摂動論的QCDとその展開

ーこれまでの研究と今後の課題ー

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Plan of the talk

1. はじめに
2. 深非弾性過程と摂動論的QCD
3. 摂動論的QCDの高次効果
4. その他
5. 今後の課題

1. はじめに

今，なぜ摂動論的QCDか?

- LHCでHiggsを発見して，標準模型を確立するには Higgs生成の強い相互作用効果の正確な評価と クォーク・グルーオンの分布関数PDFsの精密化が必要→ QCDの重要性の復活
- 将来のLinear Collider (ILC)でも，精度の高い計算が標準模型や超対称性の検証・探索に必要
- 摂動計算は最近の研究の進展によって，NNLO QCDオーダーが計算可能となった

これまでの研究

- ➢ 摂動論的QCD
- パートン分布・崩壊関数のQ^2依存性
- 深非弾性散乱の構造関数の高次補正
- 偏極深非弾性散乱と高次ツイスト効果
- 軸性量子異常と光子構造関数のQCD則
- 標的および重クォーク質量効果
- ➢ 超対称性　→　次回
- SUSYの破れと非線形実現
- ２及び3次元超重力理論（tensor calculus）
- N=4超共形代数（chiral superspace）
- N=2サイン・ゴルドン理論（保存則,S行列）

2.深非弾性過程と摂動論的QCD

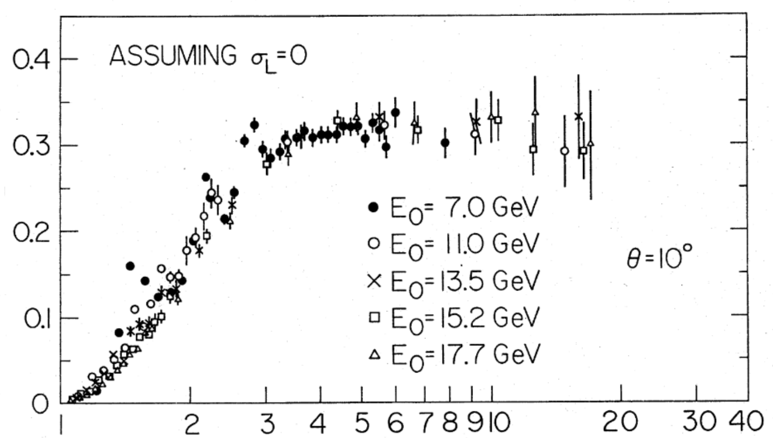
- 核子の構造の研究 (60年代）deep inelastic scattering
- Current Algebra → Bjorken scaling 1968
- SLAC-MIT experiment

$$\nu W_2(\nu, Q^2) \Rightarrow F_2(x) \quad x = \frac{Q^2}{2M\nu}$$

Parton分布関数

$$q(x),\ \ \bar{q}(x) \ \ (0 \le x \le 1)$$

$$F_2(x) = \sum_i e_i^2\, x\, (q(x) + \bar{q}(x))$$



$$\omega \equiv 2M\nu/Q^2 = 1/x$$

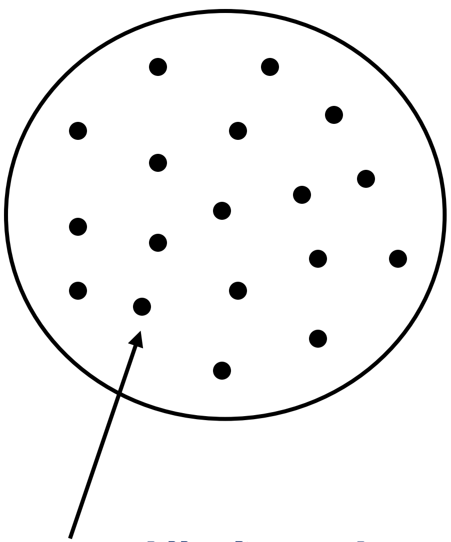
L.W.Mo SLAC-PUB-660 (1969)

Parton Model Feynman, Bjorken-Paschos

パートン描像

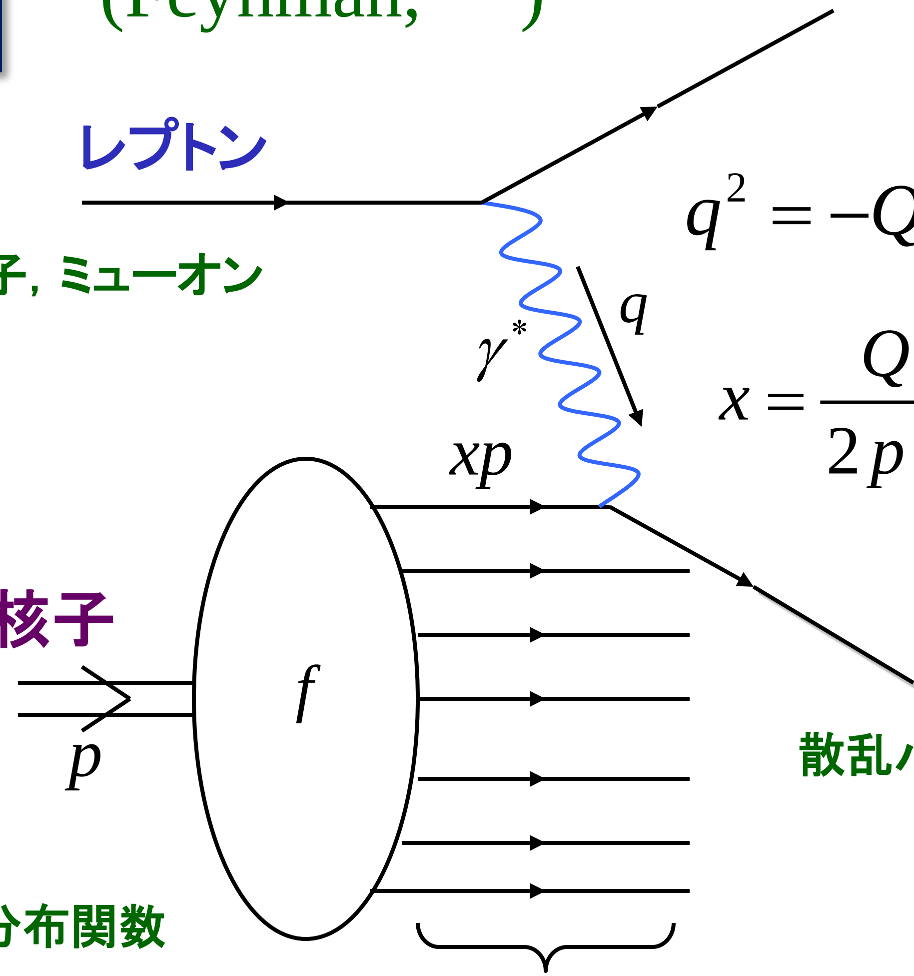
(Feynman,･･･)

核子など
ハドロン



点状構成要素

Parton



$$q^2 = -Q^2 < 0$$

$$x = \frac{Q^2}{2p\cdot q}$$

$f(x)\ (0 < x < 1)$ 自由なパートンの集まり

Scalingの破れ

- Broken scaling inv. くりこみ群　ε-展開
- Critical phenomena (物理量) $\underset{t \to t_c}{\sim} (t - t_c)^{-\nu}$
- スケーリングの破れ
- 場の理論でのくりこみ群的解析

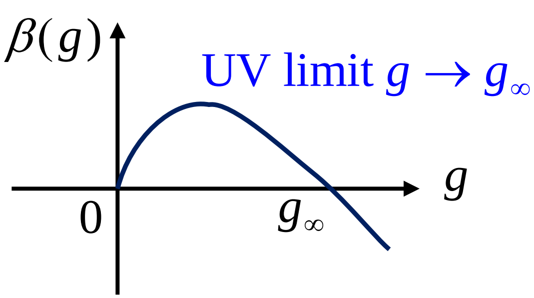
Kogut-Susskind
Scale-inv. Parton Model

$$M_n(Q^2) \equiv \int_0^1 dx x^{n-2} F_2(x, Q^2)$$

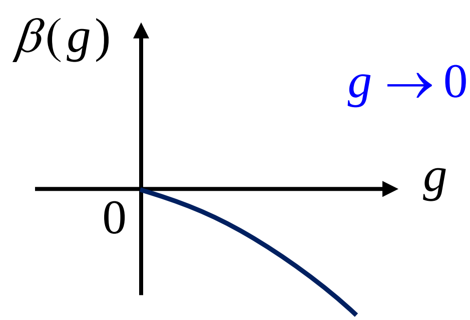
$$\sim (Q^2/Q_0^2)^{-\frac{1}{2}\gamma_n(g_\infty)}$$

$$\left\{ \begin{array}{ll} \text{fixed point theory} & \text{power breaking anomalous dim. } \gamma(g_\infty) \\ \text{asymptotically free theory} & \text{logarithmic breaking} \end{array} \right.$$

$$\sim (\ln Q^2/Q_0^2)^{-\gamma_n/2\beta_0}$$



fixed point theory



asymptotically free theory

QCDの登場(1973)

Color gauge theory (Color octet gluon) Nambu 1966

QCD

Fritzsch-Gell-Mann-Leutwyler 1973

Weinberg 1973

Asymtotic freedom

Gross-Wilczek, Politzer, ‘t Hooft 1973

・short distance ･･･漸近的自由

・long distance ･･･閉じ込め

QCD Lagrangian

g : coupling const.

$$\mathcal{L} = -\frac{1}{4} F^a_{\mu\nu} F^{a,\mu\nu} + i \sum \overline{\psi}^i_q \gamma^\mu (D_\mu)_{ij} \psi^j_q - \sum_q m_q \overline{\psi}^i_q \psi_{qi}$$

$$F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g f_{abc} A^b_\mu A^c_\nu$$

$$(D_\mu)_{ij} = \delta_{ij} - ig \sum_a (\lambda^a/2)_{ij} A^a_\mu$$

No free parameter

except for m_q

⇒ 第一原理から出発して摂動論で計算を遂行

Effective coupling constant

Fundamental constant of QCD

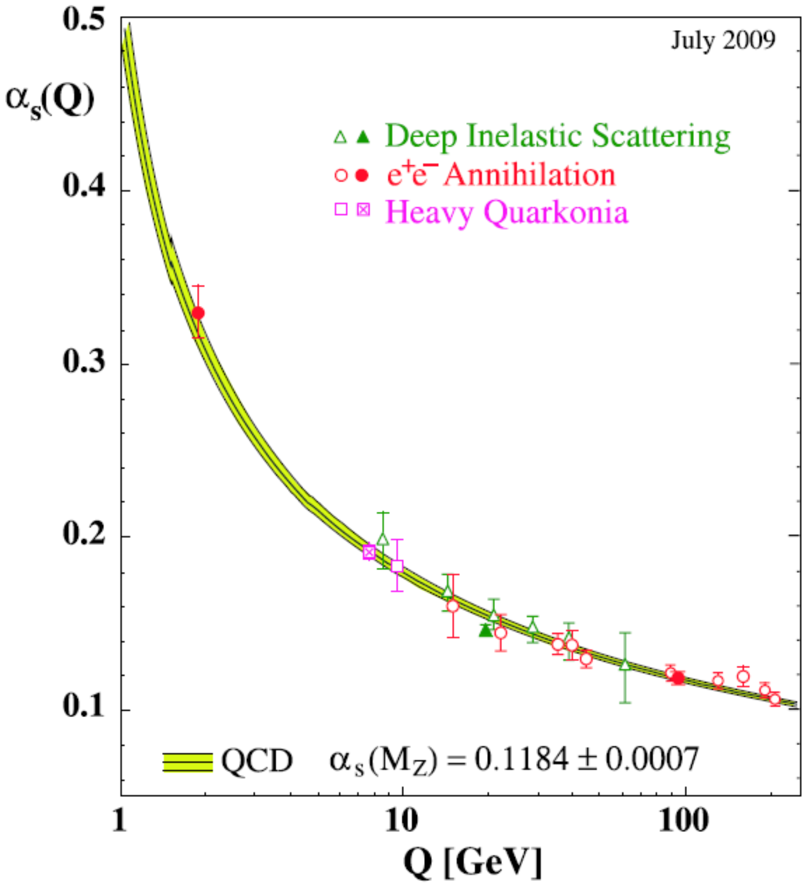
$$\Lambda_{QCD} = \mu e^{-\int \frac{dg}{\beta(g)}}$$

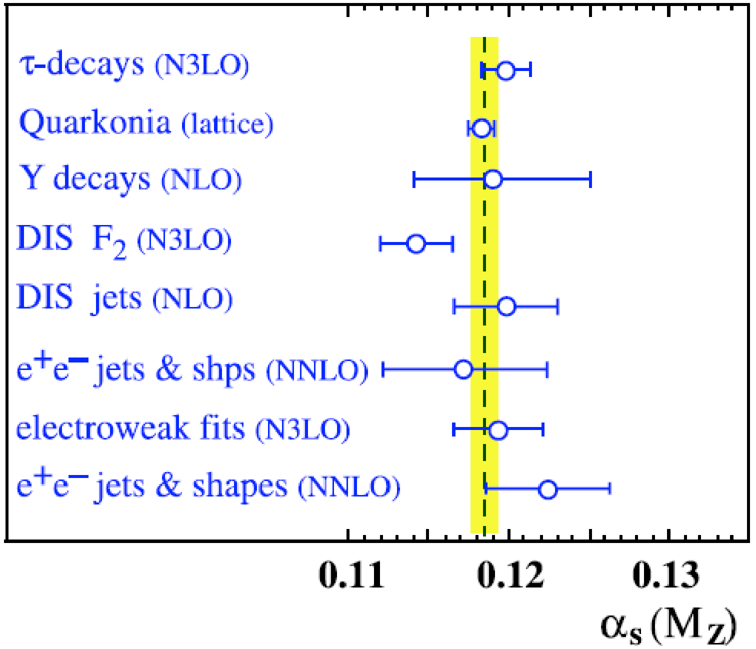
"dimensional transmutation"

$$\alpha_s(\mu^2) = \frac{4\pi}{\beta_0 \ln(\mu^2/\Lambda^2)} \times \left[1 - \frac{\beta_1}{\beta_0^2}\frac{\ln[\ln(\mu^2/\Lambda^2)]}{\ln(\mu^2/\Lambda^2)} + \cdots\right]$$

$\alpha_s(\mu_0^2)$ $\mu_0 = M_Z$

$\alpha_s(M_Z)$

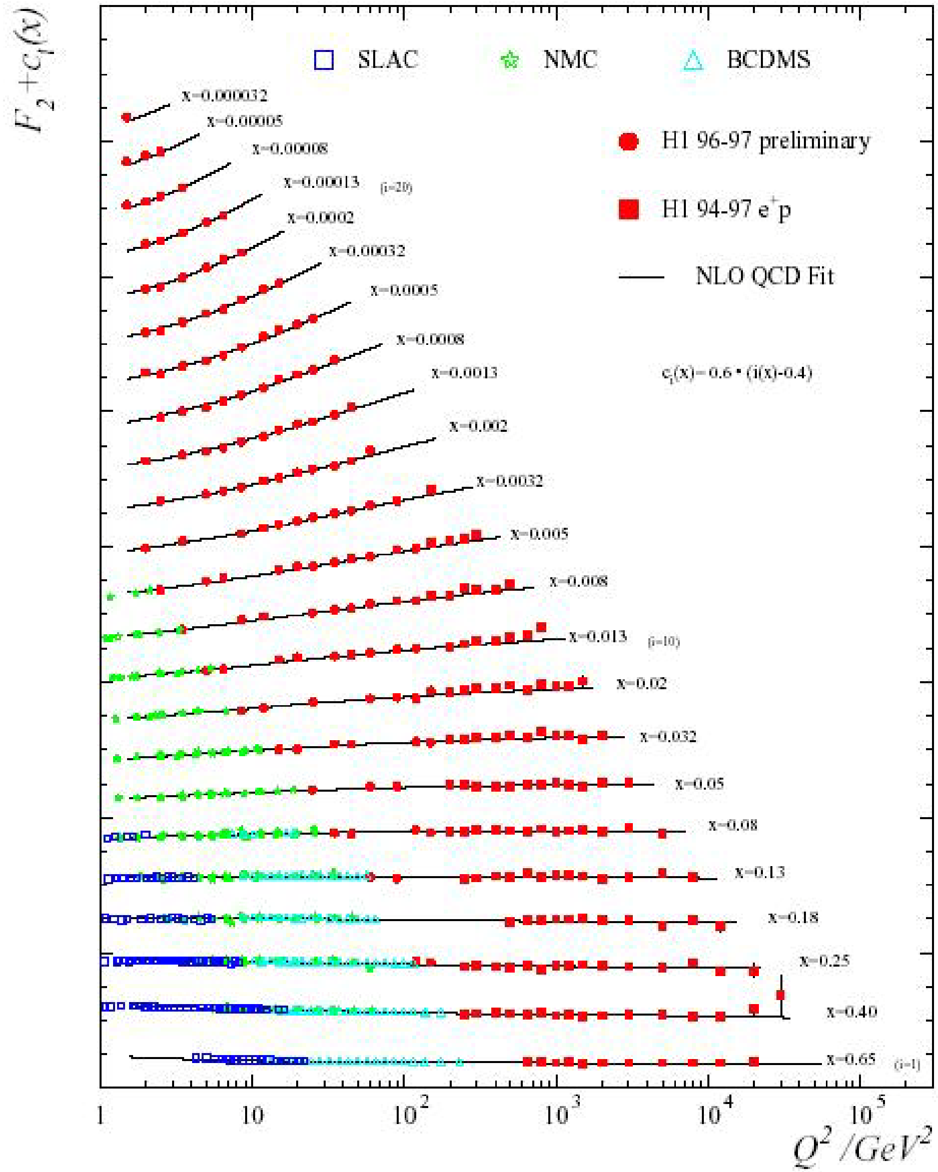




$$\alpha_s(M_{Z^0}) = 0.1184 \pm 0.0007$$

S.Bethke

Eur. Phys. J. C (2009) 64: 689–703



構造関数F_2のQ^2発展

Leading Order (LO) analysis

- OPE+RG analysis of structure function

Gross-Wilczek, Politzer,…

- DGLAP evolution equation for PDFs

Dokshitzer-Diakonov-Troyan,
Gribov-Lipatov, Altarelli-Parisi,…

- Q^2 dep. of fragmentation fn.

Georgi-Politzer, Owens, T.U.,…

- Polarized structure functions

Ahmed-Ross, Sasaki

因子化(Factorization)

short distance　　　　long distance

$\sigma \sim$ (短距離の物理) $\otimes$ (長距離の物理)

物理量　　摂動論　　convolution　　非摂動論

演算子積展開(OPE)

K.Wilson,…

$$J_\mu(x) J_\nu(0) \sim \sum_n C_n(x)\, O_n(0)$$

電磁カレント　　係数関数　　スピンnの演算子

$$\int d^4x\, e^{iqx} < p \,|\, J_\mu(x) J_\nu(0) \,|\, p > \sim \sum_{n,i} \widetilde{C}_n(q^2) < p \,|\, O^i{}_n(0) \,|\, p >$$

Factorization & PDFs

構造関数

$$F \sim f \otimes C = \tilde{f} \otimes \tilde{C}$$

PDF (Q^2dep)

scheme-依存性

Q^2 **依存性** ⟶ DGLAP eq. or OPE+RGE

Q^2発展方程式（DGLAP equation ）

$$\frac{dq(x,Q^2)}{d\ln Q^2} = \alpha_s \int_x^1 \frac{dy}{y}\left[P_{qq}\left(\frac{x}{y}\right) q(y,Q^2) + P_{qG}\left(\frac{x}{y}\right) G(y,Q^2)\right]$$

$$\frac{dG(x,Q^2)}{d\ln Q^2} = \alpha_s \int_x^1 \frac{dy}{y}\left[P_{Gq}\left(\frac{x}{y}\right) q(y,Q^2) + P_{GG}\left(\frac{x}{y}\right) G(y,Q^2)\right]$$

クォーク･グルーオン演算子

$$O_n^q = \overline{\psi}\gamma_{\mu_1} D_{\mu_2} \cdots D_{\mu_n} \psi - \text{traces}$$

クォーク場

$$O_n^G = G_{\mu_1 \alpha} D_{\mu_2} \cdots D_{\mu_{n-1}} G^{\alpha}_{\ \mu_n} - \text{traces}$$

グルーオン場

Twist
ツイスト2
の演算子

Twist=dimーspin=2

分布関数と演算子

Kodaira-TU, Nucl. Phys. B141(1978)497

$$< p | O_n^q (\mu) | p >|_{\mu^2 = Q^2} = \int_0^1 x^{n-1} q(x, Q^2) dx$$

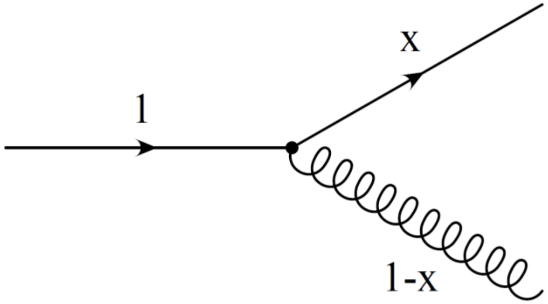
μ でくりこまれた演算子

scheme- dependence

$$< p | O_n^G (\mu) | p >|_{\mu^2 = Q^2} = \int_0^1 x^{n-1} G(x, Q^2) dx$$

Splitting functions

$$P_{qq}(x) = C_F \left(\frac{1+x^2}{1-x} \right)_+$$



"Plus distribution"

$$\int_0^1 dx \frac{f(x)}{(1-x)_+} = \int_0^{1-\varepsilon} dx \frac{f(x)}{1-x} - \int_0^{1-\varepsilon} dx \frac{f(1)}{1-x}$$

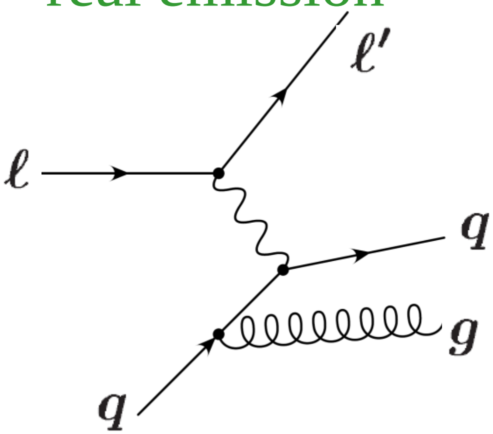
real emission

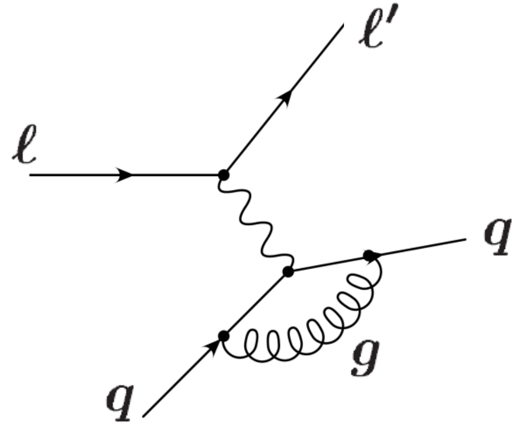
virtual correction

infrared cancel

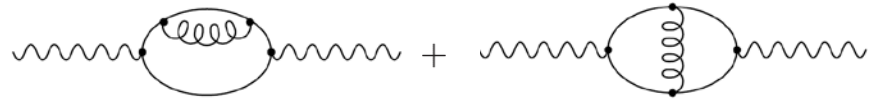
Kinoshita-Lee-Nauenberg

-Nakanishi Theorem





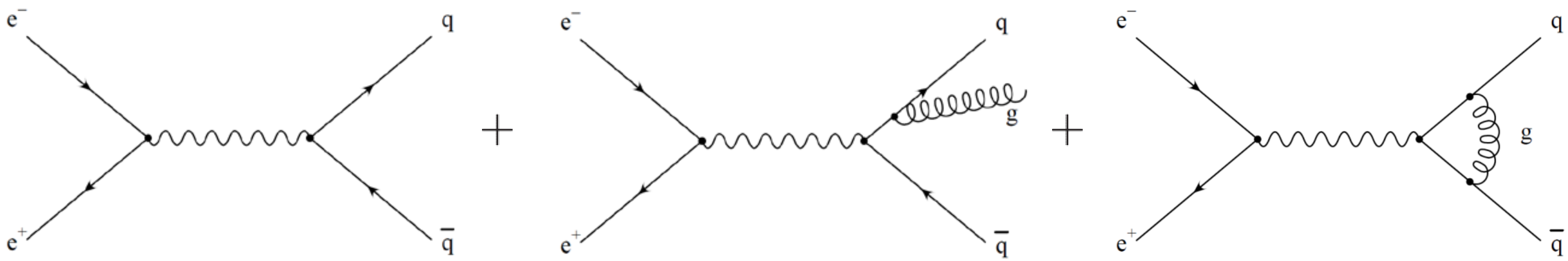
$\mathrm{e^+e^-} \to$ hadrons



$$R = \frac{\sigma(\mathrm{e^+e^-} \to \mathrm{hadrons})}{\sigma(\mathrm{e^+e^-} \to \mu^+\mu^-)} = 3\sum_{i=1}^{n_f} e_i^2 \left(1 + \frac{\alpha_s}{\pi} + \cdots\right)$$

$\mathrm{e^+e^-}$ jet production

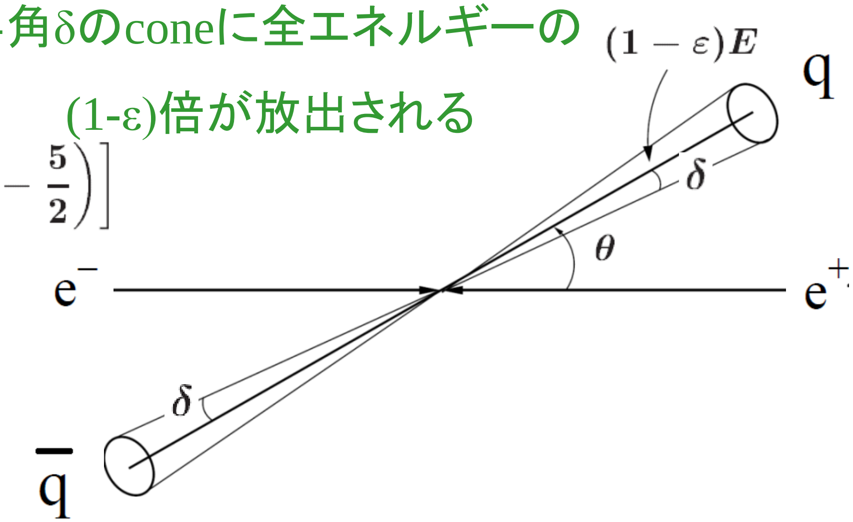
3-jet event @DESY 1979



Sterman-Weinberg jet

半角δのconeに全エネルギーの

(1-ε)倍が放出される



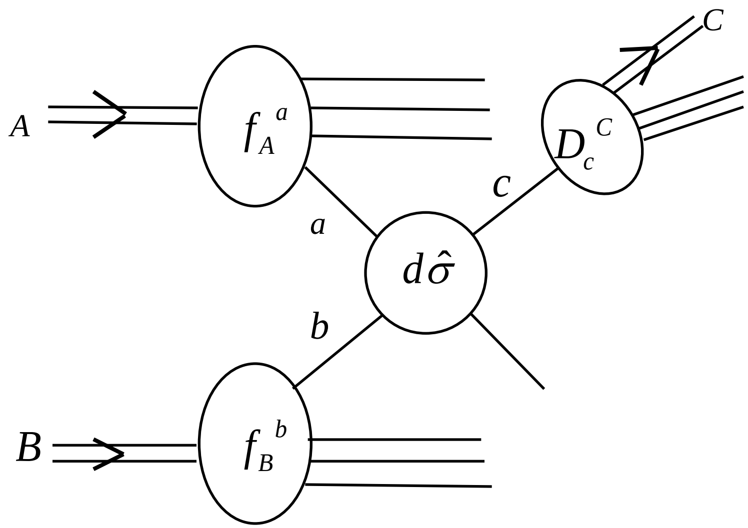
$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_0 \left[1 - \frac{\alpha_s}{\pi} C_F \left(4\ln\delta\ \ln\varepsilon + 3\ln\delta + \frac{\pi^2}{3} - \frac{5}{2}\right)\right]$$

$$\left(\frac{d\sigma}{d\Omega}\right)_0 = \frac{\alpha^2}{4s}\sum_i e_i^2 (1+\cos\theta)$$

infrared/collinear-safe quantity

Event shapes: Thrust etc.

Factorization in hadron collisions



high-energy QCD process:

$A+B\to C+X$

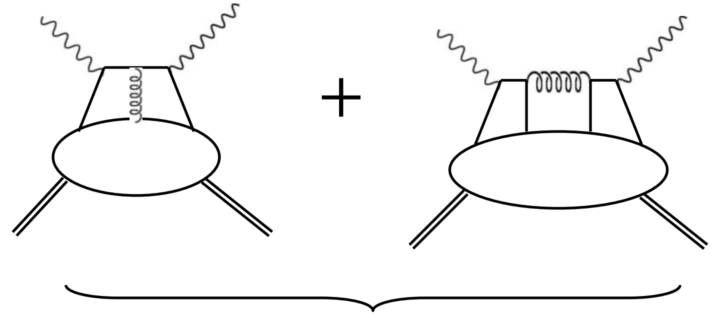
$$\frac{Q^2}{4}\le \mu_R{}^2,\mu_F{}^2,\mu_D{}^2\le 4Q^2$$

$$d\sigma=\int dx_a dx_b dz_c\, f_A{}^a(x_a,\mu_F)\otimes f_B{}^b(x_b,\mu_F)$$

$$\otimes \underbrace{d\hat{\sigma}(x_a,x_b,z_c,\mu_R,\mu_F,\mu_D)}_{\text{摂動計算可能}}\otimes D_c{}^C(z_c,\mu_D)$$

DIS, $e^+e^-\to hX$, Drell-Yan, hadron-hadron semi-inclusive･･

Higher-twist effects



Twist-3 or 4

$$M_n(Q^2) = \int_0^1 dx x^{n-2} F_2(x, Q^2)$$

$$= \sum_\tau \frac{1}{(Q^2)^{\frac{\tau-2}{2}}} A_n^{(\tau)} = A_n^{(2)} + \frac{A_n^{(4)}}{Q^2} + \frac{A_n^{(6)}}{Q^4} + \cdots$$

twist-2 twist-4 twist-6

τ twist=dim-spin

- Twist-4 4-quark 2-quark&1gluon operators
- Anomalous dimensions of 4-quark operators

Gottlieb(78) ,Okawa(80)

- Polarized structure fn. twist-3 contributes to g_2

Kodaira-Tanaka-TU-Yasui (96)

- twist-4 effects to g_1

Kawamura et al (97)

3.摂動QCDの高次効果

$$M_n(Q^2) \sim (\ln Q^2/\Lambda^2)^{-\gamma_n^0/2\beta_0}(1 + C_n^1\alpha_s + C_n^2\alpha_s^2 + \cdots)$$

Moment of structure fn.

LO NLO NNLO

$$\gamma_n(g) = \gamma_n^0\alpha_s + \gamma_n^1\alpha_s^2 + \cdots \qquad \gamma_n^0 = \int_0^1 dx x^{n-1} P^0(x)$$

1-loop 2-loop Floratos et al (78) 1-loop anomalous dim.

coefficient fn.

$$\left(\mu\frac{\partial}{\partial\mu} + \beta(g)\frac{\partial}{\partial g} - \gamma_n(g)\right) C_n(\frac{Q^2}{\mu^2}, g) = 0$$

RG eq.

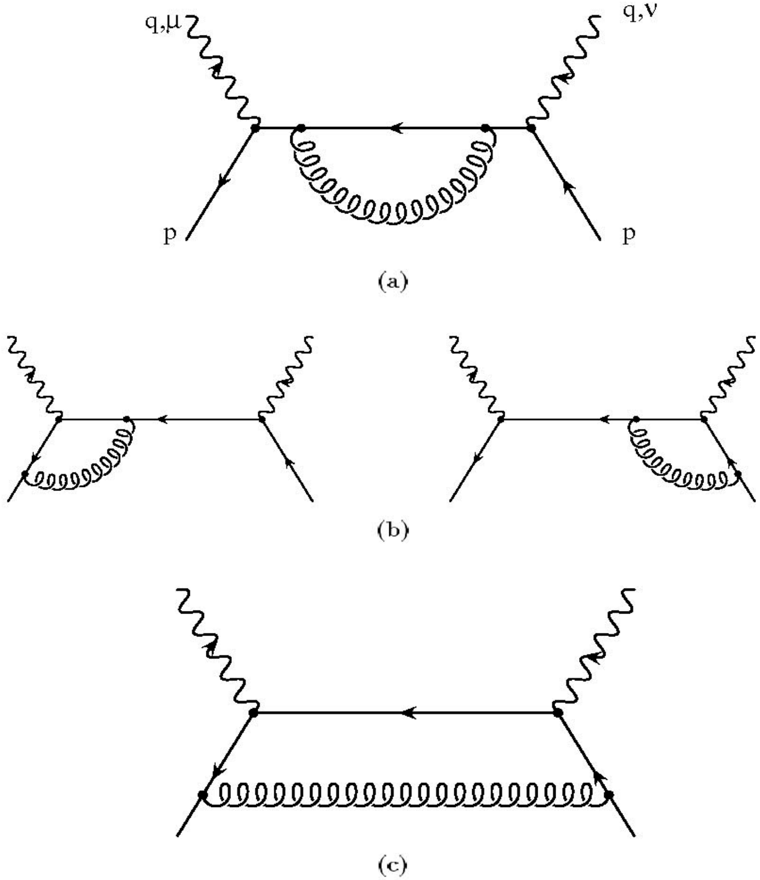
$$C_n(1,g) = 1 + B_n^1\alpha_s + \cdots \qquad C_n^1 = B_n^1 + \gamma_n^1/2\beta_0$$

1-loop Bardeen et al (78) Scheme independent

	anomalous dim.	coefficient fn.
LO	1-loop	tree
NLO	2-loop	1-loop
NNLO	3-loop	2-loop

Moch et al (04)

Virtual Compton Scattering off quark to α_s



QCDの高次補正　α_s **1次のオーダー**

QCD高次効果

物理量

Anomalous dim.

$$M(Q^2) \sim M_0 (\ln Q^2/\Lambda^2)^{-\gamma} \; (1 + C_1\alpha_s + C_2\alpha_s^2 + \ldots)$$

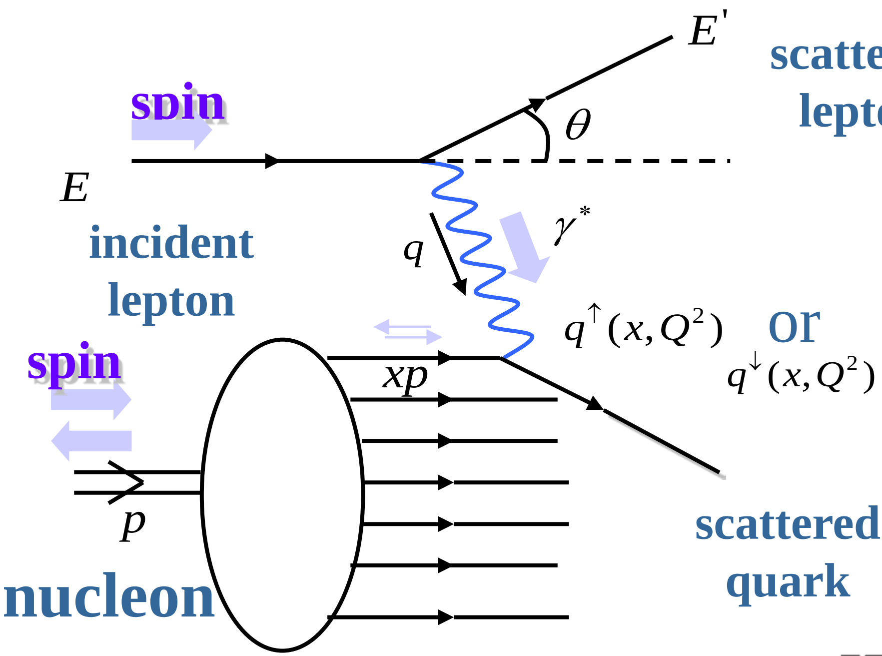
Leading-log Next-Leading-log

Bjorken和則に対する高次効果

$$\int_0^1 dx[g_1{}^p(x) - g_1{}^n(x)] = \frac{1}{6} g_A (1 - \frac{\alpha_s}{\pi} + O(\alpha_s^2))$$

Kodaira et al. 1979

偏極深非弾性散乱と構造関数



$$x = \frac{Q^2}{2p\cdot q} \qquad q^2 = -Q^2$$

Structure tensor

$$W_{\mu\nu} = W_{\mu\nu}^{[S]} + iW_{\mu\nu}^{[A]}$$

$$W_{\mu\nu}^{[S]} \Rightarrow F_1(x,Q^2), \quad F_2(x,Q^2)$$

Unpolarized structure fns.

$$W_{\mu\nu}^{[A]} \Rightarrow g_1(x,Q^2), \quad g_2(x,Q^2)$$

$$\left(\frac{d^2\sigma}{d\Omega dE'}\right)^{\downarrow\uparrow} - \left(\frac{d^2\sigma}{d\Omega dE'}\right)^{\uparrow\uparrow} \propto L_{[A]}^{\mu\nu} W_{\mu\nu}^{[A]}$$

polarized structure fns.

$$= \frac{\alpha^2}{E^2 \sin^2(\theta/2)} \left[(E + E'\cos\theta)\frac{1}{p\cdot q} g_1(x,Q^2) - \frac{Q^2}{(p\cdot q)^2} M g_2(x,Q^2) \right]$$

クォークが担う核子のスピンの割合

1988年　欧州共同原子核研究所(CERN)　EMCグループ

$$S_q = \frac{1}{2}(\Delta u + \Delta d + \Delta s) = \frac{1}{2}\Delta\Sigma$$

$$\Delta\Sigma = 0.12 \pm 0.17$$

→ クォークは核子スピンの12%しか担っていない→ "Spin Crisis"

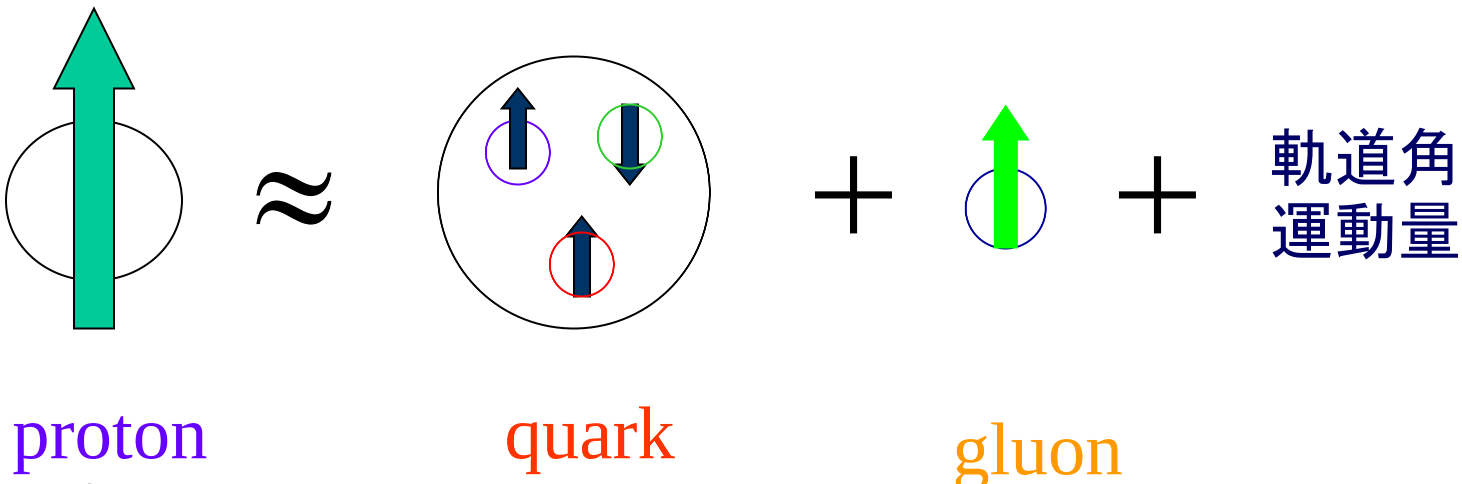
QCDの補正を入れて　SLAC, DESYのデータを解析したところ

$$\Delta\Sigma = 0.19 \sim 0.23$$

単純なクォーク模型のΔΣ=1から大きくずれる

核子のスピンの分布

$$J = \frac{1}{2}$$



$$\frac{1}{2} = \langle S_z \rangle + \langle S_G \rangle + \langle L_z \rangle$$

$$\frac{1}{2}\Delta\Sigma \qquad \Delta\Sigma \approx 0.12$$

$$\int d^4x\, e^{iqx} \langle p|J_\mu(x) J_\nu(0)|p\rangle^{[A]} \sim \varepsilon_{\mu\nu\lambda\sigma} q^\lambda \langle p|A^\sigma|p\rangle (1 - \alpha_s/\pi) + \cdots$$

$$\Delta\Sigma \approx 0.1 - 0.3 \qquad \langle p,s|\overline{\psi}\gamma_\mu\gamma_5\psi|p,s\rangle = s_\mu\, \Delta\Sigma$$

But this is relativistic quantities !

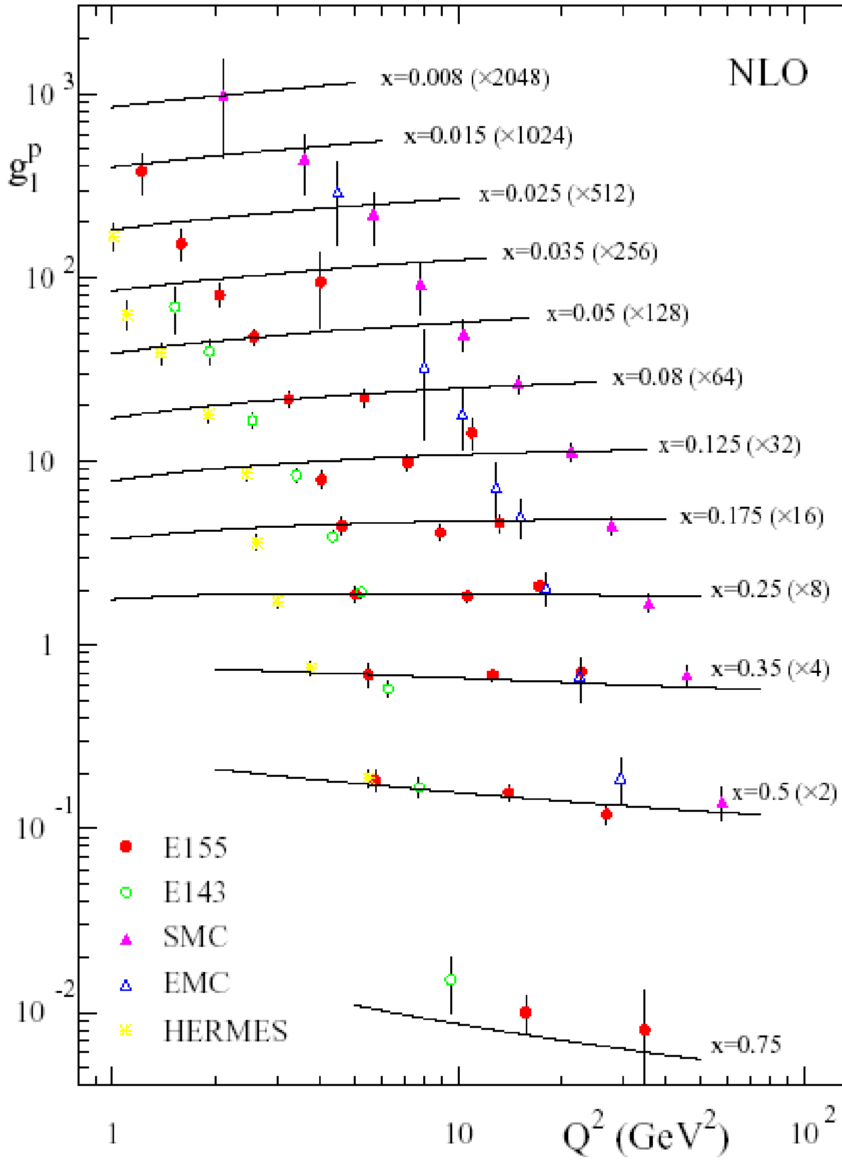
Altarelli-Ross Phys. Lett B212 (1988) 391

Gluon polarization contributes due to anomaly

$$\Delta\Sigma = \Delta\tilde{\Sigma} - n_f \frac{\alpha_s}{2\pi} \Delta\tilde{G}$$

⇒ Parton distribution functions are scheme-dependent

J. Kodaira and T. U. Nucl. Phys. B141 (1978) 497



偏極構造関数g_1のQ^2発展

1st moment sum rule

$g_1(x, Q^2)$

$\mathcal{O}(\alpha_s)$ QCD correction to the Bjorken sum rule:

$$\int_0^1 dx\, [\, g_1^p(x, Q^2) - g_1^n(x, Q^2)\,] = \frac{1}{6} g_A \left(1 - \frac{\alpha_s}{\pi}\right)$$

Kyoto Group Kodaira et al. 1979 flavor non-singlet

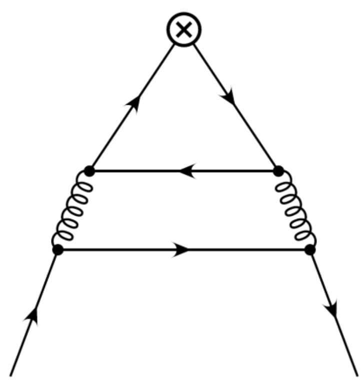
Phys.Rev.D20 (1979) 627; Nucl.Phys. B159 (1979) 99

Now $\mathcal{O}(\alpha_s^3)$ Larin-Vermaseren (1991)

flavor singlet → Axial anomaly

Kodaira Nucl.Phys. B165 (1980)129 $\gamma_1^{n=1} = 16 n_f \neq 0$

$$\int_0^1 dx\, g_1^S(x, Q^2) = \frac{1}{2} a_1^S \left[1 - \frac{33 - 8n_f}{33 - 2n_f} \frac{\alpha_s}{\pi}\right]$$



$\mathcal{O}(\alpha_s)$

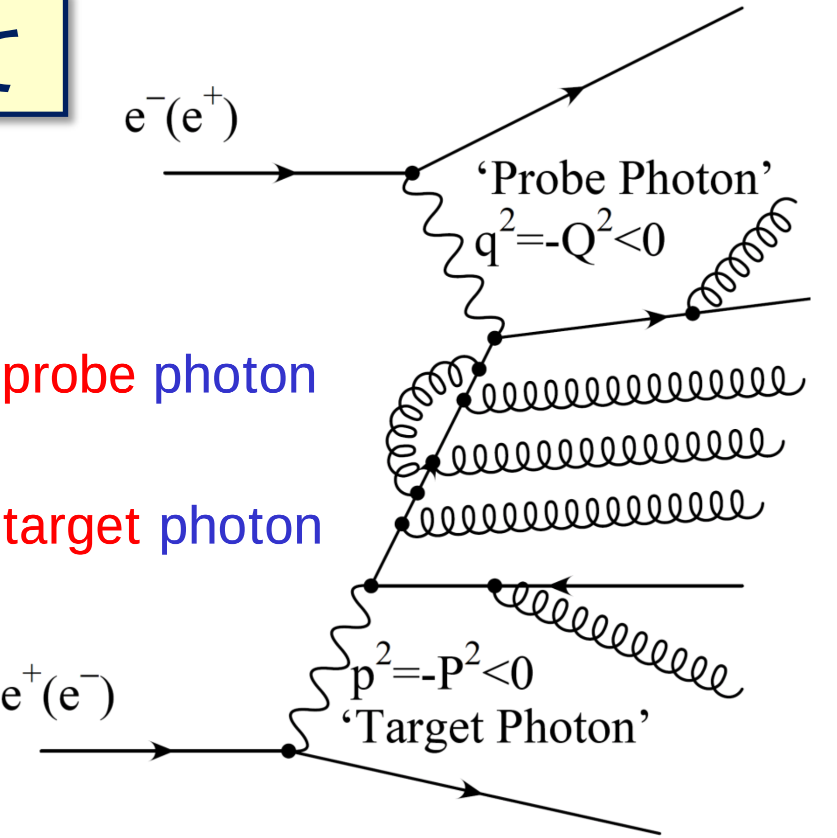
QCD correction

光子構造関数をめぐって

$$x = \frac{Q^2}{2p \cdot q}$$: Bjorken variable

$$Q^2 = -q^2 > 0$$: Mass squared of probe photon

$$P^2 = -p^2 > 0$$: Mass squared of target photon



In the kinematic region:

$$\Lambda^2 \ll P^2 \ll Q^2$$

structure fns. F_2^γ and F_L^γ

g_1^γ and g_2^γ

perturbatively calculable !

e^+e^-collision

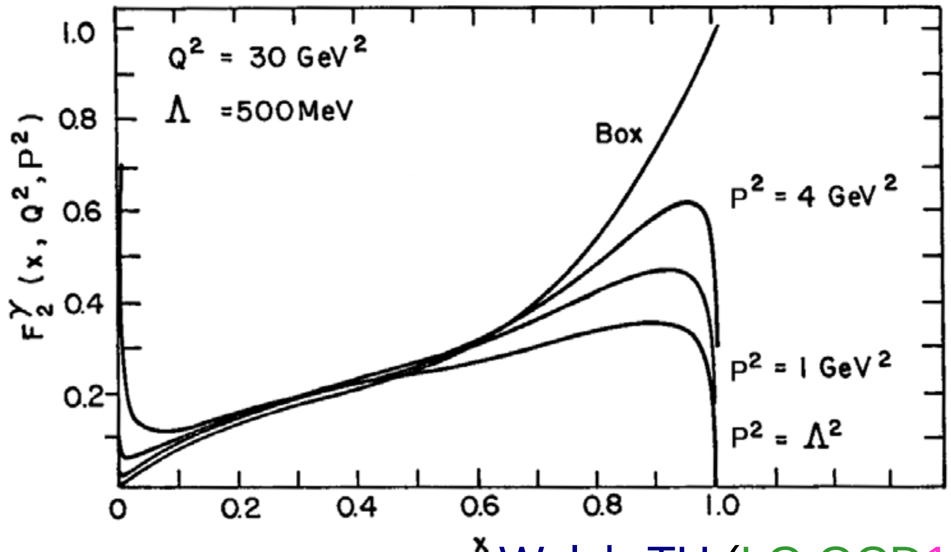
& QCD interactions

何故photon structure fn.に興味があるか?

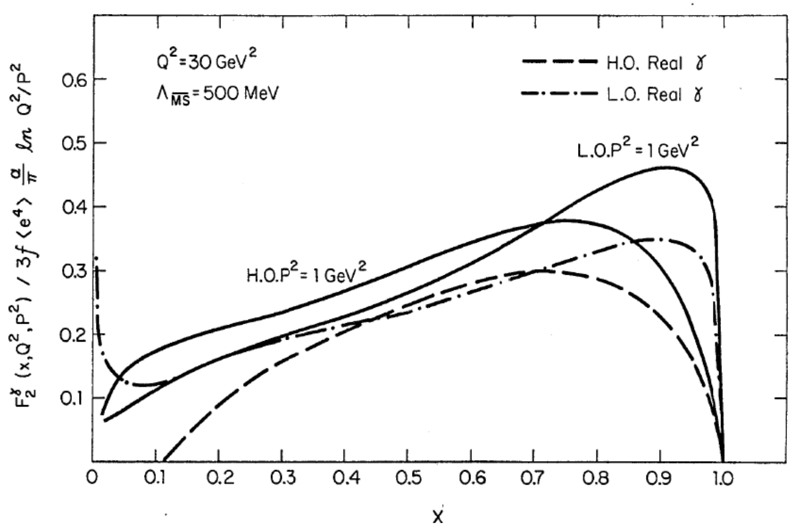
- perturbation theoryでQCDのdynamicsを調べる
  良い probe を提供する
- 将来の電子･陽電子のLinear Collider (ILC)では
  2-光子過程の新たなkinematical領域が探索可能
- 3-loop Splitting function の登場によって NNLO
  QCDオーダーのphoton structureが計算される
- Polarized Structure -> 軸性異常(axial anomaly)

LO

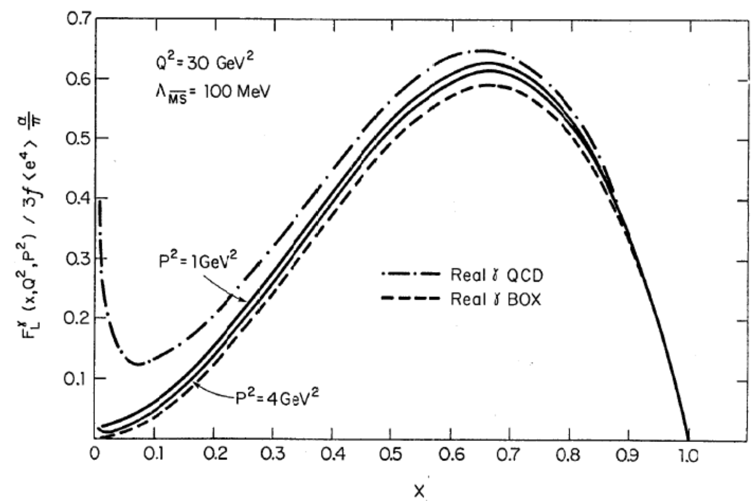
NLO



Walsh-TU (LO QCD1981)



$F_2^\gamma(x, Q^2, P^2)$

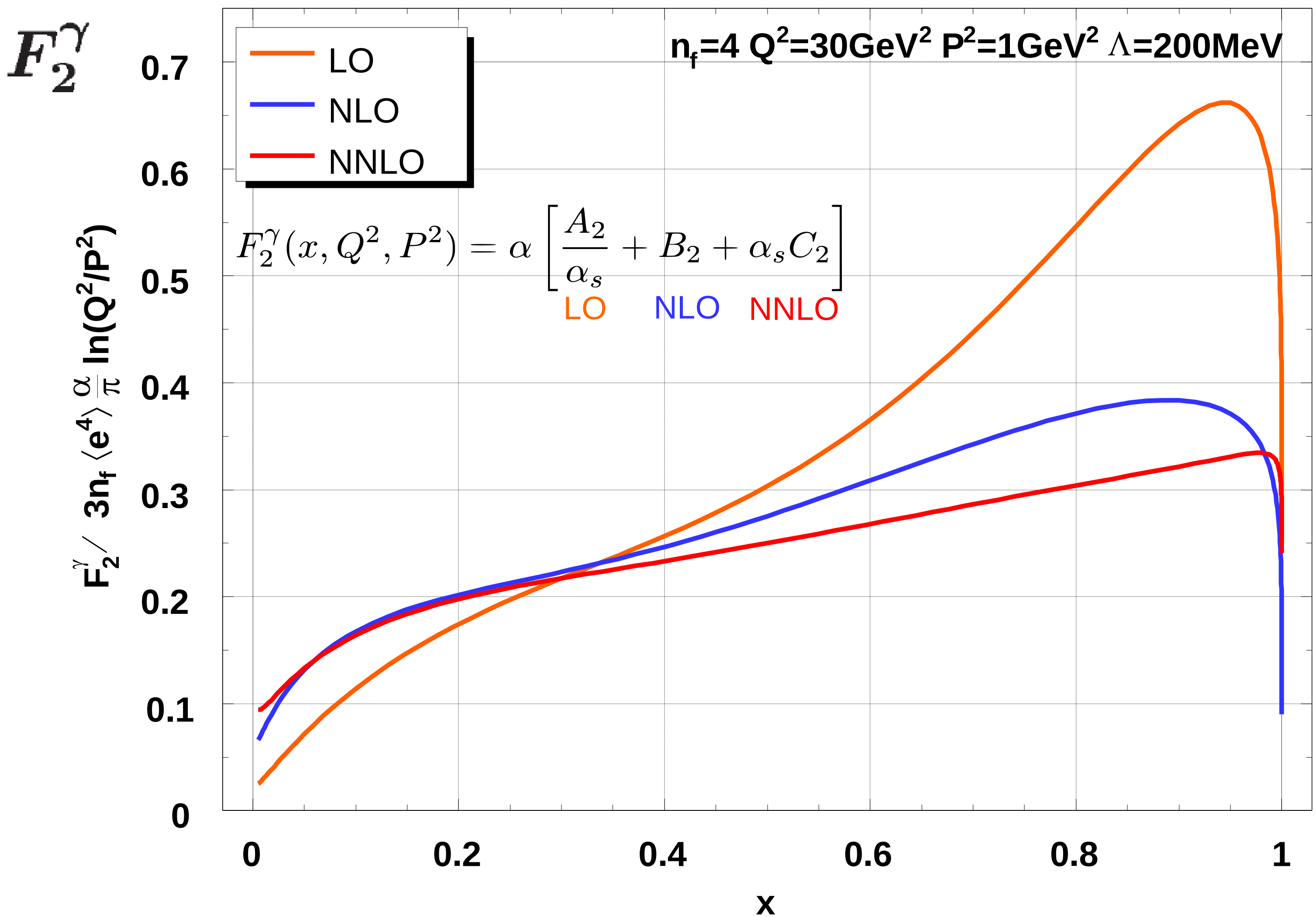


$F_L^\gamma(x, Q^2, P^2)$

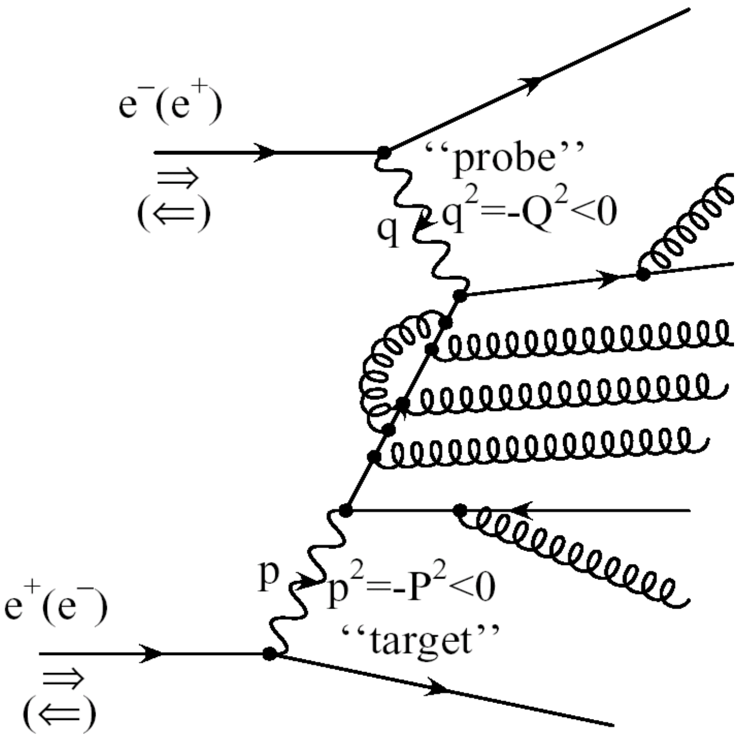
Walsh-TU, NPB199(1982)93

NNLO Analysis

K. Sasaki, T. Ueda and T.U.,
Phys. Rev.D75 (2007) 114009



偏極光子構造関数



Structure tensor $W_{\mu\nu\rho\tau}$

$$W_{\mu\nu\rho\tau} = W^S_{\mu\nu\rho\tau} + iW^A_{\mu\nu\rho\tau}$$

Anti-symmetric part

$$W^A_{\mu\nu\rho\tau} = \epsilon_{\mu\nu\lambda\sigma} q^\lambda \epsilon_{\rho\tau}{}^{\sigma\beta} p_\beta \frac{1}{p\cdot q} g_1^\gamma$$
$$+ \epsilon_{\mu\nu\lambda\sigma} q^\lambda (p\cdot q\ \epsilon_{\rho\tau}{}^{\sigma\beta} p_\beta - \epsilon_{\rho\tau\alpha\beta} p^\beta p^\sigma q^\alpha) \frac{1}{(p\cdot q)^2} g_2^\gamma$$

$\Rightarrow$ g_1^γ and g_2^γ

Polarized photon structure functions

g_1^γ ⇨ the 1st moment is related to the axial anomaly

g_2^γ ⇨ only exists for the virtual photon $P^2 \neq 0$

(No g_2^γ for real photon $P^2 = 0$)

the twist-3 effect contributes

- Evaluation of QCD corrections to the 1st moment sum rule to NNLO $O(\alpha\alpha_s^2)$
- Large Nc limit of g_2^γ to LO

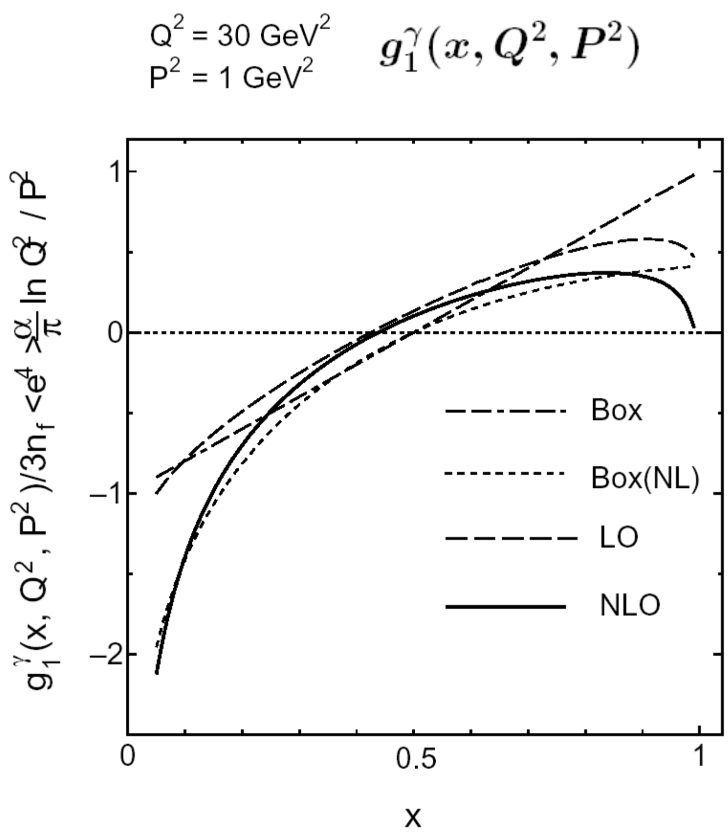
K. Sasaki, T. Ueda and T.U., Phys. Rev.D73 (2006) 094024.

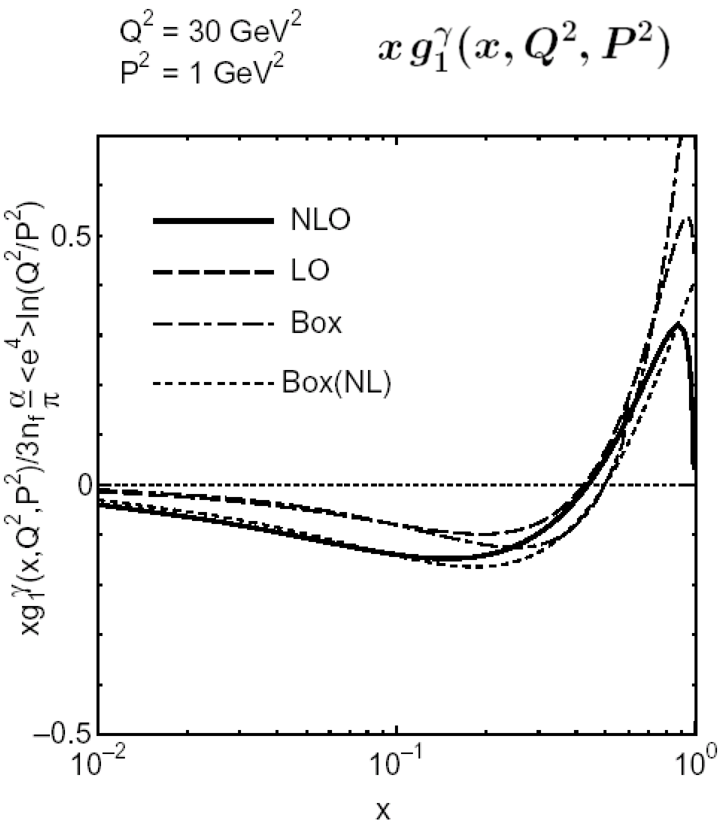
H. Baba K. Sasaki and T.U., Phys. Rev. D65 (2001)1140185.

Polarized photon structure function $g_1^\gamma(x, Q^2, P^2)$

to NLO in QCD

only twist-2 op. contributes



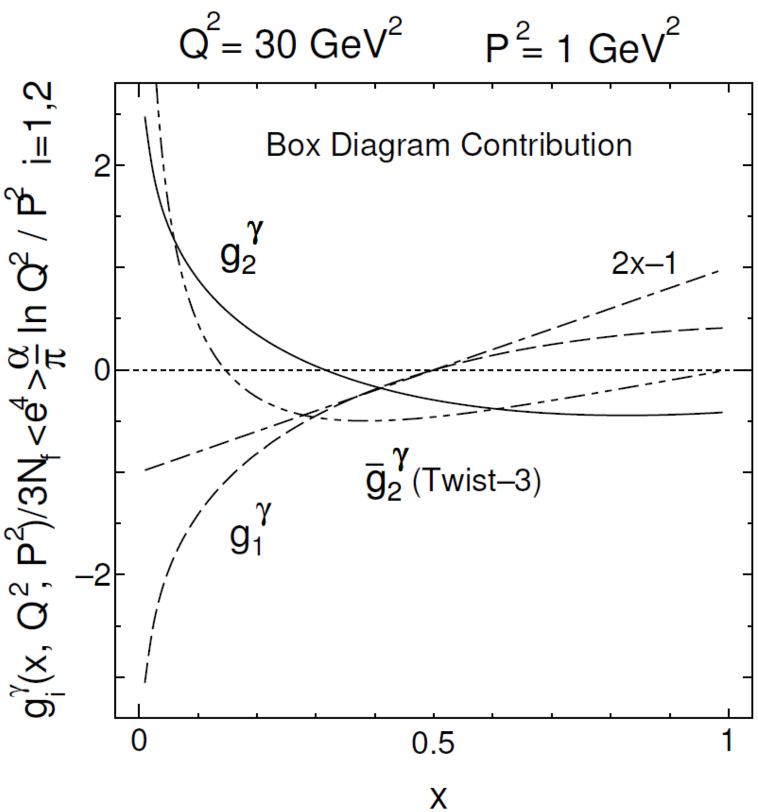


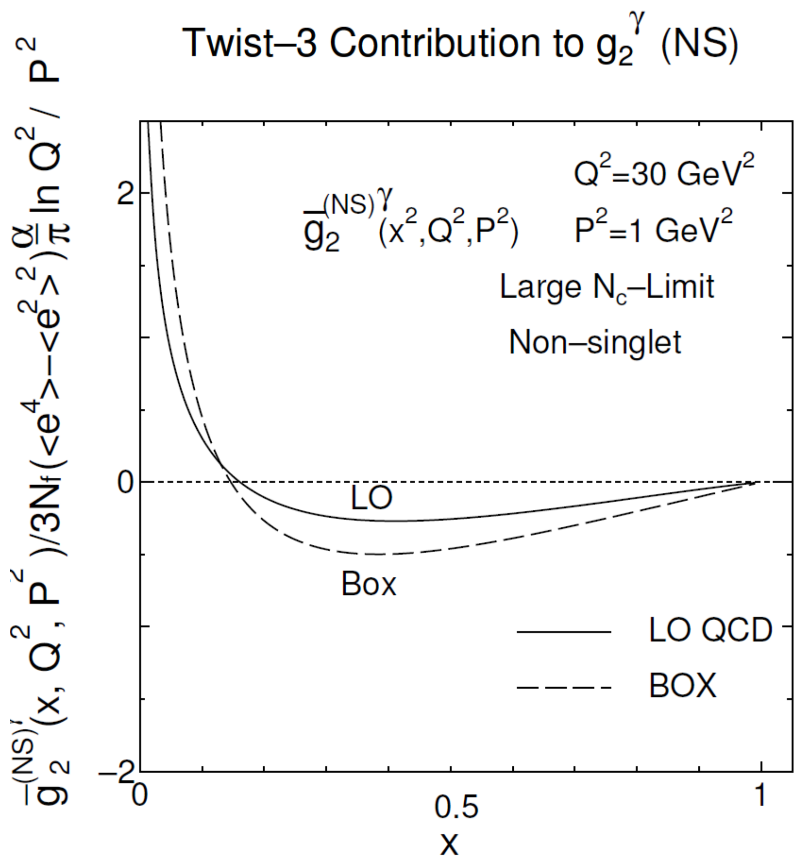
K. Sasaki and T.U., Phys. Rev.D59 (1999) 114011

H. Baba K. Sasaki and T.U., Phys. Rev. D65 (2001)1140185.

$$\int_0^1 dx x^{n-1} \bar{g}_2^{\gamma(NS)}(x,Q^2,P^2) = \frac{n-1}{n}\frac{\alpha}{4\pi}\cdot\frac{1}{2\beta_0}(-24N_f)(\langle e^4\rangle - \langle e^2\rangle^2)\frac{1}{n(n+1)}$$
$$\times\frac{1}{1+\lambda_{NS}^n/2\beta_0}\frac{4\pi}{\alpha_s(Q^2)}\left\{1-\left(\frac{\alpha_s(Q^2)}{\alpha_s(P^2)}\right)^{\lambda_{NS}^n/2\beta_0+1}\right\}$$

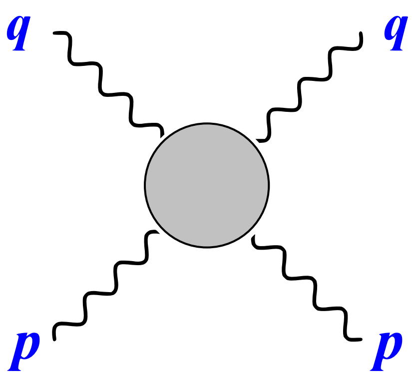
In the Large Nc limit





The 1st moment of g_1^γ is related to triangle anomaly in OPE

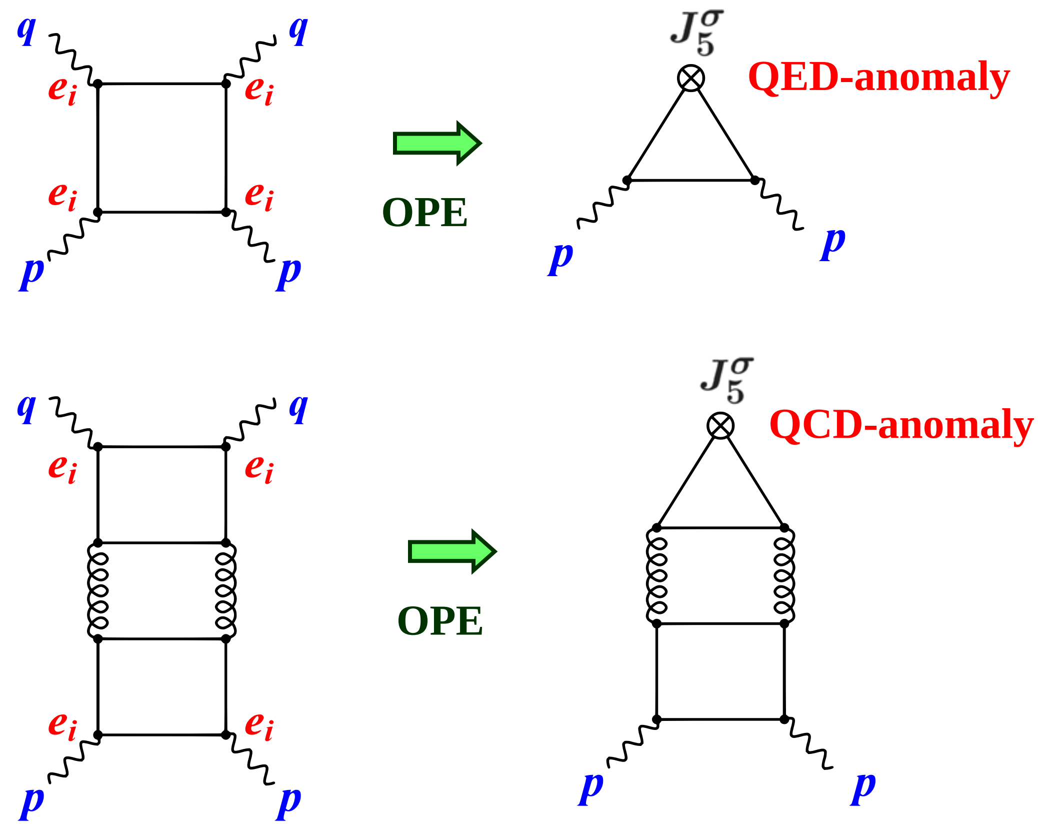
axial-vector current J_5^σ



(Box diagram)

$\sum_i^{n_f} e_i^4$:

$\left(\sum_i^{n_f} e_i^2\right)^2$:



For the virtual photon target ($P^2 \neq 0$)

In far off-shell case $\Lambda^2 \ll P^2 \ll Q^2$, perturbatively calculable

NLO result is

(no experimental input)

Λ : QCD scale parameter

n_f : # of flavor **e_i : quark charge**

$$\int_0^1 dx\, g_1^\gamma(x, Q^2, P^2)$$

$$= -\frac{3\alpha}{\pi}\left[\sum_{i=1}^{n_f} e_i^4 \Big(\underbrace{1}_{\text{LO}} - \underbrace{\frac{\alpha_s(Q^2)}{\pi}}_{\text{NLO}}\Big) - \underbrace{\frac{2}{\beta_0}\left(\sum_{i=1}^{n_f} e_i^2\right)^2 \left(\frac{\alpha_s(P^2)}{\pi} - \frac{\alpha_s(Q^2)}{\pi}\right)}_{\text{NLO}}\right] + \mathcal{O}(\alpha\alpha_s^2)$$

LO **NLO**

Now we extend this result to NNLO!

Narison-Shore-Veneziano (1993)

Sasaki-Uematsu (1999) **Shore (2005)**

1st moment sum rule to NNLO

LO NLO NNLO

$$\int_0^1 dx\, g_1^\gamma(x,Q^2,P^2)$$

$$= -\frac{3\alpha}{\pi}\left\{\left(\sum_{i=1}^{n_f} e_i^4\right)\left[1 - \frac{\alpha_s(Q^2)}{\pi} - \left(\frac{55}{12} - \frac{1}{3}n_f\right)\frac{\alpha_s^2(Q^2)}{\pi^2}\right]\right.$$

$$+ \left(\sum_{i=1}^{n_f} e_i^2\right)^2 \left[-\frac{2}{\beta_0}\left(1 - \frac{\alpha_s(Q^2)}{\pi}\right)\left(\frac{\alpha_s(P^2)}{\pi} - \frac{\alpha_s(Q^2)}{\pi}\right)\right.$$

$$+ \frac{2n_f}{\beta_0^2}\left(\frac{\alpha_s(P^2)}{\pi} - \frac{\alpha_s(Q^2)}{\pi}\right)^2$$

$$+ \frac{1}{4\beta_0}\left(\frac{\beta_1}{\beta_0} - \frac{59}{3} + \frac{2}{9}n_f\right)\left(\frac{\alpha_s^2(P^2)}{\pi^2} - \frac{\alpha_s^2(Q^2)}{\pi^2}\right)$$

$$\left.\left. - \left(\frac{53}{36} - \frac{2}{3}\zeta_3\right)\frac{\alpha_s^2(P^2)}{\pi^2} + \left(\frac{1}{36} + \frac{2}{3}\zeta_3\right)\frac{\alpha_s^2(Q^2)}{\pi^2}\right]\right\}$$

1990年代ー現在

Precision of QCD: LO→NLO→NNLO

検証から精密化へ

- QCDの量子補正をNNLOの精度に高める

Splitting functions $P_{ij}(x, \alpha_s)$

$$P_{ij}(x,\alpha_s) = \underbrace{P_{ij}^{(0)}(x)}_{\text{LO}} + \underbrace{\alpha_s P_{ij}^{(1)}(x)}_{\text{NLO}} + \underbrace{\alpha_s^2 P_{ij}^{(2)}(x)}_{\text{NNLO}} + \cdots$$

1-loop 2-loop 3-loop

Gross-Wilczek, Politzer(1974)

Floratos-Ross-Sachrajda(1978)

Moch-Vermaseren-Vogt (2004)

	# of diagrams
LO	18
NLO	350
NNLO	9607

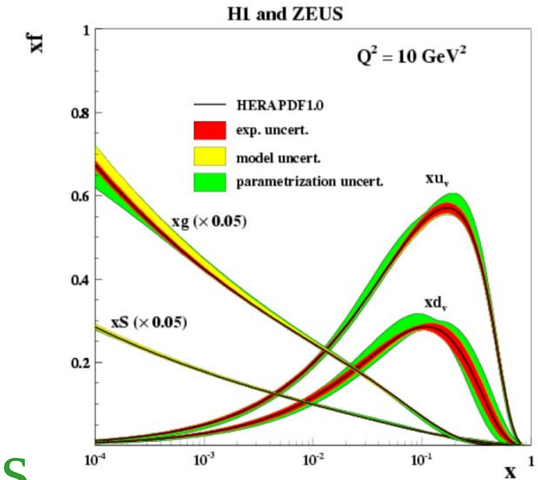
Coefficient functions

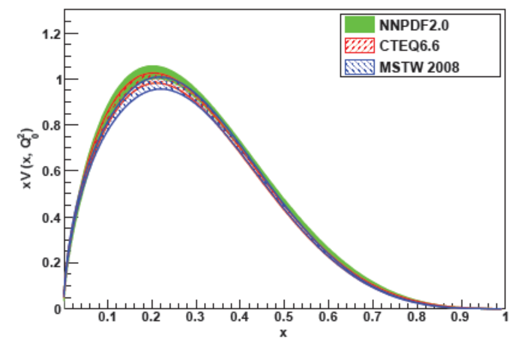
$$C_n(\alpha_s) = \underbrace{C_n^{(0)}}_{\text{tree}} + \underbrace{\alpha_s C_n^{(1)}}_{1-\text{loop}} + \underbrace{\alpha_s^2 C_n^{(2)}}_{2-\text{loop}} + \cdots$$

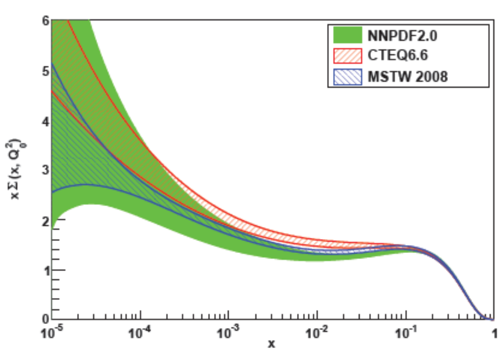
Global PDF Analysis

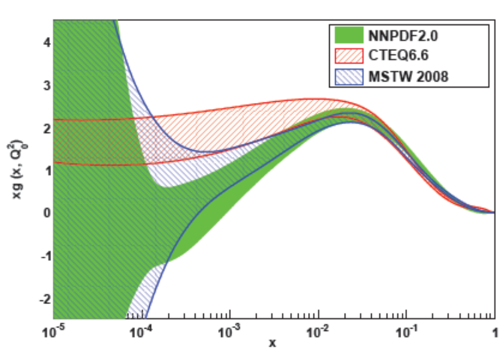
Collaborations

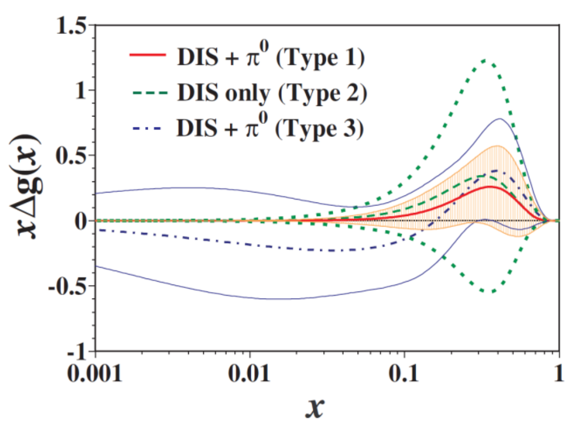
- MSTW (MRST) LO NLO NNLO
- CTEQ LO NLO Tevatron jet analysis
- NNPDF NLO Neural networks
- ABKM NNLO heavy quark effects
- GRV, AAC NLO polarized PDFs



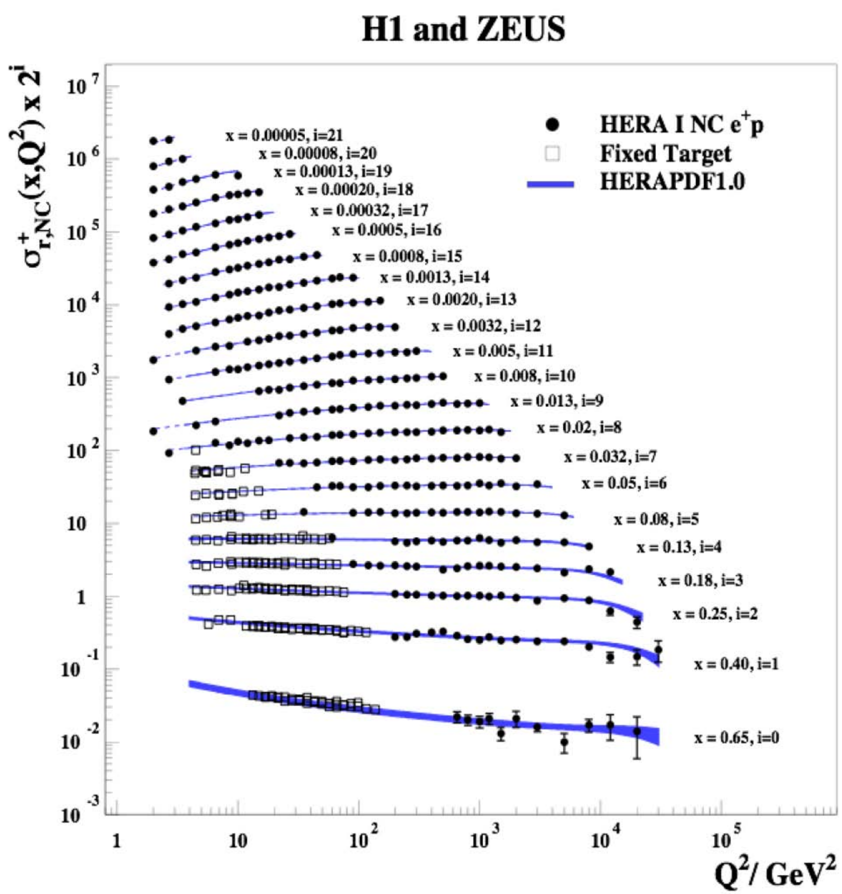


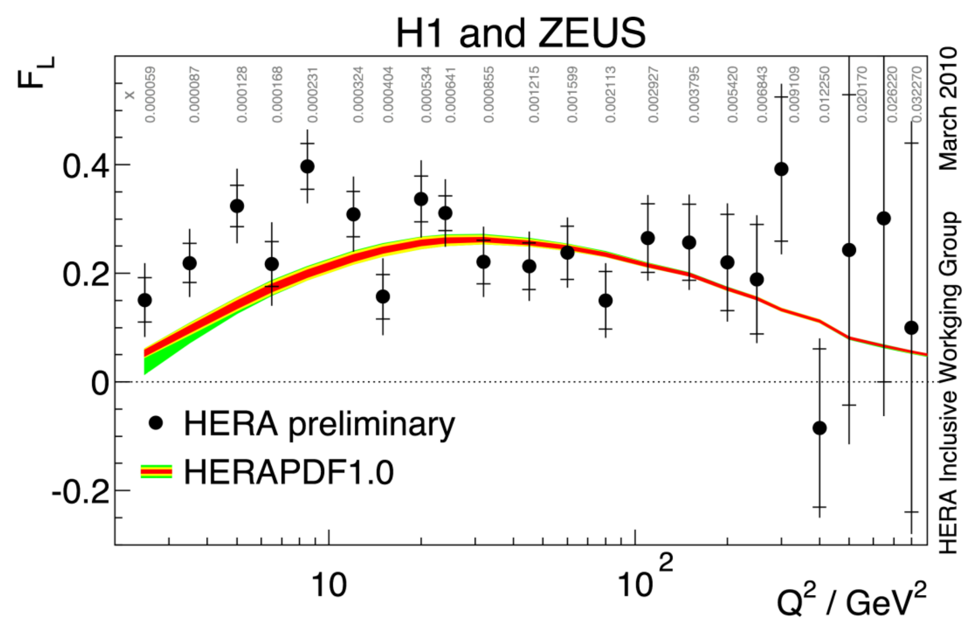






QCD and HERA data





重クォーク質量効果

Y. Kitadono, K. Sasaki, T. Ueda and TU,
Prog. Theor. Phys. 121 (2009)054019;
Phys.Rev.D81:074029,2010;
Eur.Phys.J.C70:999-1007,2010

$$F_2^\gamma(x,Q^2,P^2) = \vec{q}^{\,\gamma}(y,Q^2,P^2,m^2) \otimes \vec{C}\left(\frac{x}{y}, \frac{\overline{m}^2}{Q^2}, \bar{g}(Q^2)\right)$$

Photonstructure function　　PDF　　Coefficient function

mass dependence

Parton interpretation of twist-2 operators $\vec{O}_n$

No mass dependence

$$\int_0^1 dx x^{n-1} \vec{q}^{\,\gamma}(x,Q^2,P^2,m^2)$$

$$= \vec{A}_n\left(1, \frac{\overline{m}^2(P^2)}{P^2}, \bar{g}(P^2)\right) T\exp\left[\int_{\bar{g}(Q^2)}^{\bar{g}(P^2)} dg \frac{\gamma_n(g,\alpha)}{\beta(g)}\right]$$

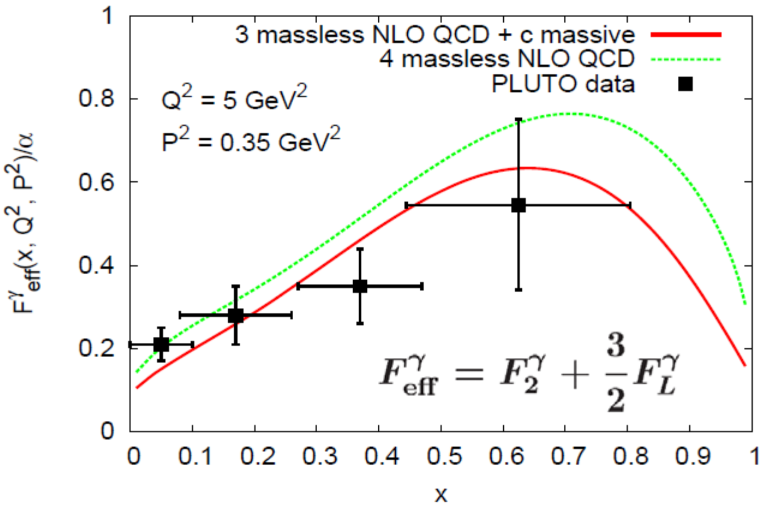
where

$$\langle\gamma(P^2)|\vec{O}_n(\mu^2)|\gamma(P^2)\rangle = \vec{A}_n\left(\frac{P^2}{\mu^2}, \frac{\overline{m}^2(\mu^2)}{\mu^2}, \bar{g}(\mu^2)\right)$$

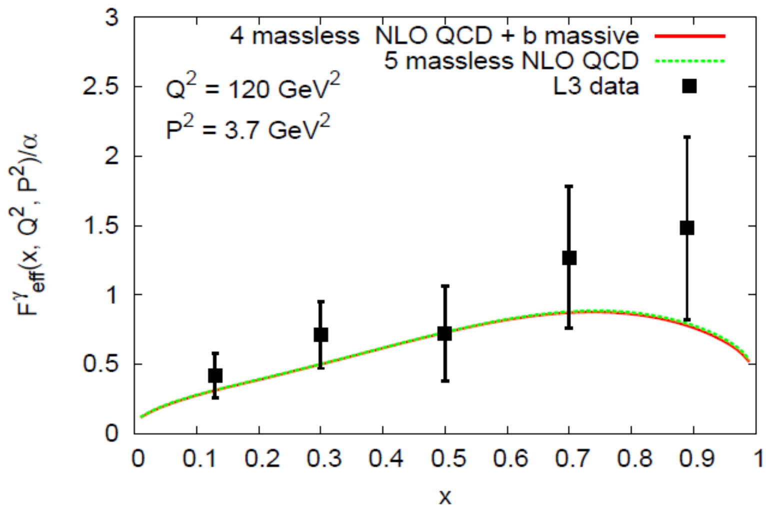
Perturbatively calculable !

mass dependence

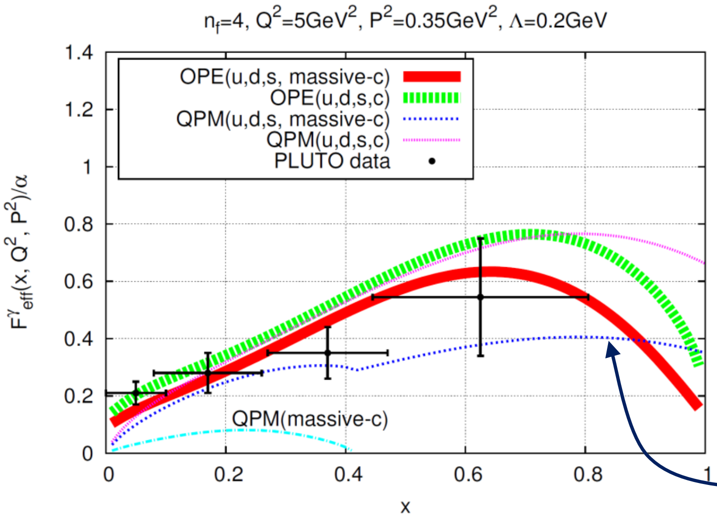
Heavy flavour effects vs. experimental data for $F_{\rm eff}^{\gamma}$



QCD prediction vs. PLUTO data



QCD prediction vs. L3 data



PM Box

In the massive quark limit

$$\Lambda_{\rm QCD}^2 \ll P^2 \ll m^2 \ll Q^2$$

Heavy quark mass threshold effects illustrated by PM

$$x_{\rm max} = \frac{1}{1 + \frac{4m^2}{Q^2}}$$

4. その他　−QCD and String Theory−

- AdS/CFT対応　　String on $AdS_5 \times S^5$〜N=4SCFT

  Maldacena

- 5次元AdS時空での弦のsemi-classicalな振る舞いとboundaryの４次元Yang-Mills理論の対応関係

  Polyakov et al

- AdS/CFT対応（弦／ゲージ双対性）とform factorおよび大角度散乱と強結合領域でのDIS構造関数

  Polchinski et al

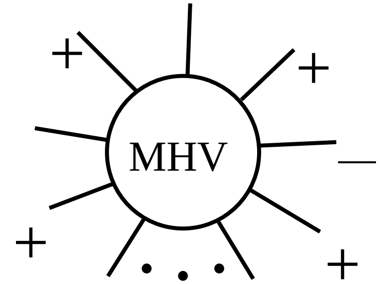
- String理論でエネルギーについてベキ的振舞い

  ⇒　5次元方向の寄与によるwarp factor

- AdS/QCD　(Holographic QCD)

  spectrum, decay width, Pomeron, BFKL anom.dim.

multi-parton amplitudes



- MHV振幅に対するParke-Taylor公式の拡張（spinor-helicity）
- Witten　Commun.Math.Phys.252(2004)189
  N=4超対称理論で運動量空間からFourier変換で得たtwistor spaceにおける散乱振幅を弦理論のインスタントンの寄与に結びつけた
- Cachazo-Svrcek-Witten (CSW) JHEP09(2004)006

最大にヘリシティーを破る(MHV)振幅をvertexに拡張し，一般のMHVでないhelicity振幅を計算するルールを与えた

- 任意の1-loop multi-leg amplitudes

A～(Box)+(triangle)+(bubble)+(tadpole)

LHC (Large Hadron Collider)

スイス･ジュネーブ郊外　CERN

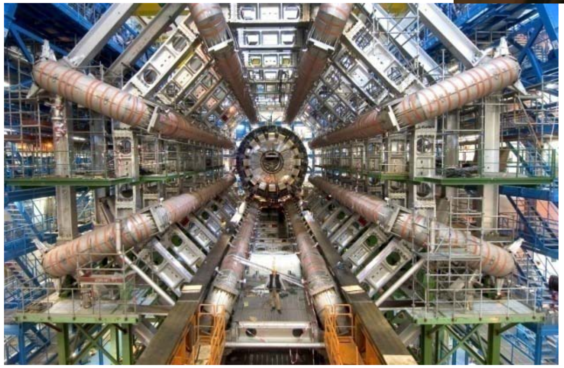
周囲27km　地下100mのトンネル
陽子･陽子衝突型加速器　約5000億円
8.3Tの超伝導磁石　1232本

アルプス

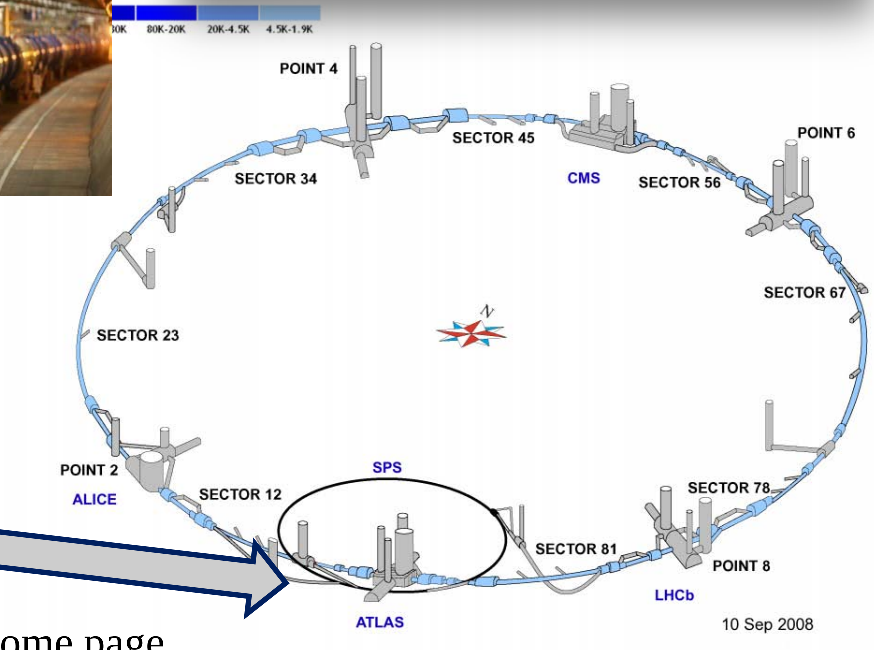
レマン湖

加速エネルギー
7TeV+7TeV=14TeV
1TeV=1兆電子ボルト

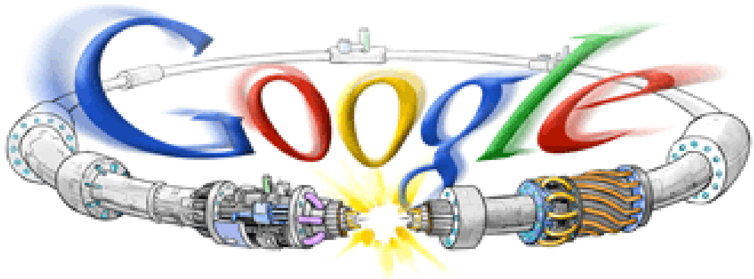
ルミノシティー10^{34} cm^{-2}s^{-1}



ATLAS測定器



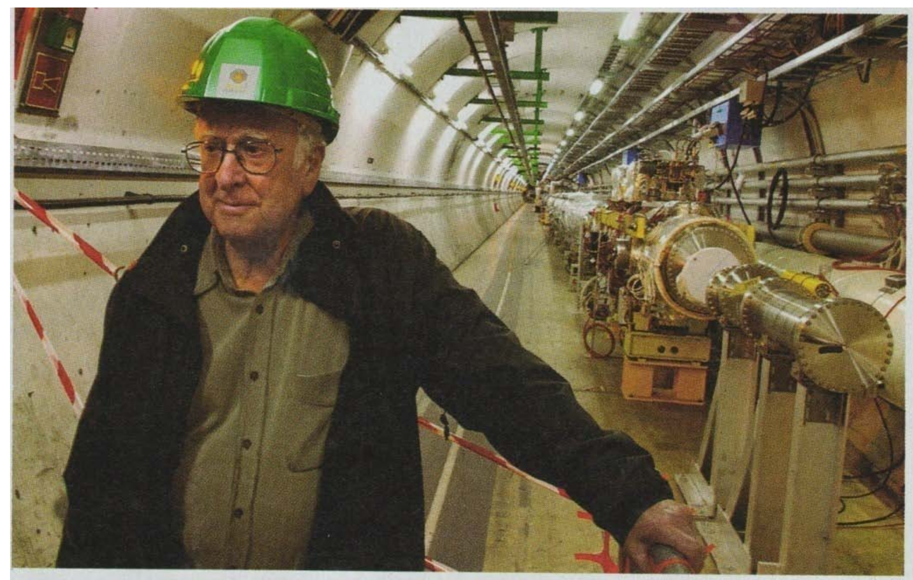
@LHC home page



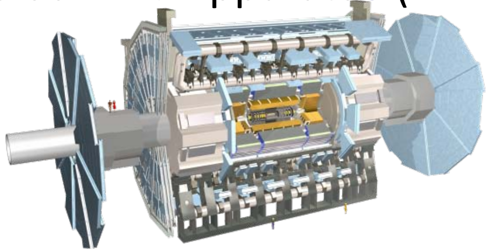
ホーキング博士

2008年9月10日　に稼働始める
450GeVビーム初周回に成功
9月19日、ヘリウム漏れ事故
2009年11月復旧
2010年3月より3.5TeV+3.5TeV開始

ヒッグスが見つからない方に100ドル賭ける　ーBBCでのラジオ番組よりー



A Toroidal LHC ApparatuS (ATLAS)



ATLASグループ　37 か国
167 研究機関
2200 人　科学者

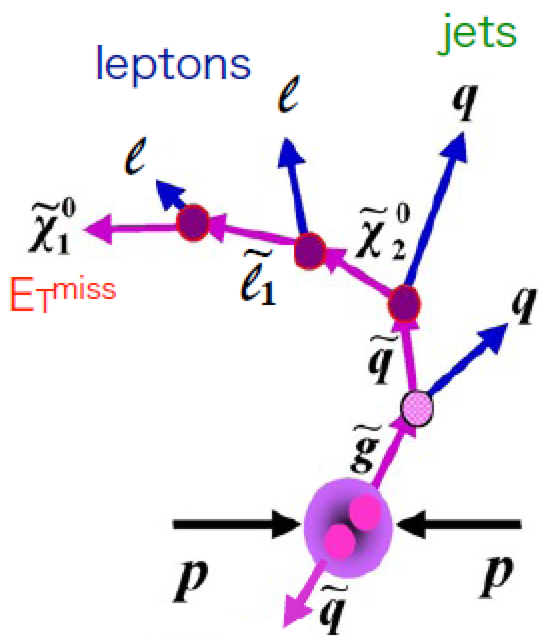
ATLAS　日本
15 研究機関
92 人　科学者

LHCとヒッグス博士

TIME紙より

LHCで超対称性は如何にして発見されるか

Missing ET



クォーク･グルーイノ対生成

より軽い超対称粒子への崩壊

安定なLSPへ（Rパリティ保存）

Multi-jets + E_T^{miss} + X トポロジー

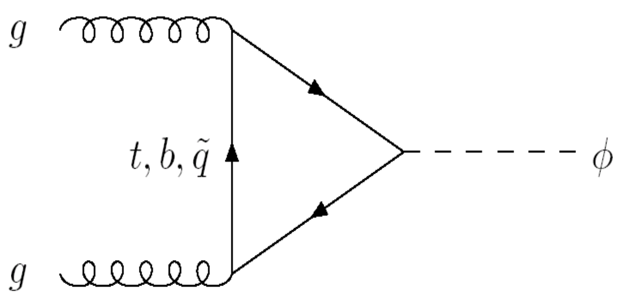
QCD @ LHC era

RHICからLHCへ

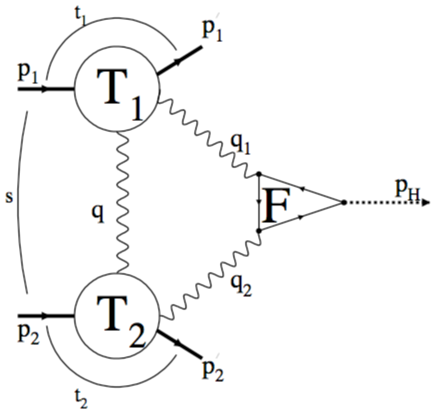
- CMS@7TeV pp collision 〜 RHIC heavy ion collision

  Ridge structure ⟹ pseud-rapidty (η) correlation
- ALICE heavy ion collision high multiplicities
- ATLAS & CMS ジェット抑制(Jet quenching)

Higgs production



gluon fusion



Diffractive production of Higgs

5.まとめと今後の課題

- QCDは30有余年を経て確立 検証から精密化へ
- 高エネルギー素粒子反応にとり必須の理論的枠組み
- 標準模型の確立とそれを超えたPhysicsの探索には強い相互作用 QCDの効果の精密な評価が必要
- 超対称粒子生成に対するQCDおよび超対称QCDの解析に摂動論的手法が有効か
- 超弦理論、AdS/CFT等の理論からのアイデアの創出

More efforts needed!