Understanding of the nucleon spin with the perturbative QCD

JPS meeting at Tokyo Univ. of Science

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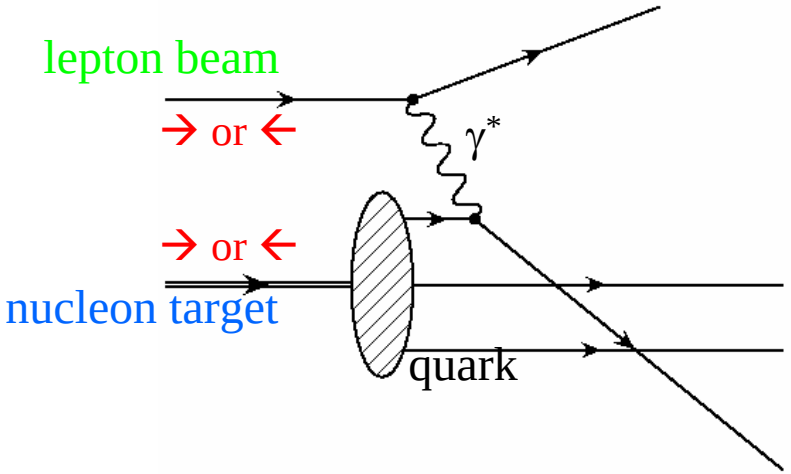
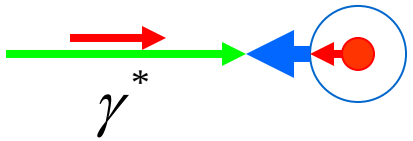
Origin of the nucleon spin 1/2 ?

- polarized DIS
  - in quark parton model



$$\Delta q(x) = q^{+}(x) - q^{-}(x)$$

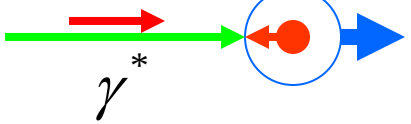
$$S_\gamma + S_N = 1/2$$



$$\gamma^*$$

$$\sigma^T_{1/2} \sim \sum_i e_i^2 q_i^{+}(x)$$

$$S_\gamma + S_N = 3/2$$



$$\gamma^*$$

$$\sigma^T_{3/2} \sim \sum_i e_i^2 q_i^{-}(x)$$

$$A_1 = \frac{\sigma^{\mathrm{T}}_{1/2} - \sigma^{\mathrm{T}}_{3/2}}{\sigma^{\mathrm{T}}_{1/2} + \sigma^{\mathrm{T}}_{3/2}} \sim \frac{\sum_i e_i^2 (q_i^{+}(x) - q_i^{-}(x))}{\sum_i e_i^2 (q_i^{+}(x) + q_i^{-}(x))} = \frac{\sum_i e_i^2 \Delta q_i(x)}{\sum_i e_i^2 q_i(x)} = \frac{g_1(x)}{F_1(x)}$$

polarized structure function

unpolarized structure function

Origin of the nucleon spin 1/2 ?

- polarized DIS

$$A_1 = \frac{\sigma_{1/2}^{\mathrm{T}} - \sigma_{3/2}^{\mathrm{T}}}{\sigma_{1/2}^{\mathrm{T}} + \sigma_{3/2}^{\mathrm{T}}} \sim \frac{\sum_i e_i^2 (q_i^+(x) - q_i^-(x))}{\sum_i e_i^2 (q_i^+(x) + q_i^-(x))} = \frac{\sum_i e_i^2 \Delta q_i(x)}{\sum_i e_i^2 q_i(x)} = \frac{g_1(x)}{F_1(x)}$$

more correctly

$$A_1 = \frac{g_1(x) - \gamma^2 g_2(x)}{F_1(x)} \qquad A_2 = \frac{2\sigma^{TL}}{\sigma_{1/2}^{\mathrm{T}} + \sigma_{3/2}^{\mathrm{T}}} = \frac{\gamma^2 (g_1(x) + g_2(x))}{F_1(x)}$$

  - experimental data

$$A = \frac{1}{P_T P_B} \frac{N_{++} - N_{+-}}{N_{++} + N_{+-}} = D(A_1 + \eta A_2) \sim D A_1$$

P_T target polarization

P_B beam polarization

D depolarization factor

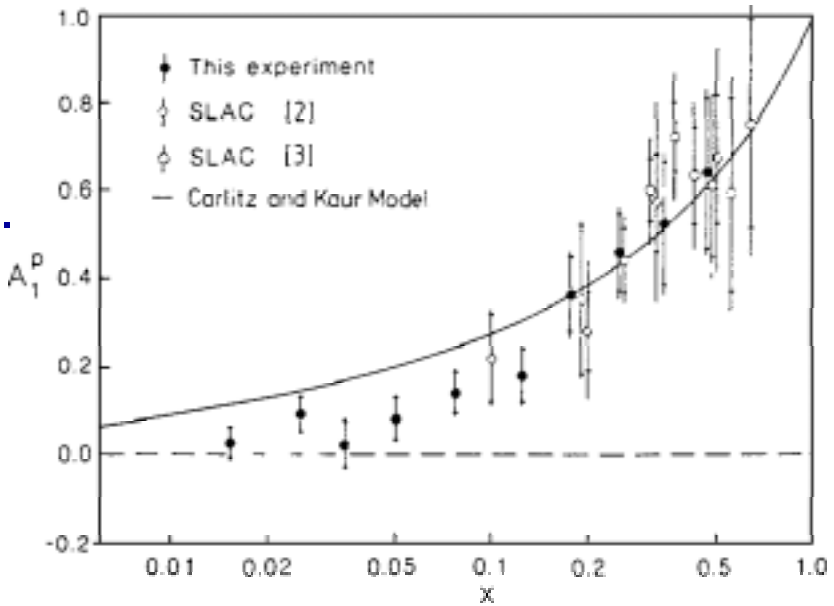
Origin of the nucleon spin 1/2 ?

- EMC experiment at CERN

  J. Ashman et al., NPB 328, 1 (1989).

$$\int_0^1 dx g_1^p(x) = \frac{1}{2}\left[\frac{4}{9}\Delta u + \frac{1}{9}\Delta d + \frac{1}{9}\Delta s\right]$$

$$= 0.123 \pm 0.013(\text{stat}) \pm 0.019(\text{syst})$$



  - combining with neutron and hyperon decay data

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

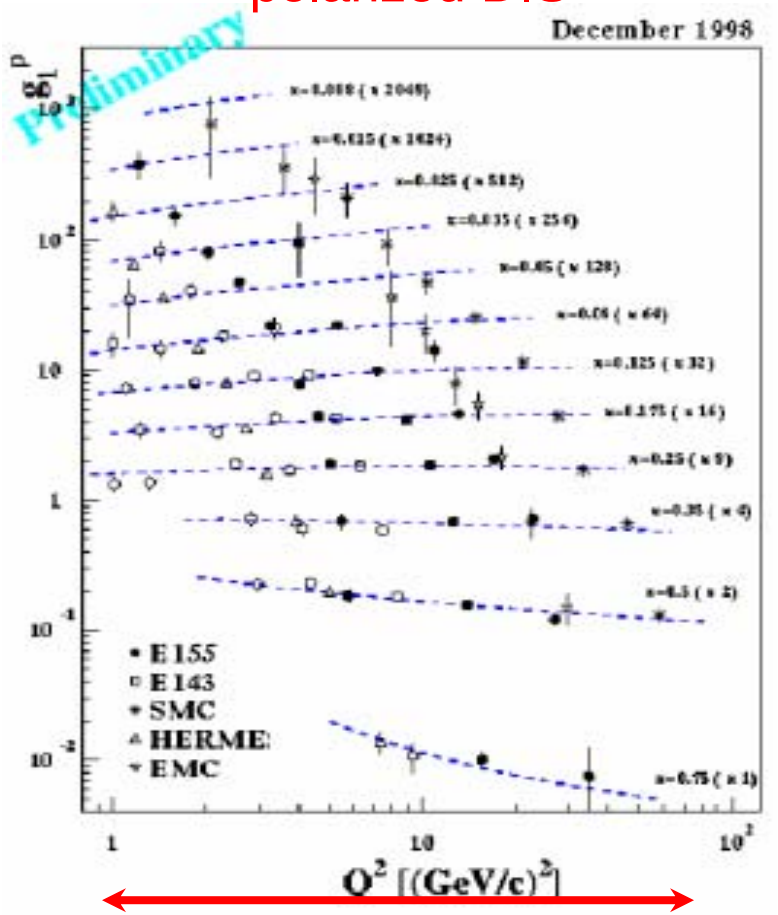
    - total quark spin constitutes a small fraction of the nucleon spin
  - integration in x = 0 ~ 1 makes uncertainty
    - more data to cover wider x region with more precise data necessary

➔ SLAC/CERN/DESY/JLAB experiments

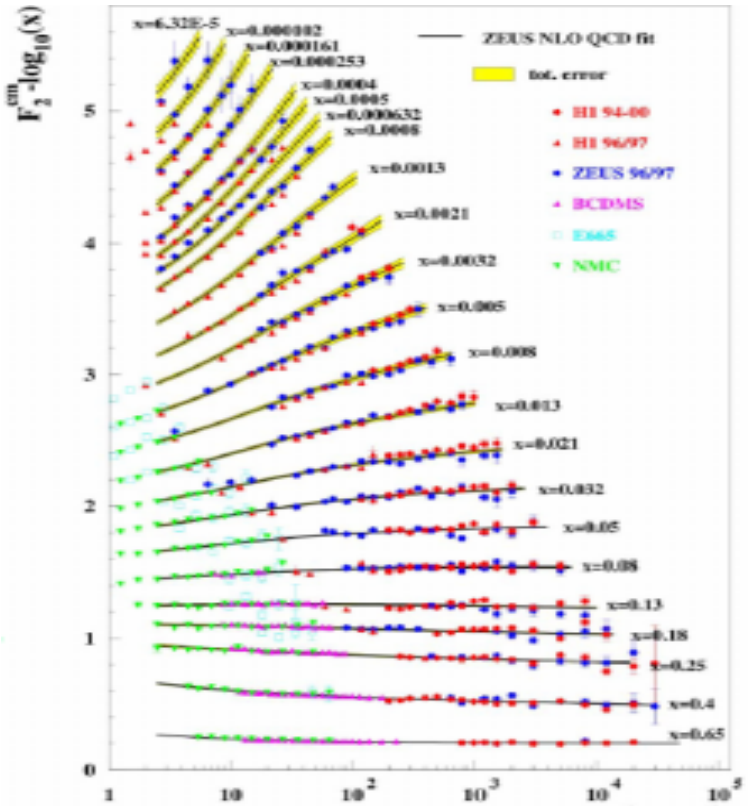
Polarized DIS

- fixed target experiments
  - spanning a limited range of Q^2

polarized DIS



unpolarized DIS



$1 < Q^2 < 100$ (GeV/c)^2

Polarized DIS

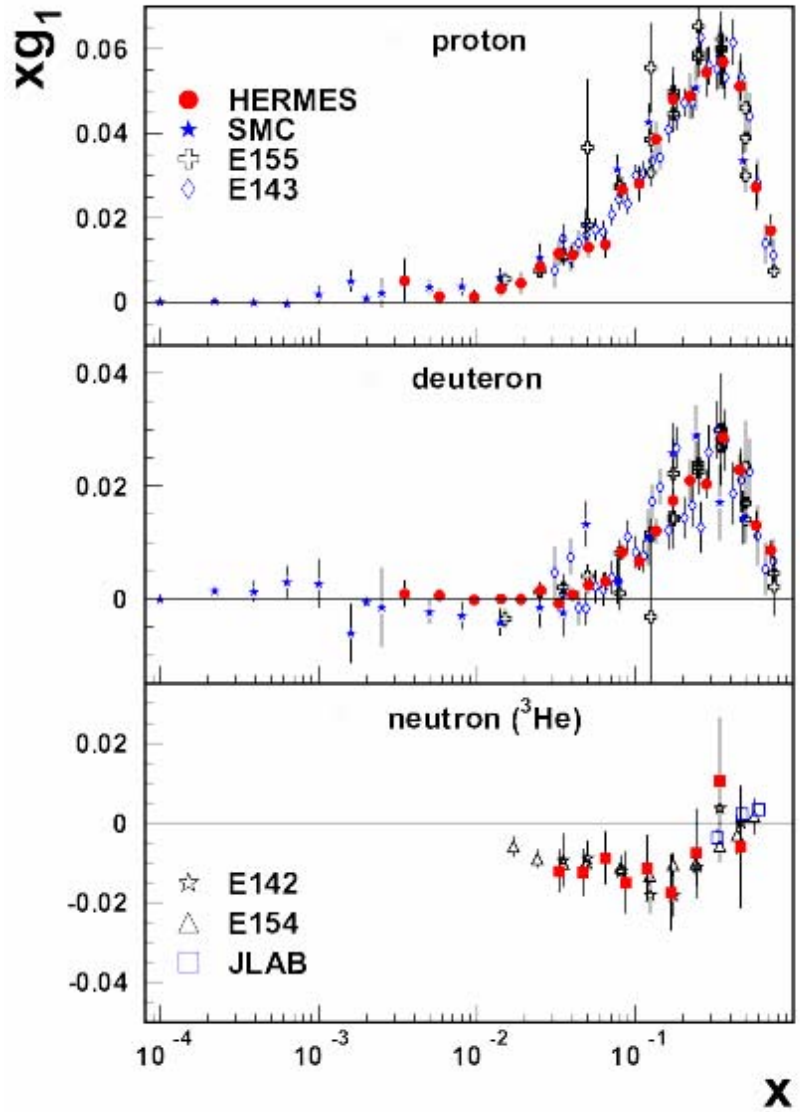
- quark contribution

$$\Delta\Sigma = 0.1 \sim 0.3$$

- origin of the nucleon spin 1/2 ?

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta g + L$$

  - gluon contribution ?
  - orbital angular momentum ?



Gluon contribution

- scaling violation in polarized DIS
  - important success of the evolution equation of the perturbative QCD
  - spanning a limited range of Q^2

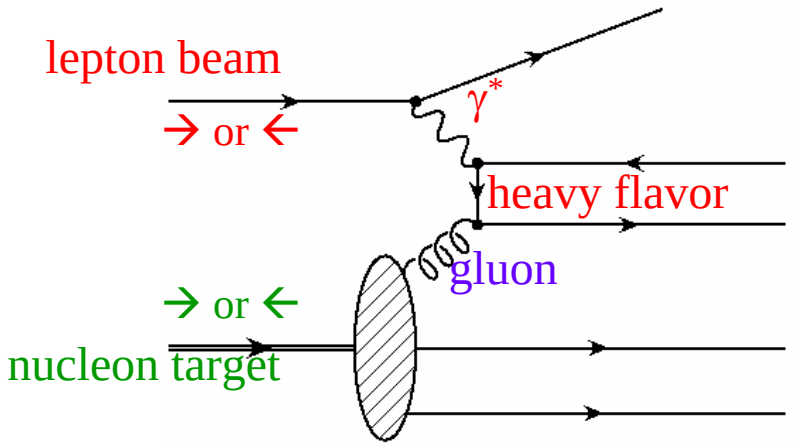
$$\mathrm{SMC}:\ \Delta g(Q^2=1\,\mathrm{GeV}^2)=0.99^{+1.17}_{-0.31}(\mathrm{stat})^{+0.42}_{-0.22}(\mathrm{syst})^{+1.43}_{-0.45}(\mathrm{th})$$

B. Adeba et al., PRD 58, 112002 (1998).

$$\mathrm{E155}:\ \Delta g(Q^2=5\,\mathrm{GeV}^2)=1.6\pm0.8(\mathrm{stat})\pm1.1(\mathrm{syst})$$

P.L. Anthony et al., PLB 493, 19 (2000).

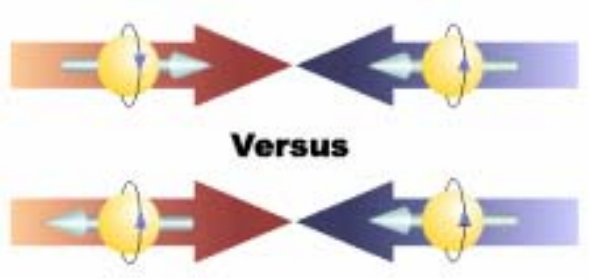
- semi-inclusive DIS
  - high-p_T hadron pairs
  - open charm production



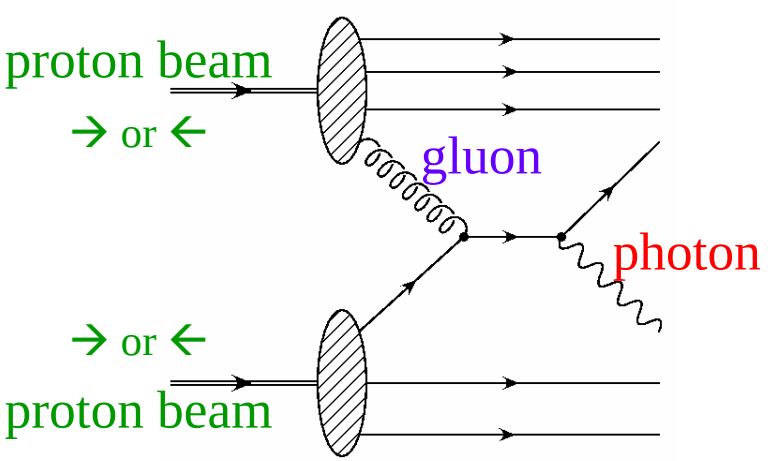
Gluon contribution

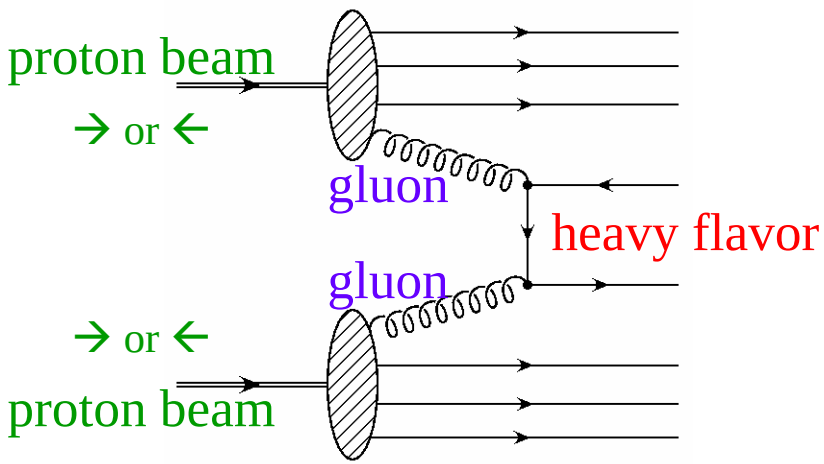
- polarized hadron collision
  - double longitudinal spin asymmetry

$$A_{LL} = \frac{d\sigma_{++} - d\sigma_{+-}}{d\sigma_{++} + d\sigma_{+-}}$$



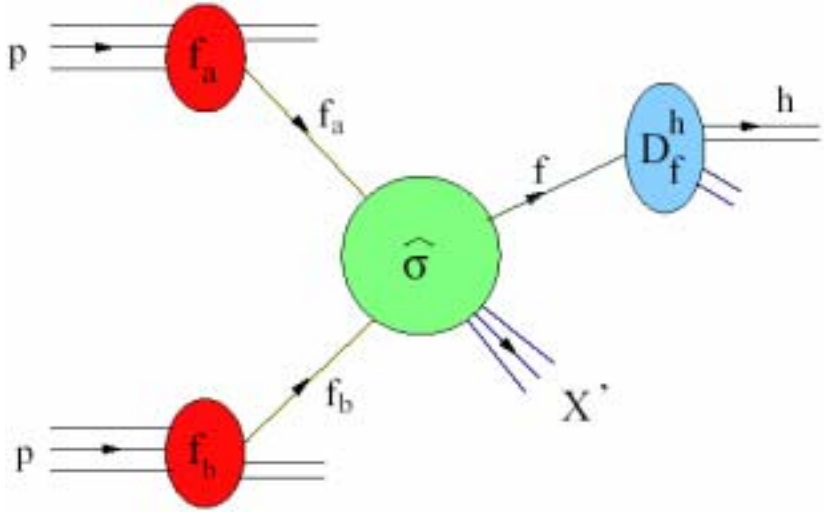
  - leading-order gluon measurement
    - direct-photon production
    - heavy-flavor production





QCD factorization

– ex. hadron production in proton collisions
  - pp→hX



$$d\sigma = \sum_{a,b,c} \int dx_a \int dx_b \int dz_c \; f_a(x_a,\mu)\, f_b(x_b,\mu)\, D_c^h(z_c,\mu)\, d\hat{\sigma}_{ab}^c(x_a P_A, x_b P_B, P_h / z_c, \mu)$$

$f_a(x_a,\mu)$, $f_b(x_b,\mu)$ parton distribution function (PDF)

$D_c^h(z_c,\mu)$ fragmentation function (FF)

} long distance term

$d\hat{\sigma}_{ab}^c(x_a P_A, x_b P_B, P_h / z_c, \mu)$ partonic cross section — short distance term

μ factorization scale – boundary between short and long distance

QCD factorization

- long distance term
  - unpol. & pol. PDFs – partonic structure of the nucleon
  - fragmentation functions
  - determined from experimental data
  - “universal” property of the nucleon – same in each reaction
  - Q^2 dependence calculated by the evolution equation of the perturbative QCD
- short distance term
  - unpol. & pol. partonic cross section – hard interaction of partons
  - calculated by the perturbative QCD – process dependent
  - the first order (next-to-leading order, NLO) corrections are generally indispensible for a firmer theoretical prediction

$$d\hat{\sigma}_{ab}^{c} = d\hat{\sigma}_{ab}^{c,(0)} + \frac{\alpha_s}{\pi} d\hat{\sigma}_{ab}^{c,(1)} + \ldots$$

QCD factorization

- factorization scale μ
  - dependence of the calculated cross section on μ represents an uncertainty in the theoretical predictions
  - dependence on μ decreases order-by-order in the perturbative QCD
  - knowledge of higher orders in perturbative expansion of the partonic cross section is important

Global analysis

- framework to combine various experimental data into a systematically controlled extraction of the unpol. & pol. PDFs, FFs
  - experimental data $a^{\mathrm{data}}(x, Q^2)$ with experimental errors $\delta a^{\mathrm{data}}(x, Q^2)$
  - function form (parametrizations) of PDFs and FFs satisfying physical requirements at the initial Q^2_0
  - Q^2 evolution of PDFs/FFs and theoretical calculation corresponding to the experimental data $a^{\mathrm{calc}}(x, Q^2)$
  - χ^2 analysis (minimization)

$$\chi^2 = \sum_a \left(\frac{a^{\mathrm{data}}(x,Q^2) - a^{\mathrm{calc}}(x,Q^2)}{\delta a^{data}(x,Q^2)} \right)^2$$

  - parameters (and errors on the parameters) determined

Global analysis

- polarized-DIS analysis
  - GRSV, LSS, BB, AAC, …
- AAC03 M. Hirai, S. Kumano, and N. Saito, PRD 69, 054021 (2004)
  - NLO analysis
  - fit A_1 data with function forms

$$\Delta f(x) = [\delta x^{\nu} - \kappa(x^{\nu} - x^{\mu})] f(x)$$

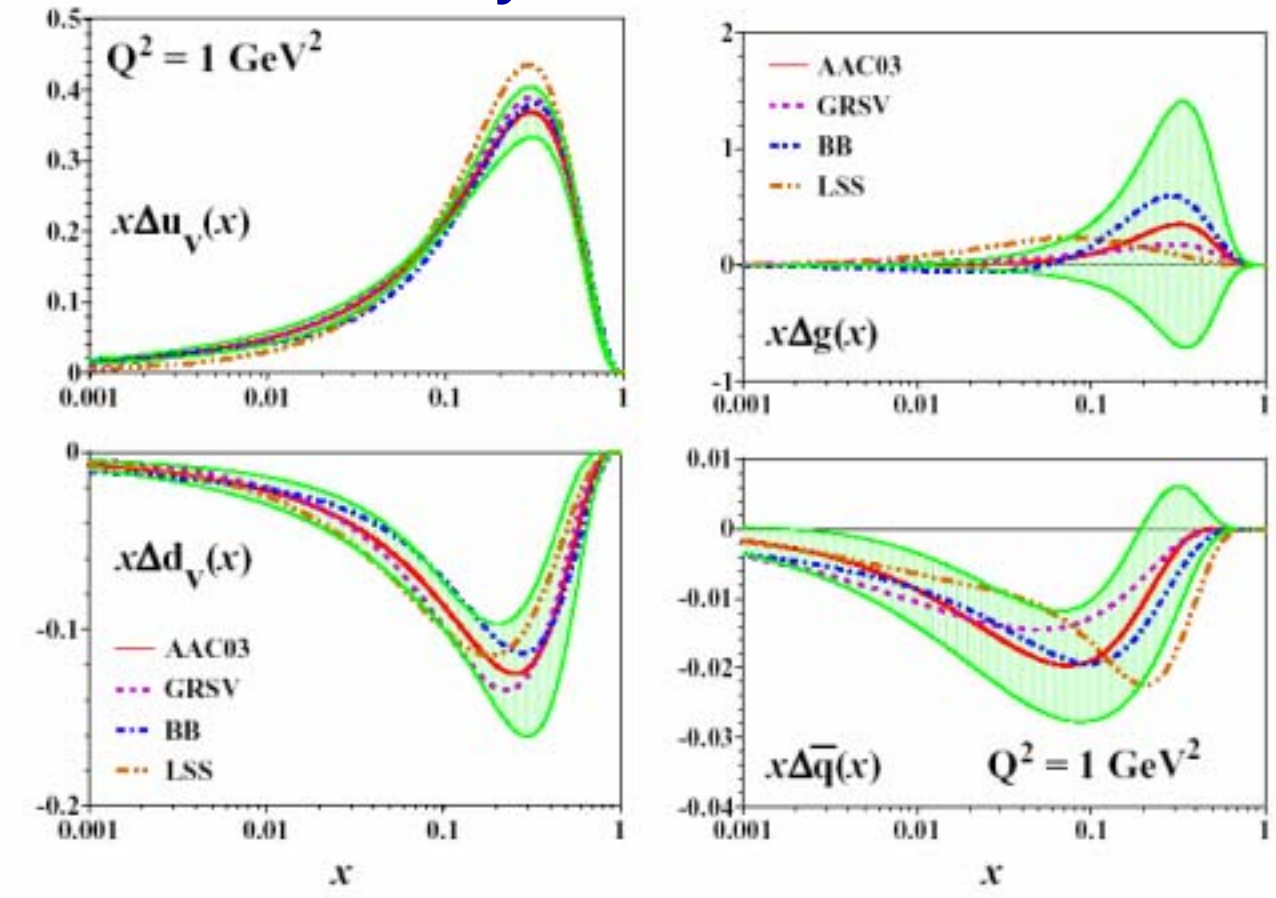
$\Delta f(x),\ f = u_v, d_v, g, \bar{q}$ polarized PDFs

$f(x)$ PDFs (GRV98)

  - experimental A_1 data
    - proton data: EMC, SMC, E130, E143, E155, HERMES
    - deuteron data: SMC, E143, E155
    - neutron (^{3}He) data: E142, E154, HERMES

Global analysis

- polarized-DIS analysis

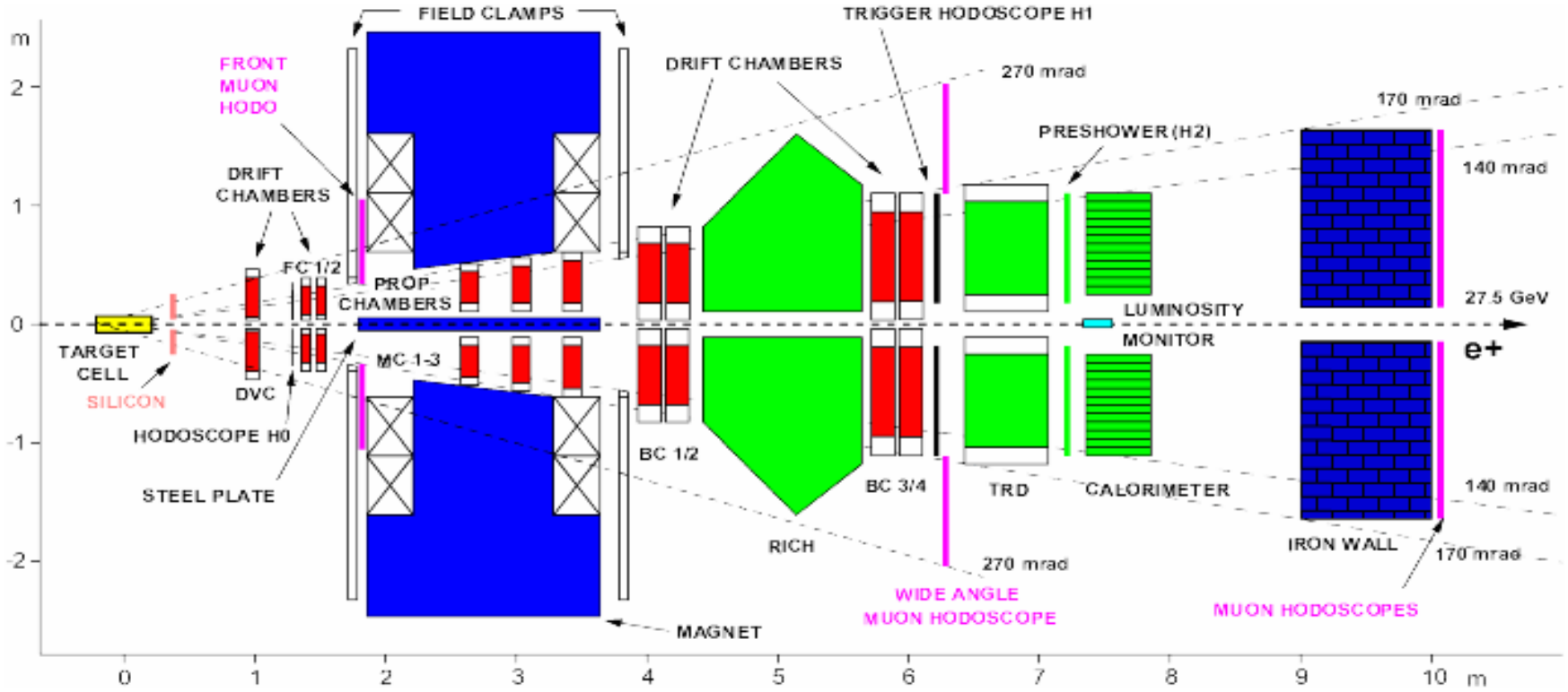


$\Delta u_v, \Delta d_v$ well determined

$\Delta g, \Delta \bar{q}$ more experimental data necessary

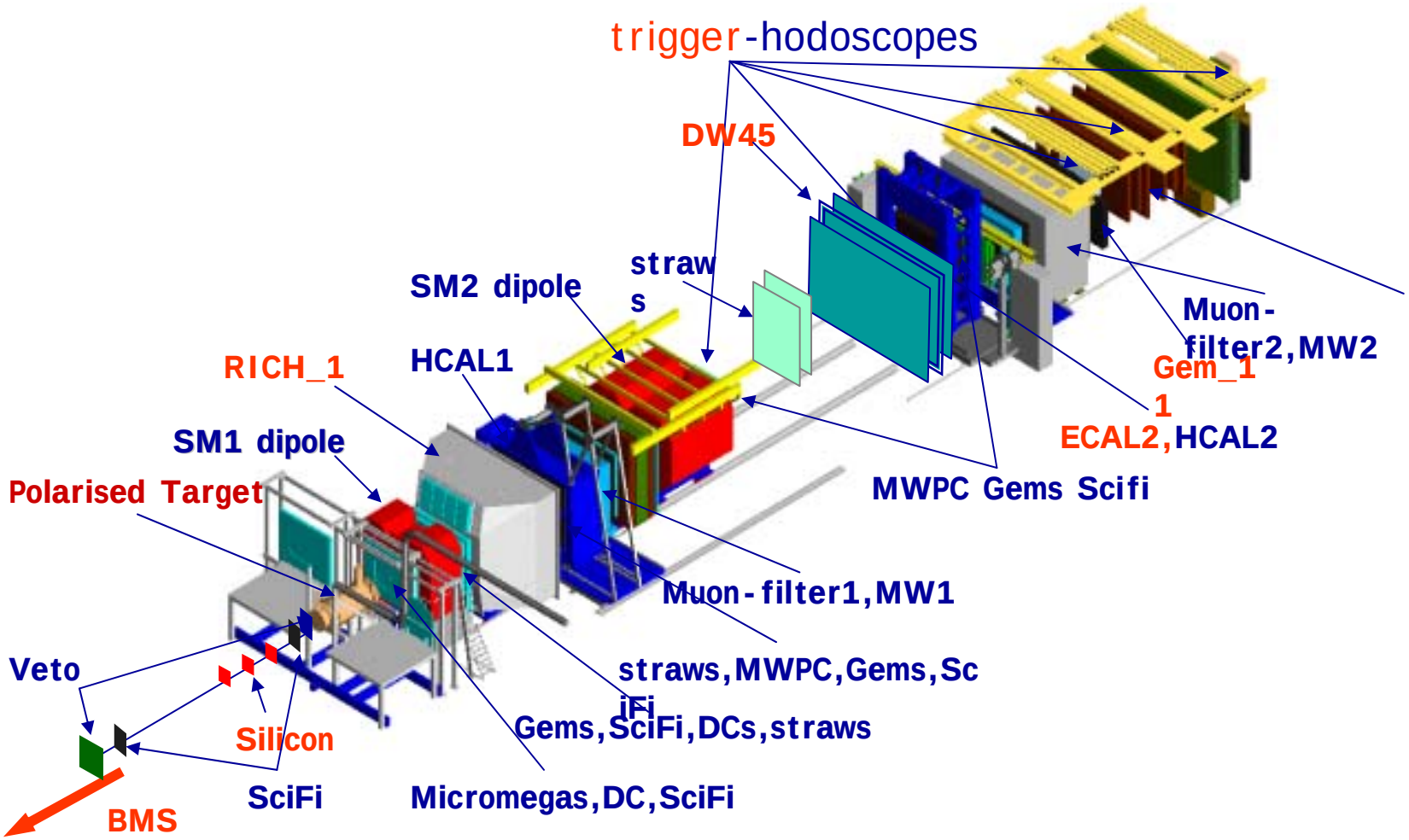
HERMES @ DESY

- semi-inclusive DIS
  - internal polarized gas target: H, D, ^{3}He, polarization (H, D) ~85%
  - electron/positron beam: 27.6 GeV, polarization ~55%



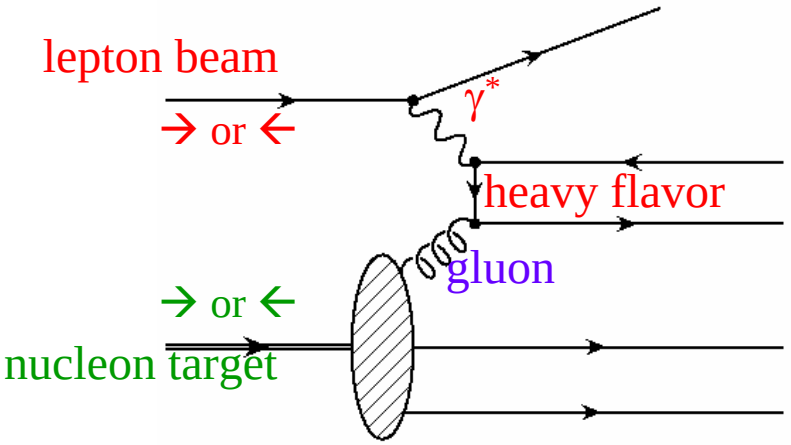
COMPASS @ CERN

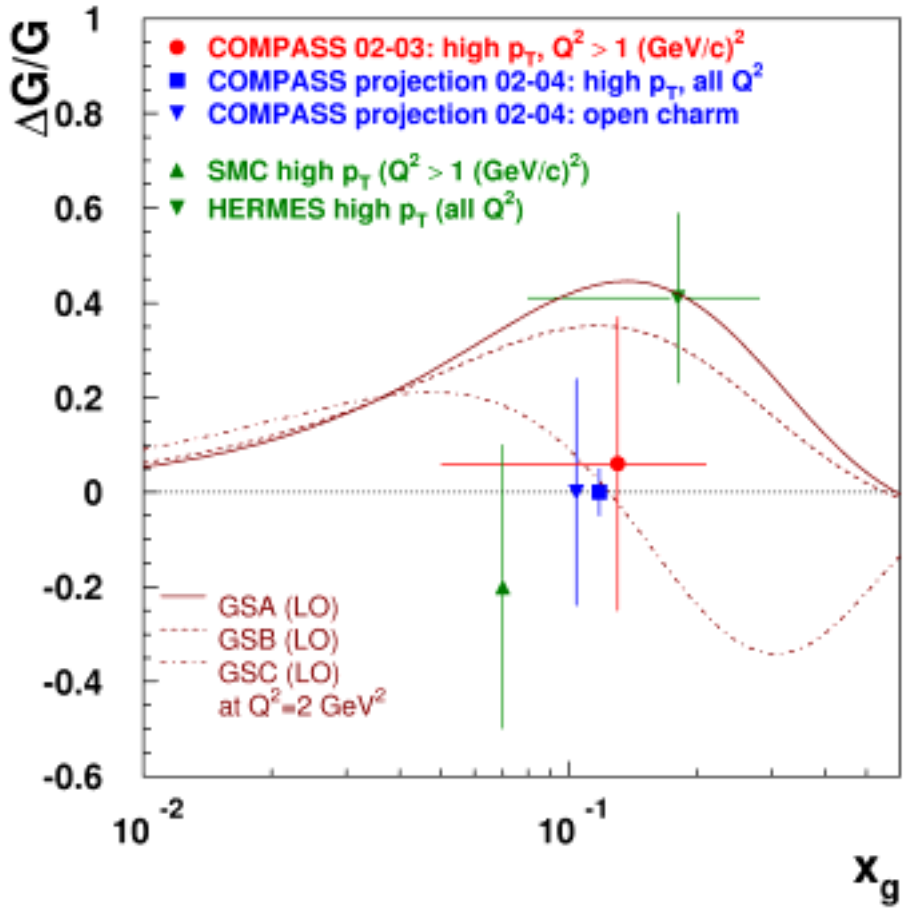
- semi-inclusive DIS
  - polarized ^{6}LiD target: polarization ~50%
  - μ^{+} beam: 160 GeV, polarization ~80%



Gluon polarization

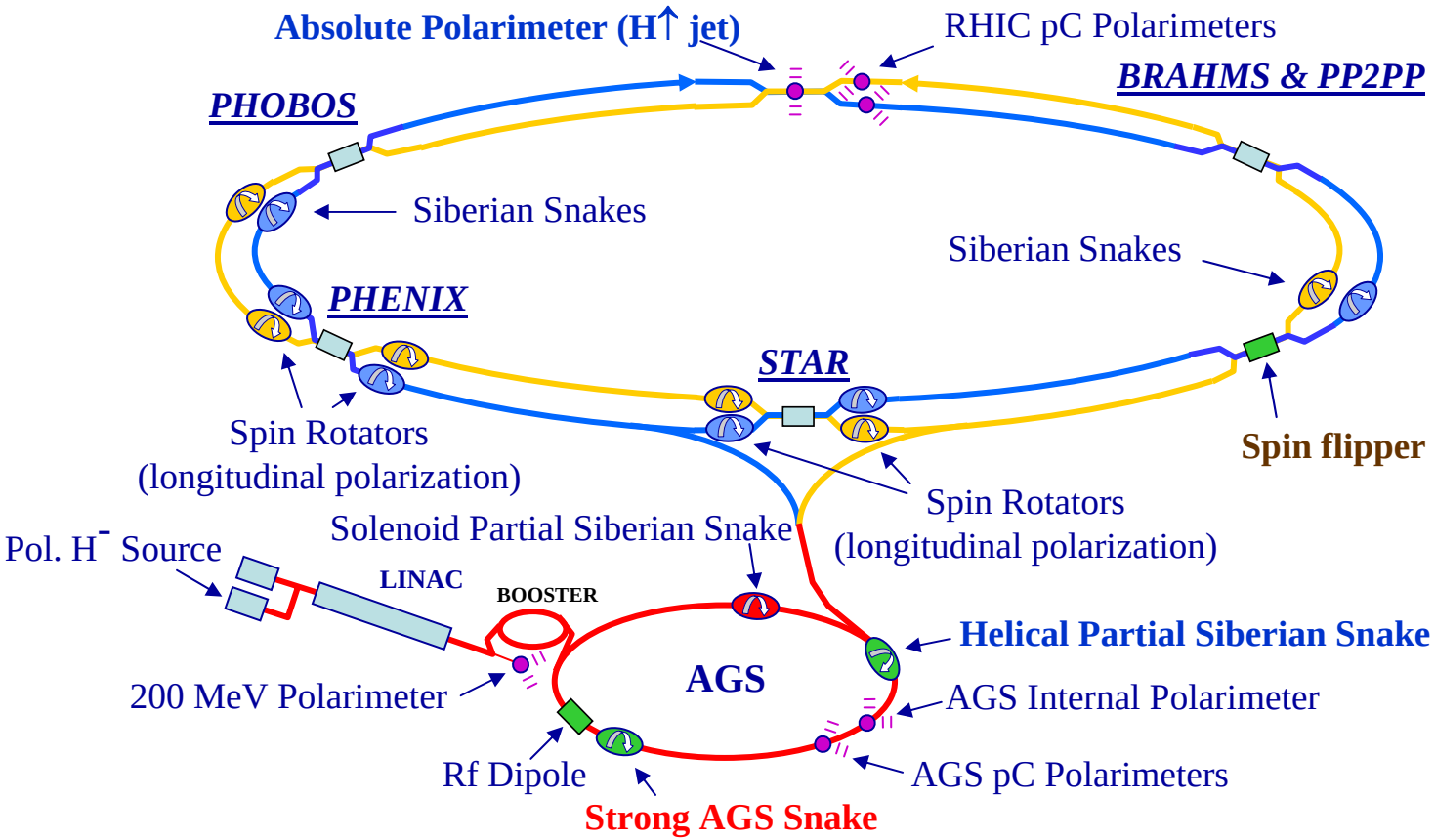
- semi-inclusive DIS
  - HERMES @ DESY
    - high-p_T hadron pairs
  - SMC @ CERN
    - high-p_T hadron pairs
  - COMPASS @ CERN
    - high-p_T hadron pairs
    - open charm (projection)



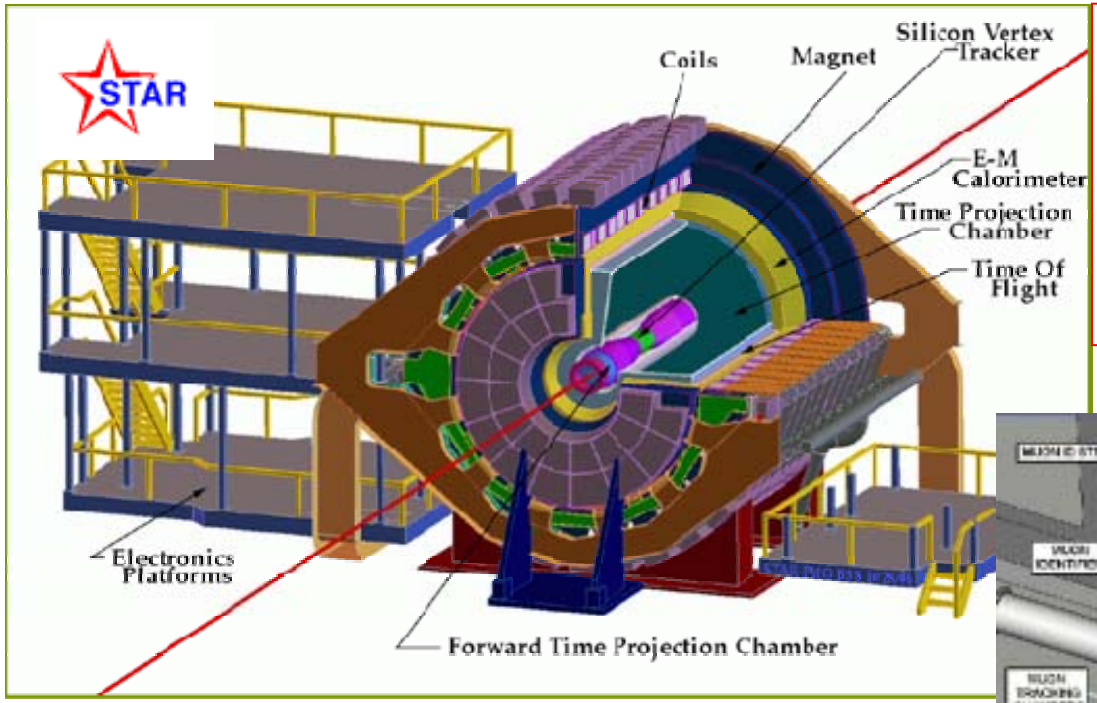


RHIC spin @ BNL

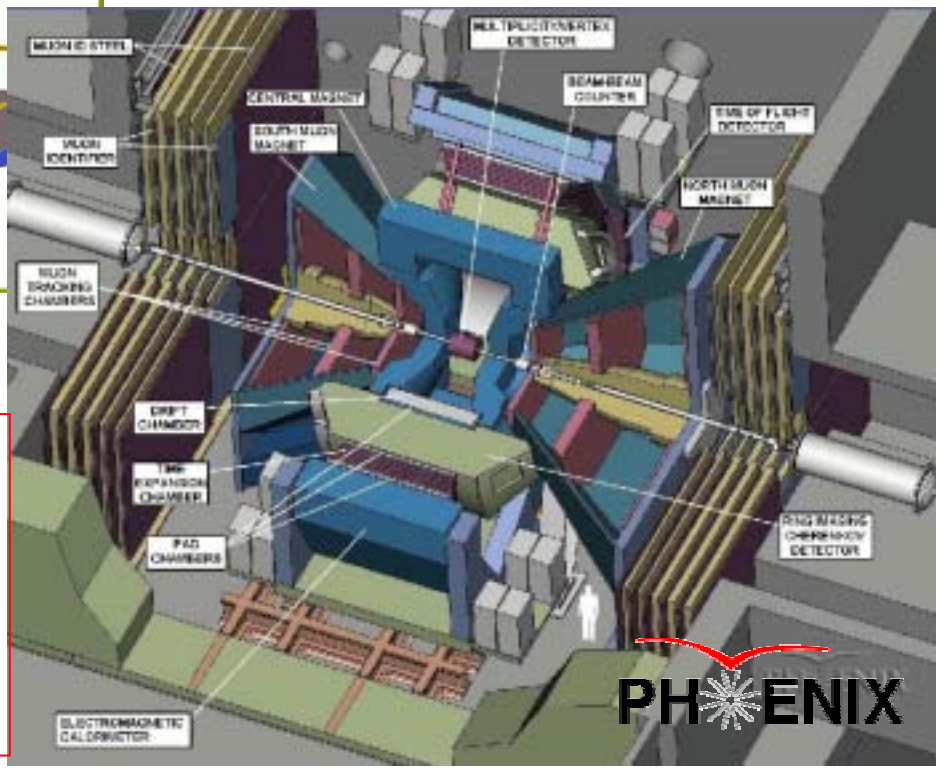
- polarized proton collider
  - energy 200 GeV (and 500 GeV in the future)
  - polarization 40% (70% in the future)



STAR and PHENIX @ BNL



- STAR detector
  - 2π coverage for jet measurement
  - barrel TPC and EMC
  - endcap EMC

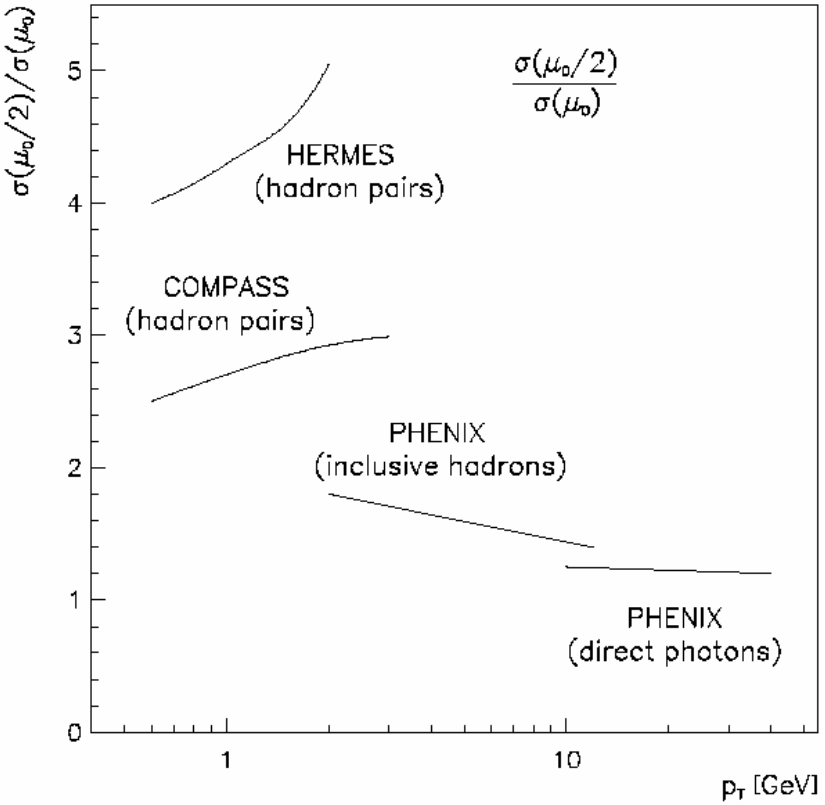


- PHENIX detector
  - limited acceptance
  - high resolution central EMCal
  - high-rate trigger and DAQ
  - forward muon detectors

Cross section

- perturbative QCD applicable ?
  - dependence of the calculated cross section on μ represents an uncertainty in the theoretical predictions

$$\frac{\sigma(\mu_0/2)}{\sigma(\mu_0)}$$



M. Stratmann and W. Vogelsang

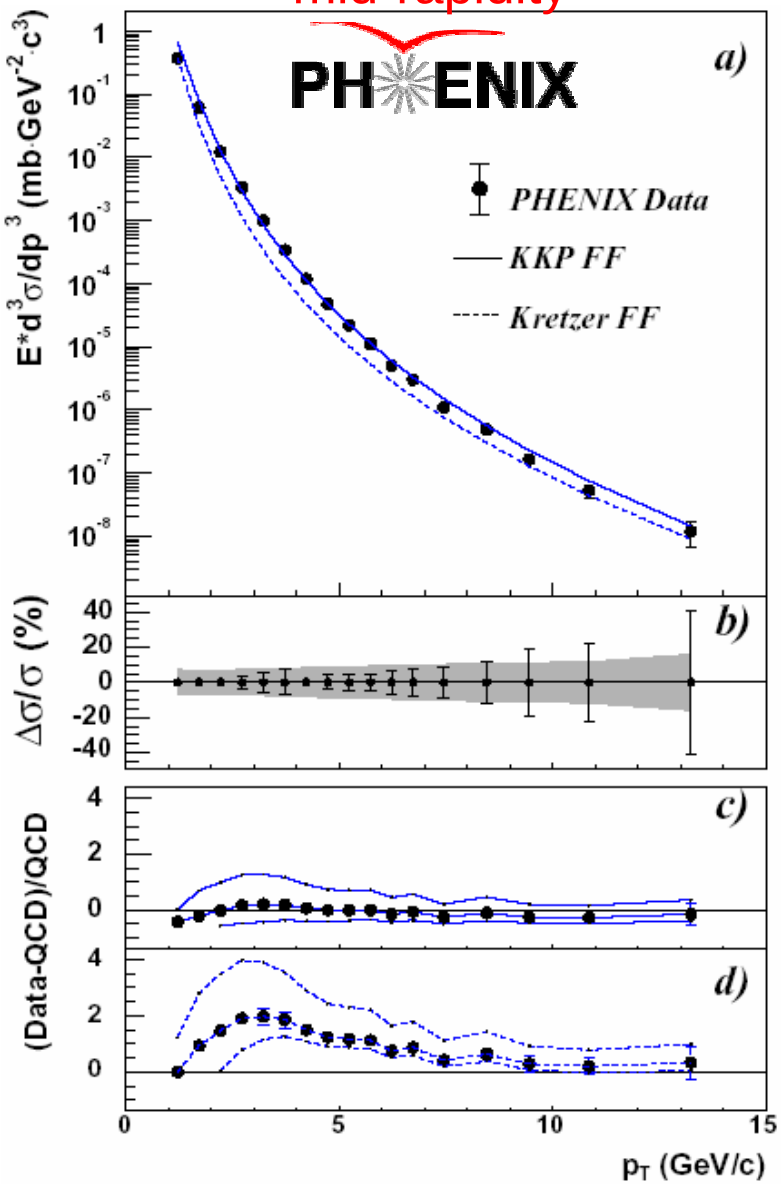
p_T (GeV/c)

Cross section

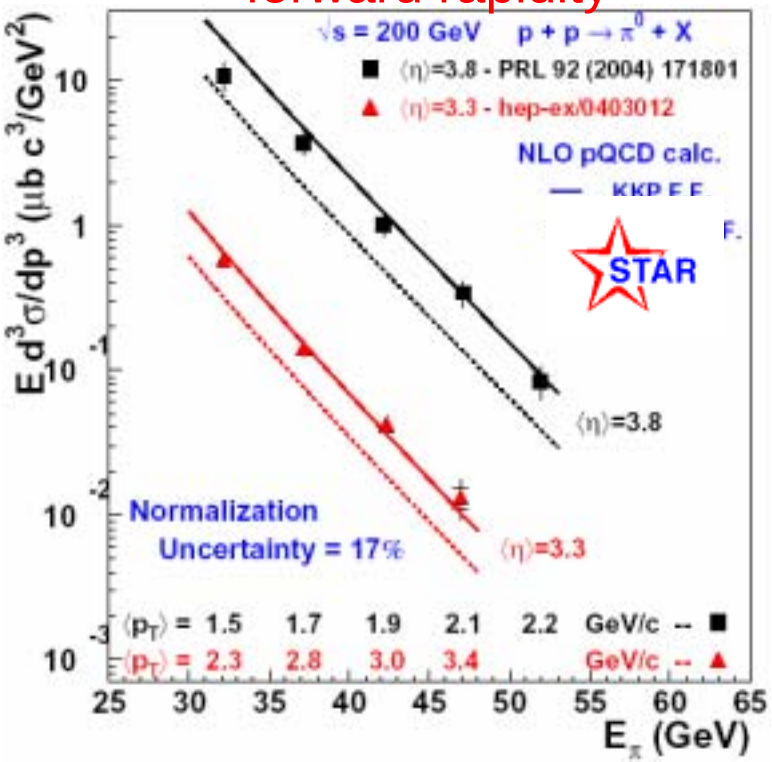
$\sqrt{s} = 200$ GeV

mid-rapidity

- comparison of π^0 cross section between data and NLO perturbative-QCD calculations
- agreement is excellent down even to $p_T \sim 1$ GeV/c



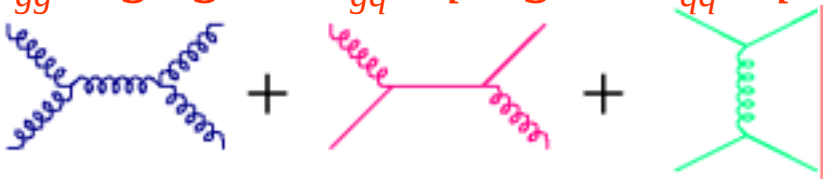
forward rapidity

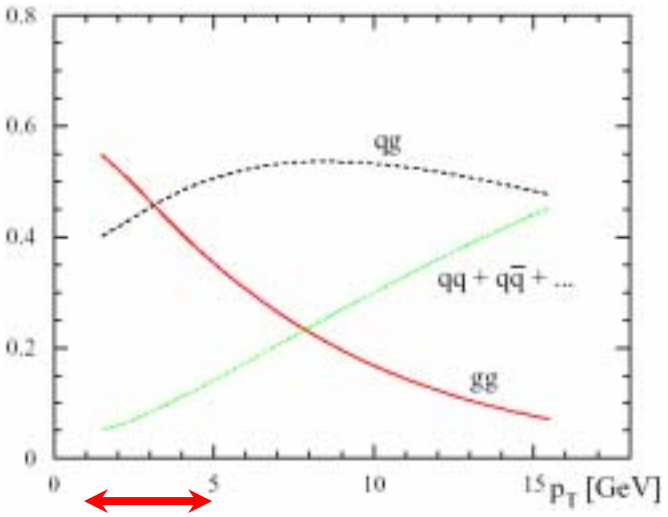


Gluon polarization

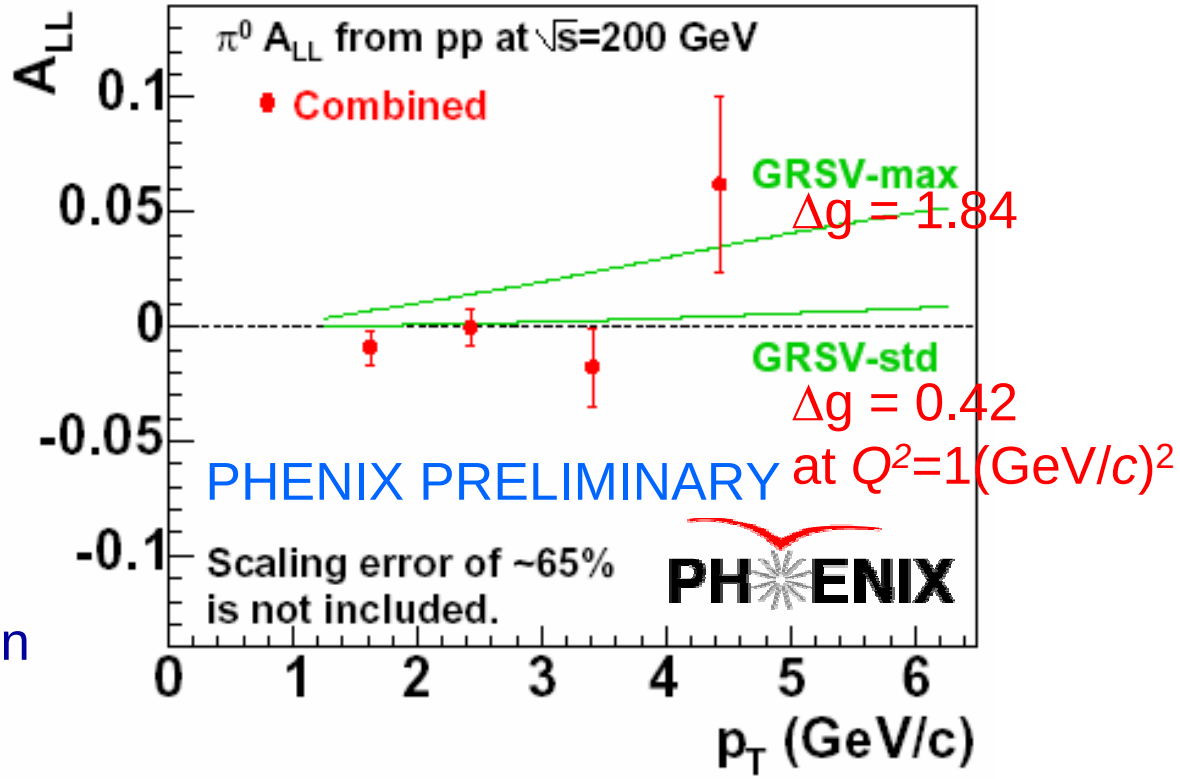
- A_{LL} in neutral pion production
  - mid-rapidity $|\eta| < 0.35$, $\sqrt{s} = 200$ GeV

$$A_{LL} = [\omega_{gg}]\Delta g\Delta g + [\omega_{gq}\Delta q]\Delta g + [\omega_{qq}\Delta q\Delta q]$$





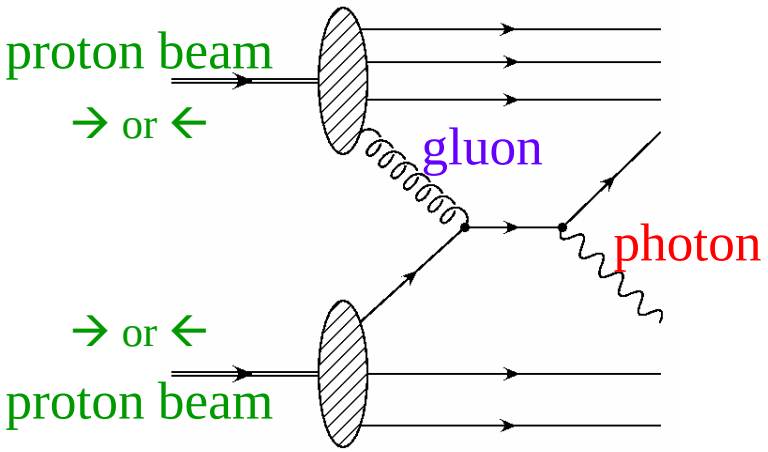
gg + qg dominant
sensitive to the gluon reaction

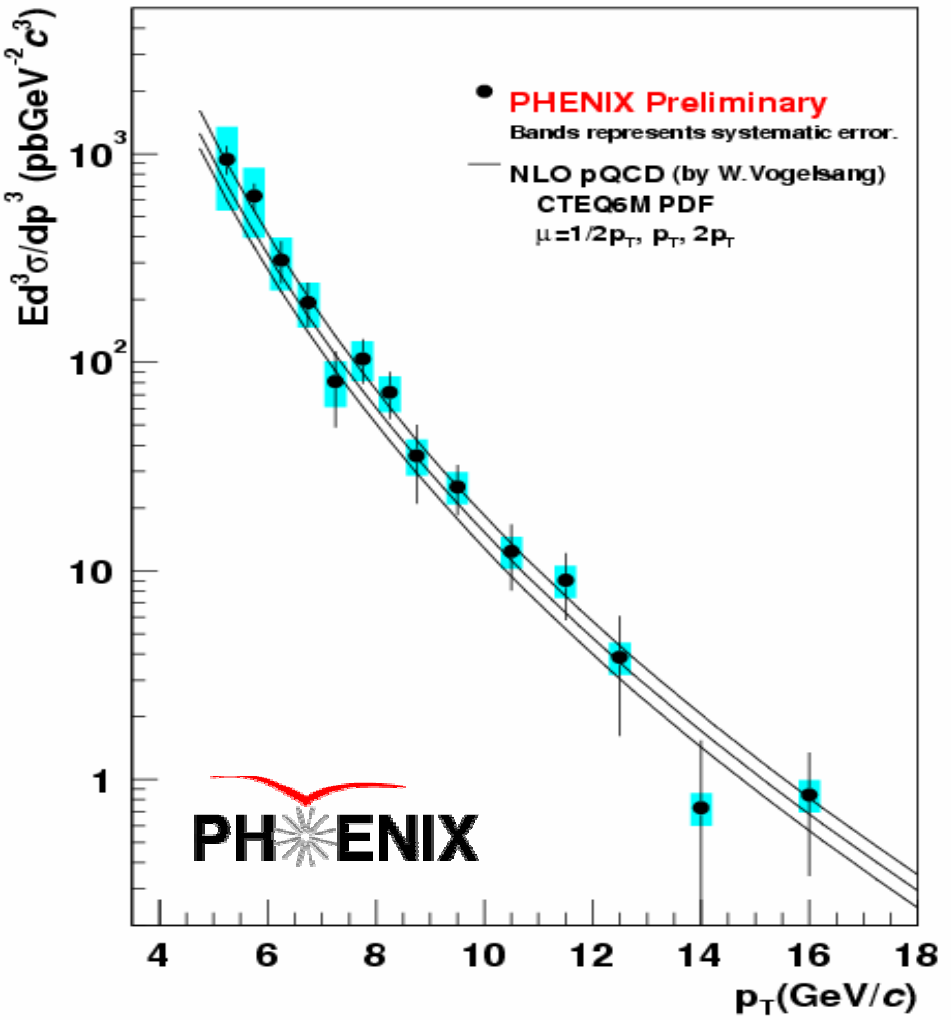


Gluon polarization

- direct photon production
  - mid-rapidity $|\eta| < 0.35$, $\sqrt{s}$ = 200 GeV
  - gluon compton process dominant ~75%

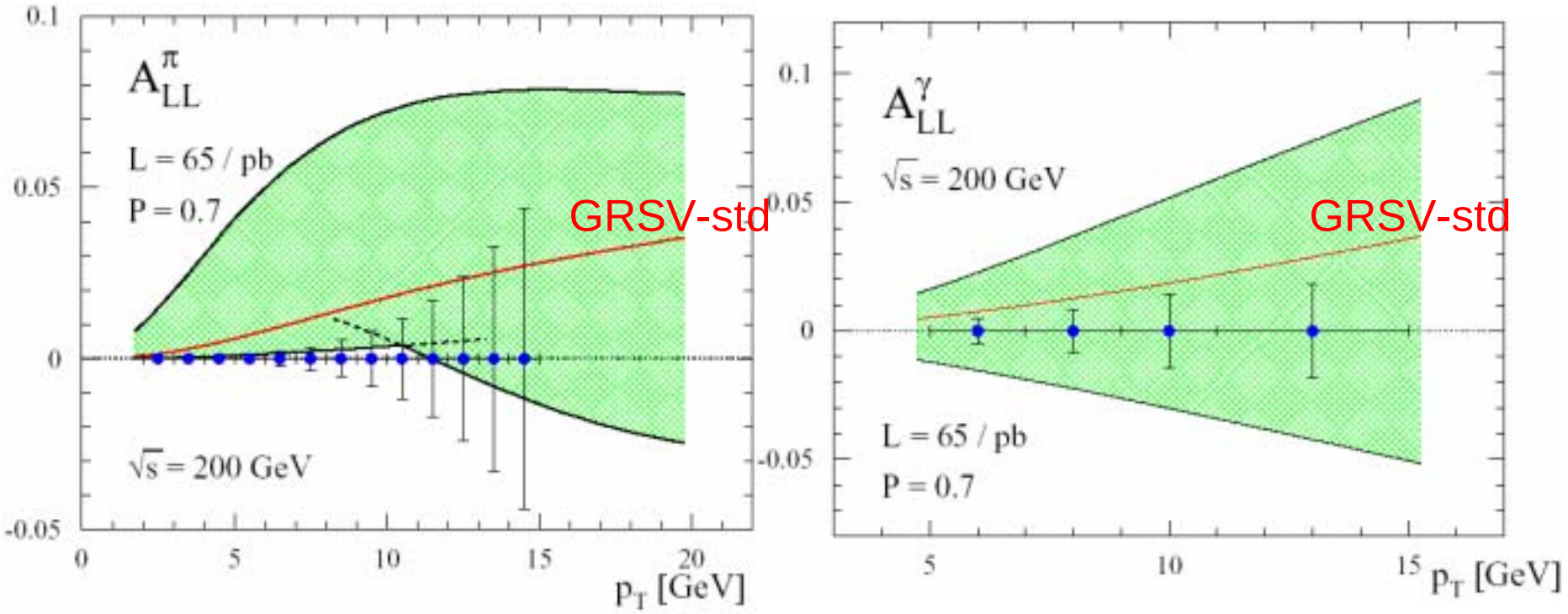
$$A_{LL}(p_T) = \frac{\Delta g(x_g)}{g(x_g)} \cdot A_1^{\,p}(x_q) \cdot \hat{a}_{LL}$$





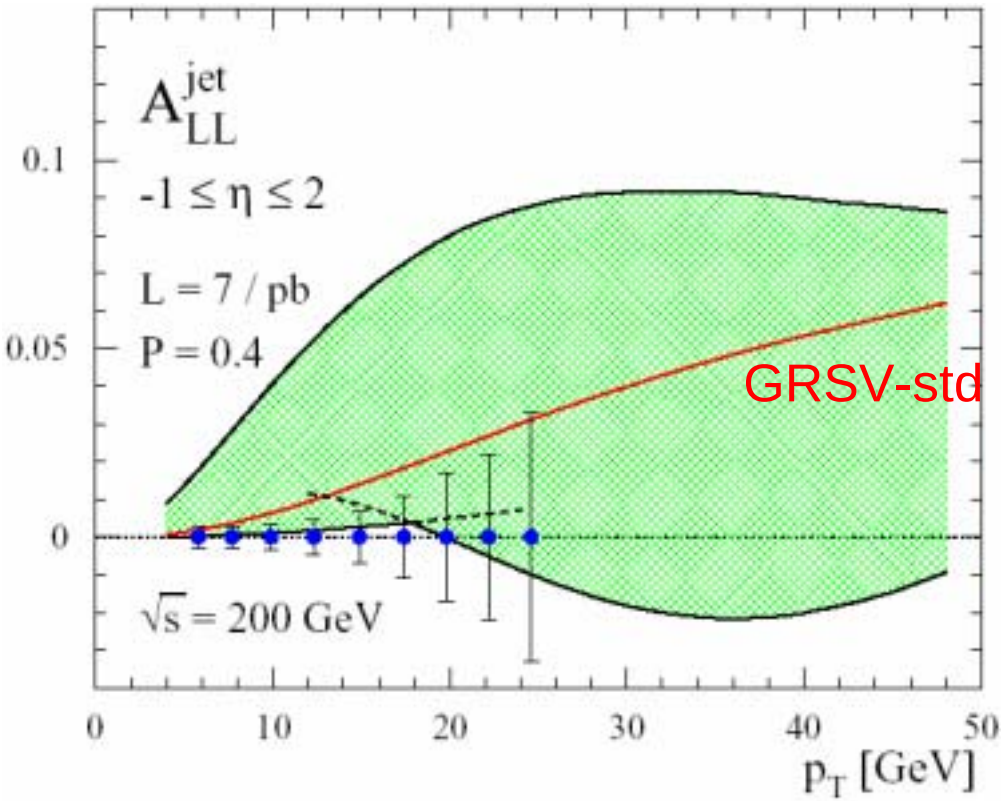
Gluon polarization

- A_{LL} projection
  - π^0 and direct photon at PHENIX
    - mid-rapidity $|\eta| < 0.35$, $\sqrt{s} = 200$ GeV
    - 2005 – 2009 runs



Gluon polarization

- A_{LL} projection
  - jet at STAR
    - $-1 < \eta < 2$
    - $\sqrt{s}$ = 200 GeV
    - 2005 run



  - coincidence channels
    - dijet, π^0-π^0, γ-jet, γ-π^0
    - reconstruction of partonic kinematics

Flavor-sorted quark polarization

- various quark and antiquark polarization individually

$$\Delta u, \Delta\bar{u}, \Delta d, \Delta\bar{d}, \Delta s, \Delta\bar{s}$$

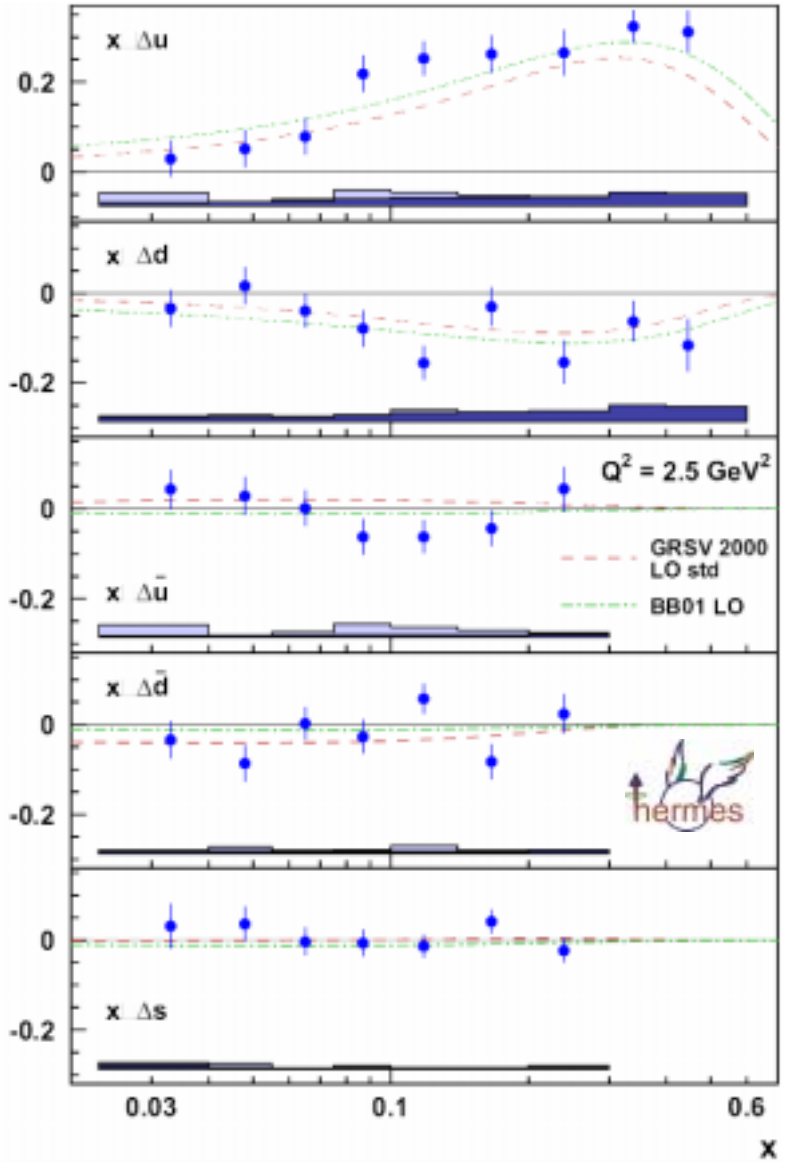
  - additional test of the smallness of the quak spin contribution $\Delta\Sigma$

- semi-inclusive DIS
  - HERMES $h = \pi^{\pm}, K^{\pm}$

$$A_1^h \sim \frac{\sum_i e_i^2 \Delta q_i(x) \int dz D_i^h(z)}{\sum_{i'} e_{i'}^2 q_{i'}(x) \int dz D_{i'}^h(z)}$$

$$= \sum_i P_q^h(x,z) \Delta q_i(x)$$

  - $P_q^h(x,z)$: purity
    - unpolarized quantity

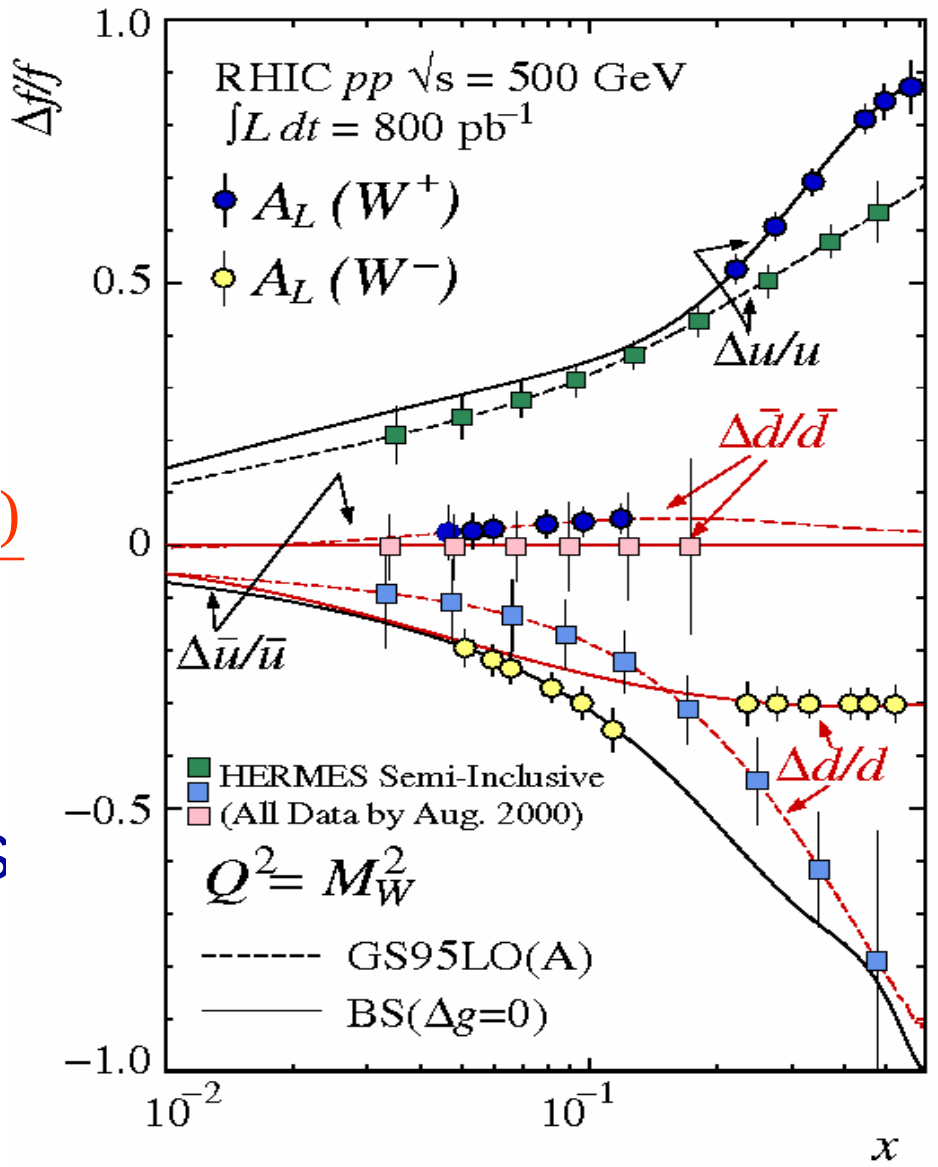


Flavor-sorted quark polarization

- weak boson production
  - RHIC spin
    - $\sqrt{s}$ = 500 GeV
    - 2009 –
  - parity-violating asymmetry A_L

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

  - no fragmentation ambiguity
  - *x*-range limited
  - complementary to HERMES semi-inclusive DIS
    - wide *x*-range
    - limited sensitivity to sea flavors

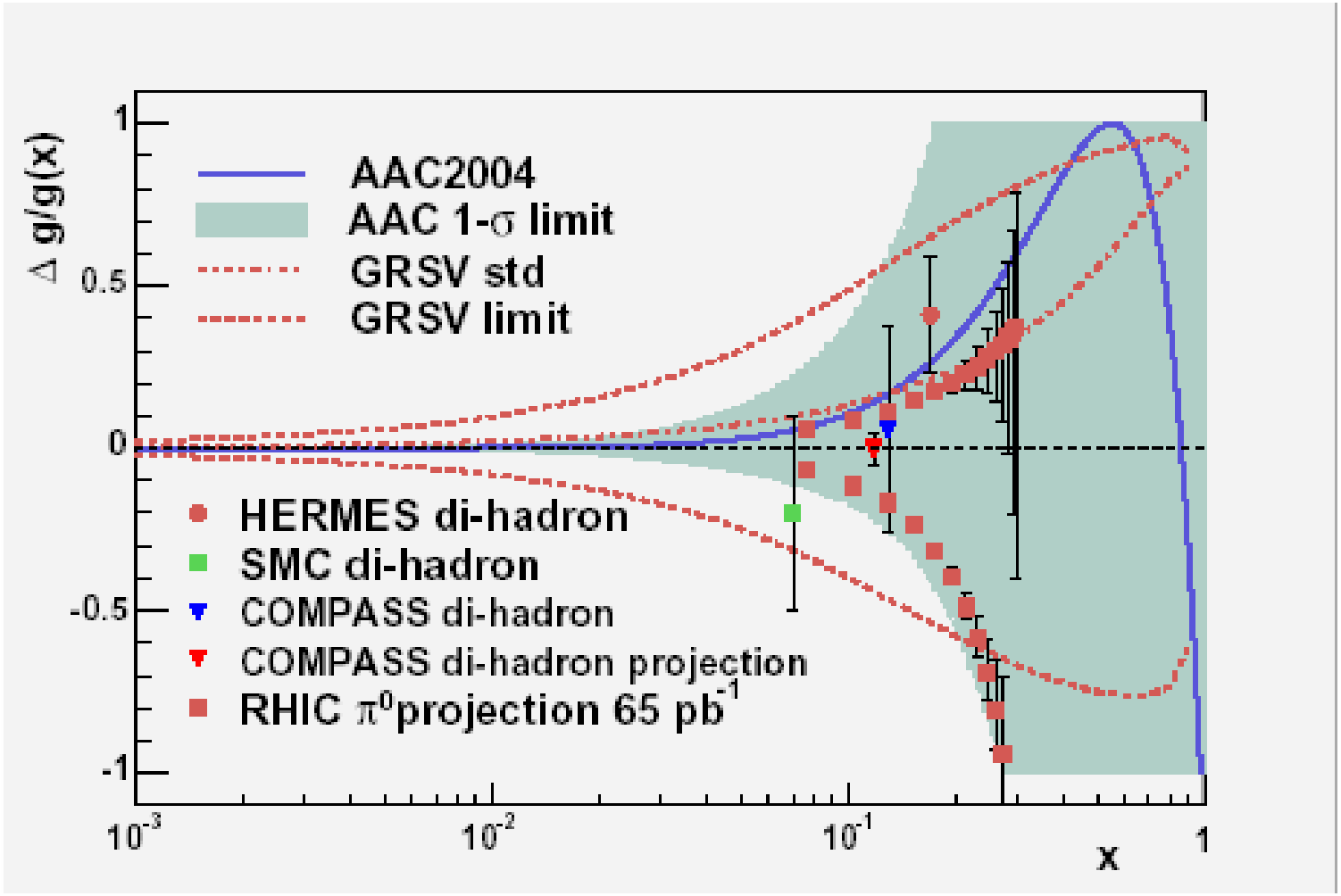


Summary

- origin of the nucleon spin 1/2 ?
  - quark contribution measured by polarized DIS $\Delta\Sigma$ = 10~30%
  - gluon contribution ?
- gluon polarization measurements
  - semi-inclusive DIS experiments – HERMES/SMC/COMPASS
    - high-p_T hadron pairs, open charm production
  - polarized proton collider – STAR & PHENIX at RHIC
    - π^0, direct photon, jet production, coincidence channels
  - first data started to arrive
  - variety of new data will arrive in next 5 years (or a decade)
- flavor-sorted quark polarization measurements
  - semi-inclusive DIS experiments
    - $\pi\pm$, K$\pm$, …
  - polarized proton collider
    - weak boson production

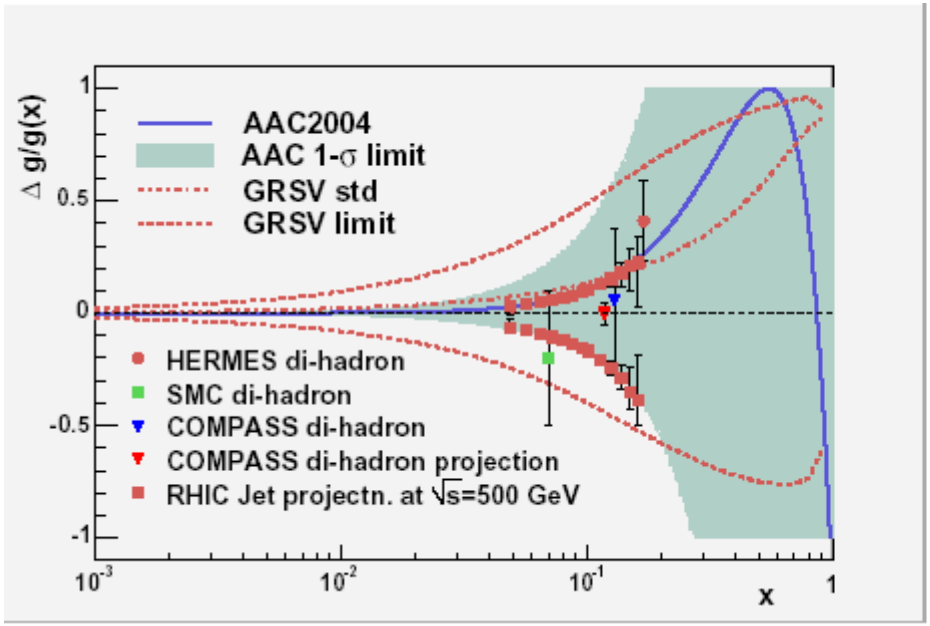
Backup Slides

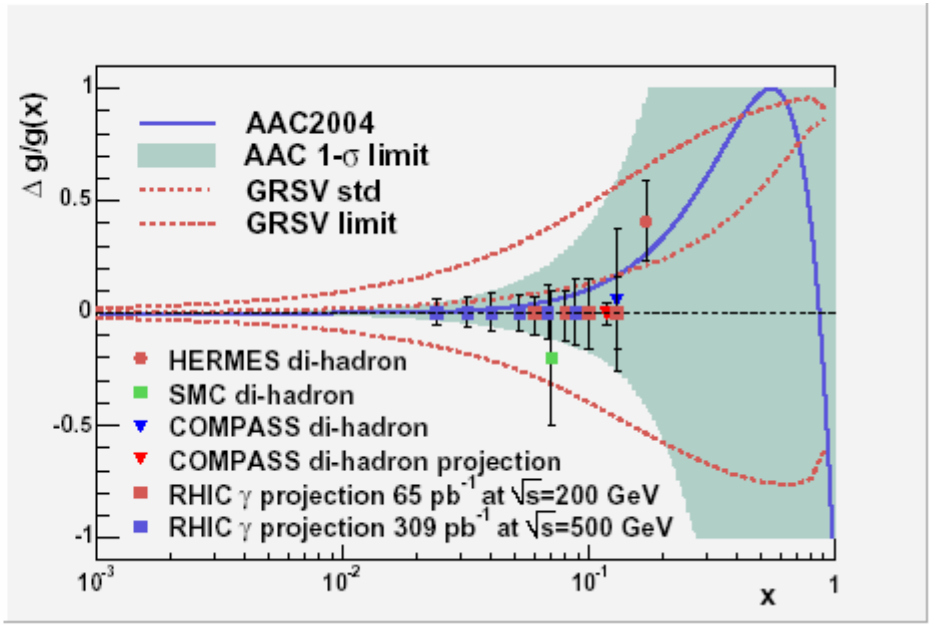
Gluon polarization



PHENIX π^0 $\sqrt{s}$ = 200 GeV

Gluon polarization





STAR jet
√s = 500 GeV

PHENIX direct photon
√s = 200 and 500 GeV