First Results from RHIC Spin Program and Future Prospects

DESY/Hamburg Seminar, May 25, 2004
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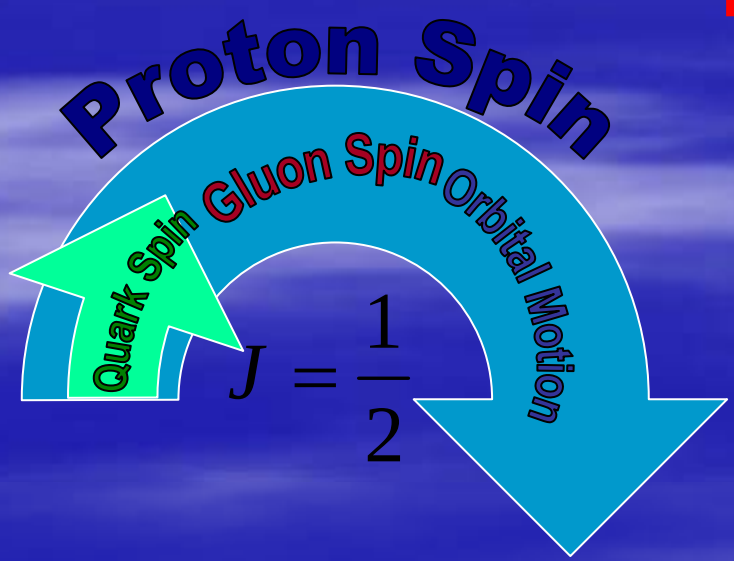
Outline

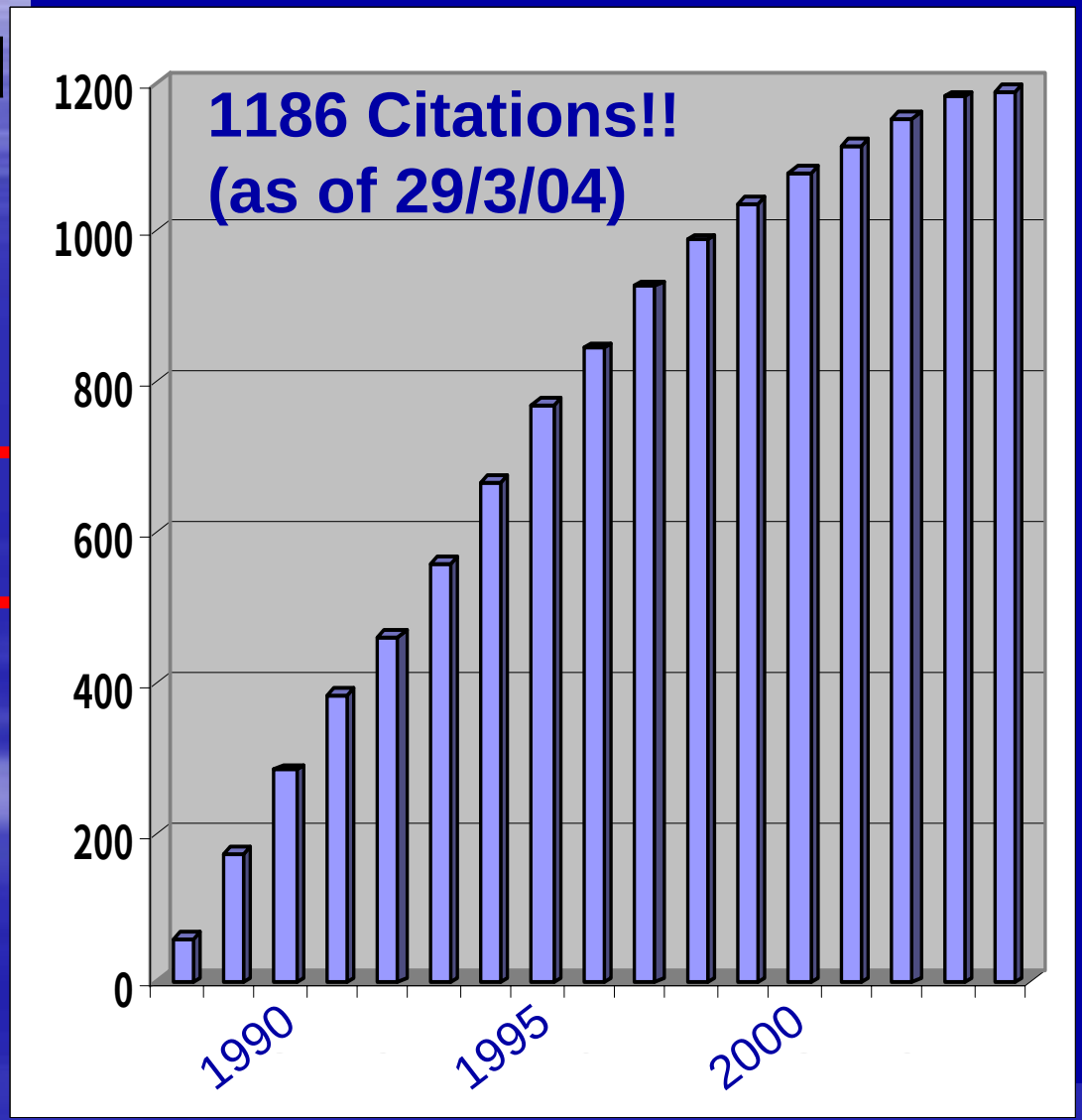
- (Heavy Introduction to) Spin Structure of the Nucleon
- RHIC Spin Program
- Polarised Proton Acceleration – Updates
- First Results
  - Gluon Polarization in the Proton
  - Single Transverse Spin Asymmetry
- Future Prospects
- Summary

"Proton Spin Crisis"

EMC PLB & NP (1988)

- Proton Spin carried by Quark Spin is ZERO??
  - Gluon Spin **?**
  - Orbital Motion **?**

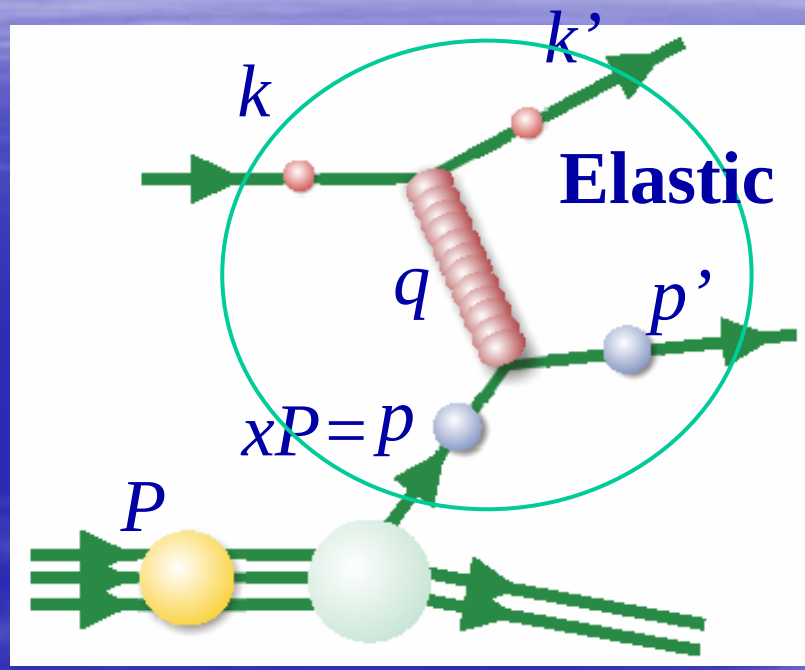




DIS of Lepton from Nucleon

- Structure Probed by Photon
  - Function of x and $Q^2=-q^2$
  - $\propto$ Charge Squared
    - Not distinguish Down and Strange
    - Insensitive to Gluon
- Objective is

$$\Delta\Sigma = \Delta U + \Delta D + \Delta S$$



- Obse

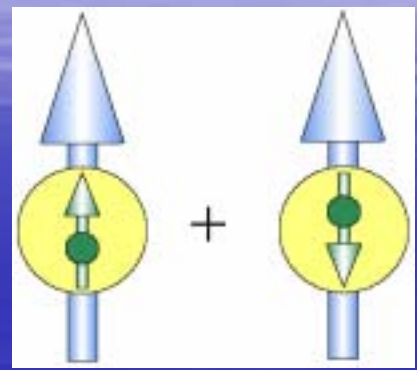
Proton $$g_1^p(x,Q^2) = \frac{1}{2}\left\{\frac{4}{9}\Delta U(x,Q^2) + \frac{1}{9}\Delta D(x,Q^2) + \frac{1}{9}\Delta S(x,Q^2)\right\}$$

Neutron $$g_1^n(x,Q^2) = \frac{1}{2}\left\{\frac{1}{9}\Delta U(x,Q^2) + \frac{4}{9}\Delta D(x,Q^2) + \frac{1}{9}\Delta S(x,Q^2)\right\}$$

Parton Distribution Functions

- Quark Distribution

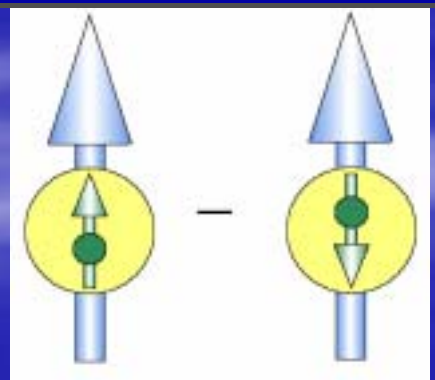
unpolarized distribution

$q(x,Q^2)=$  $=$ 

helicity distribution

$\Delta q(x,Q^2)=$ 

transversity distribution

$\delta q(x,Q^2)=$ 

- Gluon Distributions

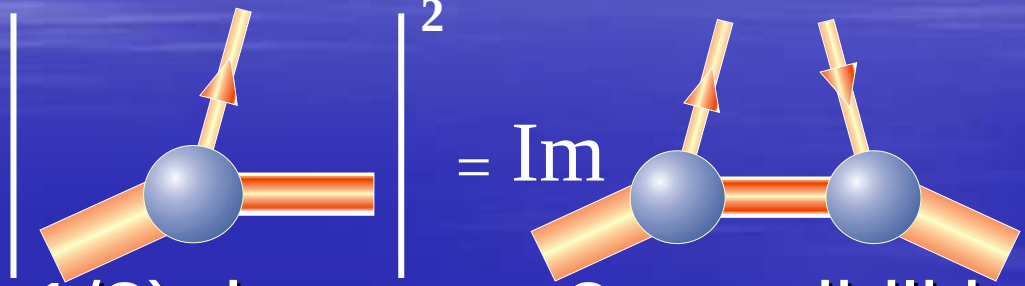
$g(x,Q^2)=$ 

$\Delta g(x,Q^2)=$ 

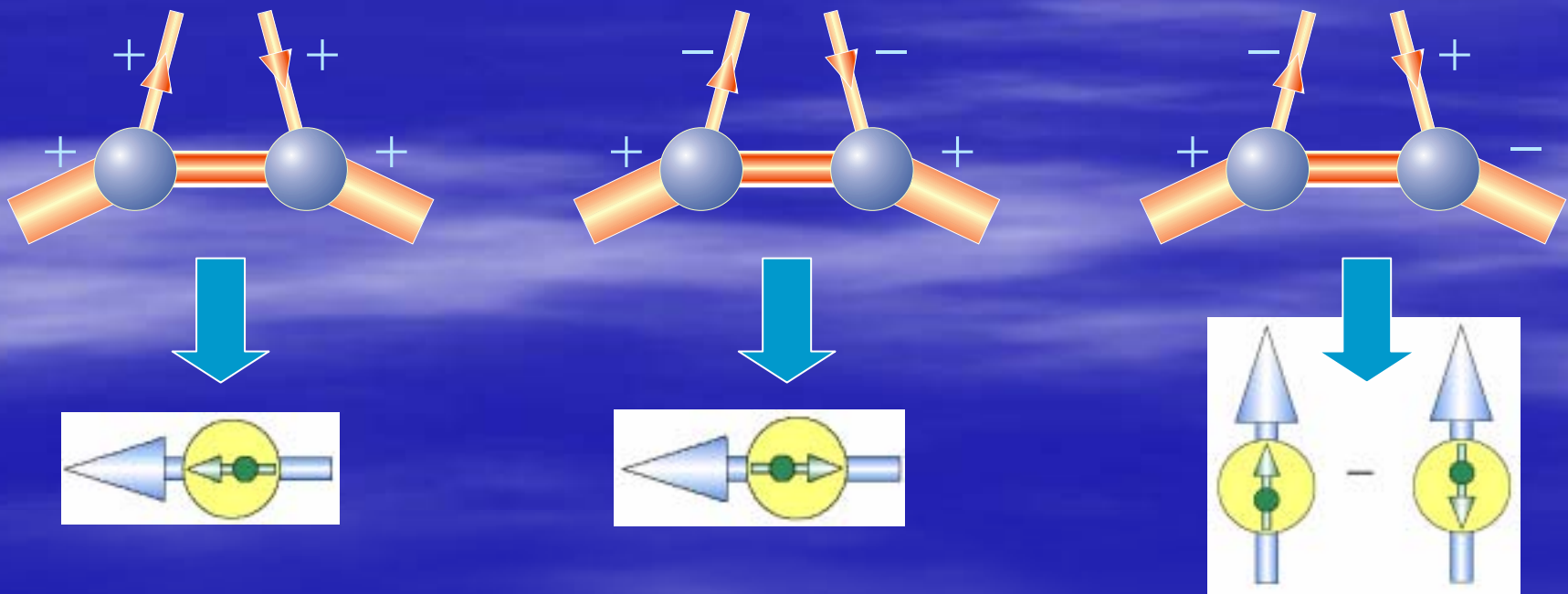
No Transverse Gluon Distribution

Helicity Amplitudes and PDFs

- Parton Distribution is connected to Forward Scattering Amplitude of Proton and Parton by Optical Theorem

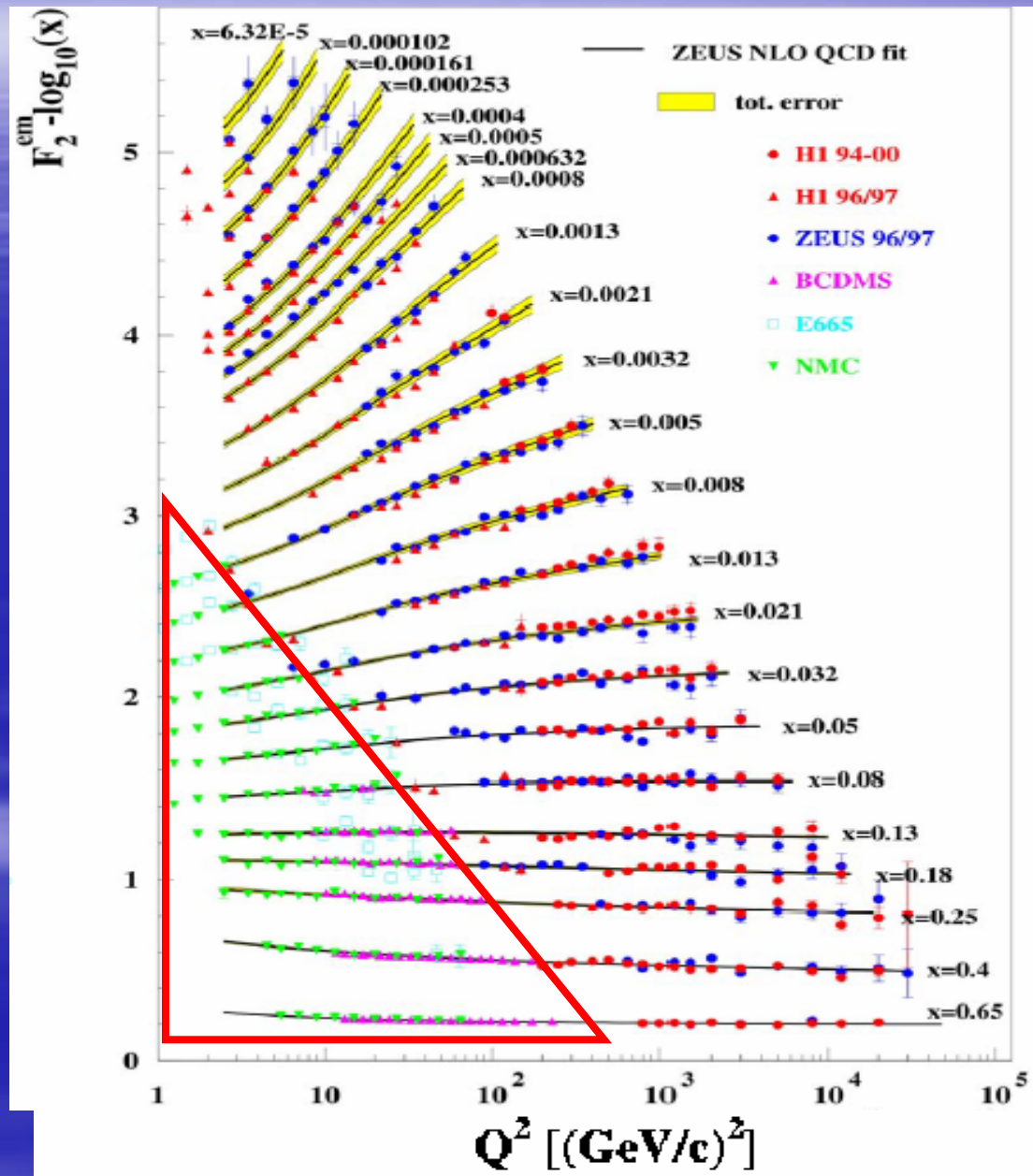


- For Proton (spin=1/2) there are 3 possibilities



Precision Data from DIS

- Precision Data in Wide Kinematical Range
  - Q^2 evolution agrees with pQCD
- Notes:
  - Only Fixed Target Spin Experiments so far…
  - Need a Collider to extend kinematical coverage



From $g_1(x,Q^2)$ to $\Delta\Sigma$

- Integrate over x (0,1) !

$$\Gamma_1^p = \frac{1}{2}\left(\frac{4}{9}\Delta U + \frac{1}{9}\Delta D + \frac{1}{9}\Delta S\right.$$

$$\Gamma_1^n = \frac{1}{2}\left(\frac{1}{9}\Delta U + \frac{4}{9}\Delta D + \frac{1}{9}\Delta S\right.$$

- Utilize Octet Baryon β-

$$\Delta U - \Delta D = 1.2692 \pm 0.0112$$

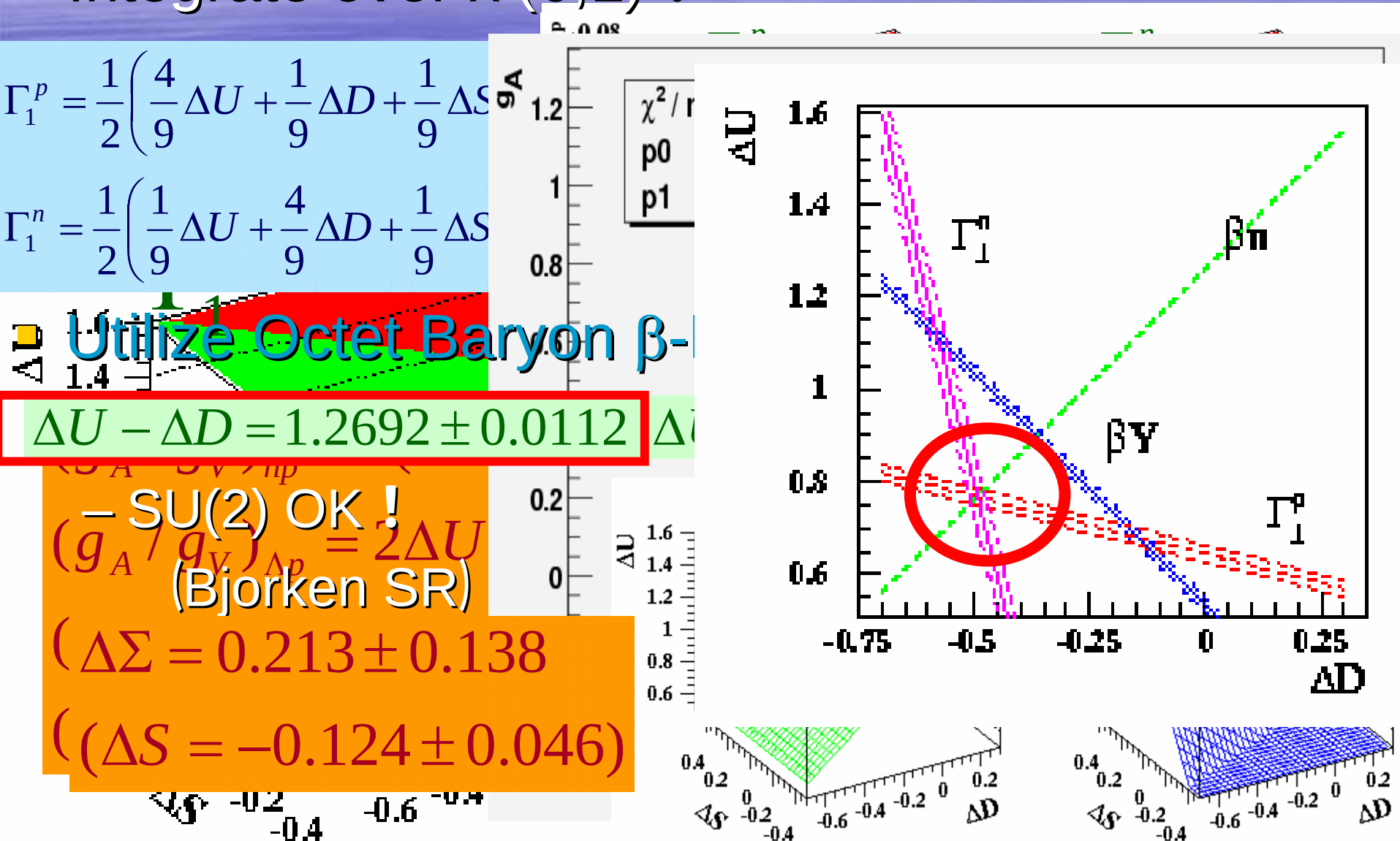
– SU(2) OK !

$$(g_A/g_V)_{Ap} = 2\Delta U$$

(Bjorken SR)

$$\Delta\Sigma = 0.213 \pm 0.138$$

$$(\Delta S = -0.124 \pm 0.046)$$



Polarised Parton Distributions

- Global QCD Analysis to Extract Polarized Quark and Gluon Distributions
  - (*a la* MRST, CTEQ)
- Four Independent Distributions are often extracted – e.g. $\Delta U(x,Q^2), \Delta D(\ ), \Delta S\ (\ ),\ \Delta g\ (\ )$
  - In unpolarised case, even more

$$u, \bar{u}, d, \bar{d}, s, \bar{s}, c, b, t, g$$

- We have ONLY TWO independent measurements $g_1^p(x, Q^2)$ and $g_1^n(x,Q^2)$
  - Q^2 evolution helps?

Separation of Pol' Quark Dist's

- Only two independent measurements
  $g_1^p(x, Q^2)$ and $g_1^n(x,Q^2)$
- Separation into 3 quark dist's relies on
  - 1st moments (employ β-decay const's), **unless**

How much do we know about $\Delta g(x)$?

- Different coupling with $\Delta g(x)$ thru Q^2 evolution

Non-Singlet Quark Distribution

$$\frac{\partial \Delta q_{NS}(x,Q^2)}{\partial(\ln Q^2)} = \frac{\alpha_S(Q^2)}{2\pi} \Delta P_{q\pm,NS}(x) \otimes \Delta q_{NS}(x,Q^2)$$

$$\begin{pmatrix} \Delta\Sigma \\ a_3 \\ a_8 \end{pmatrix} = \begin{pmatrix} \Delta U + \Delta D + \Delta S \\ \Delta U - \Delta D \\ \Delta U + \Delta D - 2\Delta S \end{pmatrix}$$

Singlet Quark Distribution

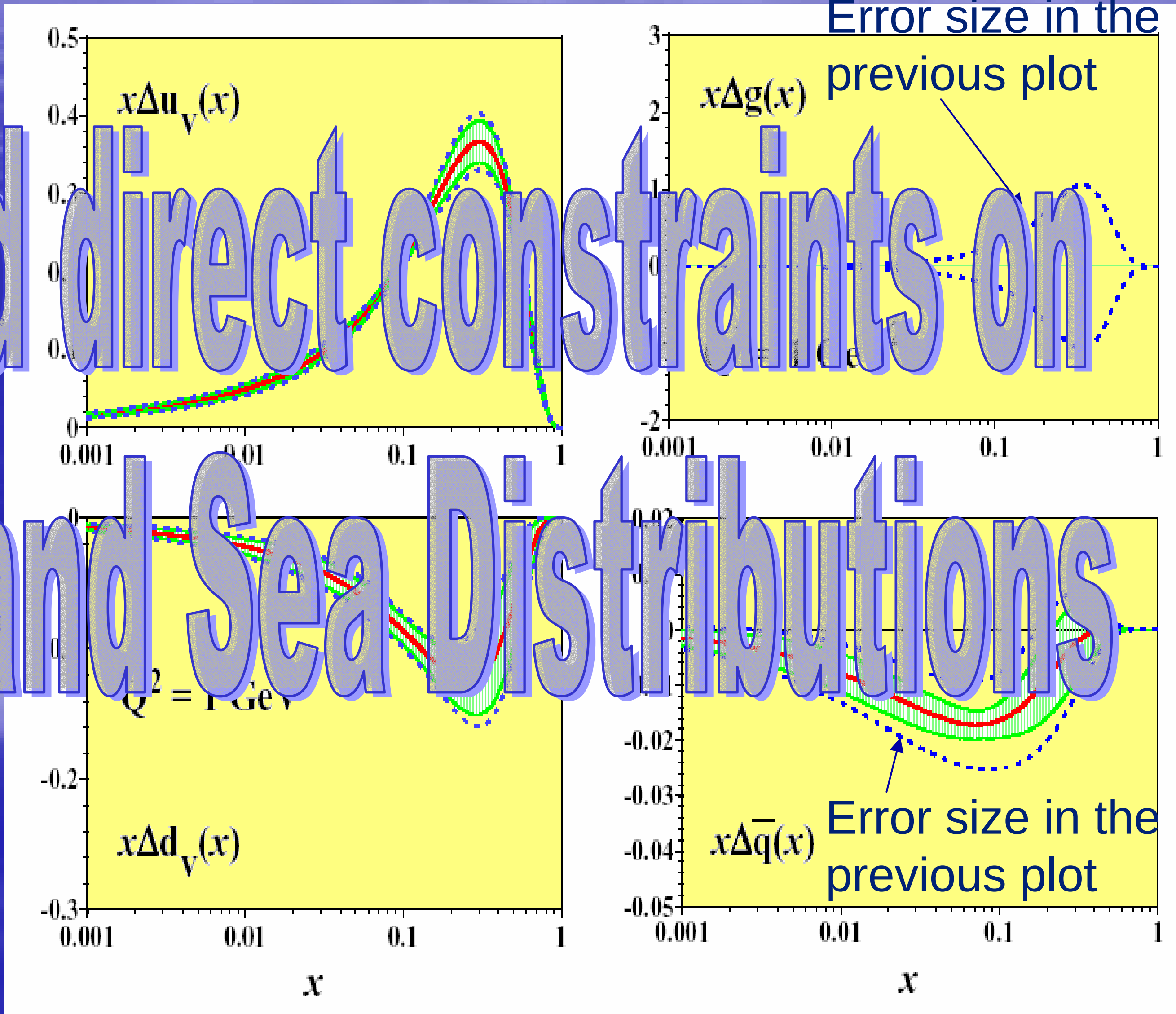
$$\frac{\partial}{\partial(\ln Q^2)} \begin{pmatrix} \Delta\Sigma(x,Q^2) \\ \Delta g(x,Q^2) \end{pmatrix} = \frac{\alpha_S(Q^2)}{2\pi} \begin{pmatrix} \Delta P_{qq}(x) & \Delta P_{qg}(x) \\ \Delta P_{gq}(x) & \Delta P_{gg}(x) \end{pmatrix} \otimes \begin{pmatrix} \Delta\Sigma(x,Q^2) \\ \Delta g(x,Q^2) \end{pmatrix}$$

Polarised PDF

Asymmetry Analysis Collaboration

M. Hirai, S. Kumano and N. Saito, PRD (2004)

- Valence Dist's are determined we
- Sea ...' i poo con ...ne
- Gluon can be either >0, =0, <0
- Ev... i we ass... 0, Ch... cha...ges only 2.5%
  - Sea quark error is reduced



We need direct constraints on Gluon and Sea Distributions

RHIC Spin Physics Program

- Accelerate and Collide Polarized Proton Beams with Hi-Polarization and Luminosity

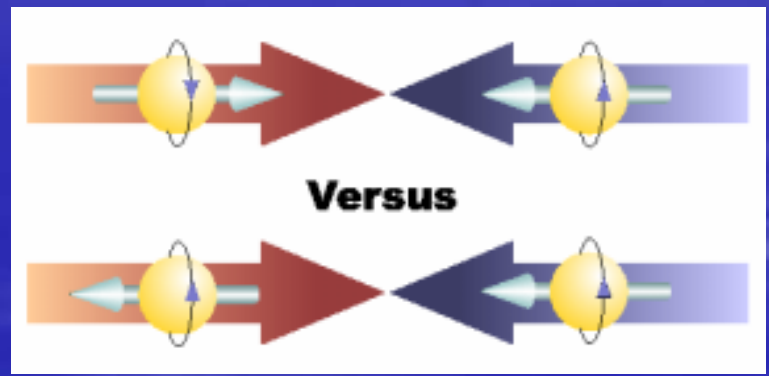
$$P_B = 70\%, \sqrt{s} = 200,500\text{GeV}, L_{\max} = 2\times10^{32}\,\text{cm}^{-2}\text{s}^{-1}$$

- Brief History
  - 1990: Polarized Collider WS in Penn-State U
  - 1991: RHIC Spin Collaboration Formed
  - 1993: PHENIX and STAR integrated Spin Program
  - 1995: RIKEN-BNL Collaboration (~$20M)
  - 2002: First Polarized Proton Collision!
  - Additional support from DOE and NSF

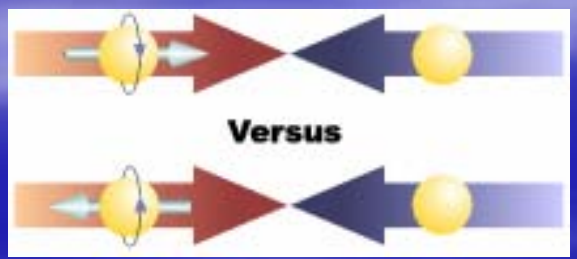
What Do We Measure at RHIC?

- We measure spin asymmetries for cross sections
- A_{LL}: double helicity asymmetry
  - Useful in extracting $\Delta g(x)$, $\Delta q(x)$ etc.

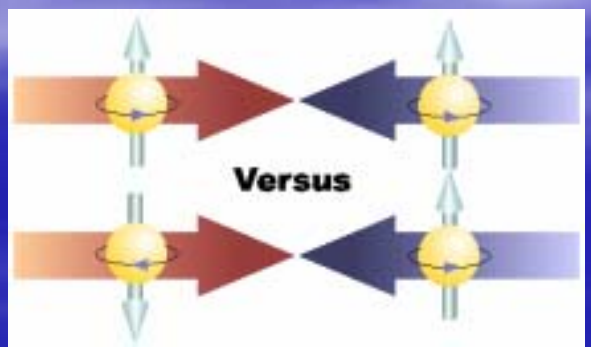
$$A_{LL} = \frac{\sigma(++) - \sigma(+-)}{\sigma(++) + \sigma(+-)}$$



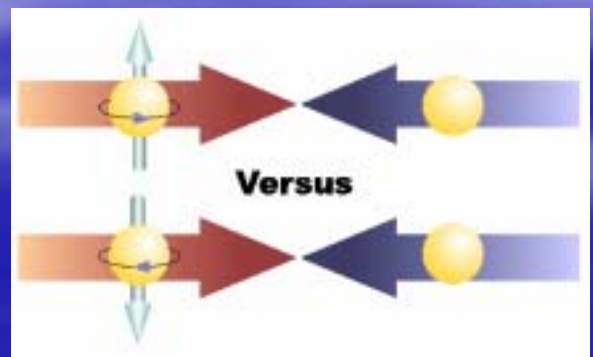
A_L:Parity Violation



A_{TT}: Transversity



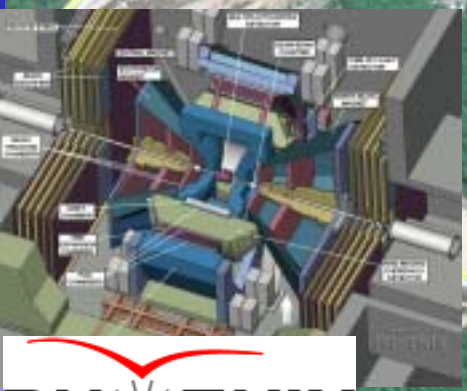
A_N:Twist-3



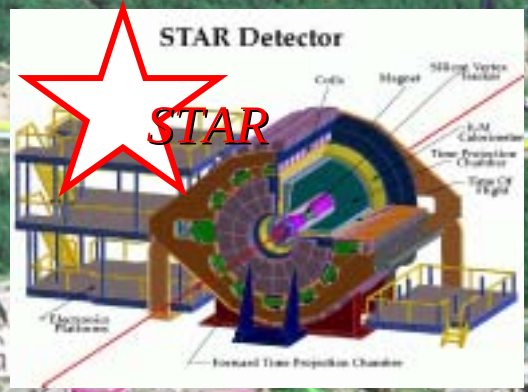
RHIC:The First Polarised pp Collider

PHOBOS

BRAHMS



RHIC



PHENIX

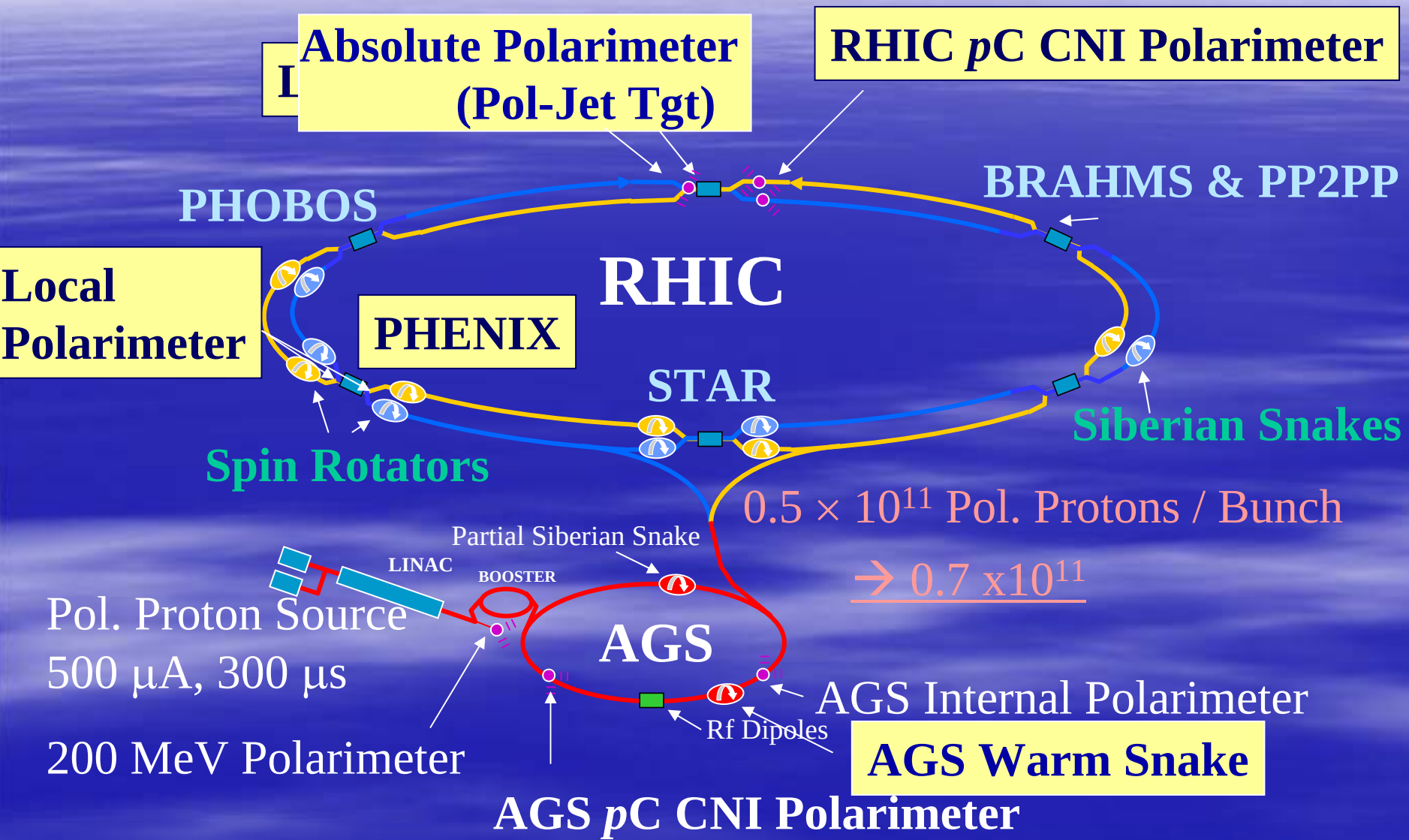
BOOSTER

LINAC

AGS

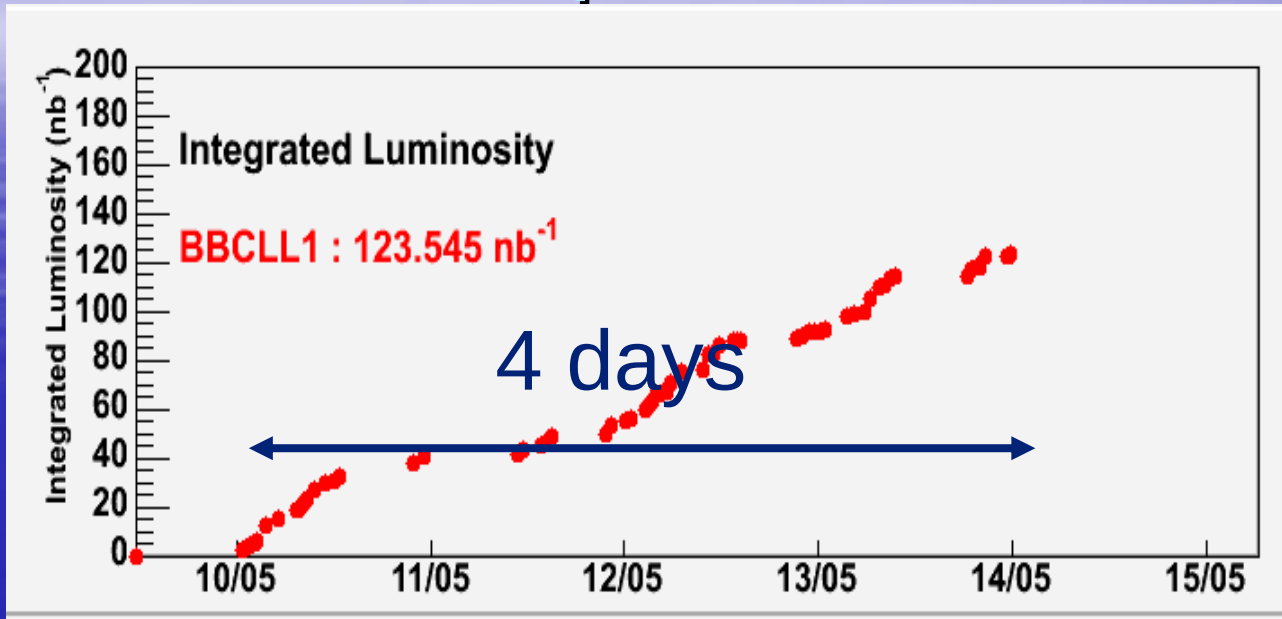
RHIC Spin Run2 →Run3 →Run4

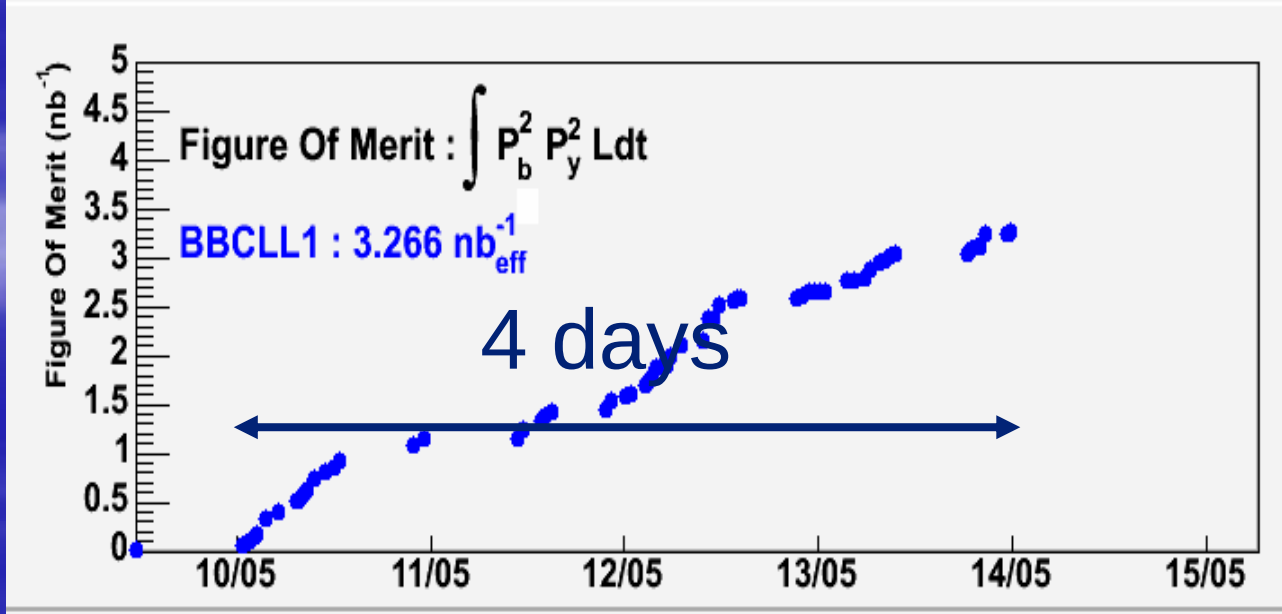
Dec 2001-Jan 2002 Apr-May 2003 Apr 2004



RHIC Spin: L and P Improvements

- Run 2: A_N
  - ~7nb^{-1}/day
  - P_B~20%
- Run-3:A_{LL}
  - 10nb^{-1}/day
  - P_B~26%
  - (AGS) 40%
- Run-4:A_{LL}
  - Only Machine Studies
  - 30nb^{-1}/day
  - P_B~40%
  - (AGS) 50%
- Run-5 :A_{LL}
  - Long pp Run planned





Run-4 Achievements (5+1 weeks)

- Improved Polarisation at AGS
  - With a new Helical Snake: 40% → 50 %
  - Further improvement with additional snake is expected in Run-5
- Established a better working point at RHIC
  - Previous tune ~ 0.22 → ~ 0.70
  - Better beam life time and polarisation observed
- Established a vacuum improvement with NEG coating
  - Significantly higher beam current can be expected in Run-5
- Commissioned Polarised Gas Jet Target
  - Need for absolute beam polarisation
- Commissioned Exp's for Hi-Luminosity
  - Luminosity Monitor, DAQ, etc.

Towards Design Luminosity

- Higher beam current and tune control are the keys

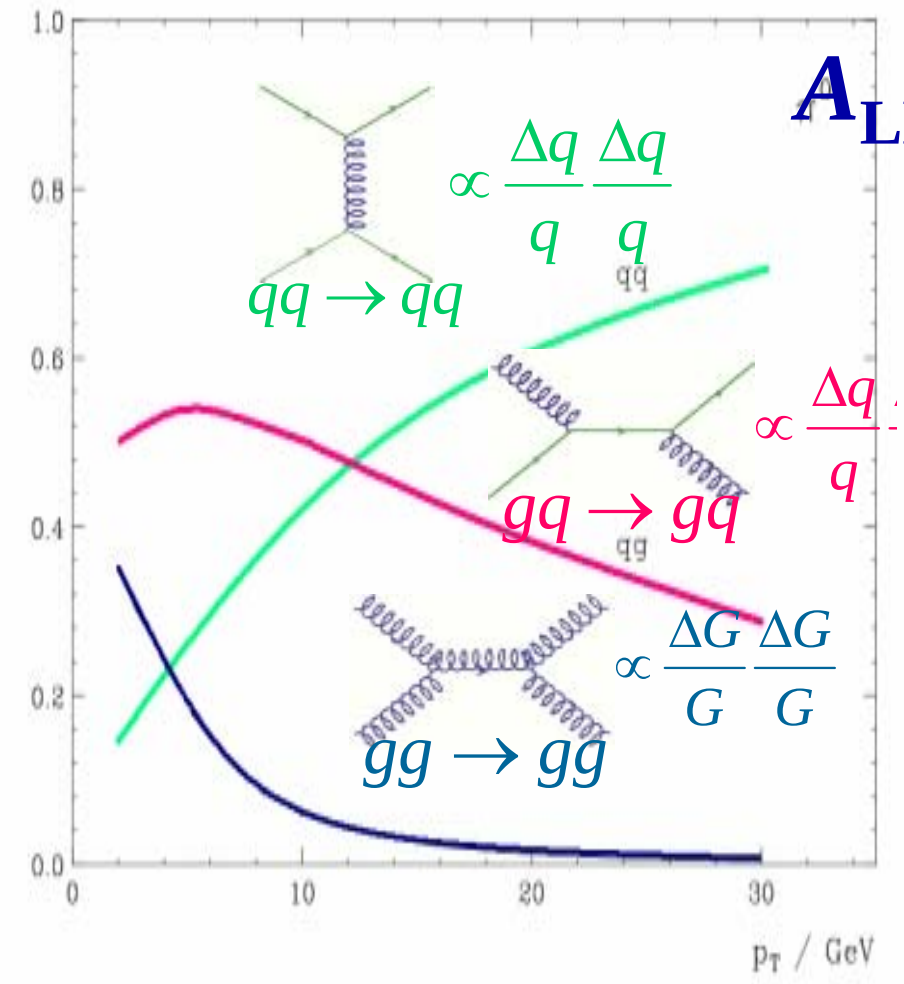
	Run-3	Run-4	Goal	Gain	Remark
# of bunches	55	55	120	2.2	
beam intensity	0.6	0.8	2.0	2.5	NEG coating to reduce e-cloud
beta* (m)	1.3	1.3	1.0	1.3	
emittance	10π	20π	20π	1.0	
useful vertex (%)	50	50	100	2.0	200 MHz storage RF cavity
Net Gain				35.5	
Uptime (%)	10	50	70	1.4	improve stability
Lavg/Lpeak	0.5	0.7	1.0	1.43	
Net Gain				2.00	
Total Gain				70.91	

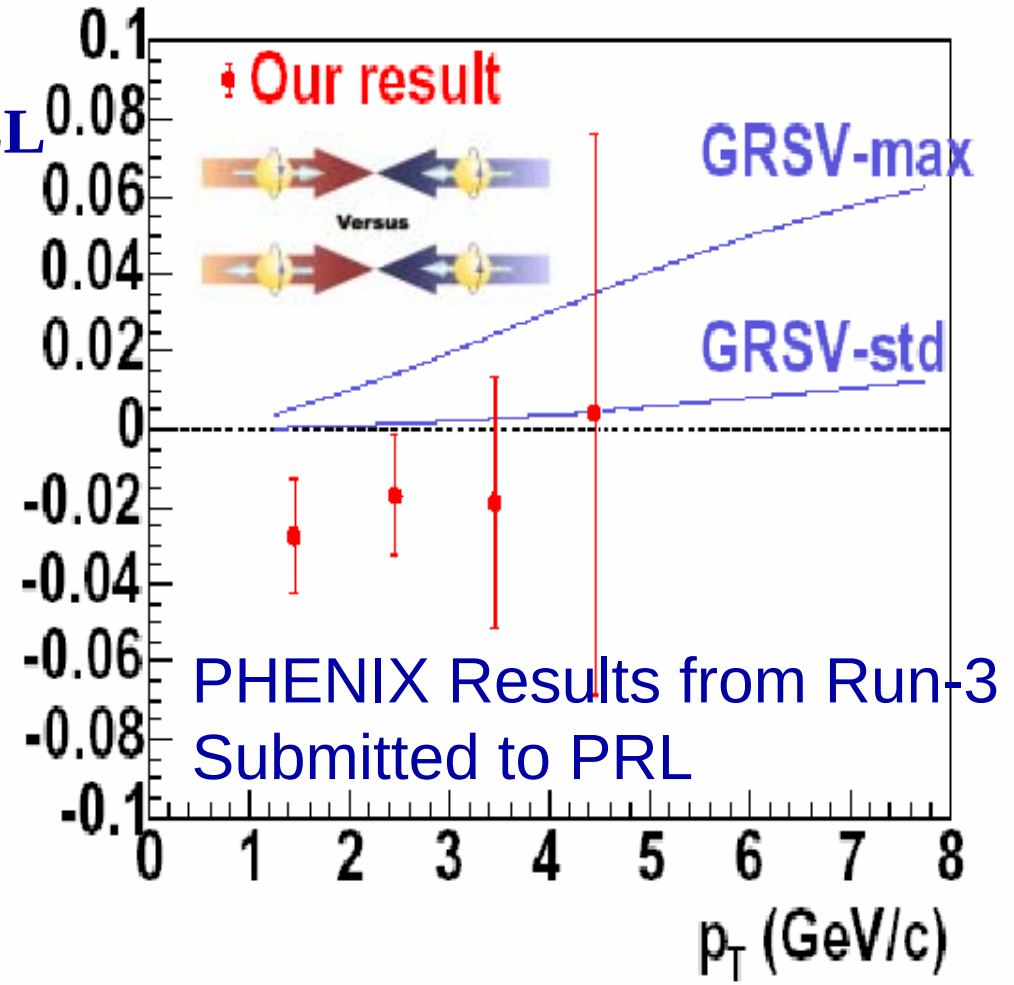
First Results from RHIC Spin

Constraints on $\Delta g(x)$ w/ π^0 Production

- $pp \rightarrow \pi^0 X$ is sensitive to $gg \rightarrow gg$ and $gq \rightarrow gq$

frac PHENIX : A_{LL} for $pp \rightarrow \pi^0 X$ at $\sqrt{s} = 200$ GeV eV



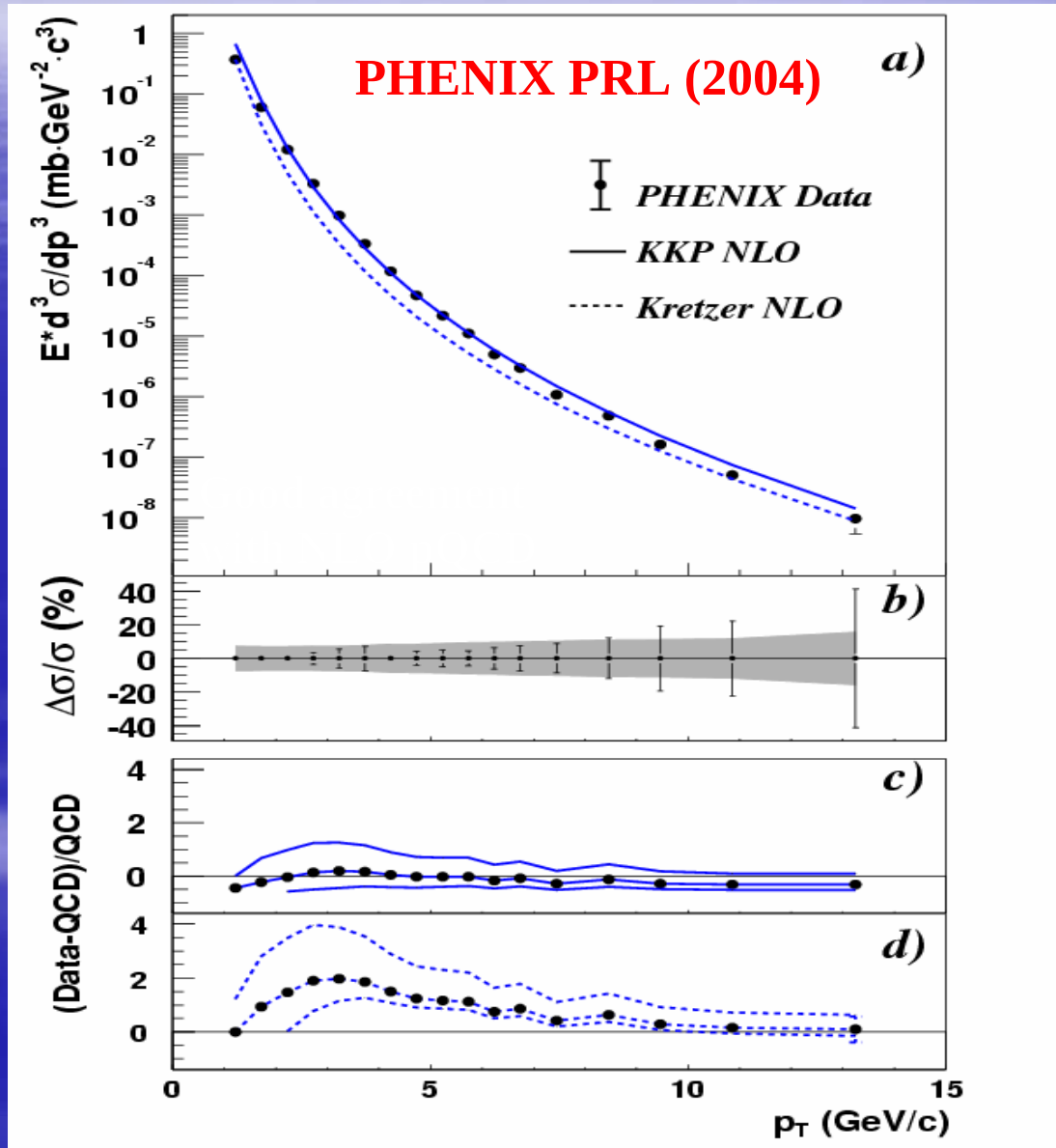


What Do We Learn?

- We need more statistics!
- pp collisions are so sensitive to $\Delta g(x)$ so that it already provides similar constraints to two decades of polarised DIS experiments
  - (yes, our preparation also taking a decade)
- Caveats:
  - Applicability of pQCD:
    - some confirmation with xsection measurement DONE
    - Intrinsic-k_T, fragmentation functions
  - $A_{LL}(\pi^0)/A_{LL}(\text{jet})$ are sensitive to
    $(\Delta g^2+\alpha\ \Delta q\Delta g+\ \beta\ \Delta q\Delta q)$; what about sign?
- It is very important to have both lepton and hadron scattering data to reveal possible systematics involved.

Precision QCD test for Hadron Prdctn

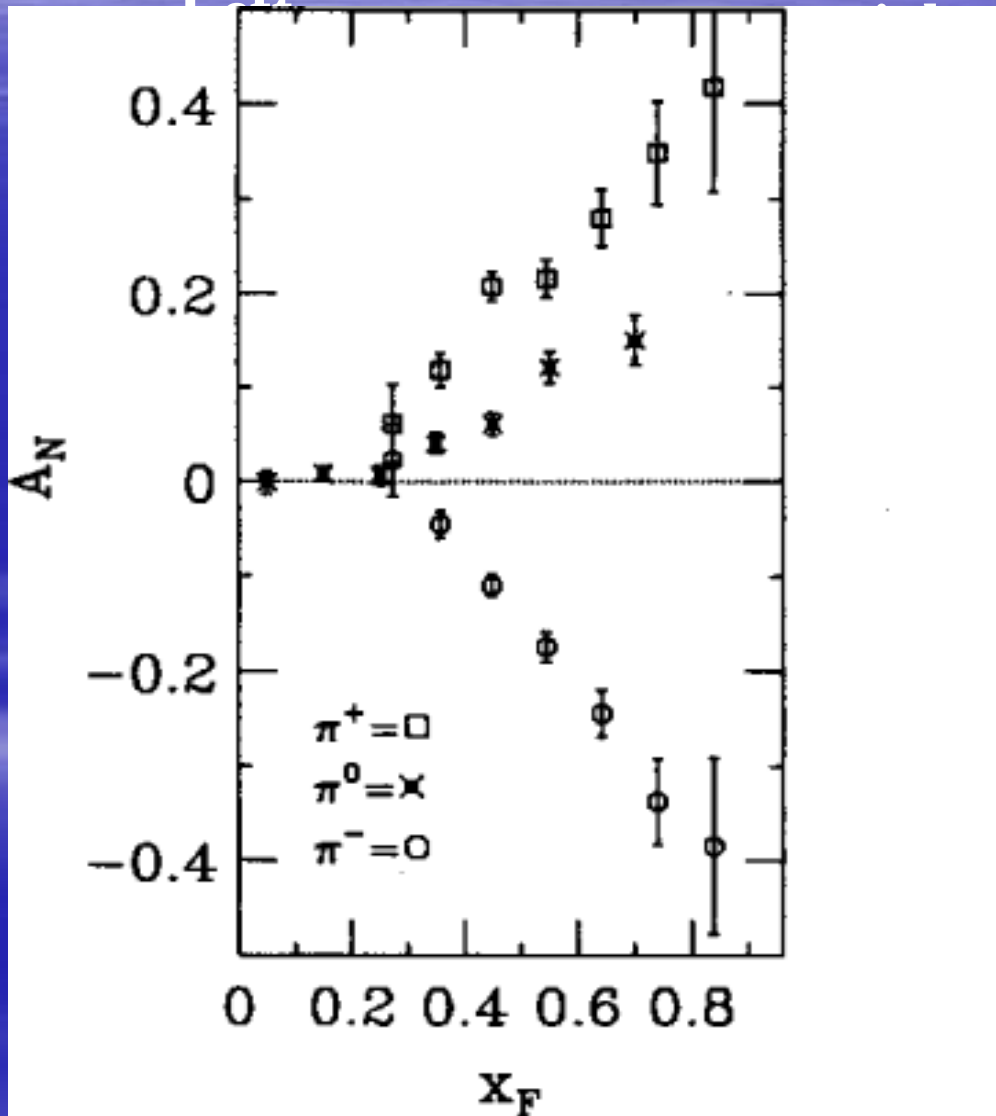
- pp→ π^0 X @ 200 GeV (PHENIX)
- Cross Section is well described by the pQCD over 8 order of magnitude!
- Sensitivity for Fragmentation Function



Single Transverse Spin Asymmetries

- Fermilab E-704 reported Large Asymmetries A_N in pion productions
- Could be explained as
  - Transversity x Spin-dep fragmentation (Collins effect), or
  - Intrinsic-k_T imbalance (Sivers effect) , or
  - Higher-twist effects
  - Or combination of above

$pp \to \pi X$ at $\sqrt{s} = 19.4\,\mathrm{GeV}$

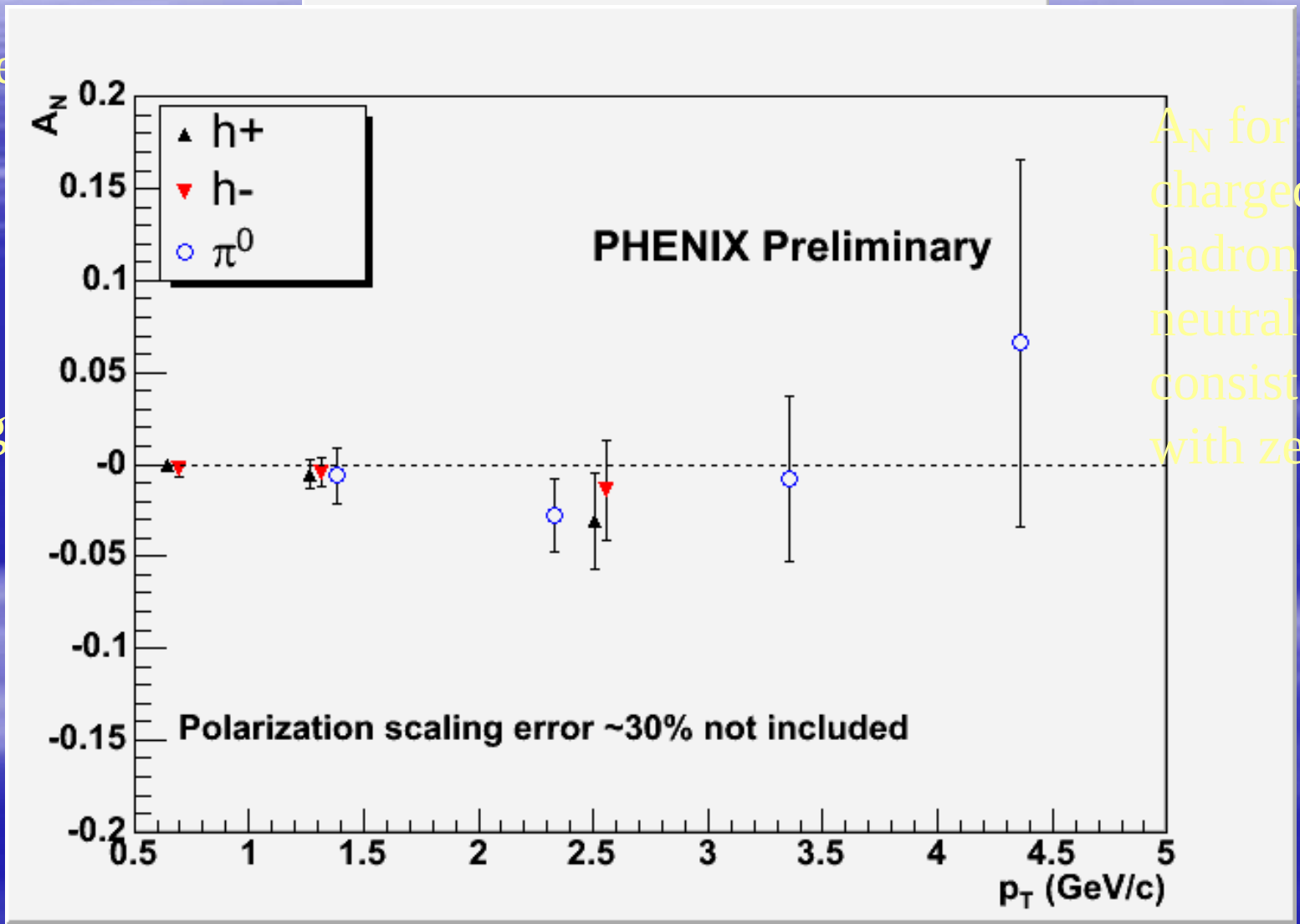


PHENIX Results: Central Rapidity

- ZERO asymmetry:

Ne

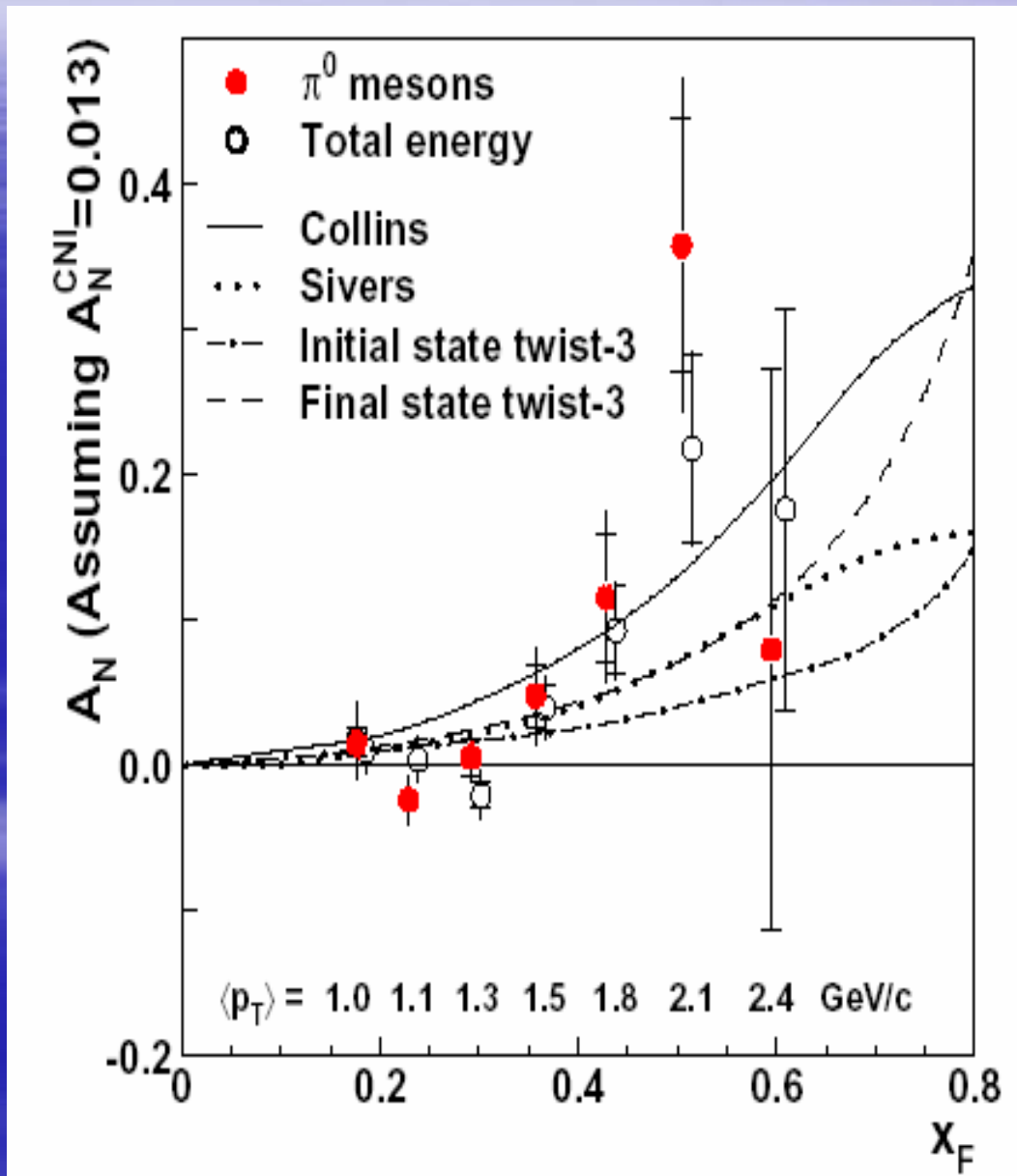
Charg



A_N for both charged hadrons and neutral pions consistent with zero.

STAR Results: Forward Rapidity

- Large Asymmetry Measured
- To distinguish models, jet axis reconstruction is required
- Probably…A_N requires large x_{BJ}, which is only achievable in hi-p_T in Central rapidity (small xsection)
- Global Analysis with HERMES results would be beneficial



Future Prospects

assuming

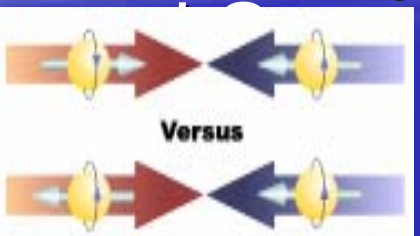
$$\int Ldt = 320\,\mathrm{pb}^{-1} \text{ at } \sqrt{s} = 200\,\mathrm{GeV}$$

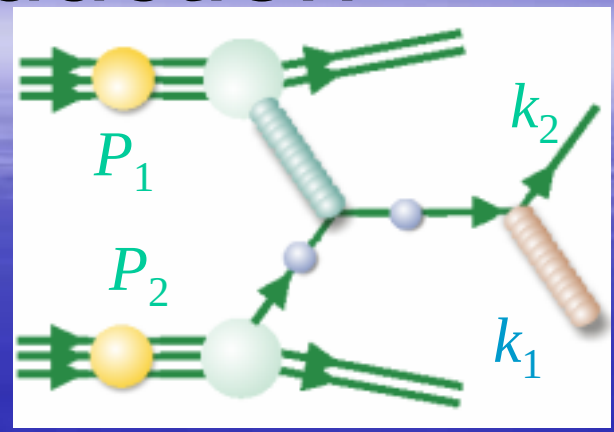
$$\int Ldt = 800\,\mathrm{pb}^{-1} \text{ at } \sqrt{s} = 500\,\mathrm{GeV}$$

with 70% polarization

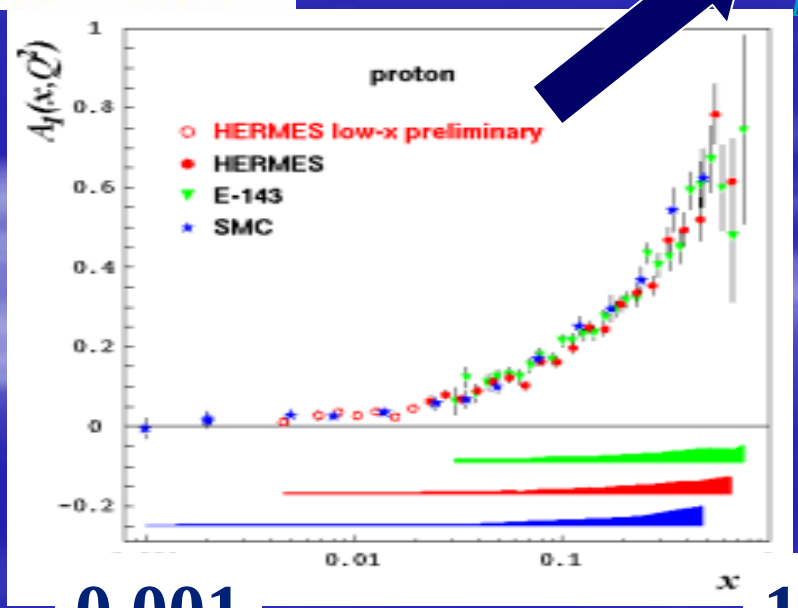
Prompt Photon Production

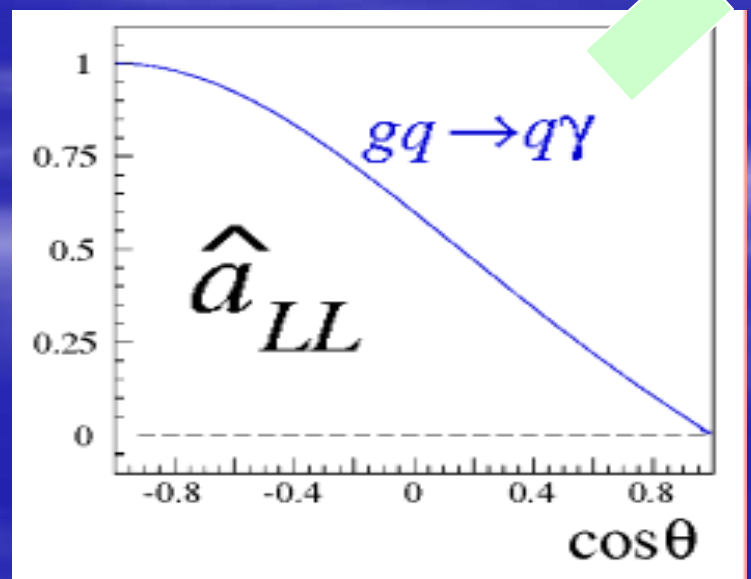
- Gluon Compton Dominates
  - 10% Contamination from Annihilation
  - No fragmentation contribution in





$$A_{LL} = \frac{\Delta g(x_1)}{g(x_1)} \otimes \frac{\sum_i e_i^2 \Delta q_i(x_2)}{\sum_i e_i^2 q_i(x_2)} \otimes a_{LL}(gq \to q\gamma)$$





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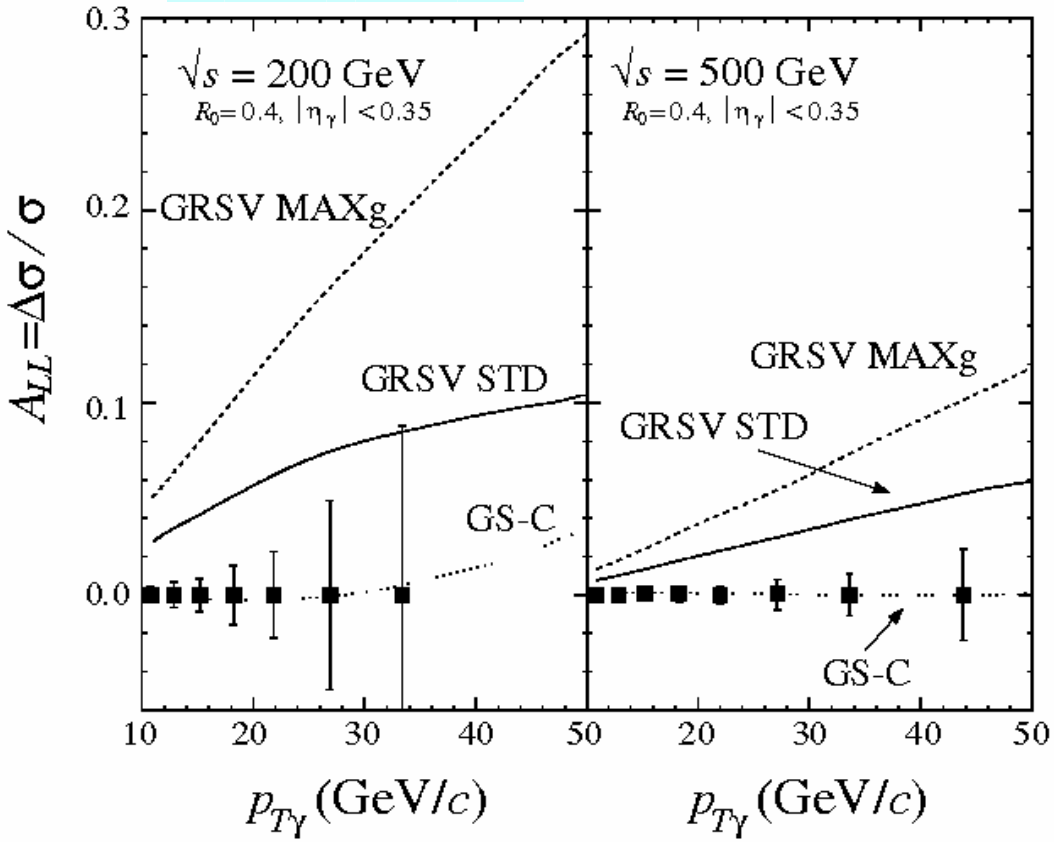
Prompt Photon Production

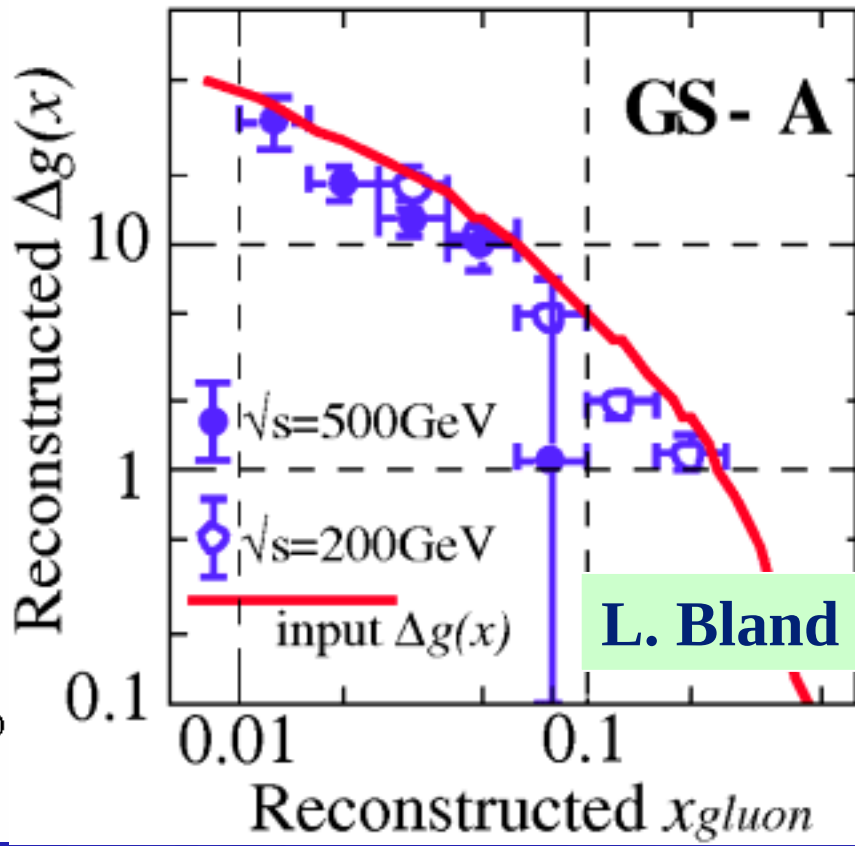
- Gold Plated mode for $\Delta g(x)$

PHENIX

STAR



W. Vogelsang et al.

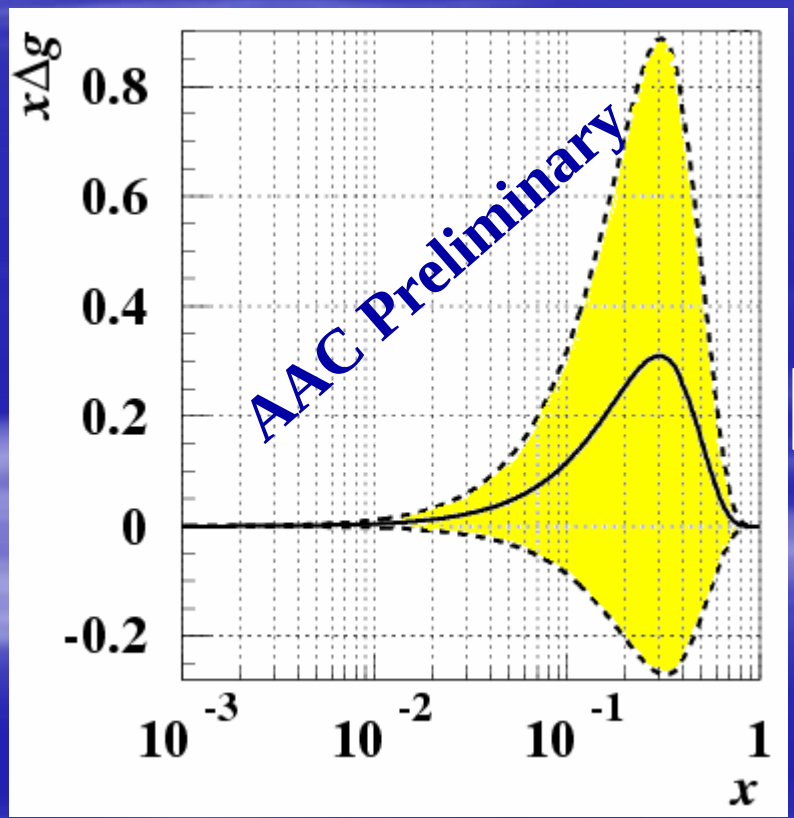


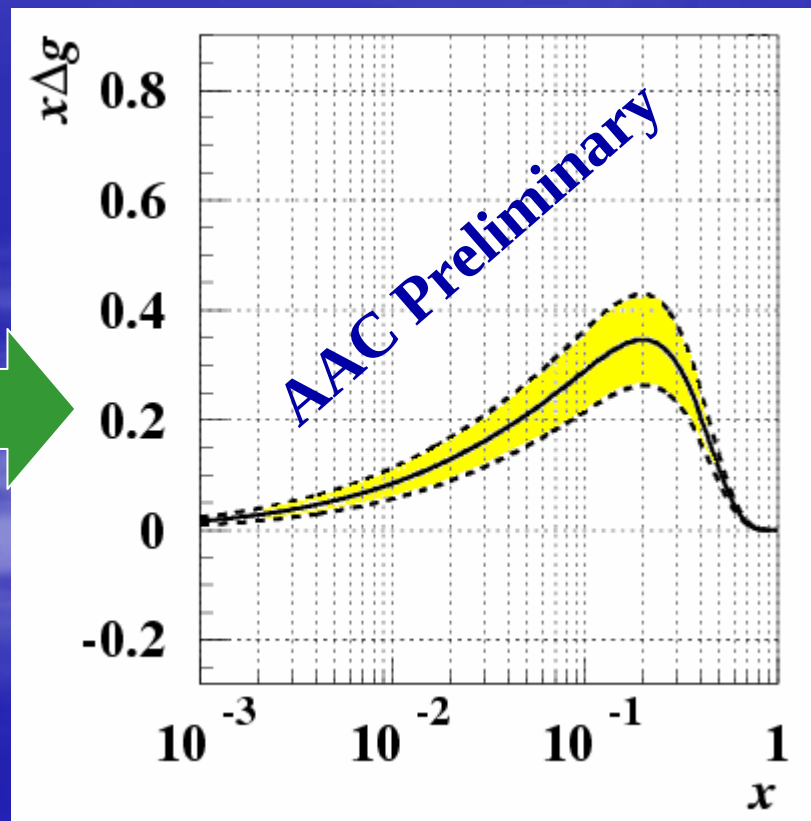
L. Bland

x-reconstructed using jet

Impact of PHENIX Prompt Photon

- If we include Future PHENIX Data into Global Analysis…

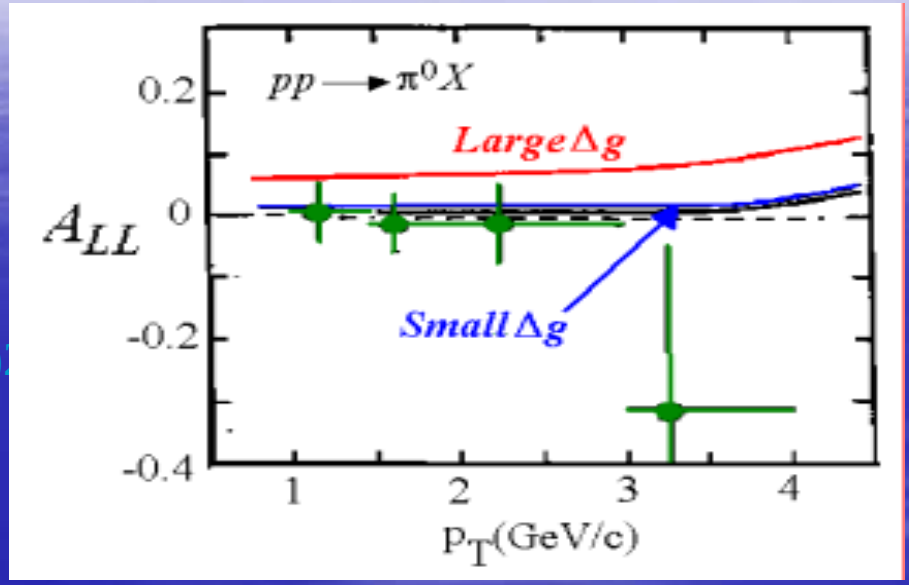


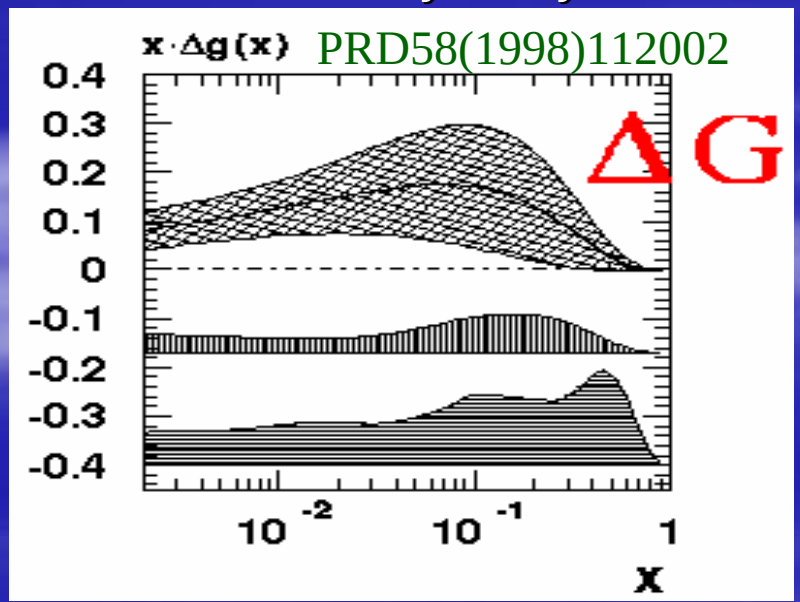


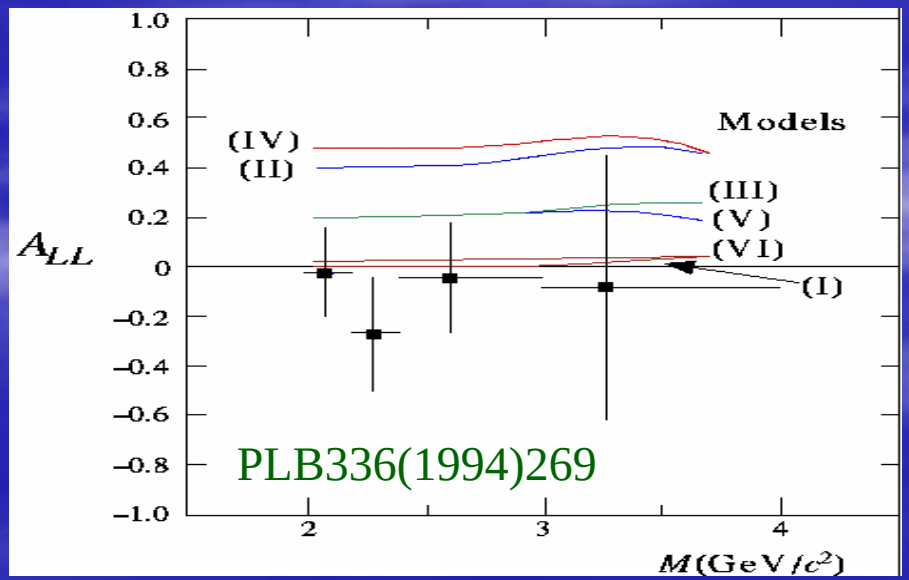
M. Hirai *et al.*

Gluon Polarization in the Proton

- Hunting for Δg
  - Direct Probe
    - FNAL E704
      - High-pT π^0
      - High-mass Multi-γ pair
    - DESY HERMES PRL 84(00)
      - High-pT hadron pair
  - Indirect Probe
    - NLO Analysis by SMC

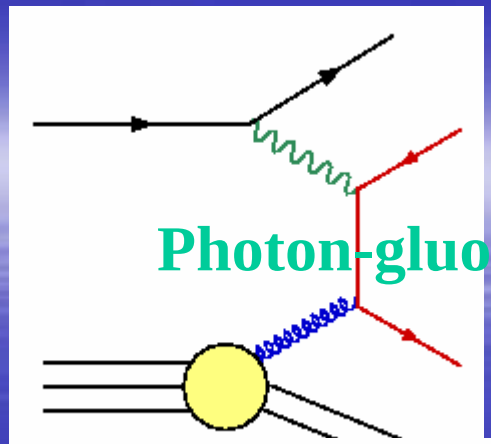


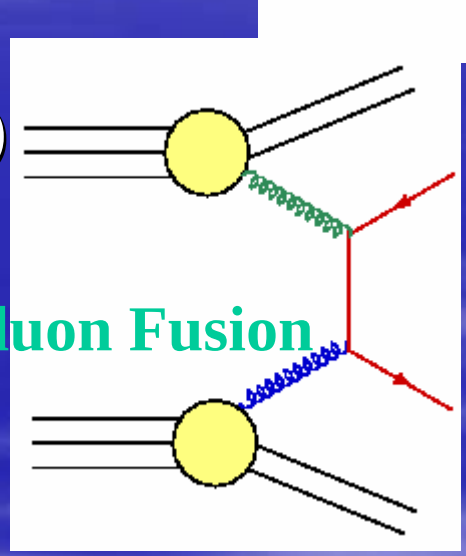


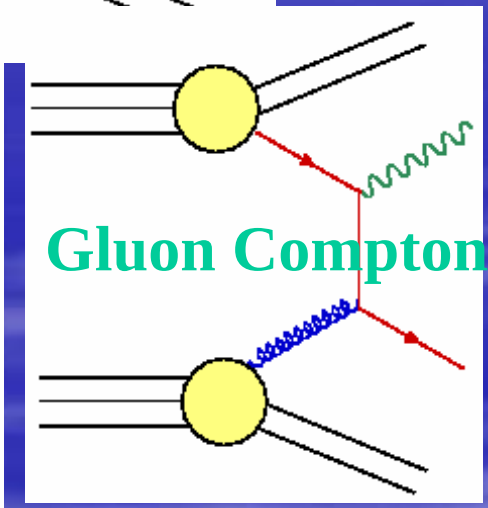


Dig out $\Delta g(x)$ & Δg !

- Current Experiments
  - HERMES High-pT hadron pair
  - RHIC Spin
    - Prompt Photon (+ jet)
    - Jet
    - Inclusive hadron
    - Heavy flavor (charm, bottom, J/y ...)
  - COMPASS
    - Open charm
    - High-pT hadron pair



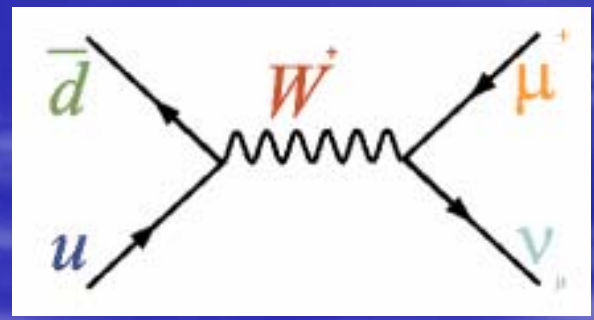


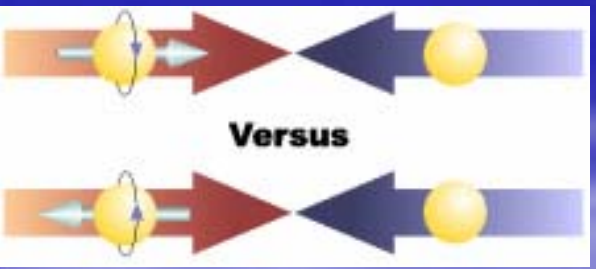


- Future Possibilities
  - EIC
  - Polarized HERA
  - TESLA-N

W Production in pp Collisions

- W is produced through pure V-A
  - Chirality is fixed → ideal for spin structure studies
- W couples to weak charge ~ flavor
  - Flavor is (almost) fixed → ideal for flavor structure studies
- Parity Violating Asymmetry A_L :



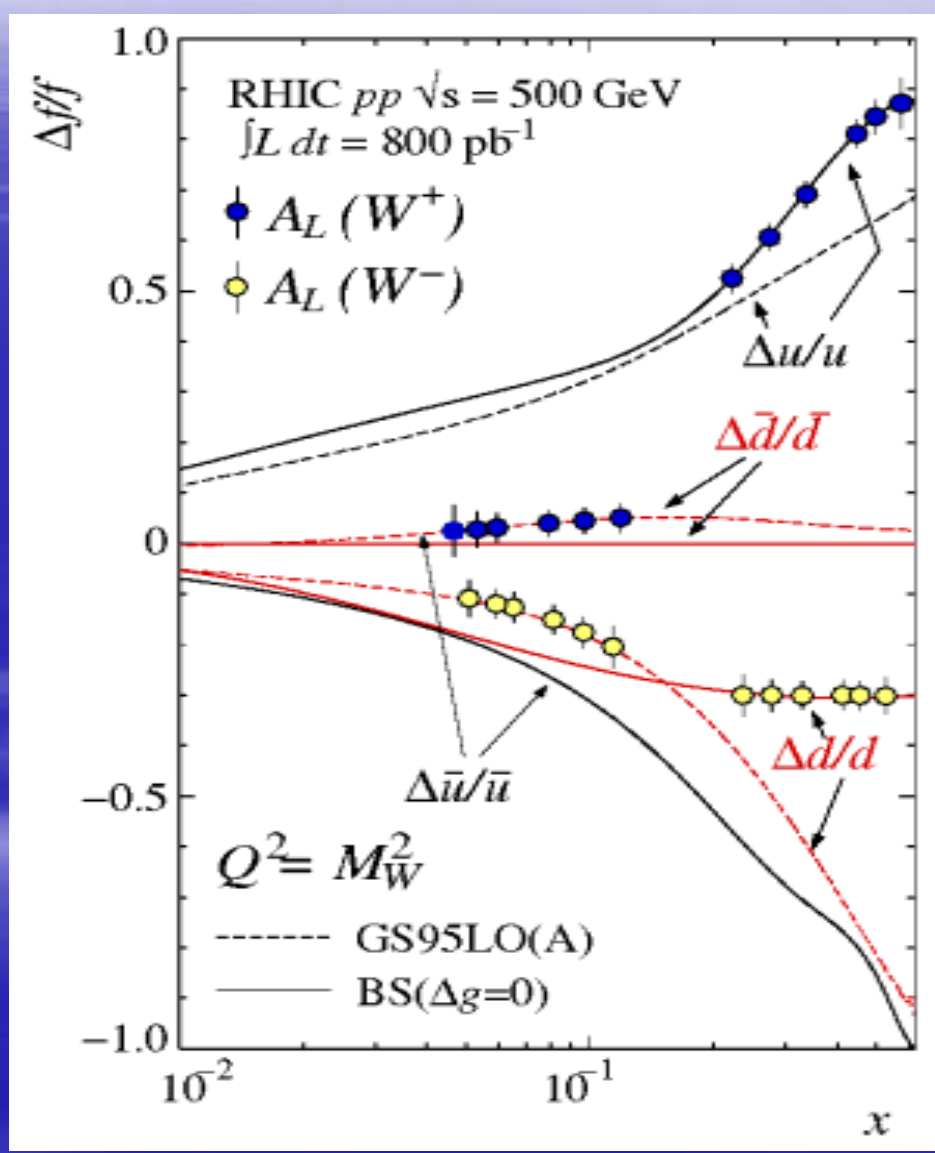


J. Soffer et al.

$$A_L^{W^+} = \frac{\Delta u(x_a)\bar{d}(x_b) - \Delta\bar{d}(x_a)u(x_b)}{u(x_a)\bar{d}(x_b) + \bar{d}(x_a)u(x_b)}$$

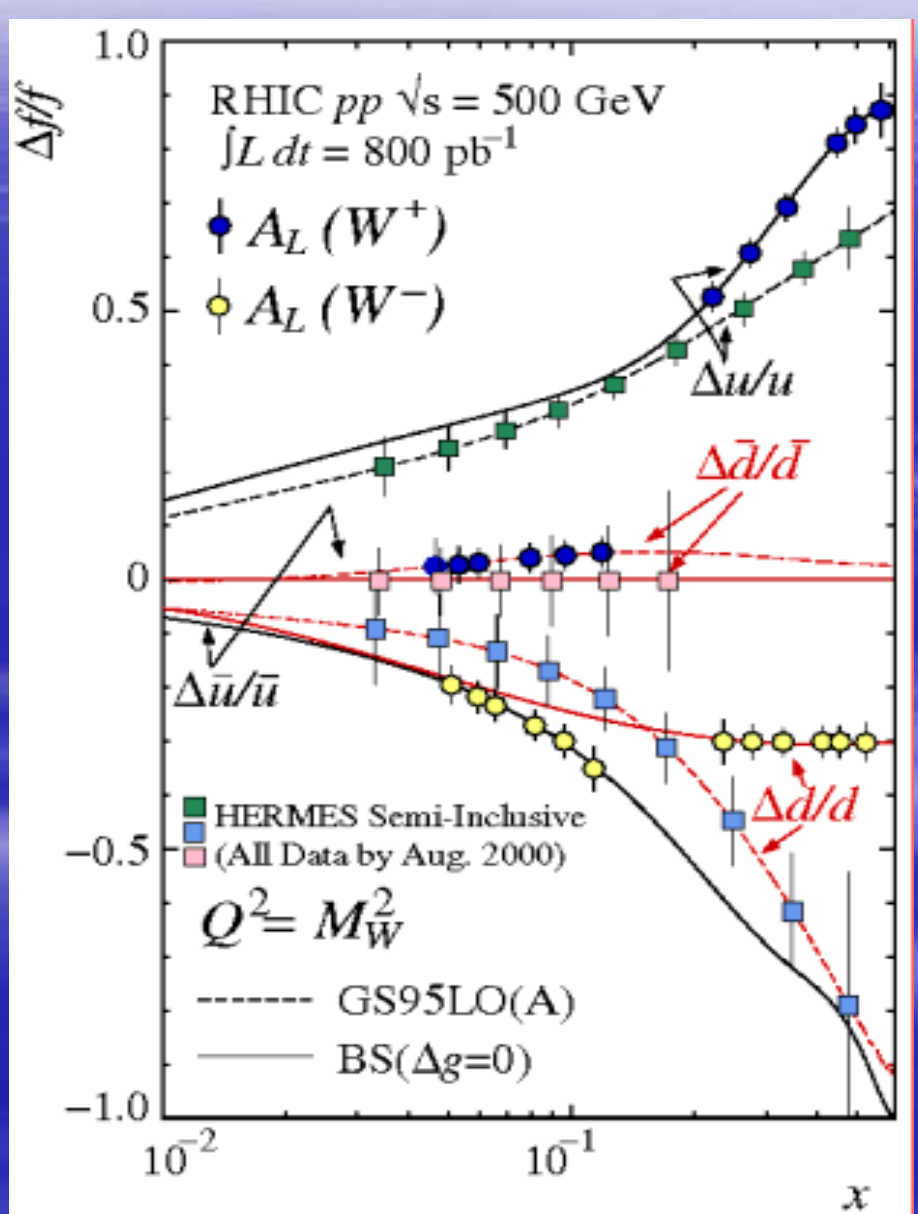
Sensitivity Goal

- Studies with PHENIX Muon Arms
  - STAR Endcap Calorimeter provides similar sensitivity
  - $A_L \sim \Delta u/u(x) \sim 0.7\text{-}0.9$ (!) at large-x
- Charm associated W production will probe Δs ($gs \rightarrow Wc$)
- Studies for upgraded Energy and Luminosity are underway...



RHIC Spin and HERMES SIDIS

- Complementary!
  - RHIC W
    - No fragmentation ambiguity
    - x-range limited
    - Useless for transversity studies
  - HERMES Semi-Inclusive DIS
    - Wide x-range
    - Could be used for transversity studies

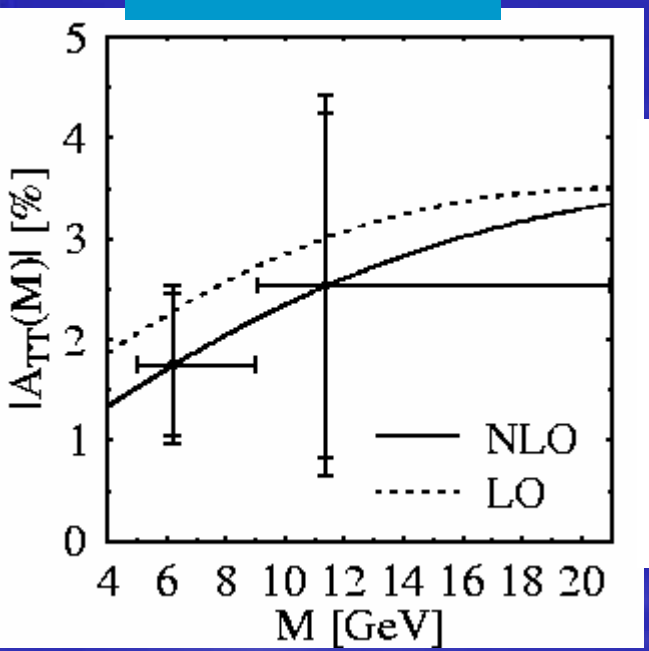


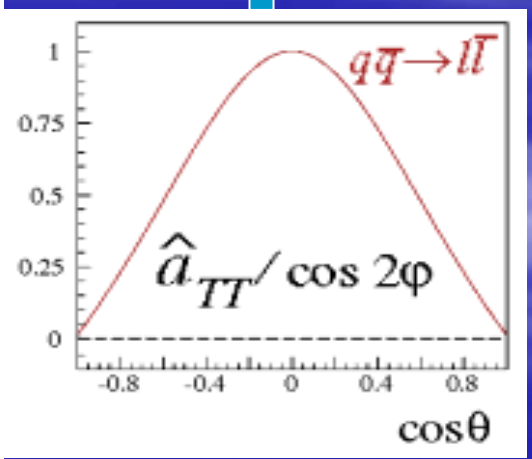
Transversity Measurements

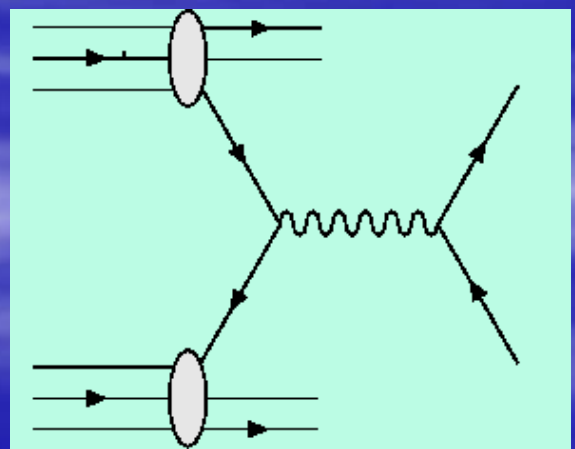
- Drell-Yan Production of Lepton Pairs
  - Clean, but low statistics (QED process)
  - Precision will be improved by L upgrade

PHENIX Muon
200 GeV

$$A_{TT} = a_{TT} \frac{\sum_i e_i^2 \delta q(x_1)\delta\bar{q}(x_2) + (1 \leftrightarrow 2)}{\sum_i e_i^2 q(x_1)\bar{q}(x_2) + (1 \leftrightarrow 2)}$$







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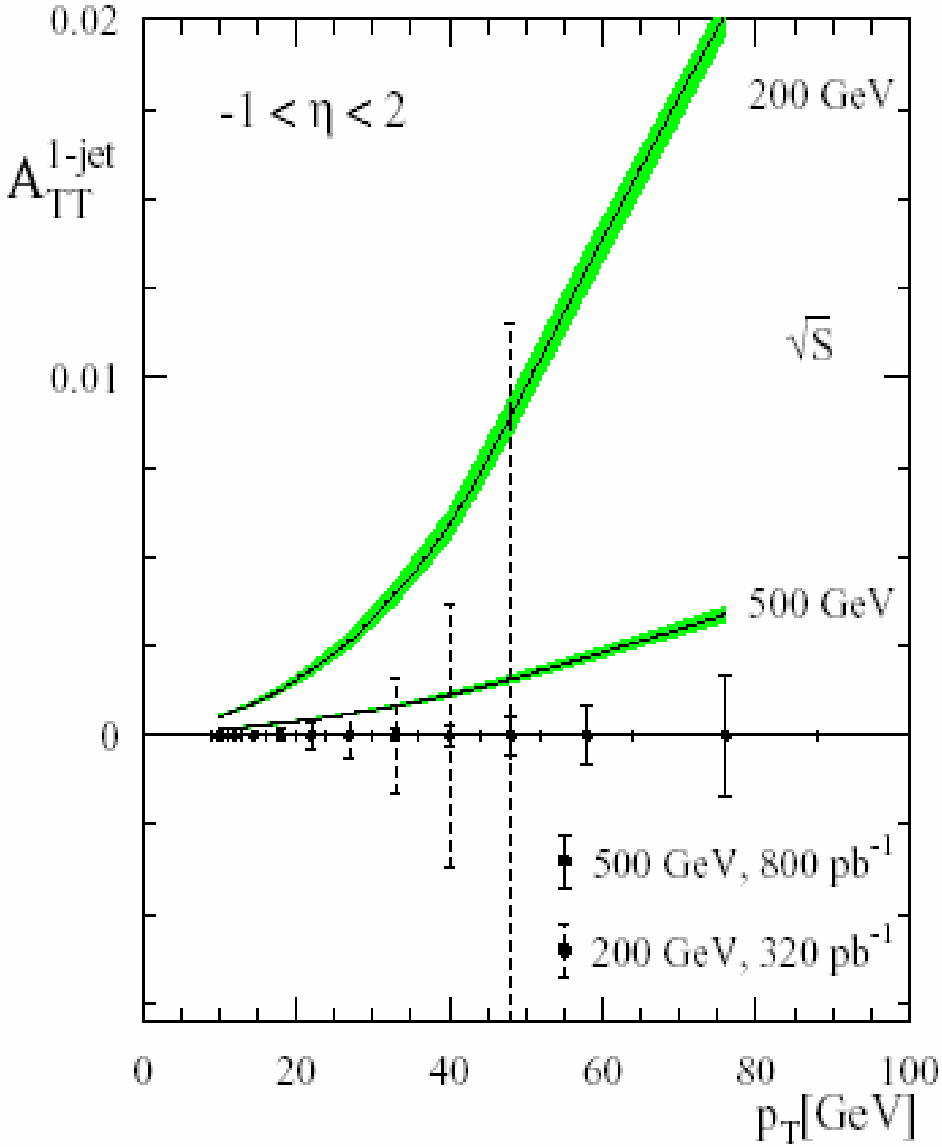
Transverse Jet Production

- Advantages:
  - Enormous yield could overcome the smallness of asymmetries
  - No mixture with Gluonic contribution
- Caveats:
  - Control of systematics will be the key for the success
    - A_{TT}~0.2% = 0.1% (if P_B=70%)
  - A_{TT} is cos2ϕ moment: statistics will be divided into several ϕ-bins

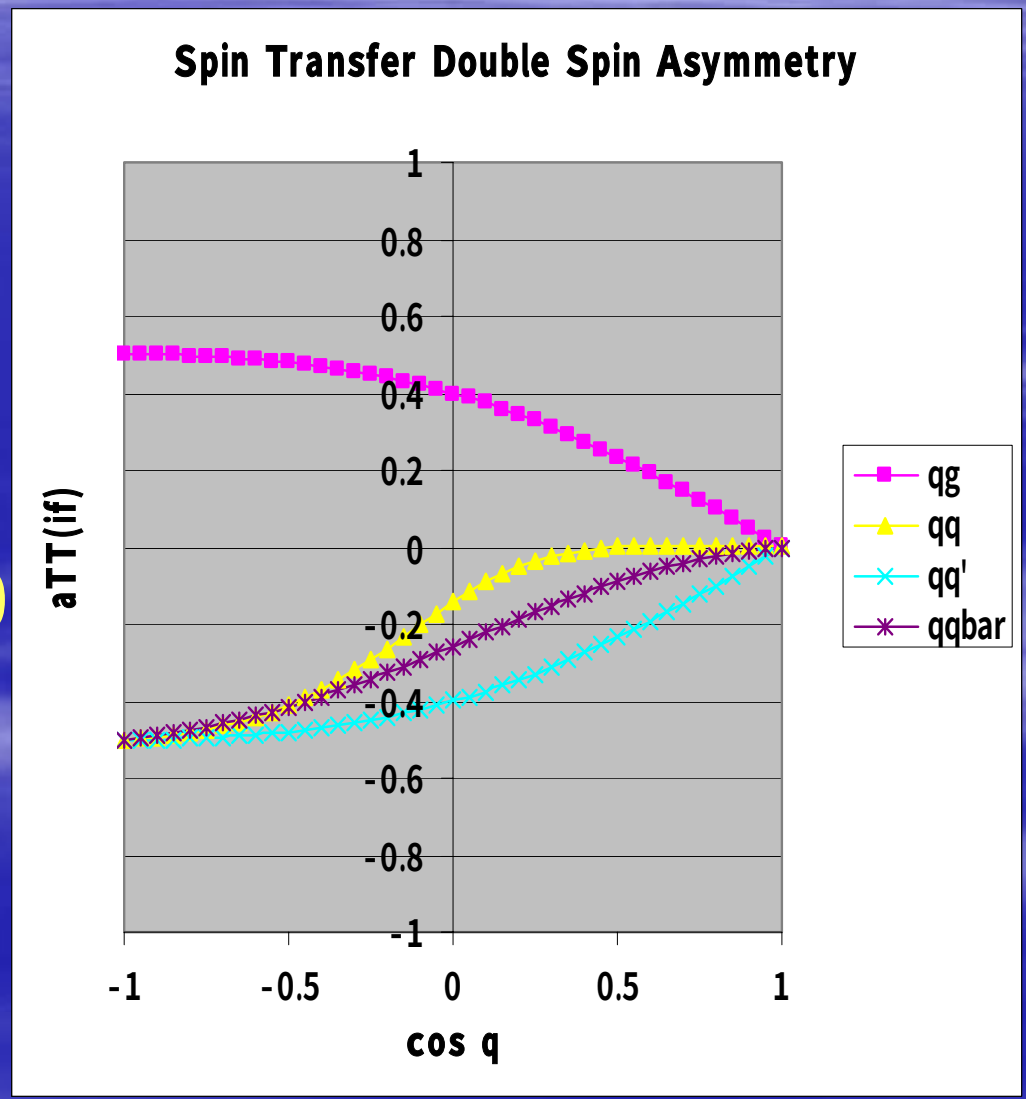


Single Transverse Spin Asymmetries

- If we have analyzer of final state quark polarization…
  - We can use Spin Transfer Double Spin Asymmetry to probe Transversity!

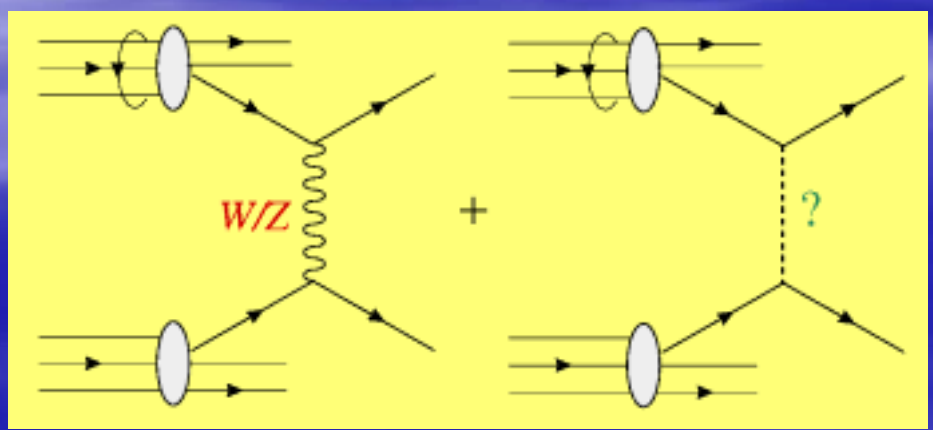
$$A_T \propto h_1(x) \otimes a_{TT}^{if} \otimes (\text{Spin Dep. Frag. Fn.})$$

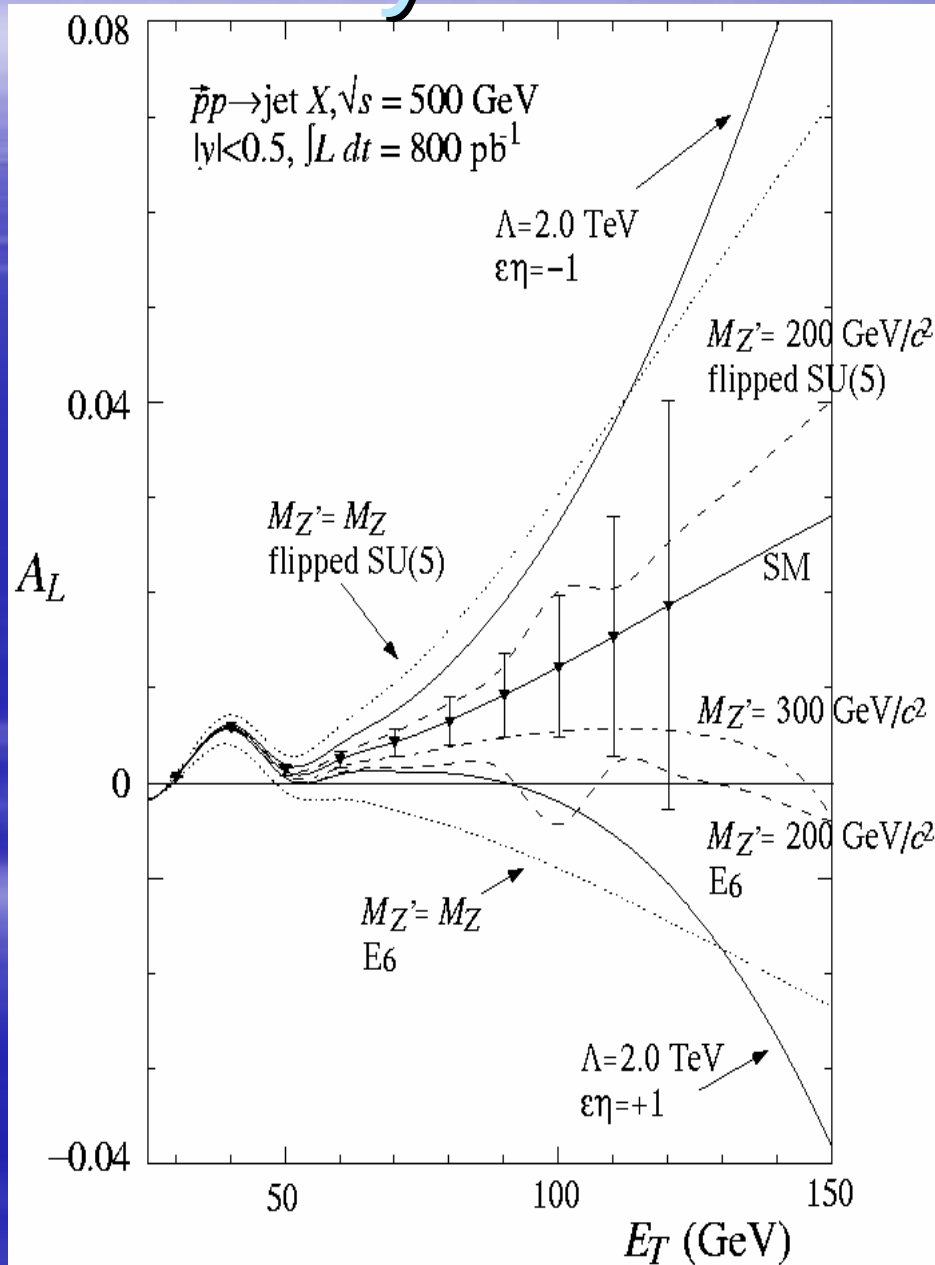
- Spin Dep. Frag. Fn. Can be studied in e+e- collisions → BELLE



Searches for New Physics

- Anomalous Parity Violation in Jet Production
  - Contact Interaction (Scale Λ)
    - CDF Λ>1.8 TeV
    - D0 Λ>2.4 TeV
    - RHIC Spin Reach Λ~3.3 TeV
  - New Gauge Boson Z'
- Need higher energy to provide useful information





RHIC Spin Roadmap

Year	P(%)	Weeks (Com/Ph)	Lumi	CM Energy	Goals
2002	20	8 (5/3)	0.15 pb^{-1}	200 GeV	Transverse Spin Systematic Studies
2003	30	8 (5/3)	0.35 pb^{-1}	200 GeV	Longitudinal Spin Gluon Polarization?
2004	50	5(5/0)	pb^{-1}	200 GeV	RHIC Commissioning Polarized Gas Jet Target
2005	70	17 (5/12)	10 pb^{-1}	200 GeV 500 GeV	Gluon Polarization Commissioning-1?
2006/7	70	19(5/14)	200 pb^{-1} pb^{-1}	200 GeV 500 GeV	Gluon Polarization Commissioning-2?
2008/9	70	19 (5/14)	400 pb^{-1}	500 GeV	W-Physics

Growing Fields…

Hi-E Heavy Ion Physics
RHIC, LHC

Hadron Collider Physics
TEVATRON
LHC

Precision Structure Stud

Future Projects
J-Parc,GSI ν-Factory?
EIC (ep, eA)?
HERA-III?, JLab-12?

Large-x
Precision,small-x
Large-x

RHIC-Spin
Gluon Polarization
Quark Polarization
Transversity
Pol. Fragmentation
Role of Strangeness

Ongoing Spin Experiments
COMPASS,HERMES
JLab

Dark Matter

Neutron EDM

e+e- Data
…LEP, BELLE

Ongoing Unpolarized Studies
HERA-II

Strangeness Nuclear Physics

Mechanism of Confinement
Lattice-QCD、Effective Model

Summary

- After a decade of efforts, RHIC Spin started to produce physics results
  - Gluon polarization by π^0 production
  - Single transverse spin asymmetry for hadron production
- Run-4 machine commissioning was very successful
- With further improvements on machine performance, exciting results are coming soon!

See our review article:
"Prospects for Spin Physics at RHIC"
G. Bunce, N. Saito, J. Soffer and W. Vogelsang
Ann. Rev. of Nucl. And Part. Science 2000