Hidden Fermion as Dark Matter in Stueckelberg Z' Model

Tzu-Chiang Yuan
National Tsing Hua University, Hsinchu
(In Collaboration with Kingman Cheung)
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Outline

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

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

- $R_\infty \to$ 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)]

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

$$\mathcal{L}_{\rm StSM} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm St}$$

$$\mathcal{L}_{\rm St} = -\frac{1}{4}C_{\mu\nu}C^{\mu\nu} + \frac{1}{2}(\partial_\mu\sigma - M_1 C_\mu - M_2 B_\mu)^2 - g_X C_\mu \mathcal{J}^\mu_X$$

- $\mathcal{J}^\mu_X$ 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 $\langle \Phi \rangle = v/\sqrt{2}$

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

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

- Diagonalize the mass matrix

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

- The $m_{Z'}^2$ and m_Z^2 are given by

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

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

- 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 $s_\phi = \sin\phi, c_\phi = \cos\phi$ and similarly for the angles ψ and θ.

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

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

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

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, $Q_{\text{neutron}} = 0$ 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

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

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 $Z' \rightarrow$ SM fermions are suppressed by mixing angles!

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

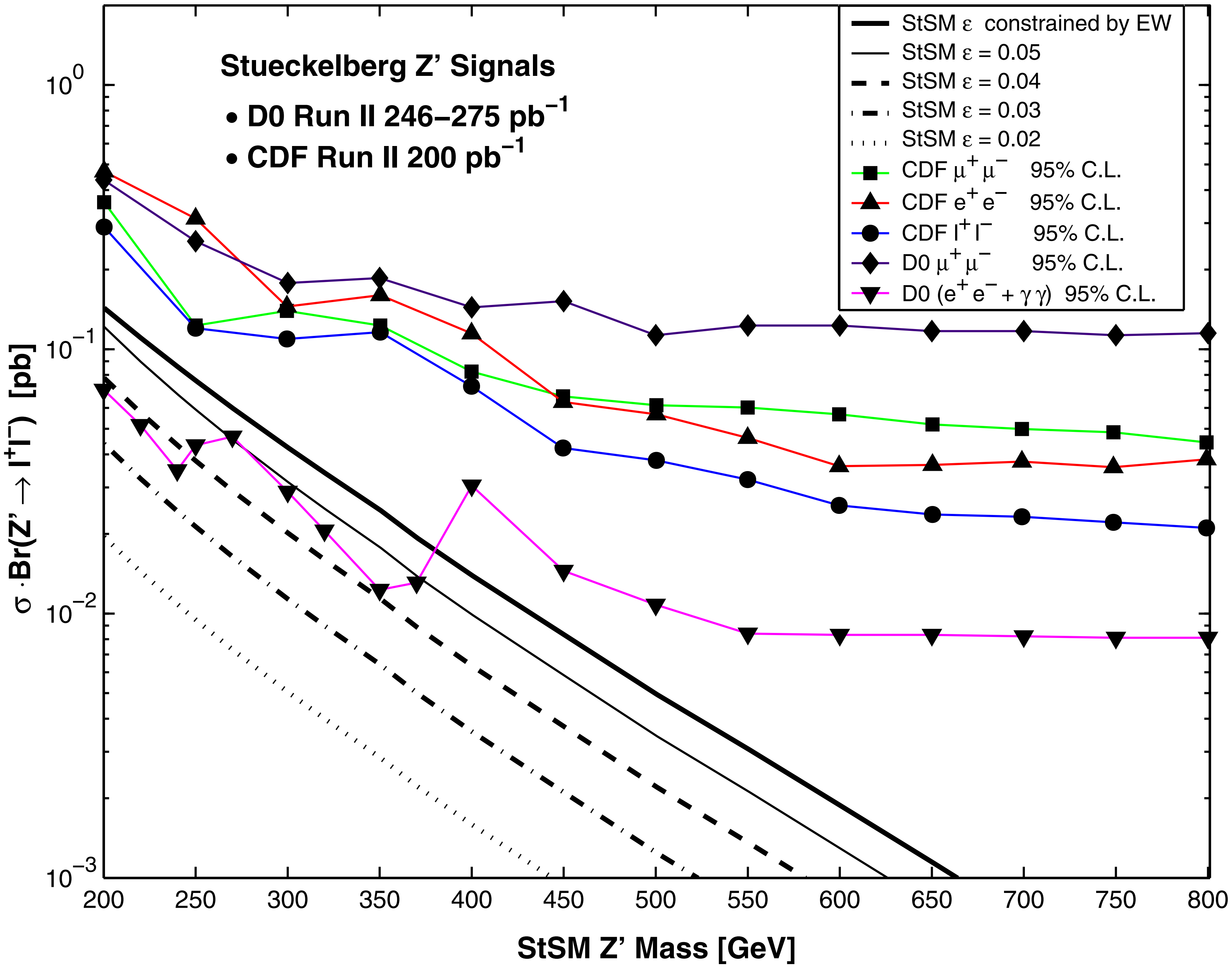


FIG. 1 (color online). Z' signal in StSM using the CDF [1] and D0 [2] data. The data put a lower limit of about 250 GeV on $M_{Z'}$ for $\epsilon \approx 0.035$ and 375 GeV for $\epsilon \approx 0.06$.

Hidden Fermions

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

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

$$\begin{aligned} \epsilon^\chi_\gamma &= g_X Q^\chi_X (-c_\theta s_\phi) \, , \\ \epsilon^\chi_Z &= g_X Q^\chi_X (s_\psi c_\phi + s_\theta s_\phi c_\psi) \, , \; \epsilon^\chi_{Z'} = g_X Q^\chi_X (c_\psi c_\phi - s_\theta s_\phi s_\psi) \end{aligned}$$

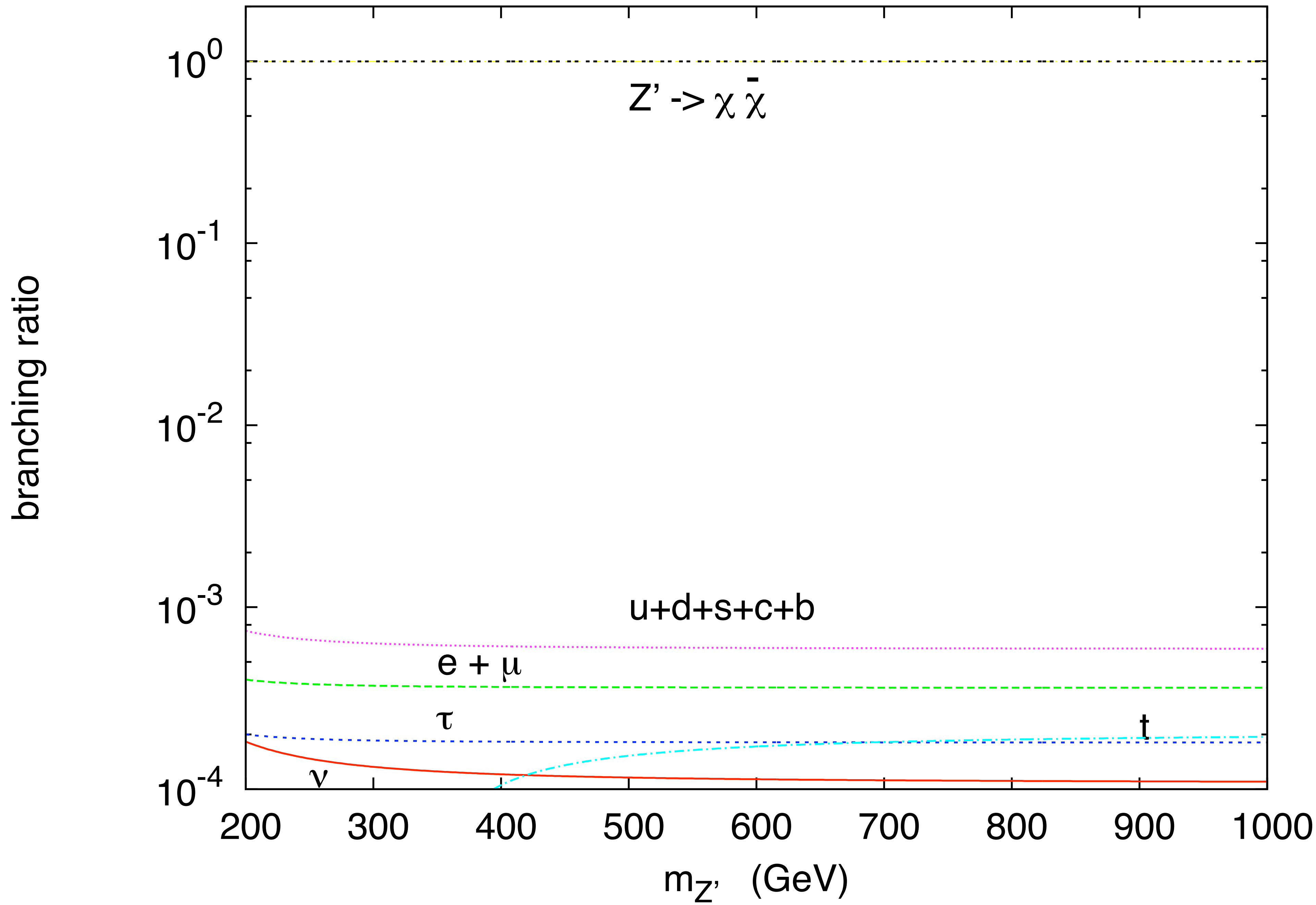
- Z' couples to χ is not suppressed. Its width needs not to be narrow. Drell-Yan constraint may be relaxed, if $Z' \to \chi\bar{\chi}$ is kinematic allowed.

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

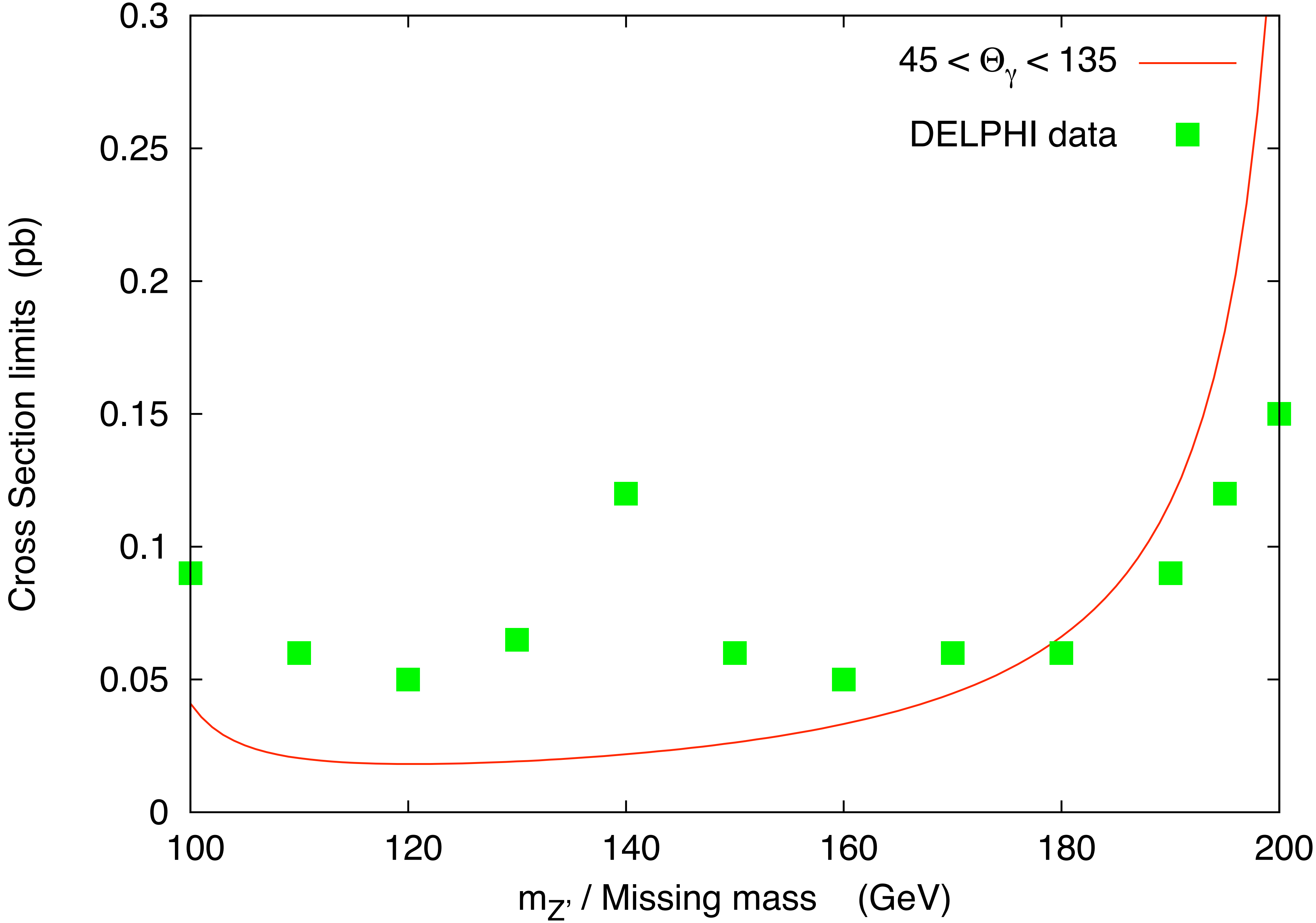
- χ is stable! In general, all hidden fermions are stable w.r.t. $U(1)_X$. [Feinberg, Kabir, and Weinberg, PRL 3, 527 (1957)]

Collider Phenomenology

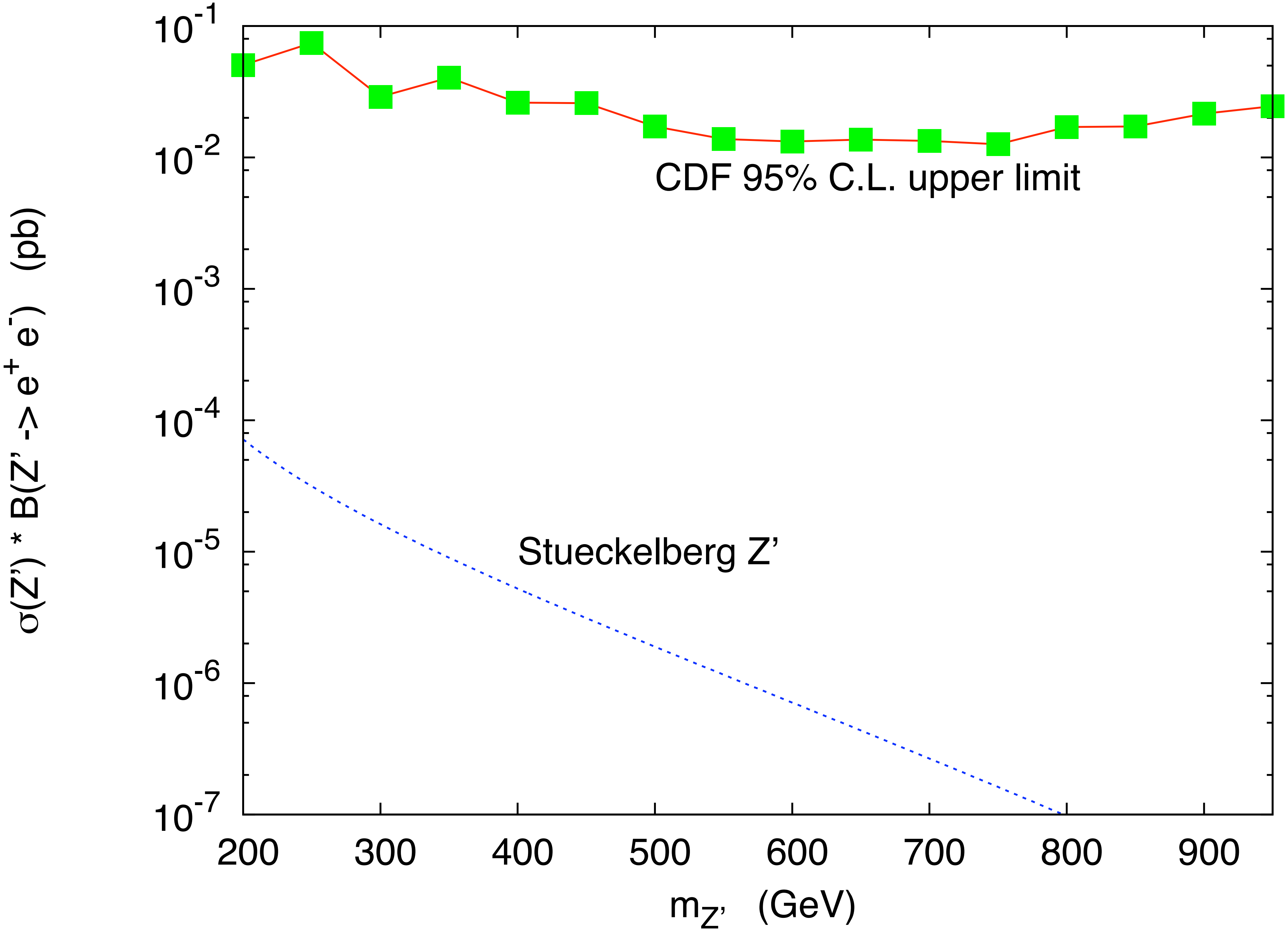
- $Z' \to$ invisible $\chi\bar{\chi}$ mode is dominant.



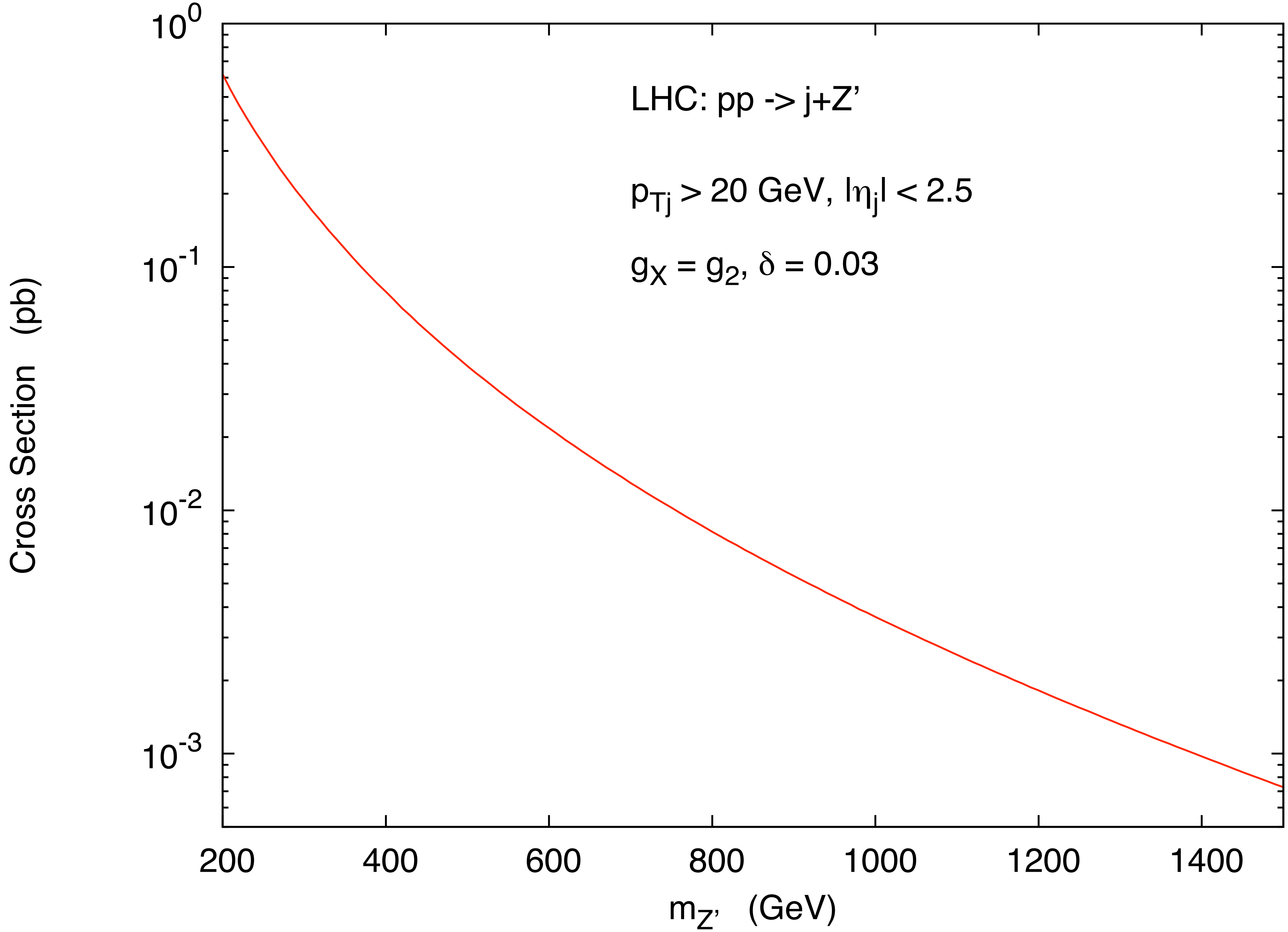
- LEPII constraint ($e^+e^- \to Z'\gamma \to \gamma$ + missing energy).



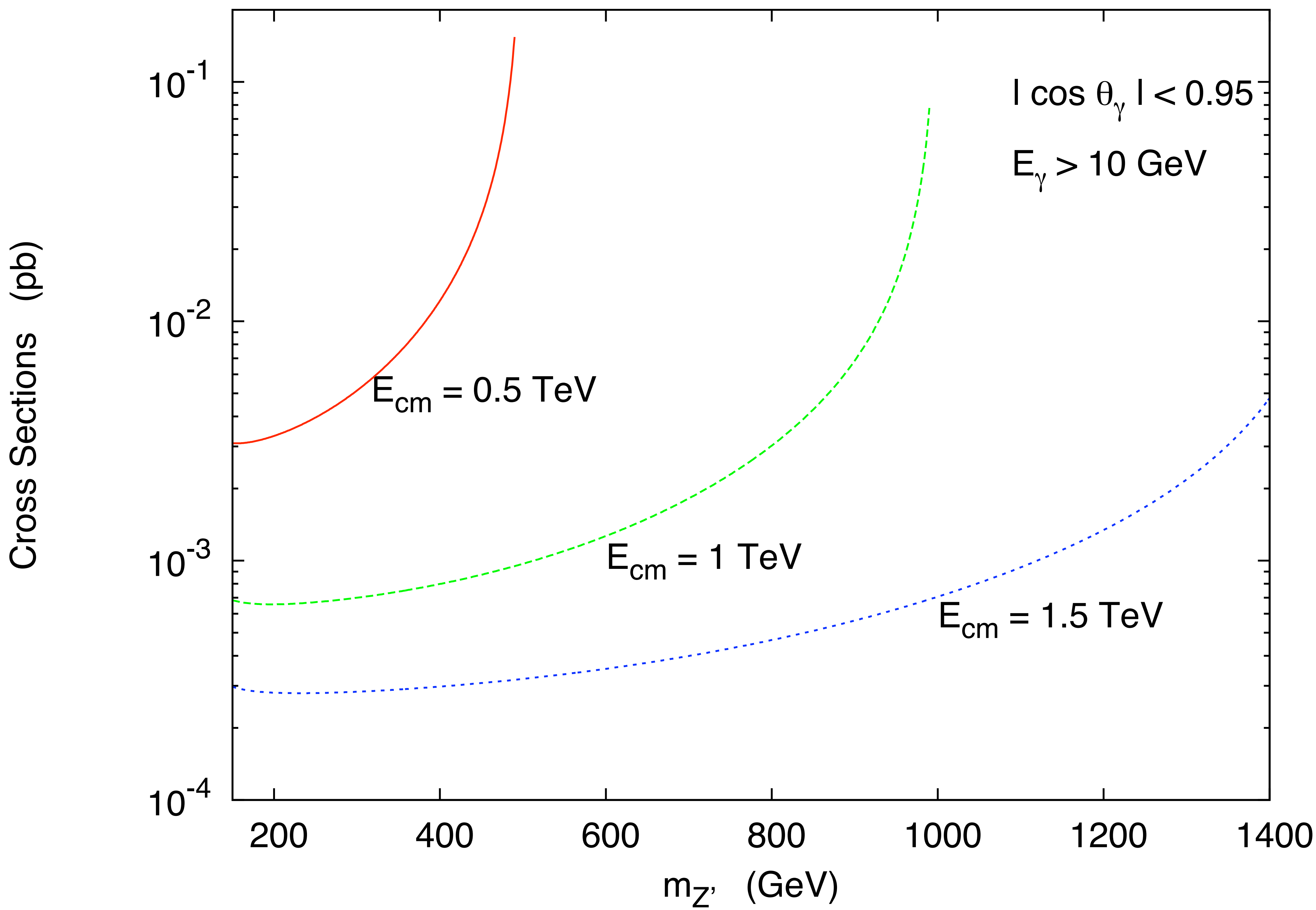
- CDF Drell-Yan constraint $(p\bar{p} \to Z' \to e^+e^-)$



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



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



Astrophysical Implication

- χ as milli-charged dark matter candidate.

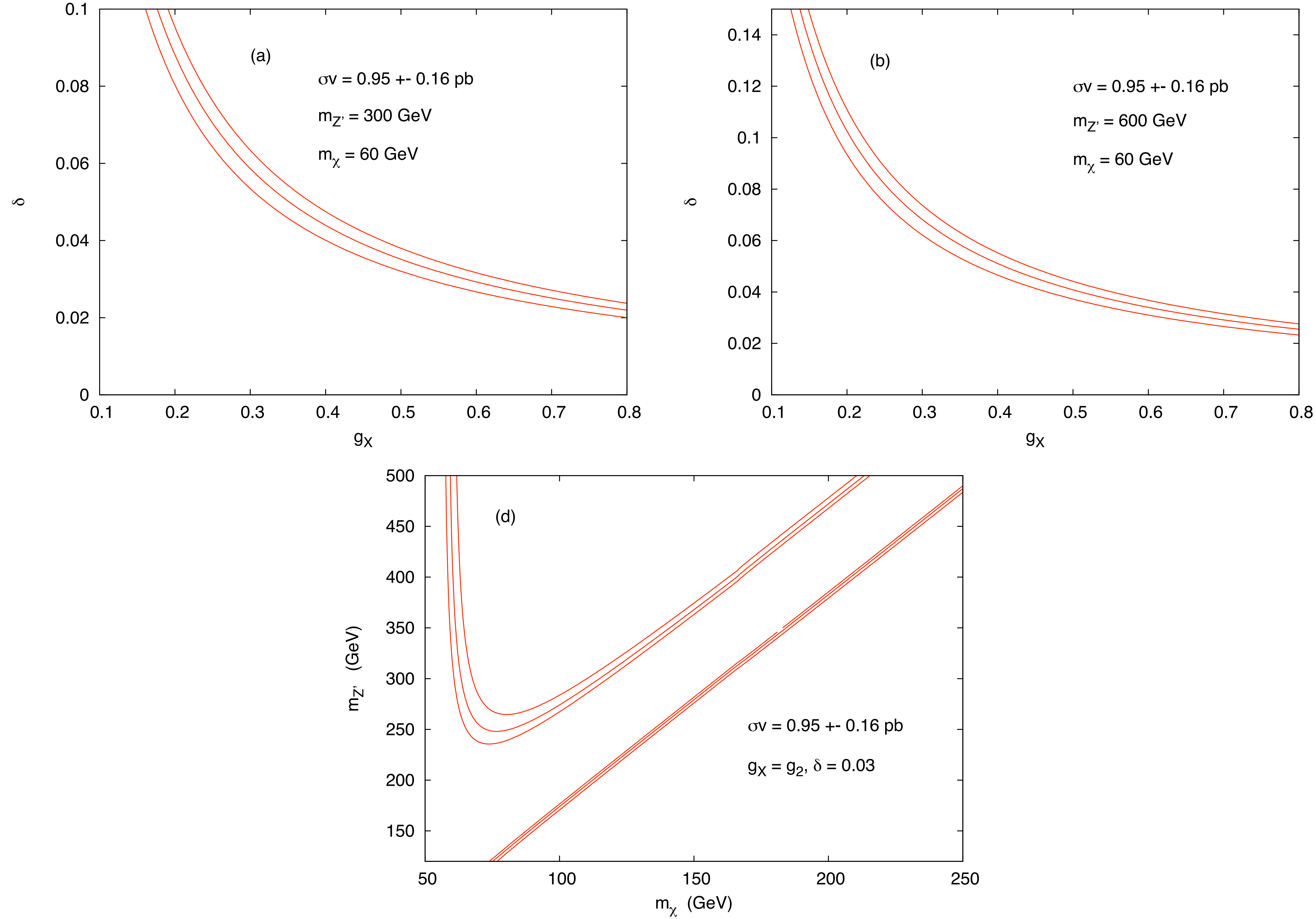
[Goldberg and Hall (1986); Holdom (1986)]

- WMAP constraint

$$\Omega_{\rm CDM} h^2 = 0.105 \pm 0.009 \quad \text{(WMAP)}$$

$$\Omega_\chi h^2 \simeq \frac{0.1\ \text{pb}}{\langle \sigma v \rangle} \rightsquigarrow \langle \sigma v \rangle \simeq 0.95 \pm 0.08\ \text{pb}$$

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

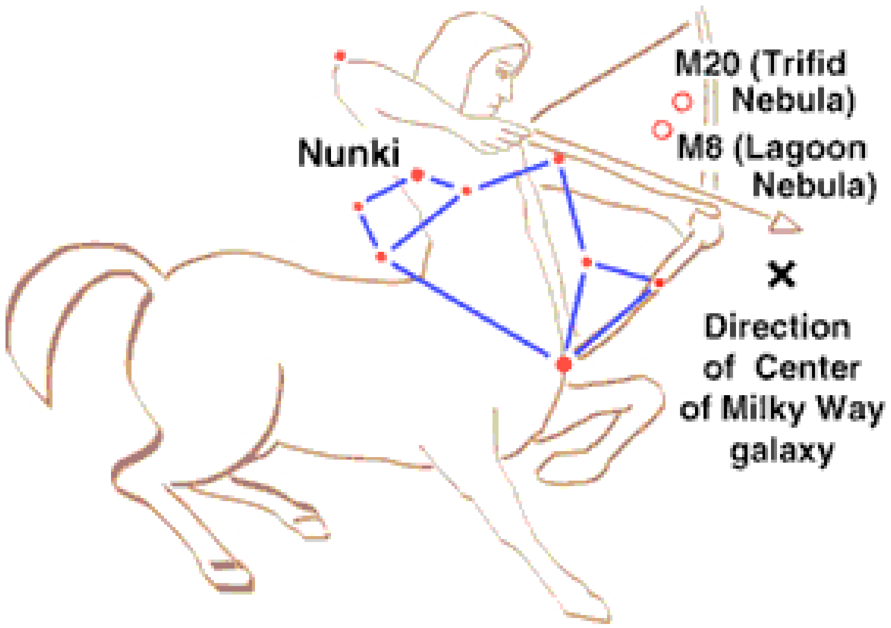
$$J(\psi) = \frac{1}{8.5\,\mathrm{kpc}} \left(\frac{1}{0.3\,\mathrm{GeV/cm}^3}\right)^2 \int_{\text{line of sight}} ds\rho^2(r(s,\psi))$$

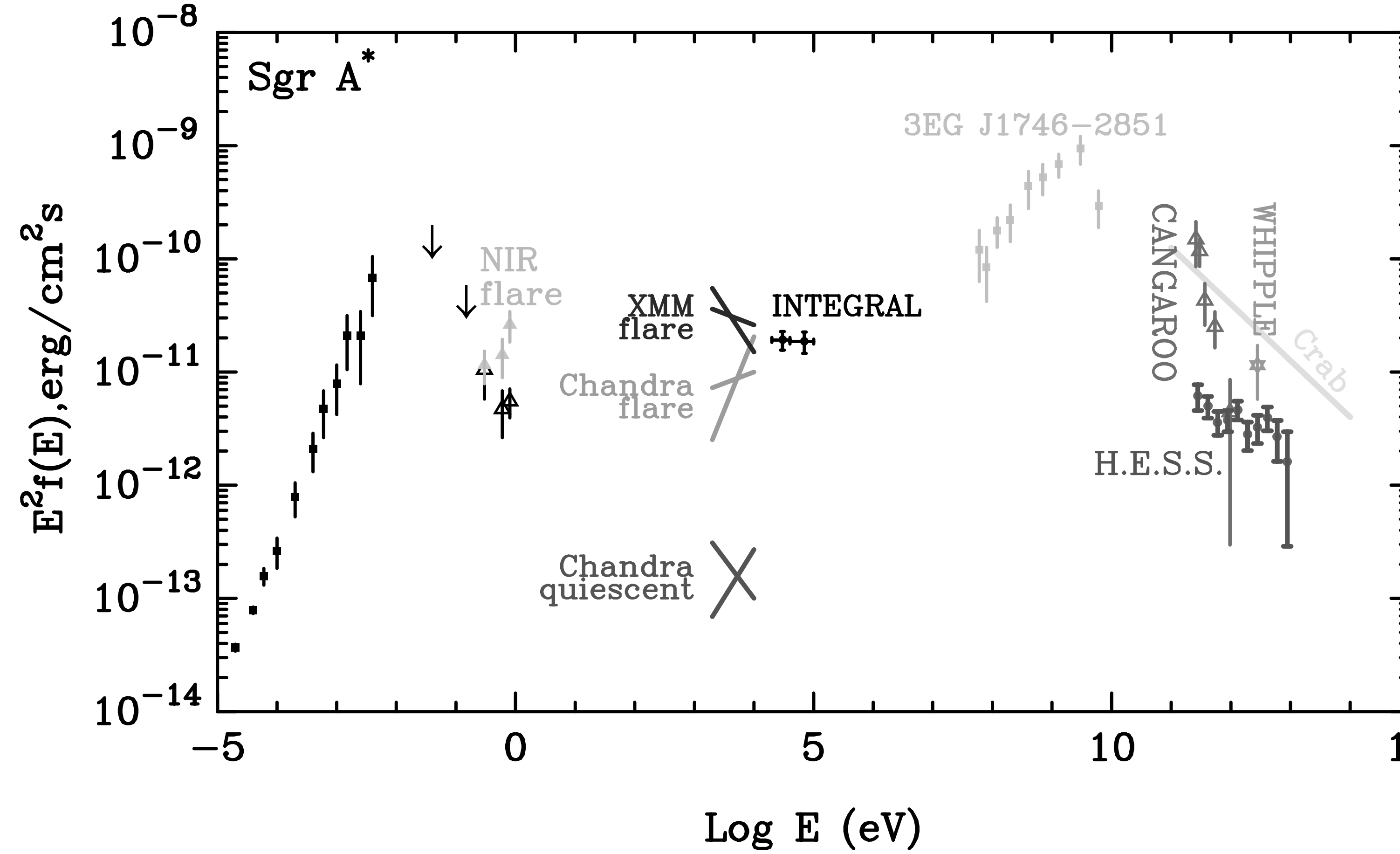
  - $J(\psi)$ depends on the halo profile ρ of the dark matter

• 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]

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





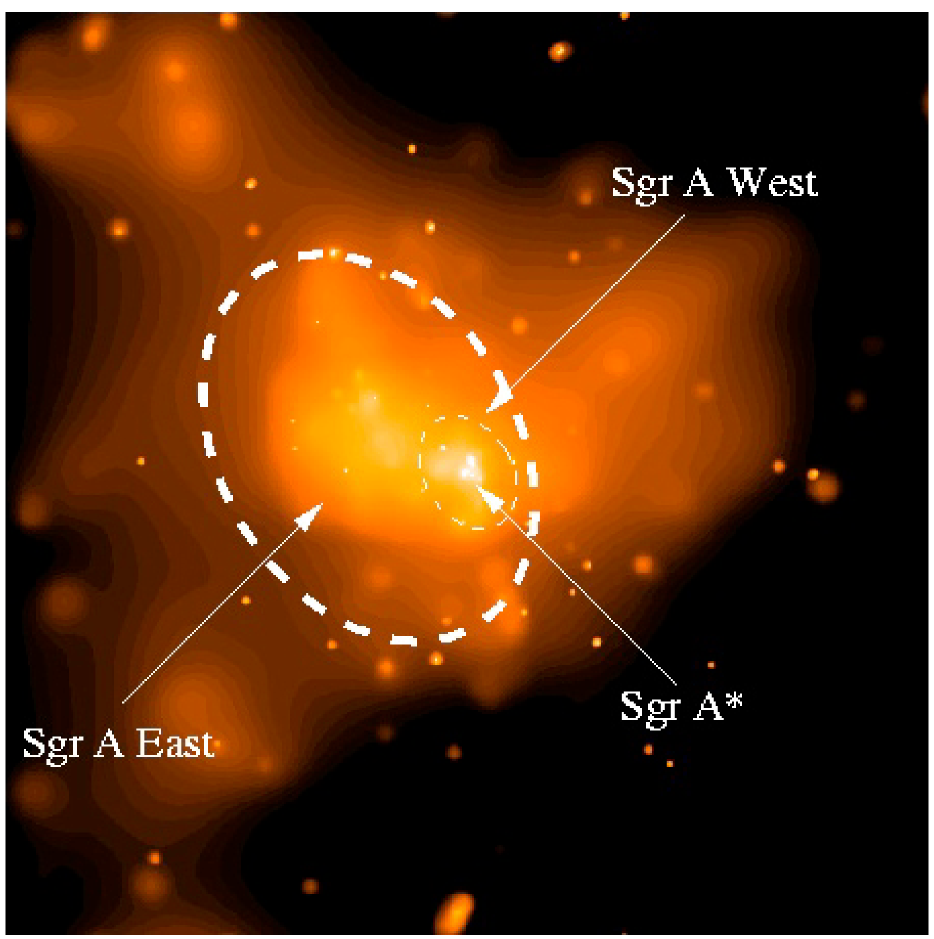
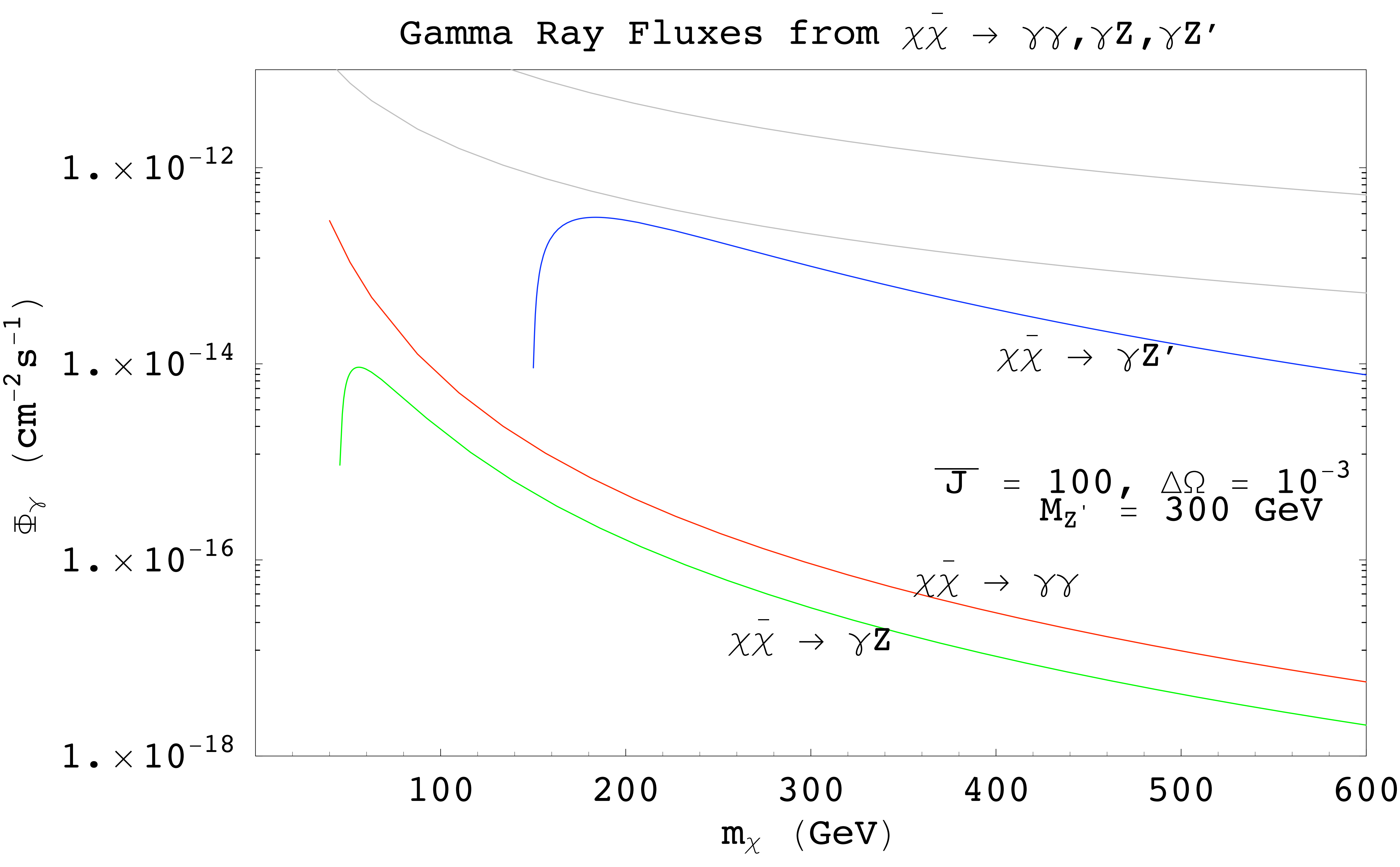


FIG. 1.—Broadband spectral energy distribution (SED) of Sgr A*. Radio data are from Zylka et al. (1995), and the IR data for quiescent state and for flare are from Genzel et al. (2003). X-ray fluxes measured by *Chandra* in the quiescent state and during a flare are from Baganoff et al. (2001, 2003).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

Conclusions

- Stueckelberg Z' extension of SM is interesting.
  - Phenomenology of Stueckelberg Z' is different from traditional Z'. Mass limits can be much lower.
  - Hidden fermion carries milli-charge.
  - Hidden fermion is viable dark matter candidate.
  - New invisible decay mode of $Z' \to \chi\bar{\chi}$ other than neutrinos has great impact on phenomenology.
  - 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!