J-PARC dimuon実験による
核子スピン構造測定

RCNP Workshop
「J-PARCハドロン実験施設の
ビームライン整備拡充に向けて」
２００７年１１月１２日（月）

後藤雄二（理研/RBRC)

内容

- イントロ
  - 核子スピン構造
  - RHICその他の偏極実験の状況、結果
- J-PARC Drell-Yan実験の物理
  - 縦偏極実験：核子スピンのフレーバー構造
  - 横偏極実験：軌道角運動量の寄与
  - その他

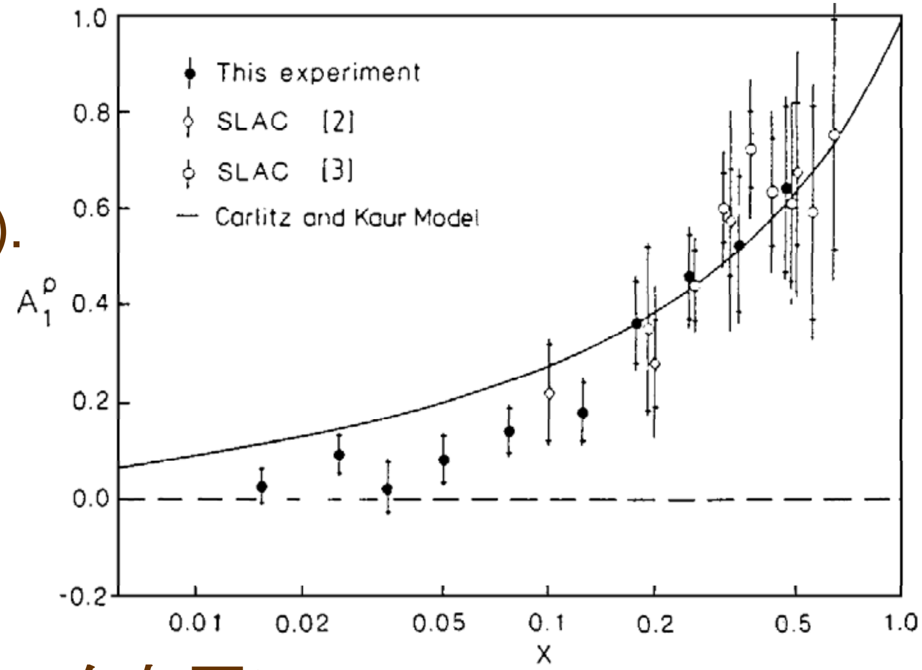
核子スピン構造

- Fundamentalな対象であるにもかかわらず、理解されていない
- QCDを基盤とする研究方法が発展している
- 核子の構造を調べるともに、QCDに対するテスト、理解となる
  - Q^2 evolution + factorization + universality
  - global QCD analysis of e^++e^-, e+p, and p+p(or pbar) data
    - unpolarized/polarized parton distribution functions
    - fragmentation functions
- 縦偏極実験と横偏極実験
  - クォークスピンとグルーオンスピンの寄与
  - クォークとグルーオンの軌道角運動量の寄与

核子スピン1/2の起源？

- EMC実験@CERN

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



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

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

  – 中性子およびハイペロン崩壊データを用いて

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

「陽子スピンの危機」

    - クォークスピンは核子スピンの小さな割り合いにしか寄与しない

  – x = 0 ~ 1 の積分による不確定性

    - より広いx領域を覆う、よりよい精度のデータが必要

➔ SLAC/CERN/DESY/JLAB 実験

偏極レプトン深非弾性散乱実験

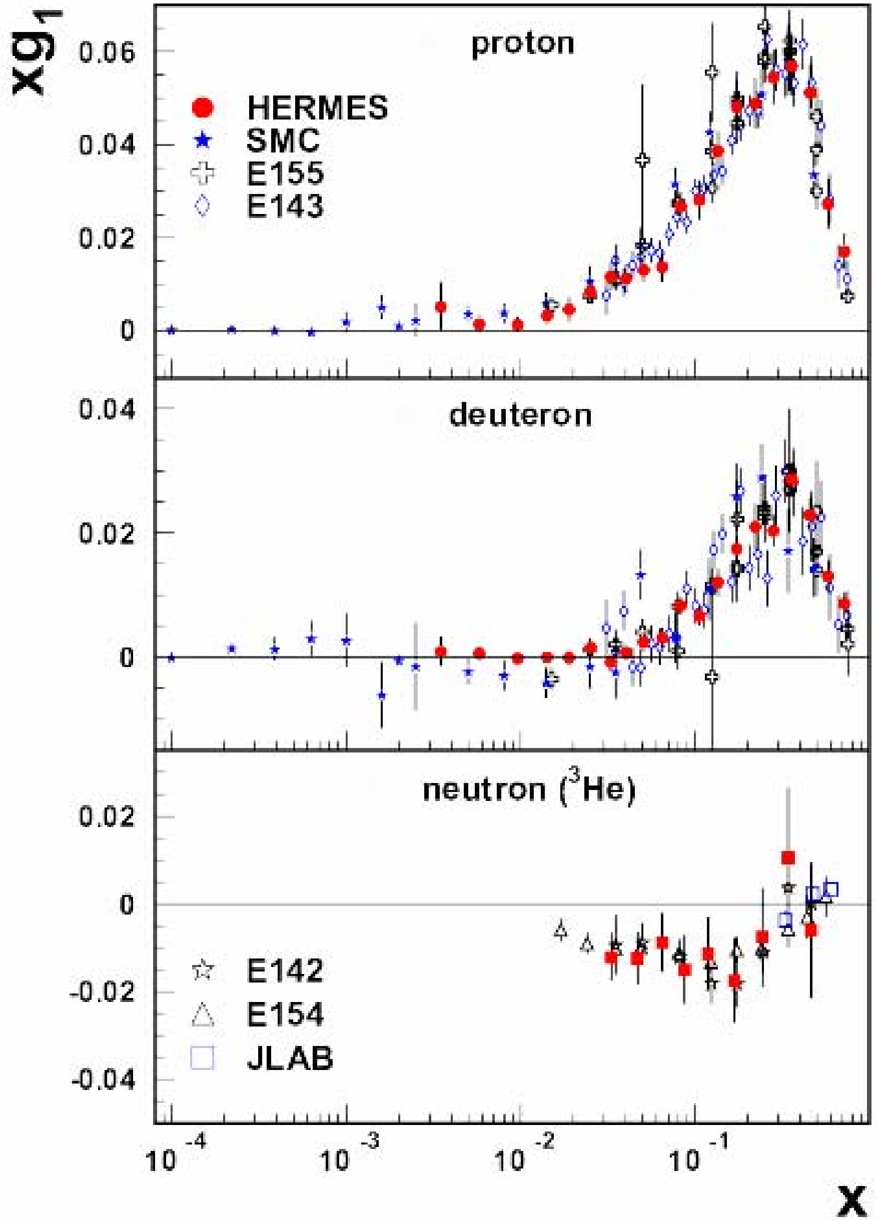
- クォークスピンの寄与

$$\Delta\Sigma \sim 0.2$$

- 核子スピン1/2の起源は何か？

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

  – グルーオンスピンの寄与？
  – 軌道角運動量？



グルーオンスピンの寄与

- 偏極深非弾性散乱実験のスケール則の破れ
  - 摂動QCDの発展方程式の重要な成功
  - Q^2の範囲が限られている

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

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

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

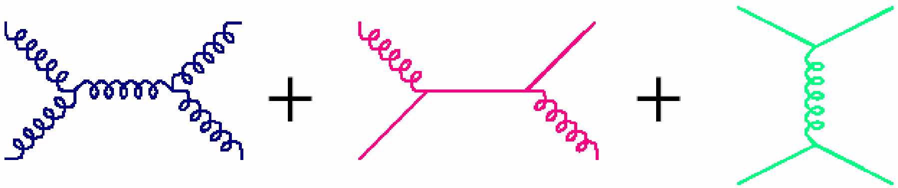
P.L. Anthony et al., PLB 493, 19 (2000).

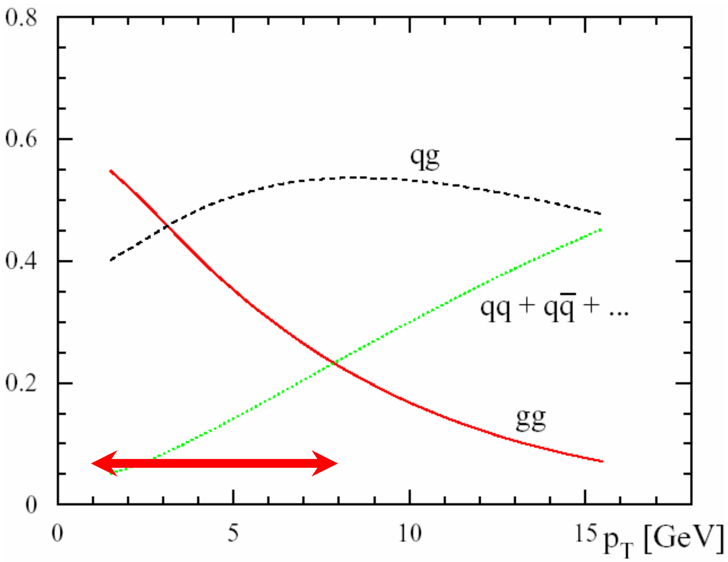
- semi-inclusive 深非弾性散乱実験
  - 高p_Tハドロン対生成
  - オープンチャーム生成
- 偏極ハドロン衝突実験
  - 光子の直接生成、重いフレーバー生成
  - 高p_Tハドロン生成、ジェット生成

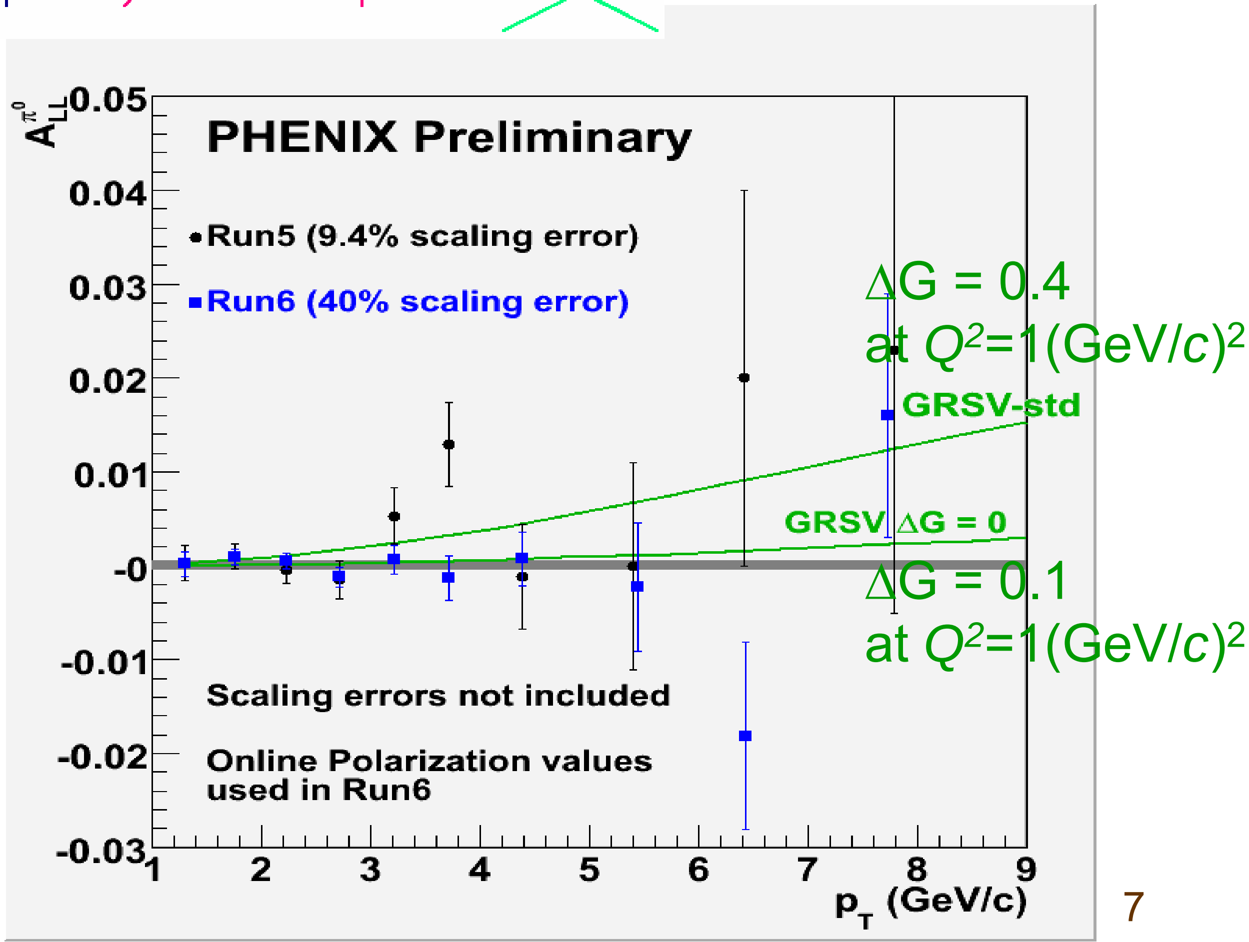
グルーオンスピンの寄与

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

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





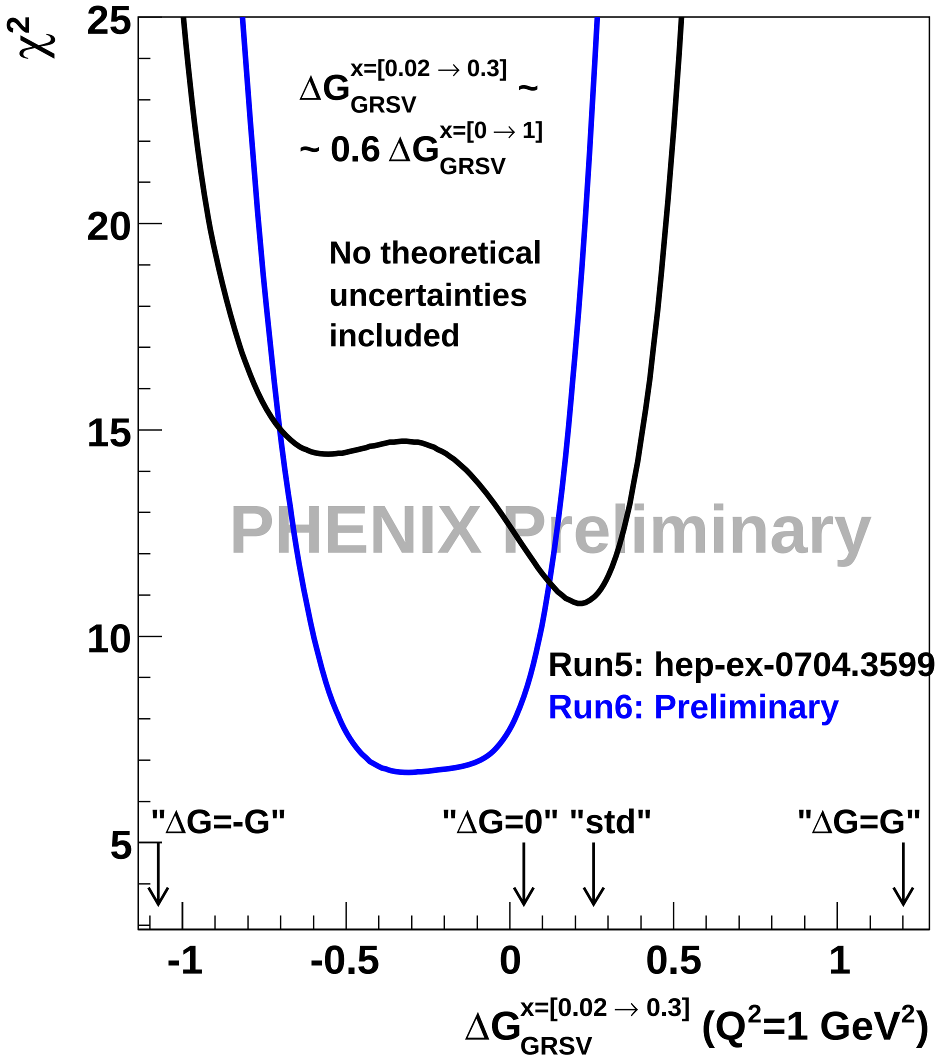


gg + qg dominant
sensitive to the gluon reaction

グルーオンスピンの寄与

- PHENIX A_{LL} of π^0
  - GRSV-std scenario, ΔG = 0.4 at $Q^2 = 1(\text{GeV/c})^2$, excluded by data on more than 3-sigma level, $\chi^2(\text{std}) - \chi^2_{min} > 9$
    - only experimental statistical uncertainties included (the effect of systematic uncertainties expected to be small in the final results)
    - theoretical uncertainties not included

Calc. by W.Vogelsang and M.Stratmann

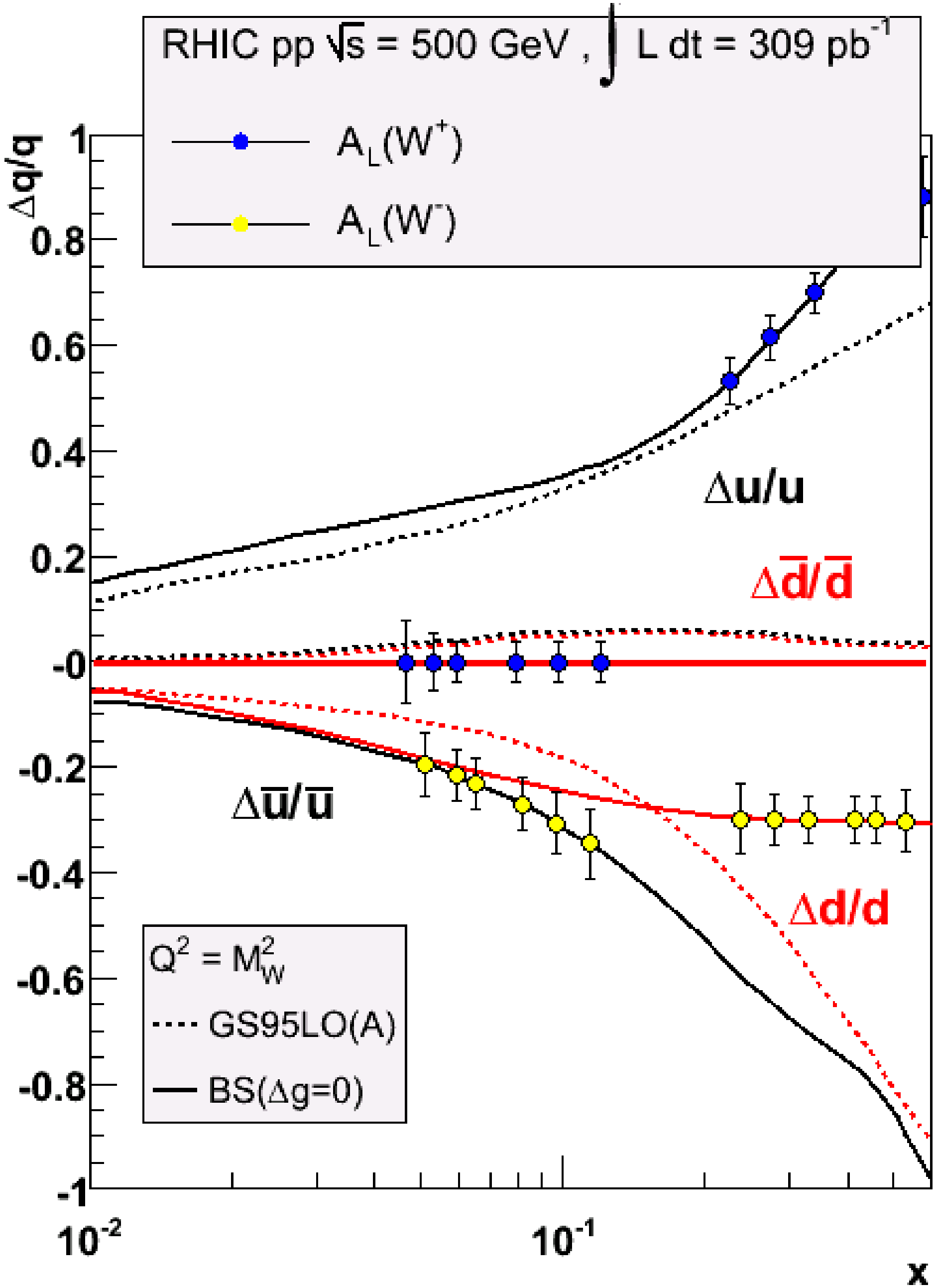


クォーク偏極分布のフレーバー依存

- weak boson production
  - RHIC spin
    - √s = 500 GeV
    - 2009 –
  - parity-violating asymmetry A_L

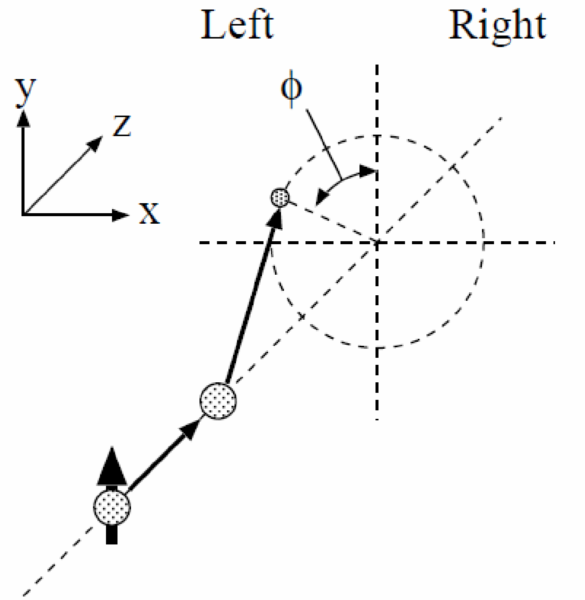
$$A_L^{W^+} = \frac{\Delta u(x_a)\bar{d}(x_b) - \Delta\bar{d}(x_a)u(x_b)}{u(x_a)\bar{d}(x_b) + \bar{d}(x_a)u(x_b)}$$

  - no fragmentation ambiguity

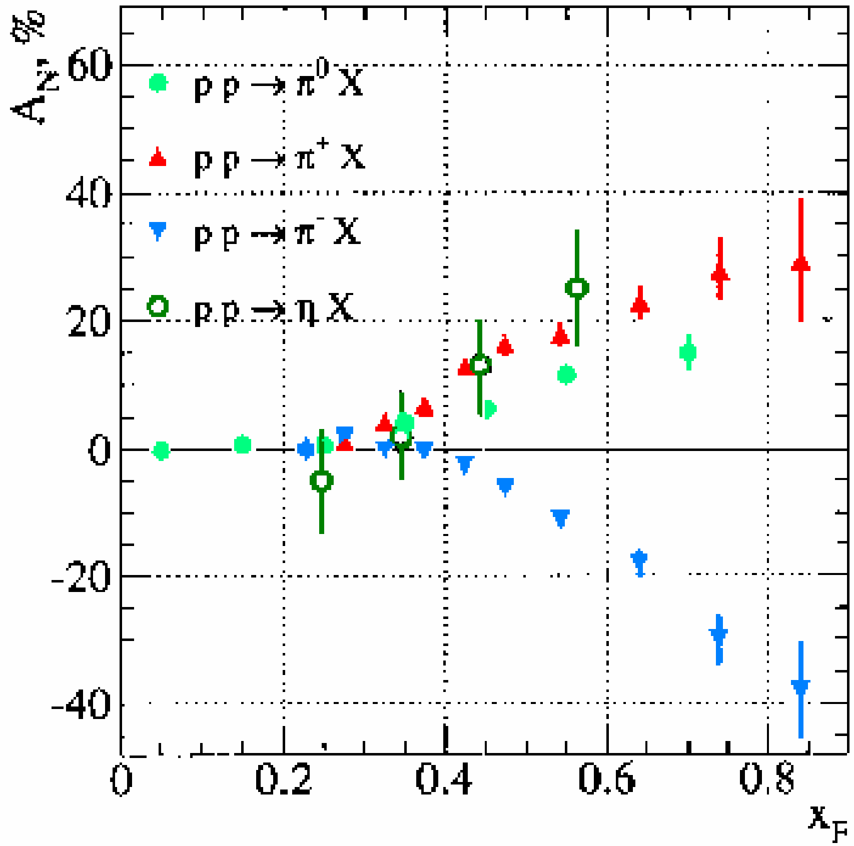


横偏極非対称度測定

- SSA (Single Spin Asymmetry)、左右非対称度



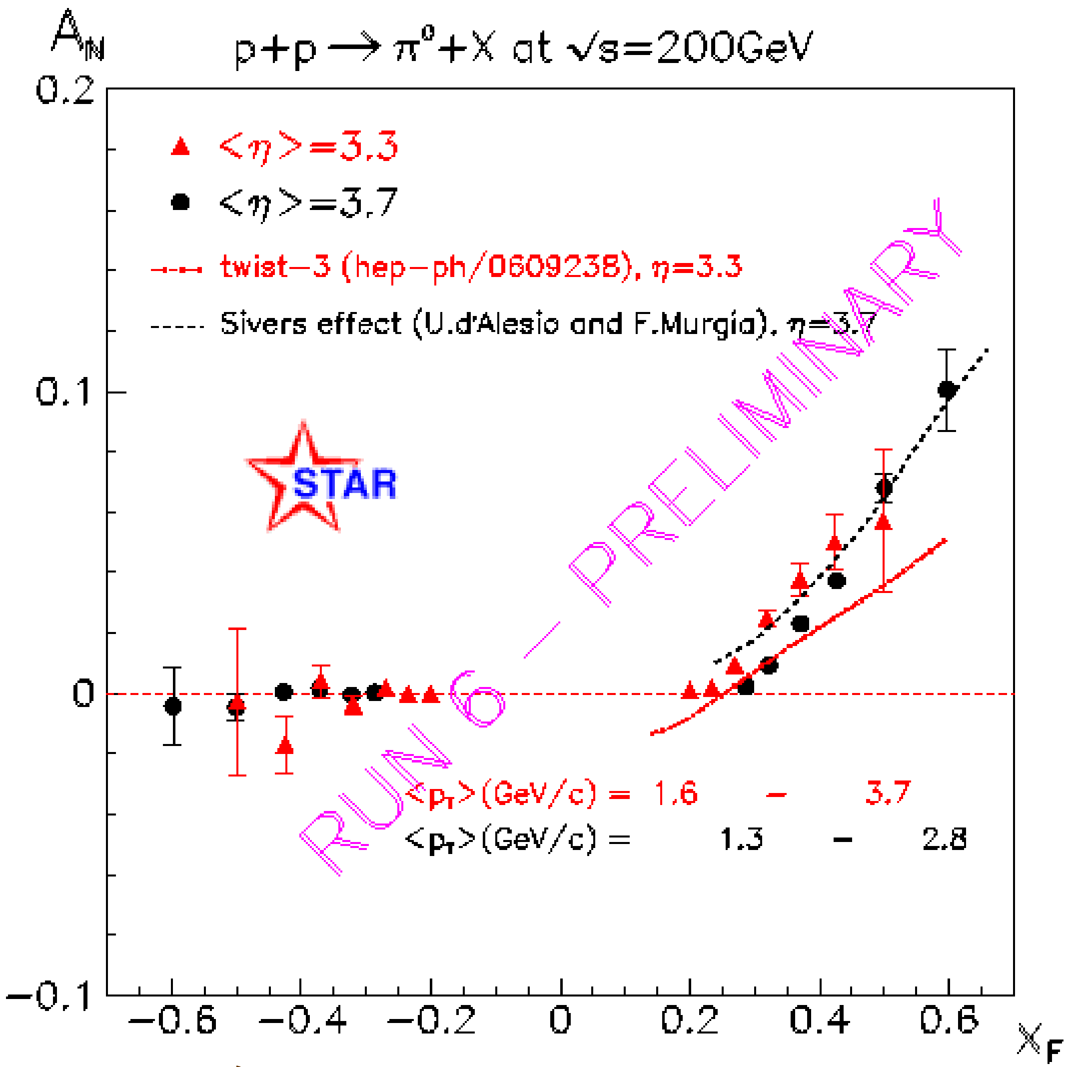
$$A_N = \frac{d\sigma_{Left} - d\sigma_{Right}}{d\sigma_{Left} + d\sigma_{Right}}$$

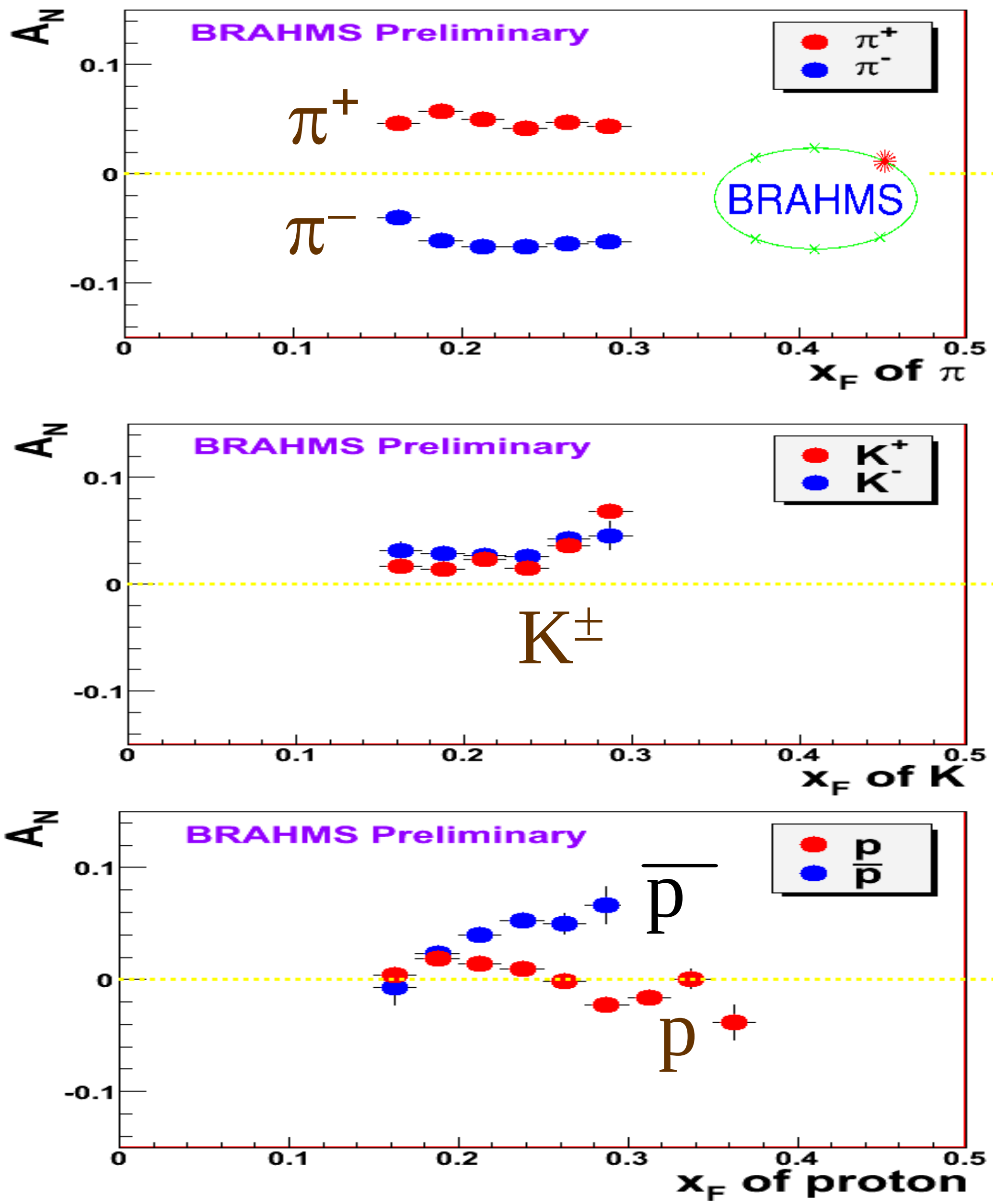


- 前方 $x_F > 0.2$
  - Fermilab-E704
    - 固定標的実験
    - $\sqrt{s}$ = 19.4 GeV
    - 非対称度 ~20%
    - 多くのQCDに基づく理論の開発

SSA (Single Spin Asymmetry）測定

- 前方
  - RHIC実験
    - √s = 200 GeV

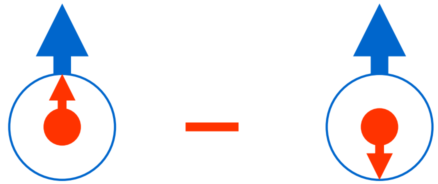




分布関数と破砕関数

- Transversity分布関数

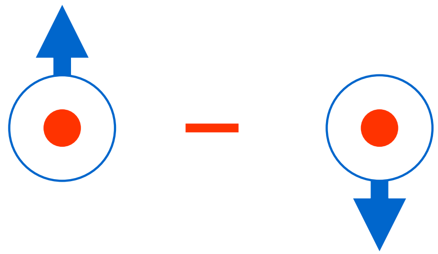
$$\delta q(x) = h_{1T}(x)$$



  - 横方向に偏極した陽子内部におけるパートンの横方向スピンの分布

- Sivers分布関数

$$f_{1T}^{\perp}(x, p_T^2)$$



  - 陽子の横方向スピンと、陽子内部の非偏極パートンの横方向運動量(p_T^2)との相関

- Collins破砕関数

$$H_1^{\perp}(z, k_T^2)$$

  - 破砕するパートンの横方向スピンと、生成されたハドロンのパートンに対する横方向運動量(k_T^2)との相関

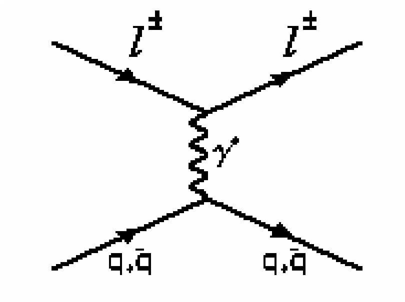
イントロのまとめ

- RHICその他の偏極実験で、核子スピンに対するグルーオンスピンの寄与についての決着は着く
- 次は核子スピンに対する軌道角運動量の寄与の測定、決定
- 横偏極に対する非対称度については、わかっていないことがまだまだある

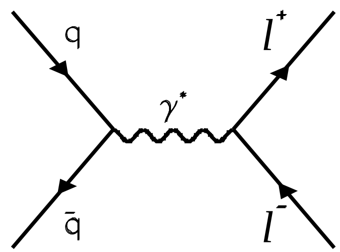
Drell-Yan実験

- ハドロン衝突で最も単純な過程

DIS



Drell-Yan



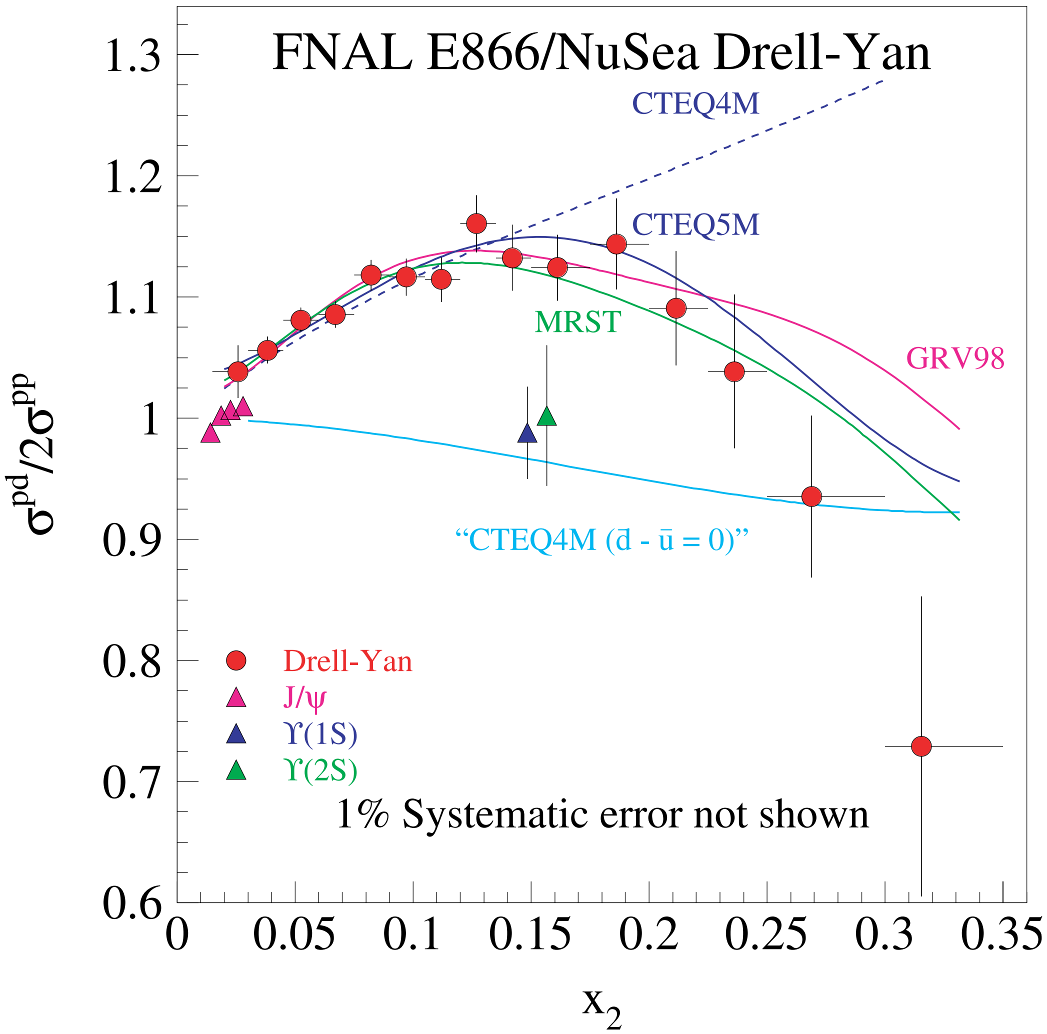
  – QCDからのfinal-state effectがない
  – 偏極Drell-Yan実験はこれまで行なわれていない
- Sea-quark分布のフレーバー非対称性
  – 非偏極測定と縦偏極測定
- 核子内部の軌道角運動量？
  – Sivers効果（Collins効果はない）
- Transversity分布関数など

Drell-Yan実験

- なぜJ-PARCか？
  - 偏極陽子ビームの可能性
    - 日本とBNLの加速器グループによる技術的な可能性の議論
  - 高強度、高輝度
    - Drell-Yan反応の断面積は小さい

Sea-quark分布のフレーバー非対称性

- Fermilab E866 Drell-Yan実験



$$\frac{\sigma^{pd}}{2\sigma^{pp}} \sim \frac{1}{2}\left[1+\frac{\bar{d}(x_2)}{\bar{u}(x_2)}\right]$$

with CTEQ5M

$$\int_{0.015}^{0.35} dx[\bar{d}(x)-\bar{u}(x)]$$

$$= 0.0803 \pm 0.011$$

$$\int_{0}^{1} dx[\bar{d}(x)-\bar{u}(x)]$$

$$= 0.118 \pm 0.012$$

Sea-quark分布のフレーバー非対称性

- 起源
  - meson-cloud模型
    - 仮想的なmeson-baryon状態

$$p \to p\pi^0, n\pi^+, \Delta\pi$$

  - カイラルクォーク模型

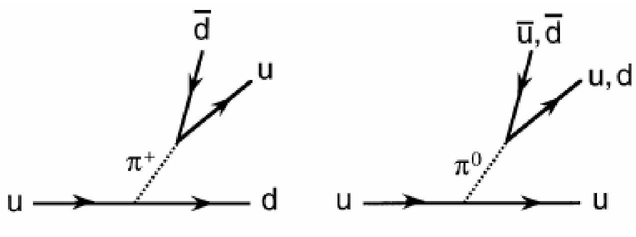


Fig. 17. Valence u quark splitting.

$\bar{d}$ distribution is softer than meson cloud model because it splits from (valence) quark

  - インスタントン模型
  - カイラルクォークソリトン模型

Sea-quark分布のフレーバー非対称性

- π^+ は陽子中の余分な dbar の起源だろうか？

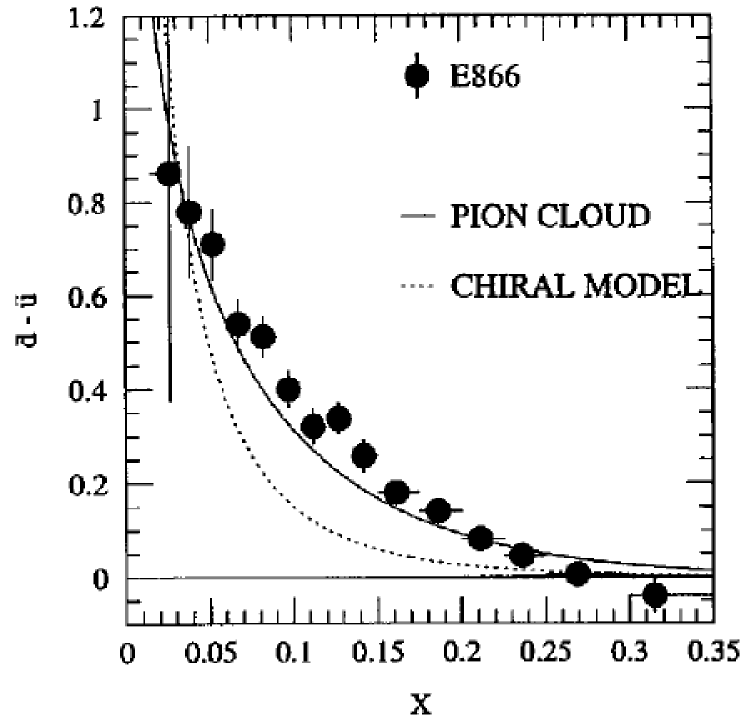


Figure 14: Comparison of the E866 [70] $\bar{d}-\bar{u}$ results at $Q^2 = 54$ GeV^2/c^2 with the predictions of pion-cloud and chiral models as described in the text.

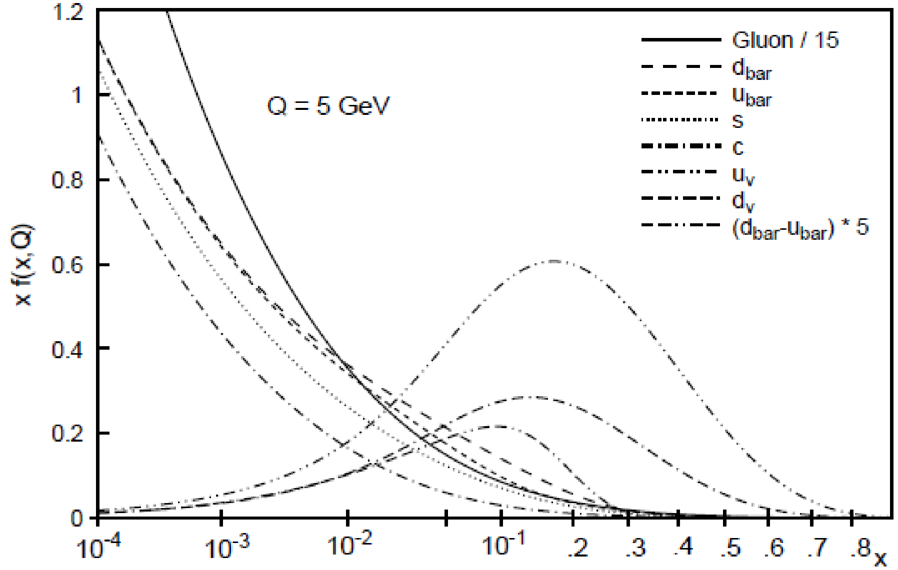
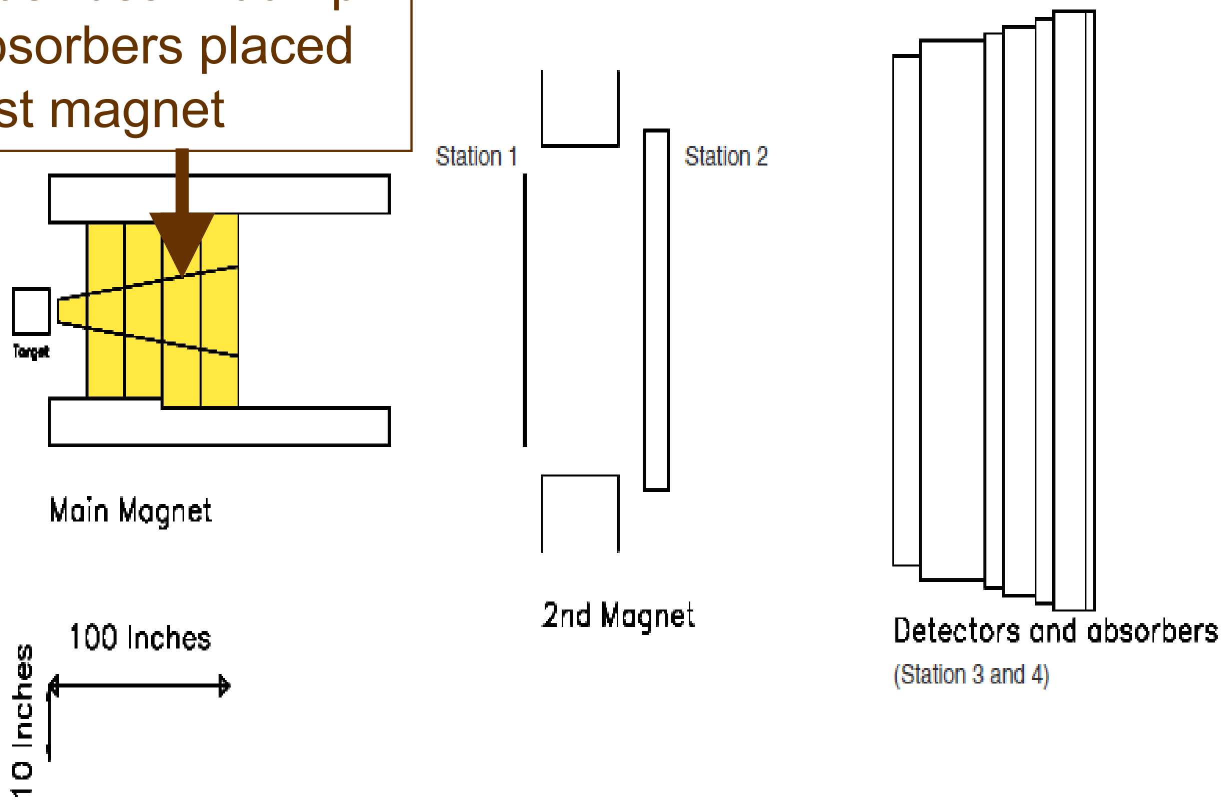


Fig. 2. Overview of CTEQ5M parton distributions at $Q = 5$ GeV. The gluon distribution is scaled down by a factor of 15, and the $(\bar{d}-\bar{u})$ distribution is scaled up by a factor of 5

J-PARC dimuon実験

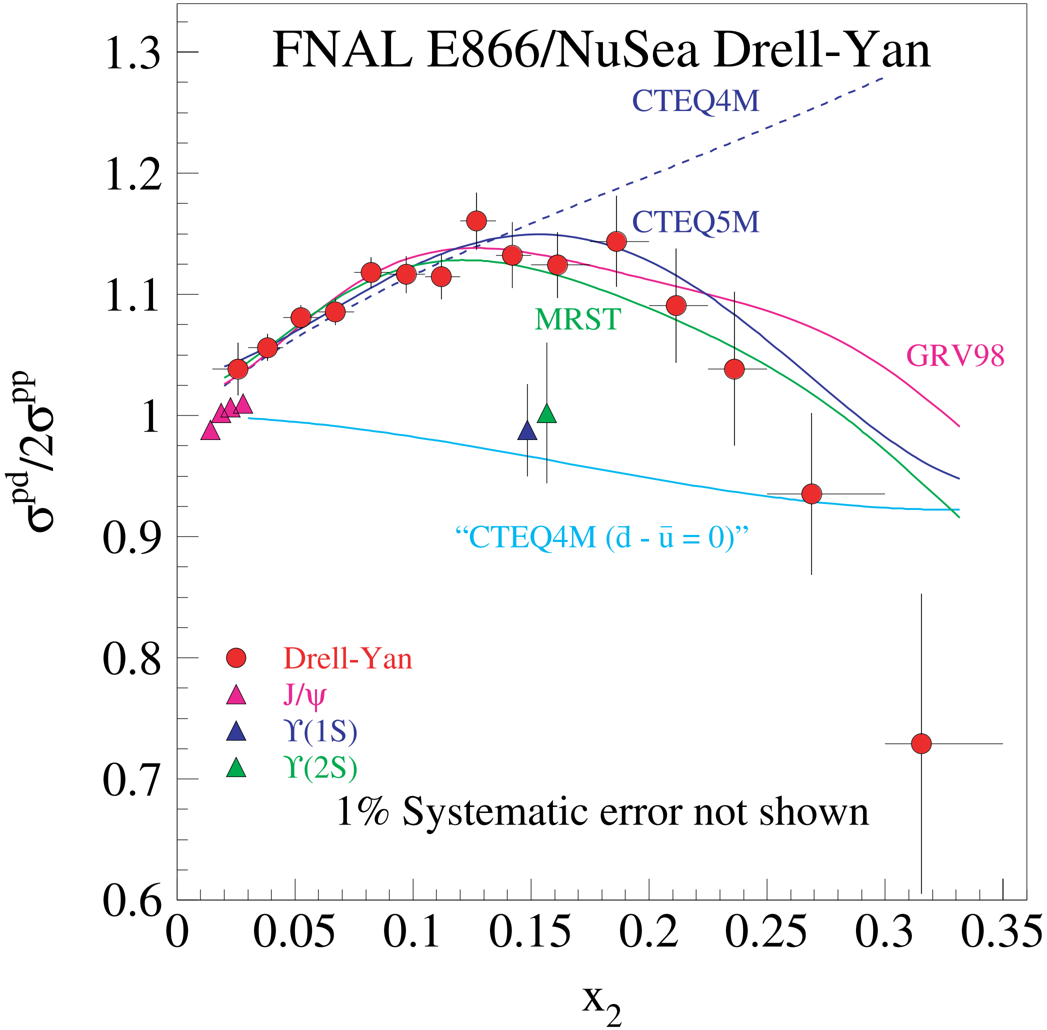
- 800-GeVビームでのFermilab実験のスペクトロメータがベース
- 長さを短く、apertureはできるだけ広く保つ
- 2台のbending-magnet、p_T キック2.5-GeV/cと0.5-GeV/c
- 3-stationのMWPCとドリフトチェンバーによるtracking
- ミューオンIDとtracking

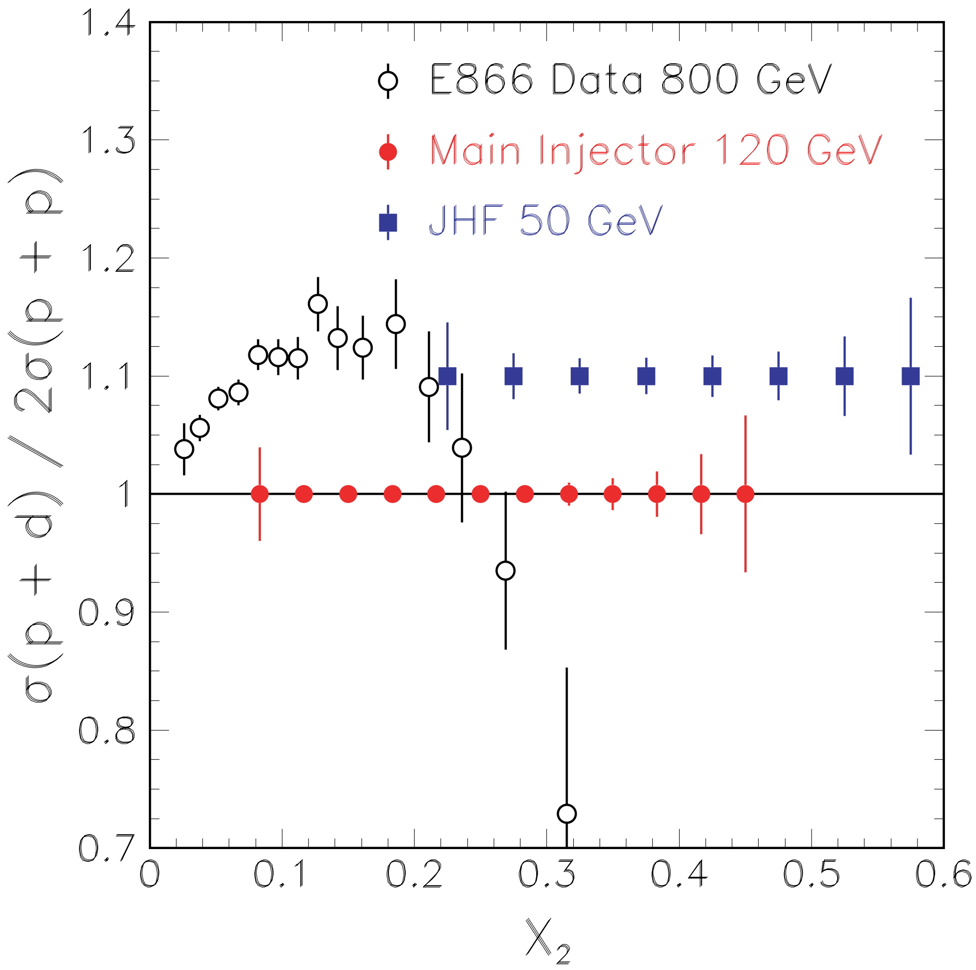
tapered copper beam dump and Cu/C absorbers placed within the first magnet



J-PARC dimuon実験

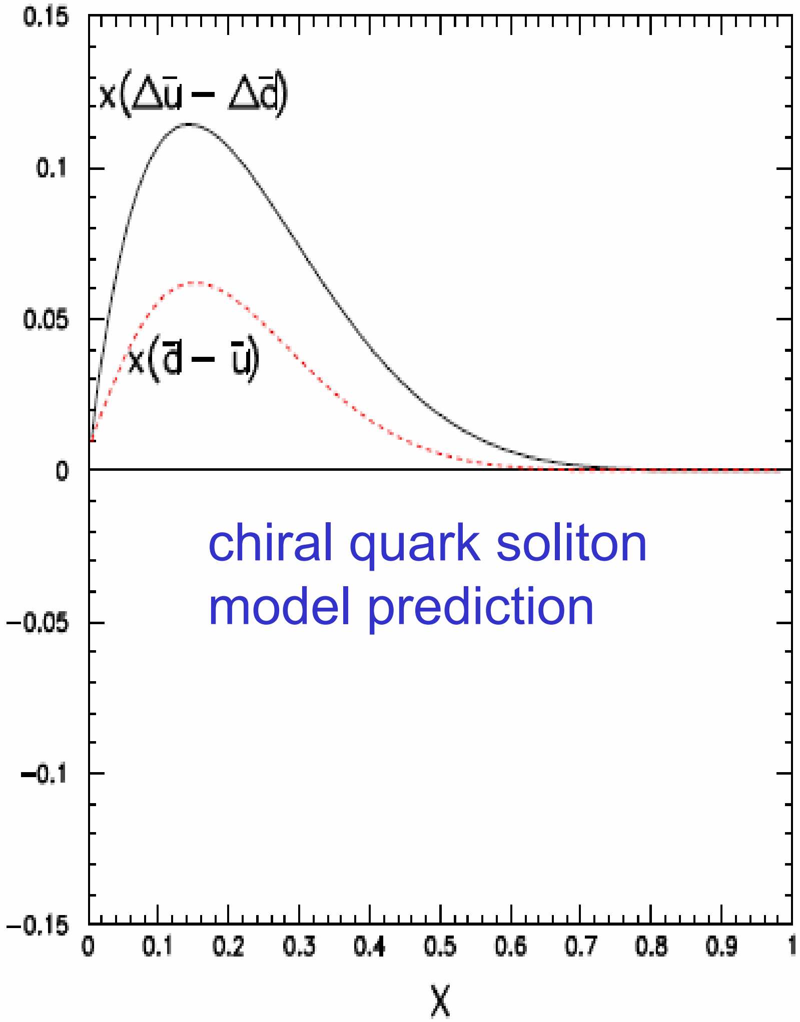
- 非偏極実験
  - 陽子ビームと陽子および重陽子ターゲット

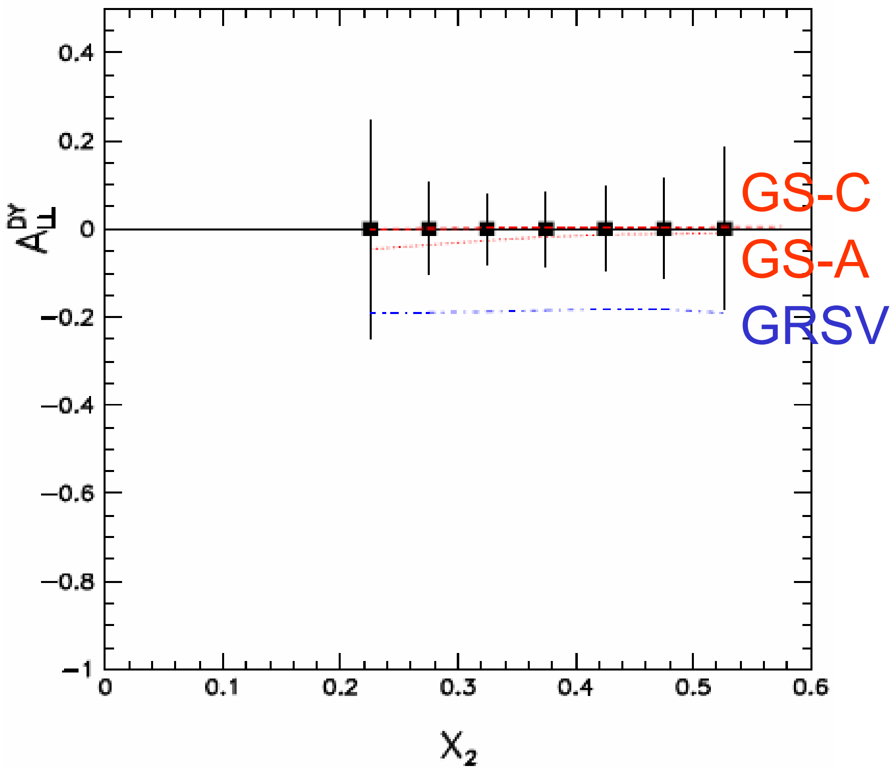




J-PARC dimuon実験

- 縦偏極Drell-Yan実験
  - A_{LL}測定
    - sea-quark偏極分布のフレーバー非対称性

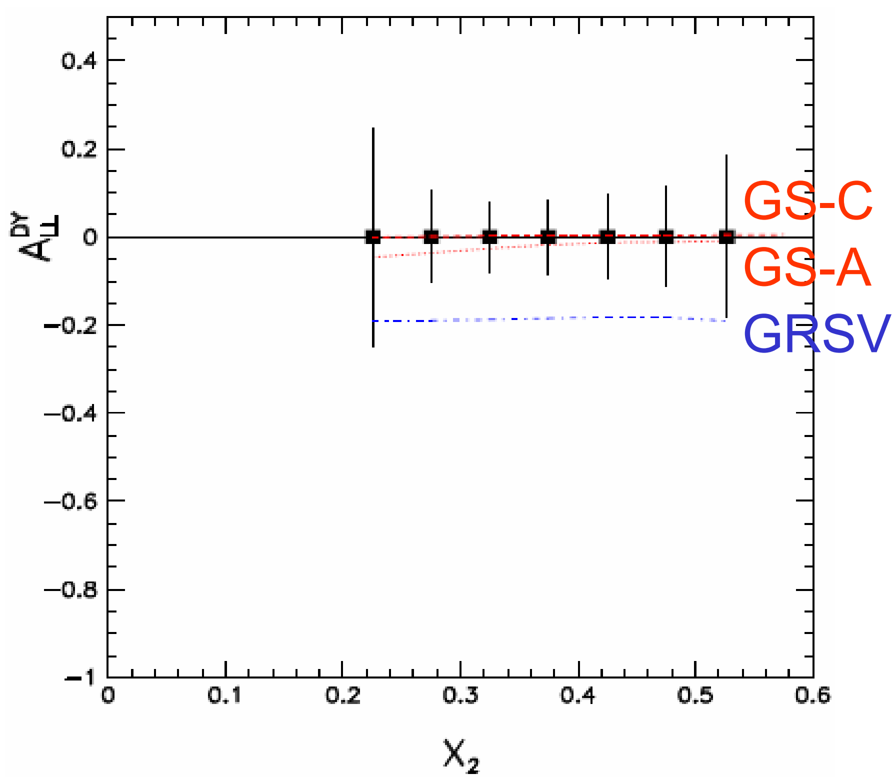


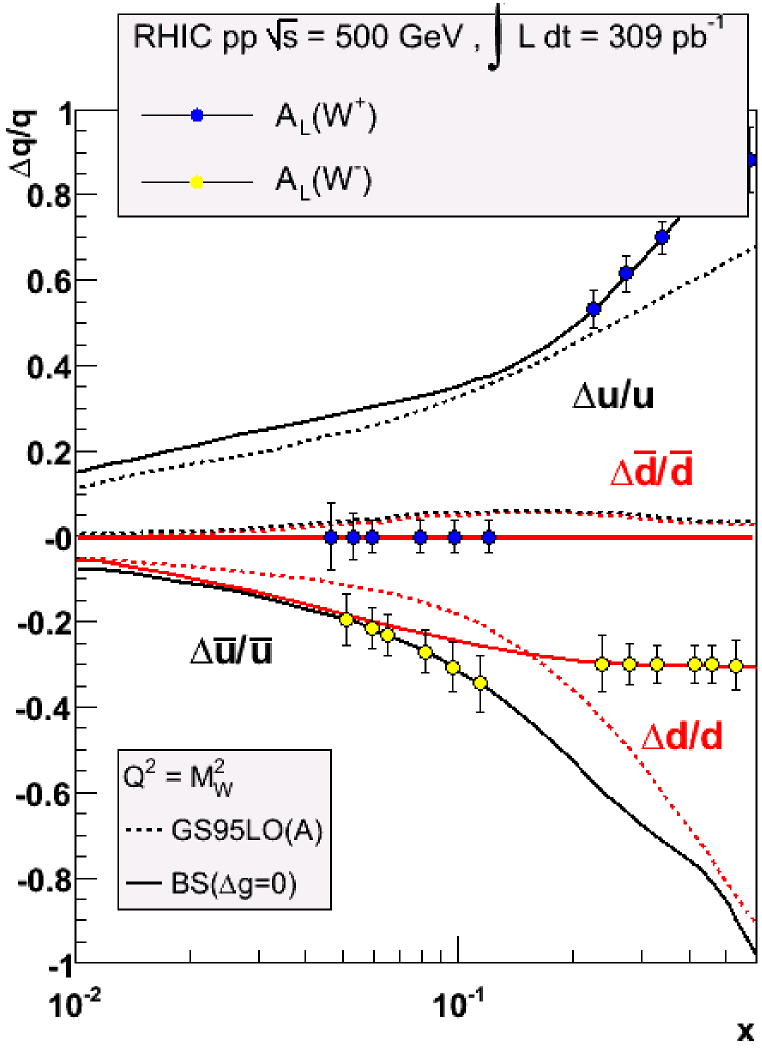


120-day run
75% polarization for a 5×10[11] protons/spill
polarized solid NH3 target, 75% hydrogen polarization and 0.15 dilution factor

Sea-quark偏極分布のフレーバー非対称性

- 偏極Drell-Yan実験
  - x: 0.25 – 0.5
- RHICでのW±生成
  - x: 0.05 – 0.1





reduction of uncertainties to determine the quak spin contribution ΔΣ and gluon spin contribution ΔG to the proton spin

J-PARC dimuon実験

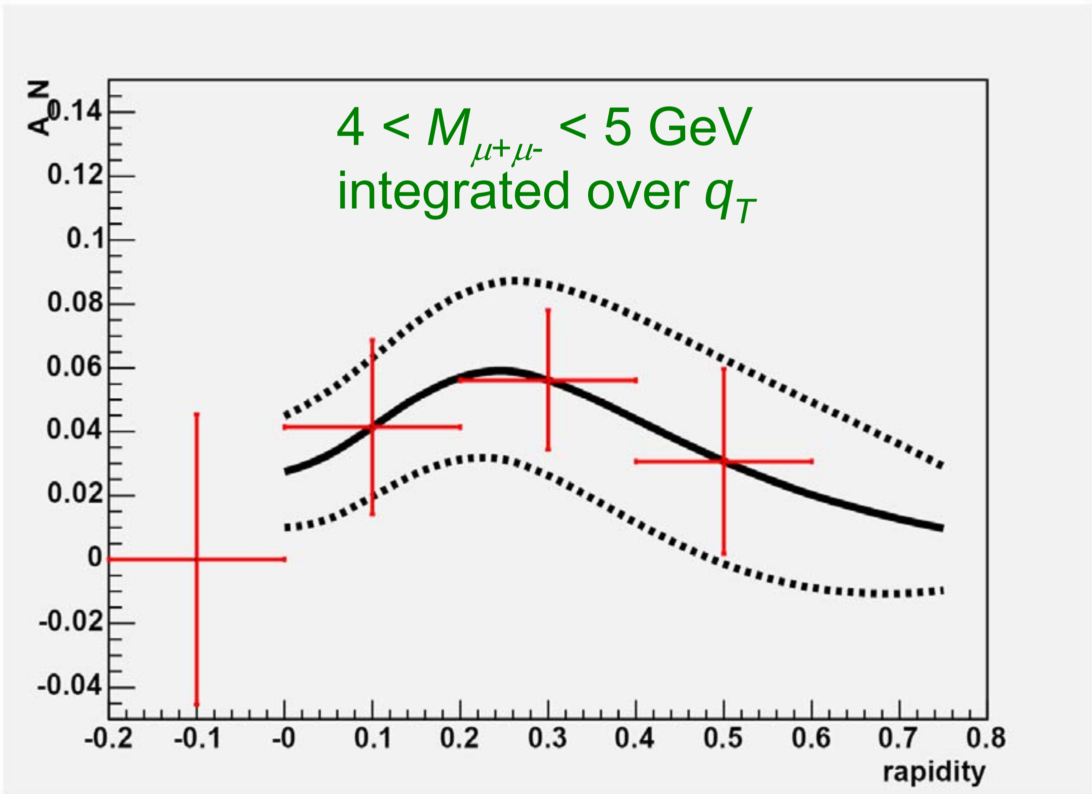
- 核子スピンに対する軌道角運動量の寄与
  - ハドロン衝突実験から直接軌道角運動量の寄与に結びつく理論はまだない
  - しかし、偏極核子中の横方向の運動に関わる効果は軌道角運動量と関係するはず
    - Sivers 効果
    - higher-twist 効果
  - A_{LL} 測定も high-x_F で軌道角運動量に sensitive…
    - Feng Yuan らの $L_z = 1$ に対する計算… [Harut Avakian, Feng Yuan, et al. arXiv:0705.1553.]

偏極Drell-Yan実験

- *SSA* (A_N) 測定
  - Ji, Qiu, Vogelsang, and Yuan
    - PRD 73, 094017 (2006)
    - 高い $q_T \sim Q$ *ではhigher-twist効果に感度が高い*
    - 適当な q_T: $\Lambda_{QCD} << q_T << Q$ *の範囲では、Sivers効果とhigher-twist効果が同じ記述を与える*
    - semi-inclusive DISのSSAについても同様: hep-ph/0604128
  - Drell-Yan実験で測定されるSivers分布関数はDIS実験で測定されるものと符号が逆になる
    - *e+pデータとp+pデータの間でのQCDに対するテスト*

偏極Drell-Yan実験

- *SSA* (A_N) measurement



Theory calculation by Ji, Qiu, Vogelsang and Yuan based on Sivers function fit of HERMES data (Vogelsang and Yuan: PRD 72, 054028 (2005))

1000 fb^{-1} (120-day run), 75% polarization, no dilution factor

偏極Drell-Yan実験

- A_{TT} measurement
  - $h_1(x)$: transversity

$$A_{TT} = \hat{a}_{TT} \cdot \frac{\sum_q e_q^2 (\bar{h}_{1q}(x_1) h_{1q}(x_2) + (1 \leftrightarrow 2))}{\sum_q e_q^2 (\bar{f}_{1q}(x_1) f_{1q}(x_2) + (1 \leftrightarrow 2))}$$

$$\hat{a}_{TT} = \frac{\sin^2\theta \cos(2\phi - \phi_{S_1} - \phi_{S_2})}{1 + \cos^2\theta}$$

- SSA measurement, $\sin(\phi+\phi_S)$ term
  - $h_1(x)$: transversity
  - $h_1^{\perp(1)}(x)$: Boer-Mulders function (1st moment of)

$$\hat{A} = -\frac{1}{2} \frac{\sum_q e_q^2 (\bar{h}_{1q}^{\perp(1)}(x_1) h_{1q}(x_2) + (1 \leftrightarrow 2))}{\sum_q e_q^2 (\bar{f}_{1q}(x_1) f_{1q}(x_2) + (1 \leftrightarrow 2))}$$

非偏極Drell-Yan実験

- Boer-Mulders function $h_1^{\perp}(x, k_T^2)$
  - angular distribution of unpolarized Drell-Yan

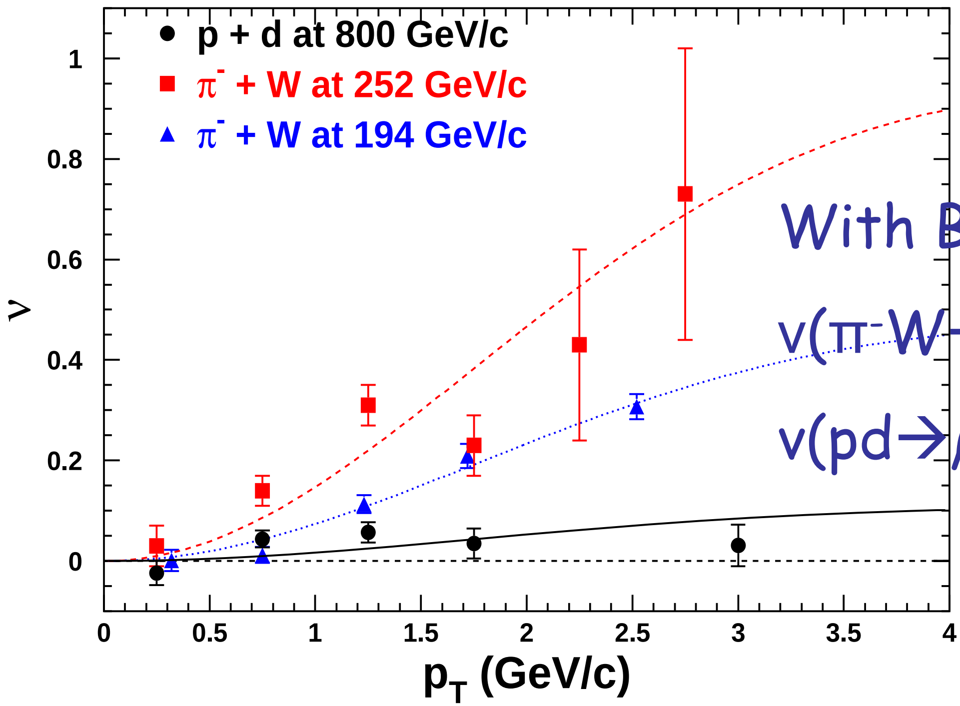
$$\left(\frac{1}{\sigma}\right)\left(\frac{d\sigma}{d\Omega}\right)=\left[\frac{3}{4\pi}\right]\left[1+\lambda\cos^2\theta+\mu\sin 2\theta\cos\phi+\frac{\nu}{2}\sin^2\theta\cos 2\phi\right]$$

  - correlation between transverse quark spin and quark transverse momentum

$$N(\phi)\propto h_1^{\perp q}(x_1,k_\perp^2)\cdot\frac{(\hat{P}\times\vec{k}_\perp)\cdot\vec{S}_q}{M}\cdot h_1^{\perp\bar{q}}(x_2,\bar{k}_\perp^2)\cdot\frac{(\hat{P}\times\vec{\bar{k}}_\perp)\cdot\vec{S}_{\bar{q}}}{M}$$

非偏極Drell-Yan実験

- Boer-Mulders function by unpol. Drell-Yan
  - Lam-Tung relation $1-\lambda=2\nu$
    - reflect the spin-1/2 nature of quarks
  - violation of the Lam-Tung relation suggests non-perturbative origin $\nu\neq 0, 1-\lambda\neq 2\nu$



With Boer-Mulders function $h_1^\perp$:

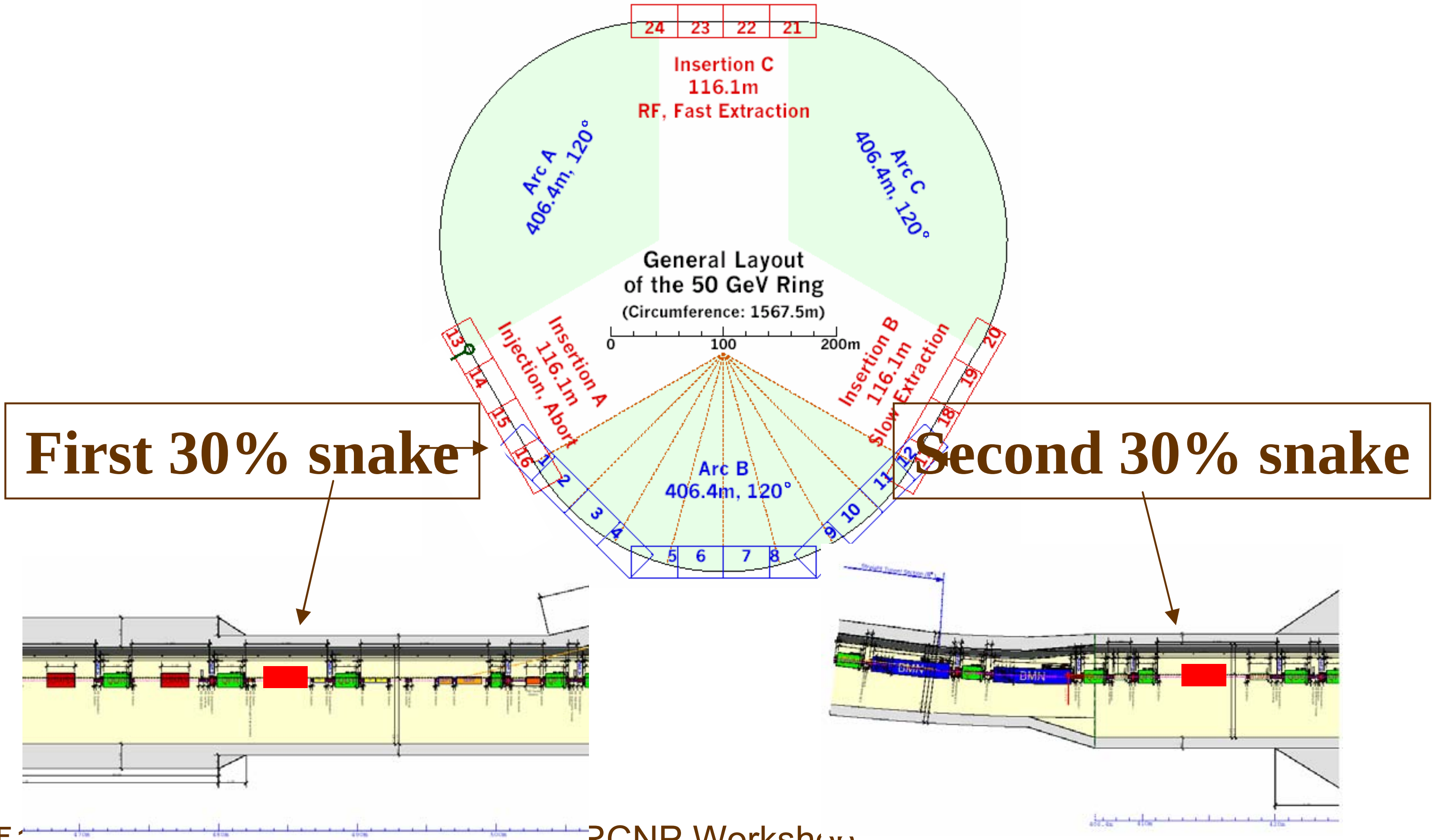
$\nu(\pi^- W\rightarrow\mu^+\mu^- X)$~valence $h_1^\perp(\pi)$*valence $h_1^\perp(p)$

$\nu(pd\rightarrow\mu^+\mu^- X)$~valence $h_1^\perp(p)$*sea $h_1^\perp(p)$

L.Y. Zhu,J.C. Peng, P. Reimer et al., hep-ex/0609005

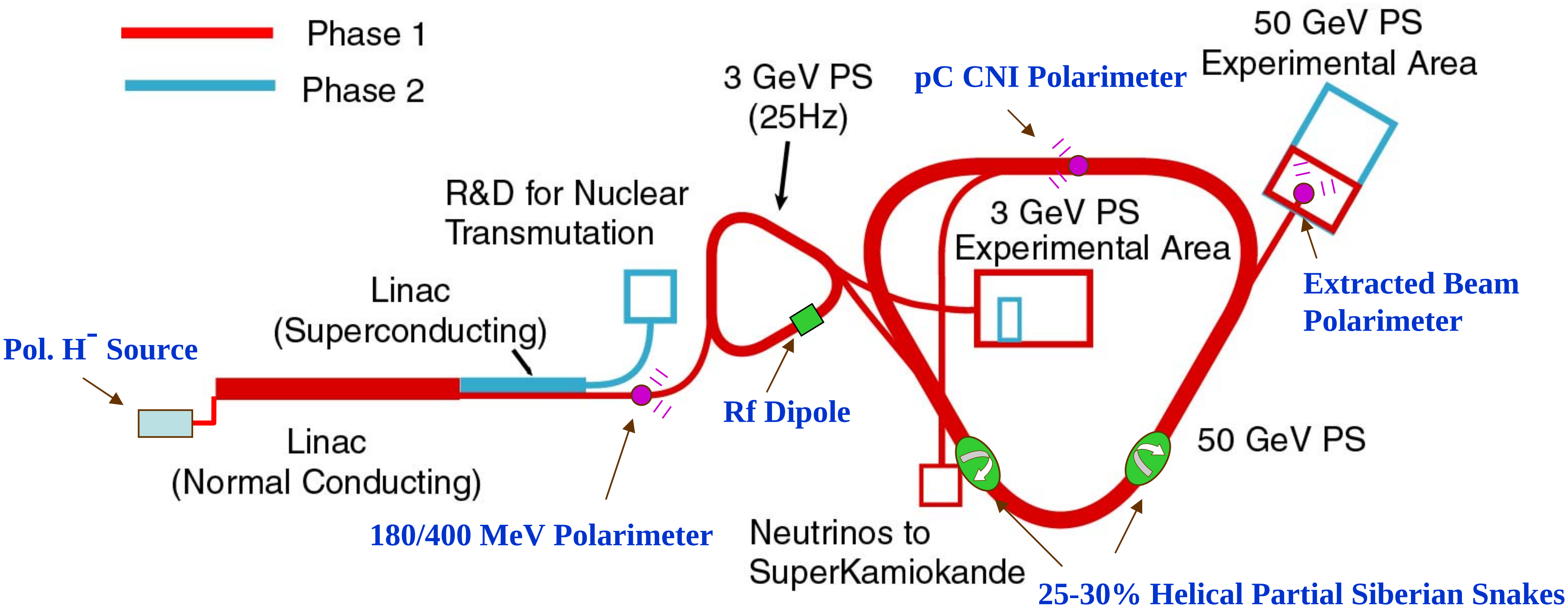
Towards the goal

- 30 GeV → 50 GeV
- unpolarized → polarized target → polarized beam
  - polarized beam study by BNL & KEK groups
  - possible locations of partial snakes in MR



Polarized proton acceleration at J-PARC

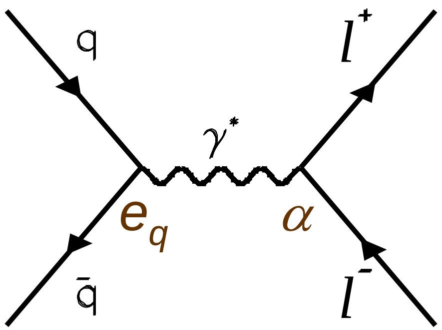
- 50 GeV polarized protons for slow extracted beam primary fixed target experiments
- low intensity (~ 10^{12} ppp), low emittance (10 π mm mrad) beams

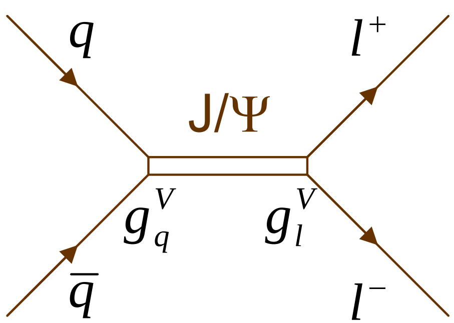


Thomas Roser (BNL), et al.

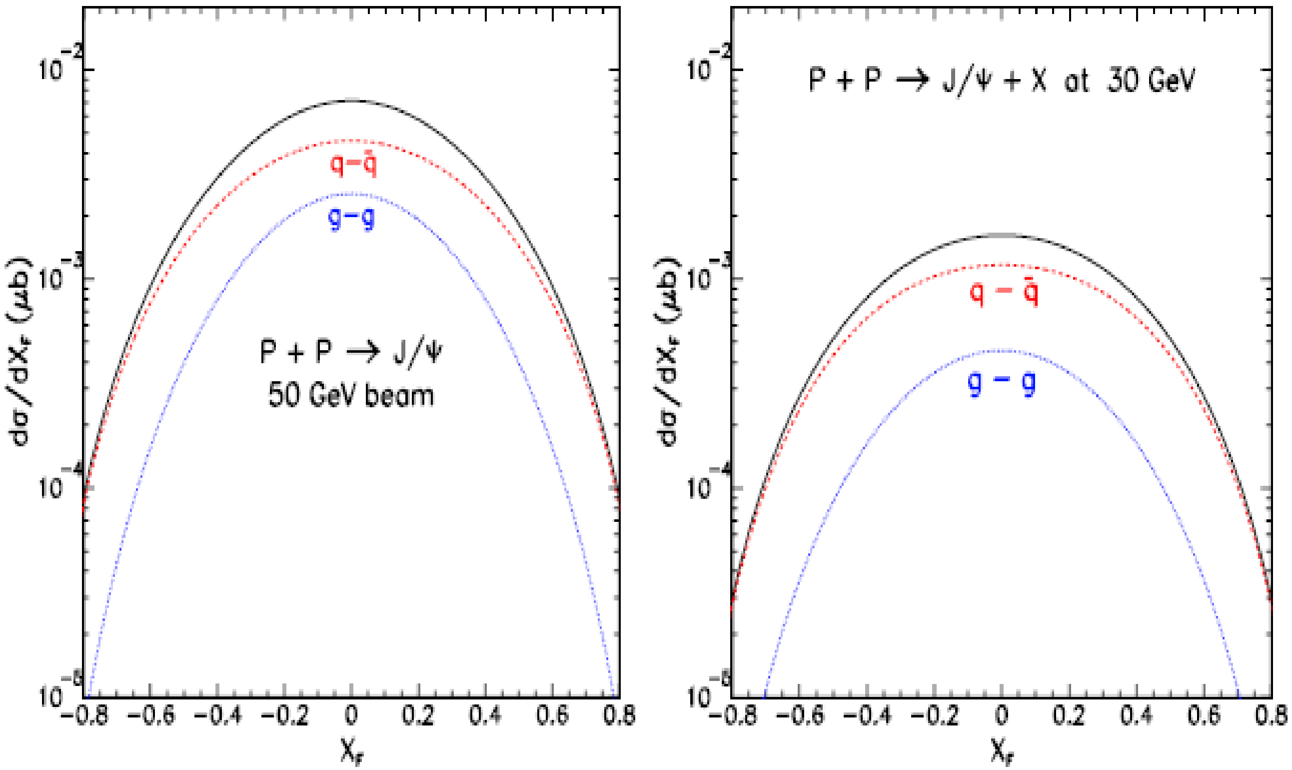
Physics at 30 GeV

- J/ψ
  - gluon fusion or quark-pair annihilation
  - quark-pair annihilation dominant
    - must be confirmed experimentally…
    - similar physics topics as Drell-Yan process





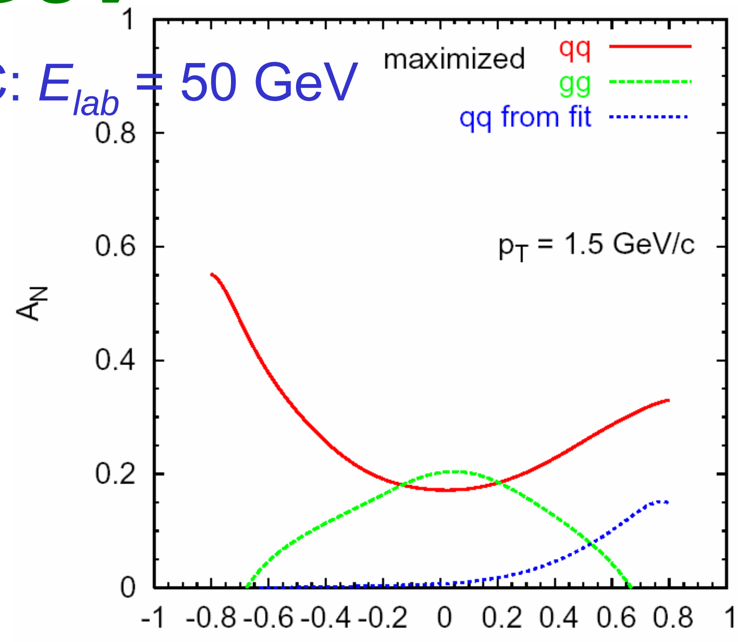
calculations by color-evaporation model



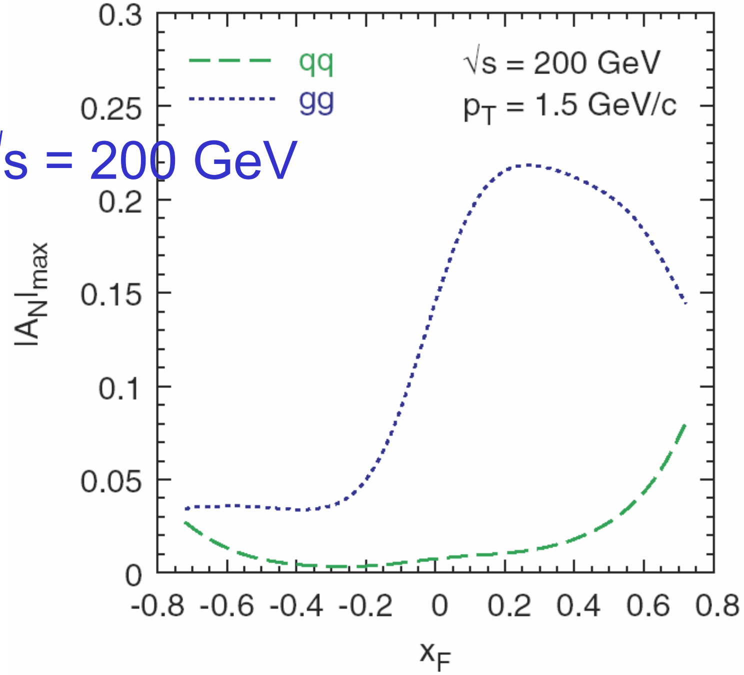
Physics at 30 GeV

- SSA measurement of open charm production
  - no single-spin transfer to the final state
  - sensitive to initial state effect: Sivers effect
  - collider energies: gluon-fusion dominant
    - sensitive to gluon Sivers effect
  - fixed-target energies: quark-pair annihilation dominant
    - sinsitive to quark Sivers effect

J-PARC: E_{lab} = 50 GeV



RHIC: √s = 200 GeV



M. Anselmino, U. D'Alesio, F. Murgia, et al.

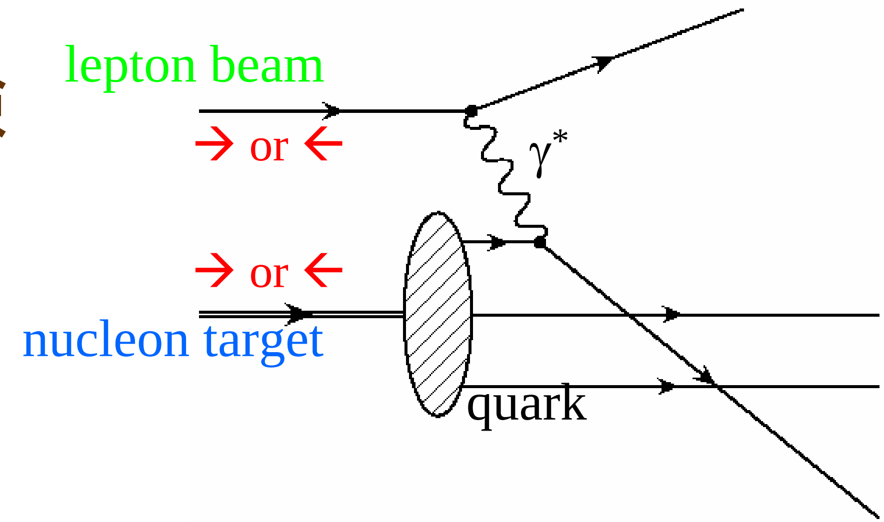
まとめ

- J-PARC dimuon 実験のスピン物理メニュー
  - 縦偏極 A_{LL} of Drell-Yan
    - sea-quark 偏極のフレーバー非対称性
  - 横偏極 A_N of Drell-Yan
    - Sivers関数（$\sin(\phi-\phi_S)$ term）
    - transversity分布関数 & Boer-Mulders関数（$\sin(\phi+\phi_S)$ term）
  - 横偏極 A_{TT} of Drell-Yan
    - transversity分布関数
  - その他（30-GeV）
    - J/Ψ: Drell-Yan と同様のメニュー?
    - A_N of open charm: Sivers関数
    - (neutron-tagged Drell-Yan)

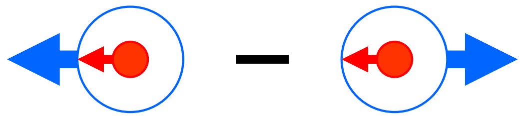
Backup Slides

核子スピン1/2の起源？

- 偏極レプトン深非弾性散乱実験
  - パートン模型



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



$$S_{\gamma} + S_{N} = 1/2 \qquad\qquad S_{\gamma} + S_{N} = 3/2$$

$$\sigma^{T}_{1/2} \sim \sum_i e_i^2 q^{+}(x) \qquad\qquad \sigma^{T}_{3/2} \sim \sum_i e_i^2 q^{-}(x)$$

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

偏極構造関数 ($g_1(x)$)

非偏極構造関数 ($F_1(x)$)

核子スピン1/2の起源？

- 偏極レプトン深非弾性散乱実験

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

more correctly

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

  - 実験データ

$$A = \frac{1}{P_T P_B} \frac{N_{++} - N_{+-}}{N_{++} + N_{+-}} = D(A_1 + \eta A_2) \sim DA_1$$

P_T target polarization

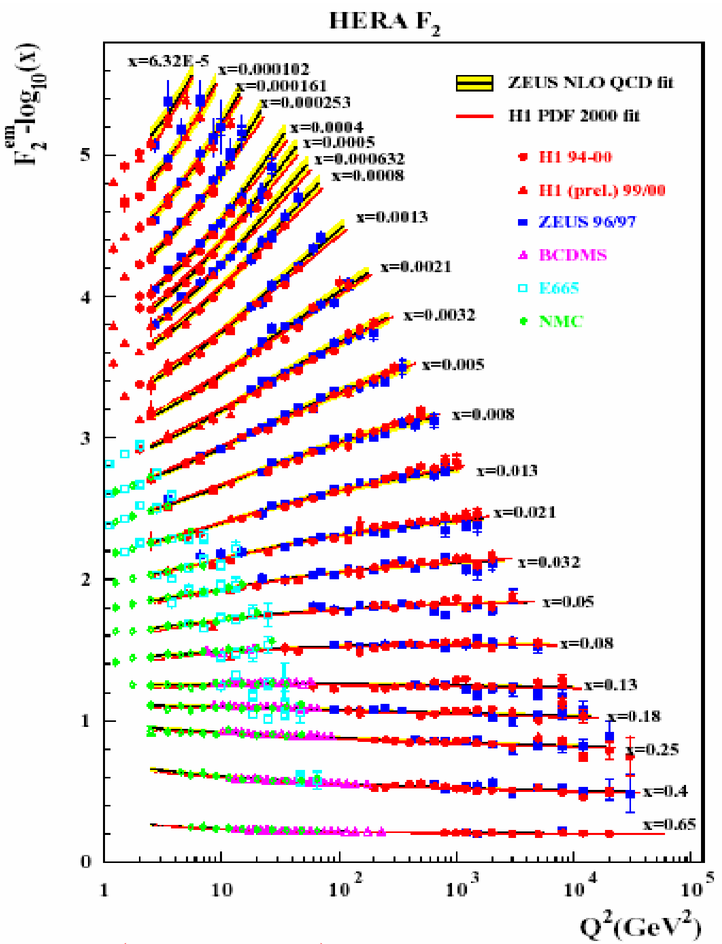
P_B beam polarization

D depolarization factor

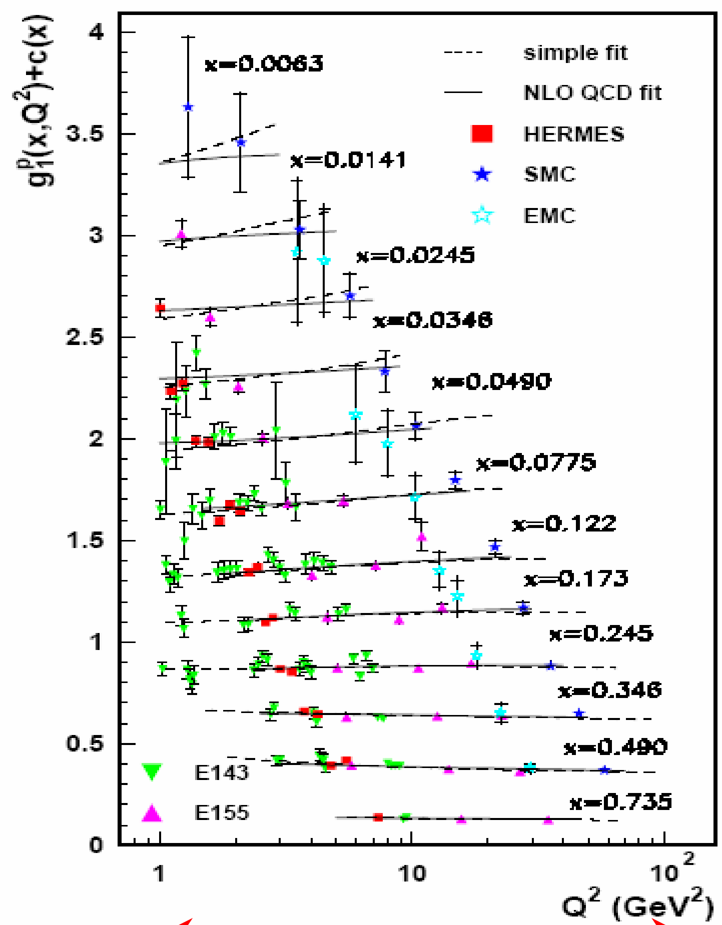
偏極レプトン深非弾性散乱実験

- 固定ターゲット実験
  - Q^2の範囲が限られている

unpolarized DIS



polarized DIS



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

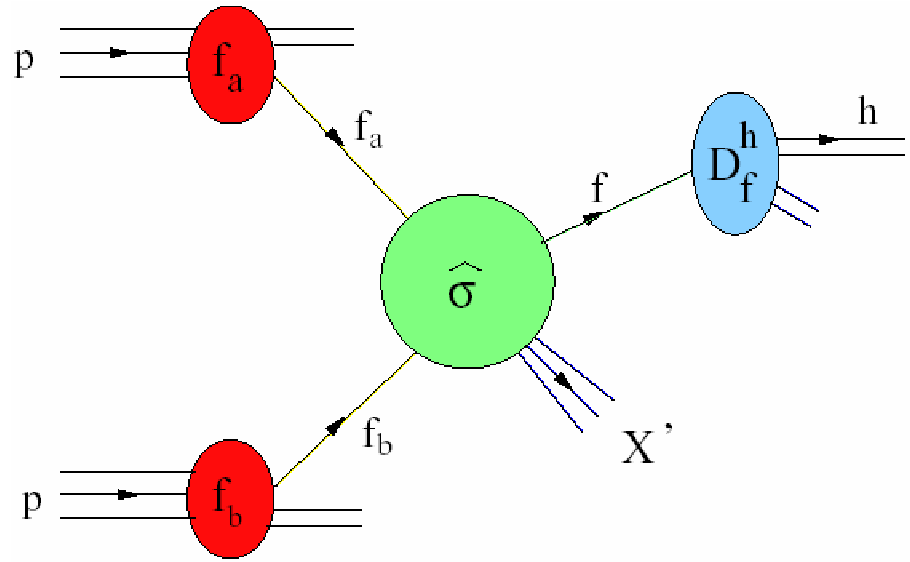
$1 < Q^2 < 100$ (GeV/c)^2

縦偏極の実験

- クォークスピンとグルーオンスピンの寄与の測定
  - QCD collinear factorization
  - Q^2 evolution
  - global analysis

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)	long distance term
$D_c^h(z_c,\mu)$	fragmentation function (FF)	
$d\hat{\sigma}_{ab}^c(x_a P_A, x_b P_B, P_h / z_c, \mu)$	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

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

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 QCD analysis

- framework to combine various experimental data into a systematically controlled extraction of the unpol. & pol. PDFs, FFs
  - experimental data $a^{\text{data}}(x, Q^2)$ with experimental errors $\delta a^{\text{data}}(x, Q^2)$
  - 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 $a^{\text{calc}}(x, Q^2)$
  - χ^2 analysis (minimization)

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

  - 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

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

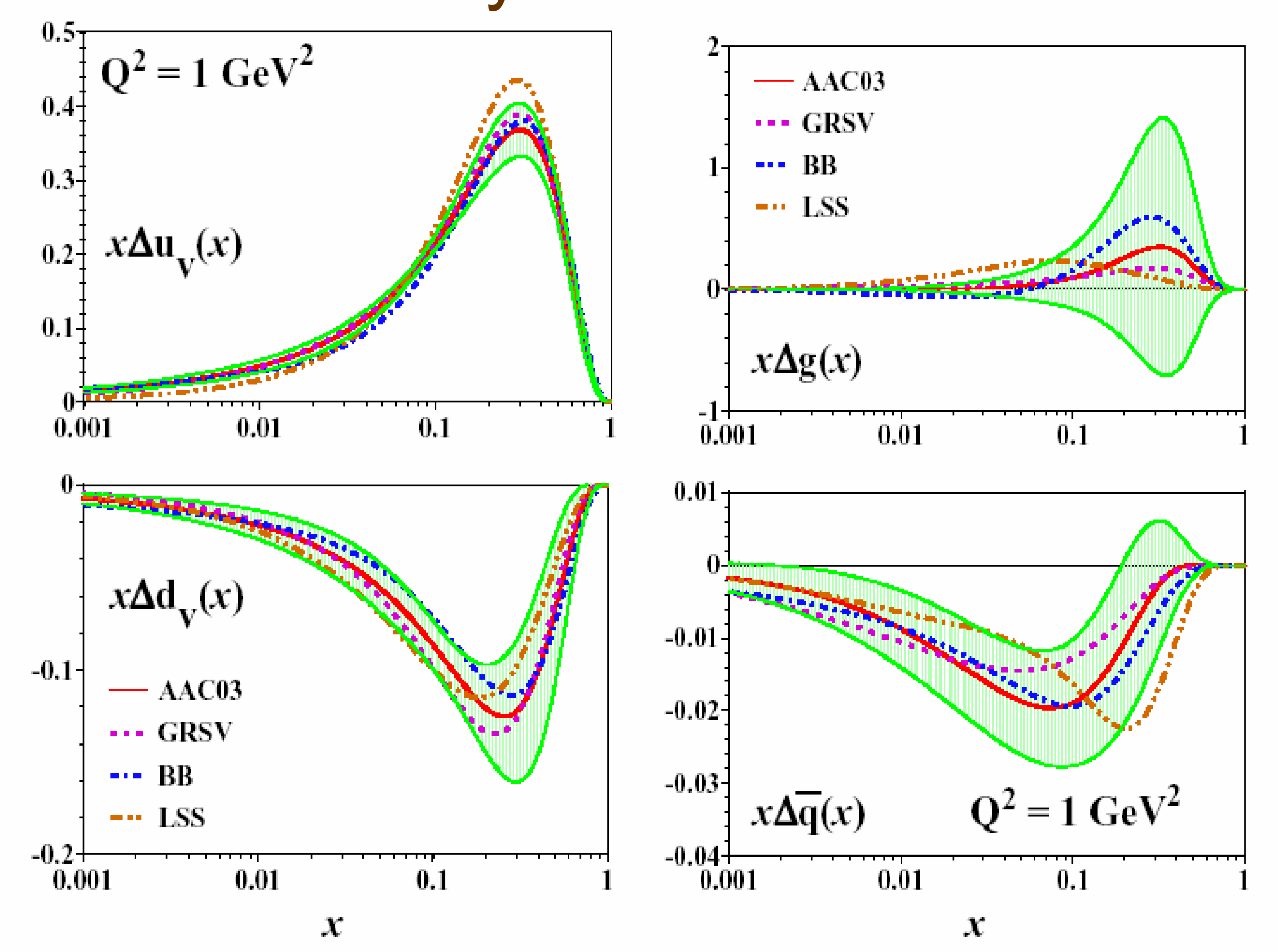
$\Delta f(x),\ f = u_v, d_v, g, \bar{q}$ polarized PDFs

$f(x)$ 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

グルーオンスピンの寄与

- 偏極深非弾性散乱実験のスケール則の破れ
  - 摂動QCDの発展方程式の重要な成功
  - Q^2の範囲が限られている

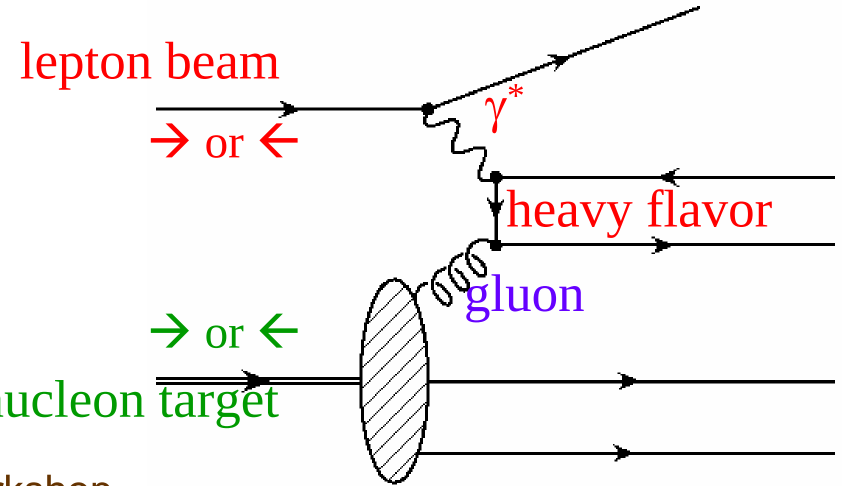
$$\text{SMC}:\ \Delta g(Q^2 = 1\,\text{GeV}^2) = 0.99^{+1.17}_{-0.31}(\text{stat})^{+0.42}_{-0.22}(\text{syst})^{+1.43}_{-0.45}(\text{th})$$

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

$$\text{E155}:\ \Delta g(Q^2 = 5\,\text{GeV}^2) = 1.6 \pm 0.8(\text{stat}) \pm 1.1(\text{syst})$$

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

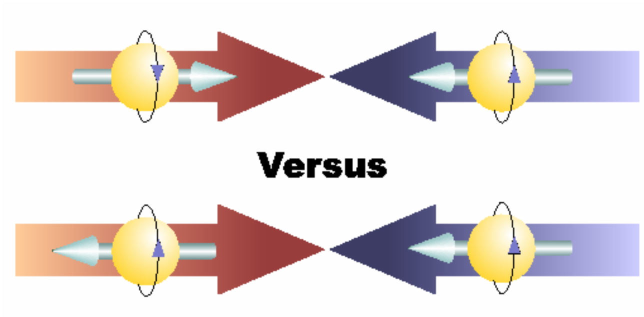
- semi-inclusive 深非弾性散乱実験
  - 高いp_Tのハドロン対生成
  - オープンチャーム生成



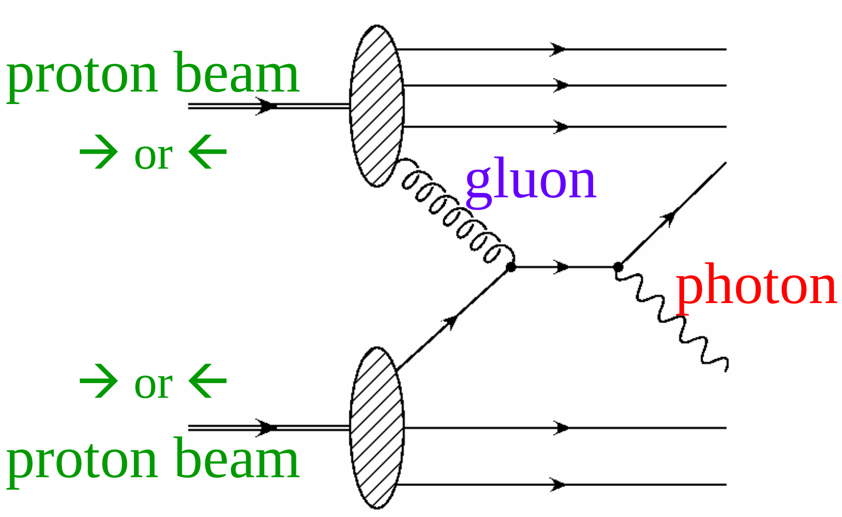
グルーオンスピンの寄与

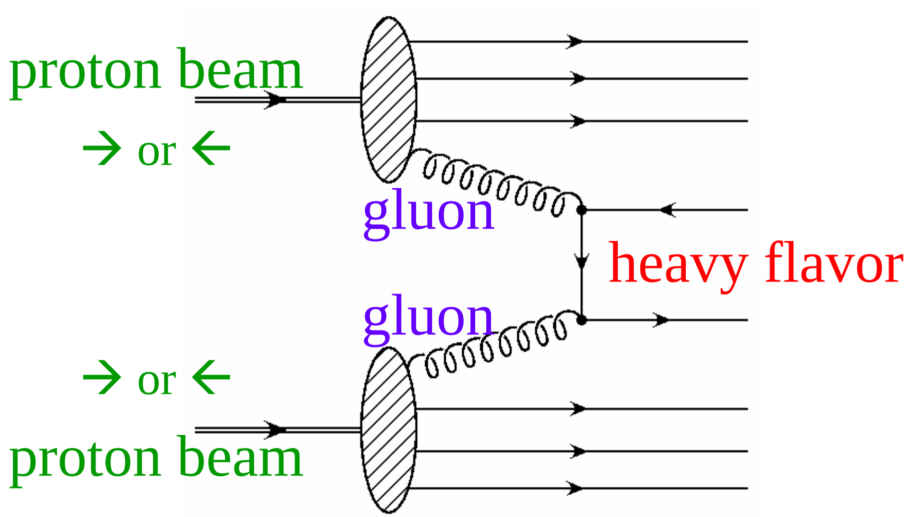
- 偏極ハドロン衝突実験
  - double helicity asymmetry

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



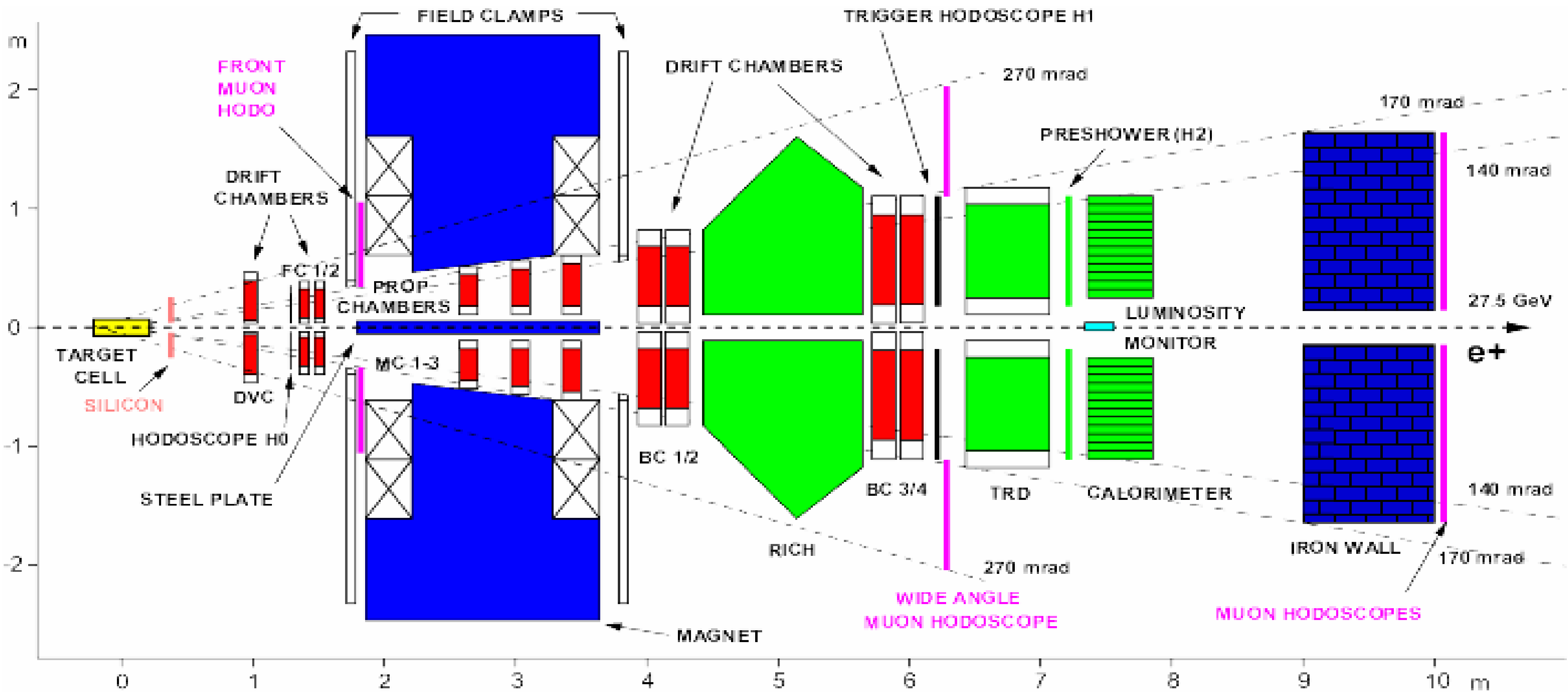
  - leading-order グルーオン測定
    - 光子の直接生成
    - 重いフレーバー生成





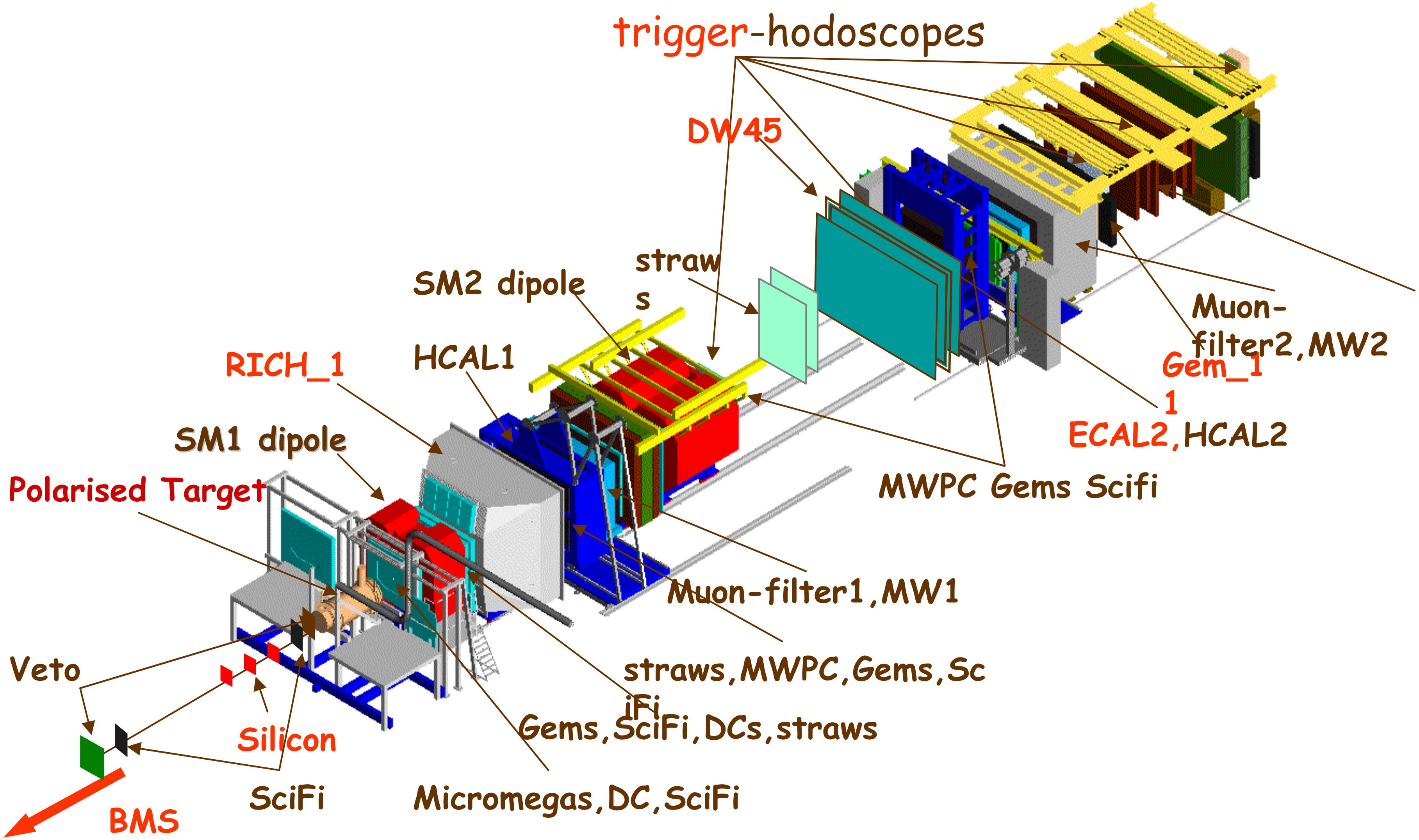
HERMES @ DESY

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



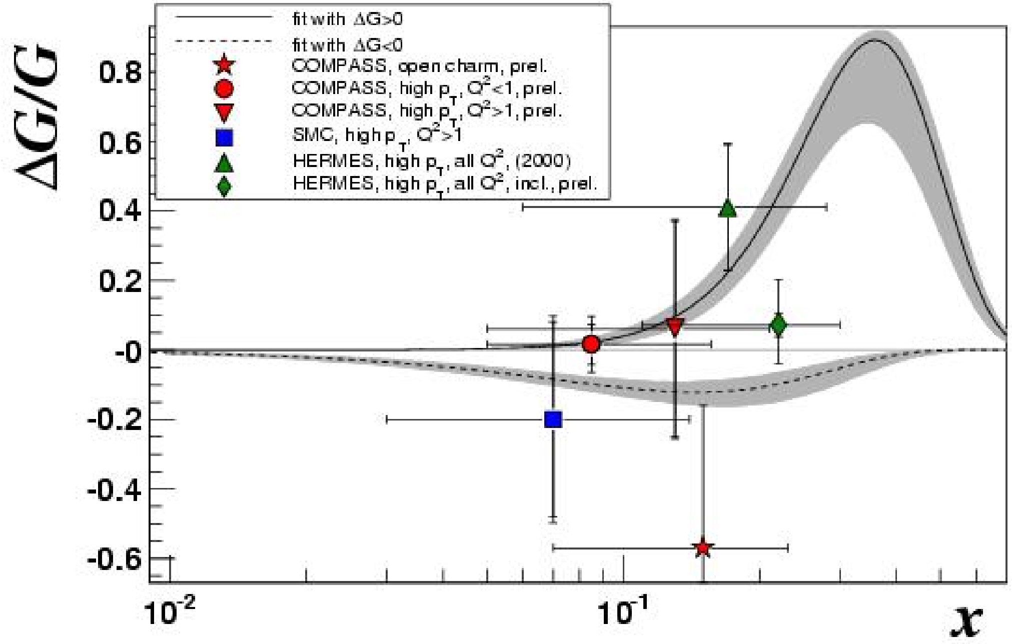
COMPASS @ CERN

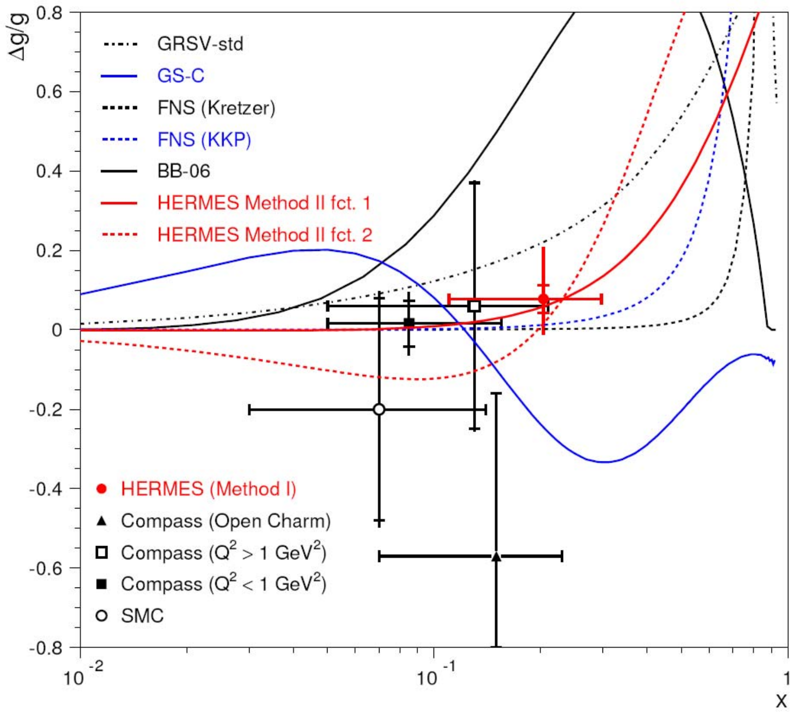
- semi-inclusive DIS
  - polarized ^{6}LiD target: polarization ~50%
  - μ^+ beam: 160 GeV, polarization ~80%

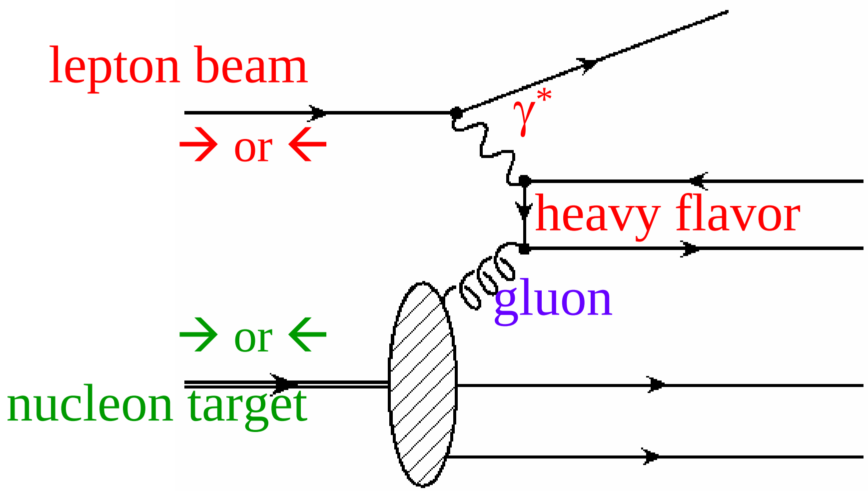


グルーオンスピンの寄与

- semi-inclusive
  深非弾性散乱実験
  - HERMES@DESY
    - 高p_Tハドロン対生成
  - SMC@CERN
    - 高p_Tハドロン対生成
  - COMPASS@CERN
    - 高p_Tハドロン対生成
    - オープンチャーム生成

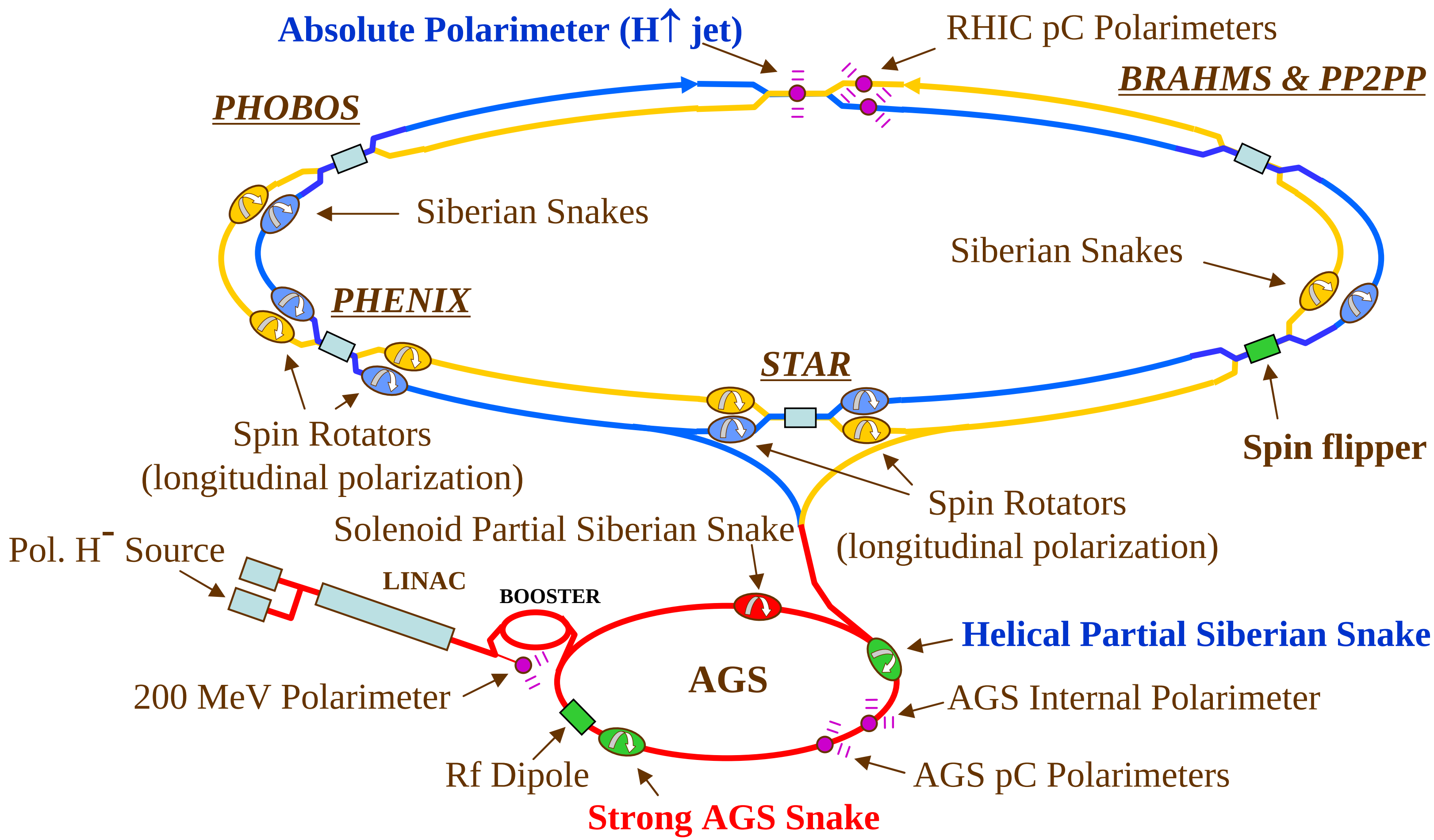




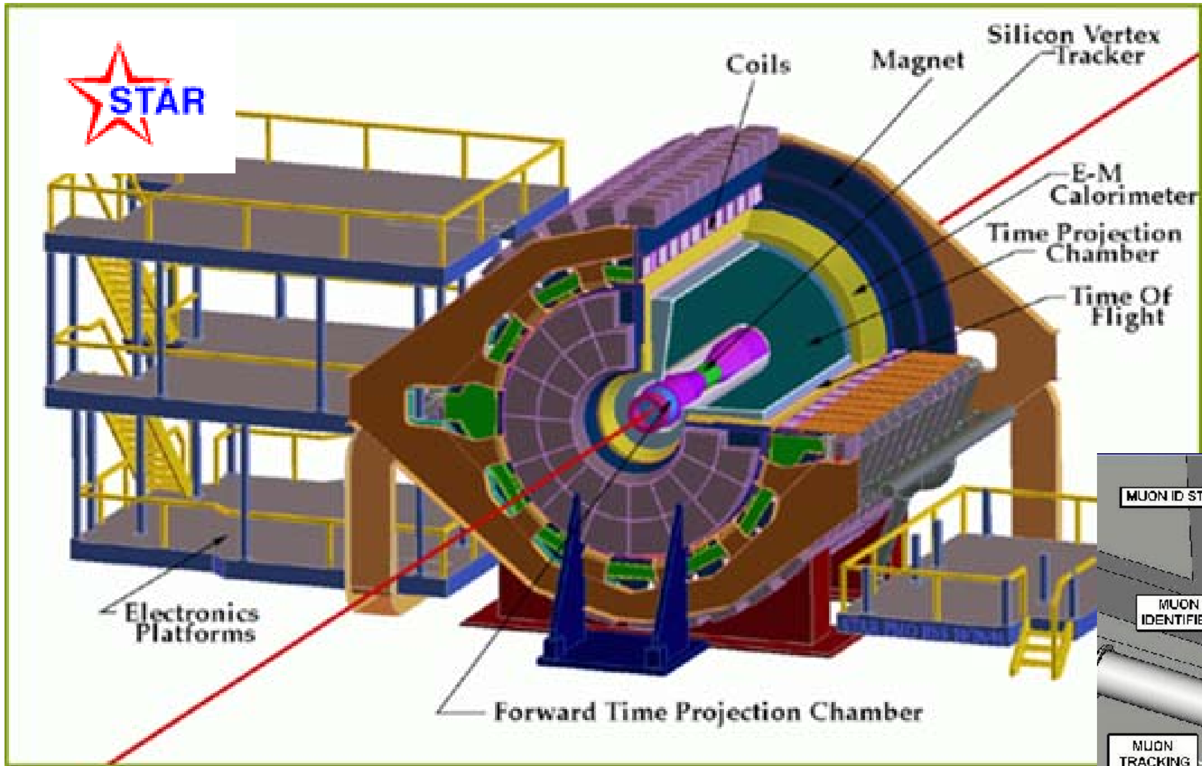


RHICスピン計画@BNL

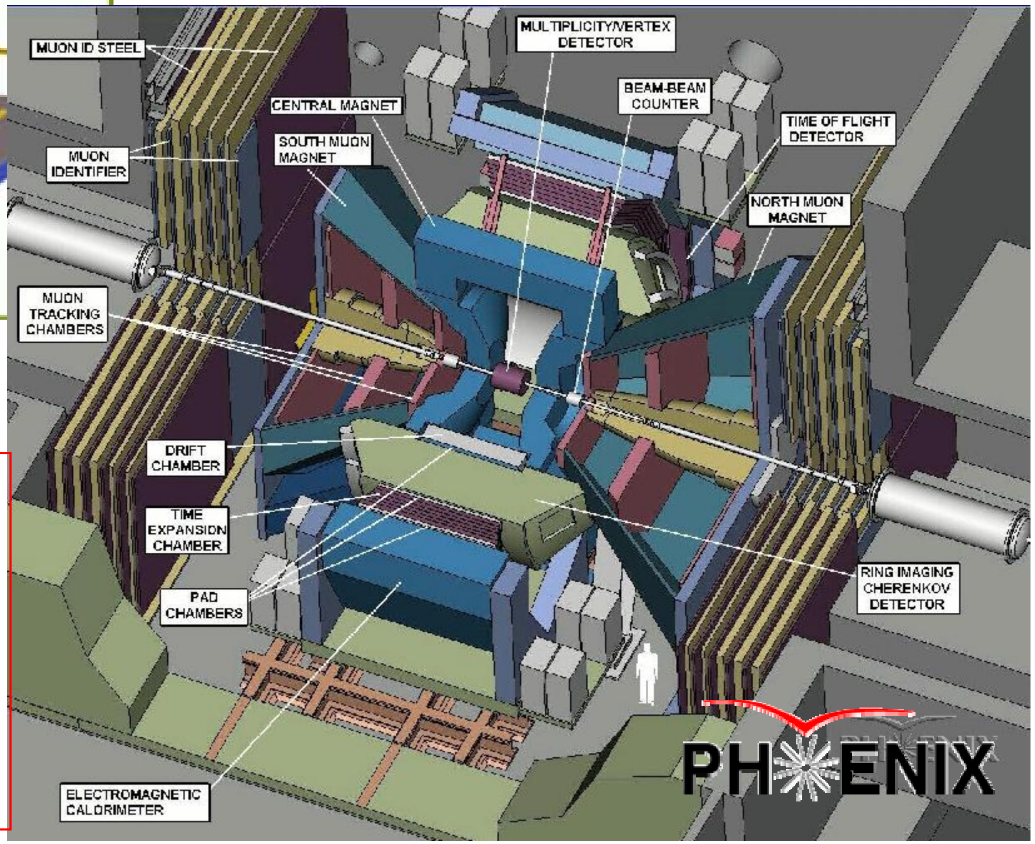
- 偏極陽子衝突型加速器
  - エネルギー 200 GeV (将来は 500 GeV)
  - 偏極度60%以上 (目標は70%)



STAR and PHENIX @ BNL



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

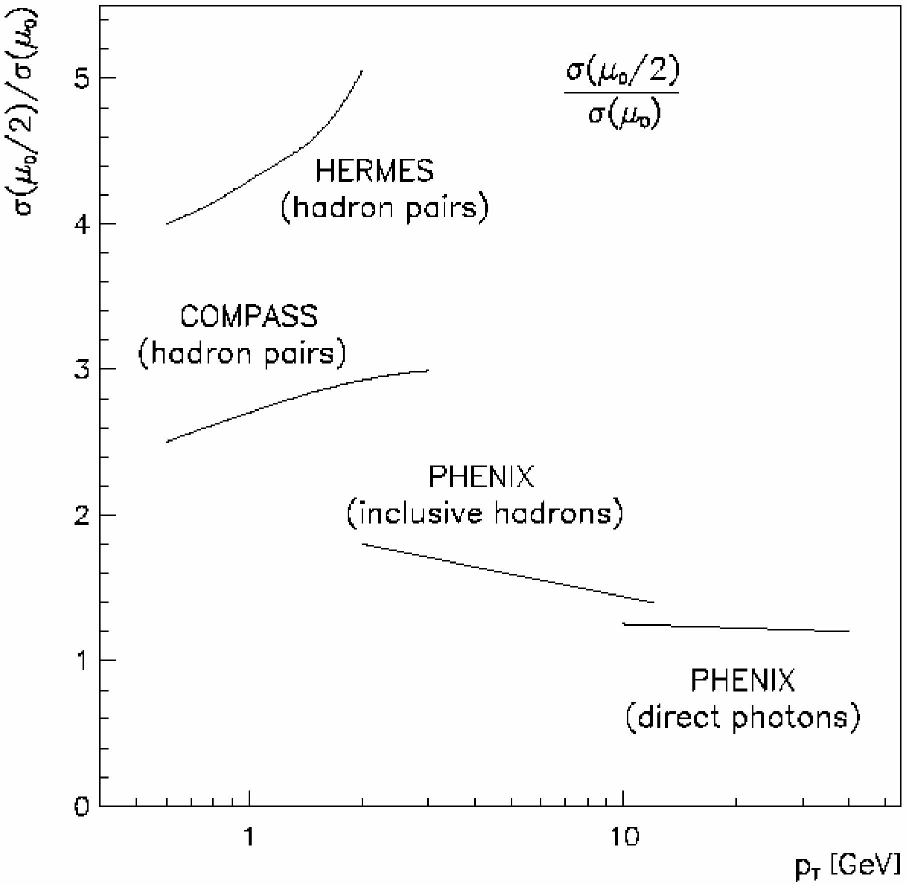


- PHENIX detector
  - limited acceptance
  - high resolution central EMCal
  - high-rate trigger and DAQ
  - forward muon detectors

生成断面積測定

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

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



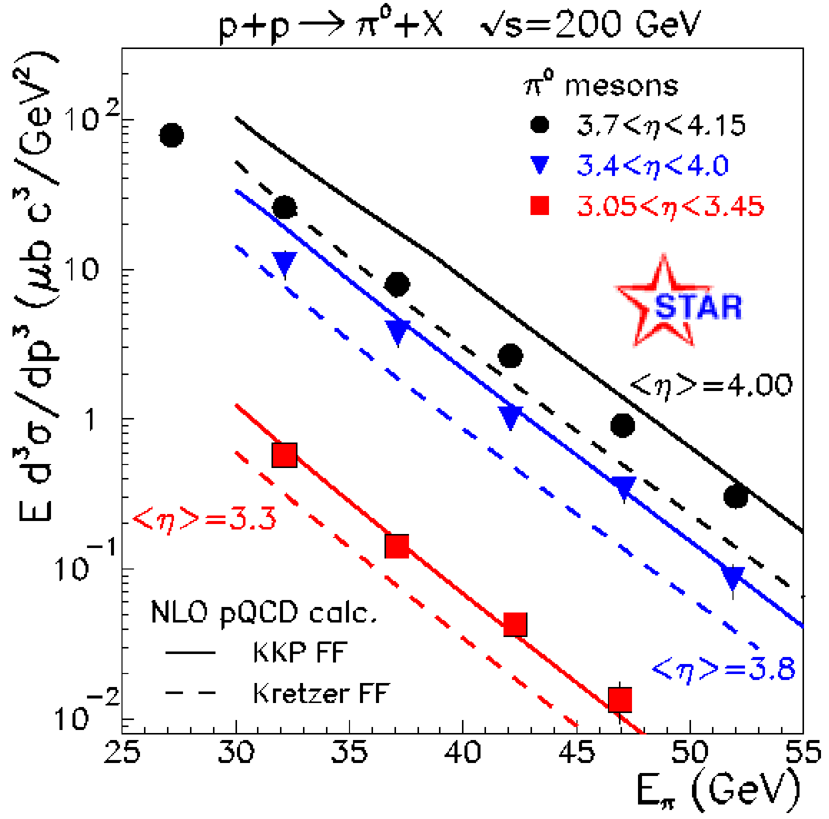
p_T (GeV/c)

M. Stratmann and W. Vogelsang

生成断面積測定

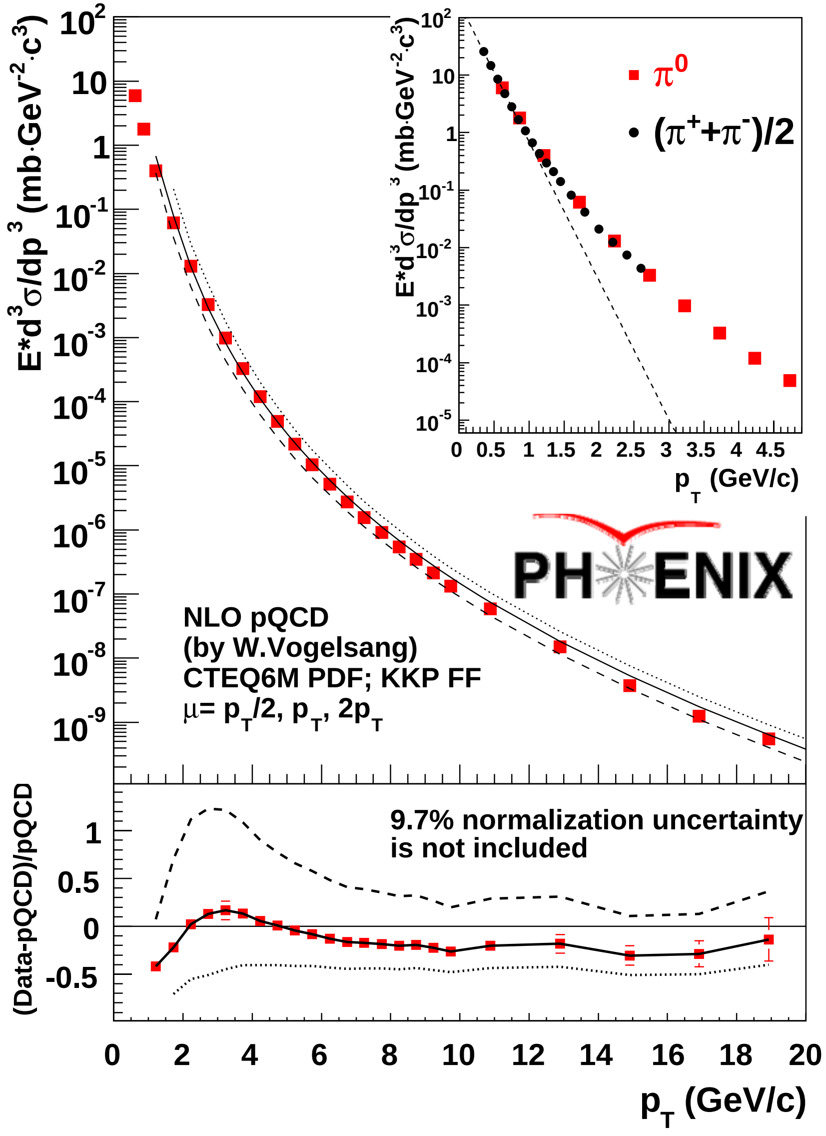
- comparison of π^0 cross section between data and NLO perturbative-QCD calculations
- agreement is excellent down even to $p_T \sim 1$ GeV/c

forward rapidity



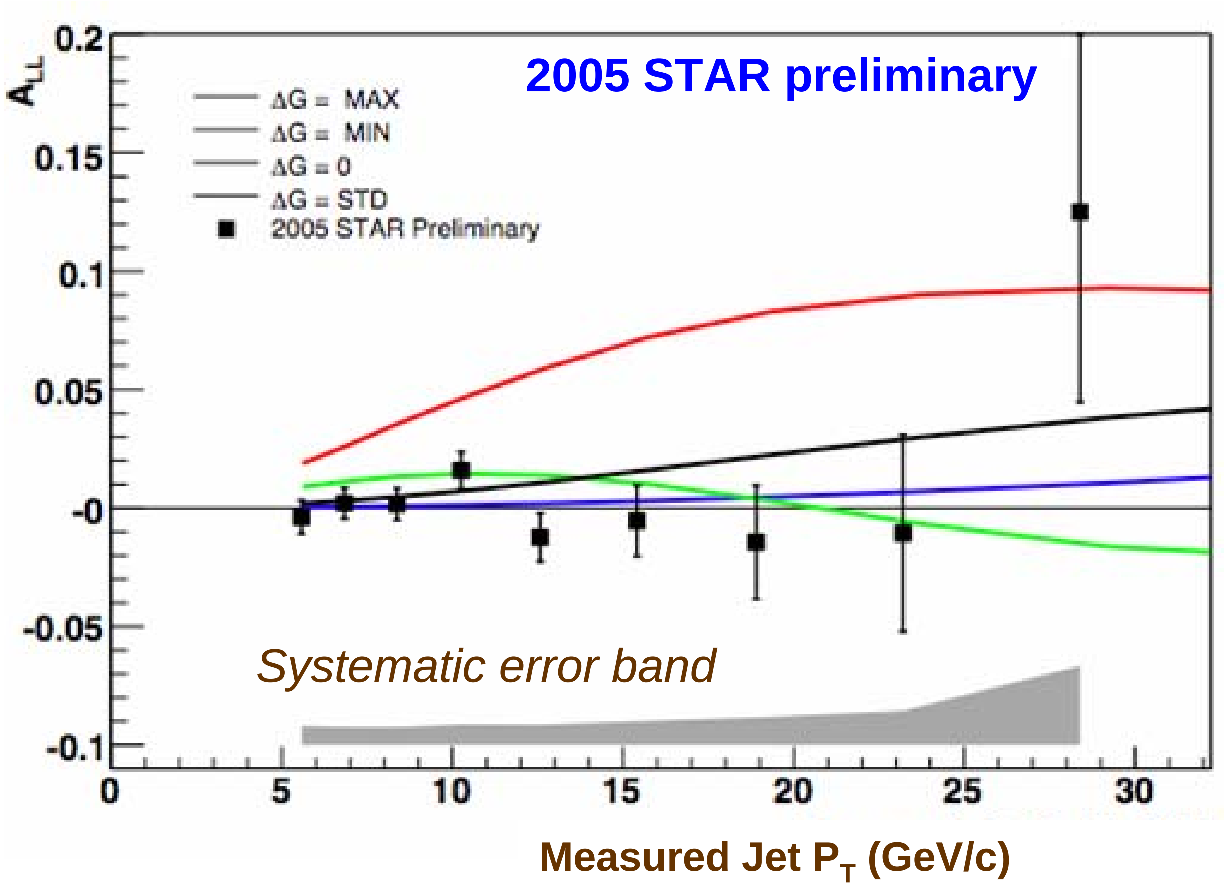
$\sqrt{s} = 200$ GeV

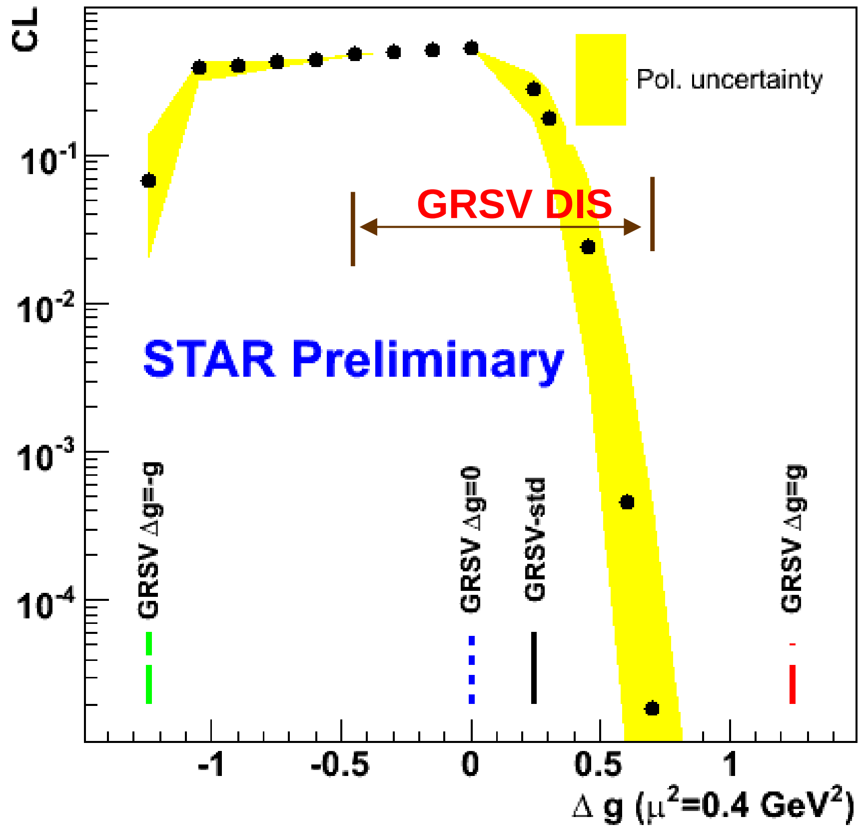
mid-rapidity



グルーオンスピンの寄与

- STAR A_{LL} of jet

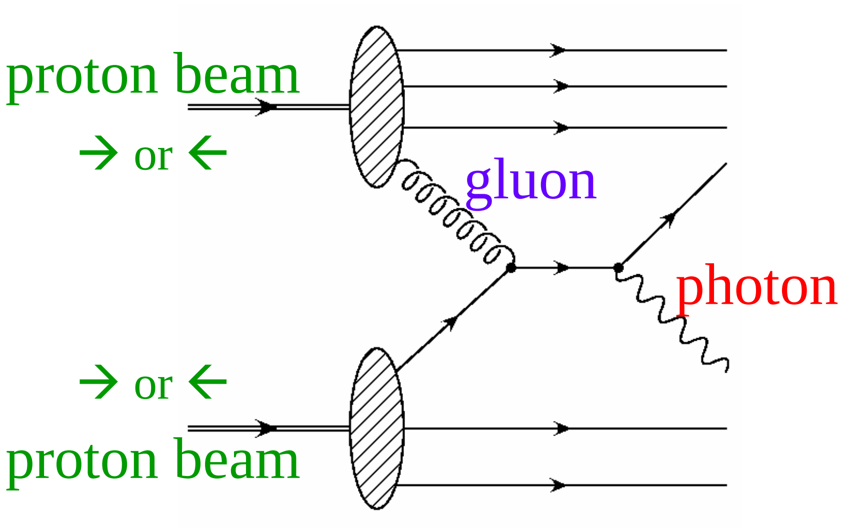


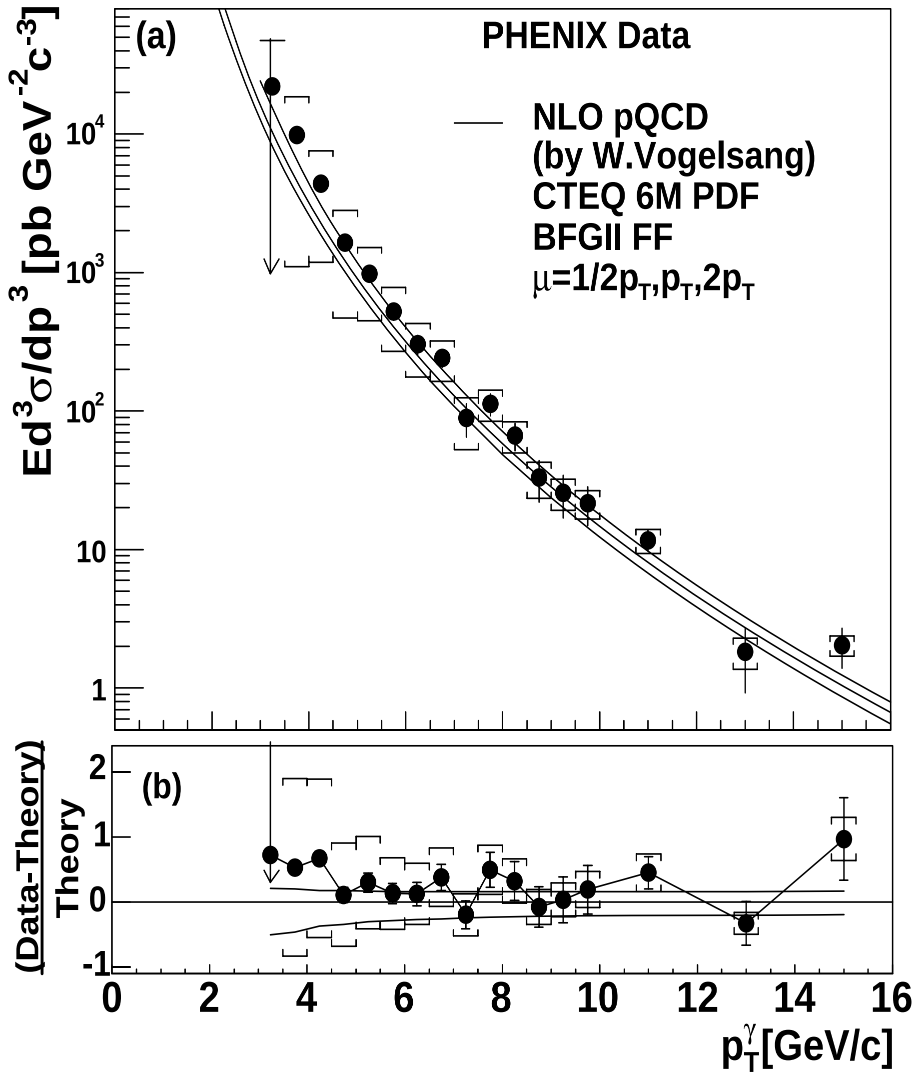


グルーオンスピンの寄与

- 直接生成光子
  - mid-rapidity $|\eta| < 0.35$, $\sqrt{s} = 200$ GeV
  - gluon compton process dominant ~75%

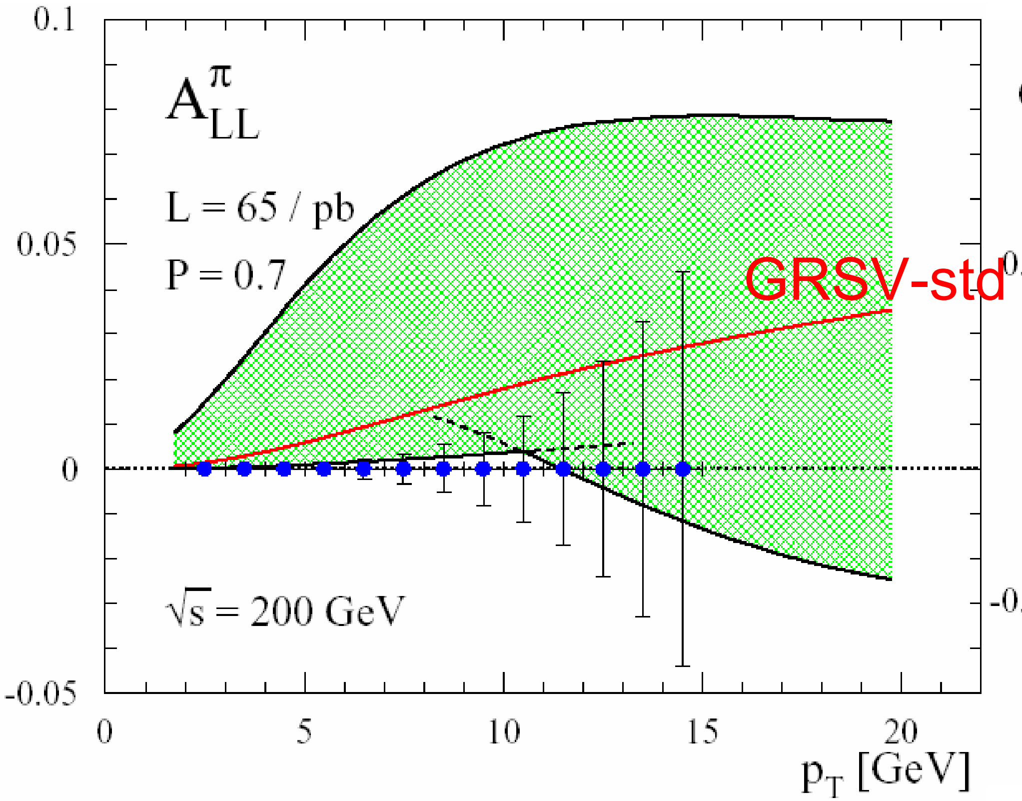
$$A_{LL}(p_T) = \frac{\Delta g(x_g)}{g(x_g)} \cdot A_1^p(x_q) \cdot \hat{a}_{LL}$$

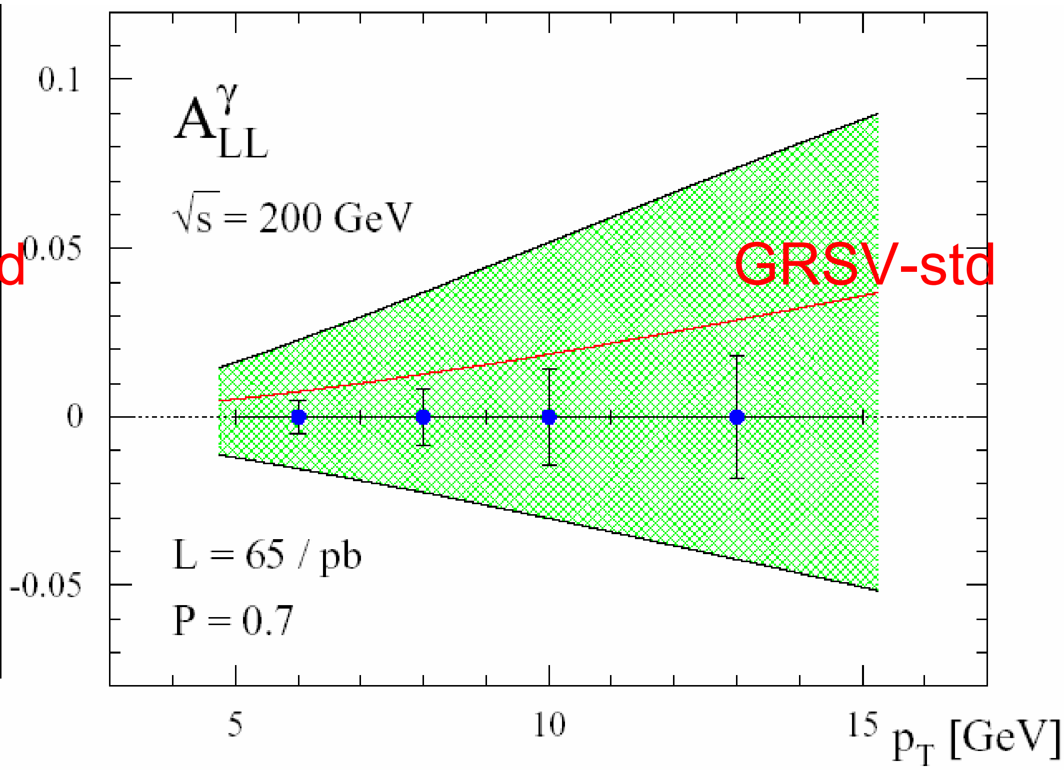




Gluon polarization

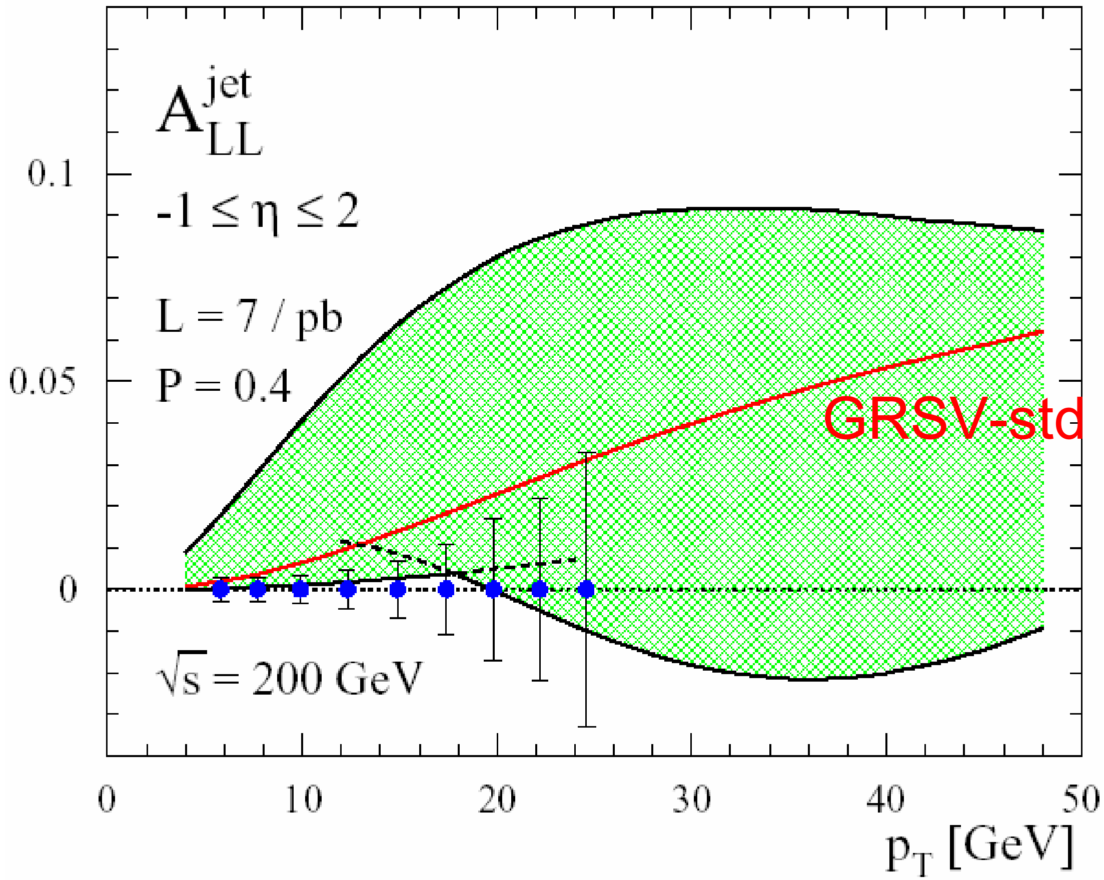
- A_{LL} projection
  - π^0 and direct photon at PHENIX
    - mid-rapidity $|\eta| < 0.35$, $\sqrt{s}$ = 200 GeV
    - 2005 – 2009 runs





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

クォーク偏極のフレーバー依存

- various quark and antiquark polarization individually

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

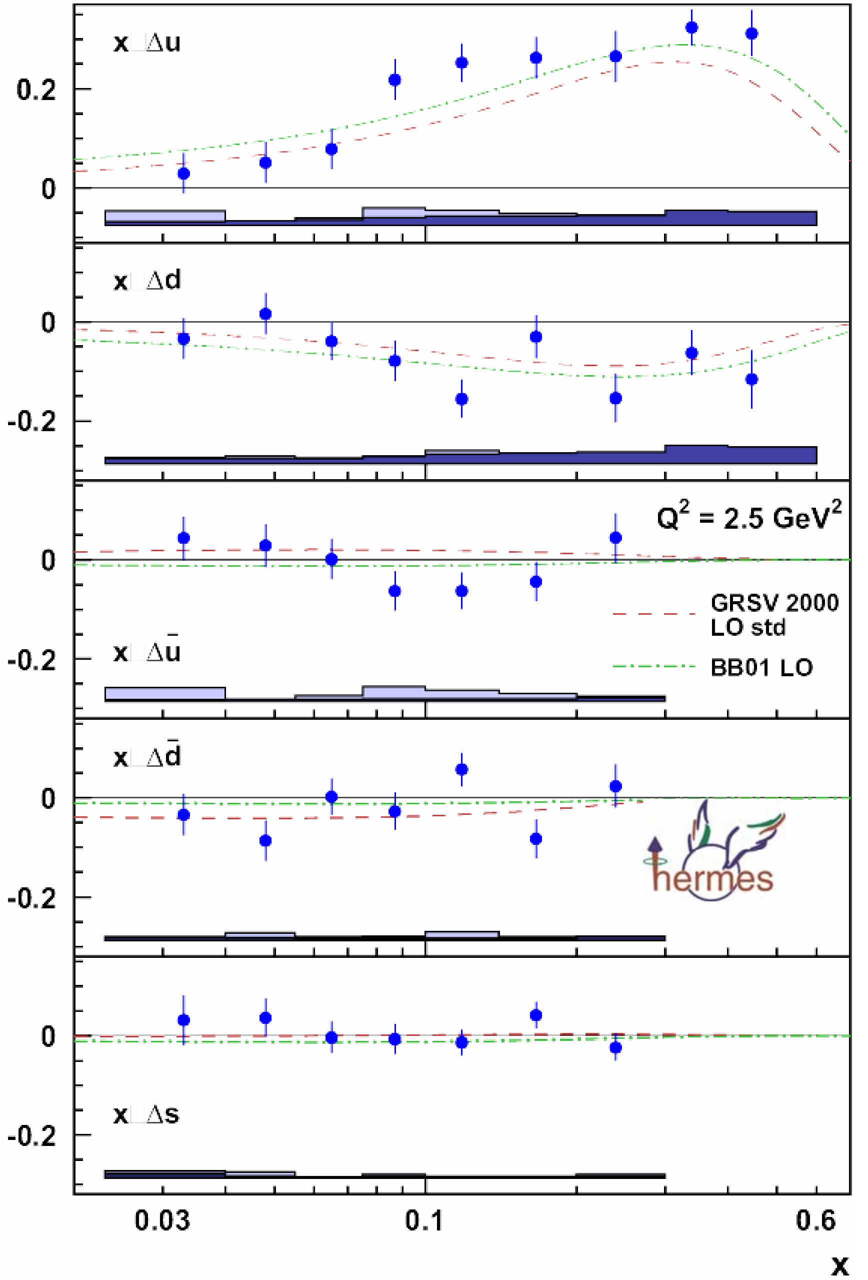
  – reduction of uncertainties to determine the quak spin contribution ΔΣ and gluon spin contribution ΔG to the proton spin

- semi-inclusive DIS
  – HERMES

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

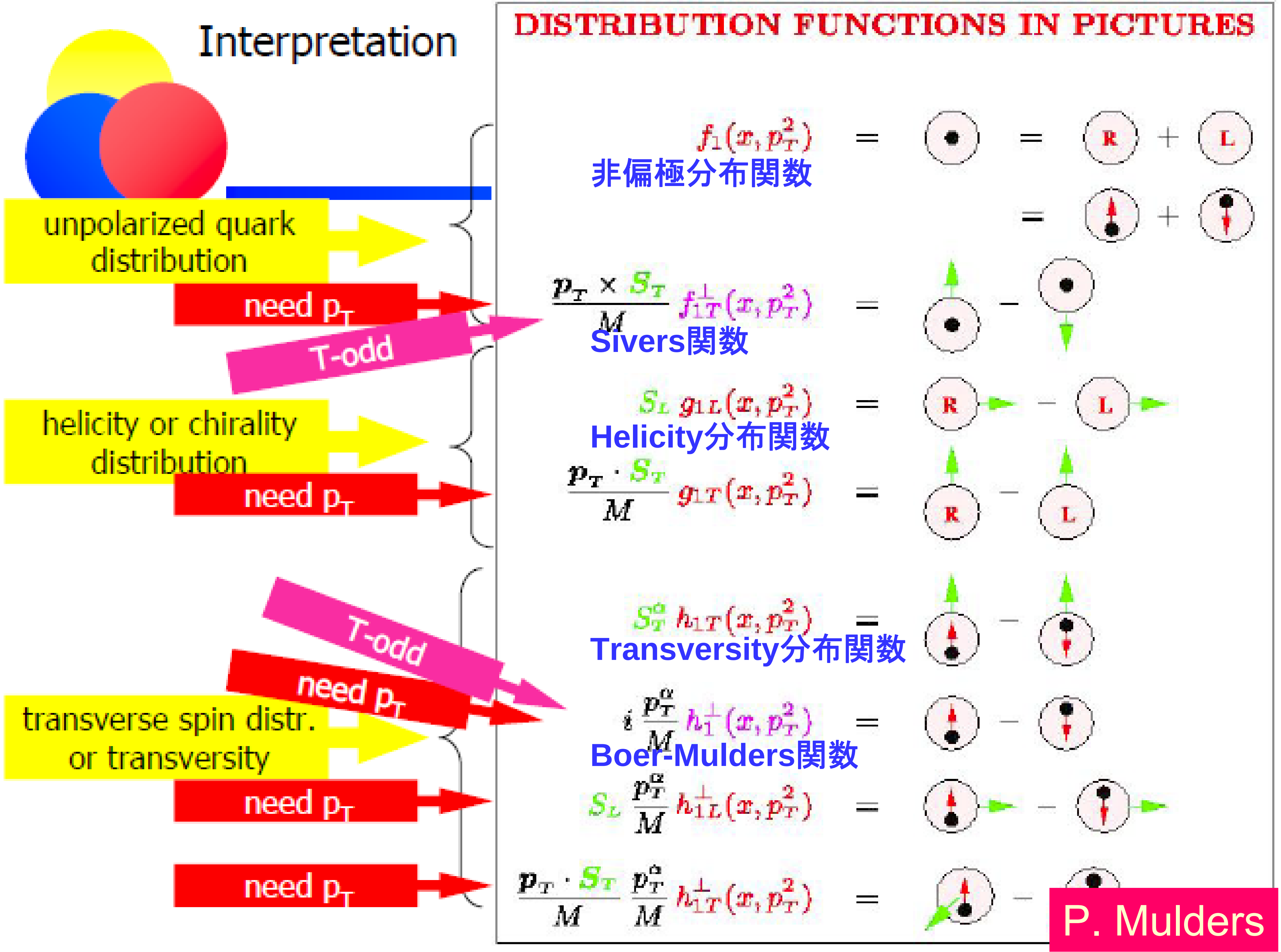
$$= \sum_i P_q^h(x,z) \Delta q_i(x)$$

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



横偏極の実験

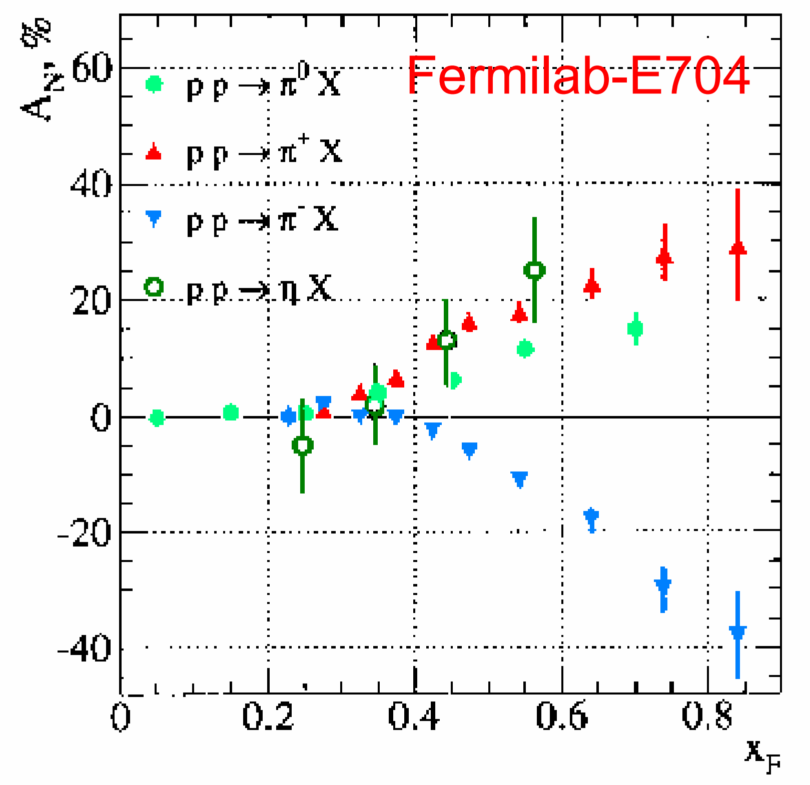
- クォークとグルーオンの軌道角運動量の寄与
  - QCDに基づく理論の開発
  - TMD (Transverse-Momentum Dependent) factorization など


Interpretation
DISTRIBUTION FUNCTIONS IN PICTURES
unpolarized quark distribution
need p_T
T-odd
helicity or chirality distribution
need p_T
T-odd
need p_T
transverse spin distr. or transversity
need p_T
need p_T
$f_1(x, p_T^2)$
非偏極分布関数
R
L
$\frac{p_T \times S_T}{M} f_{1T}^{\perp}(x, p_T^2)$
Sivers関数
$S_L\, g_{1L}(x, p_T^2)$
R
L
Helicity分布関数
$\frac{p_T \cdot S_T}{M} g_{1T}(x, p_T^2)$
R
L
$S_T^{\alpha} h_{1T}(x, p_T^2)$
Transversity分布関数
$i\frac{p_T^{\alpha}}{M} h_1^{\perp}(x, p_T^2)$
Boer-Mulders関数
$S_L \frac{p_T^{\alpha}}{M} h_{1L}^{\perp}(x, p_T^2)$
$\frac{p_T \cdot S_T}{M} \frac{p_T^{\alpha}}{M} h_{1T}^{\perp}(x, p_T^2)$
P. Mulders

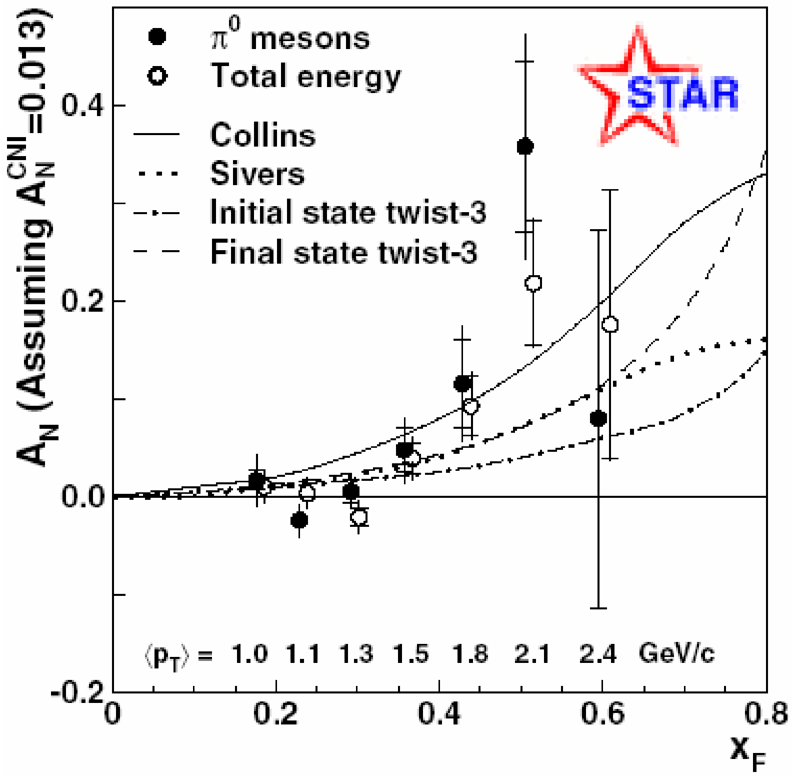
SSA (Single Spin Asymmetry) 測定

- 前方ラピディティー
  - 非対称度 ~20%
  - 多くのQCDに基づく理論の開発

√s = 19.4 GeV



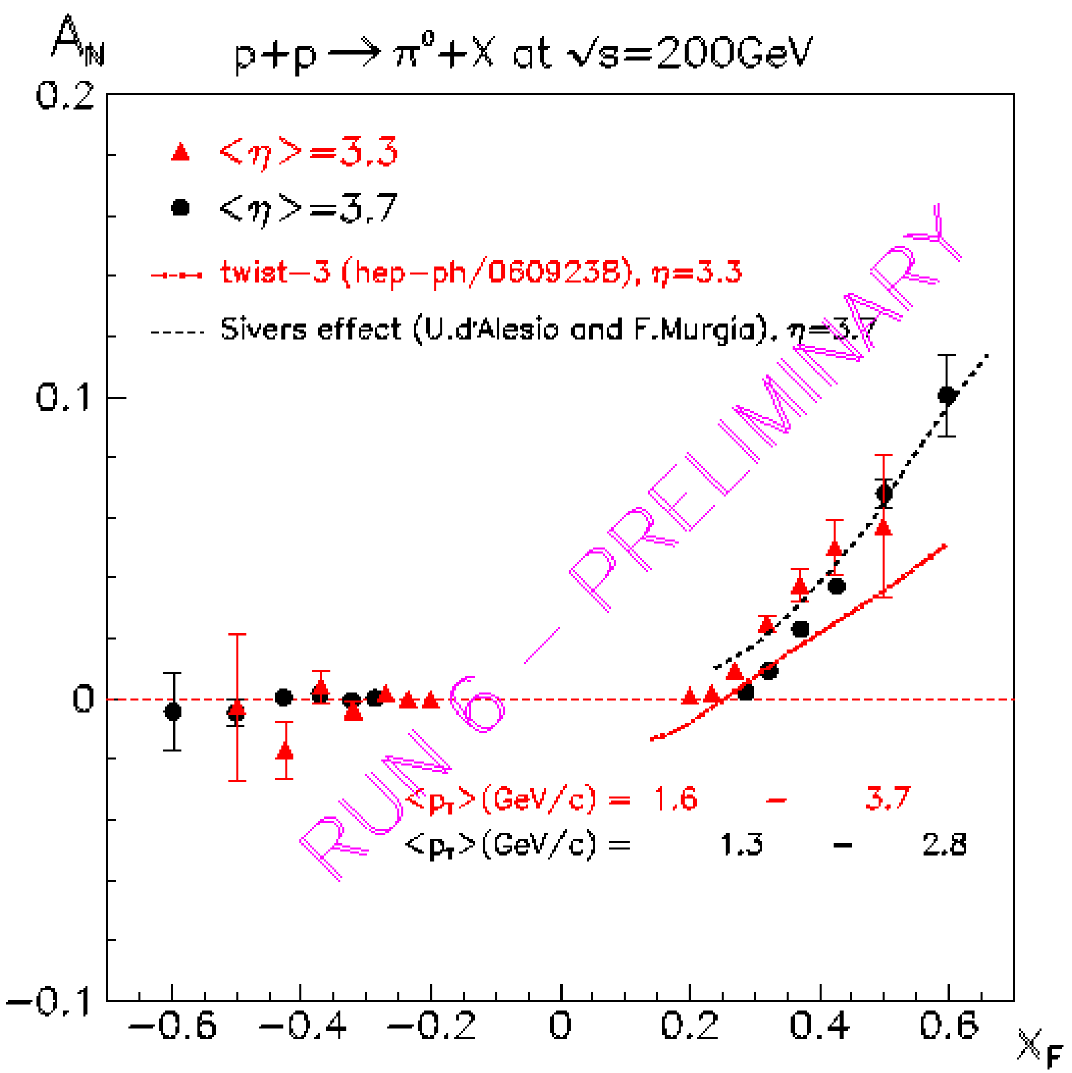
√s = 200 GeV



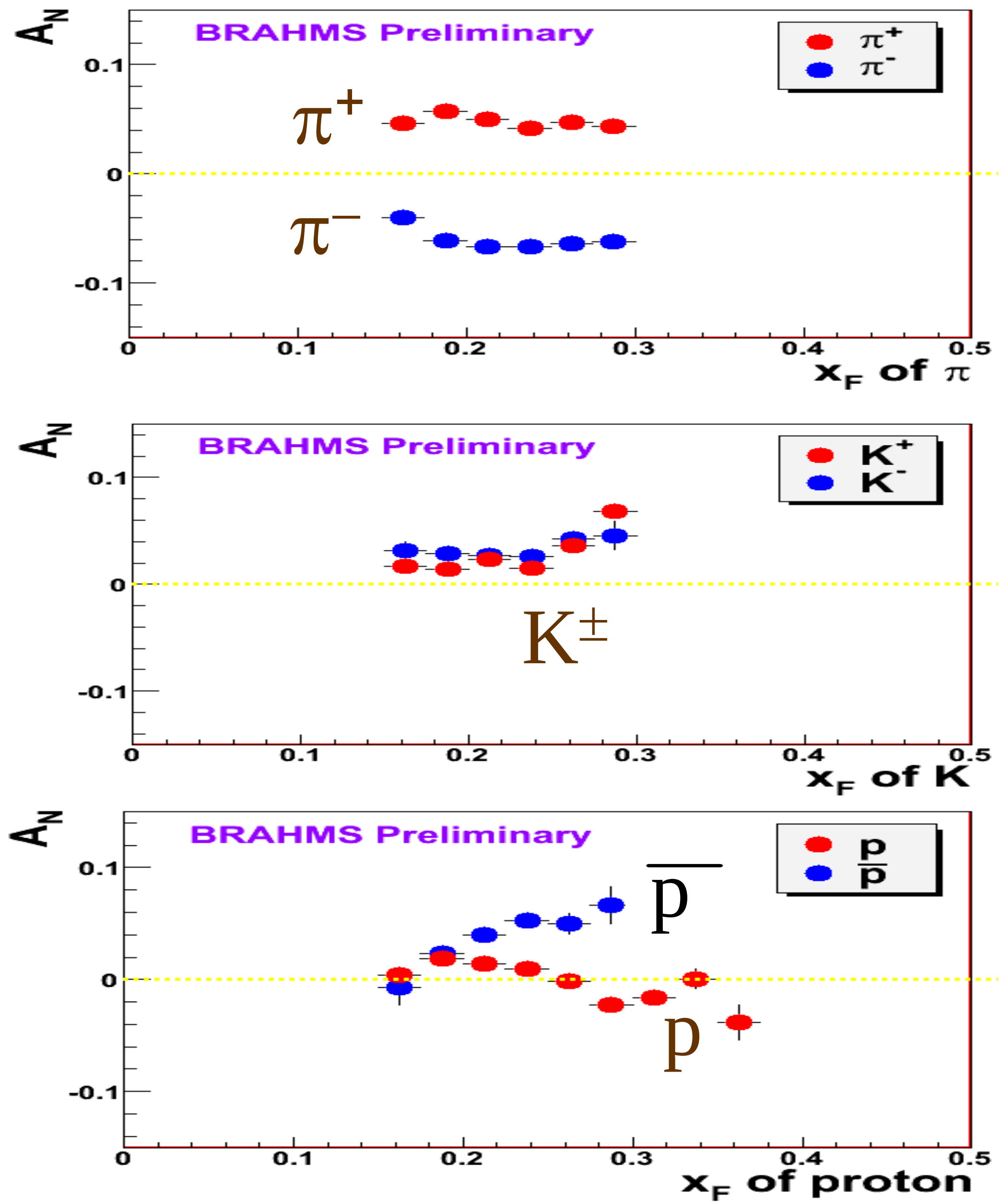
Phys.Rev.Lett. 92 (2004) 171801

前方ラピディティー

STAR

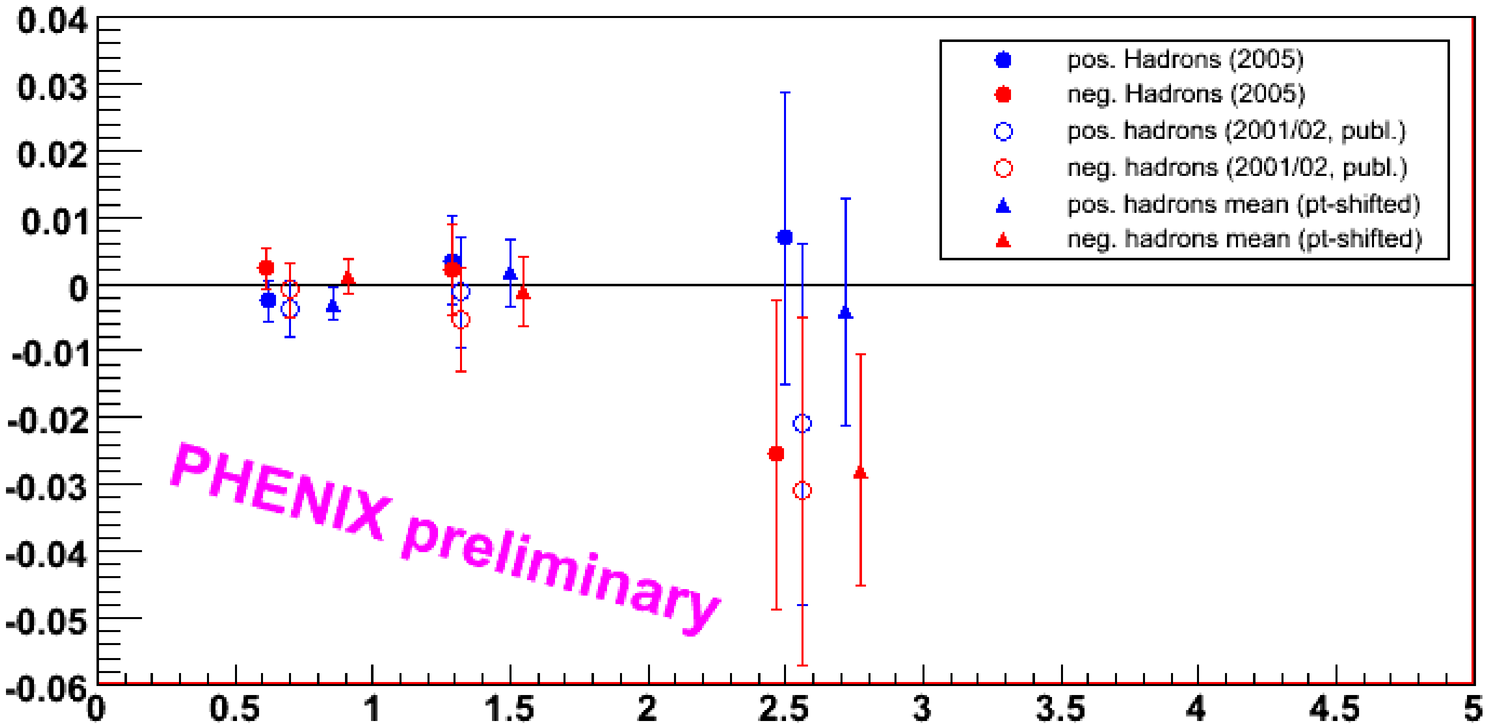


BRAHMS



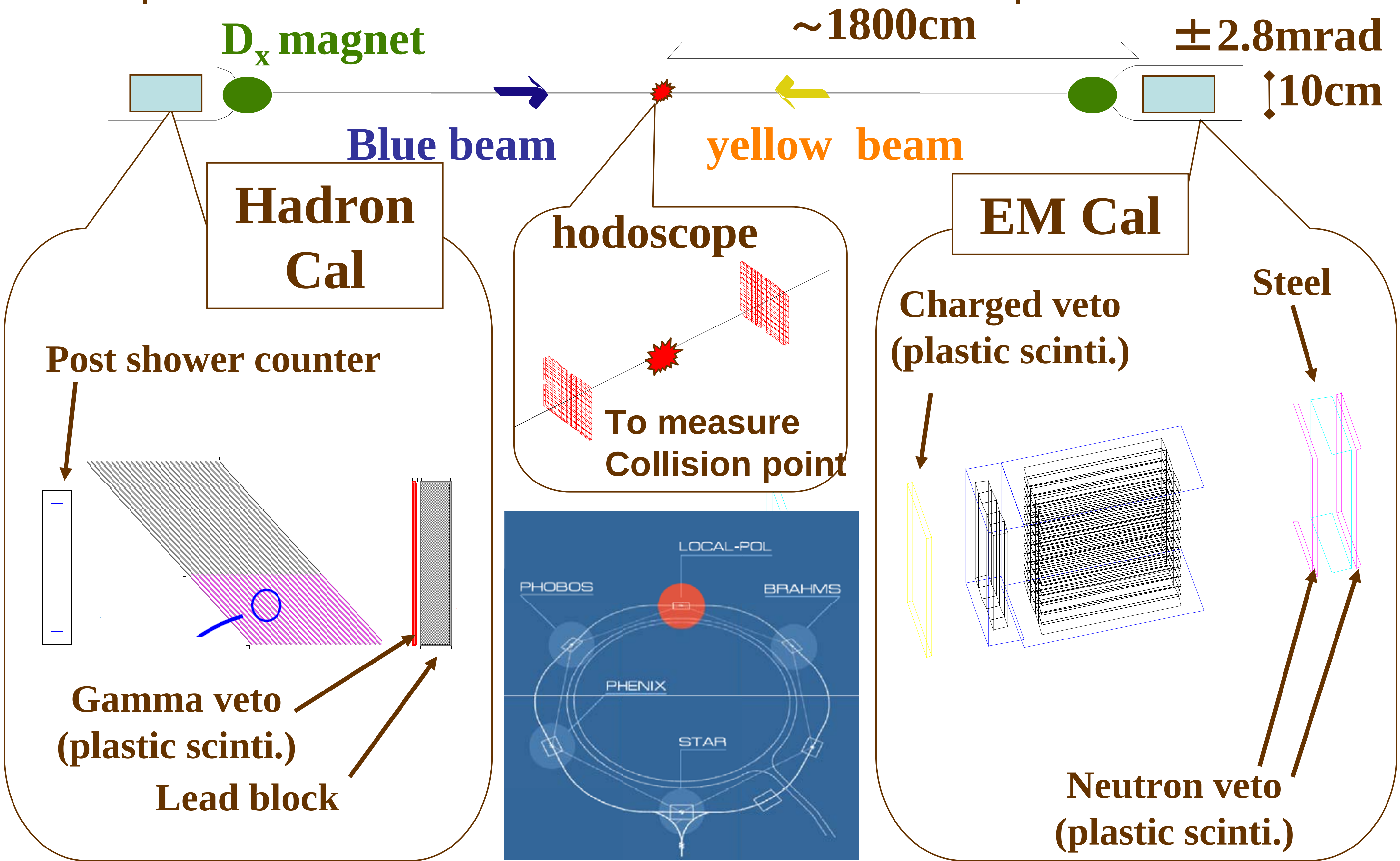
中央ラピディティー

- PHENIX
  - 異なる運動学的領域
    - contribution from both gluon-gluon and quark-gluon reactions
    - x = 0.03 – 0.1
    - small quark polarization/transversity
    - no gluon transversity in leading twist
    - negligible transversity & Collins effect contribution



中性子生成非対称度@IP12

- performed in 2001-2002 with √s = 200 GeV polarized proton collisions at the 12 o'clock collision point



中性子生成非対称度@IP12

- Phys. Lett. B 650 (2007) 325.

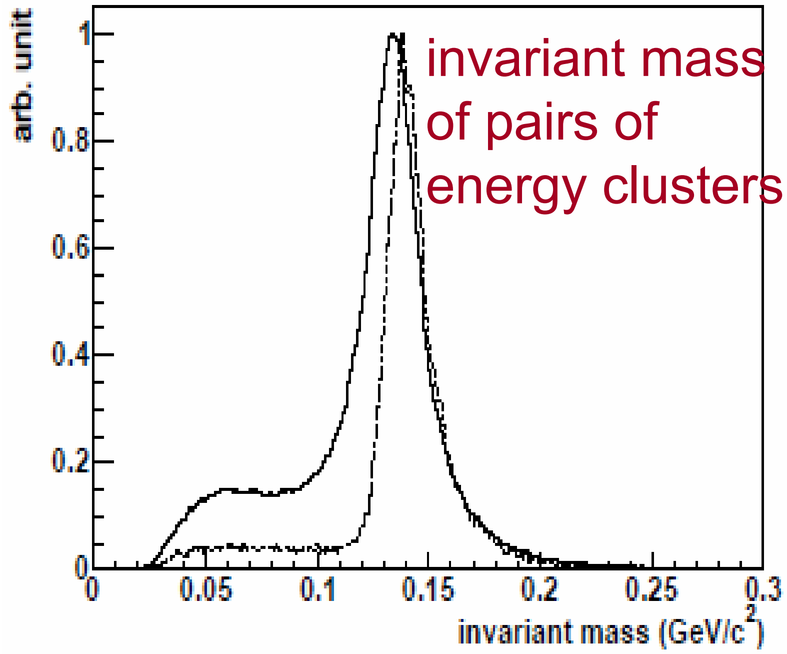


FIG. 3: Invariant mass of pairs of energy clusters in the EMCal, for 444K events with no additional selection requirements (solid) and for 35K events with photon identification (dashed).

$$A(\phi) = \frac{1}{P_B}\frac{\sqrt{N_{\uparrow,\phi}N_{\downarrow,\phi+\pi}} - \sqrt{N_{\uparrow,\phi+\pi}N_{\downarrow,\phi}}}{\sqrt{N_{\uparrow,\phi}N_{\downarrow,\phi+\pi}} + \sqrt{N_{\uparrow,\phi+\pi}N_{\downarrow,\phi}}}$$

$$= A_N \sin(\phi - \phi_0)$$

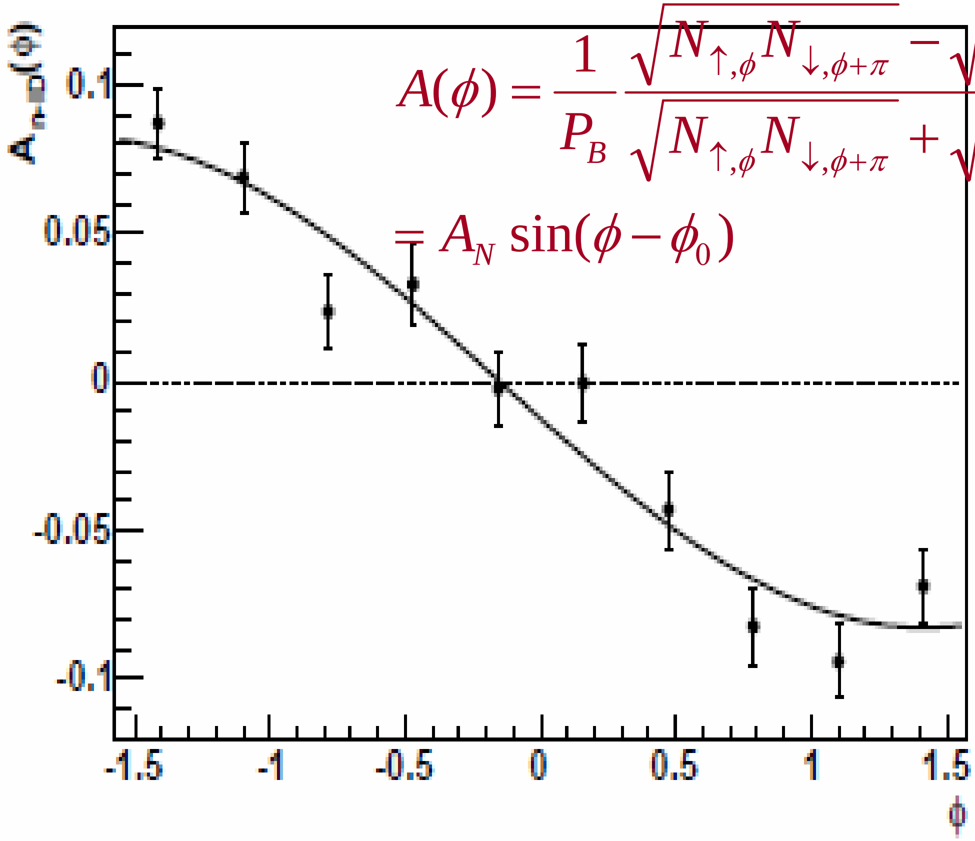
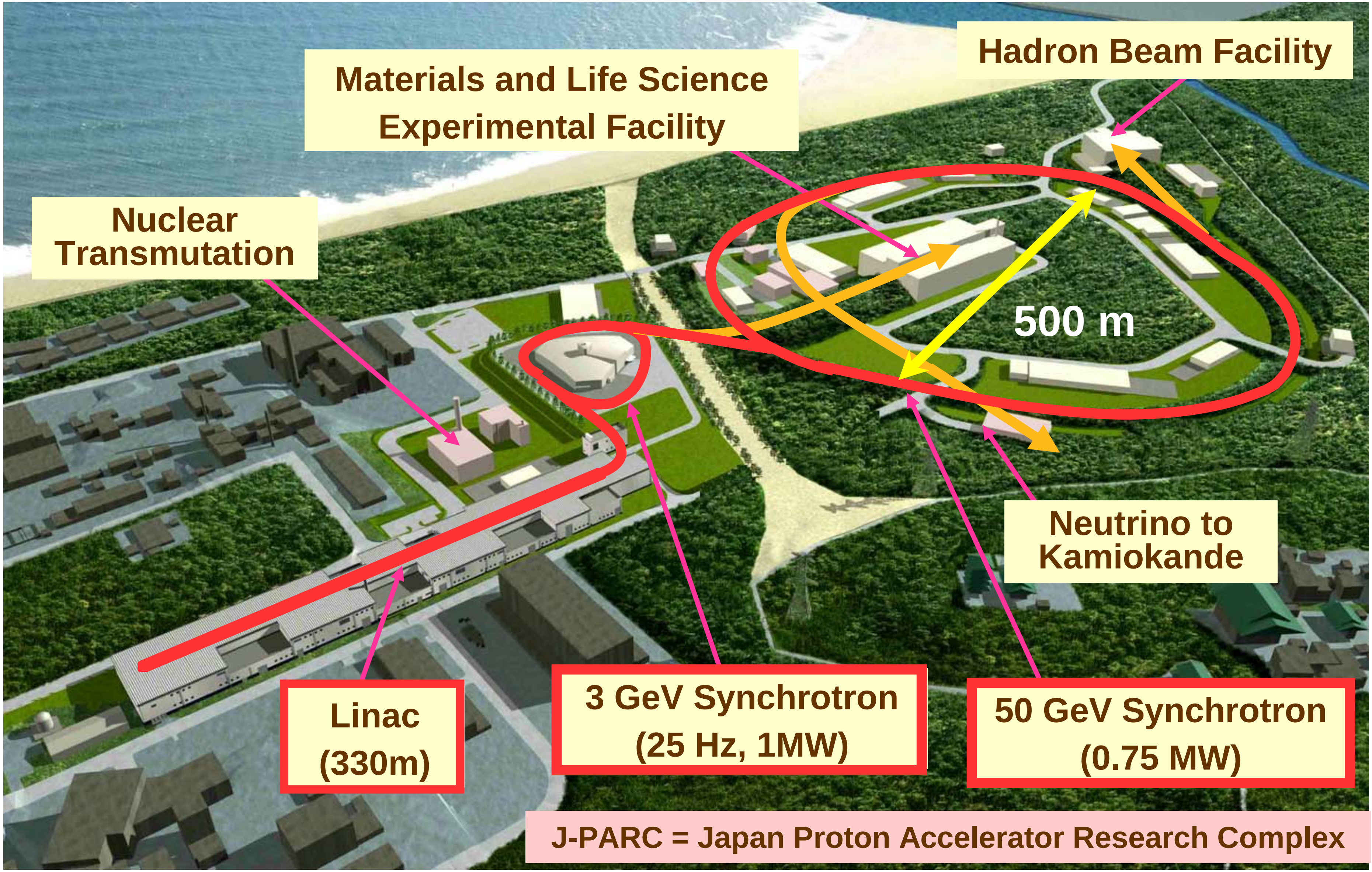


FIG. 4: Azimuthal dependence of asymmetry for the n-ID sample produced forward with respect to the polarized proton direction, based on the east detector. The error bars are statistical.

	forward	backward
neutron	$-0.090 \pm 0.006 \pm 0.009$	$0.003 \pm 0.004 \pm 0.003$
photon	$-0.009 \pm 0.015 \pm 0.007$	$-0.019 \pm 0.010 \pm 0.003$
π^0	$-0.022 \pm 0.030 \pm 0.002$	$0.007 \pm 0.021 \pm 0.001$

TABLE I: Asymmetries measured by the EMCal. The errors are statistical and systematic, respectively. There is an additional scale uncertainty, due to the beam polarization uncertainty, of $(1.0^{+0.47}_{-0.24})$.

J-PARC facility



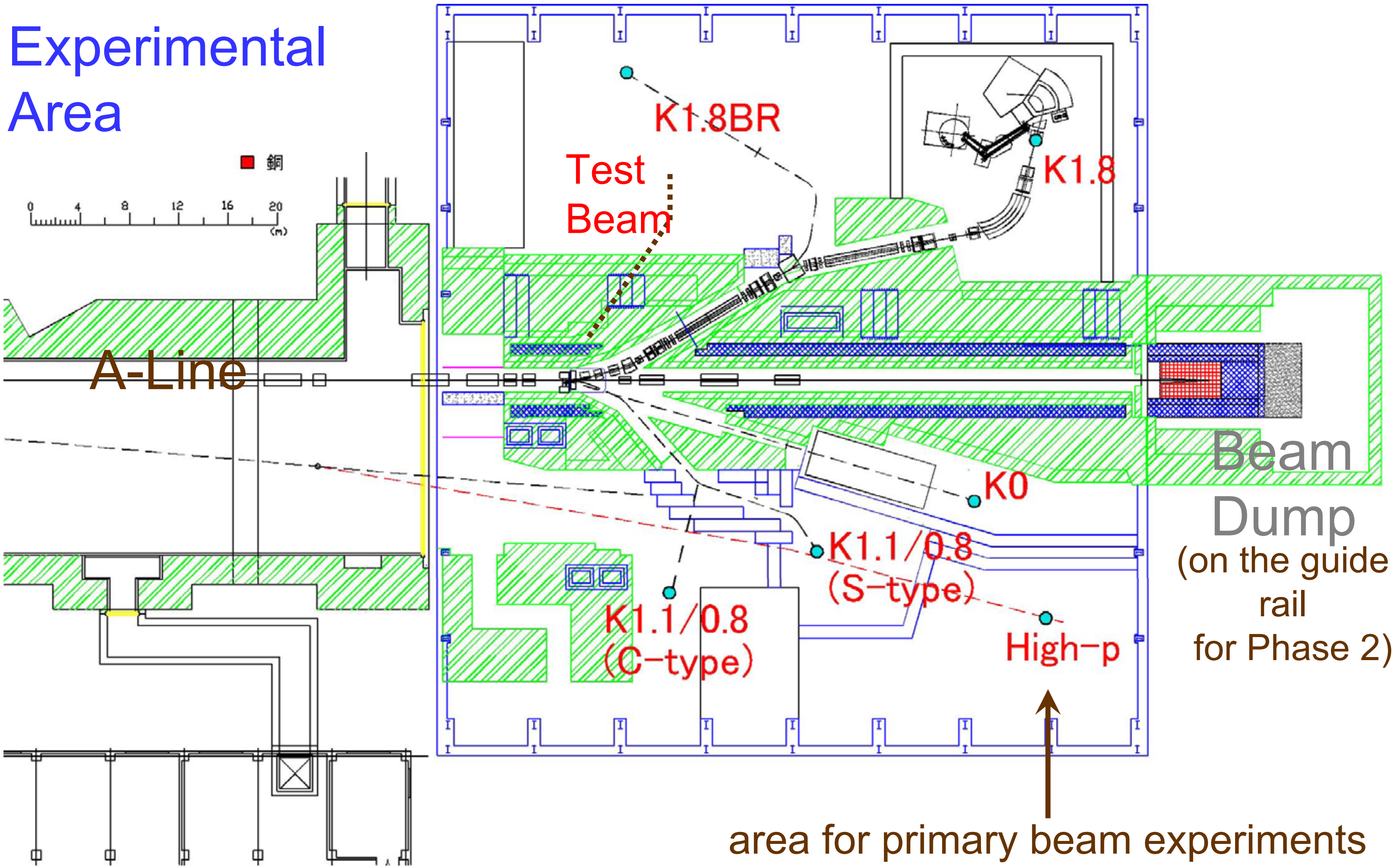
Joint Project between KEK and JAEA

J-PARC parameters

- 50 GeV beam
  - repetition 3.4 ~ 5 (or 6) sec
  - flat top width 0.7 ~ 2 (or 3) sec
  - linac energy 400 MeV
  - 3.3×10^{14} ppp, 15 μA
  - beam power 750 kW
- 30 GeV beam (phase-1)
  - linac energy 180 MeV
  - 2×10^{14} ppp, 9 μA
  - beam power 270 kW

Hadron experimental hall (phase 1)

beamlines for secondary beam experiments at the beginning of the phase1



Sea-quark分布のflavor非対称性

- Gottfried sum rule
  - in the parton model with isospin symmetry

$$I_G = \int_0^1 \frac{dx}{x}[F_2^p(x,Q^2) - F_2^n(x,Q^2)] = \frac{1}{3} + \frac{2}{3}\int_0^1 dx[\bar{u}(x,Q^2) - \bar{d}(x,Q^2)]$$

  - CERN NMC experiment

$$\int_{0.004}^{0.8} dx[F_2^p(x,Q^2) - F_2^n(x,Q^2)]$$

$$= 0.221 \pm 0.008(\text{stat.}) \pm 0.019(\text{syst.})$$

$$\text{at } Q^2 = 4\,\text{GeV}^2$$

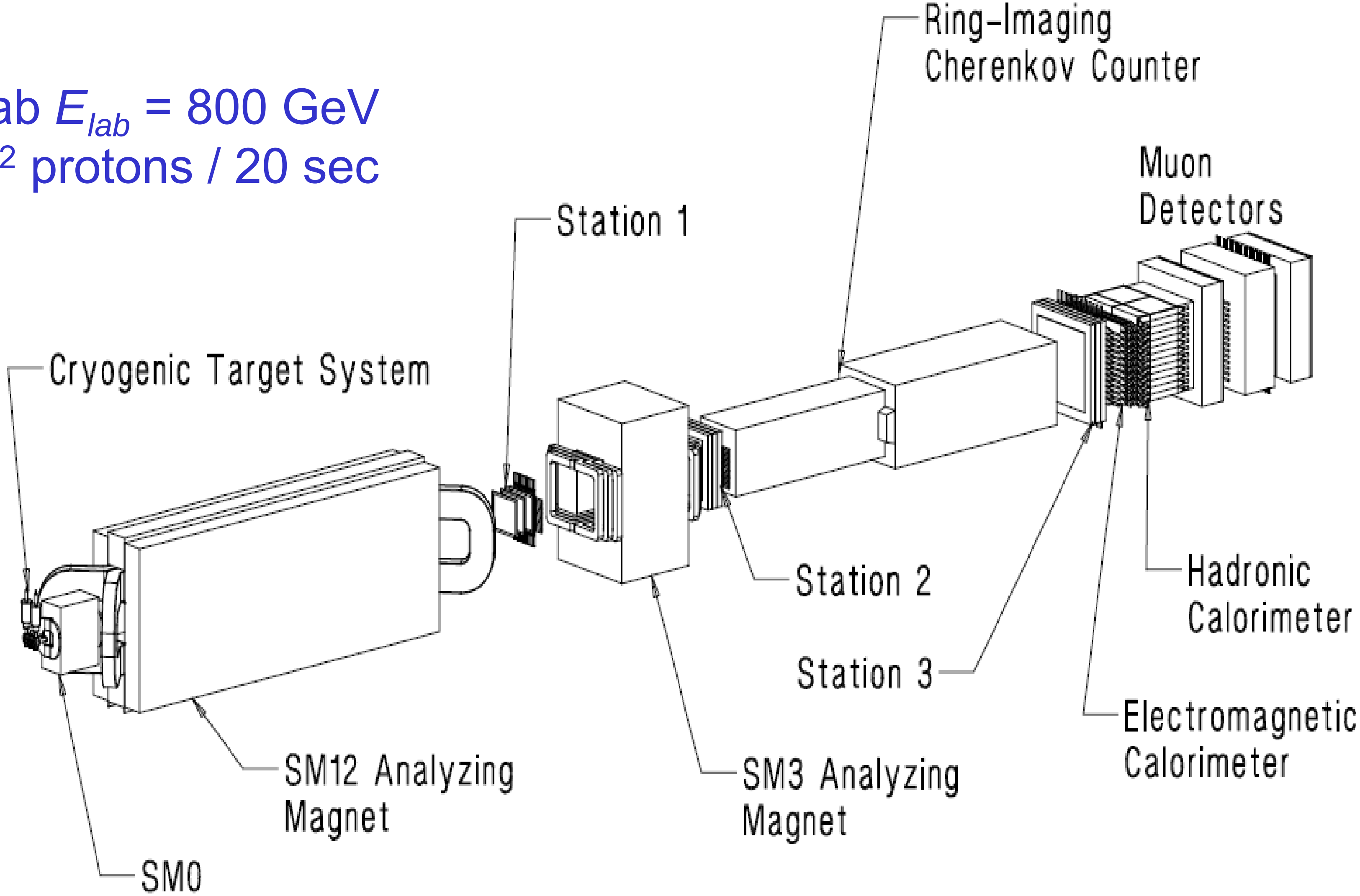
$$I_G = 0.235 \pm 0.026$$

$$\int_0^1 dx[\bar{d}(x) - \bar{u}(x)] = 0.148 \pm 0.039$$

Dimuon experiment

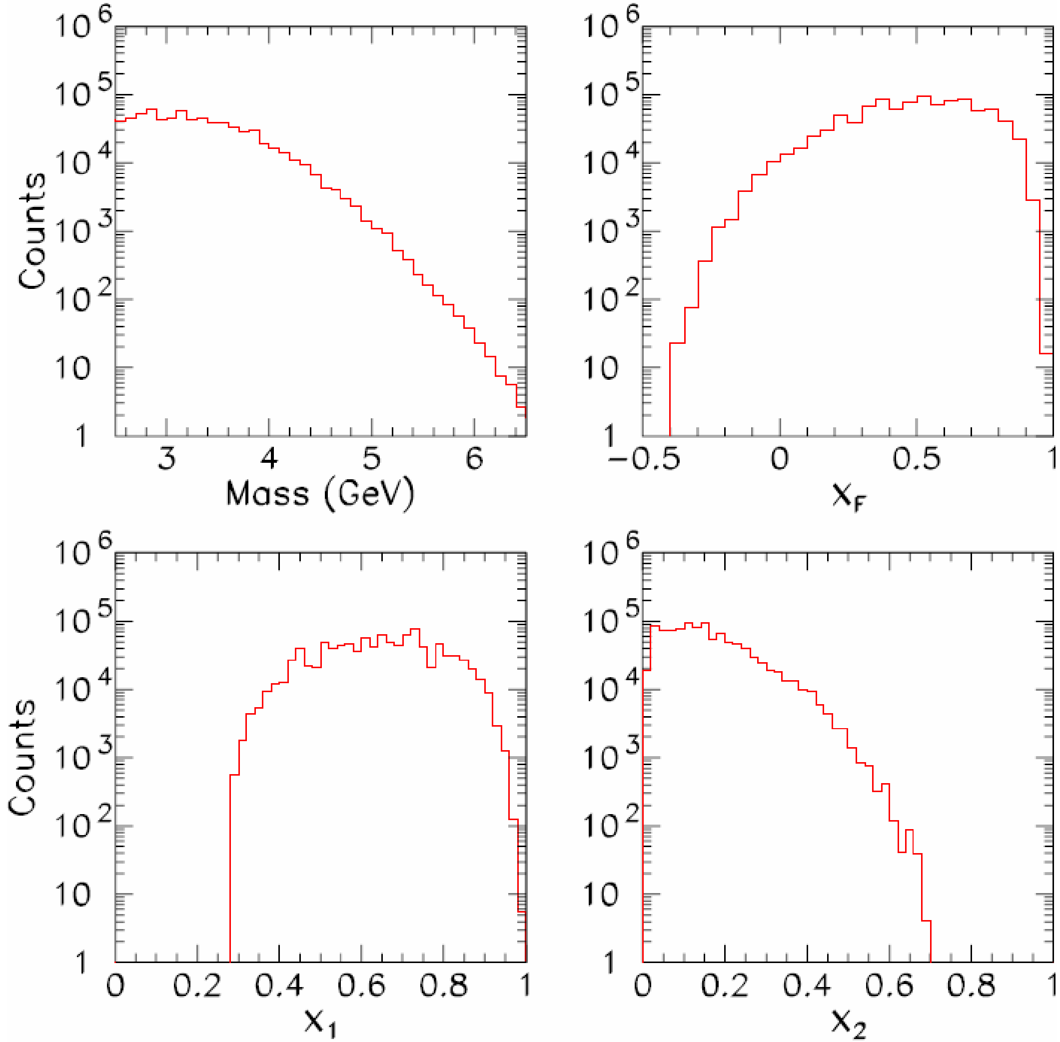
- Fermilab E866/NuSea
  - closed geometry

Fermilab E_{lab} = 800 GeV
2×10^{12} protons / 20 sec



Simulation studies

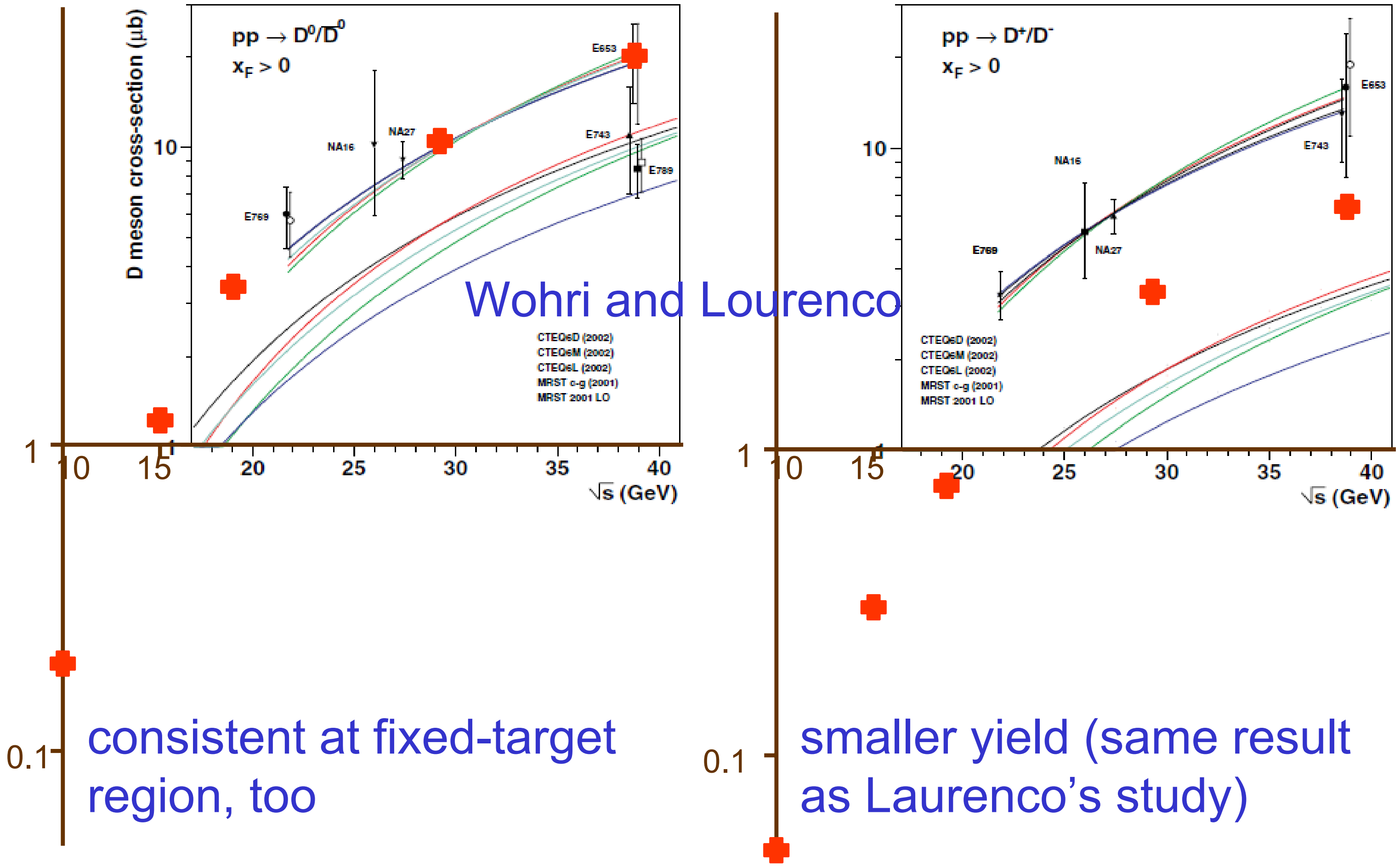
- Expected Drell-Yan counts for a two-month p+d run at 50 GeV
  - $2x10^{12}$ protons/spill
  - 50-cm long liquid deuterium target
  - assume 50 percent overall efficiency



Physics at 30 GeV

– cross section

- PYTHIA (6.228) study with PHENIX tune ($<k_T>$ = 1.5 GeV/c, M_c = 1.25 GeV/c^2, K-factor = 3.5, $Q^2 = s$)



Wohri and Lourenco

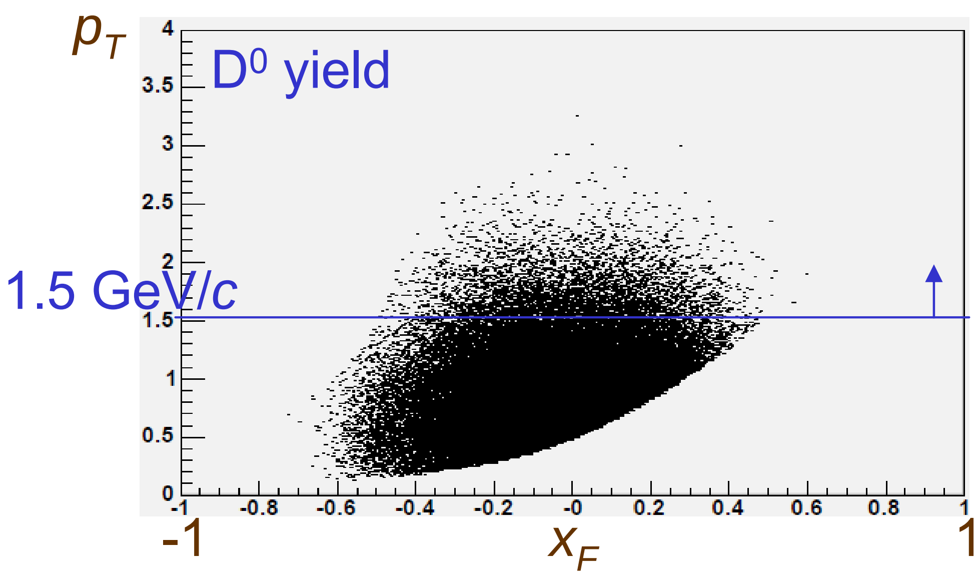
consistent at fixed-target region, too

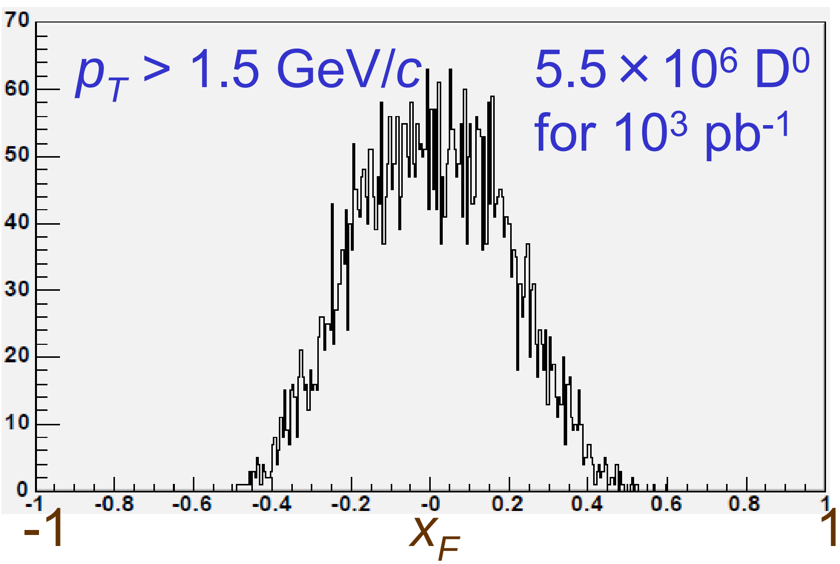
smaller yield (same result as Laurenco's study)

- J-PARC: 3-4 order smaller cross section than that at RHIC
  - can be compensated by higher intensity/luminosity at J-PARC…

D-meson

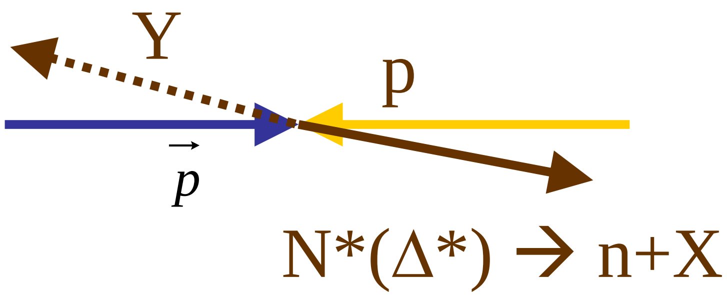
– silicon detectors to identify second decay vertex
– yield study
  - 10^9 proton/sec beam
  - 10% target
  - 2×10^{33} cm^{-2}sec^{-1}
  - $\times$ 1 week = 10^3 pb^{-1}
  - acceptance 0.05 – 0.3 to cover forward/mid-rapidity/backward





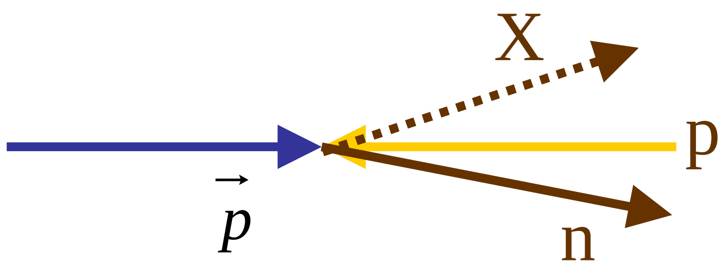
SSA measurements

- neutron-tagged measurement
  - measure A_N of coincident particles at BBC at PHENIX
  - forward neutron, forward BBC, left-right
    - $(-4.50\pm0.50\pm0.22)\times10^{-2} < 0$
  - forward neutron, backward BBC, left-right
    - $(2.28\pm0.55\pm0.10)\times10^{-2} > 0$
- asymmetry in the forward BBC has the same sign while backward particle has opposite sign A_N



initial-state effect - favored

$A_N(X) < 0,\ A_N(Y) > 0$



final-state effect

$A_N(X) > 0,\ A_N(Y)??$

SSA measurements

– neutron-tagged measurement of Drell-Yan pair…

- Jen-Chieh Peng's calculation expecting sensitivity to the meson cloud model, and measurement of pion structure

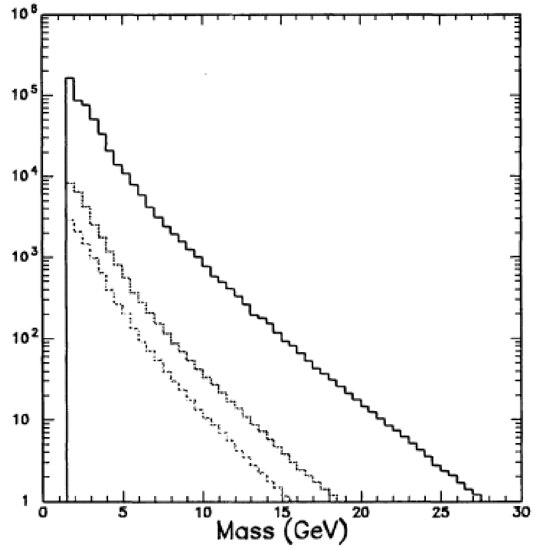
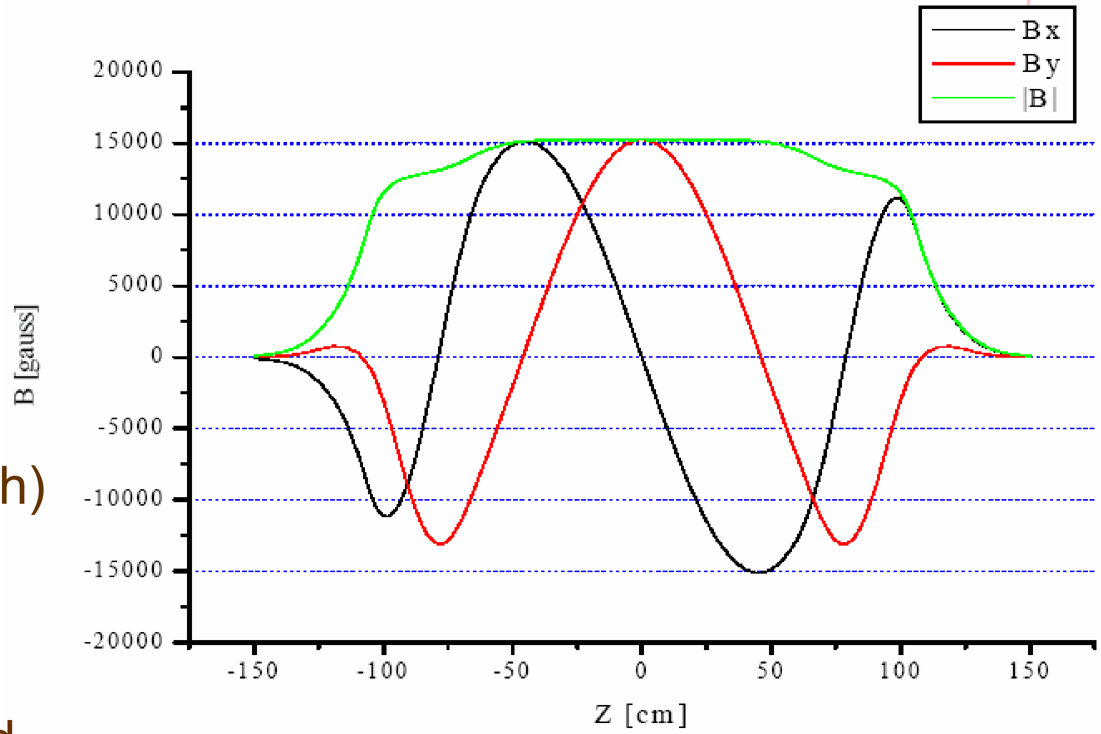


FIGURE 3. The solid curve corresponds to dimuon event distributions in one muon arm for a one-month $p+p$ PHENIX run at $\sqrt{s} = 200$ GeV. The dotted and dashed curves correspond to the yields for $p + p \to n + \mu^+\mu^- + X$ with $Y > 0.6$ and $Y > 0.8$, respectively, where Y is the fraction of proton beam momentum carried by the neutron.

Polarized proton acceleration

- AGS warm helical partial Siberian snake

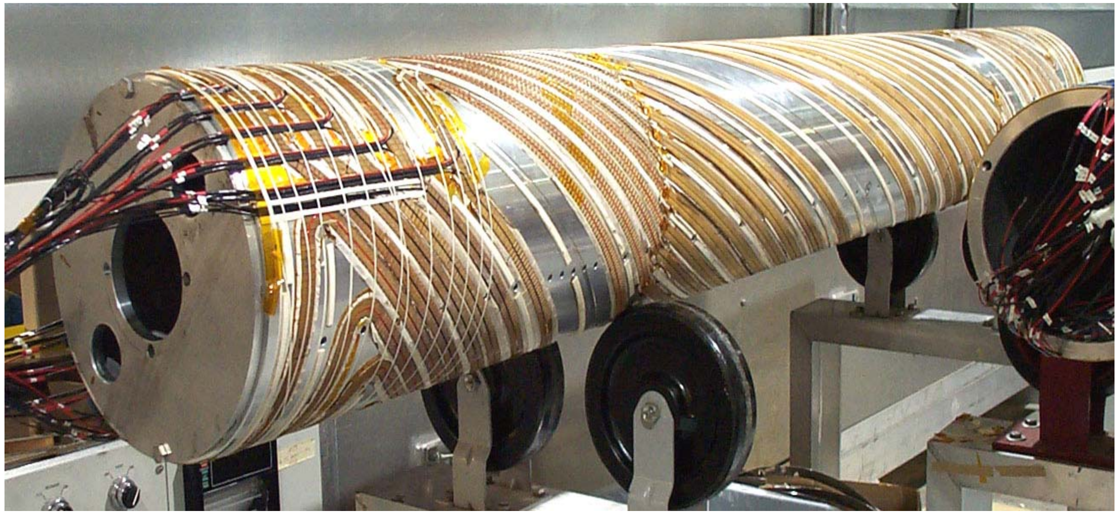


- ➢ replaced solenoidal partial snake
- ➢ same design as cold snake (dual pitch)
- ➢ 1.5 Tesla field
- ➢ ~ 6 % partial snake (w/o generating coupling)
- ➢ funded by RIKEN, built by Takano Ind.

Thomas Roser (BNL), et al.

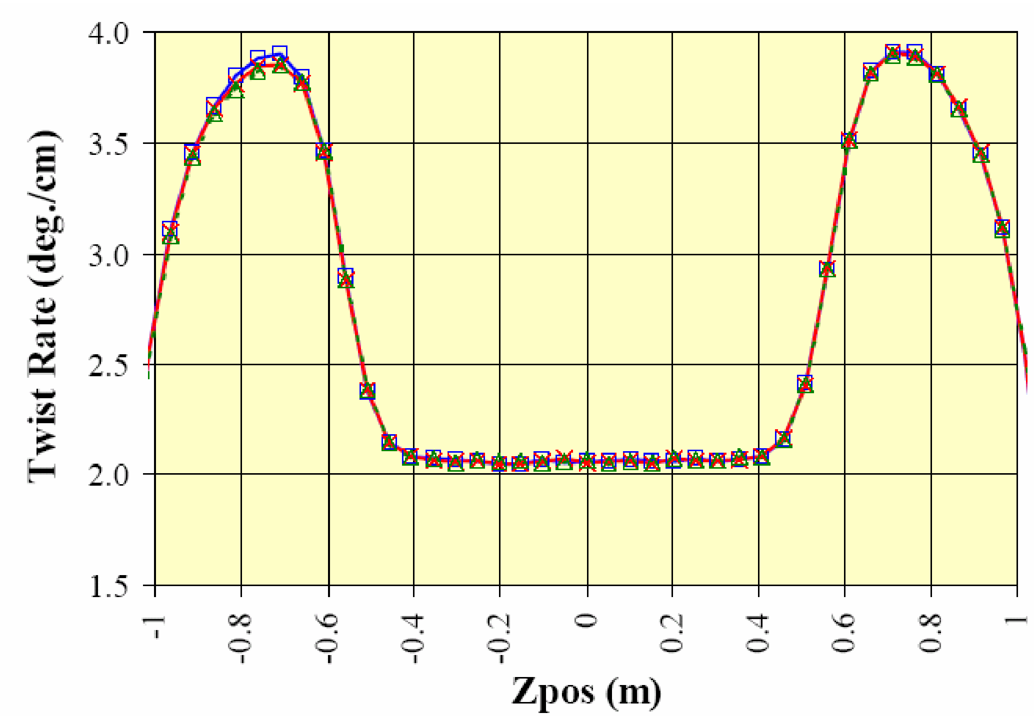
Polarized proton acceleration

- 25 % AGS super-conducting helical snake



completed helical dipole coil

correction solenoid and dipoles

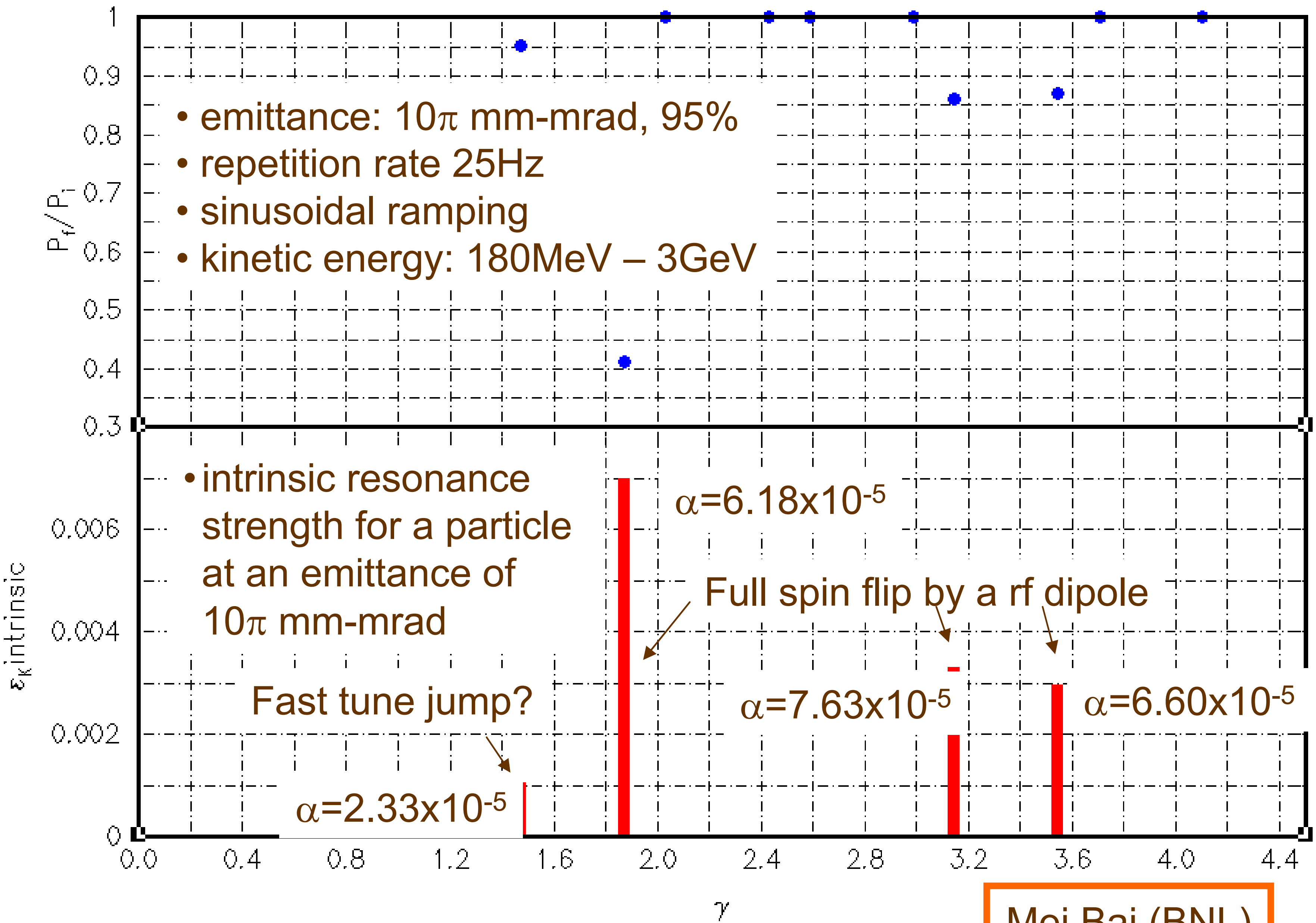


measured twist angle 2 deg/cm
in the middle ~ 4 deg/cm at ends

Thomas Roser (BNL), et al.

Polarized proton acceleration at J-PARC

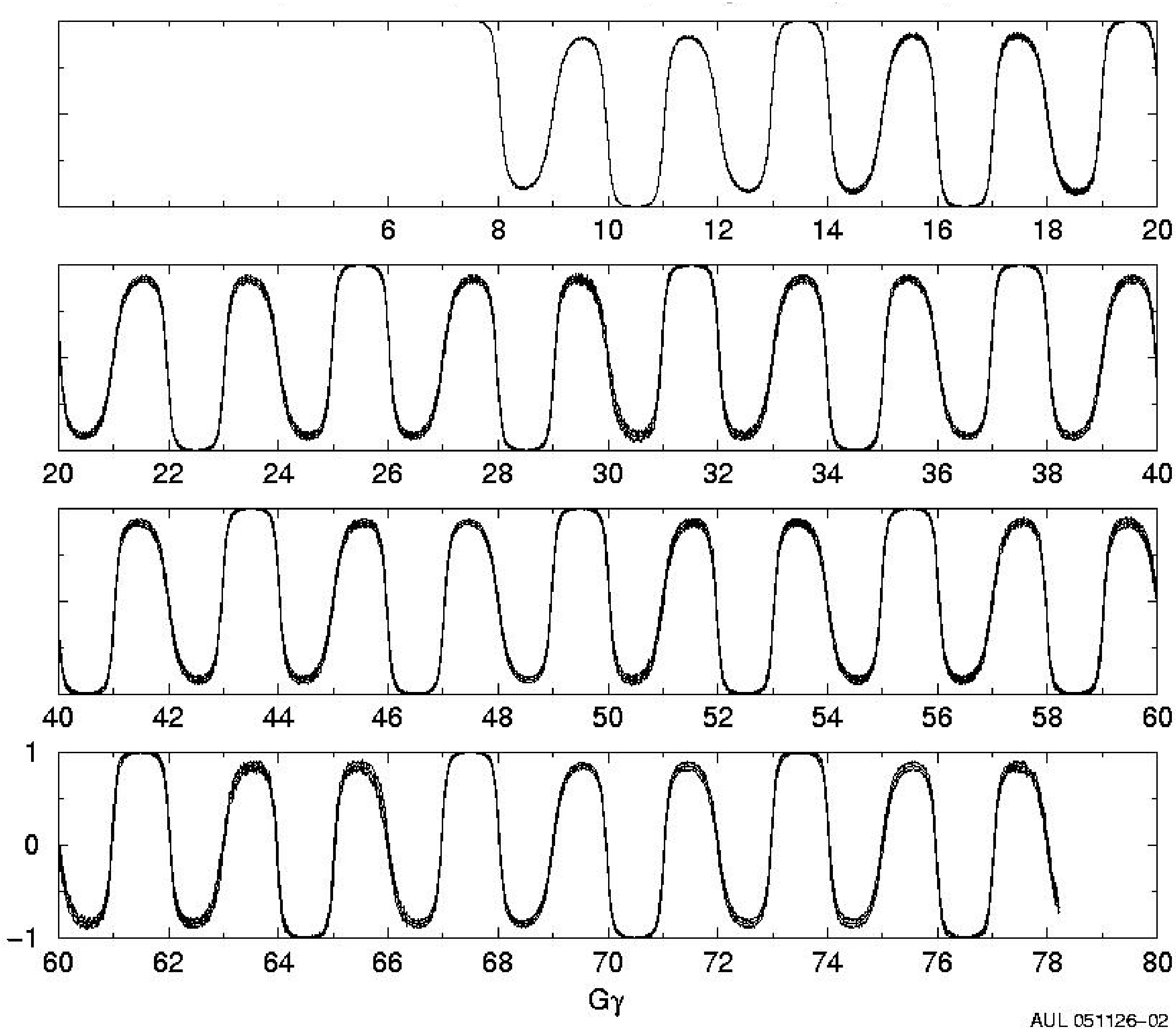
- Intrinsic resonances in RCS



Mei Bai (BNL)

Polarized proton acceleration at J-PARC

- Spin tracking in 50 GeV MR

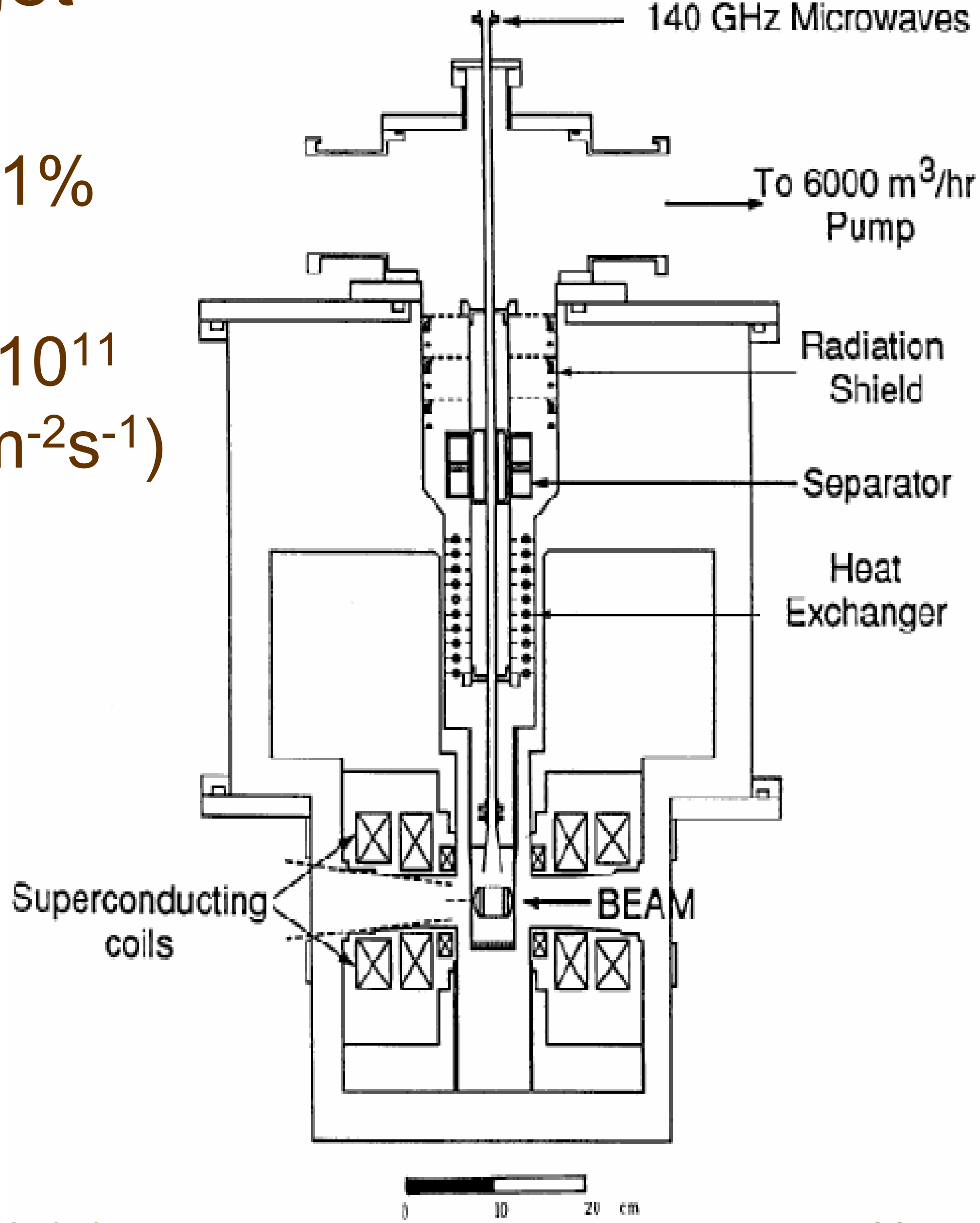


average of 12 particles on an ellipse of 4π mm-mrad

Alfredo Luccio (BNL)

Polarized target

- Michigan polarized target
  - existing at KEK
  - target thickness ~3 cm (1% target)
  - maybe operational with 10^{11} ppp (luminosity ~10^{34} $cm^{-2}s^{-1}$)



SSA measurements of neutron

– large asymmetry found at RHIC

– production mechanism of neutron

- one-pion exchange dominant – spin flip

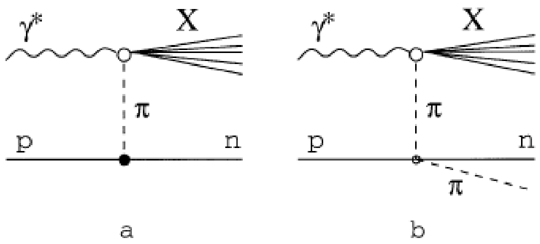


Fig. 1. One-pion-exchange diagrams contributing to the deep-inelastic scattering $ep \rightarrow e'nX$ without (**a**) and with (**b**) production of an additional pion in the proton fragmentation region

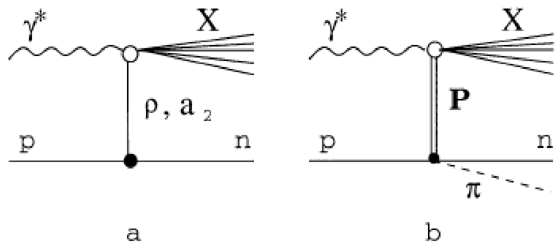


Fig. 2. The ρ- and a_2-Reggeon (**a**) and the Pomeron (**b**) exchange contributions to the deep-inelastic scattering $ep \rightarrow e'nX$

- figures for study in DIS exps. (HERA), please replace virtual photon with proton to apply them for pp reaction

– asymmetry measurement

- sensitive to interference between spin-flip term (one-pion exchange) and non-spinflip term (other reggeon exchanges)

– relation to the meson-cloud model? $p \rightarrow n\pi^+$

– neutron-tagged measurement of Drell-Yan?

- production rate
- asymmetry measurement