CLFV via scalar mediator in Deep-inelastic lepton-nucleon scattering

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CLFV模型の探索

CLFVの発見はNewPhysicsの存在を立証する

- CLFV@Decays:

  τ や μ の稀崩壊の分岐比に上限

- CLFV探索@ep collider

- 稀崩壊で探索できないCLFV相互作用を探索

- ビーム強度×核子密度でイベント数を稼げる

  Model (independent), SMEFT Analysis: Gninenko, et al.(18), Sher, et al.(04), Liao, et al.(16), Husek, et al.(21), Cirigliano et al.(21), Antusch et al.(20).

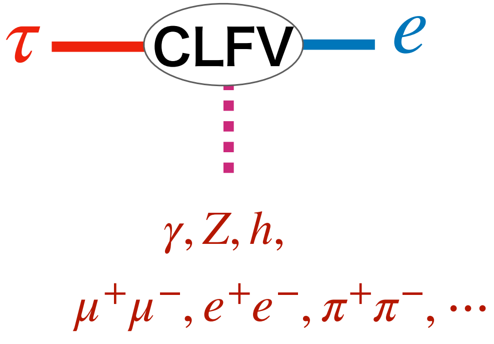
  レプトクォーク・サーチ@HERA H1 Collaboration(07),

  Susy CLFV DIS: Kanemura-Kuno-Kuze-Ota(05)

  Higgs CLFV DIS: Takeuchi-Uesaka-Yamanaka(17)

- この発表では、上記のTakeuchi, et al. の解析を発展させてレプトン核子散乱における$\mathscr{L} = \bar{\tau} e \bar{q} q$ 型のCLFVを同定するための理論解析を行う

process	bound
$\mu \to e\gamma$	4.2×10^{-13}
$\mu \to 3e$	1×10^{-12}
$\mu \to e$ conversion	7×10^{-13}
$\tau \to e\gamma$	3.3×10^{-8}
$\tau \to \mu\gamma$	4.4×10^{-8}
$\tau \to 3e$	2.7×10^{-8}
$\tau \to 3\mu$	2.1×10^{-8}
$\tau^- \to e^-\pi^+\pi^-$	2.3×10^{-8}
$\tau^- \to \mu^-\pi^+\pi^-$	2.1×10^{-8}
$h \to \mu e$	6.1×10^{-5}
$h \to \tau e$	4.7×10^{-3}
$h \to \tau\mu$	2.5×10^{-3}



ヘビークォークに強く結合するスカラー模型

Model Lagrangian

- Lepton sector (CLFV)

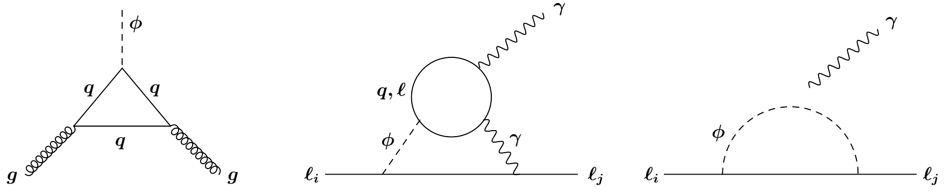
$$\mathscr{L}_\phi = -\sum_{i\neq j} \rho^\phi_{ij}\bar{\ell}_j P_L \ell_i \phi + \mathrm{h.c.}$$

- Quark sector(diagonal coupling)

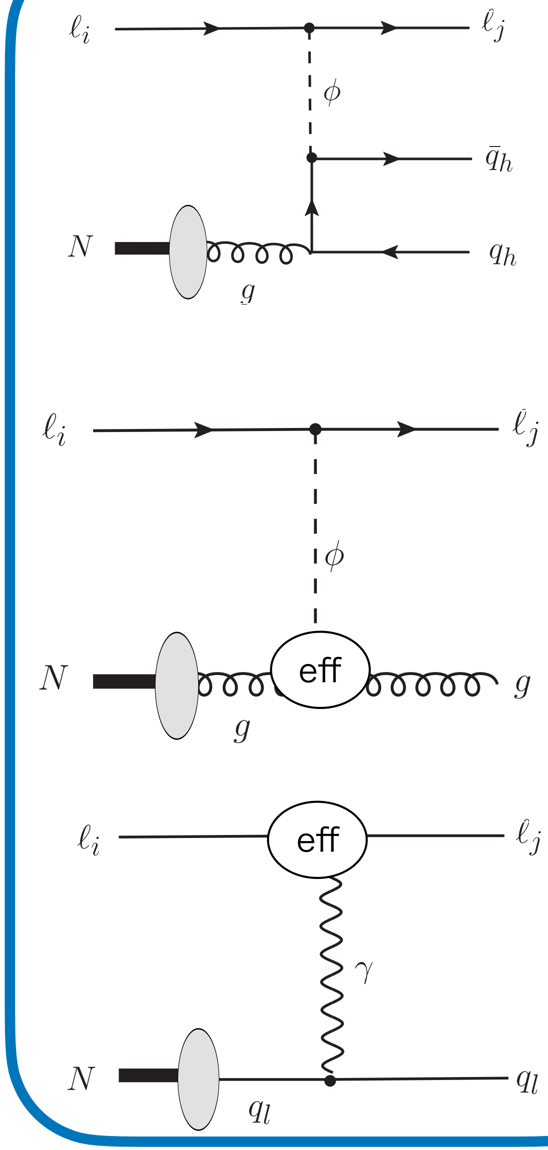
$$\mathscr{L}_\phi = -\sum_{q} \rho^\phi_{qq}\bar{q}q\phi$$

ヘビークォーク
強く結合 ↔ $\rho^\phi_{qq} \propto y_q$

- Loop induced $\mathscr{L}^\phi_{\mathrm{eff}}$

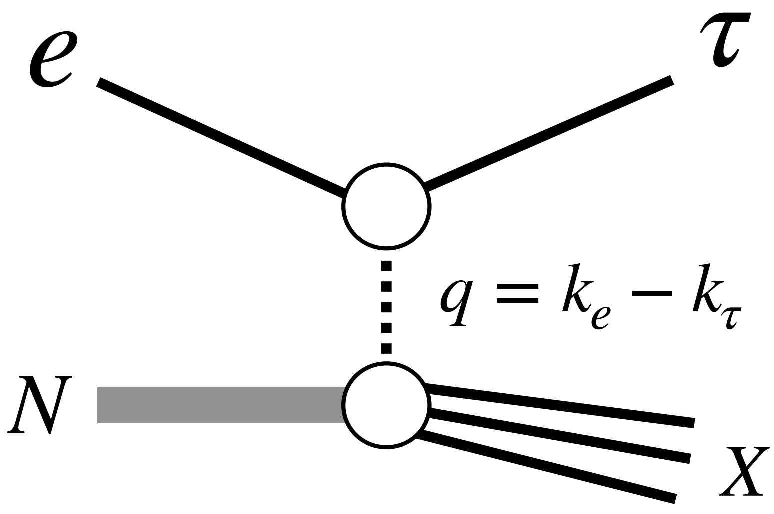


DIS subprocess



CLFV@レプトン核子散乱

$$\frac{d^2\sigma}{dxdQ^2}(eN \to \tau N) = \frac{Q^2}{16\pi(xs)^2}\frac{L_\phi(Q^2)\,F_\phi(x,Q^2)}{(Q^2+m_\phi^2)^2}$$



$$Q^2 = -q^2, \quad x = \frac{P\cdot q}{P\cdot k_e}$$

レプトン部分: L_ϕ

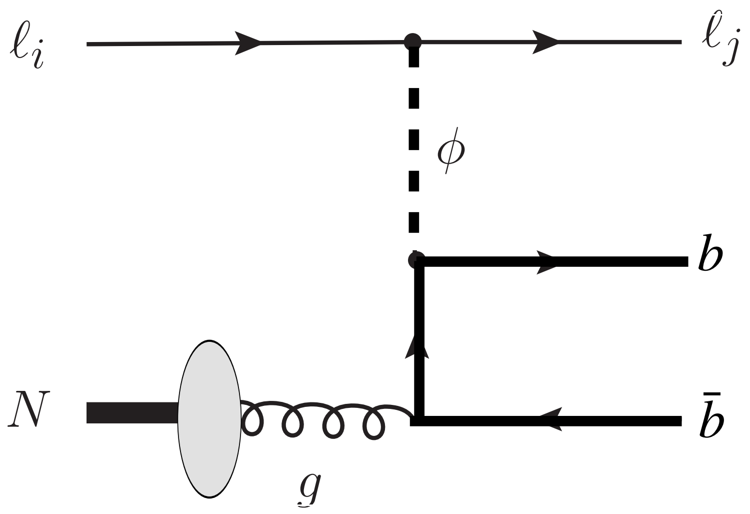
ハドロン部分: F_ϕ (構造関数)

$$\frac{\#\mathrm{event}}{\mathrm{year}} \sim 6\times 10^8 \times \left(\frac{\sigma}{1\mathrm{fb}}\right)$$

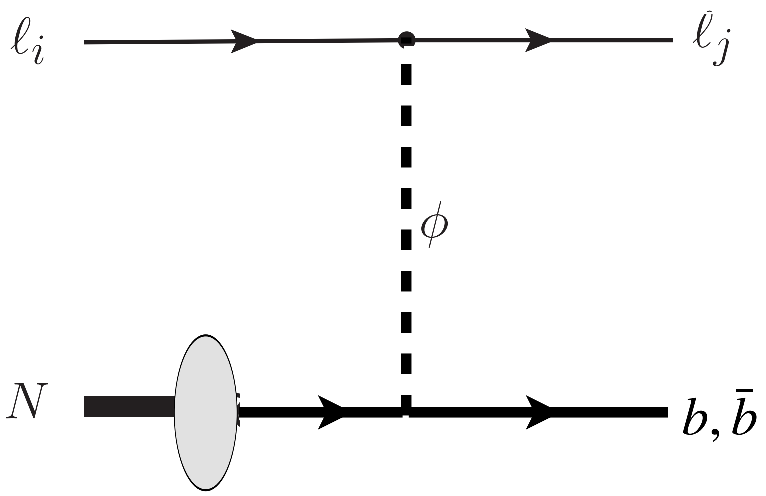
e-intensity=10^{22}/year

target mass=$100g/\mathrm{cm}^3$

今回のトーク：ヘビー・クォークに強く結合するCLFVスカラー相互作用, 特に$eN \to \tau b\bar{b}$ の計算手法について報告する。$b \leftrightarrow c$でチャーム生成も同様に計算可能。



グルーオン・モード



bエキサイテーション・モード

- **Questions**

1. ヘビークォーク質量(⇆湯川結合定数)の取り扱いはどうする？
2. 核子中(PDF)にヘビークォークが存在するのか？

➡ ACOT-scheme: Aivazis-Collins-Olness-Tung(1994)

ACOT scheme (物理描像)

1) 小さなfactorization scale $\mu_f \simeq Q \leq \mathcal{O}(m_q)$ において、ヘビークォークがデカップルした定ネエルギー有効理論がある
$\mathscr{L}(n_f = 4; q = u, d, s, c)$：核子中にヘビー・クォークは存在しないので、ヘビークォクはhard scatteringで生成される(図１)

図１

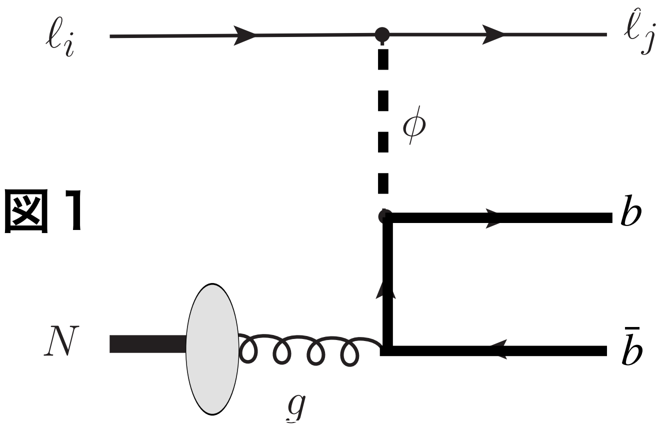
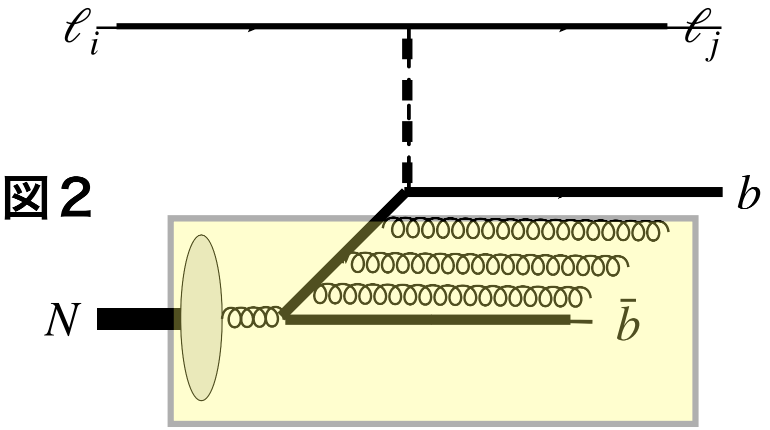


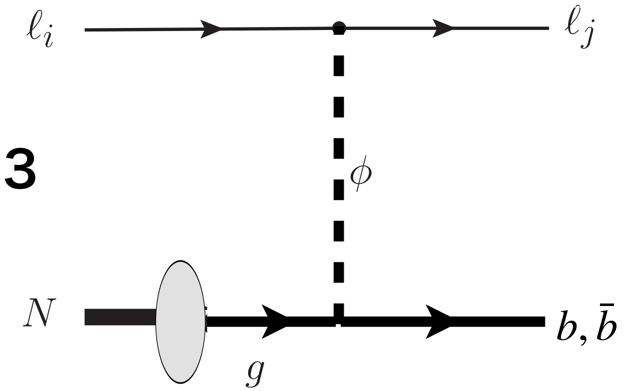
図２



3) $\mu_f \simeq Q \gg m_q$では、ヘビークォークもzero-mass的にQCD radiationを介してlight-quark/gluonと混合(図２)

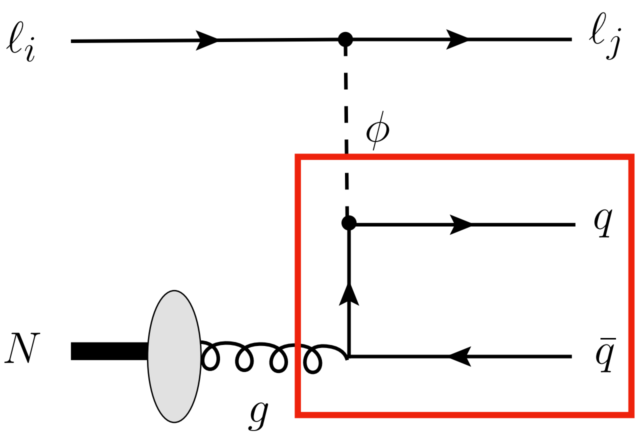
4) ヘビークォーク質量に起因する大きな対数補正 $\alpha_s \ln(Q^2/m_q^2)$(collinear singularity)を、足し上げるスキームとして、ヘビークォークPDFを導入（図３）：導入されたヘビークォークPDFは $Q^2 \gg m_q^2$ でDGLAP方程式に従い発展する。
$\mathscr{L}(n_f = 5; q = u, d, s, c, b)$が理論

図３



Heavy quark production via g->qq

$$F^{\rm M}(x,Q^2) = \int_0^1 \frac{d\xi}{\xi} C_g^{\rm M}\left(\frac{x}{\xi},\frac{Q^2}{m_q^2}\right) f_{g/N}(x,\mu_f^2)$$



$$C_g^{\rm M}\left(\frac{x}{\xi},\frac{Q^2}{m_q^2}\right) = \frac{\alpha_s T_F}{2\pi}\left\{A + B\ln\frac{1+\beta}{1-\beta}\right\}\Theta(w^2-4m_q^2)$$

$$\xrightarrow{m_q\to 0} \left(\frac{\alpha_s}{2\pi}\right)\ln\frac{Q^2}{m_q^2} \boxed{\left\{T_F\left[\left(\frac{x}{\xi}\right)^2 + \left(1-\frac{x}{\xi}\right)^2\right]\right\}}$$

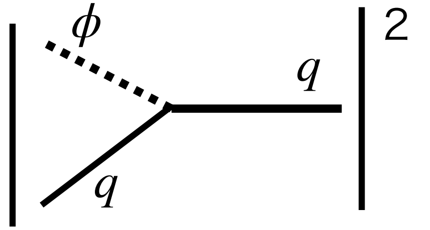
$$\left(\beta = \sqrt{1-\frac{4m_q^2}{s_{qq}}}\right)$$

g→qのsplitting function $P_{qg}(x/\xi)$

高エネルギー極限(=massless limit)の構造

$$F^{\rm M}(x,Q^2) = C_g^{\rm M}(x)\otimes f_{g/N}(x)$$

$$\longrightarrow C_q^{\rm M0}(x)\otimes\left[\left(\frac{\alpha_s}{2\pi}\right)\ln\left(\frac{Q^2}{m_q^2}\right)P_{qg}(x)\otimes f_{g/N}(x,Q^2)\right]$$



$$C_q^{\rm M0}(x) = \frac{1}{2}\delta(1-x)$$

PDF evolution

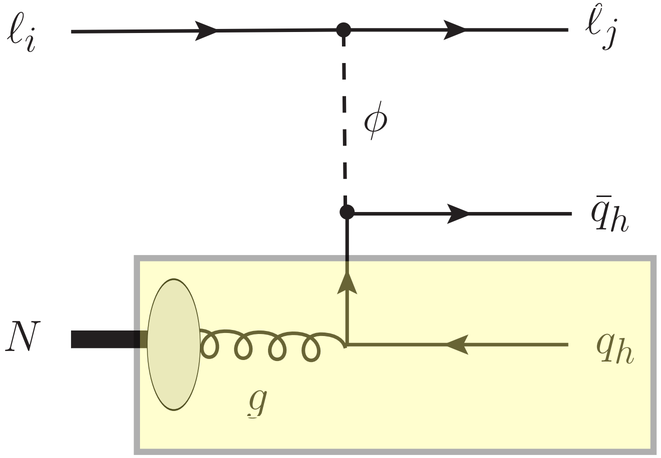
$q = f_{q/N}$

$g = f_{g/N}$

DGLAP方程式

$$\frac{d}{d\ln(Q^2)}\begin{pmatrix} q \\ g \end{pmatrix} = \frac{\alpha_s}{2\pi}\begin{pmatrix} P_{qq} & P_{qg} \\ P_{gq} & P_{gg} \end{pmatrix} \otimes \begin{pmatrix} q \\ g \end{pmatrix}$$

$$q(x, Q^2) = q(x, m_q^2) + \frac{\alpha_s}{2\pi} \ln\frac{Q^2}{m_q^2}\left\{P_{qq} \otimes q + P_{qg} \otimes g\right\}$$



高エネルギー極限(=massless limit)の構造

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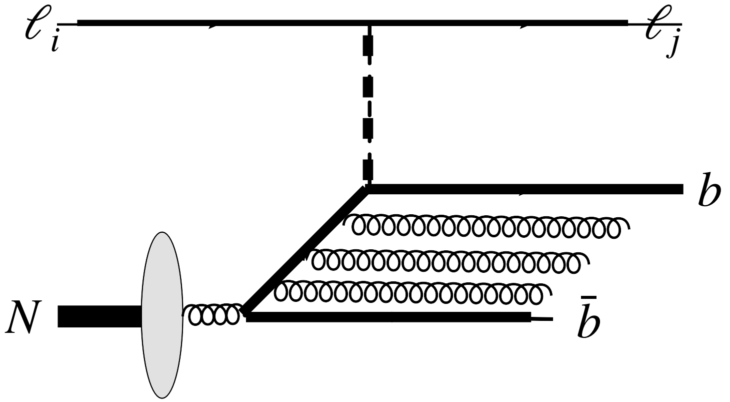
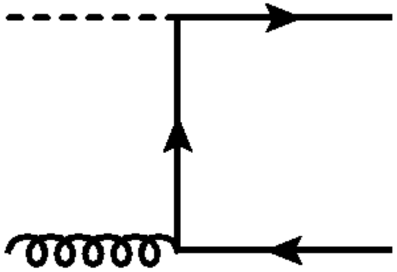
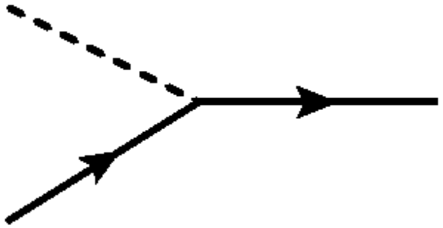
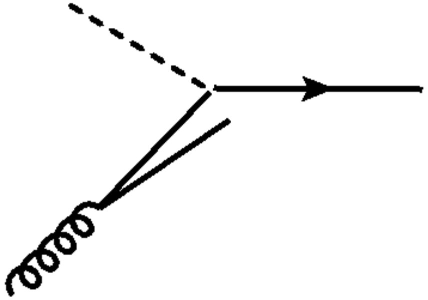
$$= C_q^{\rm M0}(x) \otimes f_{q/N}$$



スカラー構造関数 in (LO)ACOT

$F_\phi^{\mathrm{ACOT}}(x, Q^2) = \Big|$  $\Big|^2 \otimes f_{g/N}(x, Q)$

$+ \Big|$  $\Big|^2 \otimes \underline{f_{b/N}(x, Q)}$ $-\ \Big|$  $\Big|^2 \otimes f_{g/N}(x, Q)$

Defined object

＊第２項と第３項の和は摂動論的にはゼロであるが$Q^2 \gg m_q^2$ で値を持つ

Bottom PDF (Theory)

$$f_{b/N,Q^2} = \underline{f_{b/N}(x, m_b^2)} + \frac{\alpha_s}{2\pi} \ln\left(Q^2/m_q^2\right) P_{bg} \otimes f_{g/N} + \cdots$$

The first term is 0: no intrinsic bottom

構造関数の振る舞い

$$F_\phi^{\text{SACOT-}\chi}(x,Q^2) \equiv F_\phi^{\text{M}}(x,Q^2) + \left[F_\phi^{\text{ZM-}\chi}(x,Q^2) - F_\phi^{\text{sub-}\chi}(x,Q^2)\right]$$

ACOTは, $Q \sim m_q$におけるMスキームと$Q \gg m_q$のZMスキームを内挿するスキーム

F^{M} : ヘビー・クォークの質量効果を含むMassiveスキーム

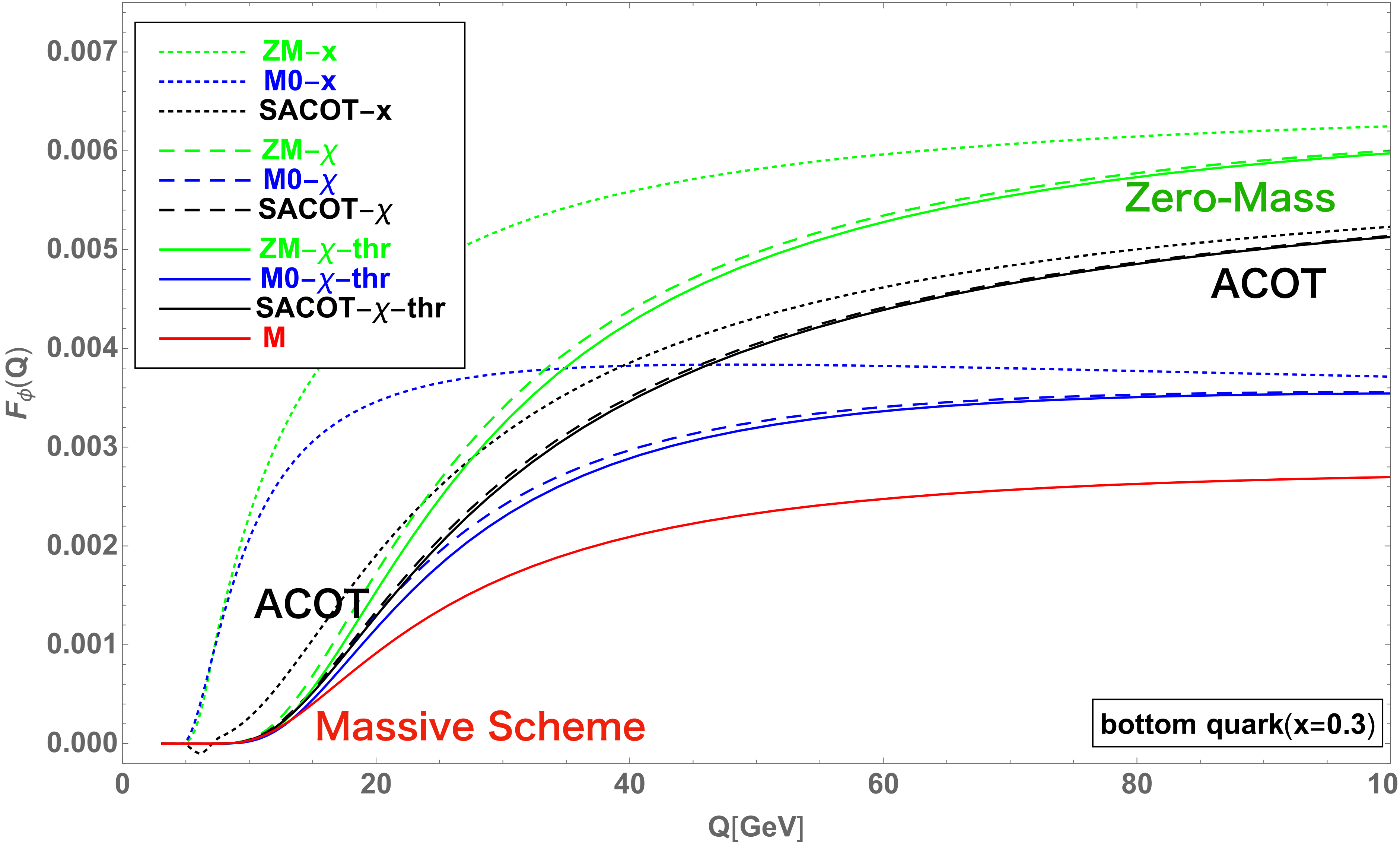
→ 閾値付近 $Q^2 \simeq m_q^2$ の振る舞いを正しく記述する ; LO $\sim O(\alpha_s)$

F^{ZM} ：Zero-Massスキーム：ZM計算だが、DGLAPのexact解を使って質量発散対数を足し上げる ; LL $\sim O(\alpha_s L)^n$

→ 高エネルギー$Q^2 \gg m_q^2$ (質量０極限)を正しく記述する

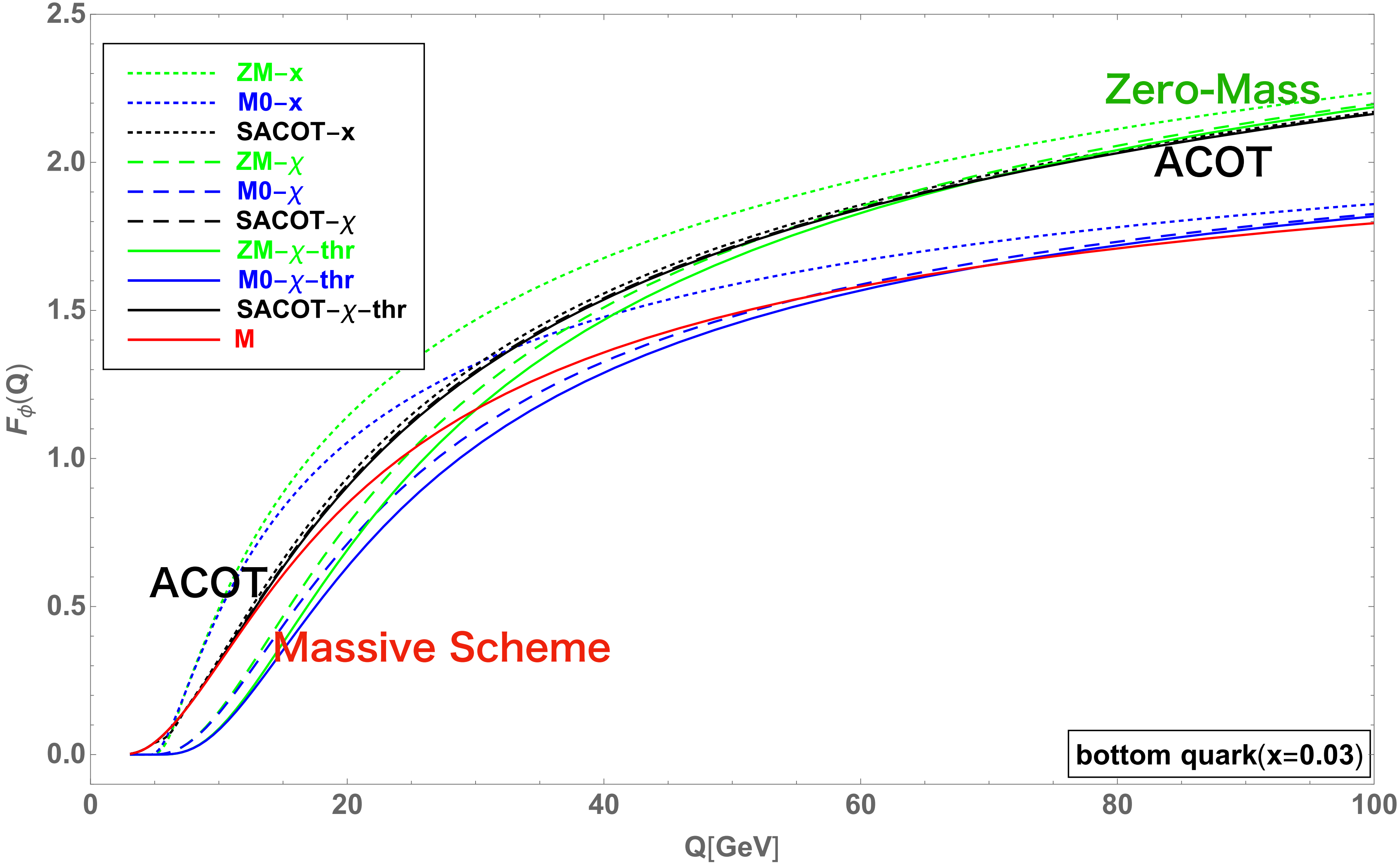
$\mathrm{F}^{\mathrm{sub}}$ ：subtraction項

→ Massive とZM スキームの重複するログ項を摂動の各オーダーで引き算する ; LO $\sim O(\alpha_s)$

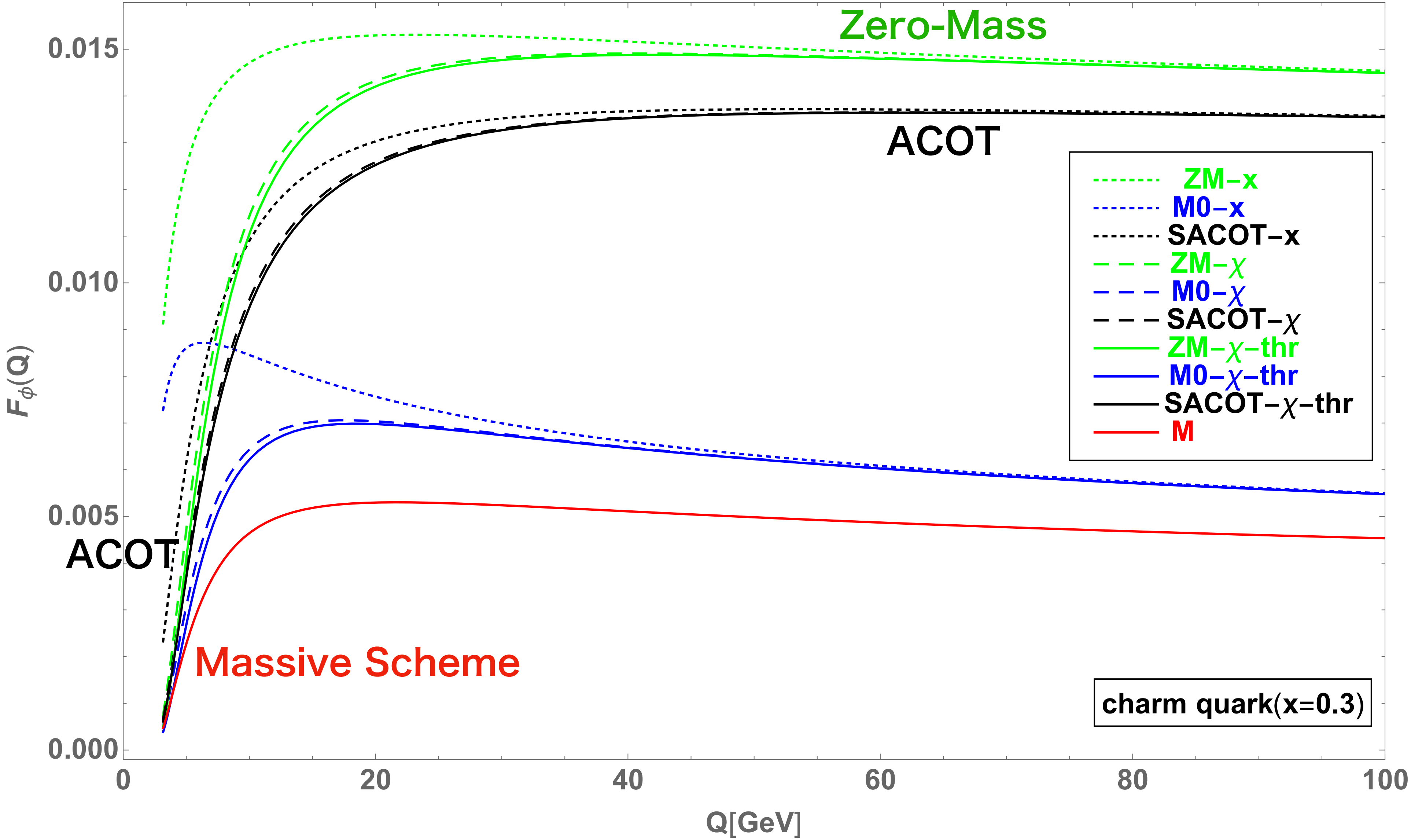


Massive Scheme $\xrightarrow{\text{ACOT}}$ ZeroMass Scheme

$Q \simeq m_q$ $\qquad$ $Q \gg m_q$



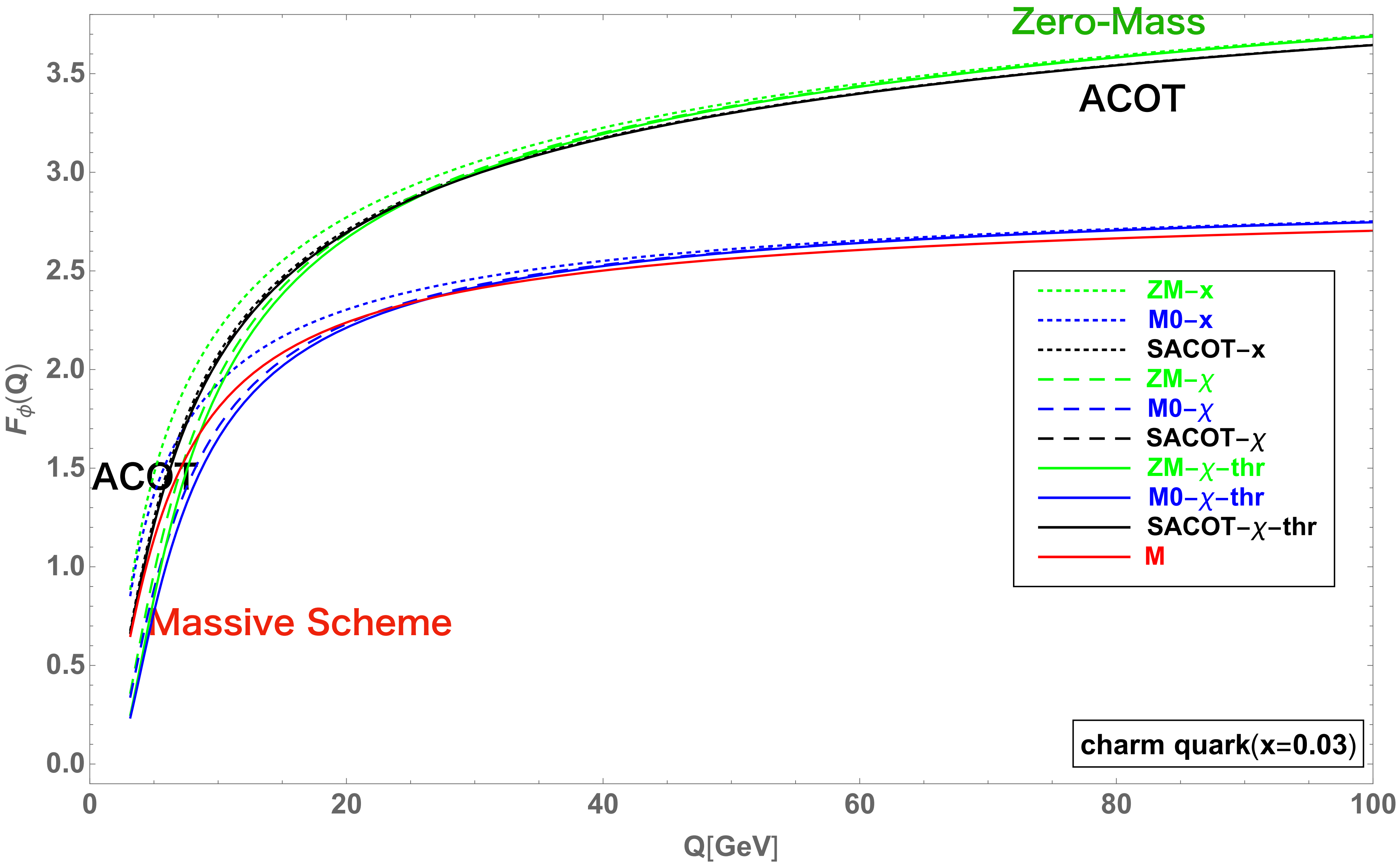
Massive Scheme $Q \simeq m_q$ ACOT → ZeroMass Scheme $Q \gg m_q$



Massive Scheme $Q \simeq m_q$

ACOT →

ZeroMass Scheme $Q \gg m_q$



Massive Scheme $Q \simeq m_q$ $\xrightarrow{\text{ACOT}}$ ZeroMass Scheme $Q \gg m_q$

断面積とACOTスキーム

$$\frac{d\sigma}{dQ} = \frac{1}{m_\phi^4} W_\phi(m_\phi^2, Q^2) \widetilde{M}_\phi(s, Q^2)$$

- CLFV mediator質量の依存性を決めるWeighting factor

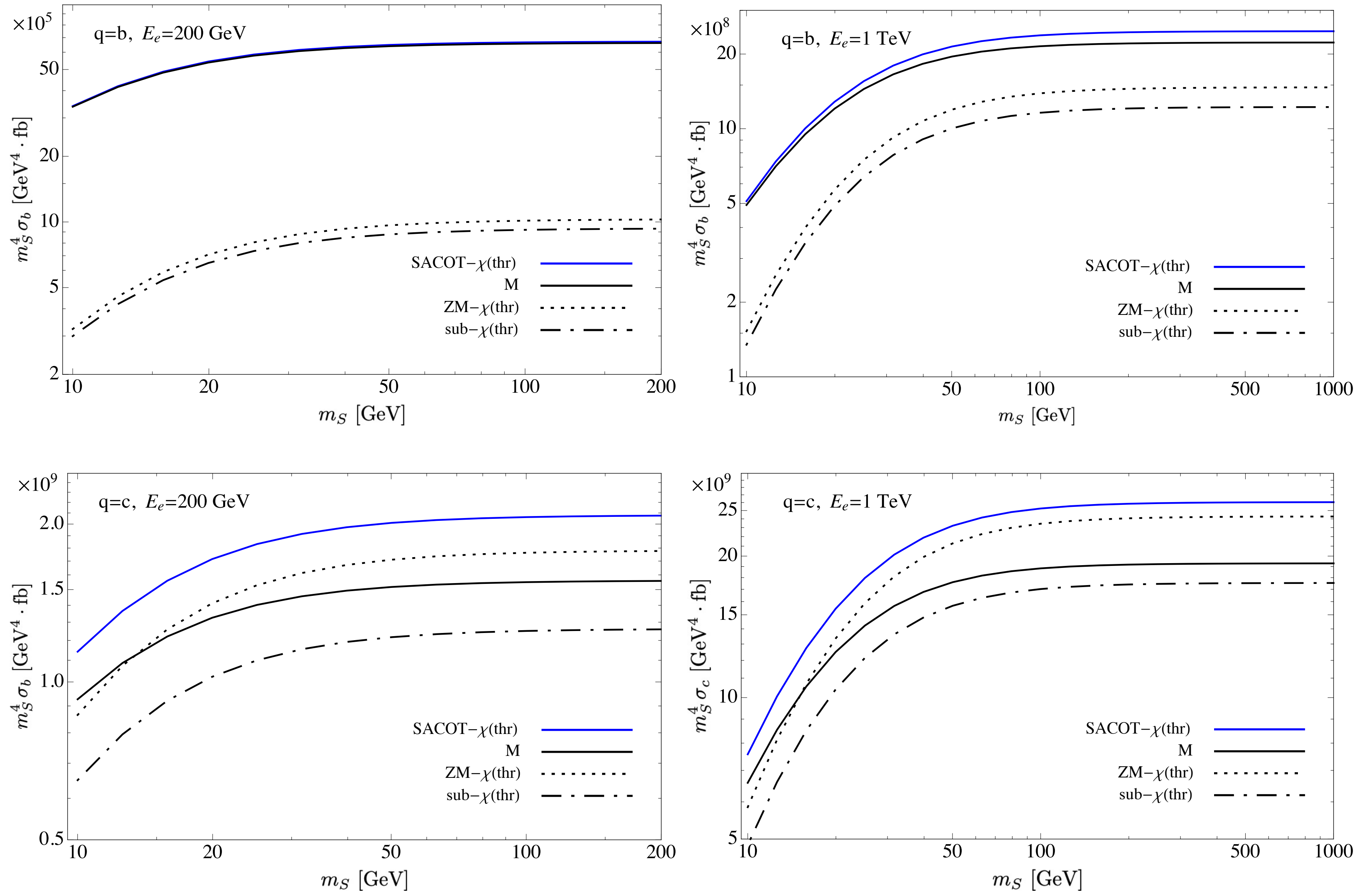
$$W_\phi(m_\phi^2, Q^2) = \left(\frac{m_\phi^2}{Q^2 + m_\phi^2} \right)^2$$

($Q^2 \geq m_\phi^2$ をカットオフする)

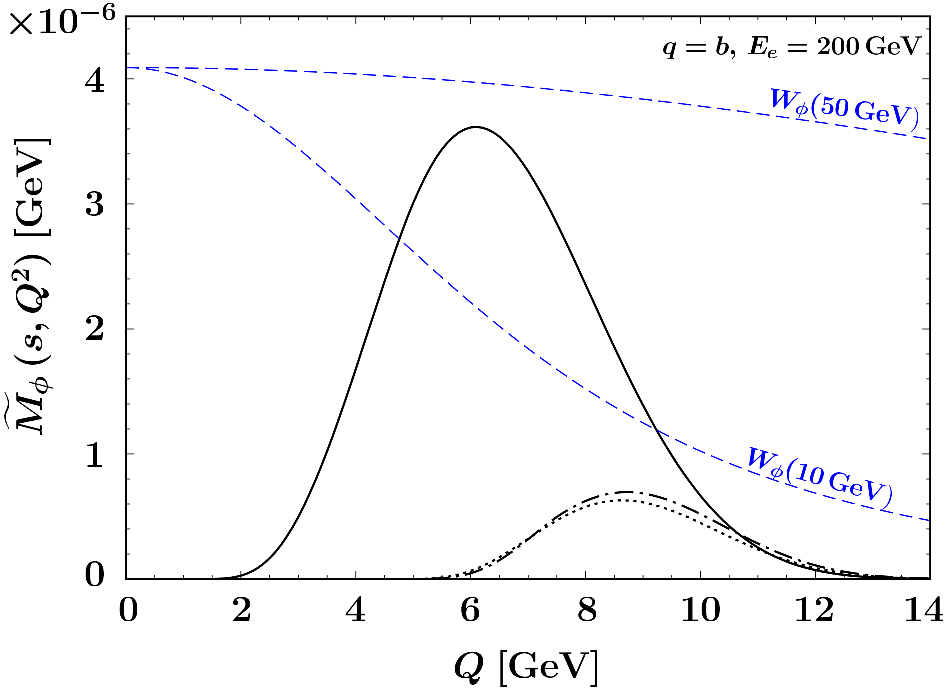
- QCDのダイナミックスの寄与を決める逆モーメント関数

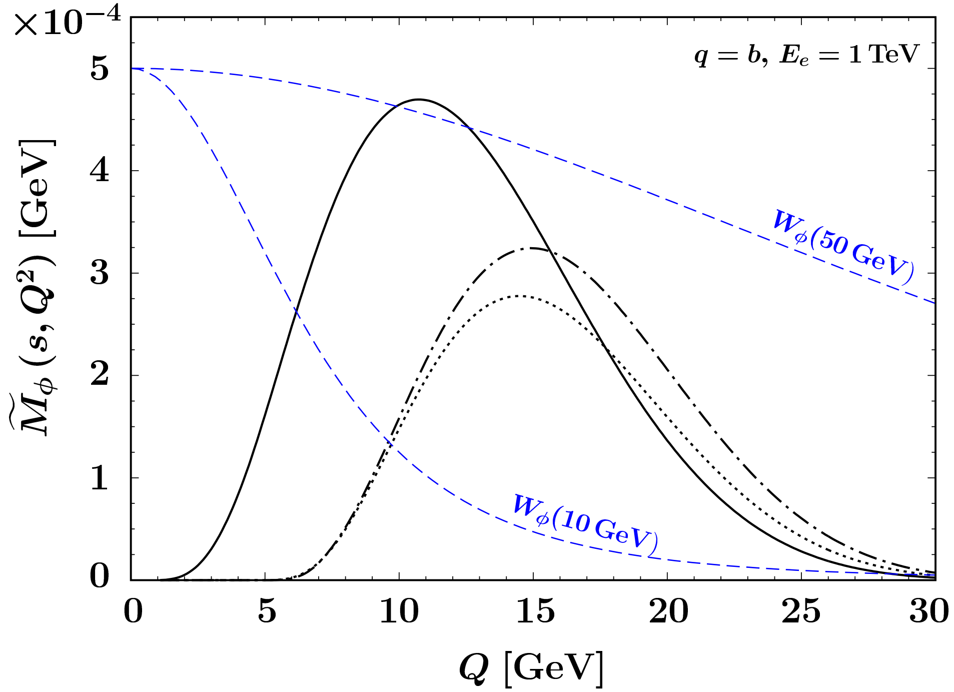
$$\widetilde{M}_\phi(s, Q^2) = \frac{Q^3(Q^2 + m_\tau^2)}{8\pi s^2} \int \frac{dx}{x^2} F_\phi(x, Q^2)$$

断面積のスカラー質量依存性



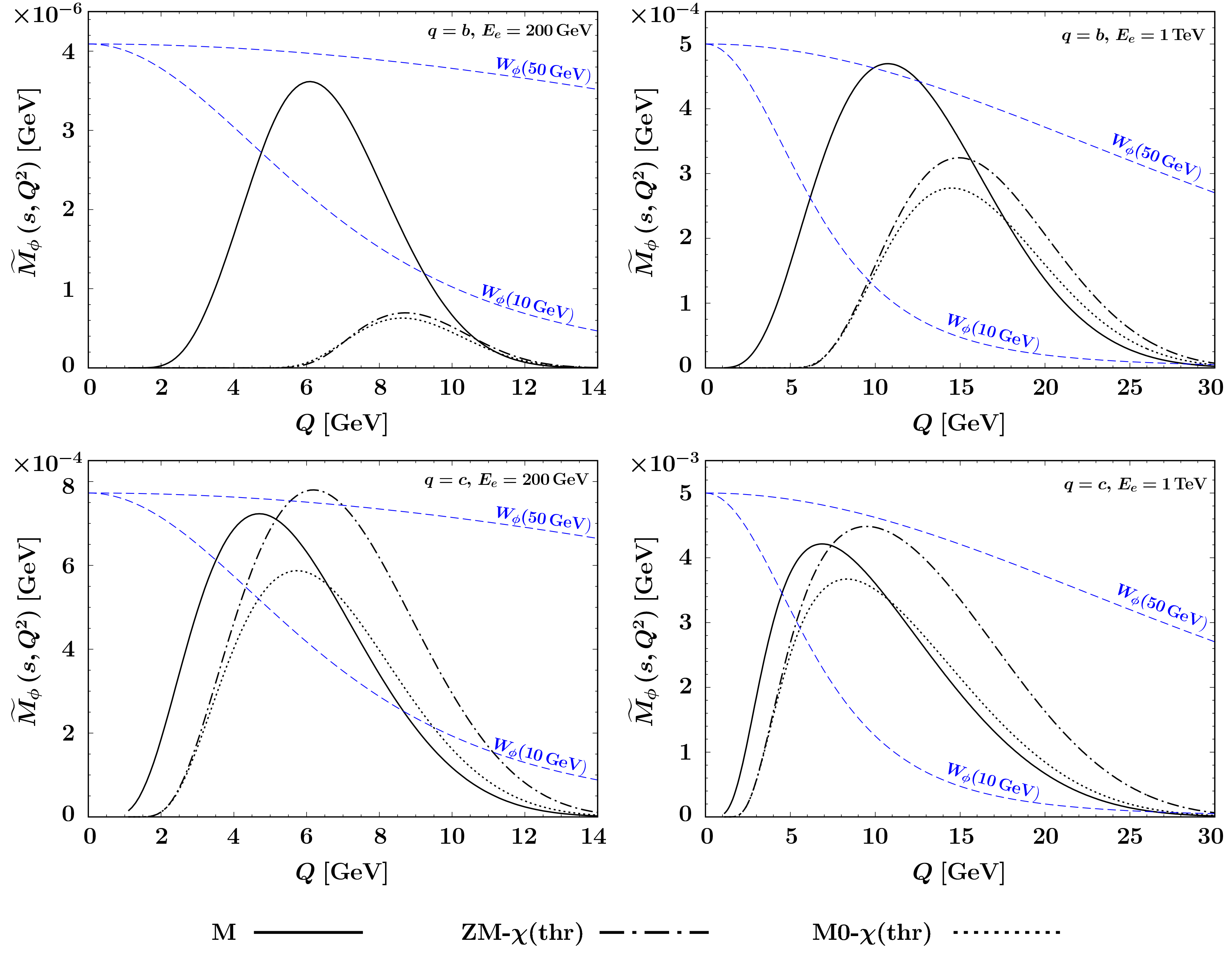
断面積公式

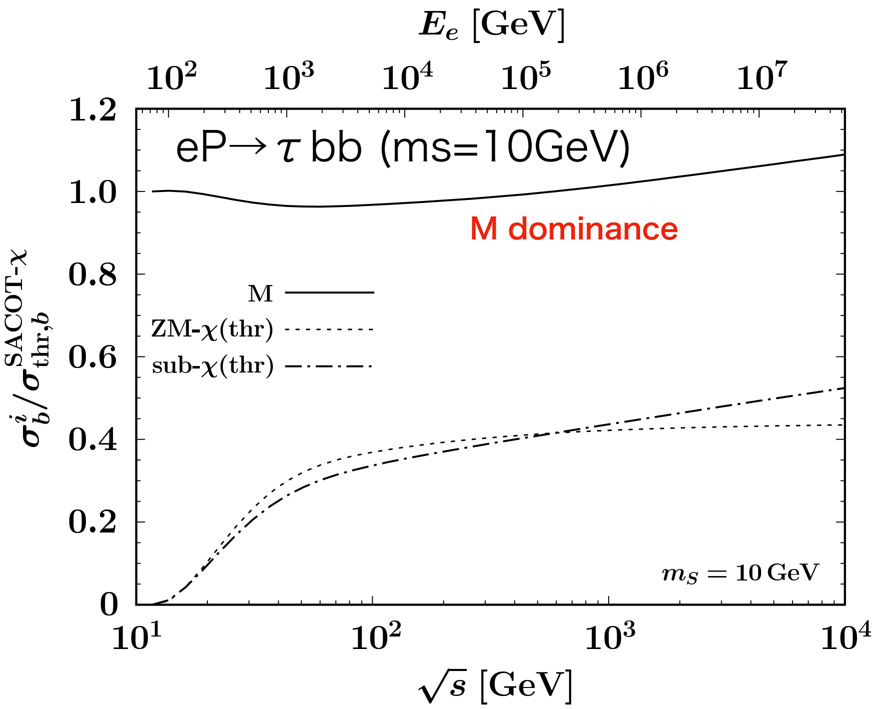


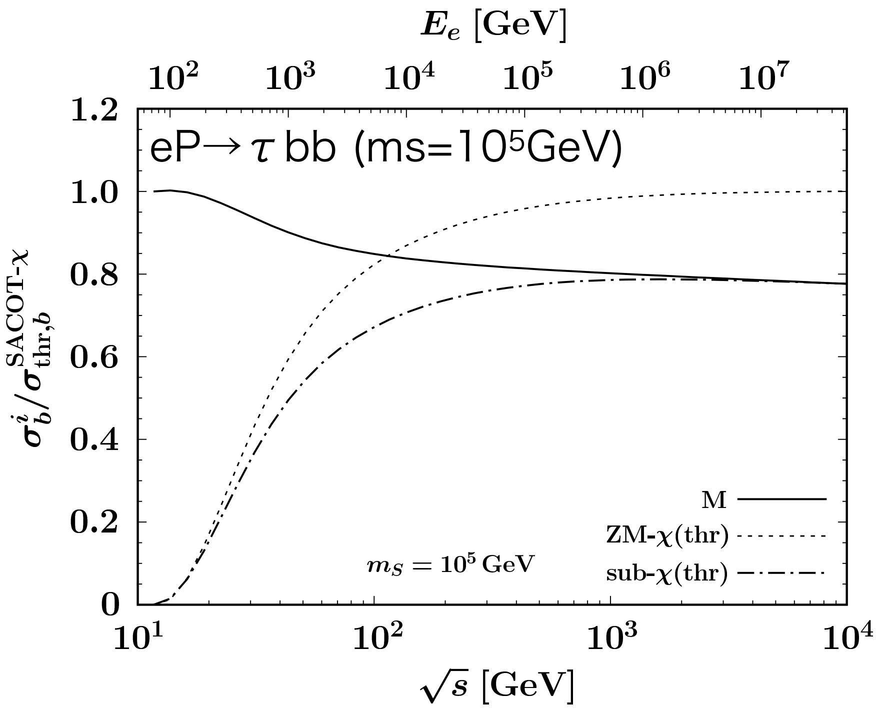


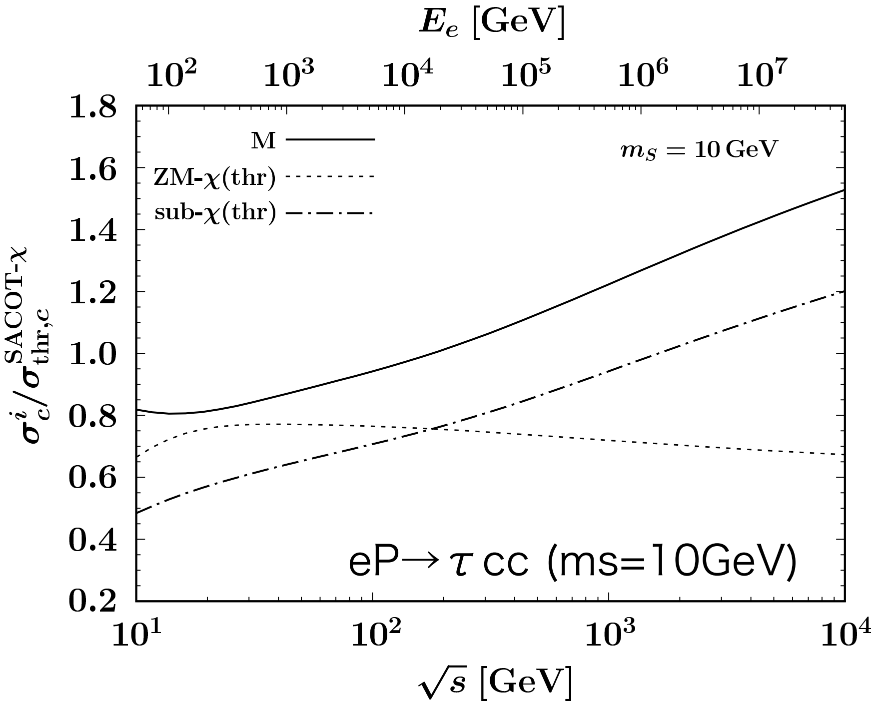
$$
\begin{aligned}
\frac{d\sigma}{dQ} &= \frac{1}{m_\phi^4} W_\phi(m_\phi^2, Q^2)\widetilde{M}_\phi(s, Q^2), \\
\widetilde{M}_\phi(s, Q^2) &= \frac{(Q^2)^{\frac{3}{2}}(Q^2 + m_\tau^2)}{8\pi s^2} M_\phi(s, Q^2), \\
W_\phi(m_\phi^2, Q^2) &= \left(\frac{m_\phi^2}{Q^2 + m_\phi^2}\right)^2,
\end{aligned}
$$

Inverse moment func




eP→τ bb (ms=10GeV)
M dominance
E_e [GeV]
10^2 10^3 10^4 10^5 10^6 10^7
$\sigma_b^i/\sigma_{\mathrm{thr},b}^{\mathrm{SACOT}\text{-}\chi}$
1.2 1.0 0.8 0.6 0.4 0.2 0
M
ZM-χ(thr)
sub-χ(thr)
$m_S = 10\,\mathrm{GeV}$
10^1 10^2 10^3 10^4
$\sqrt{s}$ [GeV]


eP→τ bb (ms=10^5GeV)
E_e [GeV]
10^2 10^3 10^4 10^5 10^6 10^7
$\sigma_b^i/\sigma_{\mathrm{thr},b}^{\mathrm{SACOT}\text{-}\chi}$
1.2 1.0 0.8 0.6 0.4 0.2 0
M
ZM-χ(thr)
sub-χ(thr)
$m_S = 10^5\,\mathrm{GeV}$
10^1 10^2 10^3 10^4
$\sqrt{s}$ [GeV]


E_e [GeV]
10^2 10^3 10^4 10^5 10^6 10^7
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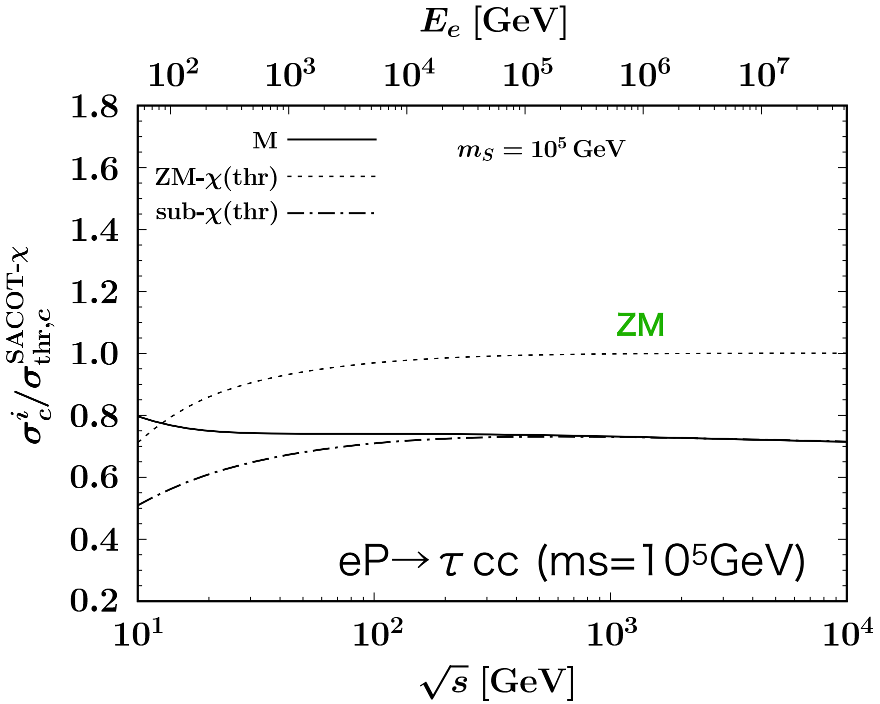
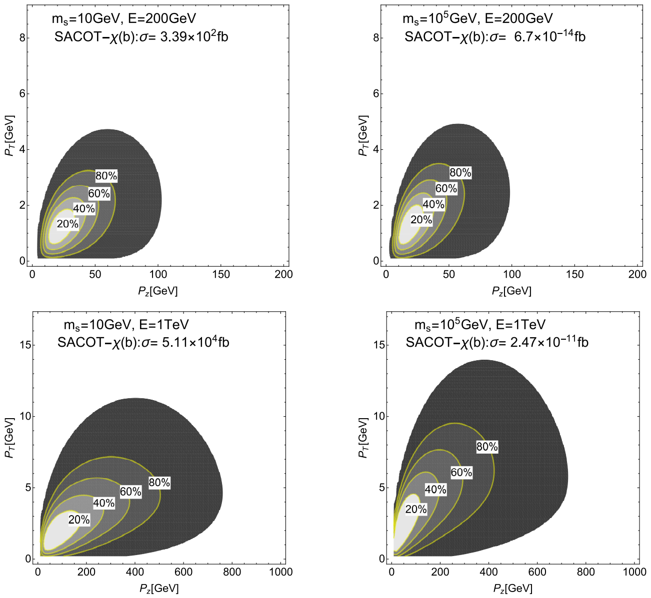
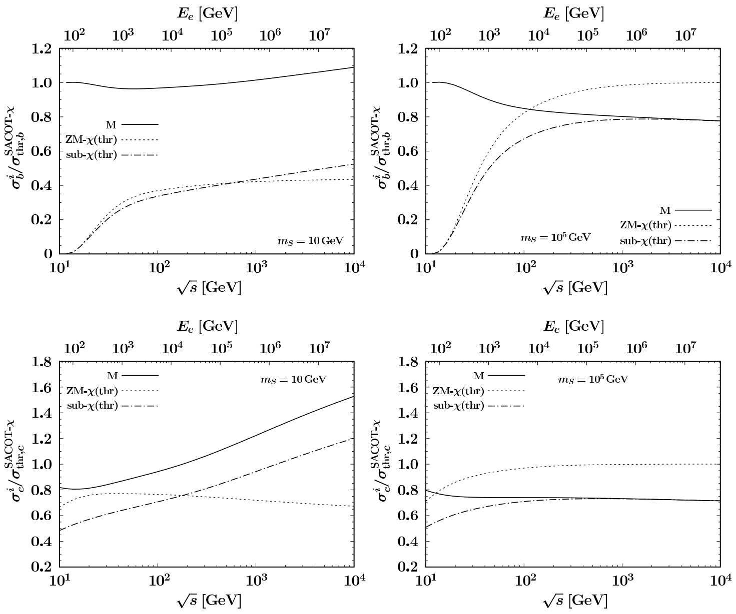
1.8 1.6 1.4 1.2 1.0 0.8 0.6 0.4 0.2
M
ZM-χ(thr)
sub-χ(thr)
$m_S = 10\,\mathrm{GeV}$
eP→τ cc (ms=10GeV)
10^1 10^2 10^3 10^4
$\sqrt{s}$ [GeV]


E_e [GeV]
10^2 10^3 10^4 10^5 10^6 10^7
$\sigma_c^i/\sigma_{\mathrm{thr},c}^{\mathrm{SACOT}\text{-}\chi}$
1.8 1.6 1.4 1.2 1.0 0.8 0.6 0.4 0.2
M
ZM-χ(thr)
sub-χ(thr)
$m_S = 10^5\,\mathrm{GeV}$
ZM
eP→τ cc (ms=10^5GeV)
10^1 10^2 10^3 10^4
$\sqrt{s}$ [GeV]

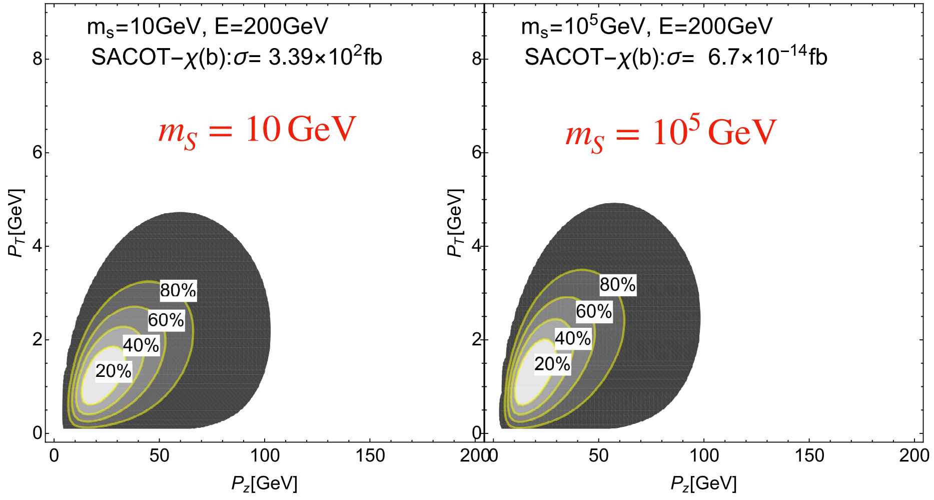




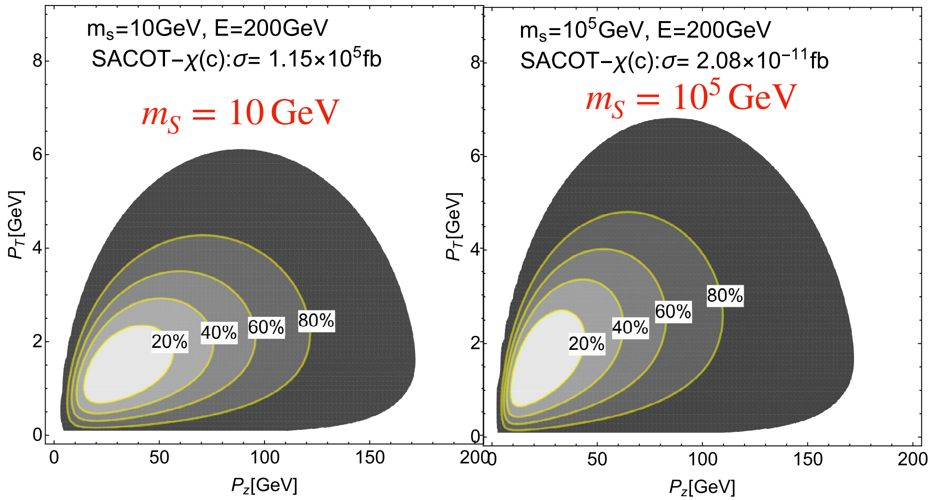
Phenomenology

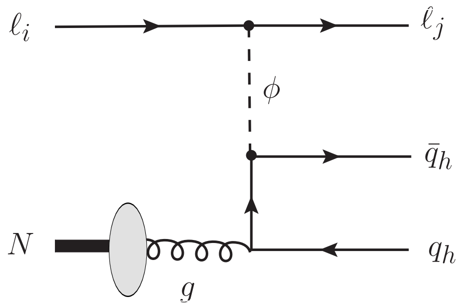
τ の運動量分布(固定ターゲート実験)

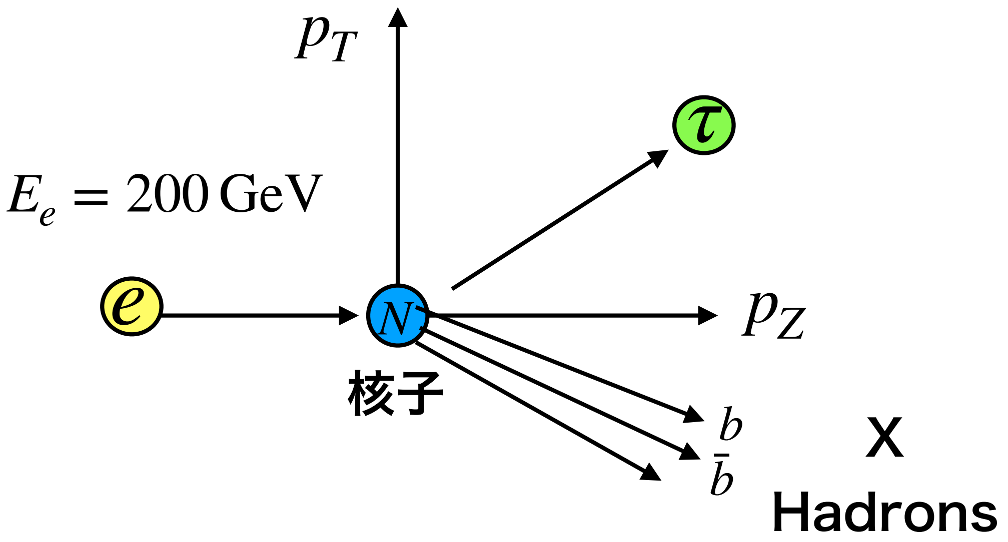
$eN \to \tau b\bar{b}X$



$eN \to \tau c\bar{c}X$



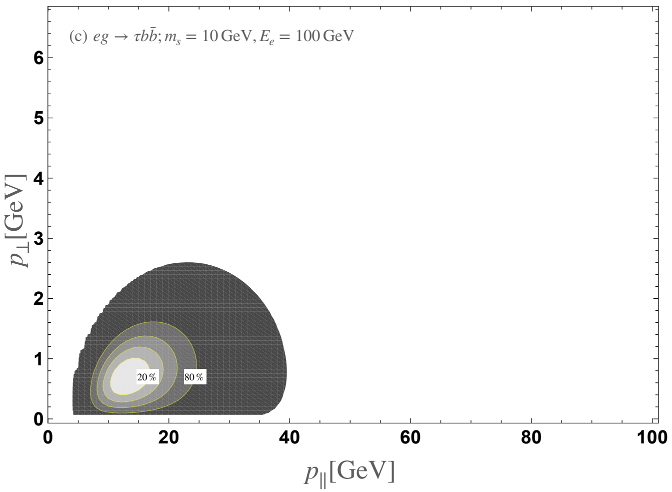




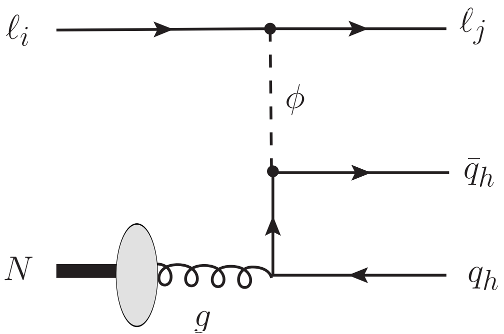
□ 断面積は$\rho_{e\tau}^2 \rho_{qq}^2 / m_S^4$で振る舞うが、分布の形状はスカラー粒子の質量に感度あり

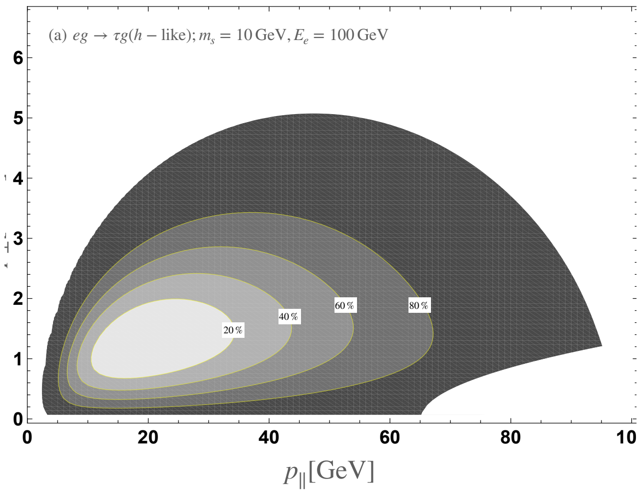
□ → ongoing work

CLFV DIS:プロセス依存性

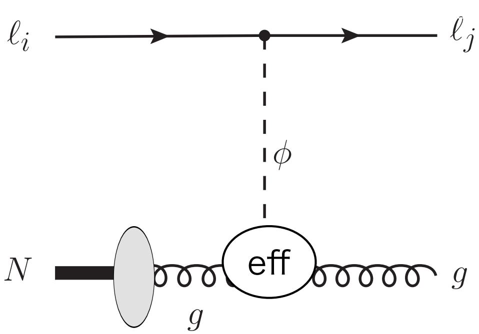


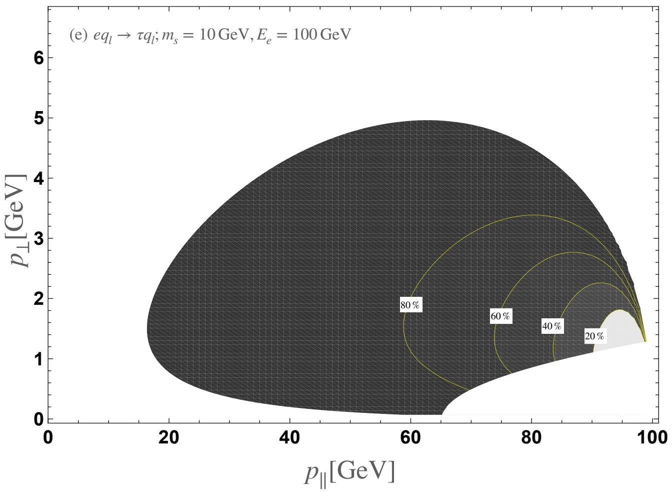
Heavy quark production



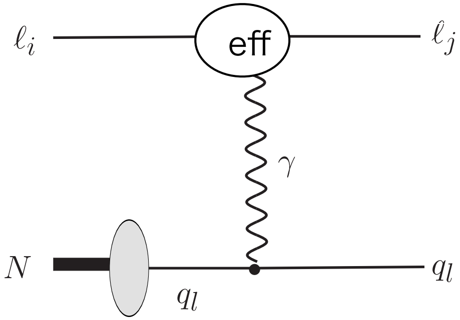


Gluon mode





Dipole mode



□ τ レプトンの運動量分布はCLFV相互作用のタイプに感度あり

イベント数

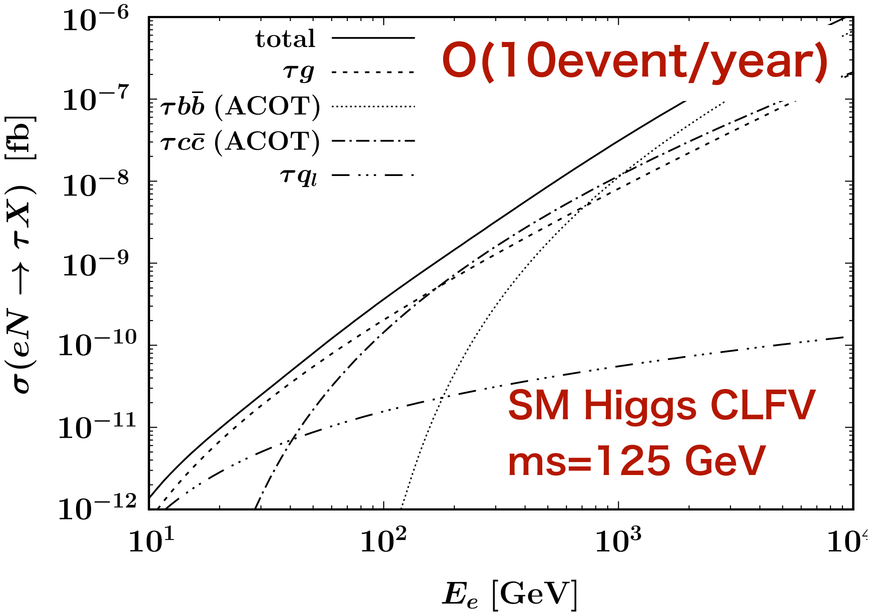
Example scenario@ ILC upgrade op. Ee=500GeV

$$\frac{\#\text{event}}{\text{year}} \sim 6\times 10^{8} \times \left(\frac{\sigma}{1\,\text{fb}}\right)$$

e-intensity=10^{22}/year , target mass=$100g/\text{cm}^3$

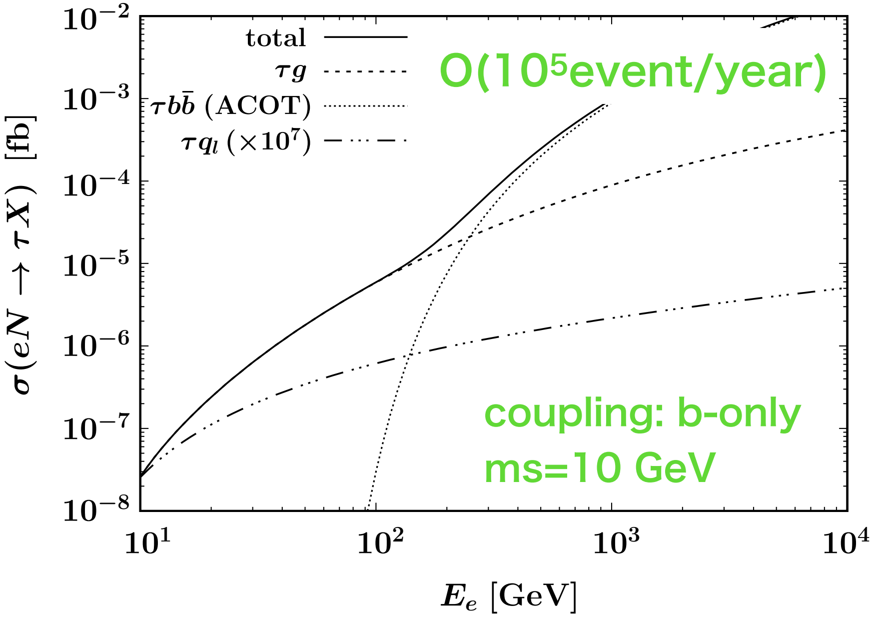
Scenario I The scalar mediator of $m_S = 125\,\text{GeV}$ whose interaction is identical with the SM Higgs one except for the CLFV interaction. The most stringent bound on the CLFV coupling comes from the Higgs CLFV searches at the LHC, $\bar{\rho}^h_{\tau e} < 2.0\times 10^{-3}$ [61], as seen in Table II, which in turn induces the bound on the dipole coupling, $\bar{D}_{\tau e} < 1.0\times 10^{-8}$, which is stronger than the direct bound seen in Table III.

Scenario II The scalar mediator couples with b quark only and $m_s = 10\,\text{GeV}$. The most stringent bound on the combination $|\rho^S_{bb}|\bar{\rho}^S_{\tau e}$ comes from the search for a CLFV decay $\tau \to e\pi^+\pi^-$, and $|\rho^S_{bb}|\bar{\rho}^S_{\tau e} < 1.3\times 10^{-4}$ [58, 64], which in turn induces the bound on the dipole coupling, $\bar{D}_{\tau e} < 6.9\times 10^{-10}$.



O(10event/year)

SM Higgs CLFV
ms=125 GeV



O(10^5event/year)

coupling: b-only
ms=10 GeV

サマリー

- ヘビークォークに強くカップルするCLFV・スカラー相互作用のモデルを調べた

- ヘビークォクーの質量効果をシステマティックに取り入れた**ACOTスキームはCLFV DISにおいて特にパワフル**である。

- コライダー実験におけるCLFV探索は、稀崩壊実験と相補的である：CLFV DIS(eN→τX)における**終状態τレプトンの運動量分布の解析はCLFV相互作用/スカラー質量の詳細を解き明かすのに重要**である。

  →トークでは、プレリミナリーな結果も発表したが、サブプロセスのフルアナリシスは現在進行中です

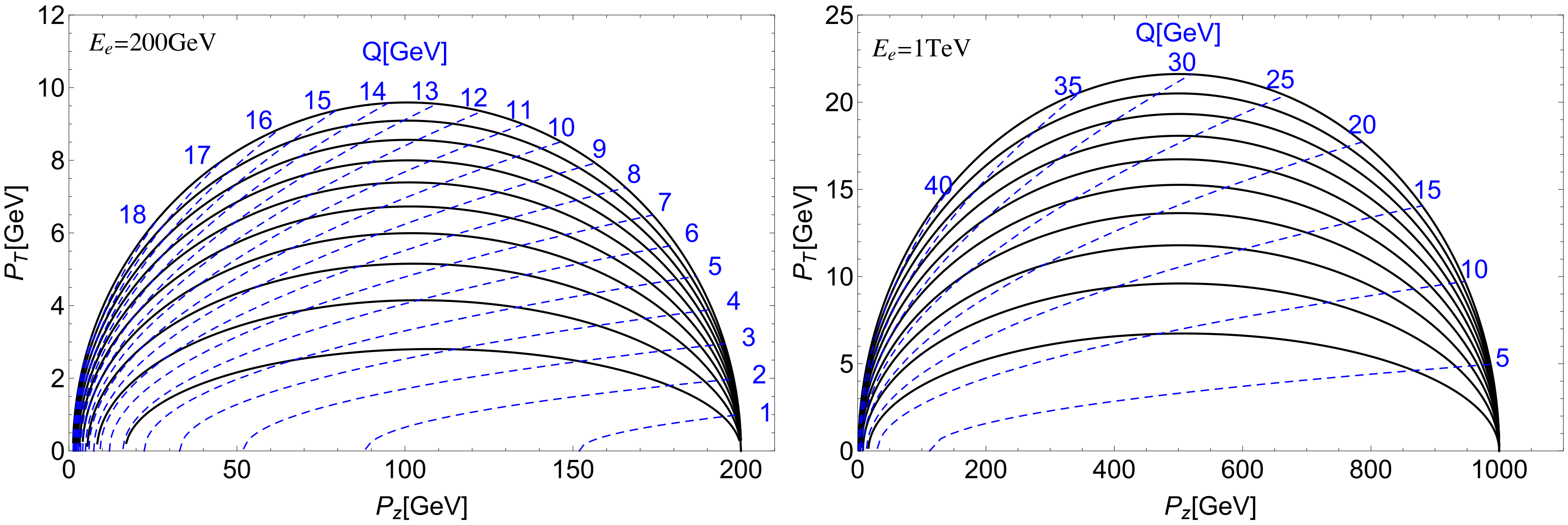
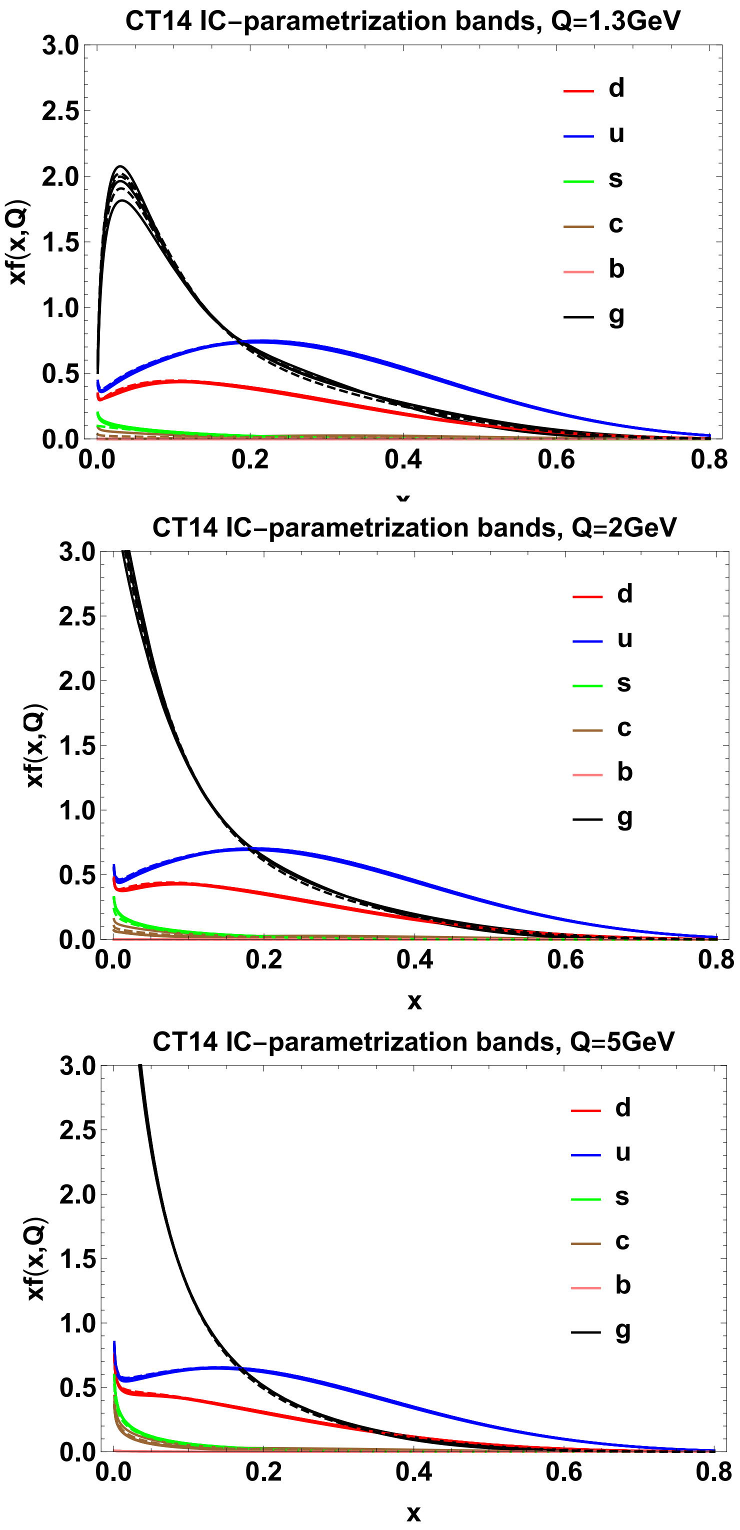


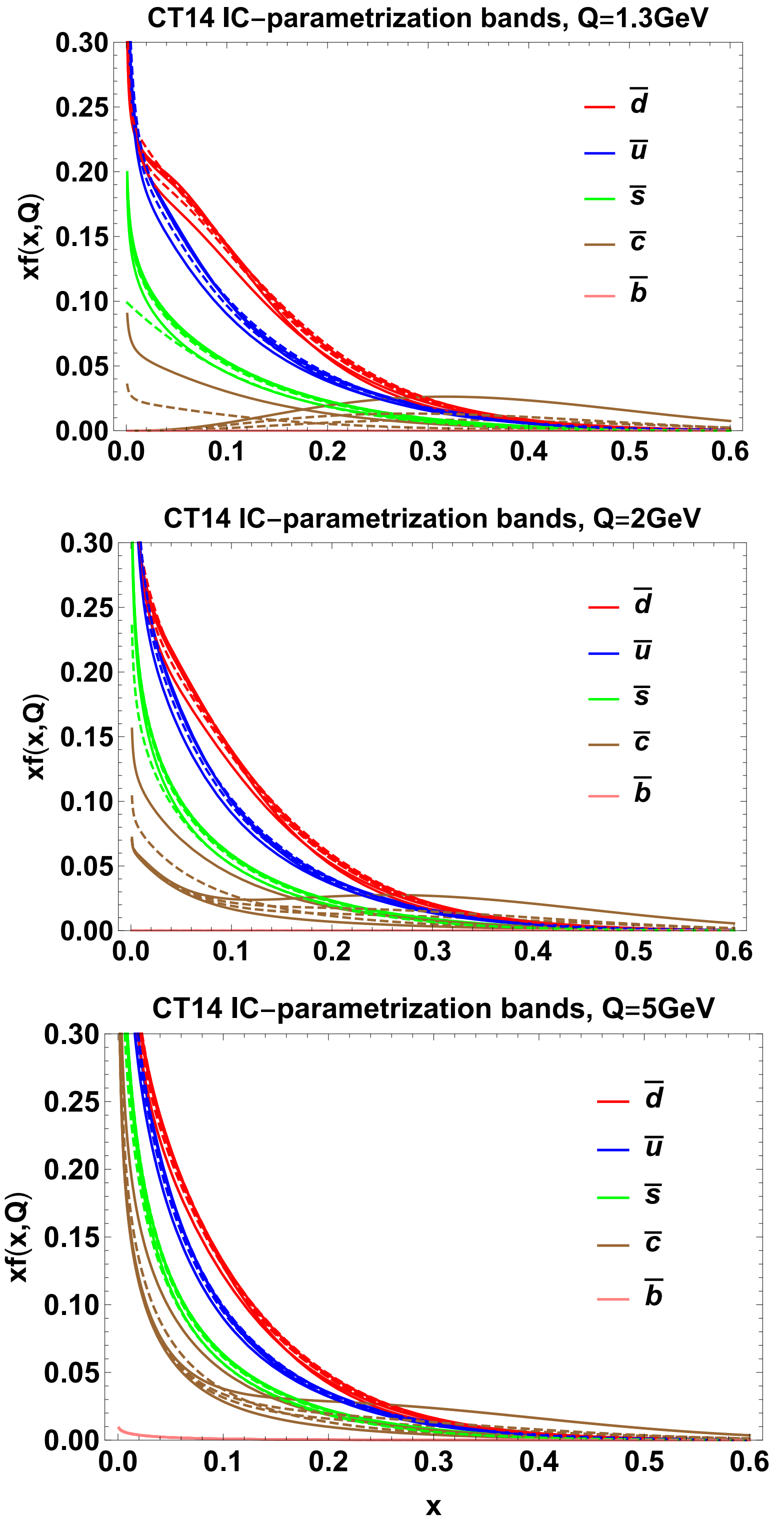
FIG. 2: The physical region of the τ-momentum for the process $eN \to \tau X$ in a fixed target experiment. The electron beam energy is $E_e = 200\,\mathrm{GeV}$(left panel)/$1\,\mathrm{TeV}$(right panel). The contour lines of fixed x (black lines) and fixed Q (dashed blue lines) are plotted in the momentum space (p_z, p_T).

Backup

Quarks

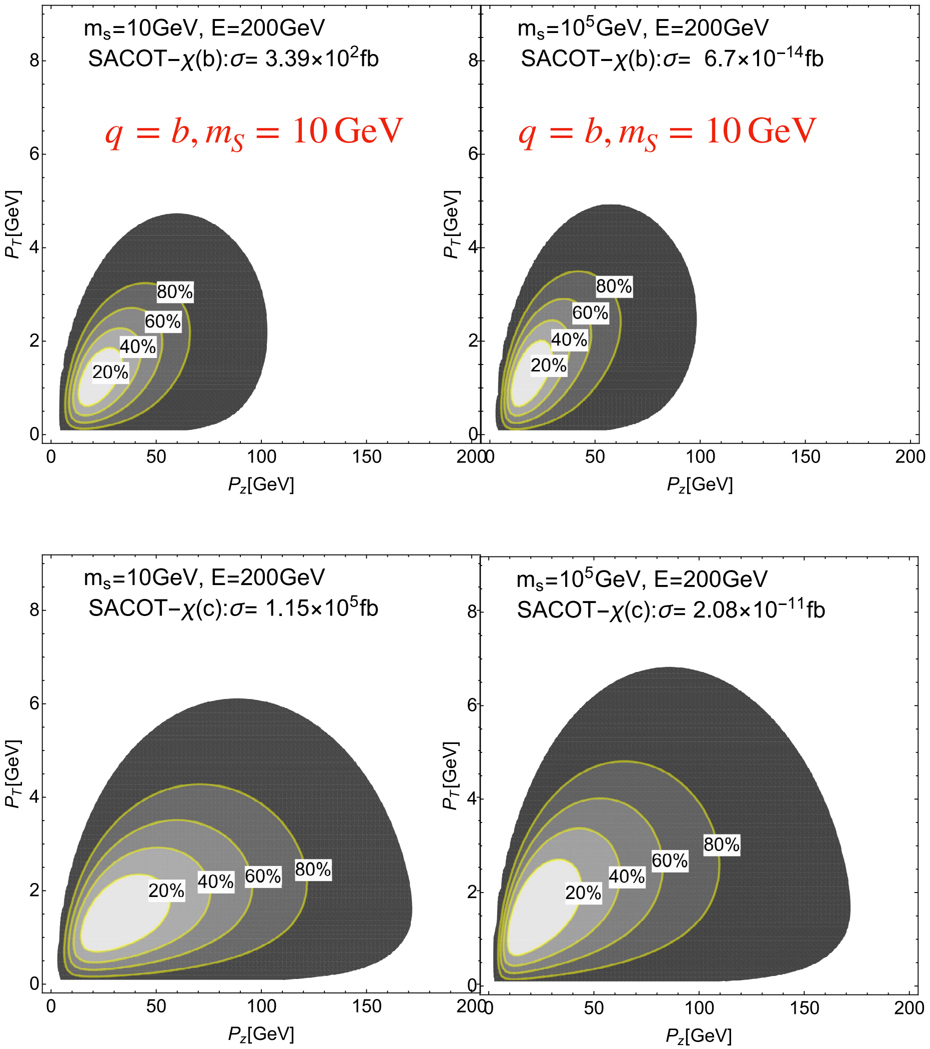


Sea Quarks

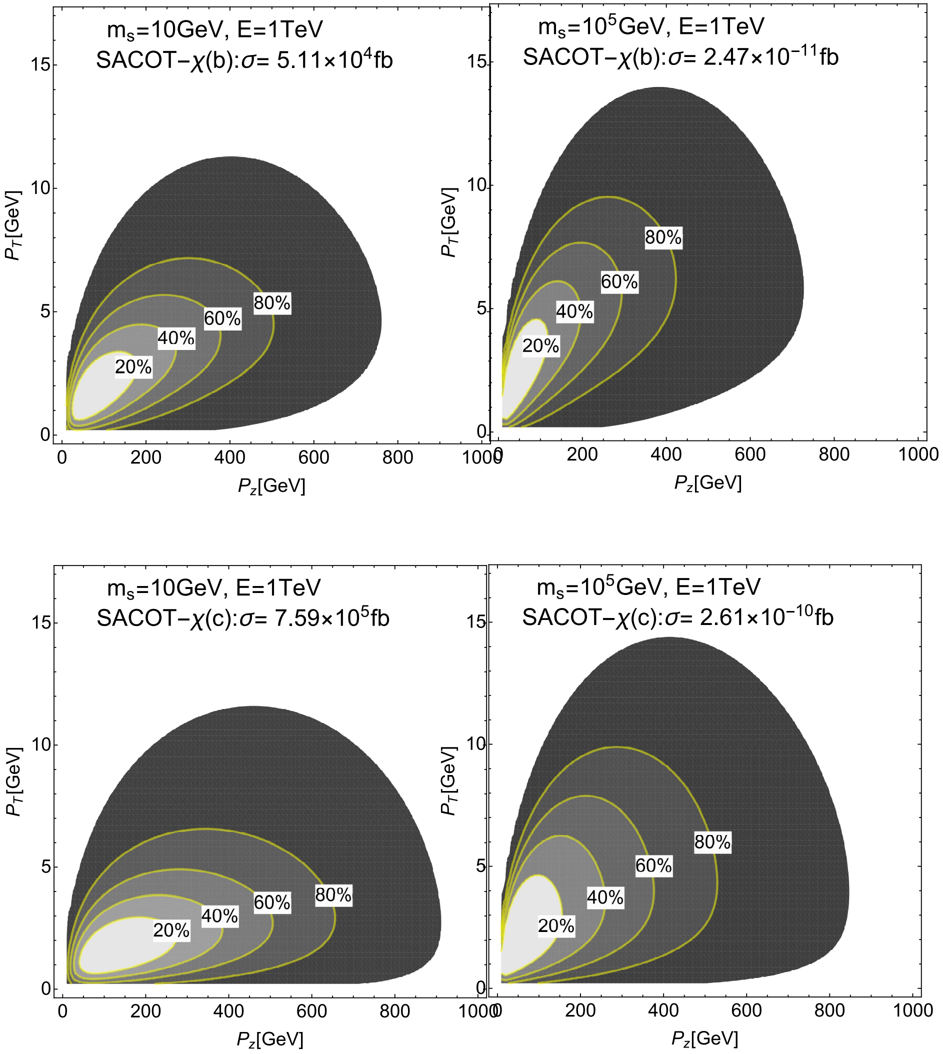


τ の運動量分布(eP→ τ bbX)

$E_e = 200\,\mathrm{GeV}$

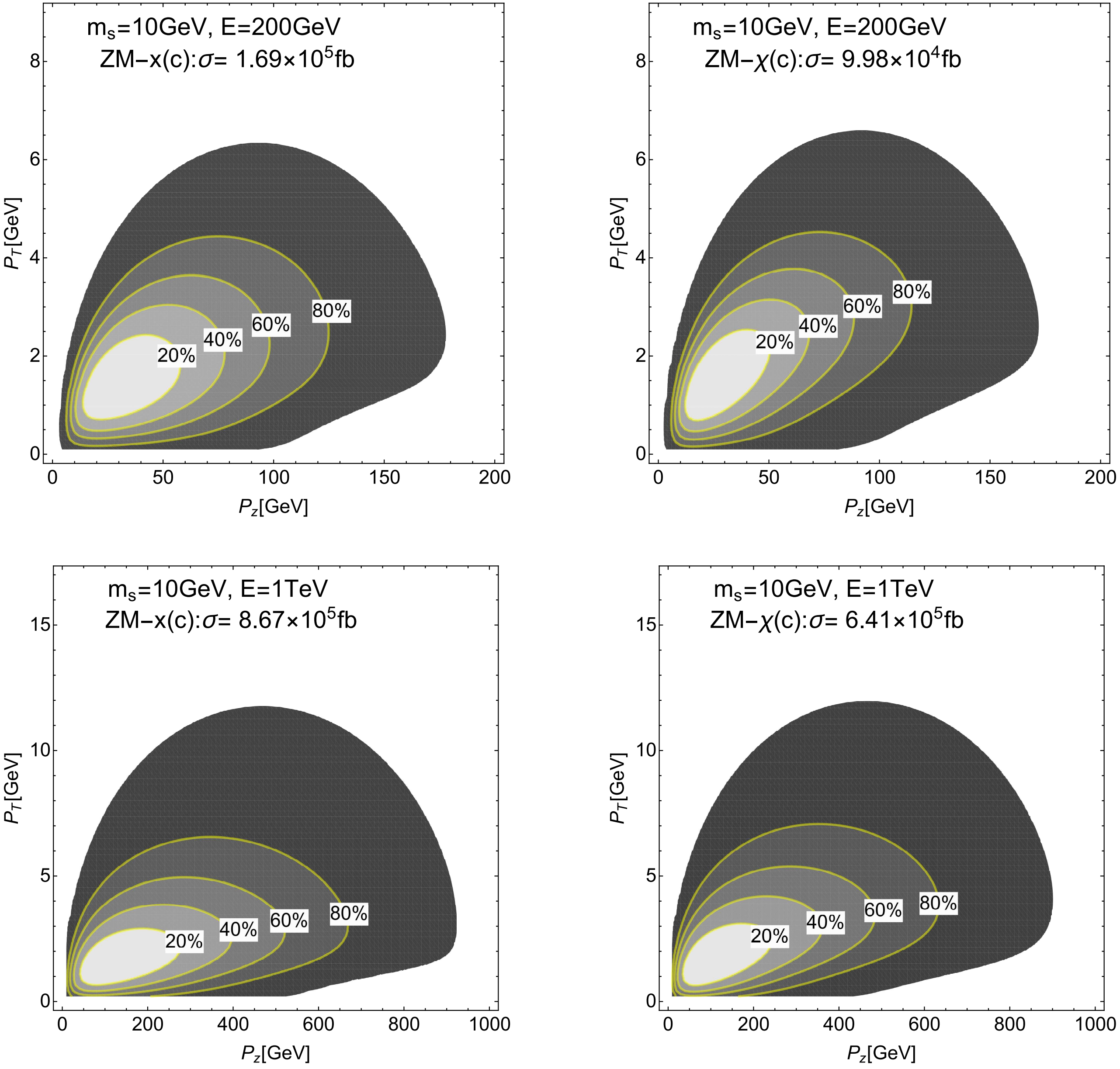


$E_e = 1\,\mathrm{TeV}$



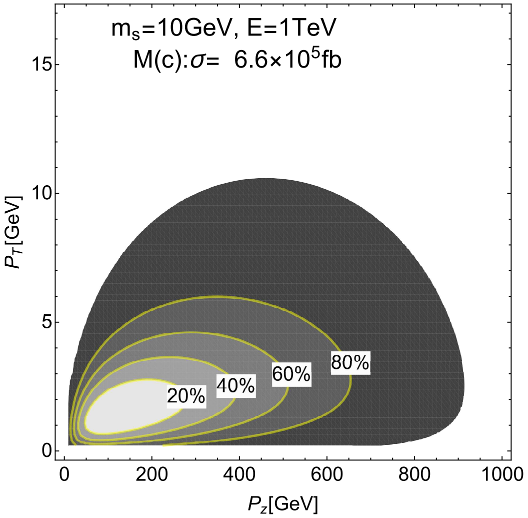
運動量分布(ZM schemes)

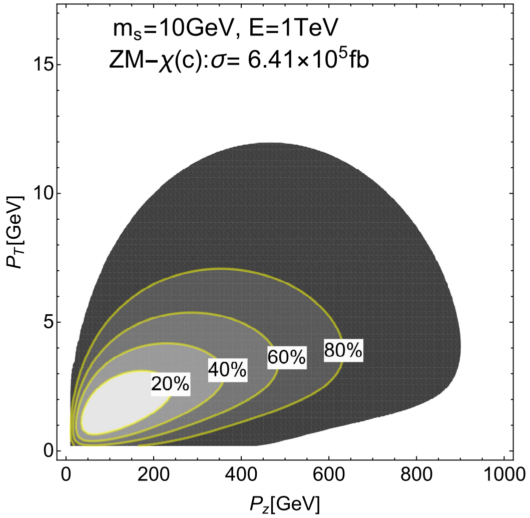
eP→τ(p)ccのτ-momentum 分布

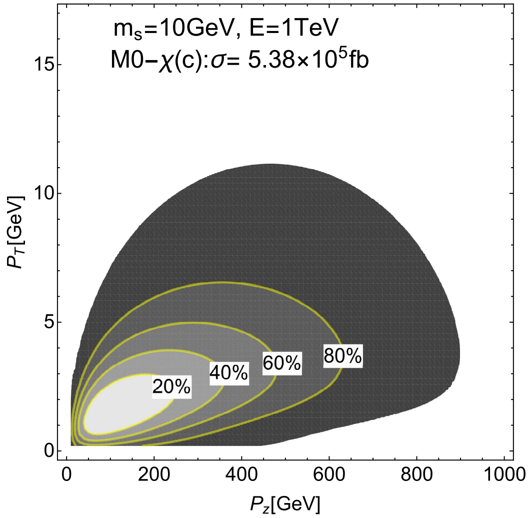


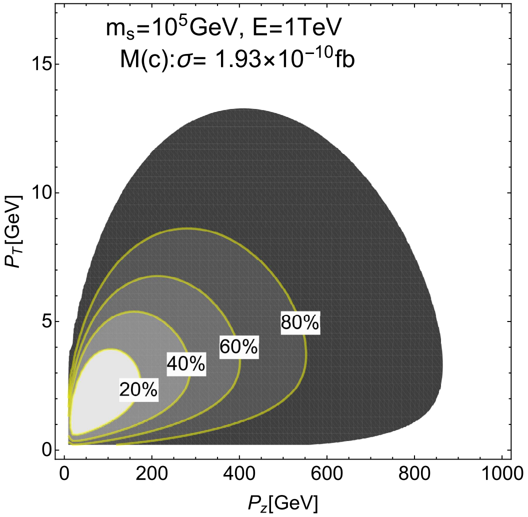
eP→τ cc(M/ZM/sub)

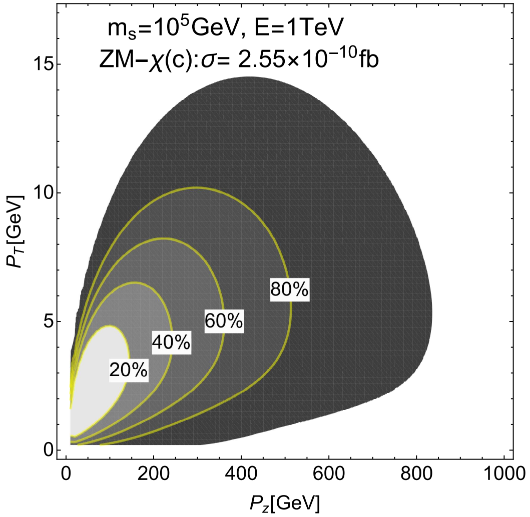
Ee=1TeV, ms=10/10^5GeV

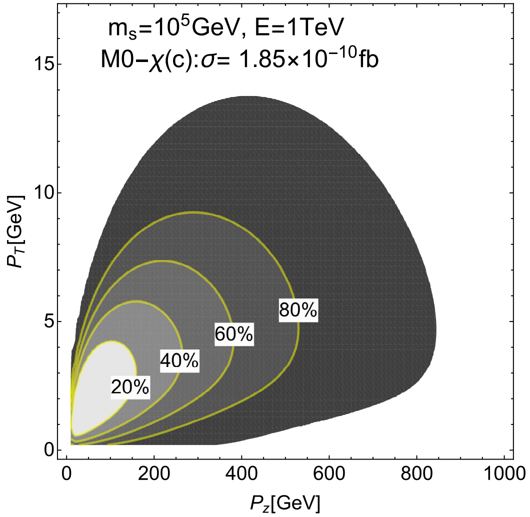












$eP \to \tau cc$(ACOT)

ACOT: Ee , msの変化