Hidden Fermion as Milli-charged Dark Matter in Stueckelberg Z' Models

Tzu-Chiang Yuan
National Tsing Hua University, Hsinchu, Taiwan

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(Based on K. Cheung and TCY, JHEP03 (2007) 120;
arXiv: hep-ph/0701107)

Outline

- Stueckelberg Z' Extension of Standard Model (StSM)
- Hidden Fermions
- Collider and Astrophysical Implication
- Conclusions

StSM

- Stueckelberg extension of SM [Kors and Nath (2004)]

$$
\begin{array}{ccccc}
SU(2)_L & \times & U(1)_Y & \times & [U(1)_X]_{\text{hidden sector}} \\
W^a_\mu & & B_\mu & & C_\mu
\end{array}
$$

$$
\begin{aligned}
\mathcal{L}_{\text{StSM}} &= \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{St}} \\
\mathcal{L}_{\text{St}} &= -\frac{1}{4} C_{\mu\nu} C^{\mu\nu} + \frac{1}{2} (\partial_\mu \sigma + M_1 C_\mu + M_2 B_\mu)^2 - g_X C_\mu \mathcal{J}^\mu_X
\end{aligned}
$$

- $\mathcal{J}^\mu_X$ is the matter (both visible and hidden sectors in general) current that couples to the hidden gauge field C_μ. More later.

- Without $U_X(1)$, one would end up massive photon! Model would be highly constrained since from PDG one has

$$
m_\gamma < 6 \times 10^{-17} \text{ eV}
$$

- After EW symmetry breaking by the Higgs mechanism $\langle\Phi\rangle = v/\sqrt{2}$

$$\frac{1}{2}(C_\mu, B_\mu, W^3_\mu)\ M^2 \begin{pmatrix} C_\mu \\ B_\mu \\ W^3_\mu \end{pmatrix}$$

$$M^2 = \begin{pmatrix} M_1^2 & M_1 M_2 & 0 \\ M_1 M_2 & M_2^2 + \frac{1}{4}g_Y^2 v^2 & -\frac{1}{4}g_2 g_Y v^2 \\ 0 & -\frac{1}{4}g_2 g_Y v^2 & \frac{1}{4}g_2^2 v^2 \end{pmatrix}$$

- $\mathrm{Det}(M^2) = 0$, one massless mode is guaranteed!
- Diagonalize the mass matrix

$$\begin{pmatrix} C_\mu \\ B_\mu \\ W^3_\mu \end{pmatrix} = O \begin{pmatrix} Z'_\mu \\ Z_\mu \\ A_\mu \end{pmatrix} \quad , \qquad O^T M^2 O = \mathrm{diag}(m^2_{Z'},\, m^2_Z,\, m^2_\gamma = 0)\ .$$

- The $m^2_{Z'}$ and m^2_Z are given by

$$m^2_{Z',\,Z} = \frac{1}{2}\left[M_1^2 + M_2^2 + \frac{1}{4}(g_Y^2 + g_2^2)v^2 \pm \Delta\right]$$

$$\Delta = \sqrt{(M_1^2 + M_2^2 + \frac{1}{4}g_Y^2 v^2 + \frac{1}{4}g_2^2 v^2)^2 - (M_1^2(g_Y^2 + g_2^2)v^2 + g_2^2 M_2^2 v^2)}$$

- The orthogonal matrix O is parameterized as

$$O = \begin{pmatrix} c_\psi c_\phi - s_\theta s_\phi s_\psi & s_\psi c_\phi + s_\theta s_\phi c_\psi & -c_\theta s_\phi \\ c_\psi s_\phi + s_\theta c_\phi s_\psi & s_\psi s_\phi - s_\theta c_\phi c_\psi & c_\theta c_\phi \\ -c_\theta s_\psi & c_\theta c_\psi & s_\theta \end{pmatrix}$$

where $s_\phi = \sin\phi, c_\phi = \cos\phi$ etc.

- m_Z mass is modified! And $m_{Z'} > m_Z$!
- Precision EW data constraints from LEP must be respected!

- The angles are related to the parameters in the Lagrangian $\mathcal{L}_{\mathrm{StSM}}$ by

$$\delta \equiv \tan\phi = \frac{M_2}{M_1} \quad , \quad \tan\theta = \frac{g_Y \cos\phi}{g_2},$$

$$\tan\psi \quad = \quad \frac{\tan\theta\ \tan\phi\, m_W^2}{\cos\theta[m_{Z'}^2 - m_W^2(1+\tan^2\theta)]} \ ,$$

where $m_W = g_2 v/2$.

- The Stueckelberg Z' decouples from the SM when $\phi \to 0$, since

$$\tan\phi = \frac{M_2}{M_1} \to 0 \ \Rightarrow \ \tan\psi \to 0 \ \text{ and } \ \tan\theta \to \tan\theta_{\mathrm{w}}$$

where θ_{w} is the Weinberg angle.

Matter current $\mathcal{J}_X$:

- If SM fermion carries X charge, one can has

$$Q_u = \frac{2}{3} - \frac{g_X}{g_Y}\tan\phi\, Q_X(u), \quad Q_d = -\frac{1}{3} - \frac{g_X}{g_Y}\tan\phi\, Q_X(d)$$

However, $Q_{\text{neutron}} = 0$ implies $Q_u + 2Q_d = 0$ to high precision.

$$Q_X(\text{SM particle}) = 0 \quad \Longrightarrow \quad \mathcal{J}_X^{\text{SM}} = 0$$

But, for the hiddden sector, one can has

$$Q_X(\text{hidden particle}) \neq 0 \quad \Longrightarrow \quad \mathcal{J}_X^{\text{hidden sector}} \neq 0$$

- Mixing effects in neutral current of SM fermions ψ_f

$$
\begin{aligned}
-\mathcal{L}_{\rm int}^{NC} &= g_2 W^3_\mu\, \bar{\psi}_f \gamma^\mu \frac{\tau^3}{2} \psi_f + g_Y B_\mu\, \bar{\psi}_f \gamma^\mu \frac{Y}{2} \psi_f \\
&= \bar{\psi}_f\, \gamma^\mu \left[\left(\epsilon^{f_L}_{Z'} P_L + \epsilon^{f_R}_{Z'} P_R \right) Z'_\mu \right. \\
&\qquad \left. + \left(\epsilon^{f_L}_{Z} P_L + \epsilon^{f_R}_{Z} P_R \right) Z_\mu + e Q_{\rm em} A_\mu \right] \psi_f
\end{aligned}
$$

where

$$
\begin{aligned}
\epsilon^{f_{L,R}}_{Z} &= \frac{c_\psi}{\sqrt{g_2^2 + g_Y^2 c_\phi^2}} \left(-c_\phi^2 g_Y^2 \frac{Y}{2} + g_2^2 \frac{\tau^3}{2} \right) + s_\psi s_\phi g_Y \frac{Y}{2} \, , \\
\epsilon^{f_{L,R}}_{Z'} &= \frac{s_\psi}{\sqrt{g_2^2 + g_Y^2 c_\phi^2}} \left(c_\phi^2 g_Y^2 \frac{Y}{2} - g_2^2 \frac{\tau^3}{2} \right) + c_\psi s_\phi g_Y \frac{Y}{2} \, .
\end{aligned}
$$

- Constraints on StSM.

[Feldman, Liu, and Nath, PRL 97, 021801 (2006)]

  - Z mass shift requires ($m_Z/M_1 \ll 1$)

$$|\delta \equiv \tan\phi = M_2/M_1| \leq 0.061\sqrt{1-(m_Z/M_1)^2}$$

  - Drell-Yan data of Stueckelberg Z'

$$\begin{aligned} m_{Z'} &> 250 \text{ GeV} \quad \text{for} \quad \delta \approx 0.035\ , \\ m_{Z'} &> 375 \text{ GeV} \quad \text{for} \quad \delta \approx 0.06\ . \end{aligned}$$

  - Z' width is narrow, since $Z' \to$ SM fermions are suppressed by mixing angles!

[Feldman, Liu, and Nath, PRL 97, 021801 (2006)]

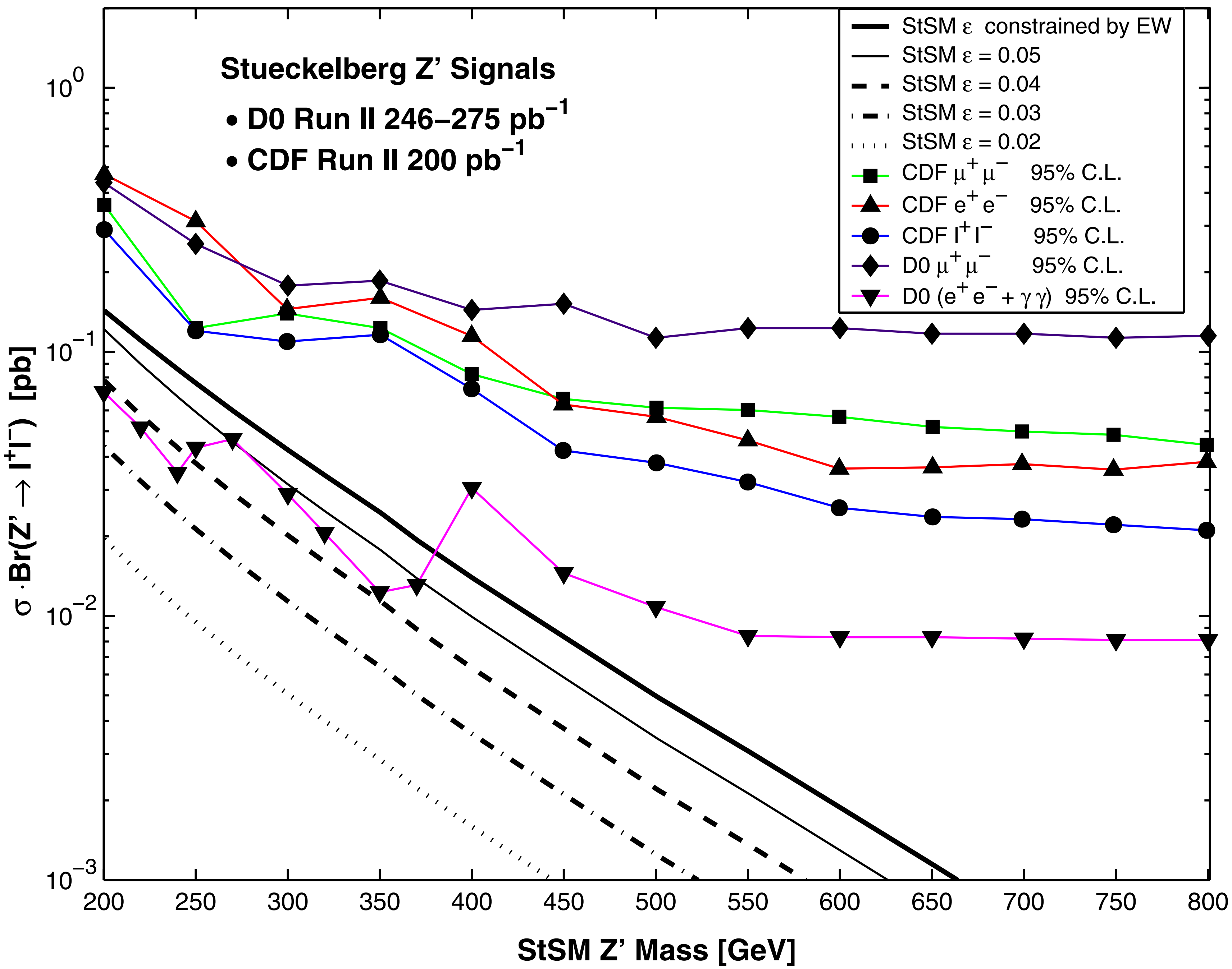


FIG. 1 (color online). Z' signal in StSM using the CDF [1] and D0 [2] data. The data put a lower limit of about 250 GeV on $M_{Z'}$ for $\epsilon \approx 0.035$ and 375 GeV for $\epsilon \approx 0.06$.

Hidden Fermions [K. Cheung and TCY, JHEP03 (2007) 120]

- Add a pair of Dirac fermion χ and $\bar{\chi}$ in the hidden sector

$$\begin{aligned}
\mathcal{J}_X^{\mu\chi} &= \bar{\chi}\gamma^\mu Q_X^\chi \chi \\
-\mathcal{L}_{\rm int}^{NC} &= \cdots + g_X C_\mu \mathcal{J}_X^{\mu\chi} \\
&= \cdots + \bar{\chi}\gamma^\mu \left[\epsilon_\gamma^\chi A_\mu + \epsilon_Z^\chi Z_\mu + \epsilon_{Z'}^\chi Z'_\mu\right] \chi
\end{aligned}$$

$$\begin{aligned}
\epsilon_\gamma^\chi &= g_X Q_X^\chi (-c_\theta s_\phi) \, , \\
\epsilon_Z^\chi &= g_X Q_X^\chi (s_\psi c_\phi + s_\theta s_\phi c_\psi) \, , \; \epsilon_{Z'}^\chi = g_X Q_X^\chi (c_\psi c_\phi - s_\theta s_\phi s_\psi)
\end{aligned}$$

- Z' couples to χ is not suppressed. Its width needs not to be narrow. Drell-Yan constraint may be relaxed, if $Z' \to \chi\bar{\chi}$ is kinematic allowed.

- Photon couples to χ can be milli-charged! $(\epsilon_\gamma^\chi \ll e)$

- More over, χ is stable! In general, all hidden fermions are stable w.r.t. $U(1)_X$.

- χ is a milli-charged dark matter candidate!

[Davidson, Hannestad and Raffelt, JHEP05 (2000) 03]

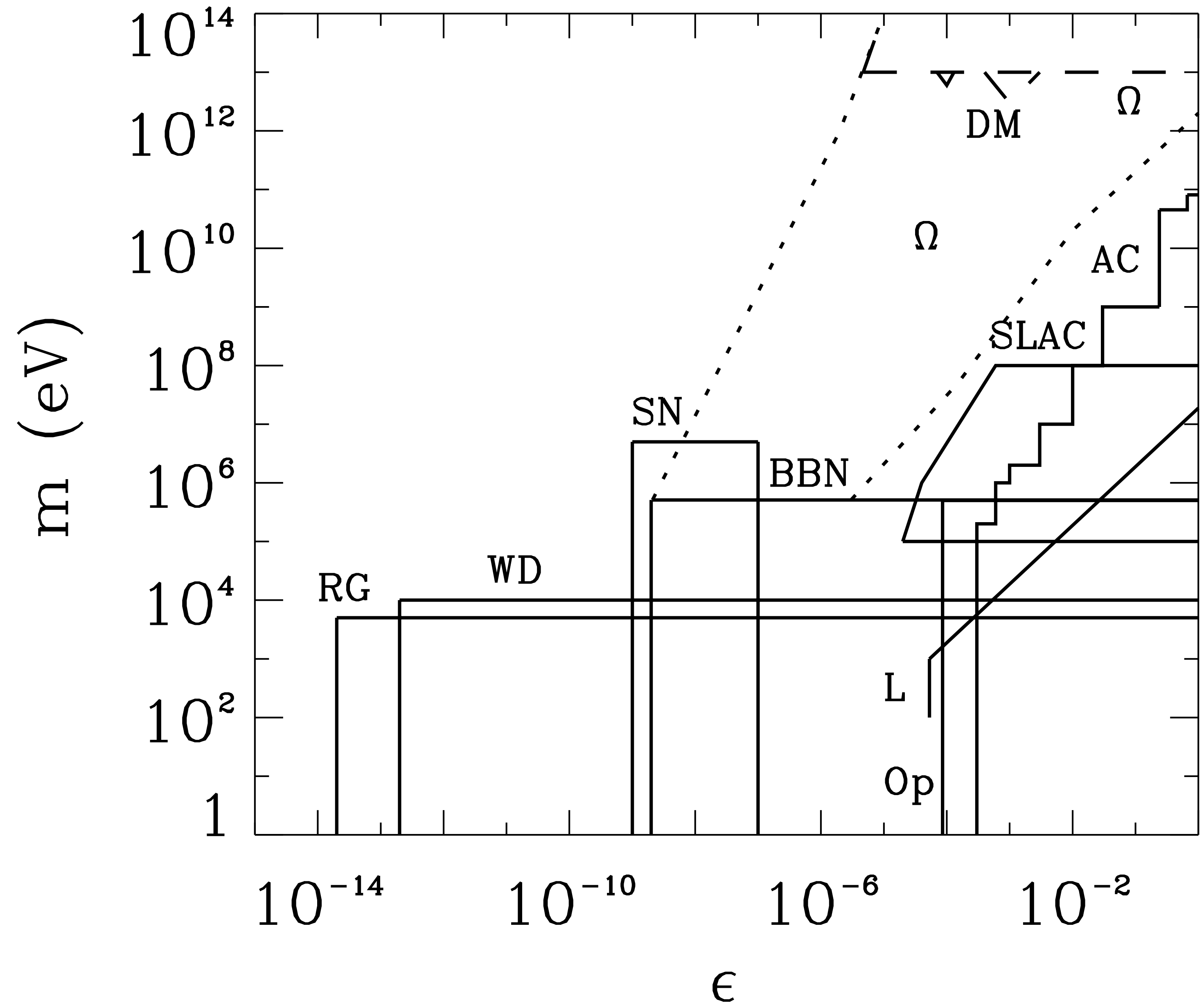
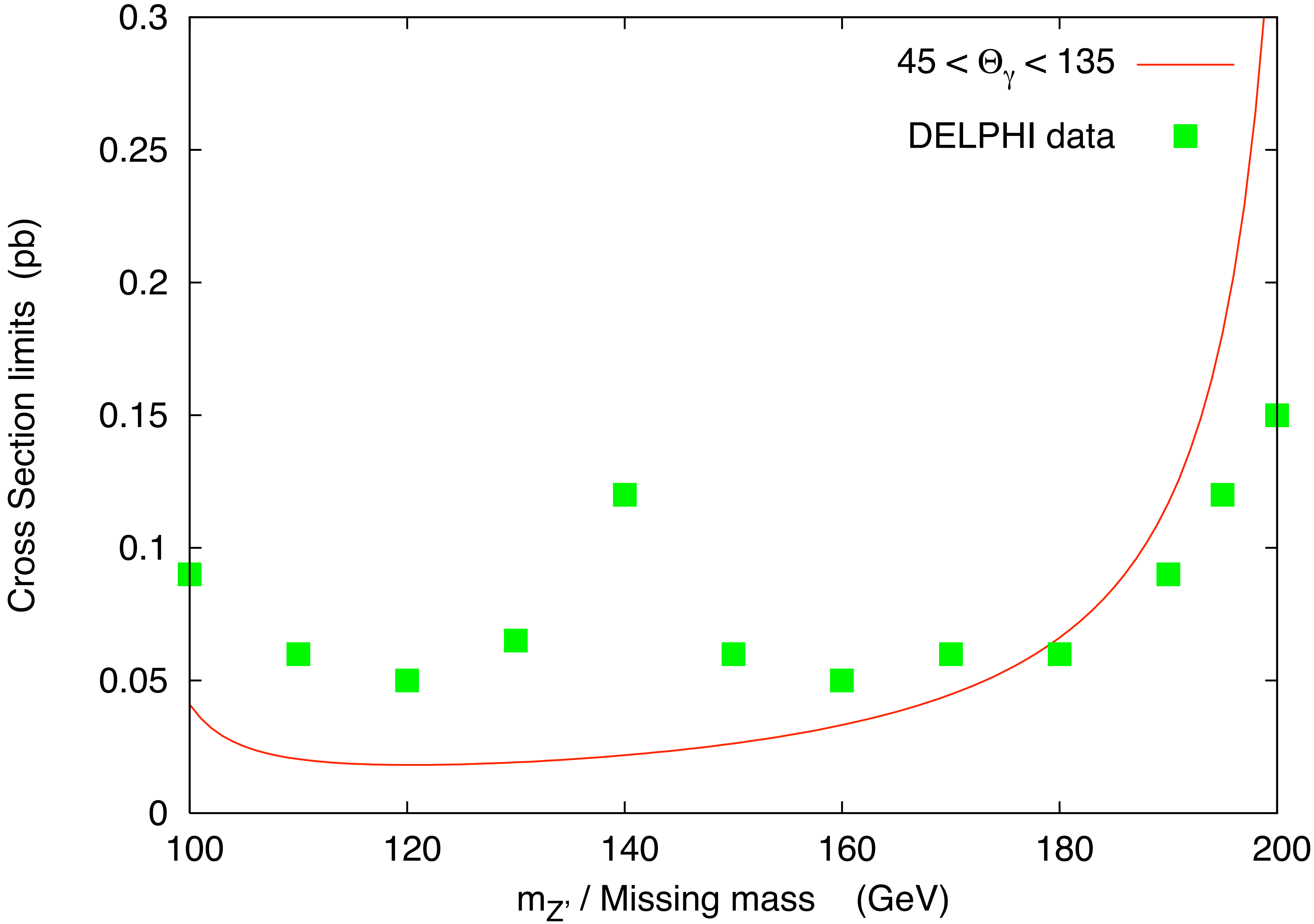


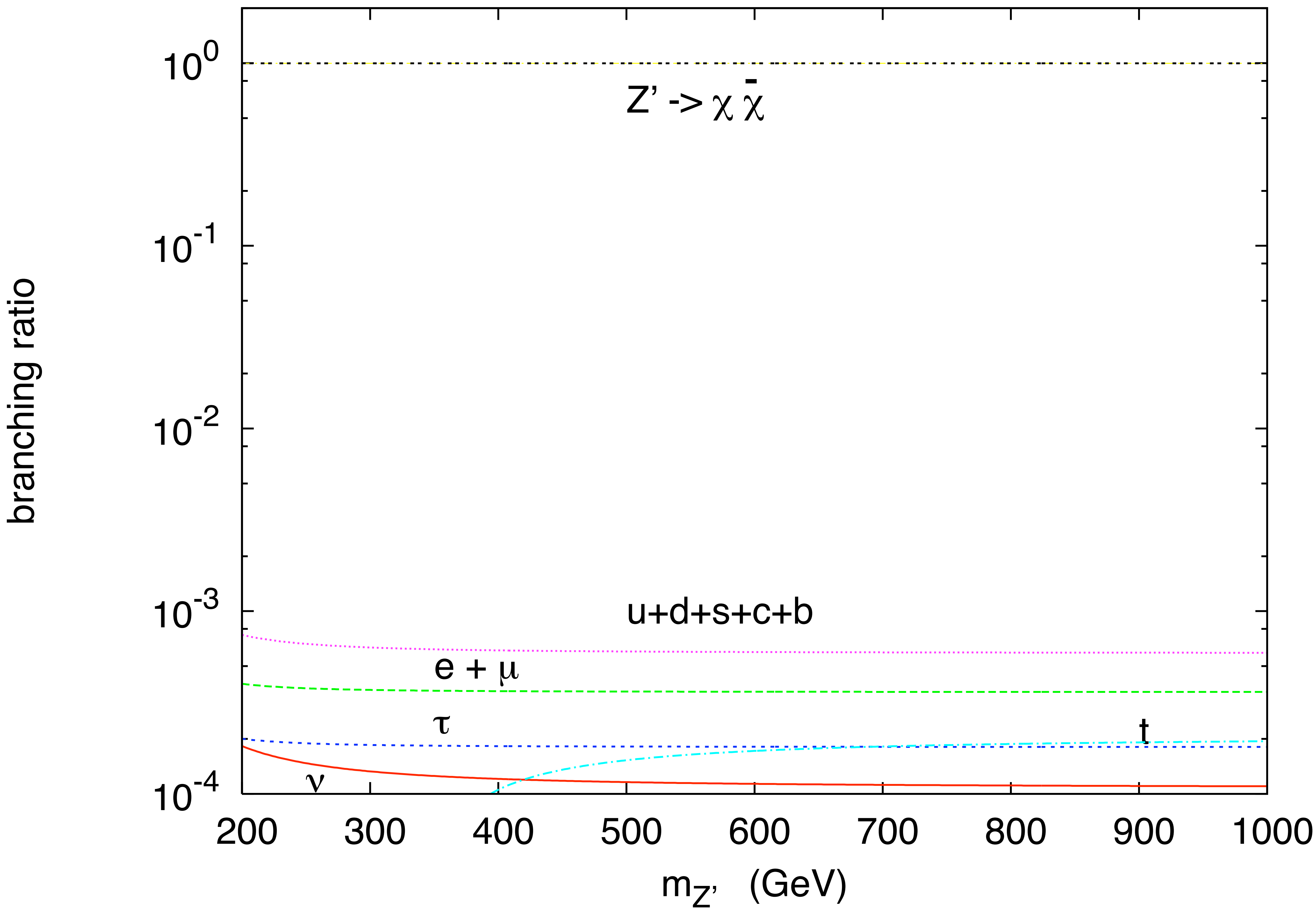
Figure 1: Regions of mass-charge space ruled out for milli-charged particles. The solid and dashed lines apply to the model with a paraphoton; solid and dotted lines apply in the absence of a paraphoton. The bounds arise from the following constraints: AC — accelerator experiments; Op — the Tokyo search for the invisible decay of ortho-positronium [27]; SLAC — the SLAC milli-charged particle search [28]; L — the Lamb shift; BBN — nucleosynthesis; Ω — $\Omega < 1$; RG — plasmon decay in red giants; WD — plasmon decay in white dwarfs; DM — dark matter searches; SN — Supernova 1987A.

Collider Phenomenology

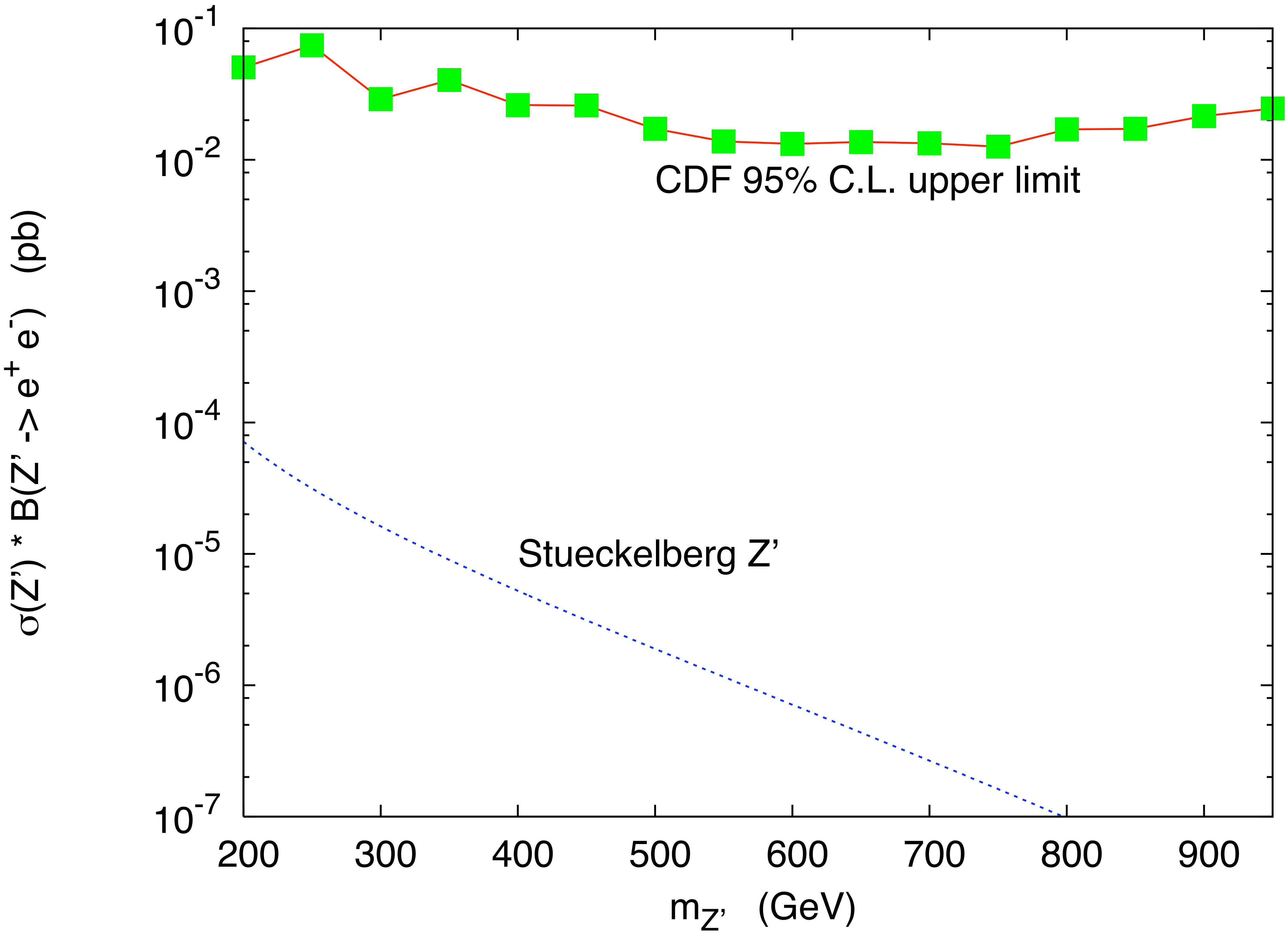
- LEPII constraint ($e^+e^- \to Z'\gamma \to \gamma$ + missing energy) is mild.



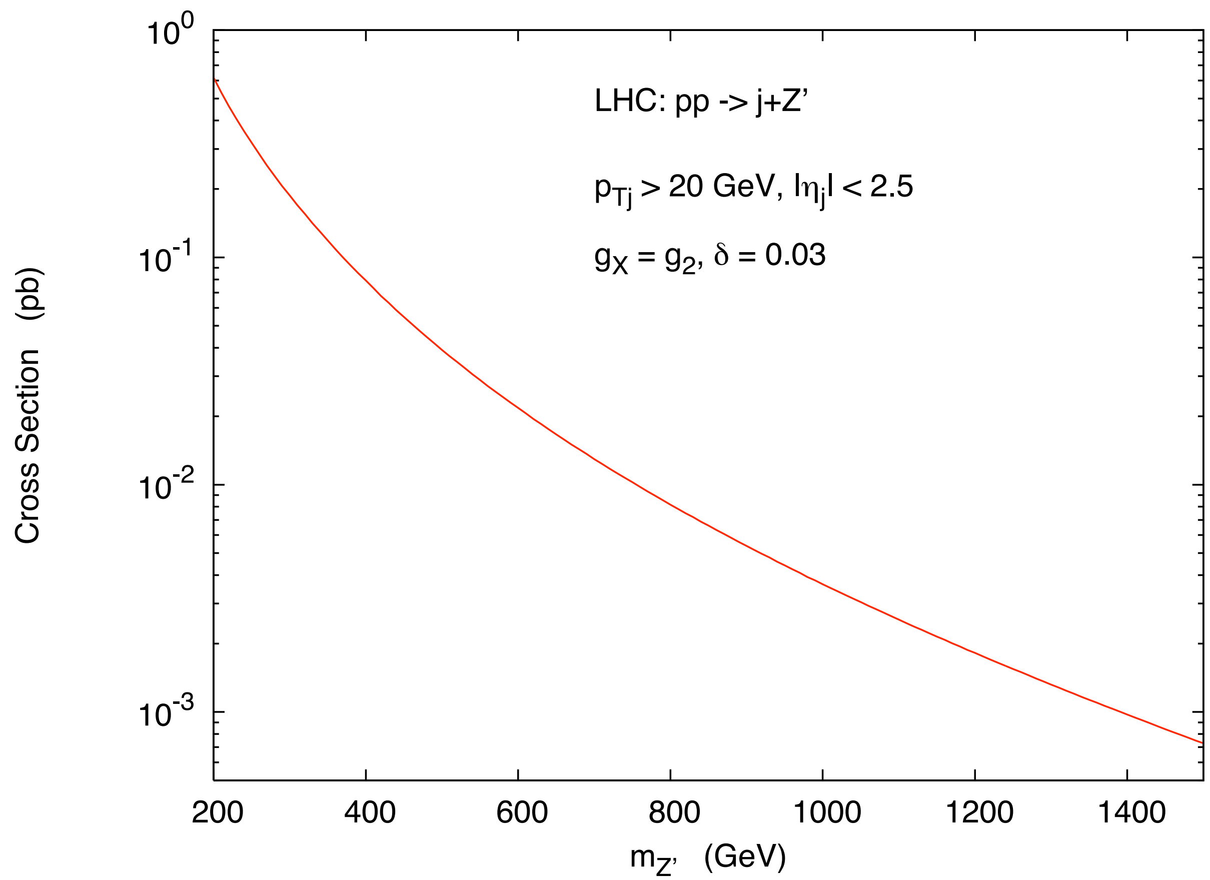
- Branching ratios for Z' with $g_X = g_2$, $\delta = 0.03$ and $m_\chi = 60$ GeV.

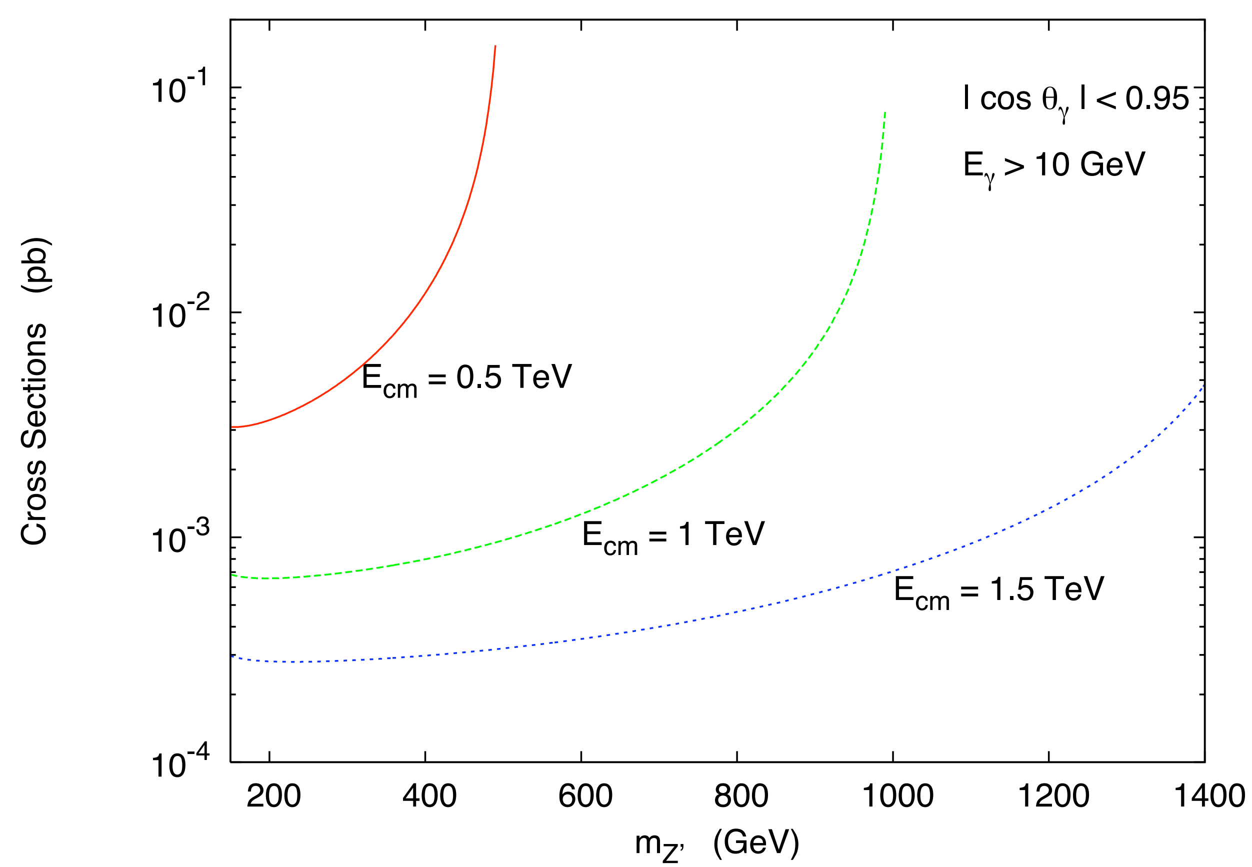


- CDF Drell-Yan ($p\bar{p} \to Z' \to e^+e^-$) data provides no constraint.



- LHC and ILC predictions





- $pp \longrightarrow Z' +$ monojet $\longrightarrow \chi\bar{\chi}$ + monojet
- $e^+e^- \longrightarrow Z' + \gamma \longrightarrow \chi\bar{\chi} + \gamma$
- $g_X = g_2$ and $\delta = 0.03$

Astrophysical Implication

- χ as milli-charged dark matter candidate.

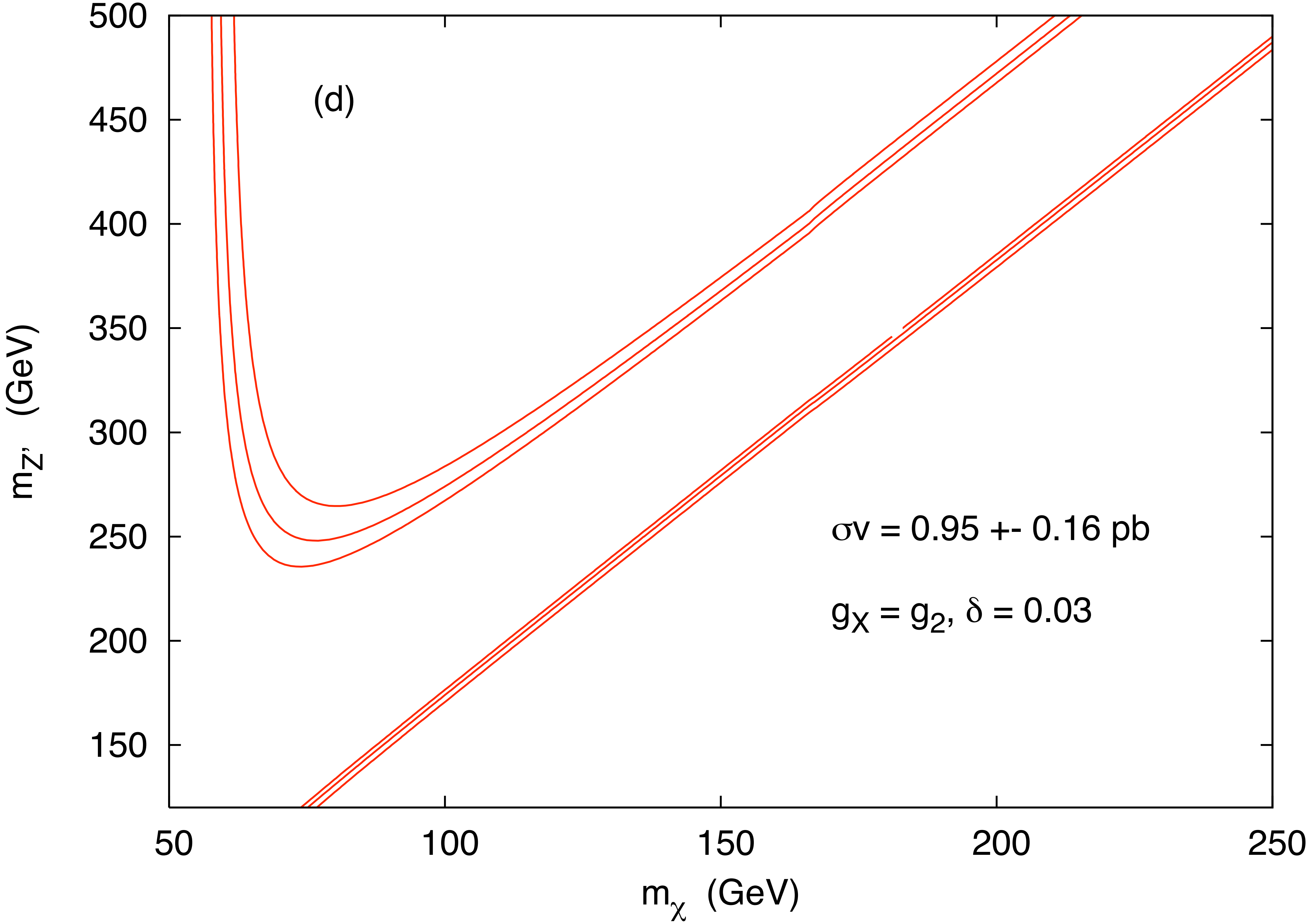
[Holdom Phys. Lett. B166, 196 (1986); Goldberg and Hall, Phys. Lett. B174, 151 (1986)]

- WMAP-3 constraint

$$\Omega_{\mathrm{Cold-Dark-Matter}} h^2 = 0.1045^{+0.0072}_{-0.0095}$$

$$\begin{aligned} \Omega_\chi h^2 &\simeq \frac{s_0}{\rho_{\mathrm{tot}}} \left(\frac{\pi}{45 g_*} \right)^{1/2} \frac{k_B T_f / m_\chi^2 c^2}{m_{\mathrm{Pl}} / \hbar^2 \cdot \langle \sigma v \rangle} \\ &\simeq \frac{0.1 \text{ pb}}{\langle \sigma v \rangle} \rightsquigarrow \langle \sigma v \rangle \simeq 0.95 \pm 0.08 \text{ pb} \end{aligned}$$

- Relic density calculation – $\chi \bar{\chi} \to f_{\mathrm{SM}} \bar{f}_{\mathrm{SM}}, \gamma Z', Z Z'$ are considered; thermal average in σv is ignored, and $v^2 \simeq 0.1$ is used.



- WMAP constraint $\Longrightarrow g_X \sim g_2$ and $\delta = \tan\phi = M_2/M_1 \sim O(10^{-2})$

- Indirect detection of χ
  - Monochromatic line from $\chi\bar{\chi} \to \gamma\gamma, \gamma Z, \gamma Z'$ could be "smoking gun" signal of dark matter annihilation at Galaxy center.
  - Photon flux

$$\Phi_\gamma(\Delta\Omega, E) \approx 5.6 \times 10^{-12} \frac{dN_\gamma}{dE_\gamma} \left(\frac{\sigma v}{\mathrm{pb}}\right) \left(\frac{1\,\mathrm{TeV}}{m_\chi}\right)^2 \overline{J}(\Delta\Omega)\Delta\Omega\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$$

with the quantity $J(\psi)$ defined by

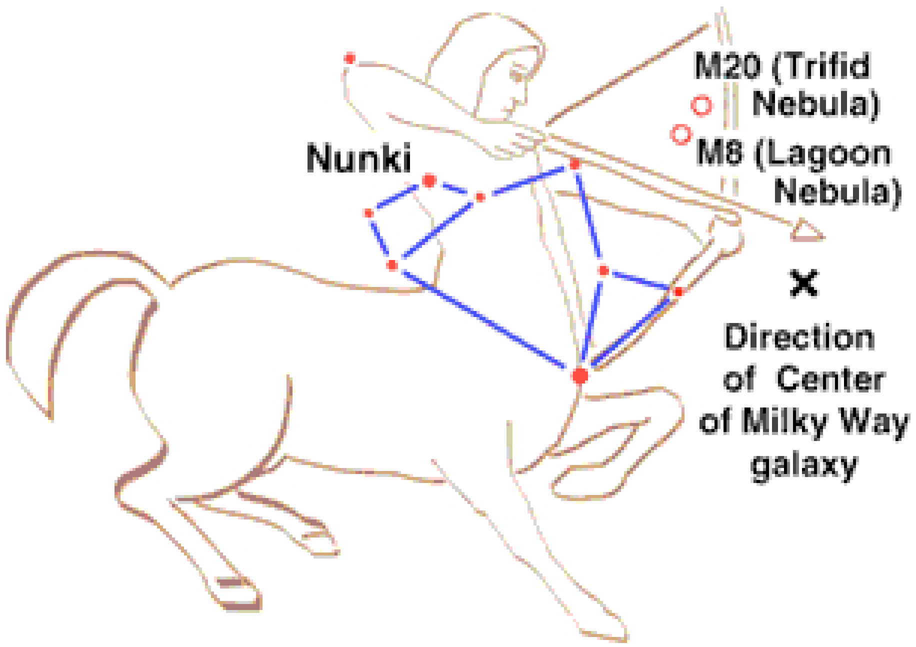
$$J(\psi) = \frac{1}{8.5\,\mathrm{kpc}} \left(\frac{1}{0.3\,\mathrm{GeV/cm^3}}\right)^2 \int_{\text{line of sight}} ds \rho^2(r(s,\psi))$$

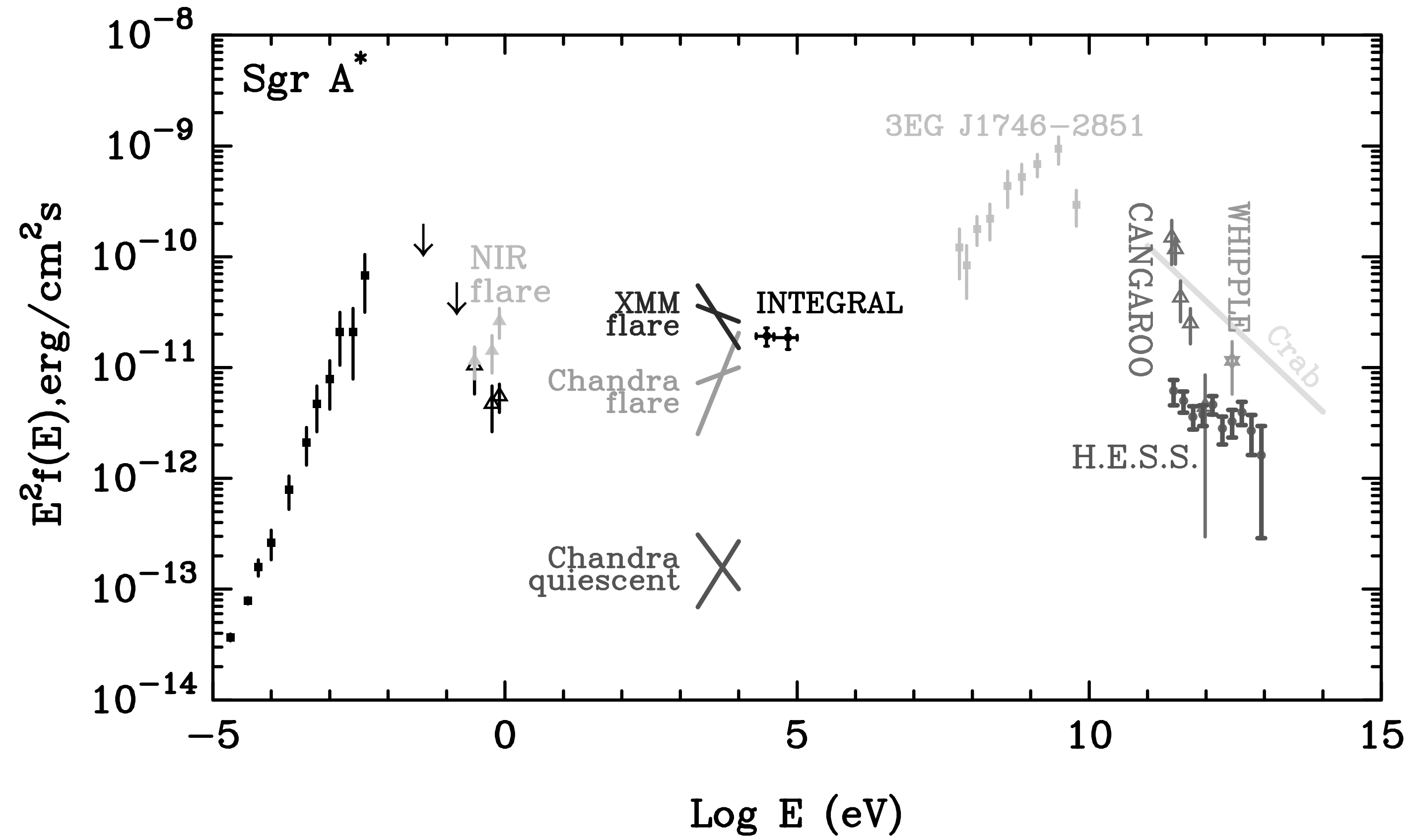
  - $J(\psi)$ depends on the halo profile ρ of the dark matter

- TeV gamma-rays from Sgr A* (hypothetical super-massive black hole) near the Galactic center had been observed recently by CANGAROO, Whipple, HESS.

- These may play the role of continuum background for dark matter detection. Detectability of photon line above continuum background at GLAST and HESS [Zaharijas and Hooper, PRD **73** (2006) 103501]

$$\text{Photon flux} \gtrsim 1.9 \times (\text{TeV}/m_\chi)^2 \times (10^{-14} - 10^{-13})\ \text{cm}^{-2}\ \text{s}^{-1}$$





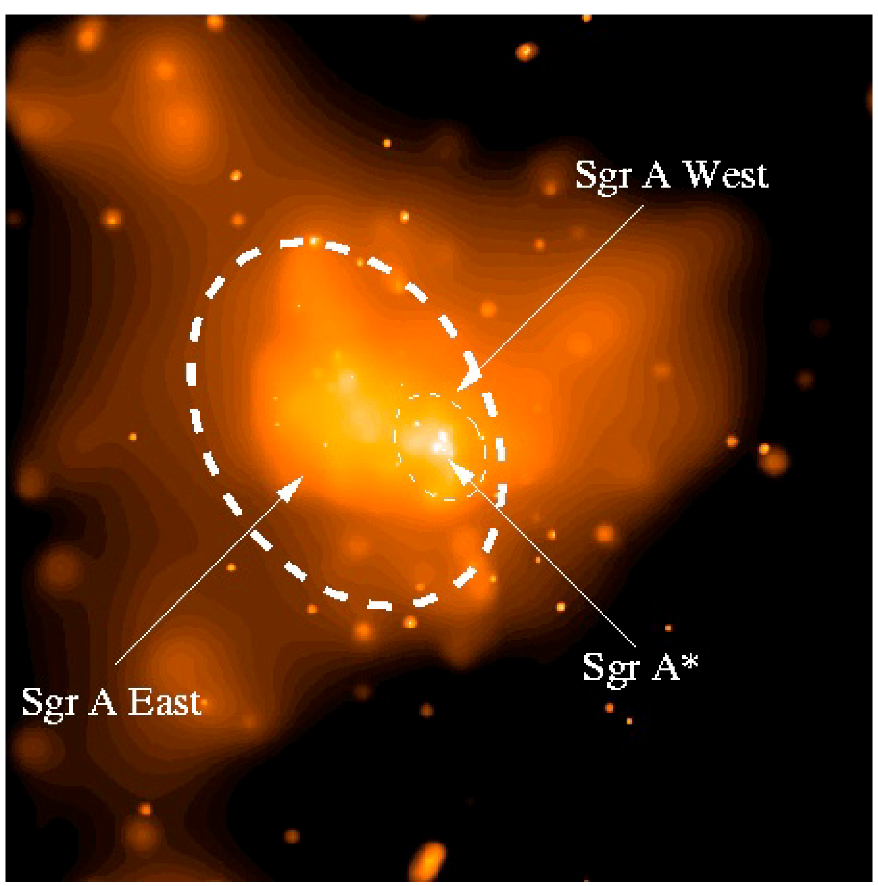
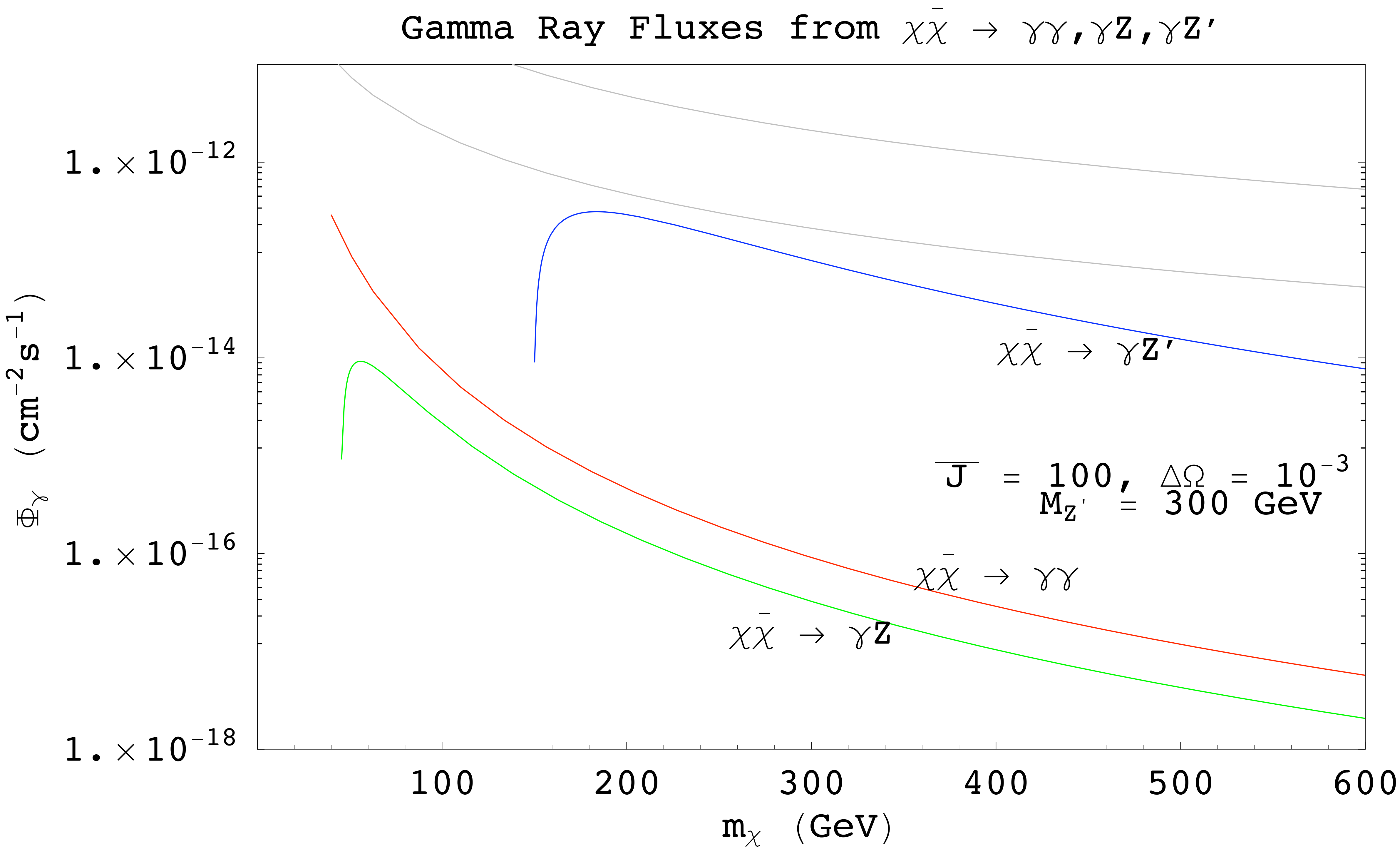


FIG. 1.—Broadband spectral energy distribution (SED) of Sgr A*. Radio data are from Zylka et al. (1995), and the IR data for quiescent state and for flare are from Genzel et al. (2003). X-ray fluxes measured by *Chandra* in the quiescent state and during a flare are from Baganoff et al. (2001, 2003). *XMM-Newton* measurements of the X-ray flux in a flaring state is from Porquet et al. (2003). In the same plot we also show the recent *INTEGRAL* detection of a hard X-ray flux; however, because of relatively poor angular resolution, the relevance of this flux to Sgr A* hard X-ray emission (Bélanger et al. 2004) is not yet established. The same is true also for the EGRET data (Mayer-Hasselwander et al. 1998), which do not allow localization of the GeV source with accuracy better than 1°. The very high energy gamma-ray fluxes are obtained by the CANGAROO (Tsuchiya et al. 2004), Whipple (Kosack et al. 2004), and HESS (Aharonian et al. 2004) groups. Note that the GeV and TeV gamma-ray fluxes reported from the direction of the Galactic center may originate in sources different from Sgr A*; therefore, strictly speaking, they should be considered as upper limits of radiation from Sgr A*. [*See the electronic edition of the Journal for a color version of this figure.*]

Aharonian and Neronov, Astrophys. Journal 619, 306 (2005)

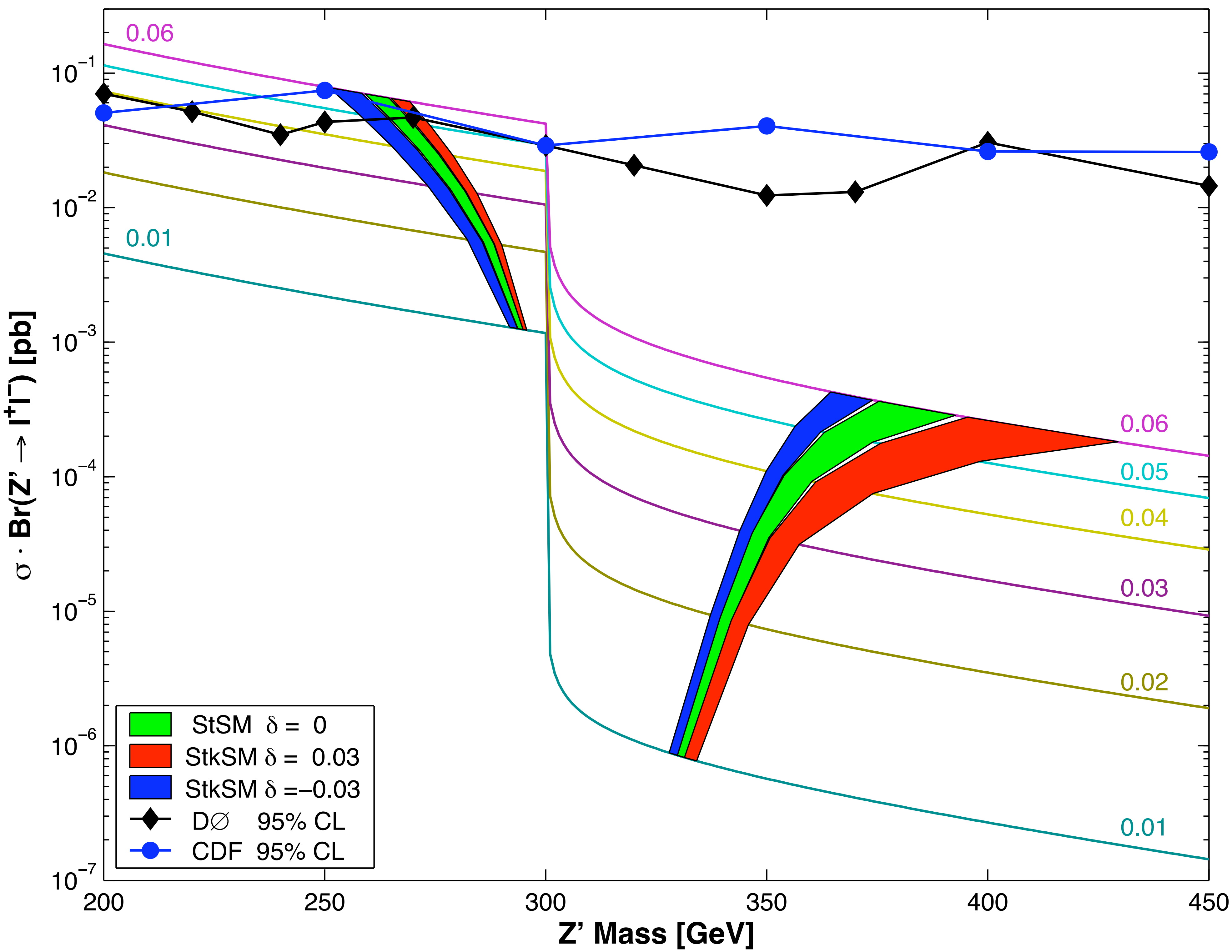


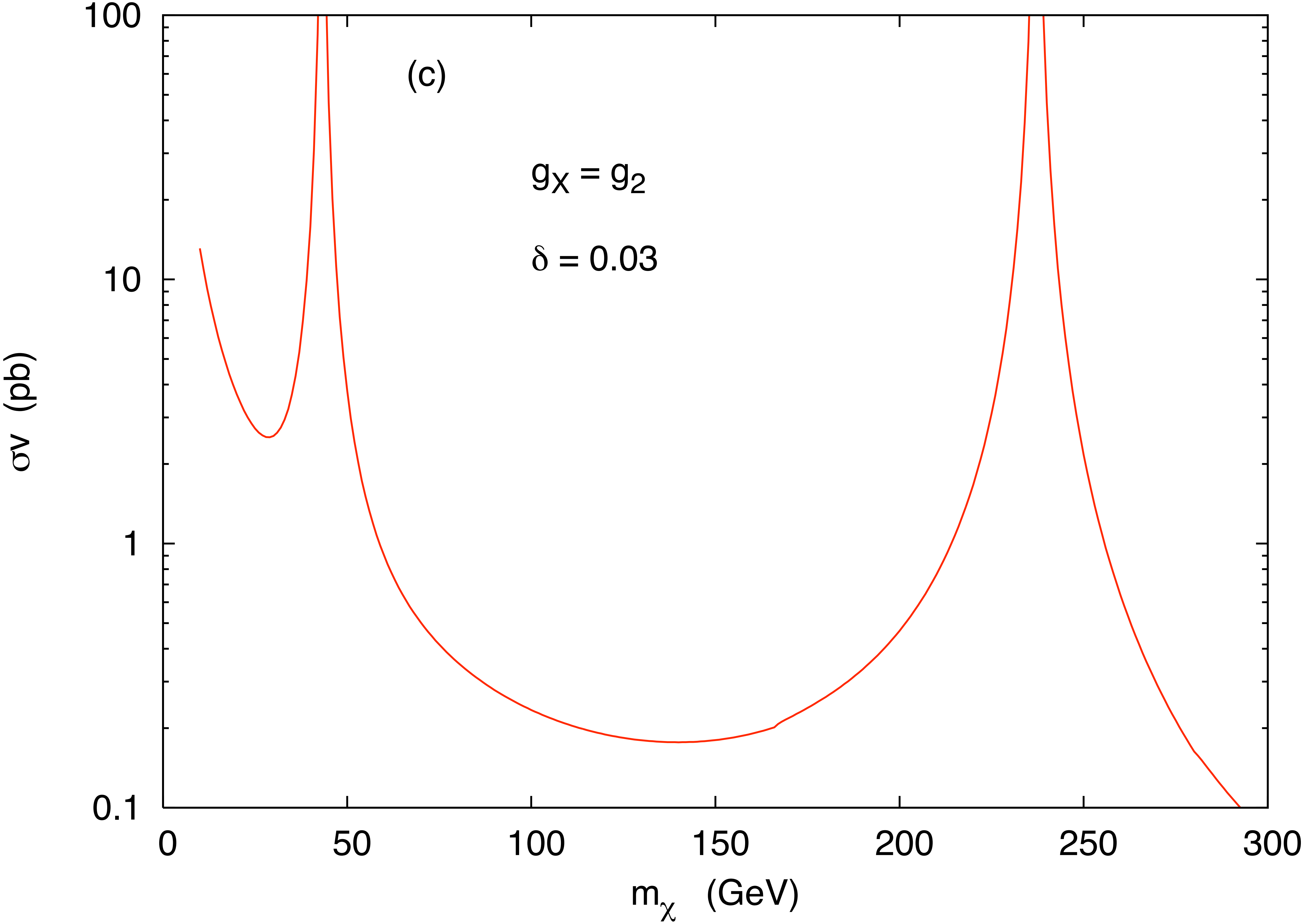
Gamma Ray Fluxes from $\chi\bar{\chi} \to \gamma\gamma, \gamma Z, \gamma Z'$
$\chi\bar{\chi} \to \gamma Z'$
$\bar{J} = 100,\ \Delta\Omega = 10^{-3}$
$M_{Z'} = 300$ GeV
$\chi\bar{\chi} \to \gamma\gamma$
$\chi\bar{\chi} \to \gamma Z$
$1. \times 10^{-12}$
$1. \times 10^{-14}$
$1. \times 10^{-16}$
$1. \times 10^{-18}$
Φ_γ $(\mathrm{cm}^{-2}\mathrm{s}^{-1})$
100
200
300
400
500
600
m_χ (GeV)

Conclusions

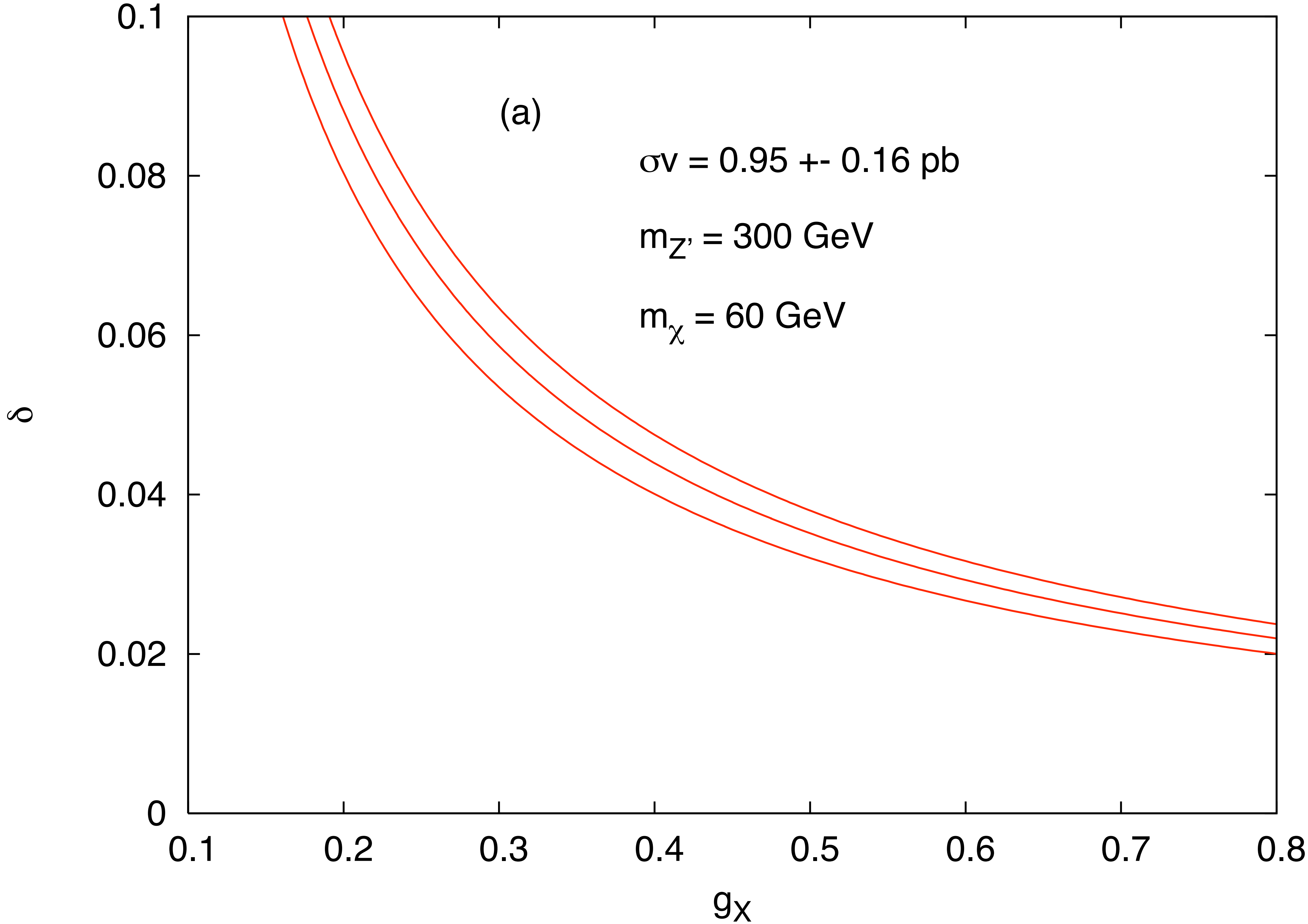
- Phenomenology of Stueckelberg Z' is different from traditional Z'. Mass limits can be much lower, as low as 200 GeV.
- Hidden fermion – milli-charge, viable dark matter candidate.
- New invisible decay mode of $Z' \to \chi\bar{\chi}$ other than neutrinos.
- Hidden fermion annihilation at Galactic center can give rise "smoking gun" signal of monochromatic line that may be probed by next generation of gamma-ray exps.
- Other possible impacts of hidden milli-charged fermions in the context of Stueckelberg Z' models like CMB, BBN, density fluctuations, direct detection, etc .... might worthy of further studies.

Feldman, Liu, Nath (hep-ph/0702123)

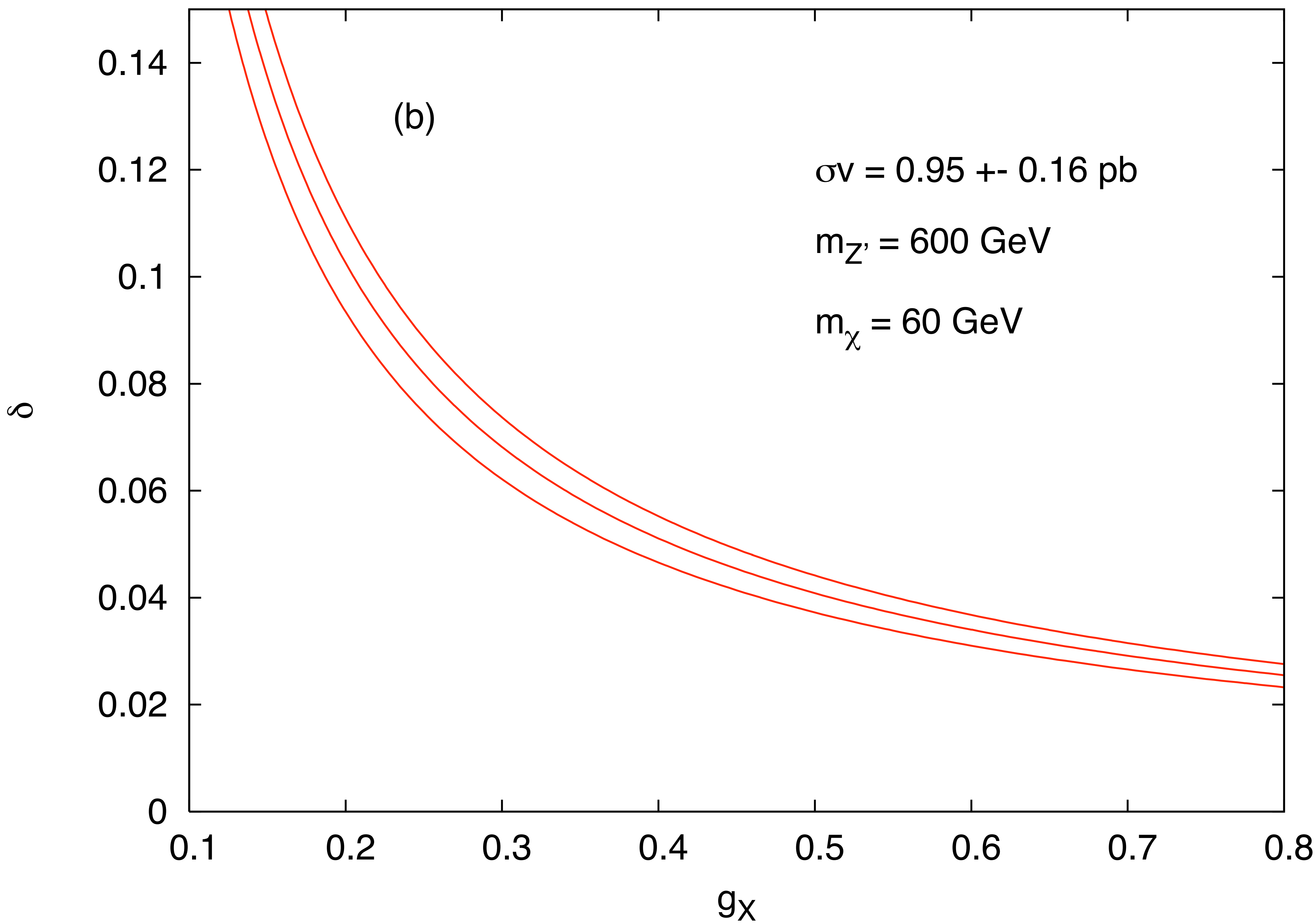




(c)
$g_X = g_2$
$\delta = 0.03$
100
10
1
0.1
0
50
100
150
200
250
300
σv (pb)
m_χ (GeV)



(a)
σv = 0.95 +- 0.16 pb
m_{Z'} = 300 GeV
m_χ = 60 GeV
δ
g_X
0.1
0.08
0.06
0.04
0.02
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8



0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
δ
g_X
(b)
σv = 0.95 +- 0.16 pb
$m_{Z'}$ = 600 GeV
m_χ = 60 GeV