クォーク･グルーオンレベルで見た核子スピンの起源

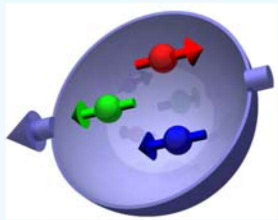
岩田高広

山形大学　理学部

原子核物理研究会　「広い意味での核反応研究のこれから」　2009/ 02/21 @　宮崎

核子スピンに何が起こったか？

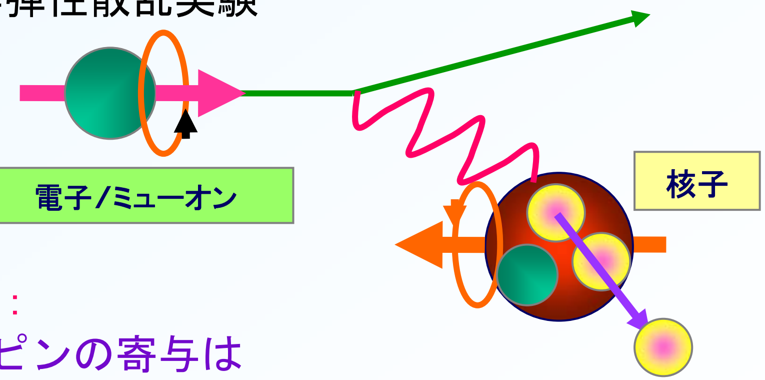
クォークモデル



核子スピン：クォークスピンの合成

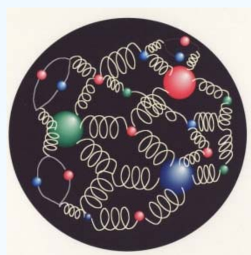
クォークスピン寄与は１００％

偏極深部非弾性散乱実験



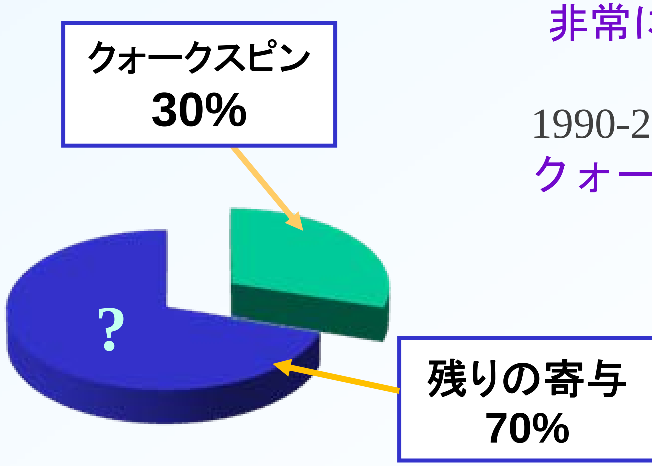
QCDパートン描像

valence quarks +
sea-quarks
& gluons



1988　EMC：
クォークスピンの寄与は
非常に少ない！➔　spin crisis

1990-2008　SMC, SLAC,HERMES, COMPASS：
クォークスピンは寄与は約30% (@ Q^2=3 GeV^2)



Q^2=3GeV^2

Missing Spin の問題

(spin puzzle / Dark Spin)

核子スピンを担う候補

核子のスピン和則

$$\Delta\Sigma = \sum_i \Delta q_i^{\uparrow} - \Delta q_i^{\downarrow} + \Delta \bar{q}_i^{\uparrow} - \Delta \bar{q}_i^{\downarrow}$$

$$\frac{1}{2} = \frac{1}{2}\underbrace{\Delta\Sigma}_{\text{quark spin}} + \underbrace{\Delta G}_{\text{gluon spin}} + \underbrace{\langle L_z \rangle}_{\text{orbital}}$$

$$\Delta G = G^{\uparrow} - G^{\downarrow}$$

Missing Spinの候補

1）グルーオンスピン

グルーオン　：　QCDにおけるゲージ粒子（スピン1）

核子の4元運動量の半分近くを運ぶ

核子中でのグルーオン偏極度は？

2）クォーク・グルーオンの軌道回転

クォークモデルではクォークの軌道回転は無い

QCDパートン描像では、どうなるか？

COMPASS実験

CERNでの11カ国の国際共同研究
日本グループ　：　山形大学、宮崎大学、KEK、中部大学

偏極深部非弾性散乱実験

160GeV 偏極ミューオンビーム（SPS）　&　偏極核子標的

スペクトロメータ　：　散乱ミューオン　＋　ハドロンの同時検出

主な研究課題

1）　<u>グルーオン偏極度の測定</u>
　　直接測定　/　間接測定

2）　クォークスピン寄与のフレーバー分解、Valence/sea 分解

3）　クォークの横運動量依存分布（Sivers関数）

4）　クォークの横方向偏極効果（transversity、Collins効果）

5）　Λ偏極

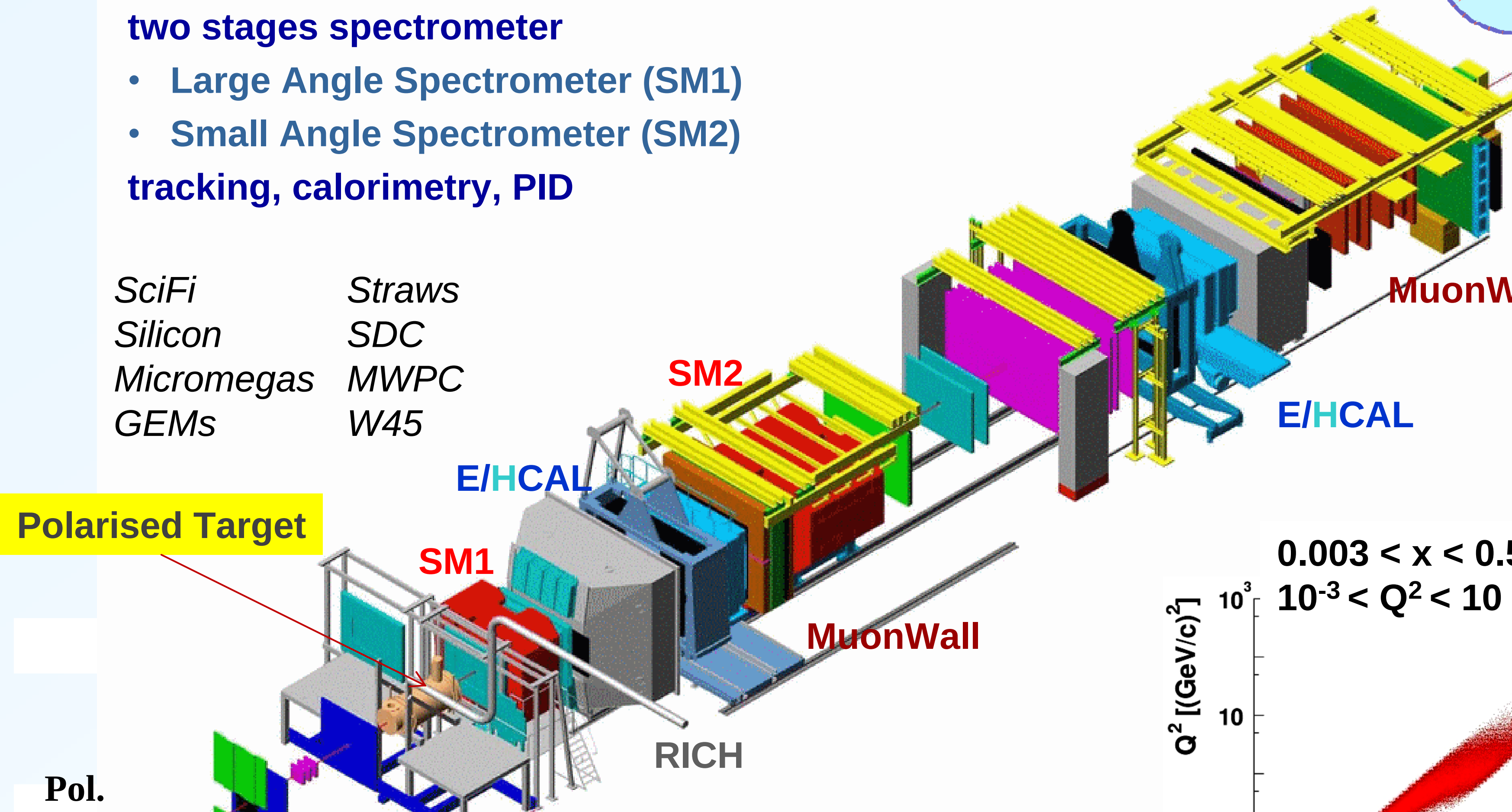
COMPASS SETUP

two stages spectrometer

- **Large Angle Spectrometer (SM1)**
- **Small Angle Spectrometer (SM2)**

tracking, calorimetry, PID

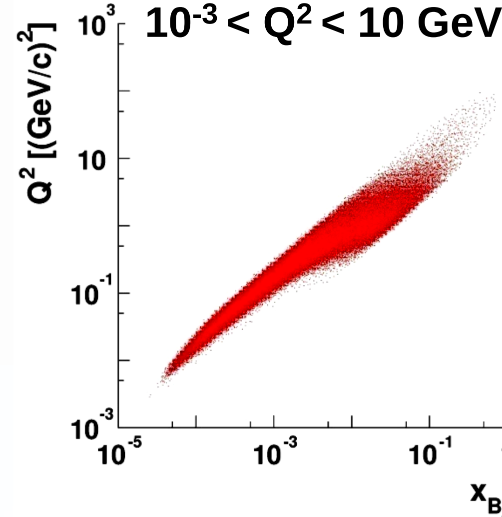
SciFi	*Straws*
Silicon	*SDC*
Micromegas	*MWPC*
GEMs	*W45*



E_{μ}=160GeV
I_{μ}=2x10^{8}/spill,
spill=4.8s, cycle=16.8s
P_{μ} =80%

- **high energy beam**
- **broad kinematical range**
- **large angular acceptance**

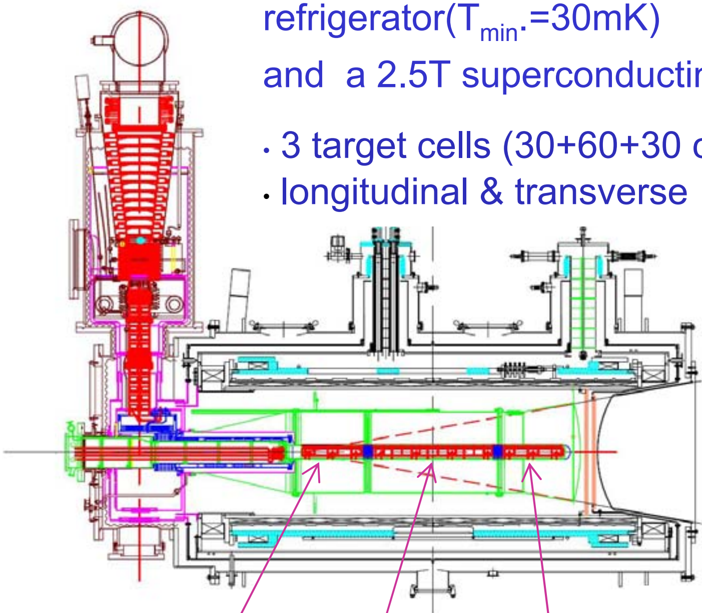
$0.003 < x < 0.5$
$10^{-3} < Q^2 < 10$ GeV^2



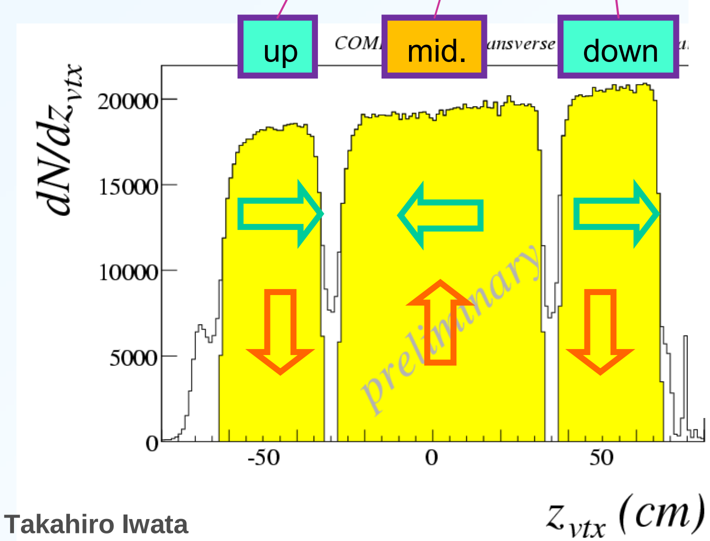
THE POLARIZED TARGET SYSTEM

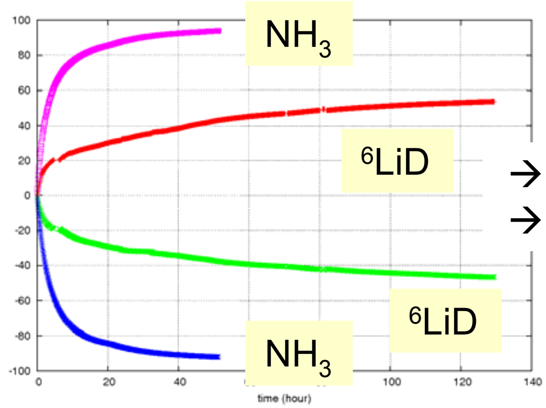
DNP technique with a dilution refrigerator($T_{min.}$=30mK)
and a 2.5T superconducting magnet

- 3 target cells (30+60+30 cm)
- longitudinal & transverse modes



世界最大の偏極標的

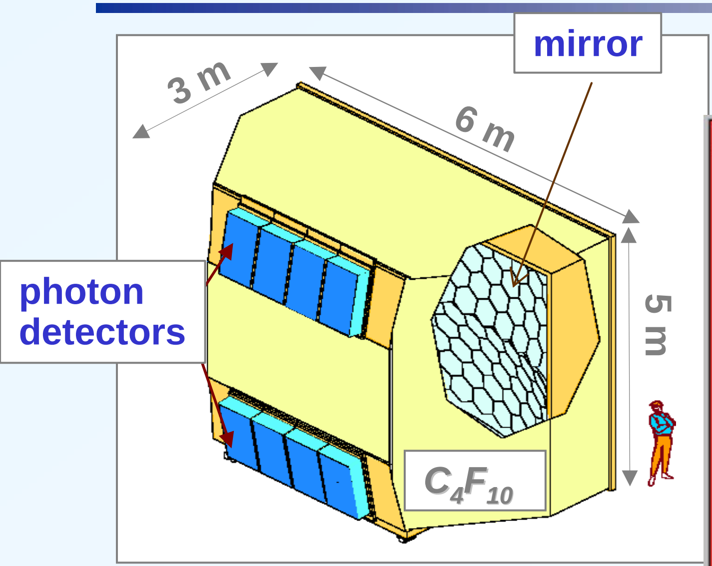


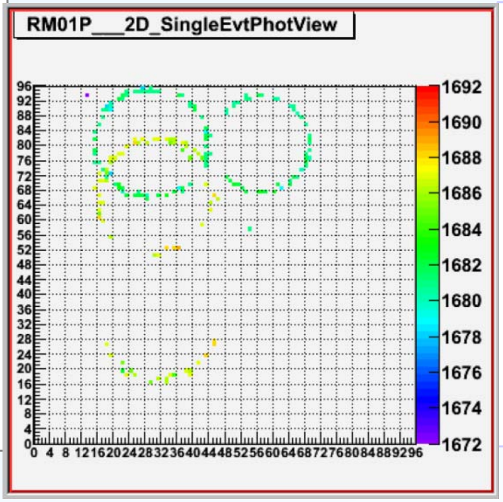


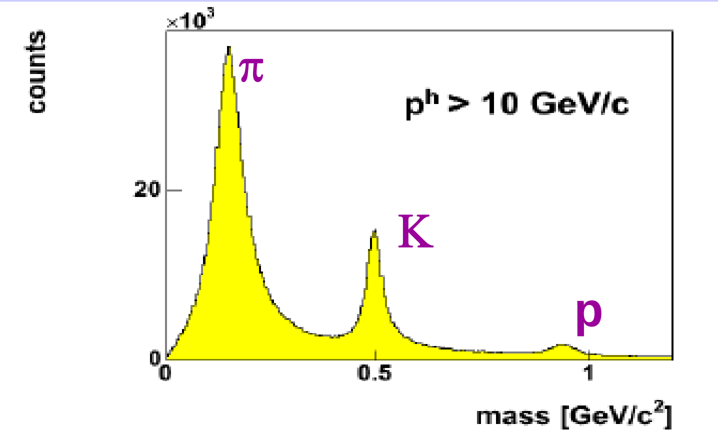
→ Polarization of NH_3 ~90%
→ Polarization of ^{6}LiD ~50%

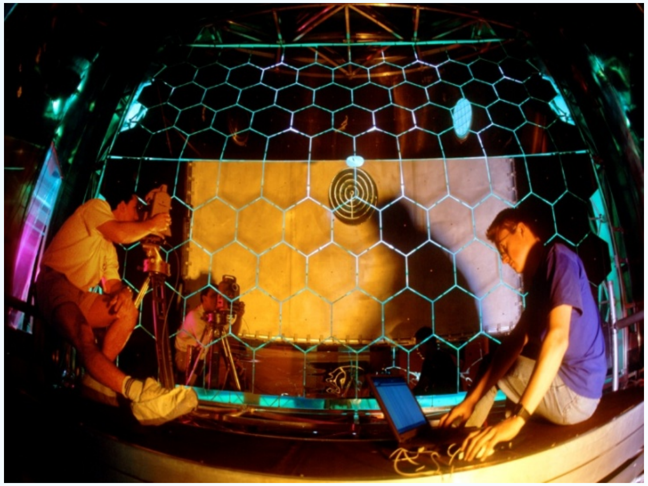
- ^{6}Li (~ α+d) also polarized
  → dilution factor f=50%

THE RICH DETECTOR









- radiator gas: C_4F_{10}
- mirror wall: 20 m^2 surface
- photon-detectors:
  - •outer part (75%) MWPC(pad RO) with CsI cathode
  - • inner part(25%) 576 MAPMTs with indiv. telescope

Installed in 2005,
Used in data taking from 2006

threshold momenta

- p_π = 2 GeV/c
- p_K = 9 GeV/c
- p_P =17 GeV/c

DIRECT MEASUREMENTS OF ΔG/G

グルーオン偏極度: $\frac{\Delta G}{G}$

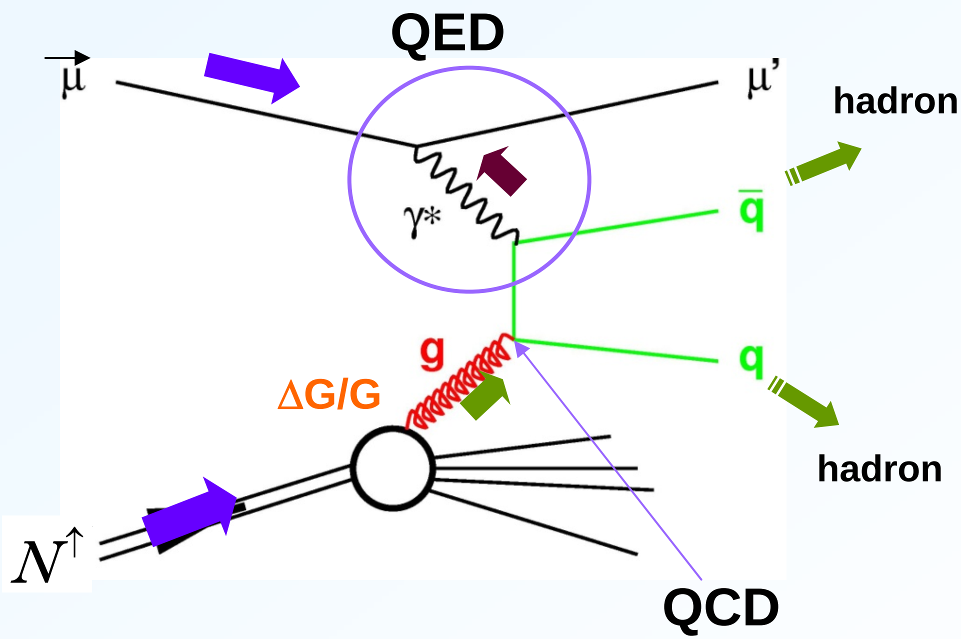
直接測定

Theory (QCD)

グルーオンが関与する反応の非対称度

$$A_{LL} = \langle \hat{a} \rangle \times \frac{\Delta G}{G}$$

Photon Gluon Fusion: $\gamma + g \rightarrow q\,\bar{q}$



q = u,d,s

"HIGH p_T HADRON PAIRS"

2 hadrons with high p_T

☺ large statistics

☹ physical BG: MC dependent

・hard scale: p_T

q = c

"OPEN CHARM"

one charm hadron detected

☺ small phys. BG, less MC dependent

☹ small statistics

- hard scale: charm mass, $\mu^2 = 4m_c^2$
- COMPASS original

ΔG/G FROM OPEN CHARM

$D^0(1865) \to K^- + \pi^+ \quad (\text{or } \overline{D}^0 \to K^+ + \pi^-)$

BR:4%

Kaon id. by RICH

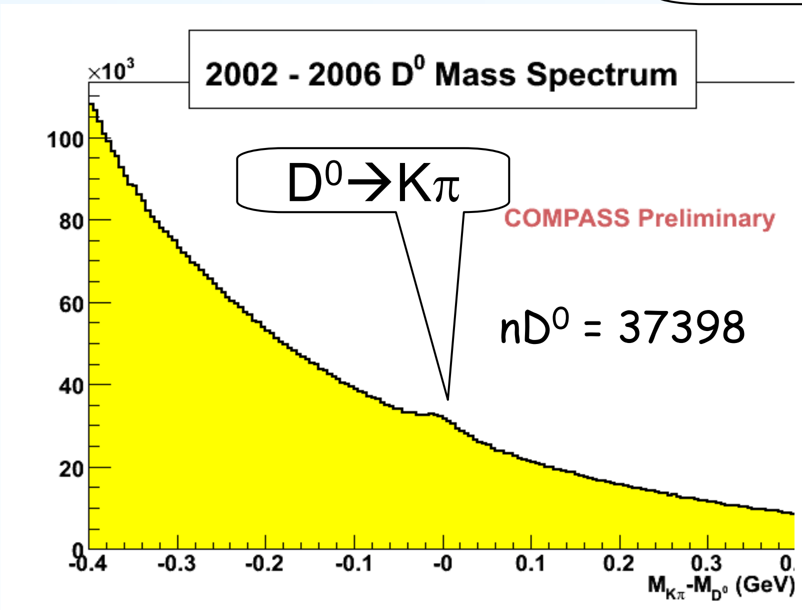
D* tagging

$D^{*\pm}(2010) \to D^0 + \pi^{\pm}_{slow}$

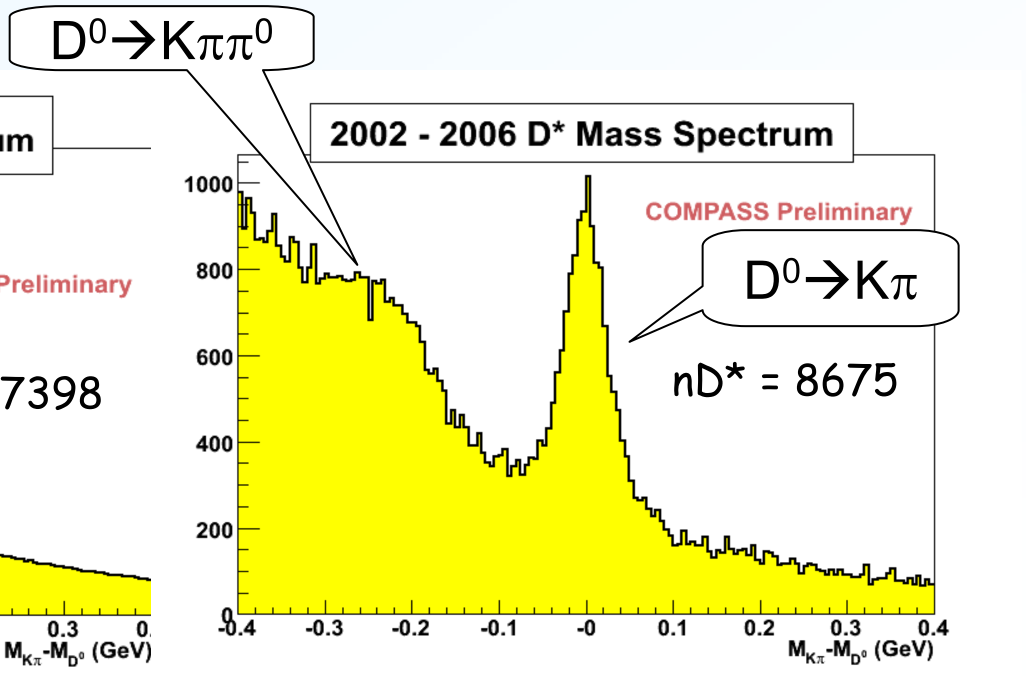
BR:68%

$K + \pi$

untagged



$M_{K\pi} - M_{D^0}\,(GeV)$



$M_{K\pi} - M_{D^0}\,(GeV)$

INDIRECT MEASUREMENT OF $\Delta G/G$

間接測定

- Polarized inclusive DIS

$$e^{\uparrow} + N^{\uparrow} \rightarrow e' + X$$

→ polarized structure function: $g_1 (x,Q^2)$

at LO-QCD $$g_1(x,Q^2) = \frac{1}{2}\sum_i e_i^2 \boxed{\Delta q_i}$$ ← クォーク偏極

at NLO-QCD

$$g_1(x,Q^2) = \frac{1}{9}\left(\boxed{C_{NS} \otimes \left[\pm\frac{3}{4}\Delta q_3 + \frac{1}{4}\Delta q_8\right] + C_S \otimes \Delta\Sigma} + C_G \otimes \boxed{\Delta G}\right)$$

クォーク偏極　　グルーオン偏極

$$\Delta q_3 = \Delta u - \Delta d \qquad \Delta q_8 = \Delta u + \Delta d - 2\Delta s$$

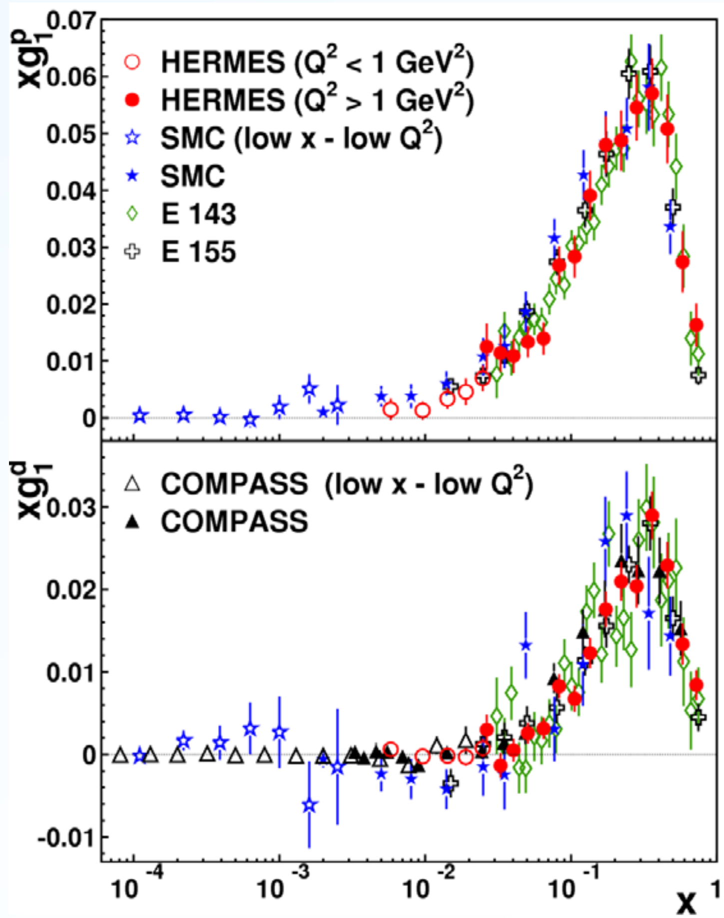
C_{NS}, C_S, C_G are Wilson coefficients given by QCD

Fit world data with QCD DGLAP eq. ,

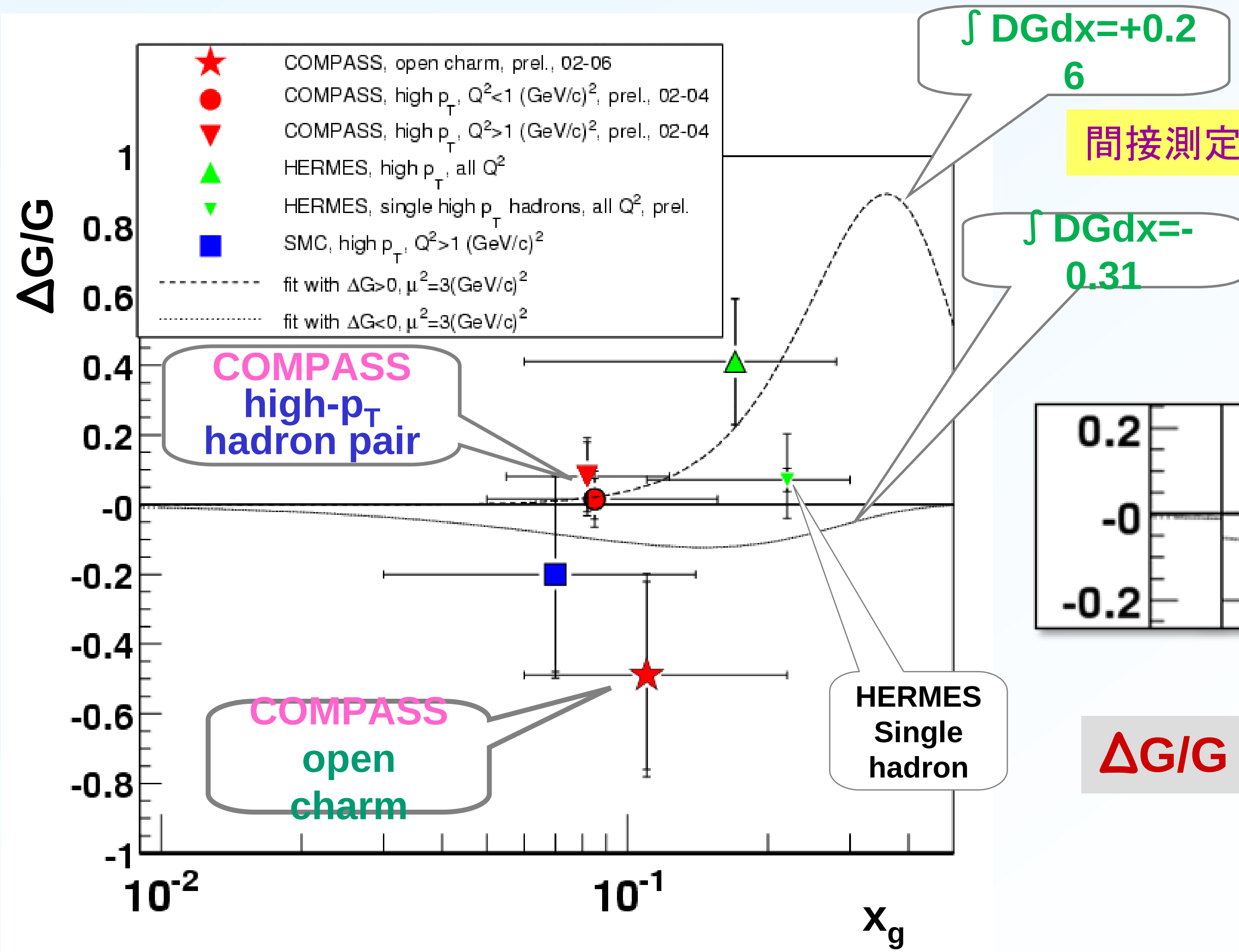
$\Delta\Sigma(x) = \sum_i \Delta q_i$: クォーク偏極の和

$\Delta G(x)$: グルーオン偏極

が同時に得られる



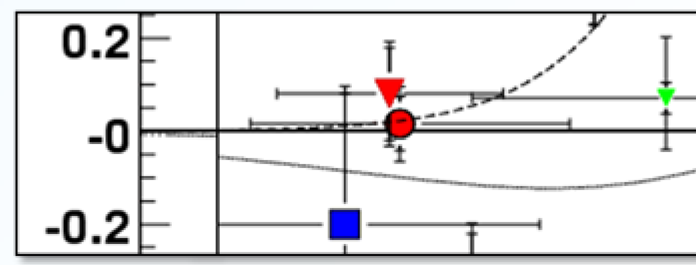
RESULTS FOR ΔG/G



間接測定

QCD Fit to g_1
COMPASS06
Q^2 = 3 Gev^2

Assuming ΔG(x_g) without nodes

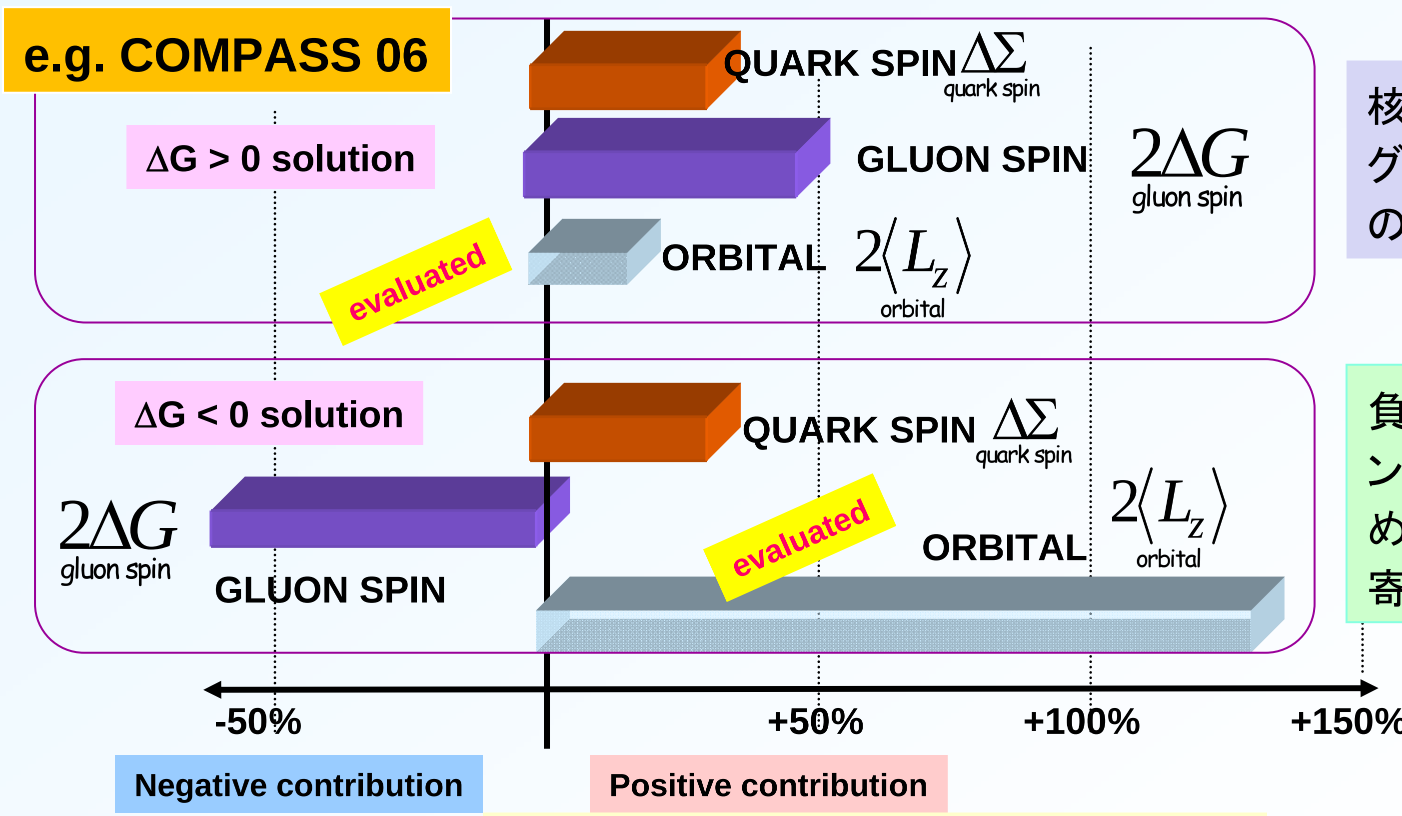


ΔG/G ≈0 @ x_g ≈ 0.1

RECALL: charm point at larger scale (μ^2 = 13 Gev^2)

CONTRIBUTIONS TO NUCLEON SPIN

$$\frac{1}{2}=\frac{1}{2}\underbrace{\Delta\Sigma}_{\text{quark spin}}+\underbrace{\Delta G}_{\text{gluon spin}}+\underbrace{\langle L_z\rangle}_{\text{orbital}} \rightarrow 100\ \% = \underbrace{\Delta\Sigma}_{\text{quark spin}}+\underbrace{2\Delta G}_{\text{gluon spin}}+\underbrace{2\langle L_z\rangle}_{\text{orbital}}$$



核子スピンの半分は
グルーオンスピン
の寄与

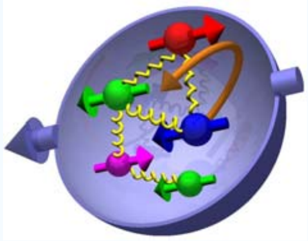
負のグルーオンスピ
ン寄与を打ち消すた
めに大きな軌道回転
寄与が必要

- グルーオンスピン寄与は本質的
- 軌道回転寄与も無視できない

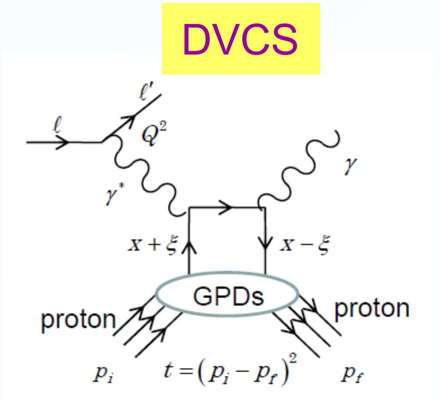
COMPASSでの今後の研究の方向性

- グルーオンスピン寄与の確定
  - 蓄積データの解析、 新たなデータ収集(統計精度の向上)

- クォークの軌道回転寄与の研究

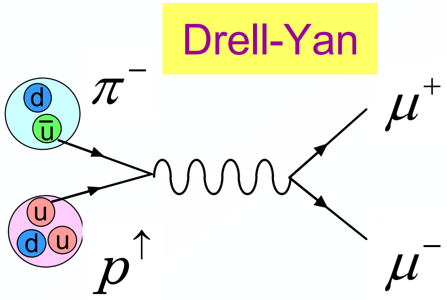


  - 一般化パートン分布(GPD)
    - 深部仮想コンプトン散乱(DVCS)の検出
    - Jiの全角運動量和則からクォークの軌道回転寄与を抽出



$$J^q = \frac{1}{2}\Delta q + L_z = \lim_{t\to\infty,\xi\to 0}\frac{1}{2}\int_{-1}^{1} x\left[H^q(x,\xi,t)+E^q(x,\xi,t)\right]dx$$

  - 偏極ドレルヤン
    - Boer-Mulder分布関数(クォークのL･S結合)
    - Sivers分布関数(クォークの軌道回転効果)



BACKUP SLIDES

QCD FIT WITH g_1 DETAILS

Start from PDFs at initial $Q^2=Q^2_0$

$\Delta\Sigma$, Δq_3, Δq_8 ,ΔG

$$\Delta q_k(x) = \eta_k \frac{x^{\alpha_k}(1-x)^{\beta_k}(1+\gamma_k x)}{\int_0^1 x^{\alpha_k}(1-x)^{\beta_k}(1+\gamma_k x)\,dx}$$

constraints

$$\eta_3 = F + D$$
$$\eta_8 = 3F - D$$
$$\gamma_3 = \gamma_8 = \gamma_G = 0$$

DGLAP: ***to go from Q^2_0 to Q^2_{data}***

non-singlet

$$\frac{d}{dt}\Delta q_{NS} = \frac{\alpha_s(t)}{2\pi} P_{qq}^{NS} \otimes \Delta q_{NS}$$

$$\Delta q_{NS} = (3/4)\left[\Delta q_3 + (1/3)\Delta q_8\right]$$

singlet & gluon

$$\frac{d}{dt}\begin{bmatrix}\Delta\Sigma \\ \Delta G\end{bmatrix} = \frac{\alpha_s(t)}{2\pi}\begin{bmatrix} P_{qq}^S & 2n_f P_{qG}^S \\ P_{Gq}^S & P_{GG}^S \end{bmatrix} \otimes \begin{bmatrix}\Delta\Sigma \\ \Delta G\end{bmatrix}$$

where $t=\log(Q^2/\Lambda^2)$ and P_{qq},P_{qG},P_{Gq} are polarized splitting functions

g_1^{fit} at the Q^2_{data}

at NLO

$$g_1^{fit}(x,Q^2) = \frac{1}{9}\left(C_{NS}\otimes\left[\pm\frac{3}{4}\Delta q_3 + \frac{1}{4}\Delta q_8\right] + C_S \otimes \Delta\Sigma + C_G \otimes \Delta G\right)$$

where C_{NS},C_S,C_G are Wilson coefficients

minimize

$$\chi^2 = \sum_i \frac{\left[g_1^{fit}(x_i,Q^2) - g_1^{\exp}(x_i,Q^2)\right]^2}{\left[\sigma(x_i,Q^2)\right]^2}$$

get $(\alpha_k, \beta_k, \gamma_k, \eta_k)$

V.Yu.Alexakhin et al.,Phys.Lrtt.B647(2007)8-17

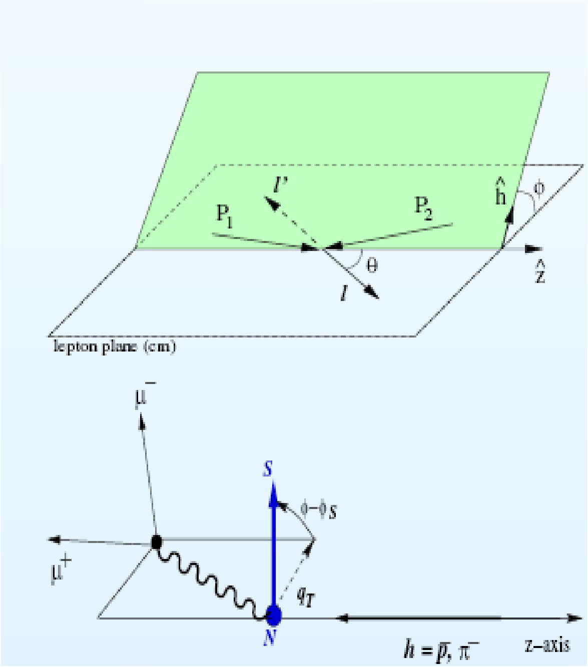
QUARK DISTRIBUTION STUDY IN DY

unpol. DY

$$\hat{k} \propto \bar{h}_{1q}^{\perp(1)}(x_1)\cdot h_{1q}^{\perp(1)}(x_2)$$

FF free

cos2ϕ modulation relates to Boer-Mulders function



single polarized DY

B.M. function

Transversity

$$A^{\sin(\phi+\phi_S)} \propto \boxed{\bar{h}_{1q}^{\perp(1)}(x_1)}\cdot \boxed{h_{1q}(x_2)}$$

$$A^{\sin(\phi-\phi_S)} \propto \boxed{f_1^{\bar{q}}(x_1)}\cdot \boxed{f_{1T}^{\perp(1)q}(x_2)}$$

Unpol. PDF

Sivers function

prediction

$$f_{1T}^{\perp}|_{DY} = -f_{1T}^{\perp}|_{SIDIS}$$

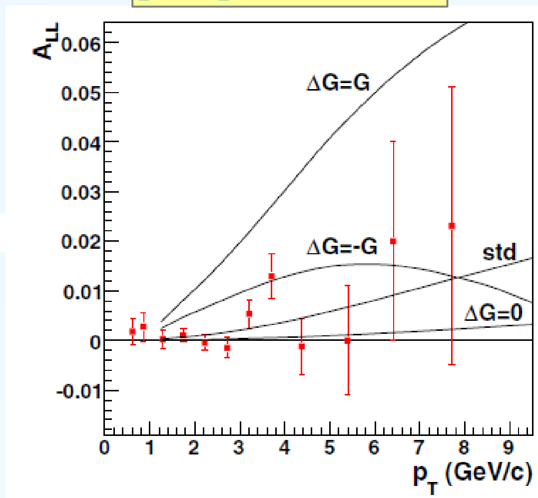
Collins , PL **B536** (2002) 43

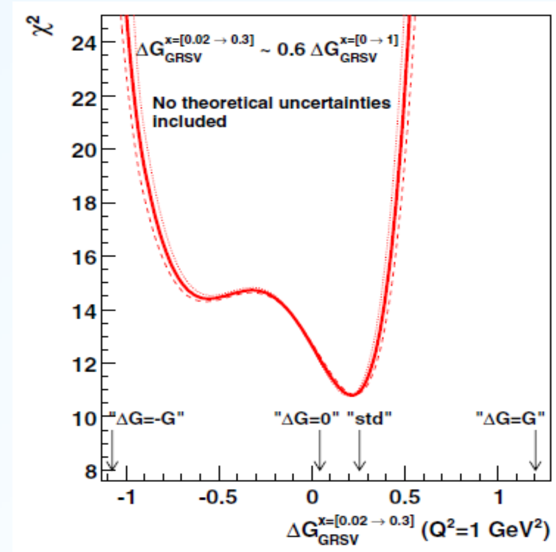
ΔG/G FROM RHIC-SPIN

PH ENIX

PHYSICAL REVIEW D 76, 051106(R) (2007)

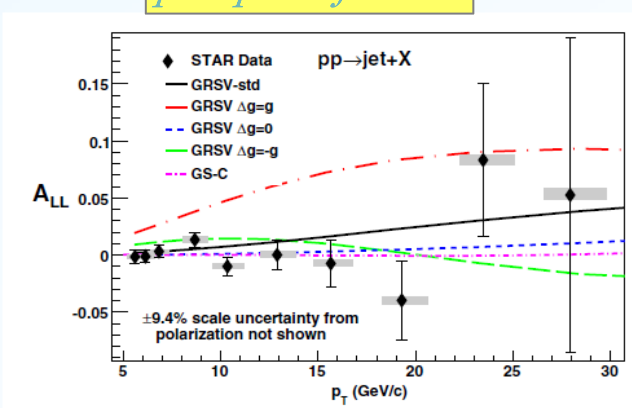
$p^{\uparrow} + p^{\uparrow} \rightarrow \pi^0 + X$

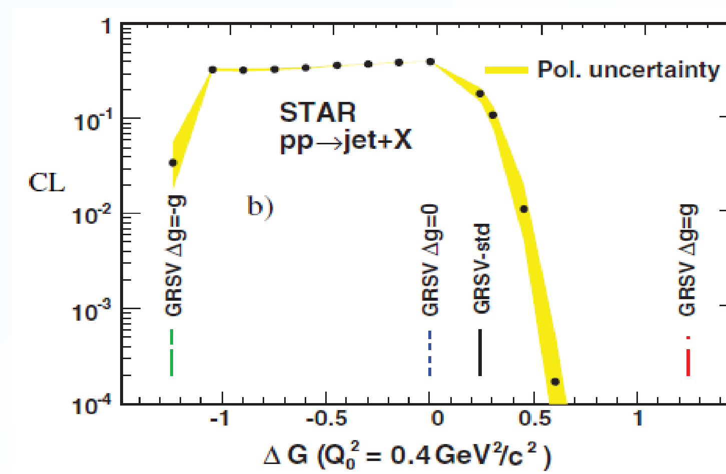




STAR

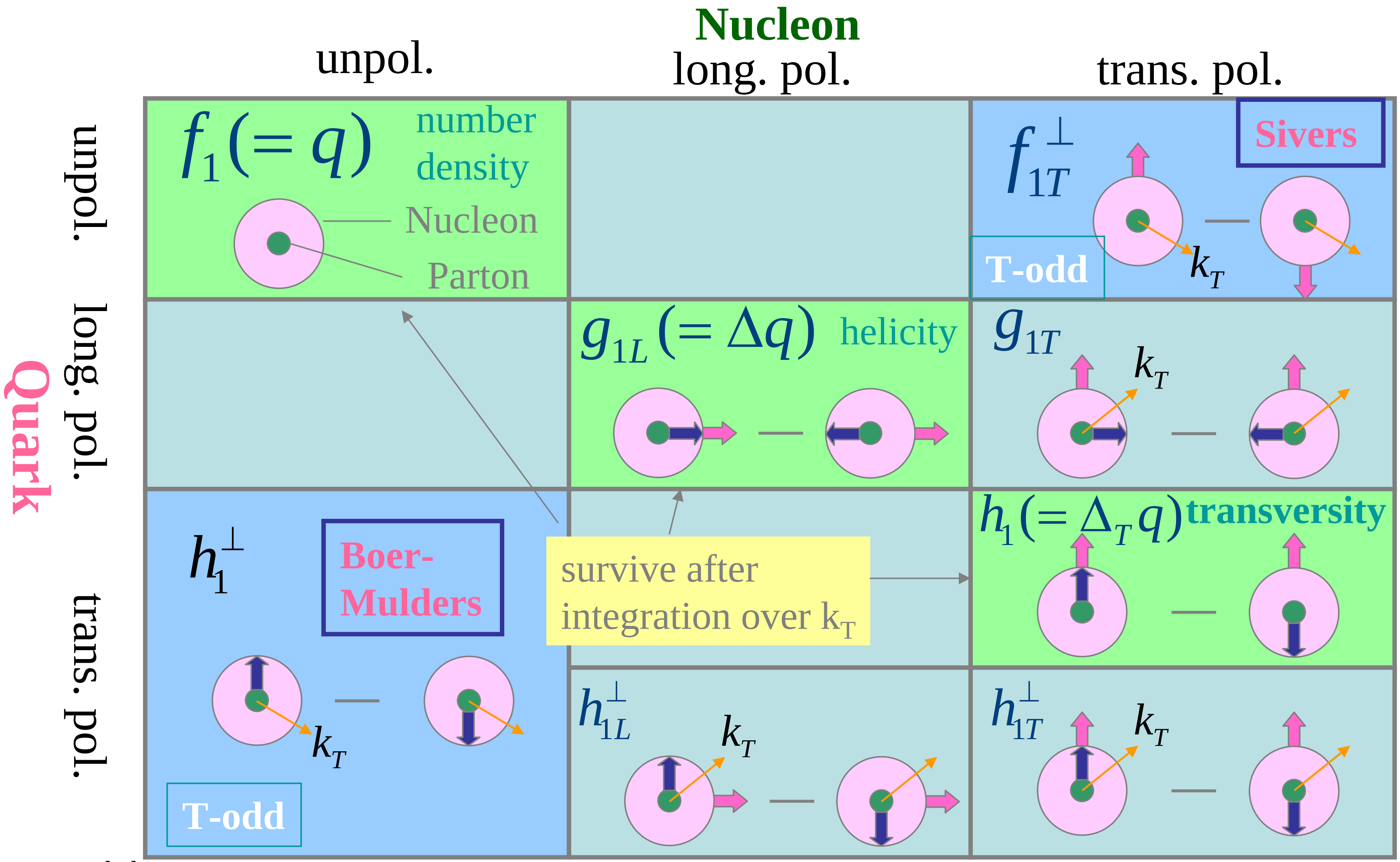
$p^{\uparrow} + p^{\uparrow} \rightarrow jet + X$





PRL **100**, 232003 (2008)

TRANSVERSE MOMENTUM DEPENDENT PDFs

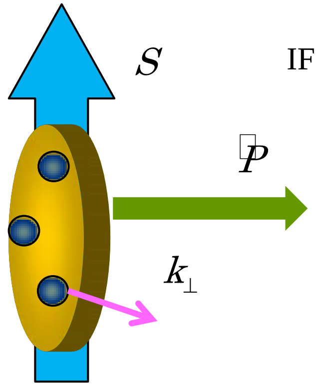


Takahiro Iwata

Sivers: distribution of unpol. quarks in ⊥ pol. proton

$$f_{q/p^\uparrow}(x,\mathbf{k}_\perp) = f_1^q(x,\mathbf{k}_\perp^2) - f_{1T}^{\perp q}(x,\mathbf{k}_\perp^2)\frac{(\hat{\mathbf{P}}\times\mathbf{k}_\perp)\cdot S}{M}$$

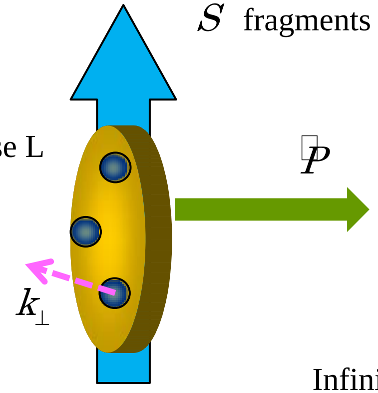
Asymptotic transverse momentum of the active quark ***after*** it has left the target and ***before*** it fragments into hadrons



IF $f_{1T}^{\perp q}(x,k_\perp^2)\neq 0$

$\neq$

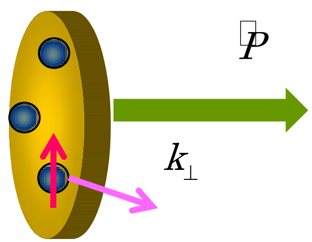
Case L



Infinite Momentum Frame

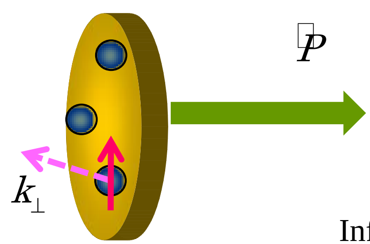
Boer-Mulders: distribution of ⊥ pol. quarks in unpol. proton

$$f_{q^\uparrow/p}(x,\mathbf{k}_\perp) = \frac{1}{2}\left[f_1^q(x,\mathbf{k}_\perp^2) - h_1^{\perp q}(x,\mathbf{k}_\perp^2)\frac{(\hat{\mathbf{P}}\times\mathbf{k}_\perp)\cdot S_q}{M}\right]$$



IF $h_1^{\perp q}(x,k_\perp^2)\neq 0$

$\neq$



Infinite Momentum Frame