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

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(JHEP03 (2007) 120; arXiv: hep-ph/0701107)

Seminar at Chung Yuan Christian University (April 24, 2007)

Outline

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

Introduction

- Stueckelberg Lagrangian (1938)

$$\mathcal{L} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \frac{m^2}{2}(B_\mu - \frac{1}{m}\partial_\mu\sigma)(B^\mu - \frac{1}{m}\partial^\mu\sigma)$$

- Gauge invariant

$$\delta\mathcal{L} = 0 \quad \text{under} \quad \delta B_\mu = \partial_\mu\epsilon \ , \quad \delta\sigma = m\epsilon$$

- R_ξ gauge: $\mathcal{L}_{R_\xi} = -(\partial_\mu B^\mu + \xi m\sigma)^2/2\xi$

$$\mathcal{L}+\mathcal{L}_{R_\xi} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \frac{m^2}{2}B_\mu B^\mu - \frac{1}{2\xi}(\partial_\mu B^\mu)^2 + \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - \xi\frac{m^2}{2}\sigma^2$$

- $R_\infty \rightarrow$ Unitary gauge: $B_\mu^{'} = B_\mu - \frac{1}{m}\partial_\mu\sigma$

$$\mathcal{L} + \mathcal{L}_{R_\infty} \Longrightarrow -\frac{1}{4}B_{\mu\nu}^{'}B^{'\mu\nu} + \frac{m^2}{2}B_\mu^{'}B^{'\mu}$$

- Massive QED. Unitarity and renormalizability are manifest!

- Stueckelberg mechanism only works for abelian group!
- However, Stueckelberg shows up in compactification and string theory.
- 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.

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

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

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

- 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.

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

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

[Ryutov (1997), magneto-hydrodynamics of solar wind to earth's orbit].

• The angles are related to the parameters in the Lagrangian $\mathcal{L}_{\rm StSM}$ 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

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

where $\theta_{\rm w}$ 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, $Q_{\rm neutron} = 0$ implies $Q_u + 2Q_d = 0$ to high precision.

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

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

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

where

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

- Constraints on StSM.

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

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

$$|\delta| \leq 0.061\sqrt{1-(m_Z/M_1)^2}$$

- Drell-Yan data of Stueckelberg Z'

$$m_{Z'} > 250 \text{ GeV} \qquad \text{for} \qquad \delta \approx 0.035 \ ,$$
$$m_{Z'} > 375 \text{ GeV} \qquad \text{for} \qquad \delta \approx 0.06 \ .$$

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

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

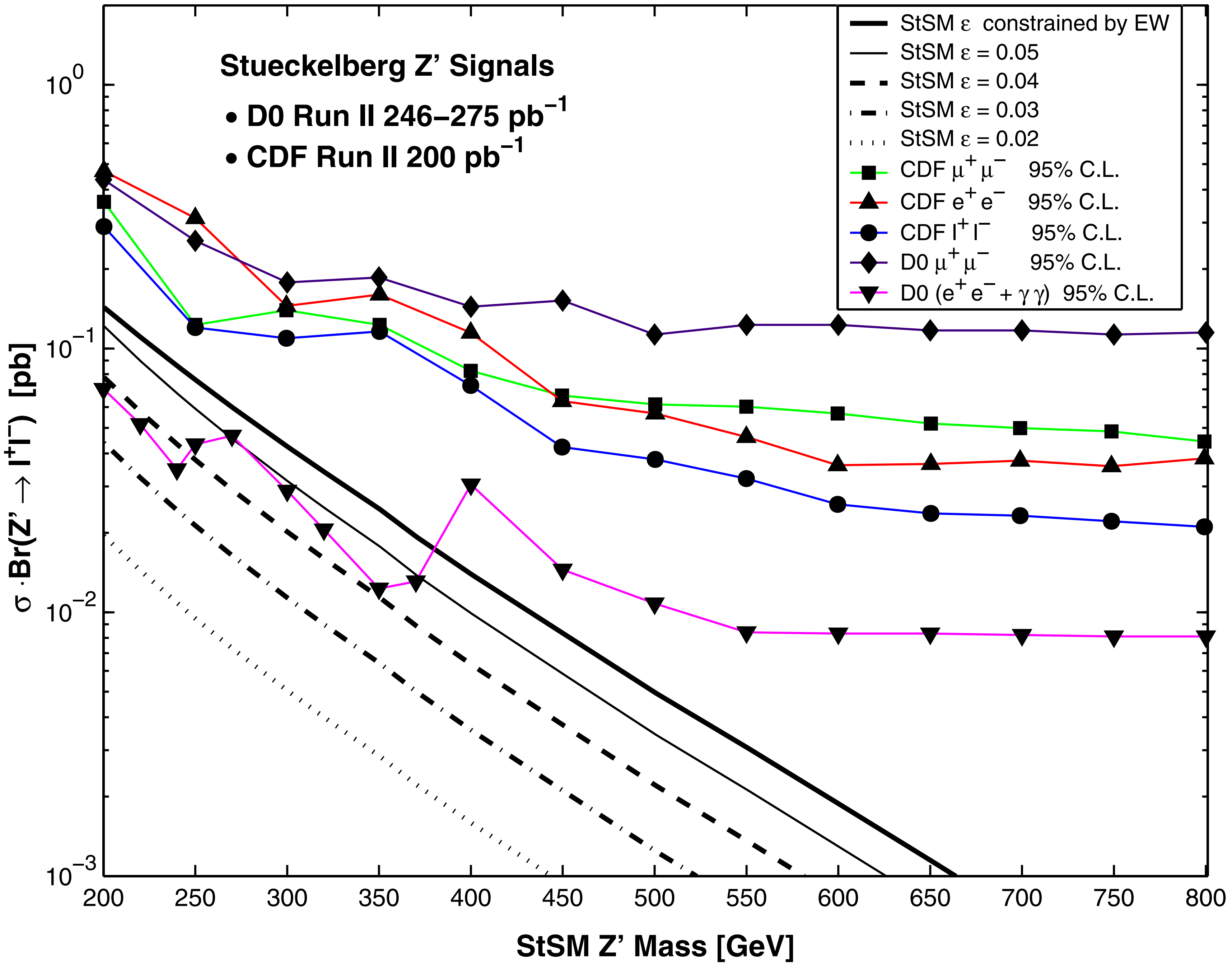


FIG. 1 (color online). Z' signal in StSM using the CDF [1] and D0 [2] data. The data put a lower limit of about 250 GeV on $M_{Z'}$ for $\epsilon \approx 0.035$ and 375 GeV for $\epsilon \approx 0.06$.

Hidden Fermions

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

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

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

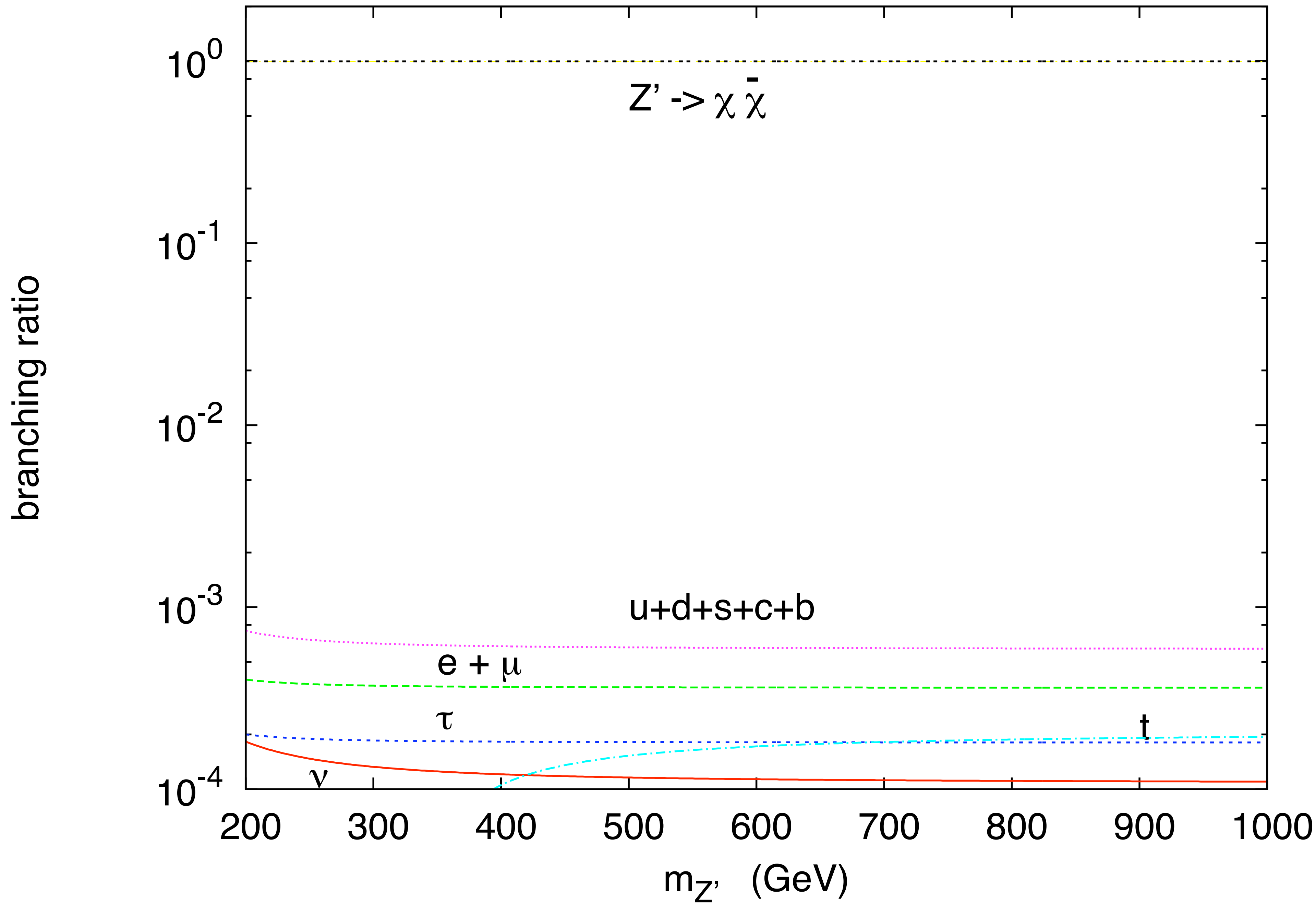
- Z' couples to χ is not suppressed. Its width needs not to be narrow. Drell-Yan constraint may be relaxed, if $Z' \to \chi\bar{\chi}$ is kinematic allowed.

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

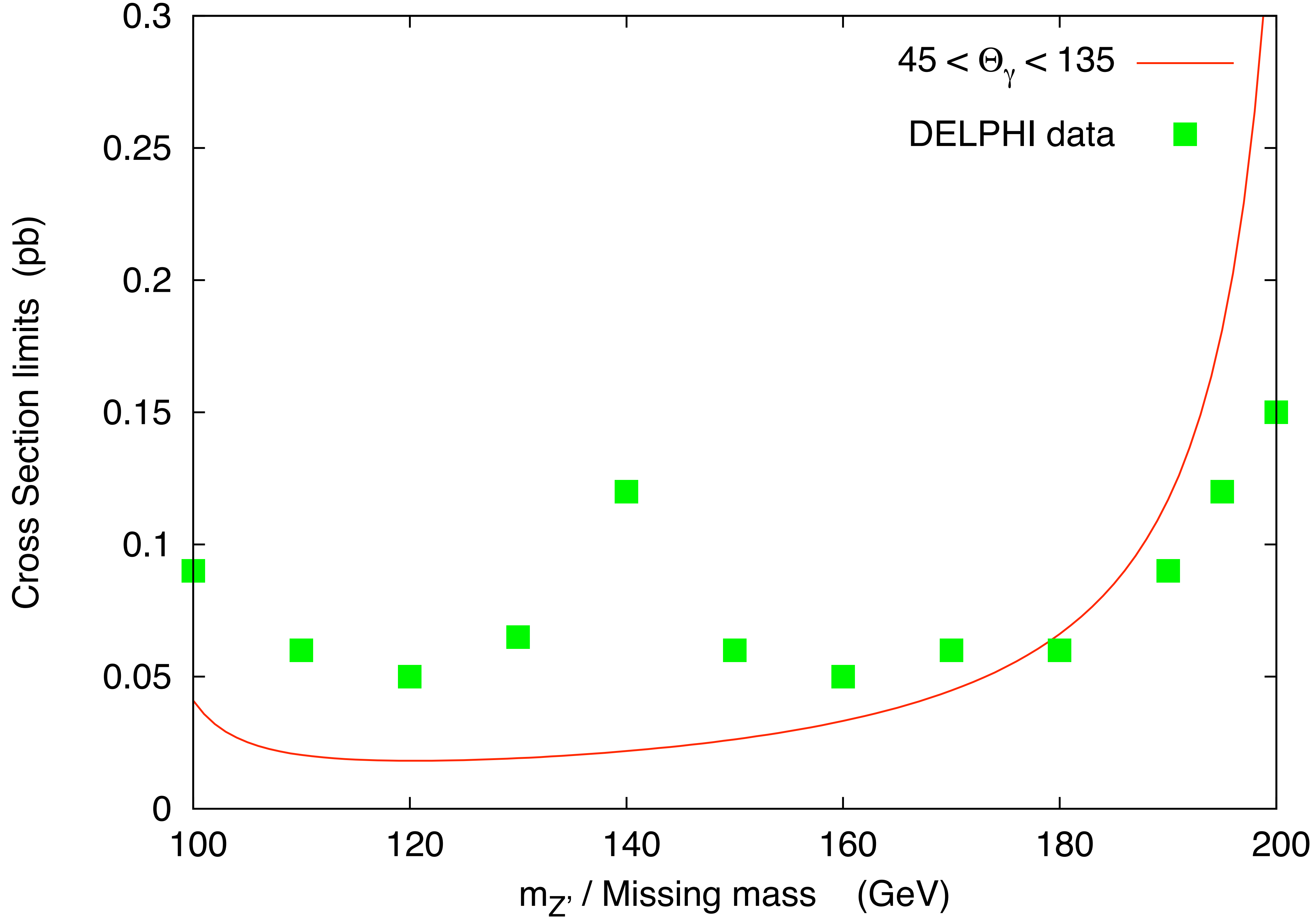
- χ is stable! In general, all hidden fermions are stable w.r.t. $U(1)_X$. [Feinberg, Kabir, and Weinberg, PRL 3, 527 (1957)]

Collider Phenomenology

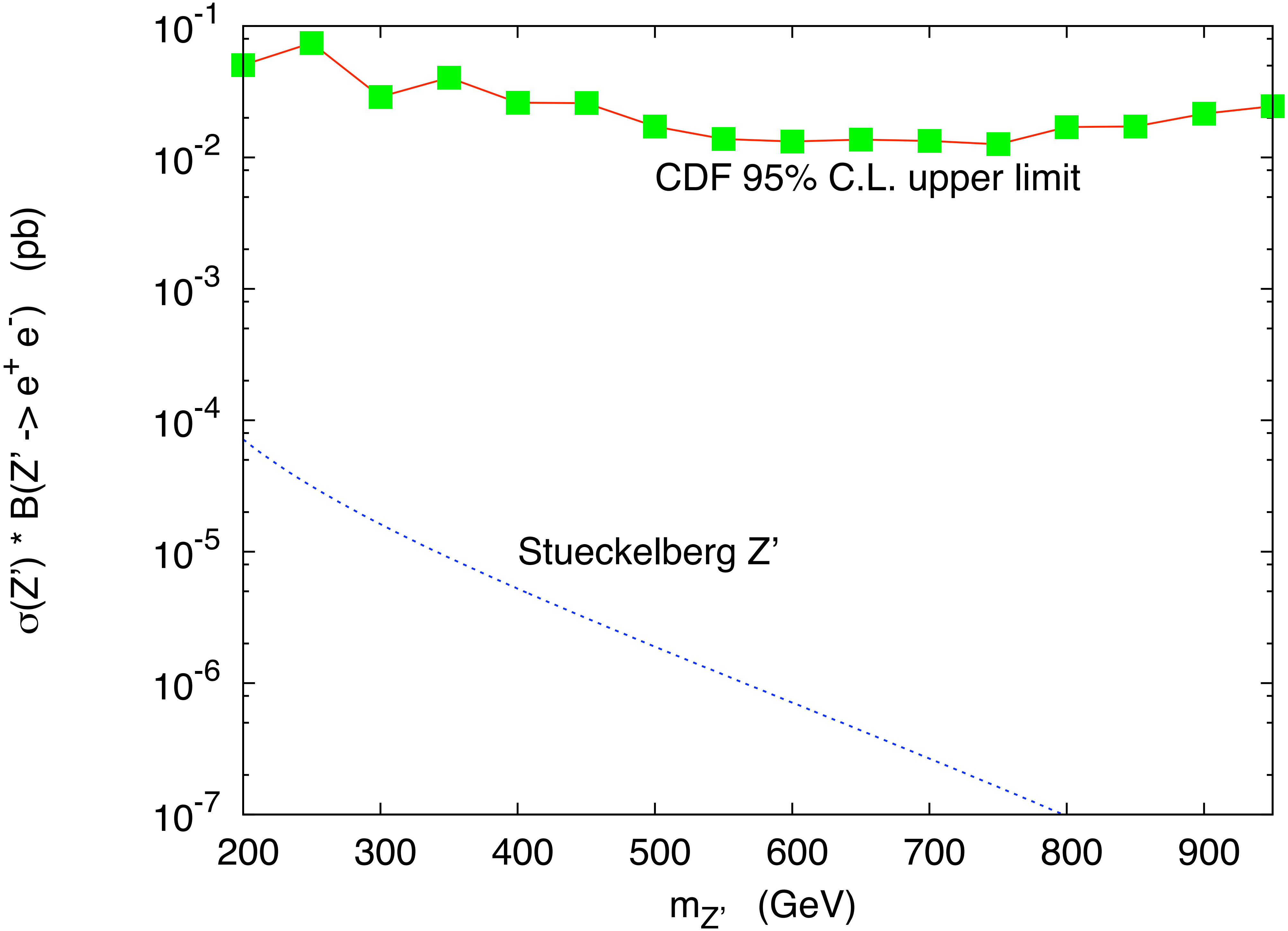
- $Z' \to$ invisible $\chi\bar{\chi}$ mode is dominant.



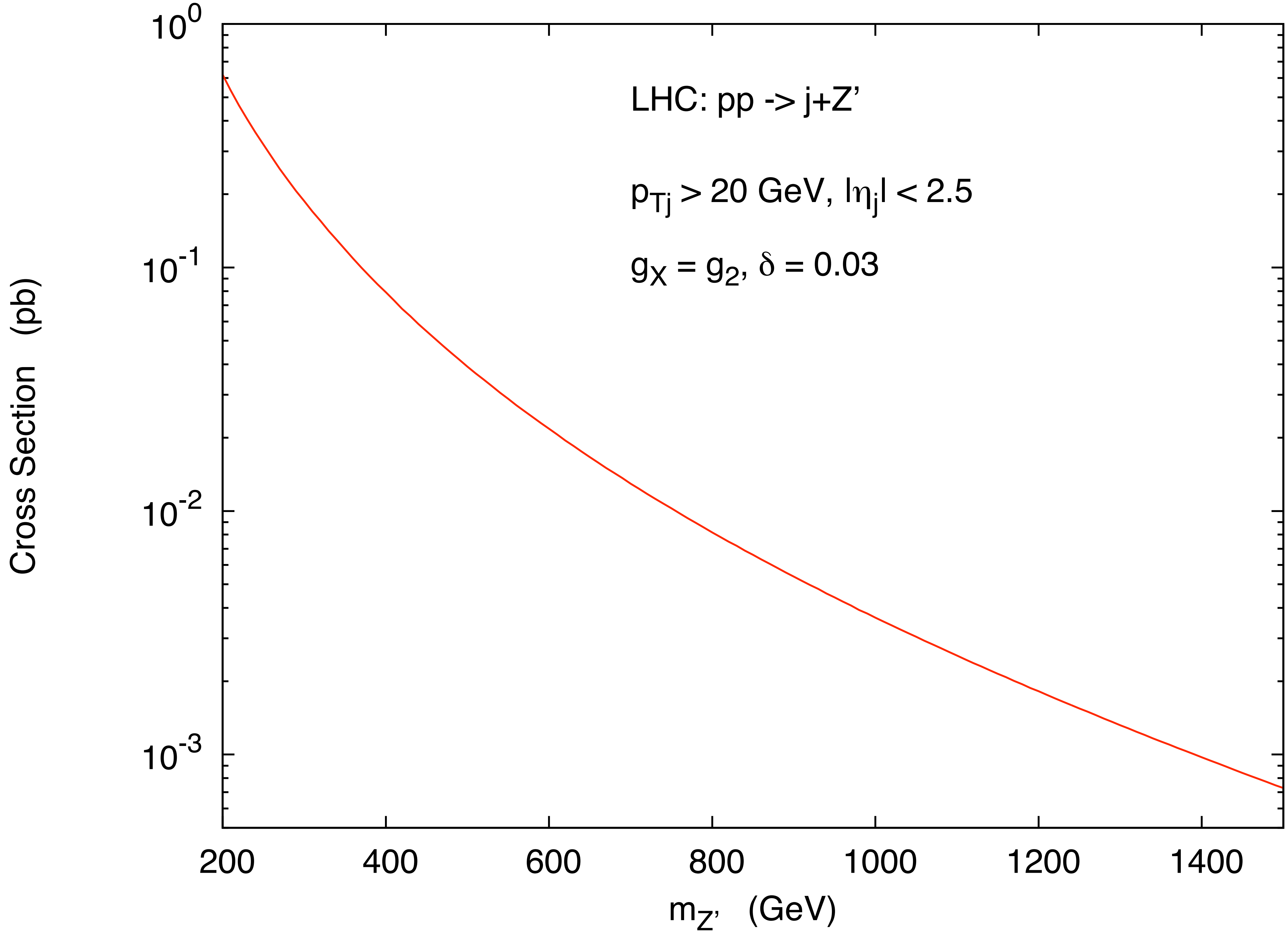
- LEPII constraint ($e^+e^- \to Z'\gamma \to \gamma$ + missing energy).



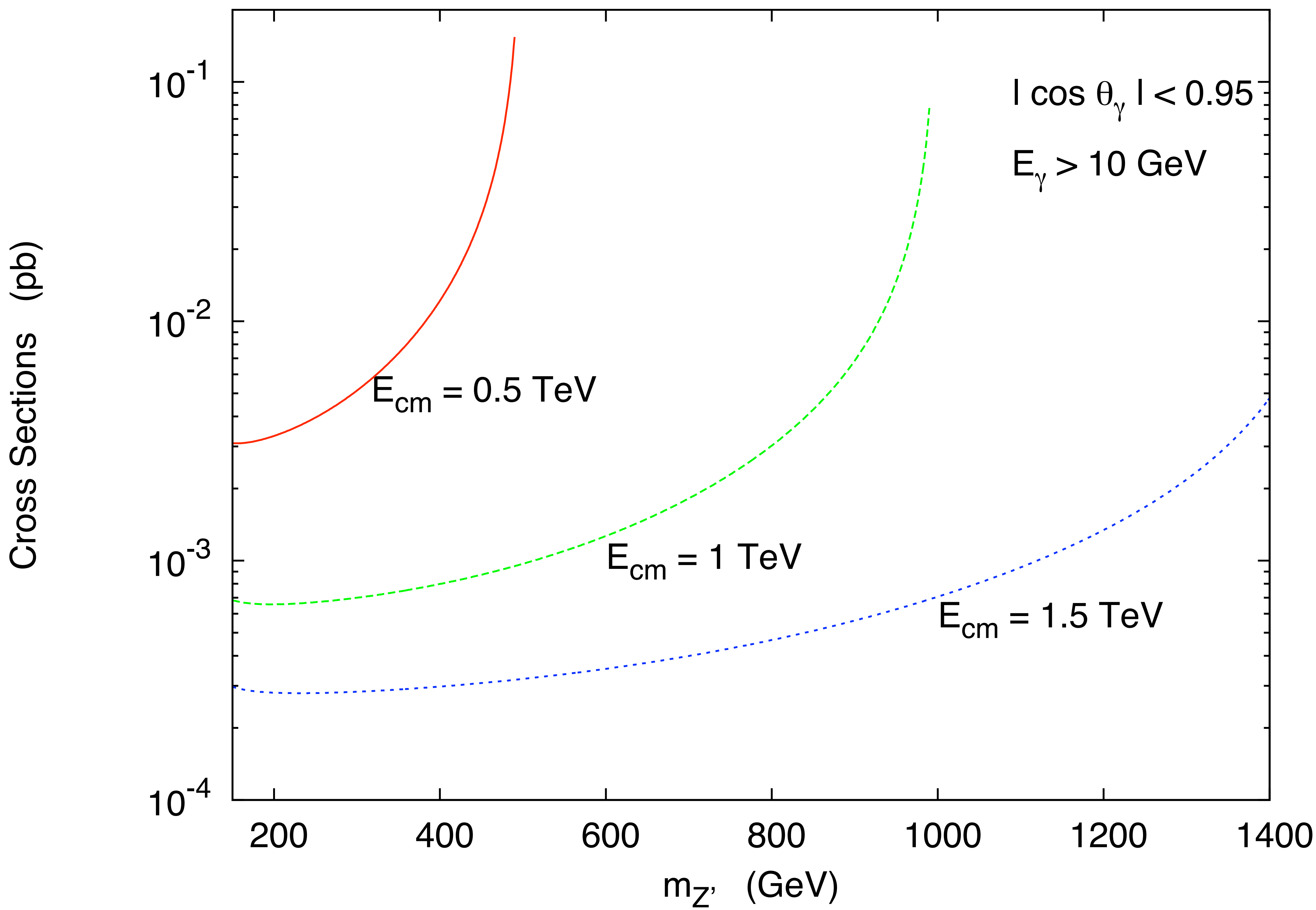
- CDF Drell-Yan constraint ($p\bar{p} \to Z' \to e^+e^-$)



• LHC prediction: $pp \to Z'+$ monojet



• ILC prediction: $e^+e^- \to Z' + \gamma$



Astrophysical Implication

- χ as milli-charged dark matter candidate.

[Goldberg and Hall (1986); Holdom (1986)]

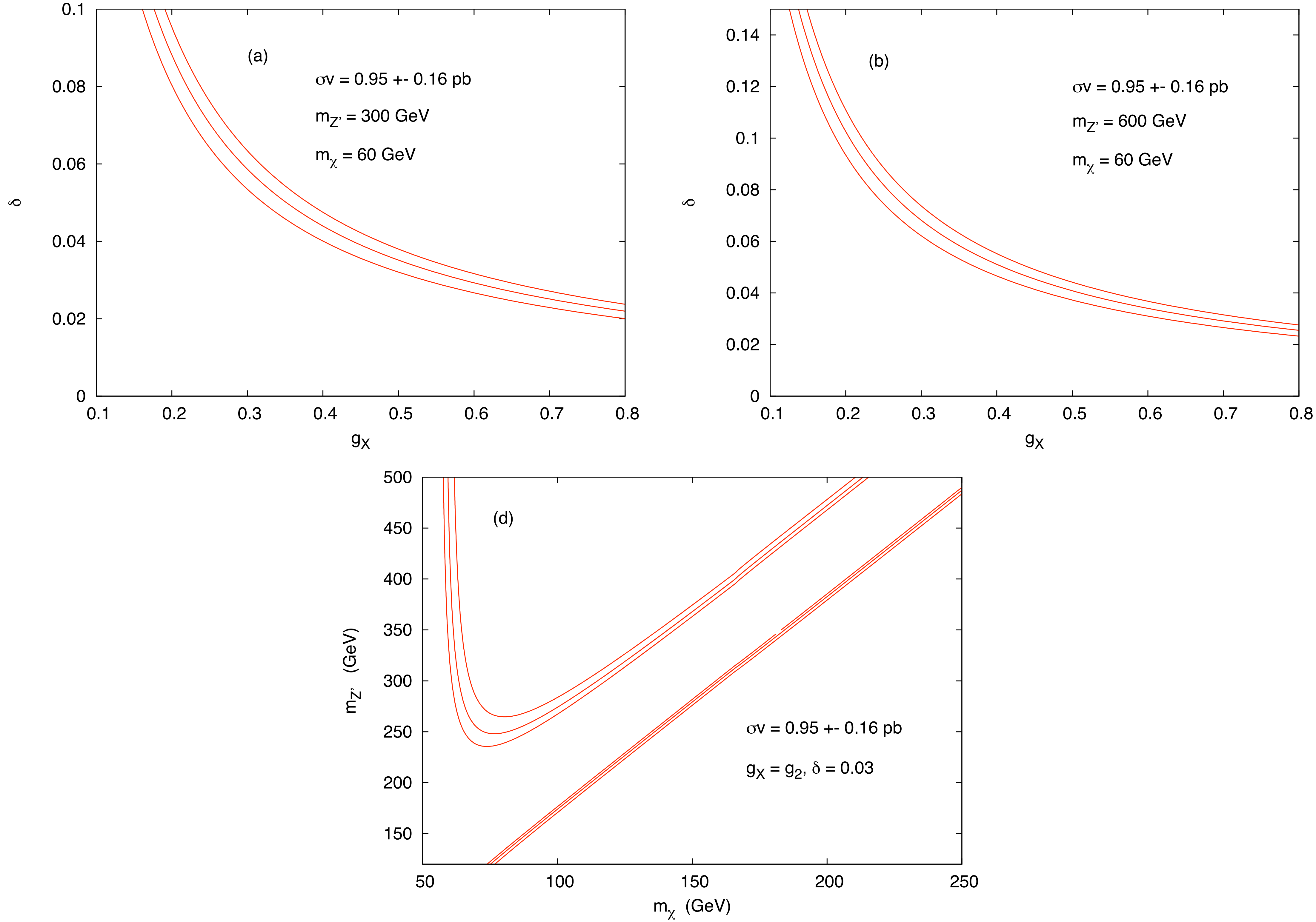
- WMAP constraint $[\Omega = \sum_i \Omega_i = \sum_i \rho_i/\rho_c$ and $\rho_c \equiv 3H_0^2/8\pi G]$

$$\Omega_{\rm baryon} h^2 = 0.0223^{+0.0007}_{-0.0009}, \quad \Omega_{\rm matter} h^2 = 0.127^{+0.007}_{-0.013}$$

$$\rightsquigarrow \Omega_{\rm Cold-Dark-Matter} h^2 = 0.105^{+0.007}_{-0.013}$$

$$\begin{aligned} \Omega_\chi h^2 &\simeq 0.3 \left(\frac{x_f}{10}\right) \left(\frac{g_*(m_\chi)}{100}\right)^{1/2} \frac{10^{-39}{\rm cm}^2}{\langle \sigma v \rangle} \\ &\simeq \frac{0.1 \text{ pb}}{\langle \sigma v \rangle} \rightsquigarrow \langle \sigma v \rangle \simeq 0.95 \pm 0.08 \text{ pb} \end{aligned}$$

- Relic density calculation – $\chi\bar{\chi} \to f_{\rm SM}\bar{f}_{\rm SM}, \gamma Z', ZZ'$ 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

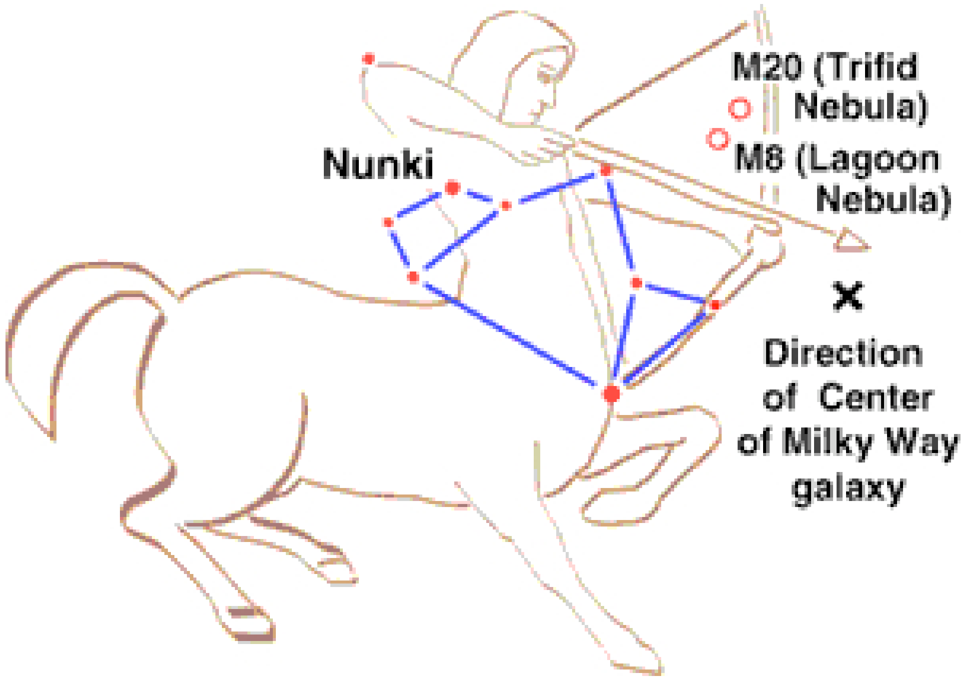
$$J(\psi) = \frac{1}{8.5\,\mathrm{kpc}} \left(\frac{1}{0.3\,\mathrm{GeV/cm}^3}\right)^2 \int_{\text{line of sight}} ds \rho^2(r(s,\psi))$$

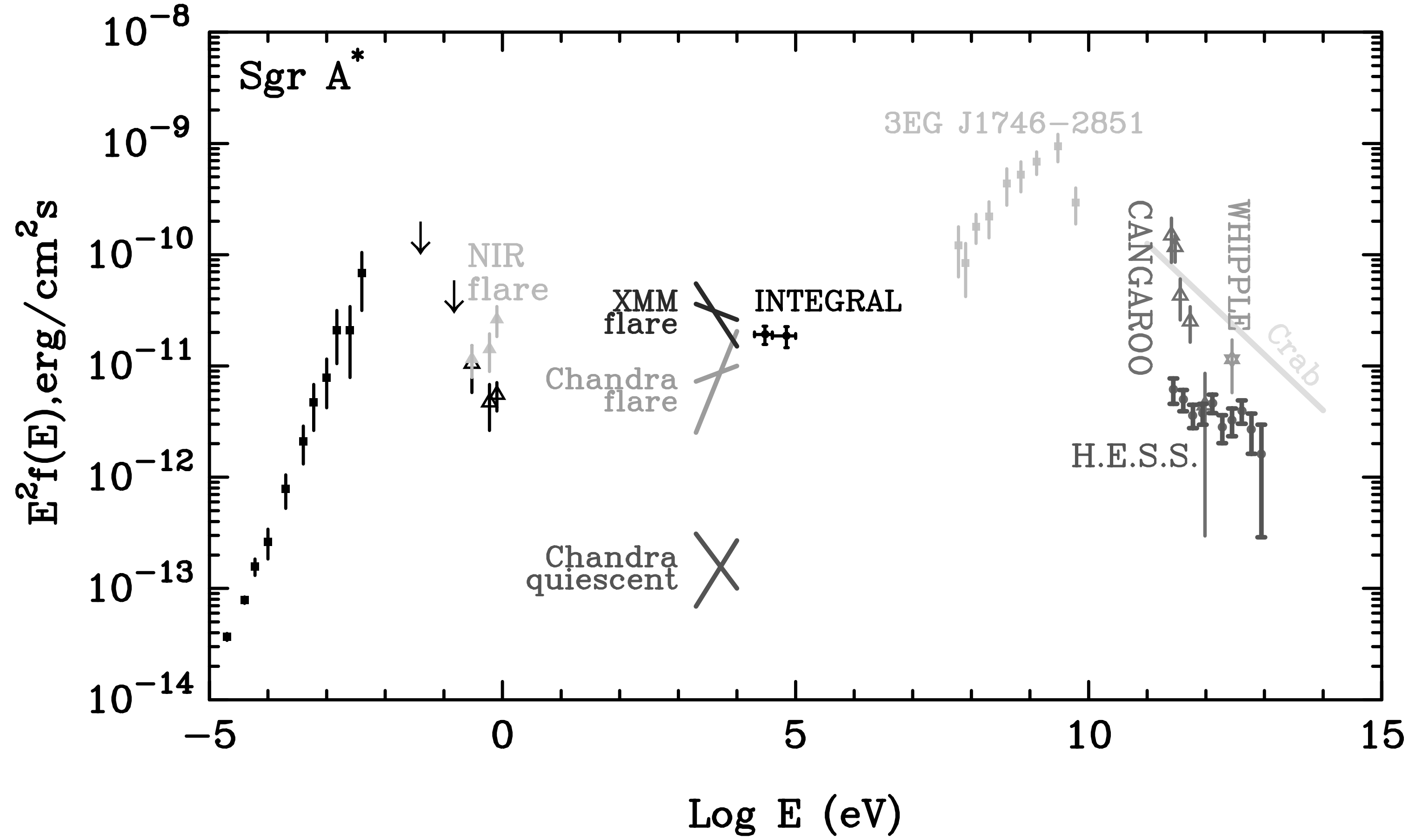
  - $J(\psi)$ depends on the halo profile ρ of the dark matter

• 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]

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





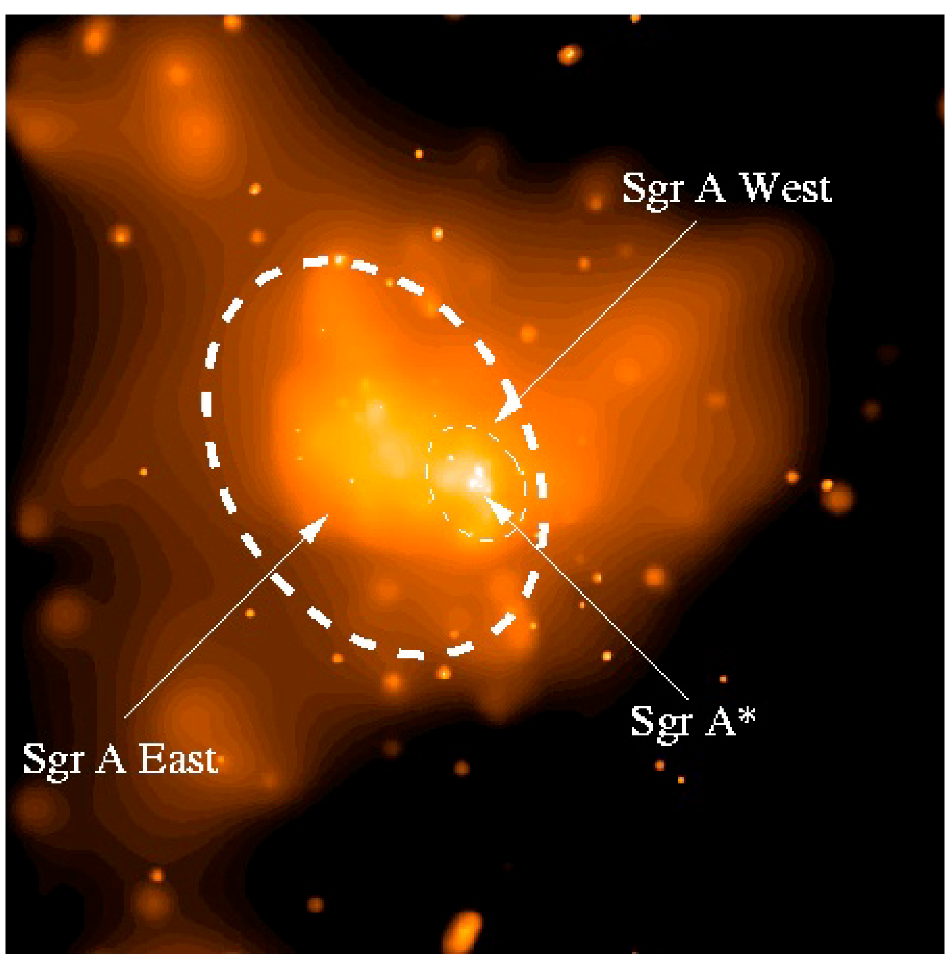
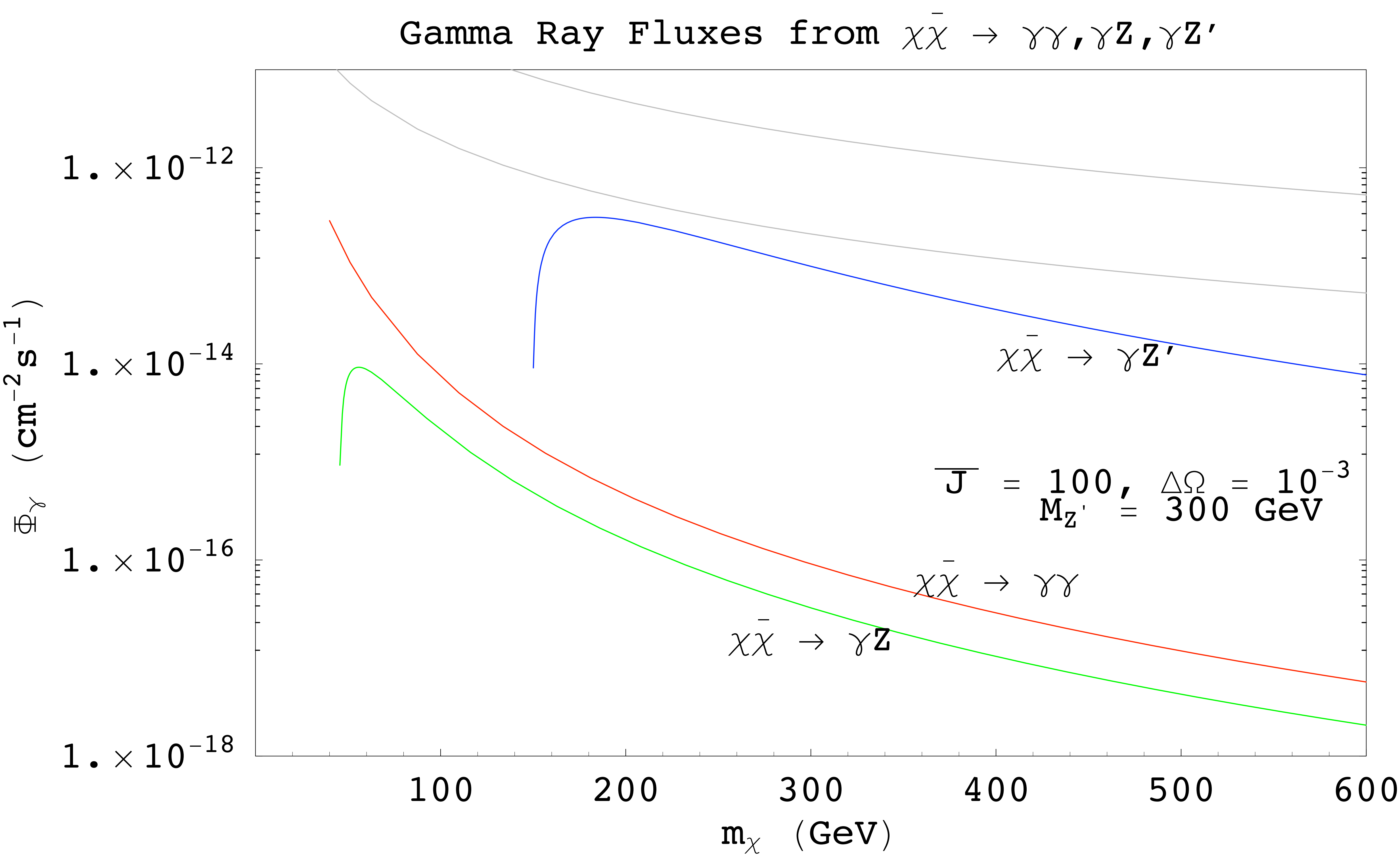


FIG. 1.—Broadband spectral energy distribution (SED) of Sgr A*. Radio data are from Zylka et al. (1995), and the IR data for quiescent state and for flare are from Genzel et al. (2003). X-ray fluxes measured by *Chandra* in the quiescent state and during a flare are from Baganoff et al. (2001, 2003). *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 $\chi\bar{\chi} \rightarrow \gamma\gamma, \gamma Z, \gamma Z'$
$\chi\bar{\chi} \rightarrow \gamma Z'$
$\bar{J} = 100, \Delta\Omega = 10^{-3}$
$M_{Z'} = 300$ GeV
$\chi\bar{\chi} \rightarrow \gamma\gamma$
$\chi\bar{\chi} \rightarrow \gamma Z$
$1. \times 10^{-12}$
$1. \times 10^{-14}$
$1. \times 10^{-16}$
$1. \times 10^{-18}$
Φ_γ $(cm^{-2}s^{-1})$
100
200
300
400
500
600
m_χ (GeV)

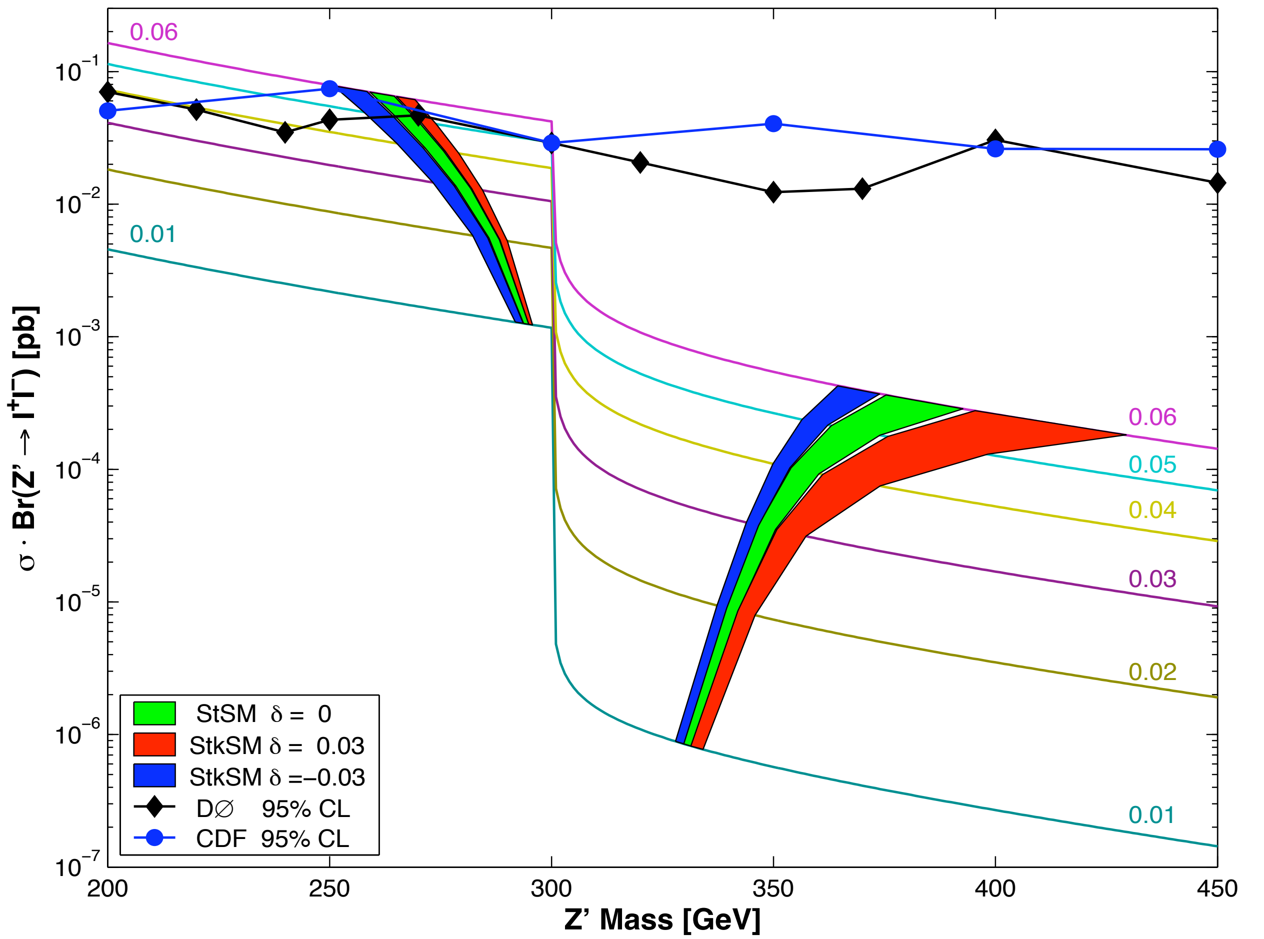


FIG. 4: An exhibition of the dilepton signal $\sigma \cdot Br(Z' \to l^+l^-)$ at the Tevatron consistent with the WMAP-3 relic density constraint as a function of $M_{Z'}$ when $2M_\chi = 300$ GeV. The curves in ascending order are for values of $\bar{\epsilon}$ in the range $(0.01 - 0.06)$ in steps of 0.01. The dilepton signal has a dramatic fall as $M_{Z'}$ crosses the point $2M_\chi = 300$ GeV where the Z' decay into the hidden sector fermions is kinematically allowed, widening enormously the Z' decay width. The green shaded regions are where the WMAP-3 relic density constraints are satisfied for the case when there is no kinetic mixing. Red and blue regions are for the case when kinetic mixing is included. The DØ data set [48] was collected in the search for narrow resonances (RS) and is a stronger constraint to apply on this model than the recent CDF [47] data which put constraints on the parameter space when the Z' can decay only into matter in the visible sector.

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

Conclusions

- Phenomenology of Stueckelberg Z' is different from traditional Z'. Mass limits can be much lower.
- 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 can be probed by next generation of gamma-ray exps. However, it faces big challenge from astrophysical background, e.g. gamma-ray from Sgr A*. Perhaps continuum spectrum from secondary photons due to processes like $\chi\bar{\chi} \to f_{\rm SM}\bar{f}_{\rm SM}, W^+W^-, \ldots$ are important!
- Other impacts in CMB, BBN, density fluctuations, direct detection .... needs further studies.