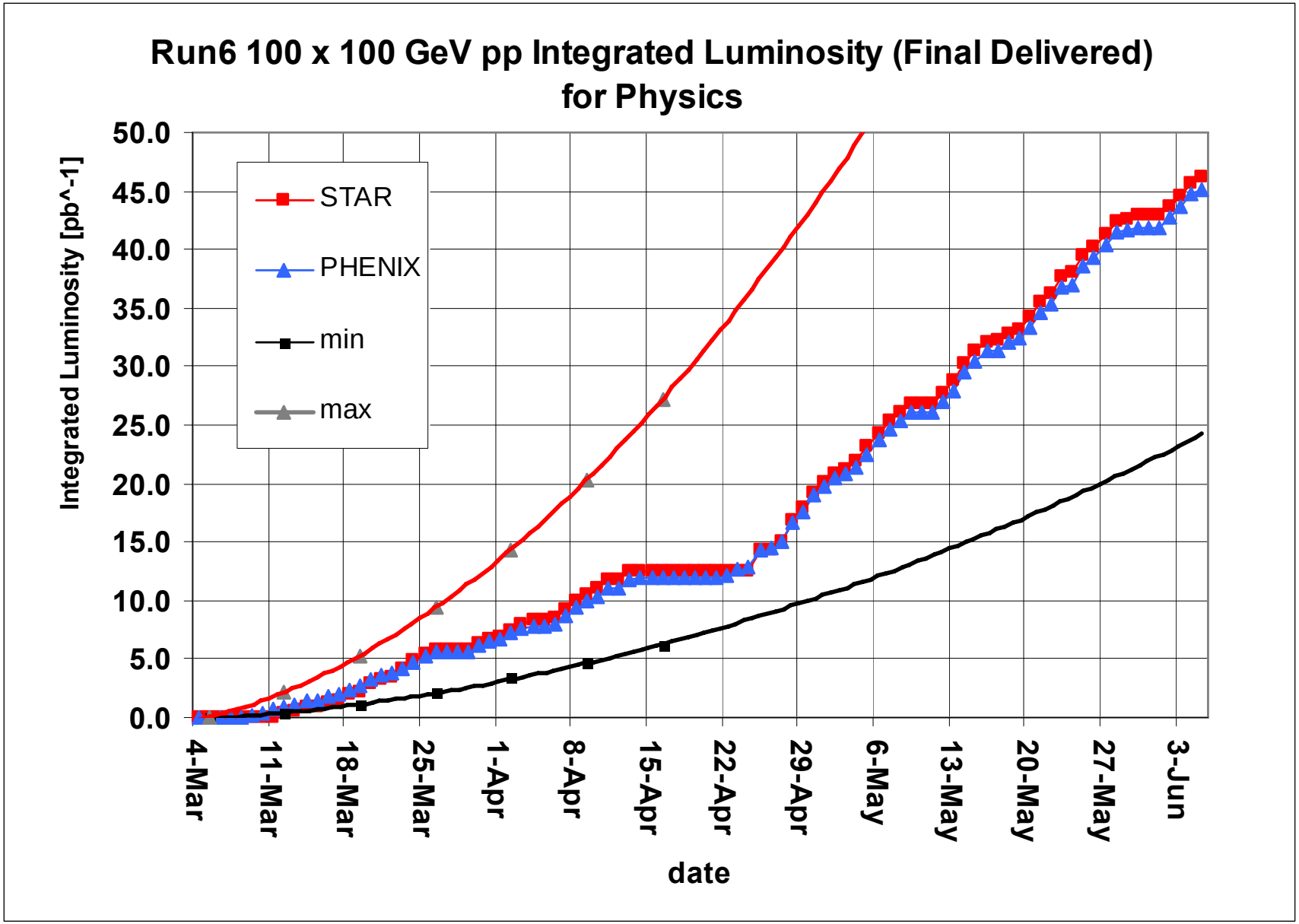
RHIC Polarized Collider



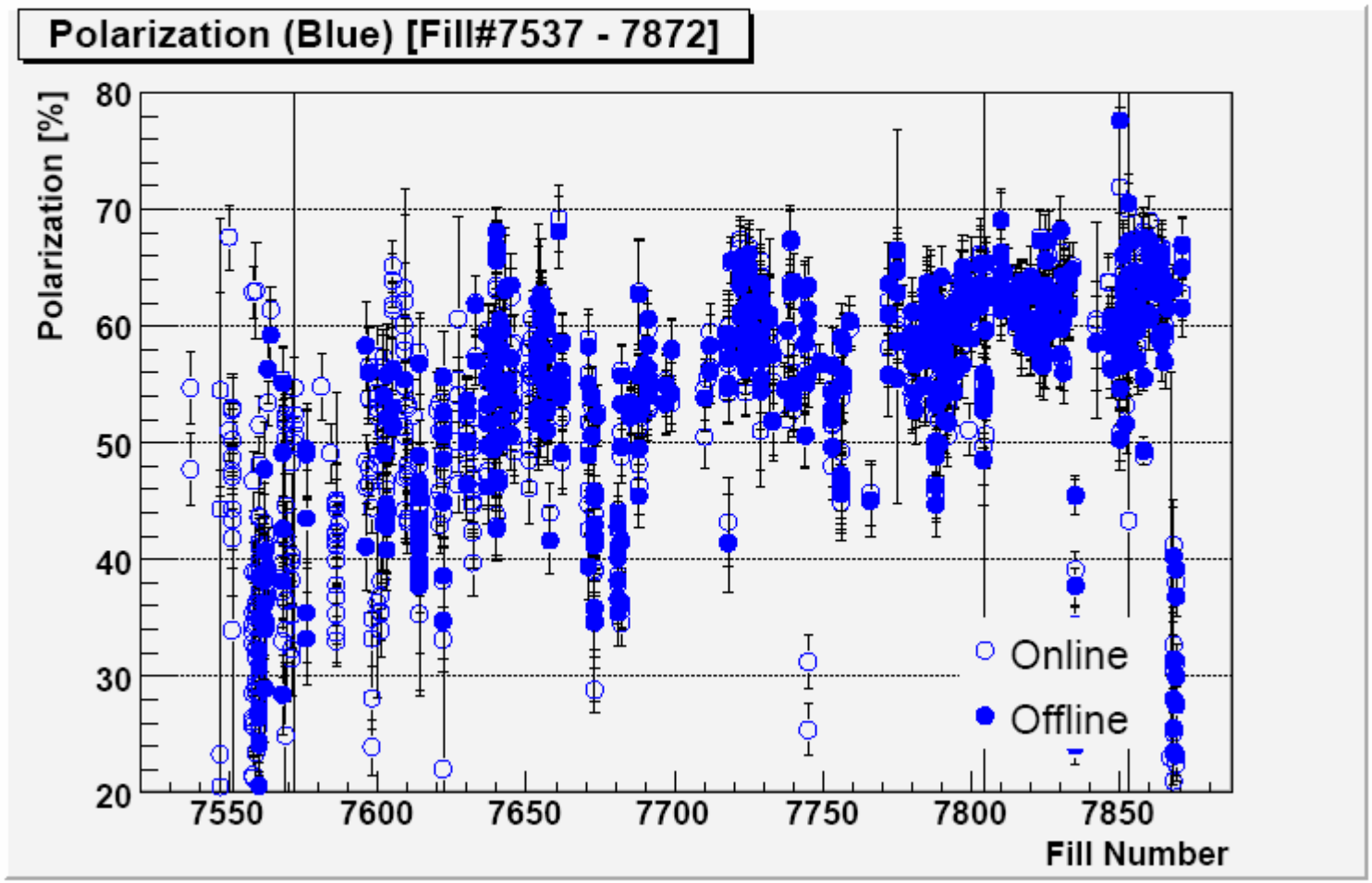
2006: 1 MHz collision rate; P=0.6

RHIC Spin Runs

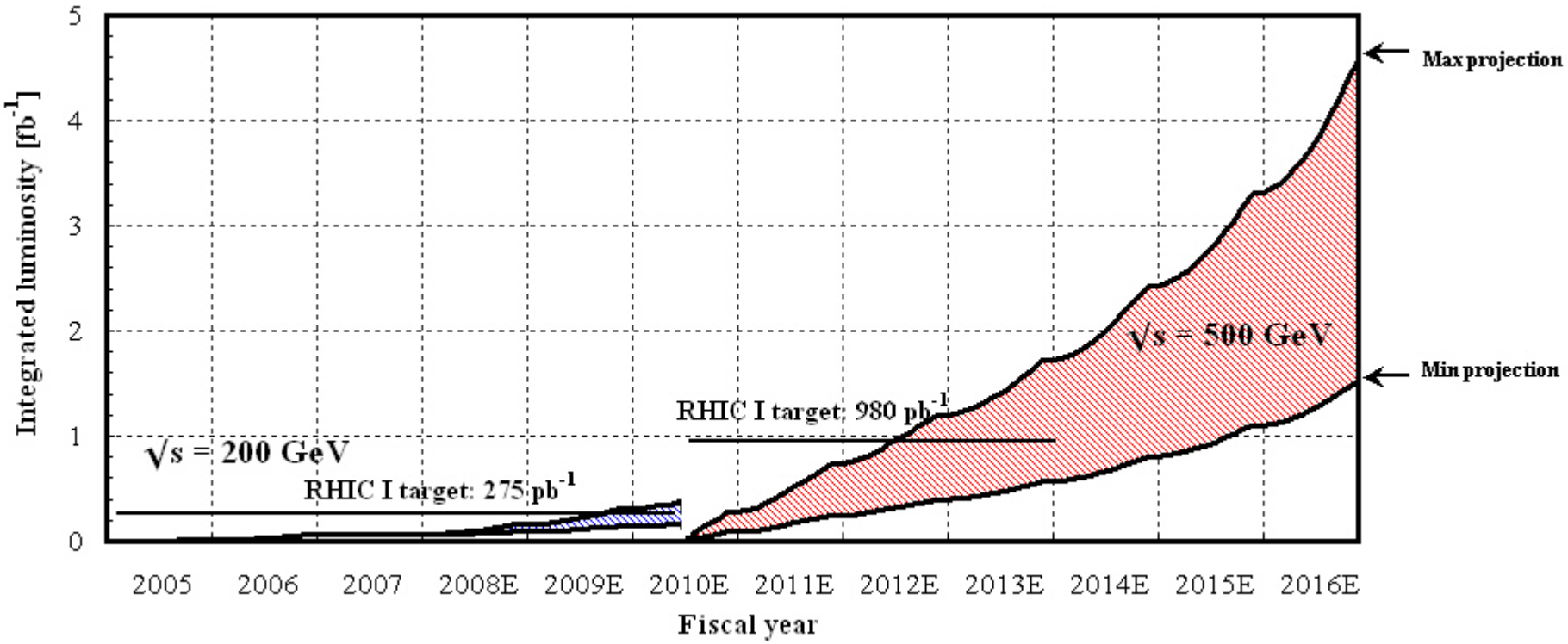
	P	L(pb^-1)	Results
2002	15%	0.15	first pol. pp collisions! disc. large n asymmetry
2003	30%	1.6	pi^0, photon cross section, A_LL(pi^0), 3 PRLs
2004	40%	3.0	polarized hydrogen jet, PLB
2005	50% (P^4 x L = 0.8)	13	warm snake (RIKEN); large gluon pol. ruled out
2006	60% (P^4 x L = 6)	46	cold snake; first long spin run (prelim. to Kyoto)


Run6 100 x 100 GeV pp Integrated Luminosity (Final Delivered) for Physics
Integrated Luminosity [pb^-1]
50.0
45.0
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
STAR
PHENIX
min
max
4-Mar
11-Mar
18-Mar
25-Mar
1-Apr
8-Apr
15-Apr
22-Apr
29-Apr
6-May
13-May
20-May
27-May
3-Jun
date

Polarization Measurements
2006 Run



Luminosity Projection to 2016



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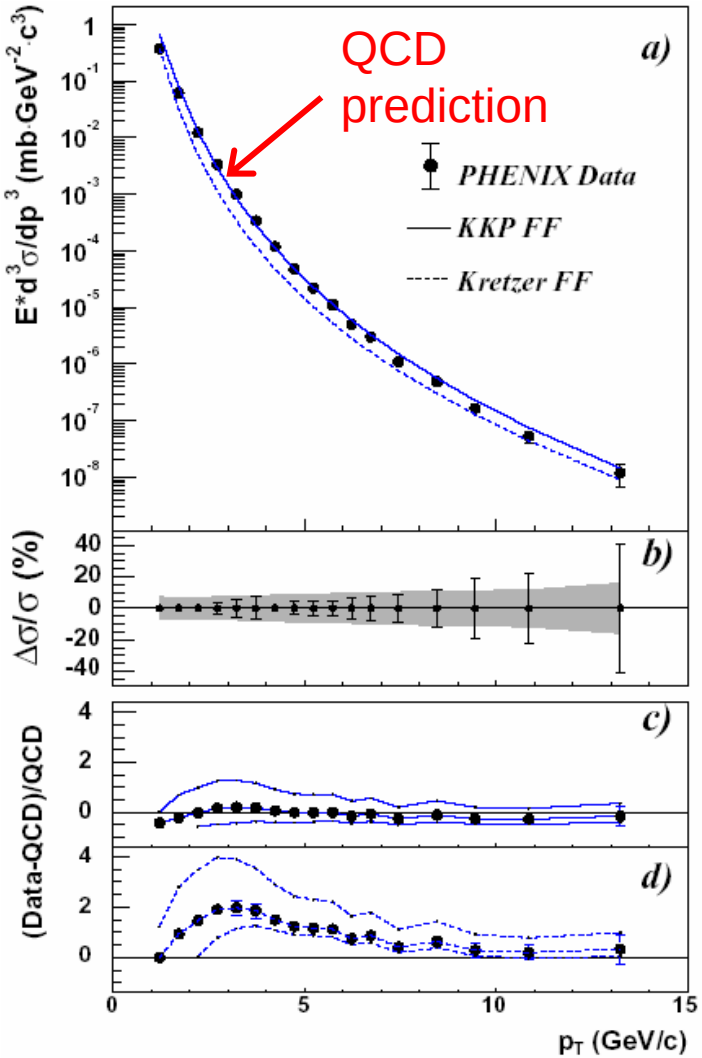
Cornerstones to the RHIC Spin program

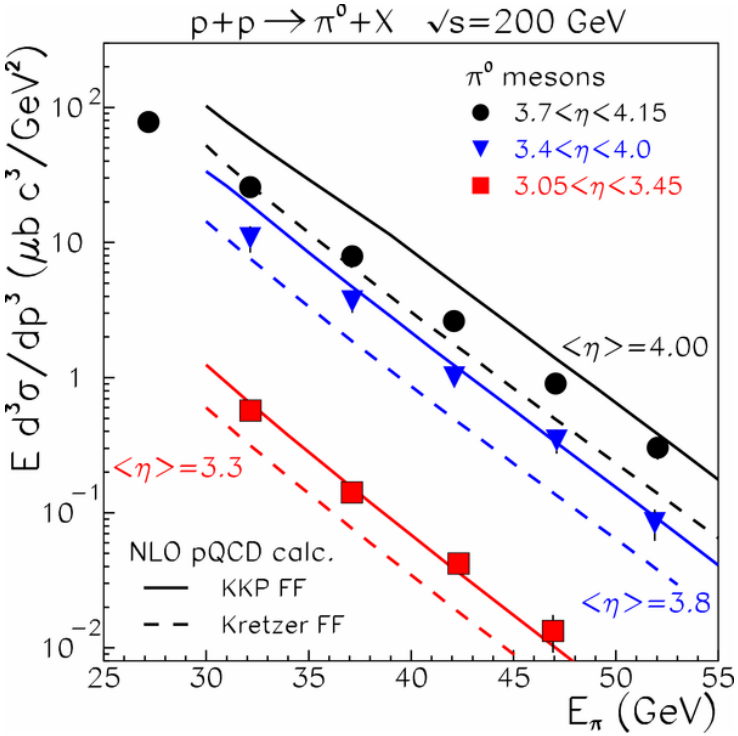
$pp \rightarrow \pi^0 X$

Mid-rapidity: PHENIX



PRL **91**, 241803 (2003)

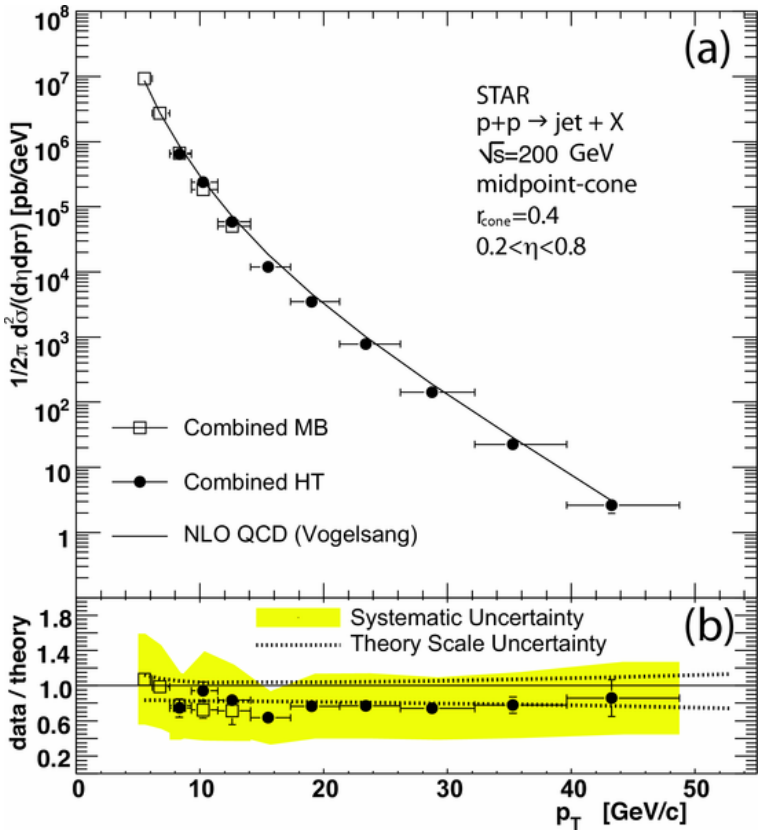
Forward: STAR



PRL **97**, 152302 (2006)

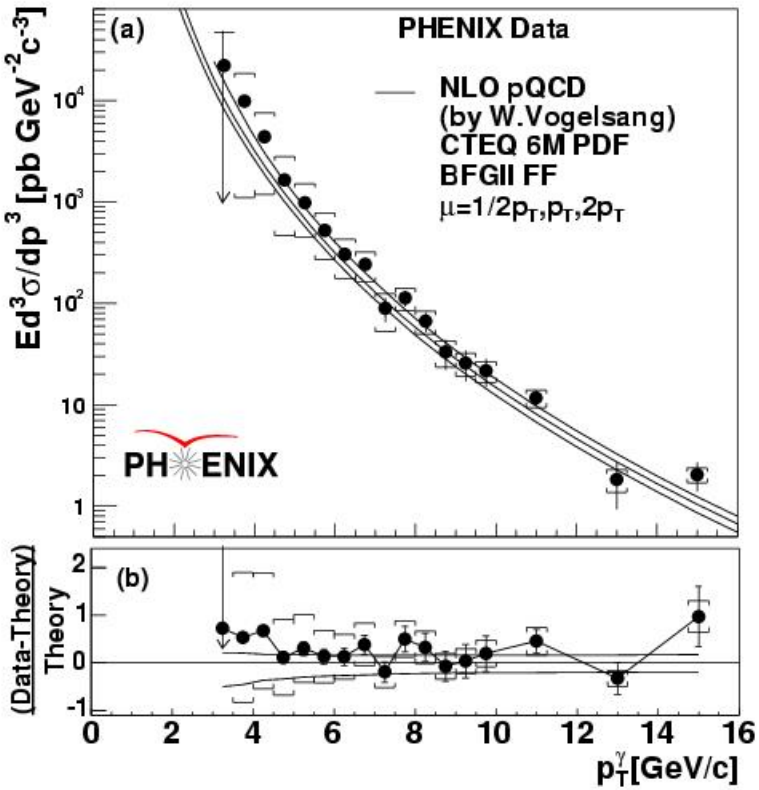
And Jets and Direct γ

$pp \rightarrow$ jet X : STAR



PRL 97, 252001 (2006)

$pp \rightarrow \gamma$ X : PHENIX



PRL 98, 012002 (2007)

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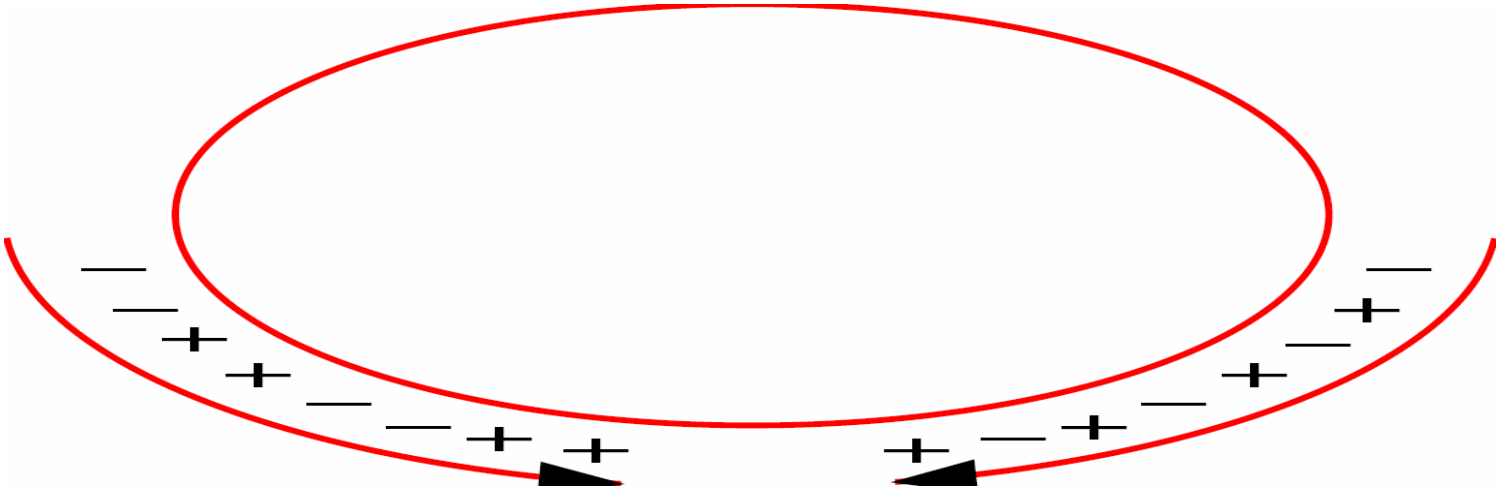
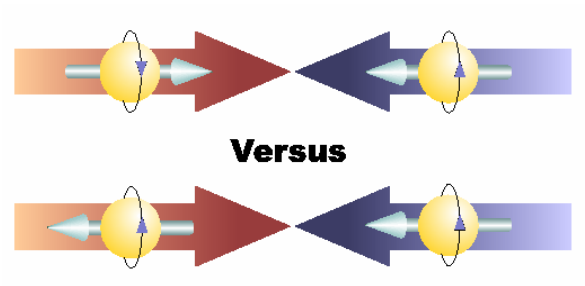
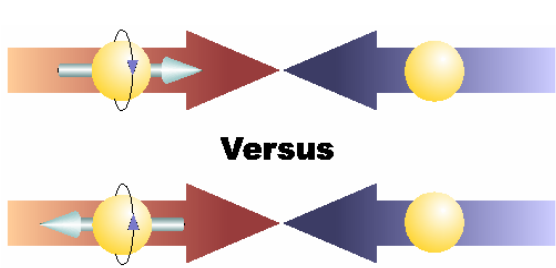
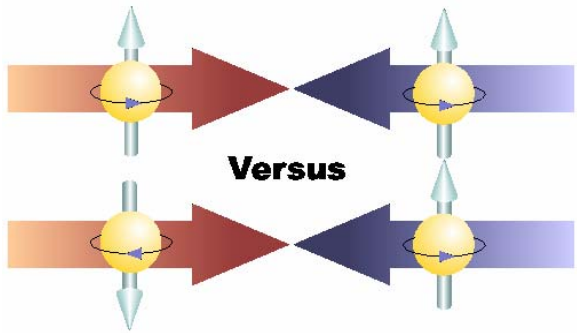
Exquisite Control of Systematics

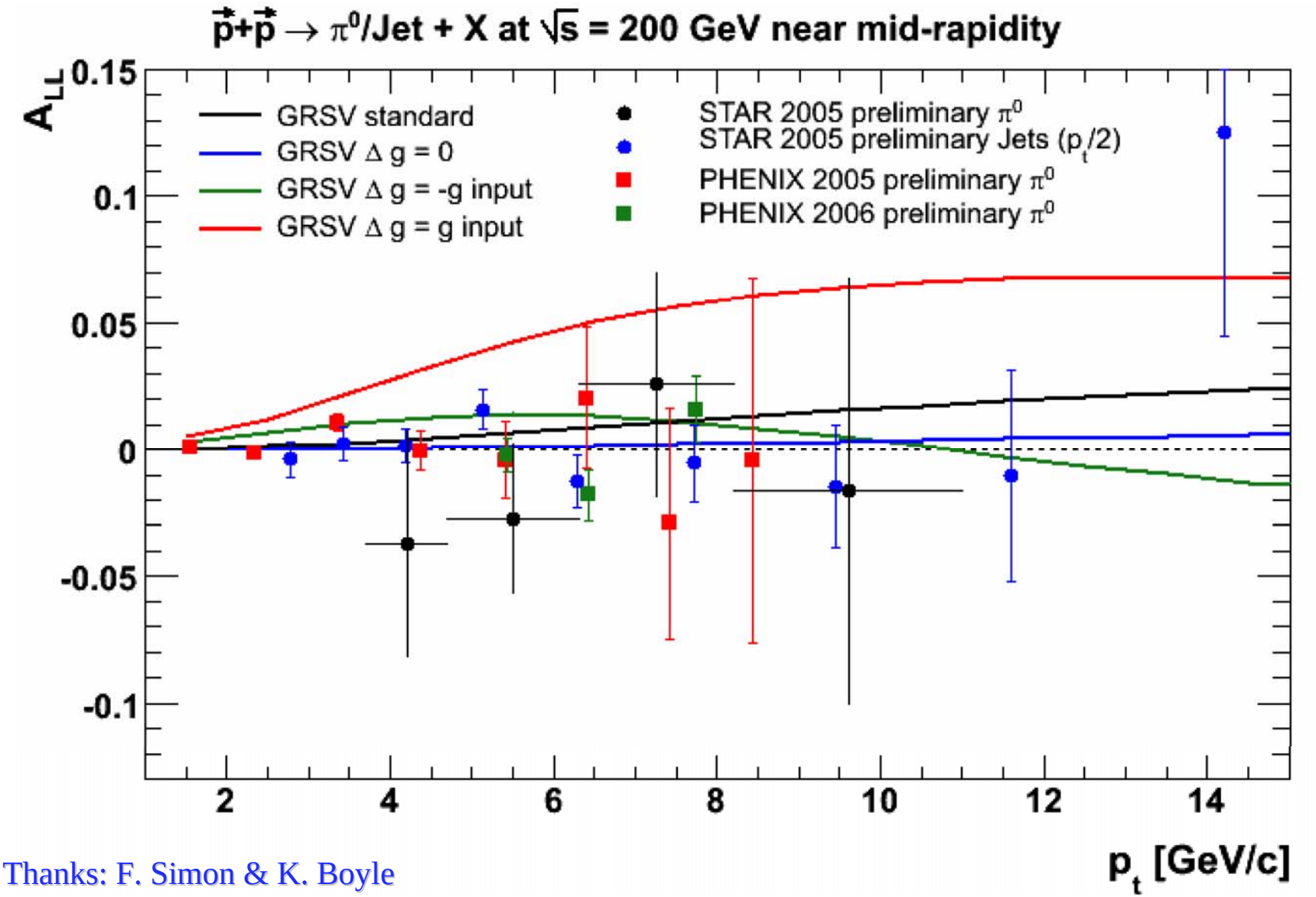








RHIC Spin: inclusive π^0 and jet

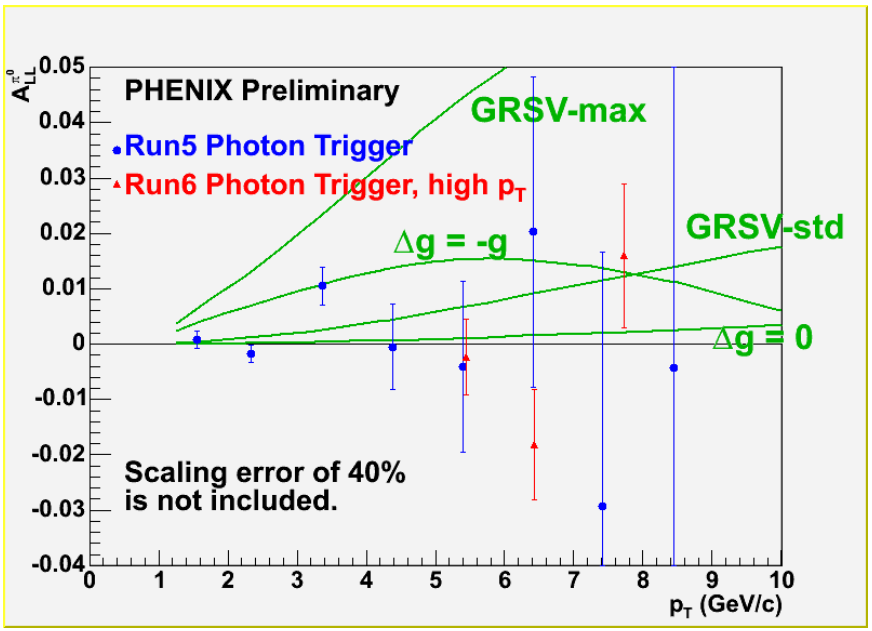


Thanks: F. Simon & K. Boyle

Kyoto Spin2006

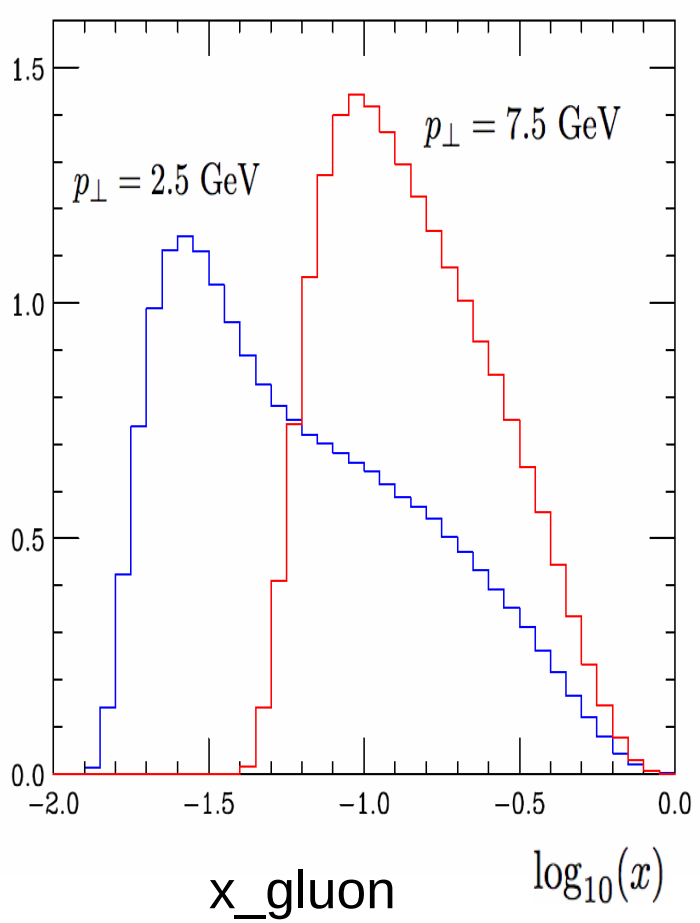
$A_{LL}(p_T)$ and $\Delta G(x)$

A_LL vs. p_T
(for pi^0)



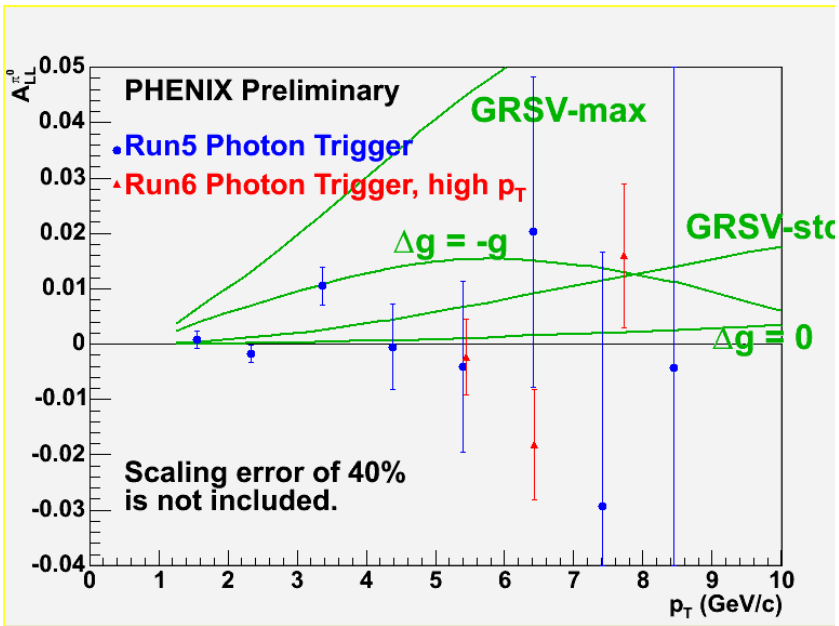
From NLO pQCD:
x_gluon range

"N"

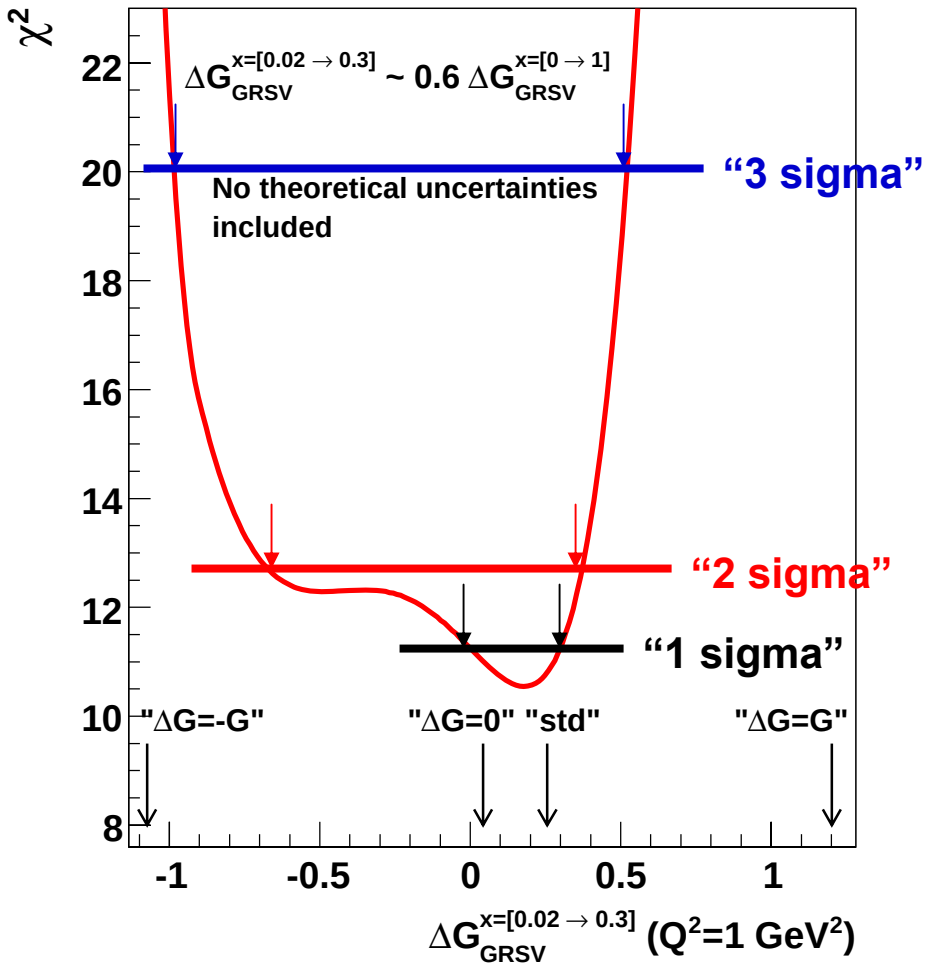


x_gluon

$A_{LL}(p_T)$ and $\Delta G(x)$
--use model (GRSV)



Chi^2 vs. Delta G (GRSV)

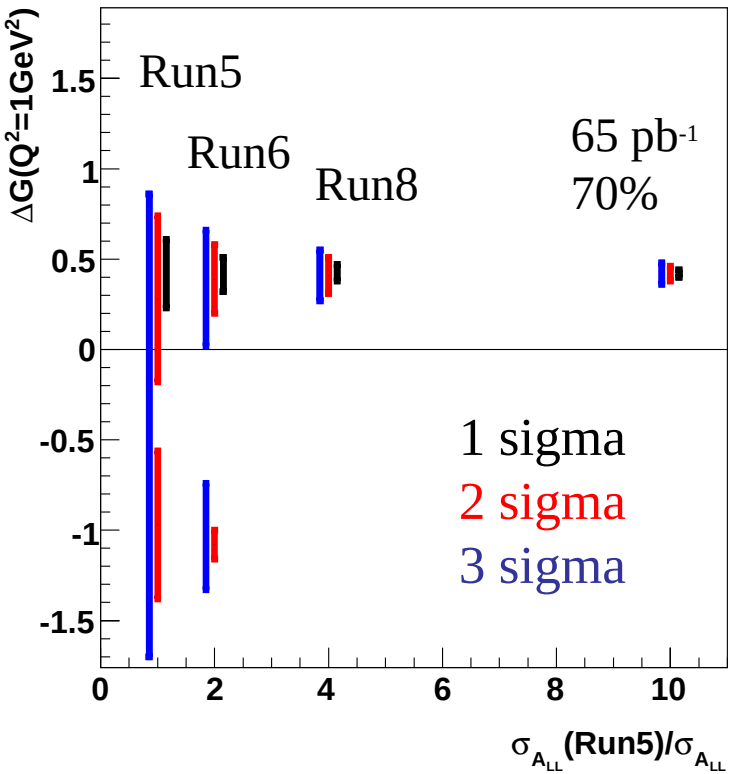


Sensitivity to Delta G

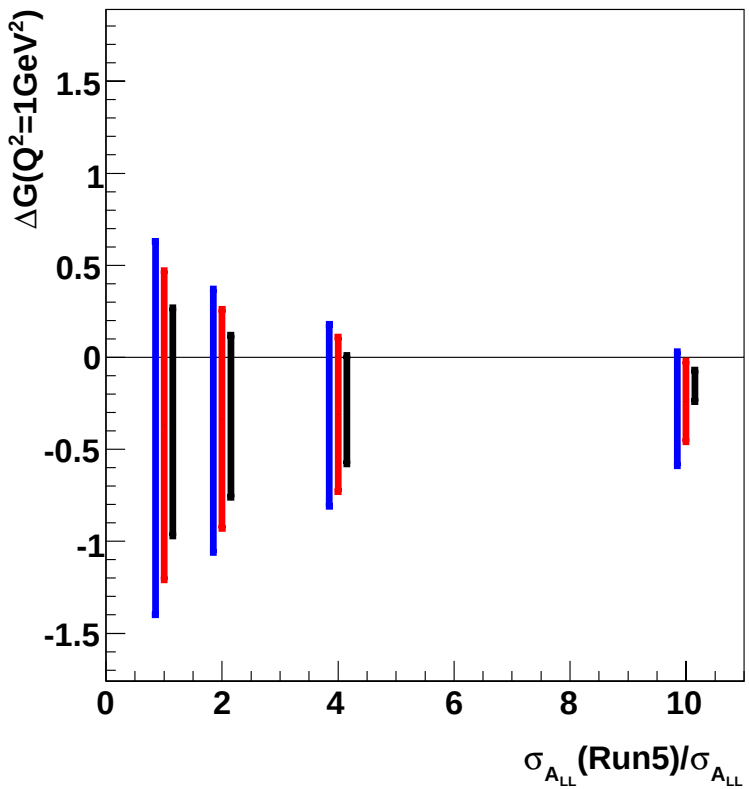
--for pi^0

--for GRSV model, no theory uncertainties

Data = GRSV-std



Data = GRSV-0



For probed x_gluon range: 0.02-0.3

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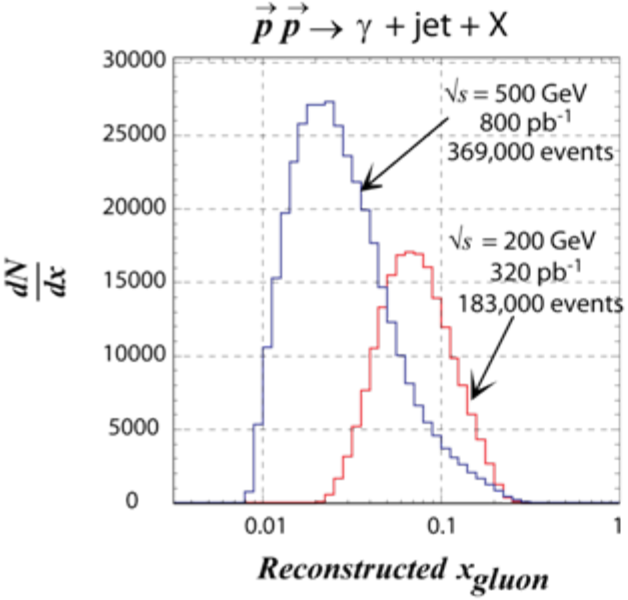
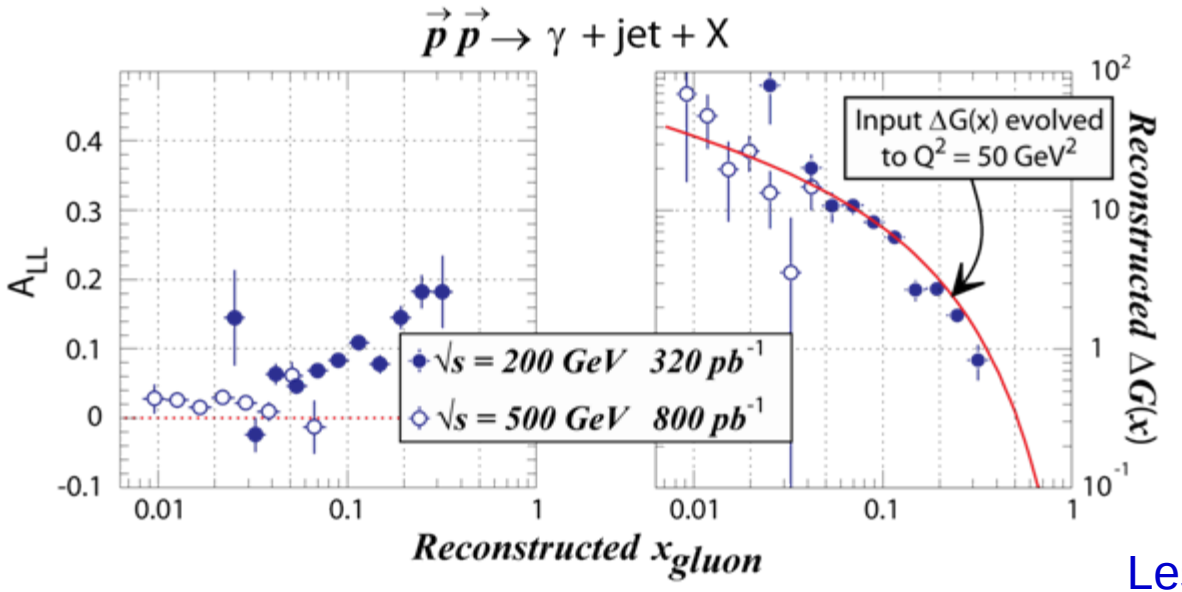
Photon + jet → Delta G(x)



- A_{LL} at $\sqrt{s} = 500$ GeV predicted to be quite small using Gehrmann-Stirling set A
  $\Rightarrow$ concern about instrumental asymmetries
- The extended coverage in x_{gluon} provided by $\sqrt{s} = 500$ GeV measurements is essential to reduce extrapolation errors.
  Uncertainty in integral ΔG 5× smaller with both $\sqrt{s} = 200$ and 500 GeV measurements



Les Bland, 1998

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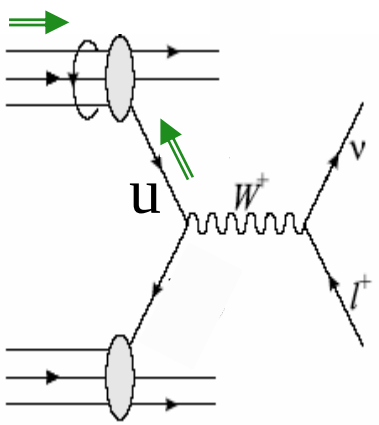
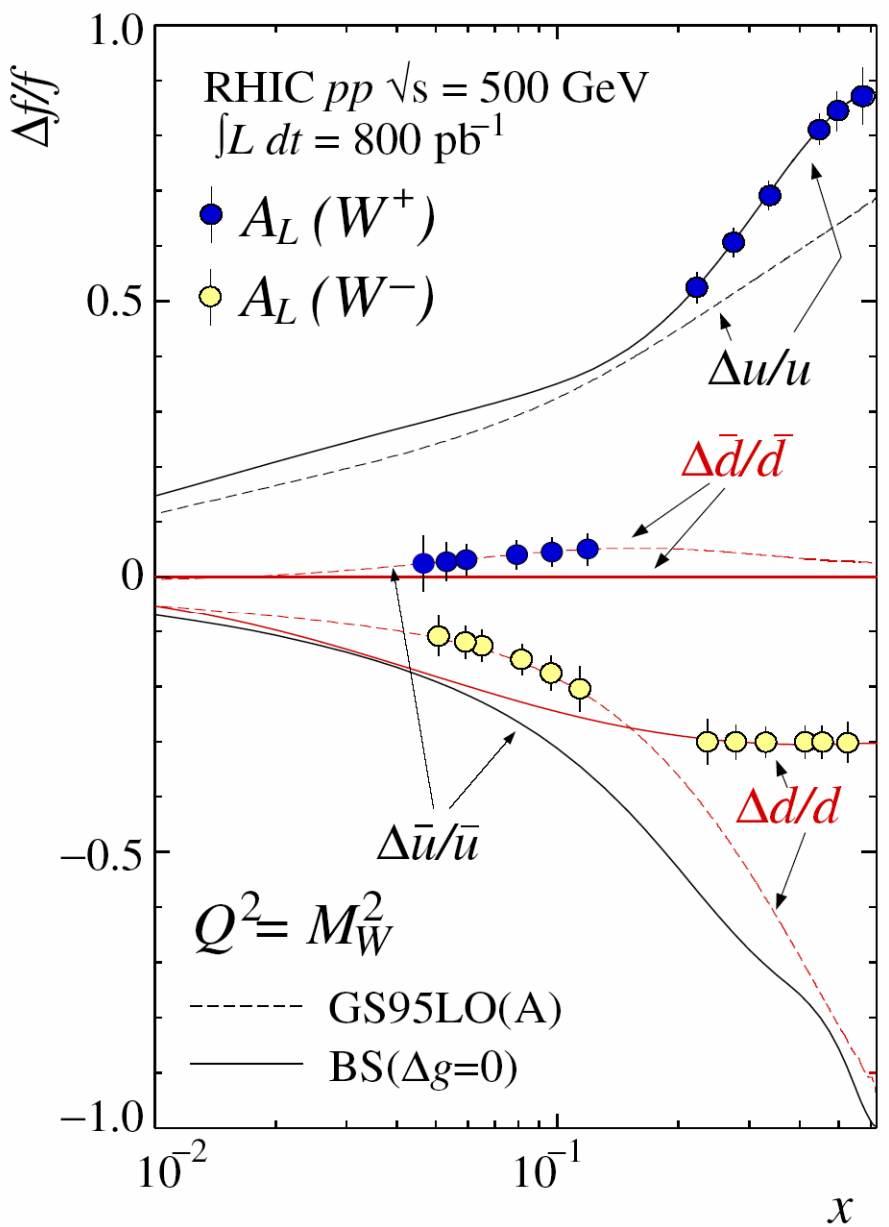
Δq-$\bar{\Delta} q$ at RHIC via W production



unpol.

$$\Delta d + \bar{u} \rightarrow W^-$$
$$\Delta \bar{u} + d \rightarrow W^-$$
$$\Delta \bar{d} + u \rightarrow W^+$$
$$\Delta u + \bar{d} \rightarrow W^+$$

$$\mathbf{A_L} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$



Expected start: 2009

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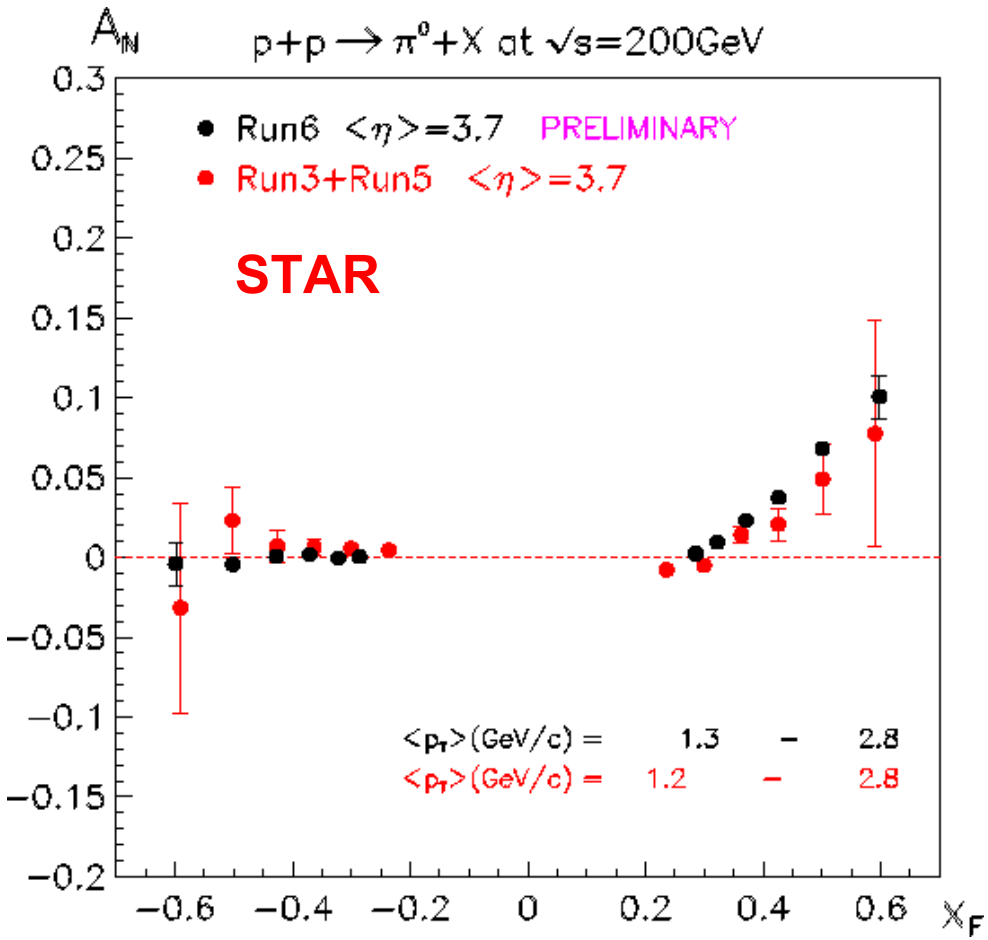
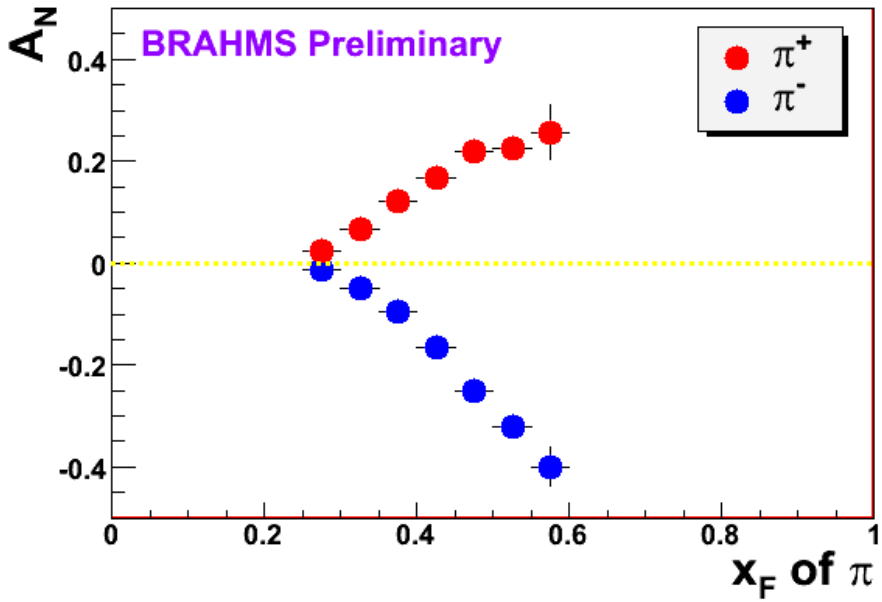
Charged and neutral pion A_N



$A_N(\pi)$ at 62 GeV

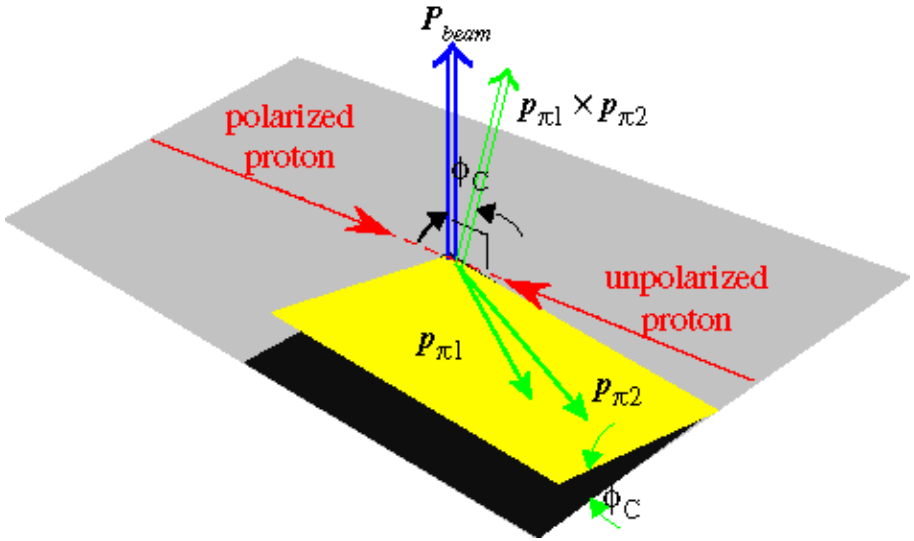


Kyoto Spin2006

Disentangling Dynamics of Single Spin Asymmetries

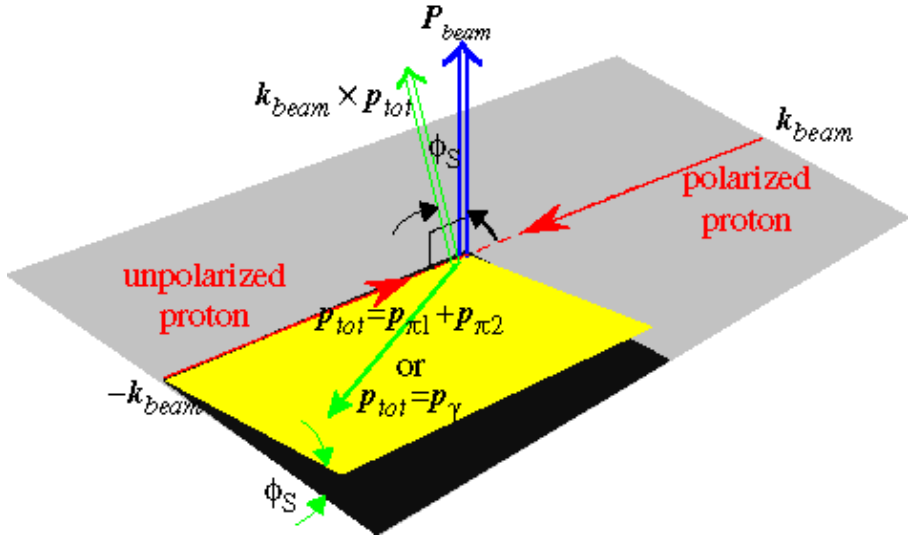
Spin-dependent particle correlations

Collins/Hepplemann mechanism requires transversity and spin-dependent fragmentation



Polarized quark → left-right asymmetry of fragmentation around jet axis

Sivers mechanism asymmetry is present for forward jet or γ



k_T asymmetry of quark in proton → left-right asymmetry of quark jet around polarized beam direction

Large acceptance of the STAR Forward Meson Spectrometer will enable disentangling dynamics of spin asymmetries.

RHIC Spin Summary—LRP

The key points for RHIC Spin are:

- Spin structure of proton
- Strongly interacting probes
- P=60%, L=2x10^31, root(s)=200 GeV in 2006
- Cross sections for pi^0, jet, direct photon described by pQCD
- Helicity asymmetries: sensitivity to gluon spin contribution to proton
- Photon+jet: gluon pol. vs. x_gluon
- W boson parity violating production: ubar and dbar polarizations in proton
- Very large transverse spin asymmetries in pQCD region
- Theoretical advances on cross section, helicity, and transverse spin
- The RHIC Spin Plan and three goals for "RHIC II"

Theory based on pQCD

- **Cross sections:**

--NLO for all processes

--global analysis, DIS and RHIC, pdf and fragmentation (*)

--understanding lower p_T with pQCD

--understand lower root(s), eta dependence (*)

- **Helicity:**

--NLO for all processes (*)

--global analysis, DIS and RHIC (*)

--understand lower root(s) (*)

- **Transverse spin:**

--Sivers (k_T): Sivers <- -> q-g correlations; DIS to pp;

(S x k_T) to L ? (*)

--New probes: dijet k_T (*); photon + jet, Drell-Yan (k_T) (*)

--Transversity: from jet axis-pi correlation (*)

*** work in progress or to do

RHIC Spin Summary—LRP

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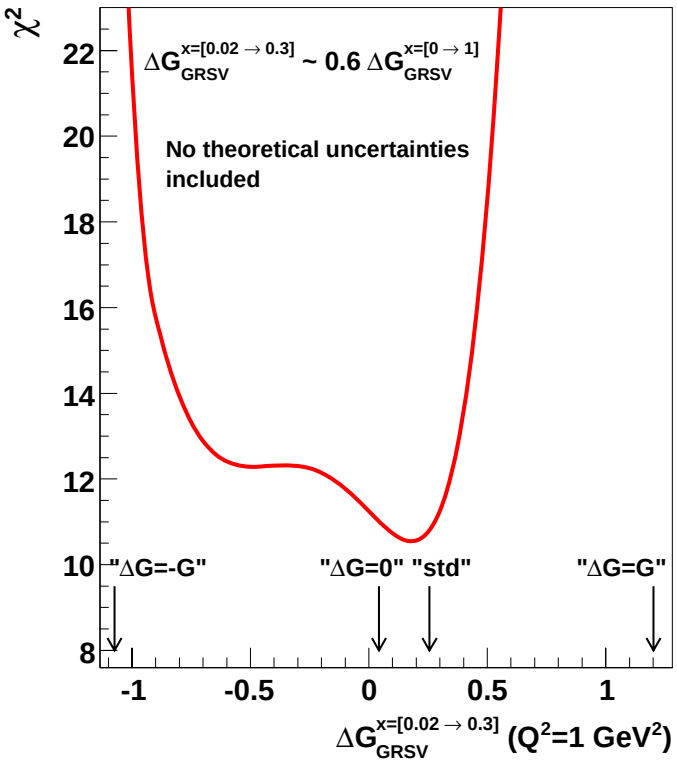
Sensitivity to Delta G

--for pi^0 (and jet, direct photon)

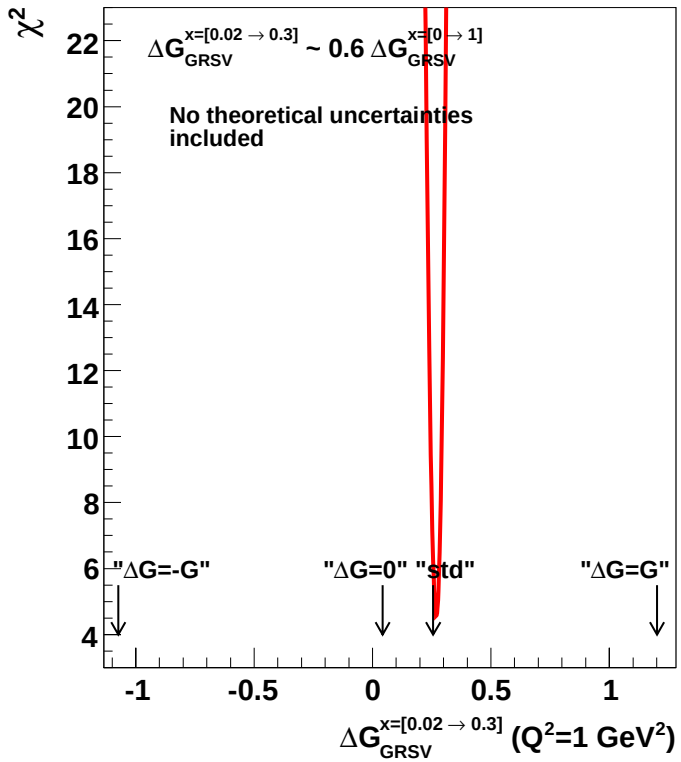
--for GRSV model, no theory uncertainties

Data = GRSV-std only

2005 pi0 A_LL prelim.

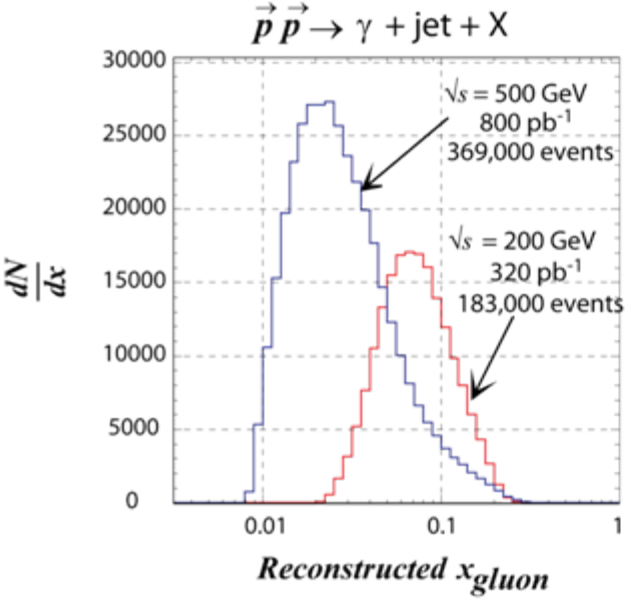


pi0 A_LL 65 pb^-1

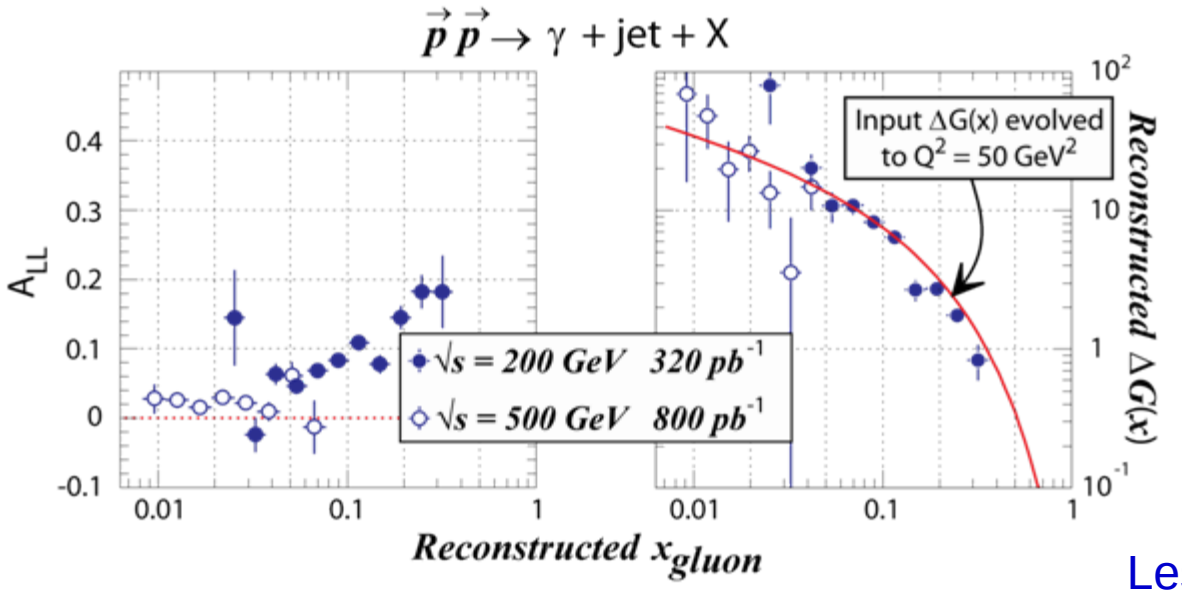


For probed x_gluon range: 0.02-0.3

Photon + jet → Delta G(x)

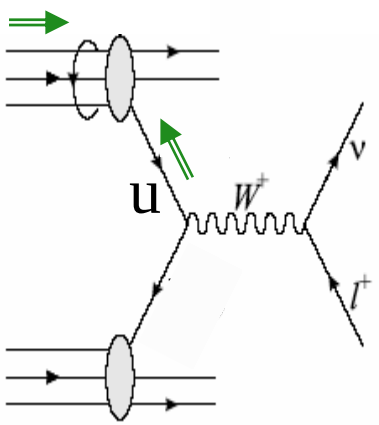


- A_{LL} at $\sqrt{s} = 500$ GeV predicted to be quite small using Gehrmann-Stirling set A
  $\Rightarrow$ concern about instrumental asymmetries
- The extended coverage in x_{gluon} provided by $\sqrt{s} = 500$ GeV measurements is essential to reduce extrapolation errors.
  Uncertainty in integral ΔG 5× smaller with both $\sqrt{s} = 200$ and 500 GeV measurements



Les Bland, 1998

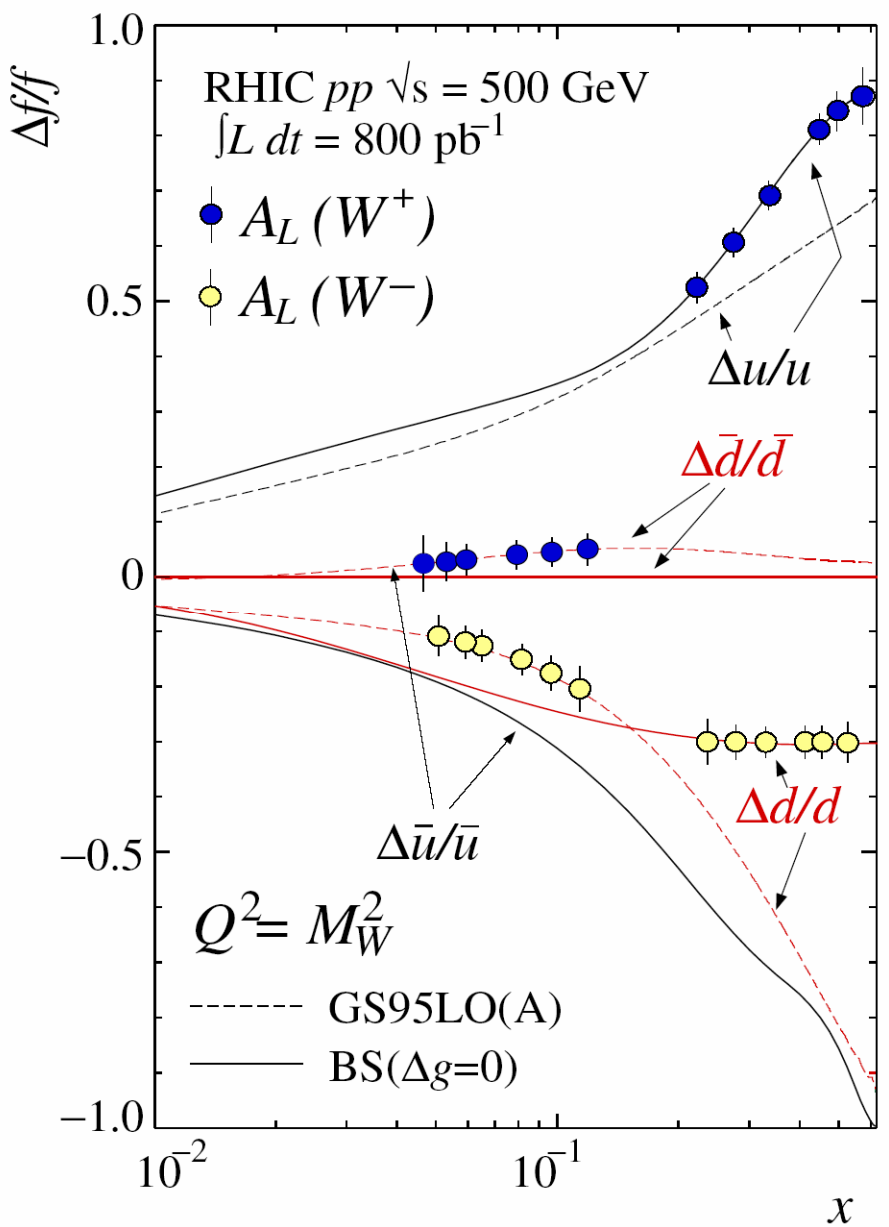
Δq-$\bar{\Delta} q$ at RHIC via W production



unpol.

$$\Delta d + \bar{u} \rightarrow W^-$$
$$\Delta \bar{u} + d \rightarrow W^-$$
$$\Delta \bar{d} + u \rightarrow W^+$$
$$\Delta u + \bar{d} \rightarrow W^+$$

$$\mathbf{A_L} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$



Expected start: 2009

Explore (Sxk_T) with Drell Yan

--Hermes (DESY) has observed significant "Sivers" effect: left-right asymmetry of pion vs. (S x k_T) in semi-inclusive DIS, e + p → e' + pi + X

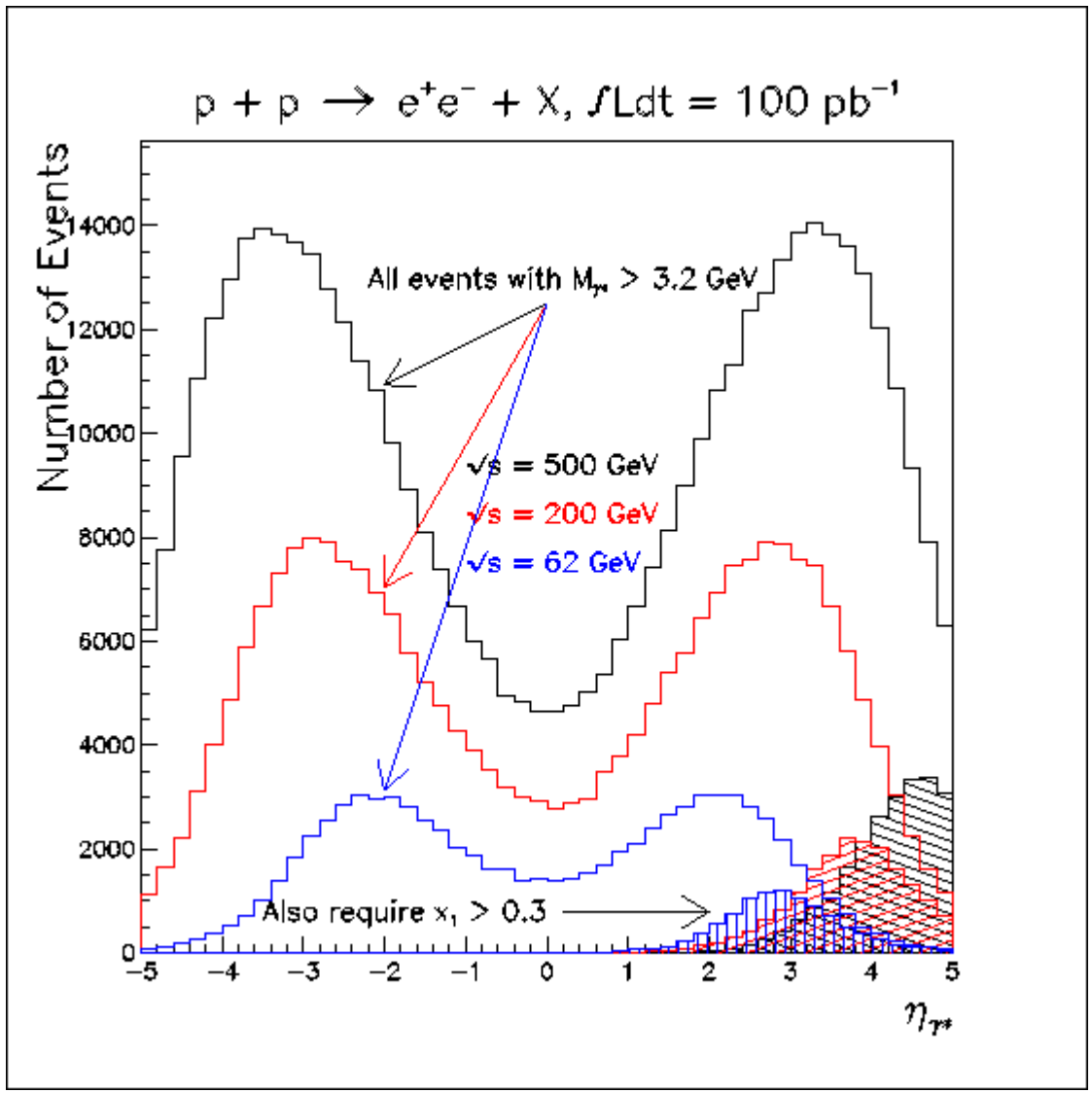
--Asymmetry "requires" final state interaction of scattered quark with remnant of proton

--Turning reaction around, polarized proton-proton Drell-Yan production should show a similar left-right asymmetry from (S x k_T) of a valence quark in the polarized proton scattering from an anti-quark in the other proton

--The Drell Yan asymmetry "requires" an initial state interaction between the quark or anti-quark with the other proton remnant

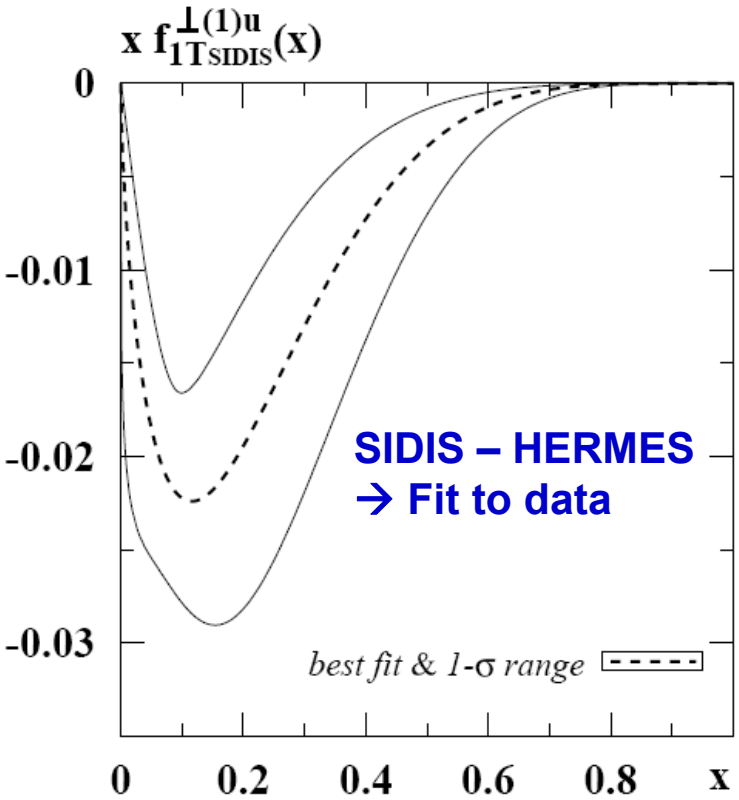
--The Drell Yan initial state interaction is repulsive; the DIS final state interaction is attractive → the asymmetries should have opposite signs

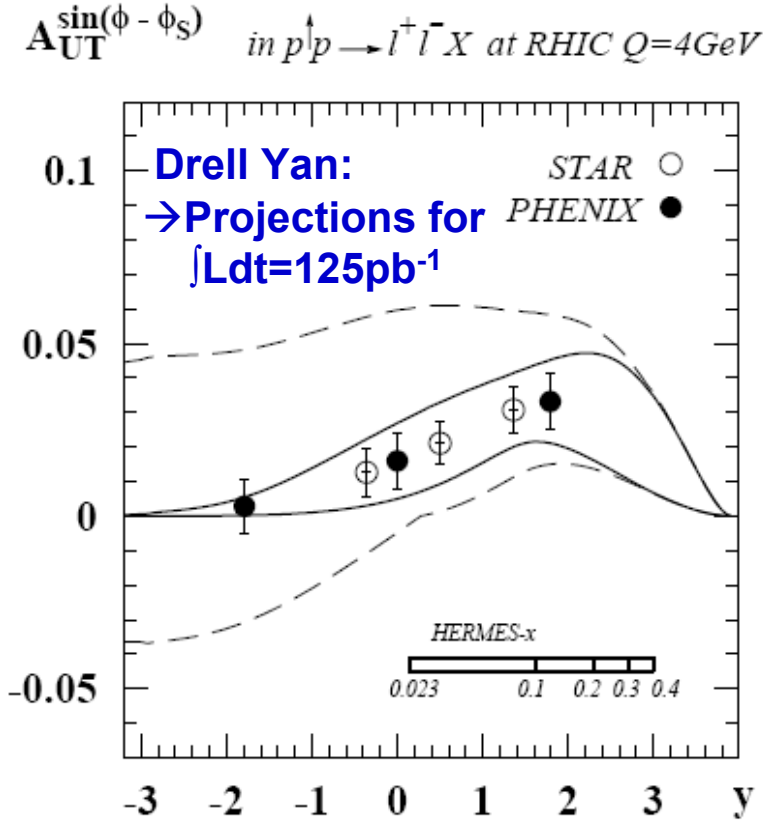
Use Drell Yan to study k_T(quark)?



Sivers Effect : SIDIS to Drell Yan

Collins et al. Phys.Rev.D73:094023,2006





$$f_{1T}^{\perp}(x, p_T^2)_{SIDIS} \stackrel{?}{=} -f_{1T}^{\perp}(x, p_T^2)_{DY}$$

Caveats and Issues

- Continued spin running time
- High luminosity and high polarization
- Be able to handle high luminosity
- Direct photon identification and background
- Jet axis identification
- W backgrounds and W identification
- Continued strong theoretical support
- Multiple ways to probe our understanding of the physics
- The unmeasured x_gluon range for gluon polarization