Technihadrons — spectrum and collider phenomenologies

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In collaboration with S. Matsuzaki and K. Yamawaki,
and K. Terashi for further collider studies

Sakata Memorial KMI Mini-Workshop on
"Strong Coupling Gauge Theories Beyond the Standard Model"
(SCGT14Mini)

Outline

1. Introduction
2. Effective Lagrangian
3. Collider phenomenologies
4. Summary

1. Introduction

Higgs... Elementary or Composite ?

Higgs... **Elementary** **or** **Composite ?**

↓ ↓

Standard Model **or** Technicolor **?**

(SM) (TC)

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It is an analogue of **what actually happened in nature** (chiral symmetry breaking and confinement by QCD)

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No, TC is based on the most **conservative** idea

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....

And it is more **natural**: Higgs is a boundstate made of techni-fermions (no fine-tuning problem)

Higgs... Elementary or Composite ?

Standard Model or Technicolor ?
(SM) (TC)

TC is **interesting**

- existence of the Higgs itself is related to the dynamical origin of the EWSB
- many types of techni-hadrons

(SM: just an elementary scalar + potential…)

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Let's study a scenario which is more **natural**, **conservative**, and **interesting**

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Technicolor

What kind of Technicolor?

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One-family model (Farhi-Susskind model)

$$\underbrace{\begin{pmatrix} u \\ d \\ u \\ d \\ u \\ d \\ e \\ \nu_e \end{pmatrix} \begin{pmatrix} c \\ s \\ c \\ s \\ c \\ s \\ \mu \\ \nu_\mu \end{pmatrix} \begin{pmatrix} t \\ b \\ t \\ b \\ t \\ b \\ \tau \\ \nu_\tau \end{pmatrix}}_{\text{SM fermions}} \quad \underbrace{\begin{pmatrix} U_1 \\ D_1 \\ U_1 \\ D_1 \\ U_1 \\ D_1 \\ E_1 \\ N_1 \end{pmatrix} \cdots \begin{pmatrix} U_{N_{\mathrm{TC}}} \\ D_{N_{\mathrm{TC}}} \\ U_{N_{\mathrm{TC}}} \\ D_{N_{\mathrm{TC}}} \\ U_{N_{\mathrm{TC}}} \\ D_{N_{\mathrm{TC}}} \\ E_{N_{\mathrm{TC}}} \\ N_{N_{\mathrm{TC}}} \end{pmatrix}}_{\text{Techni-fermions}}$$

What kind of Technicolor?

$\mathrm{SU}(N_{\mathrm{TC}})$ gauge theory with 8 fundamental fermions

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- candidate for Walking TC
  LatKMI Collaboration (2013)

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K. Yamawaki, M. Bando, K.-i. Matumoto (1986)

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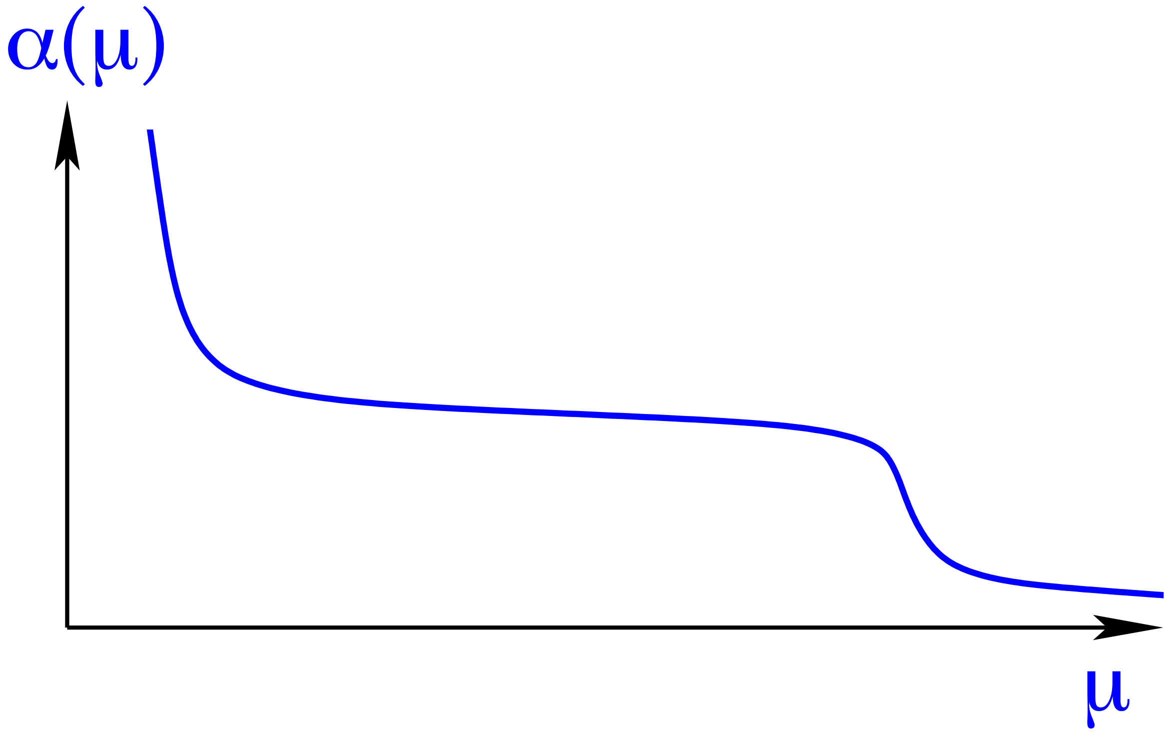
approximately scale invariant gauge theory with large mass anomalous dimension



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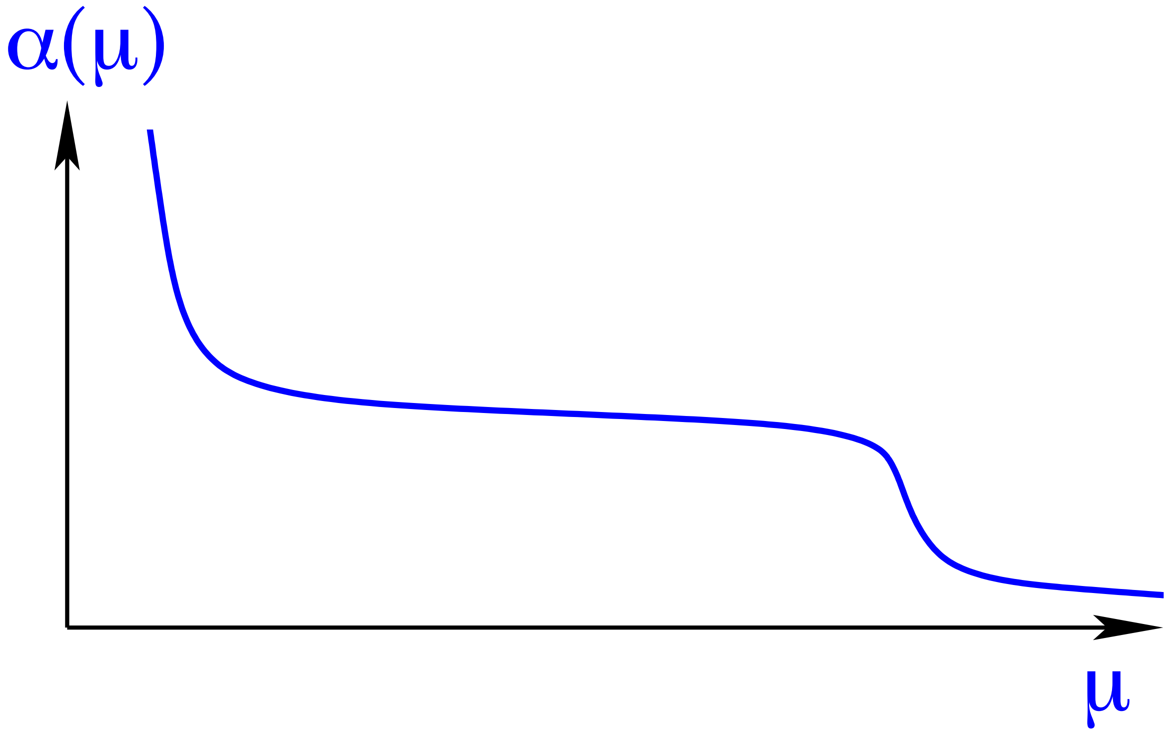

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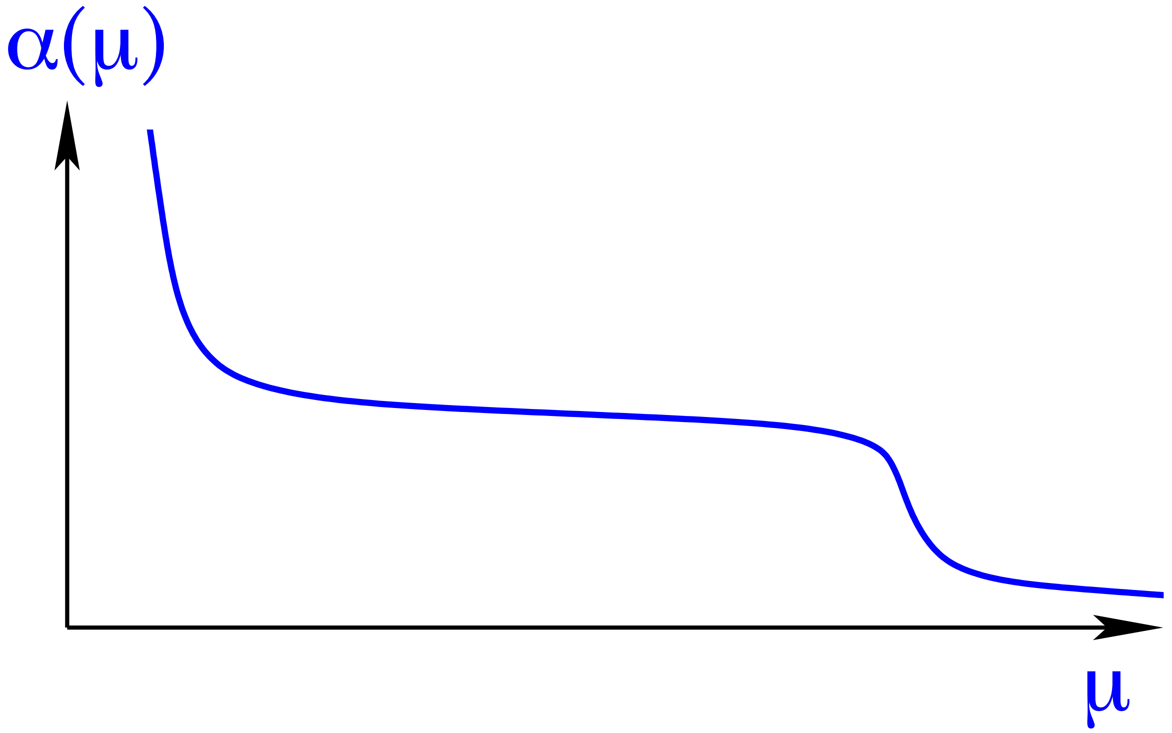

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- existence of a light scalar boundstate (Techni-Dilaton)

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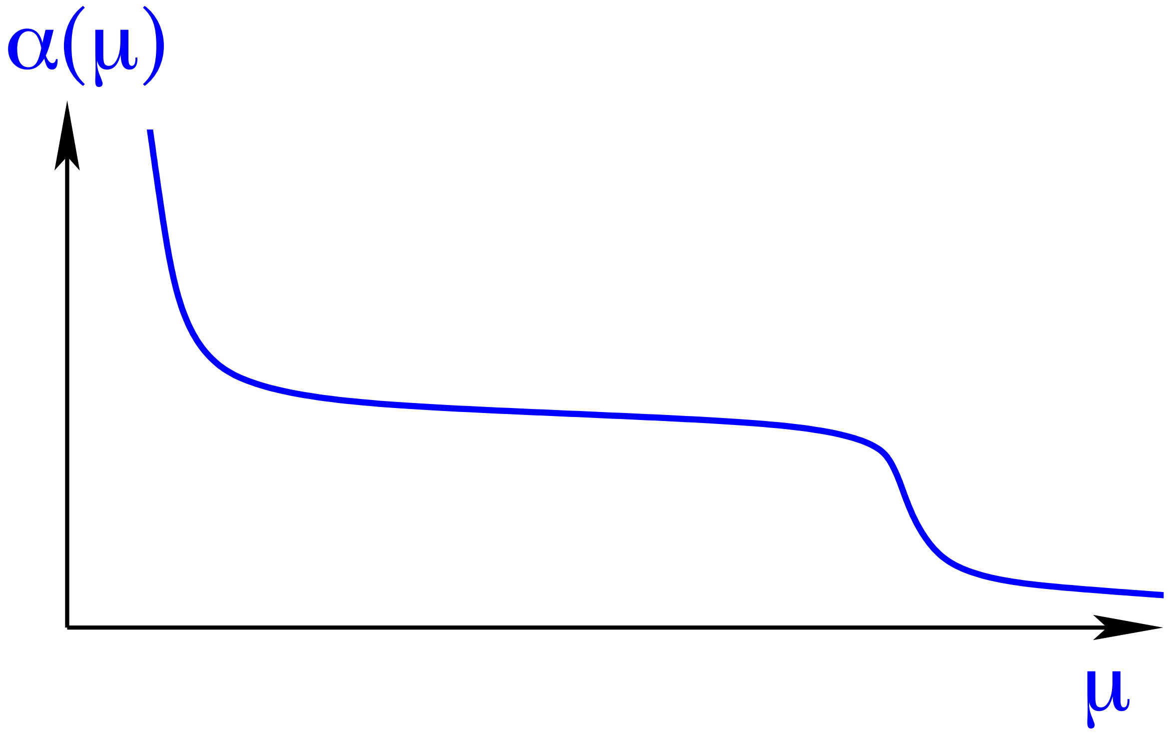

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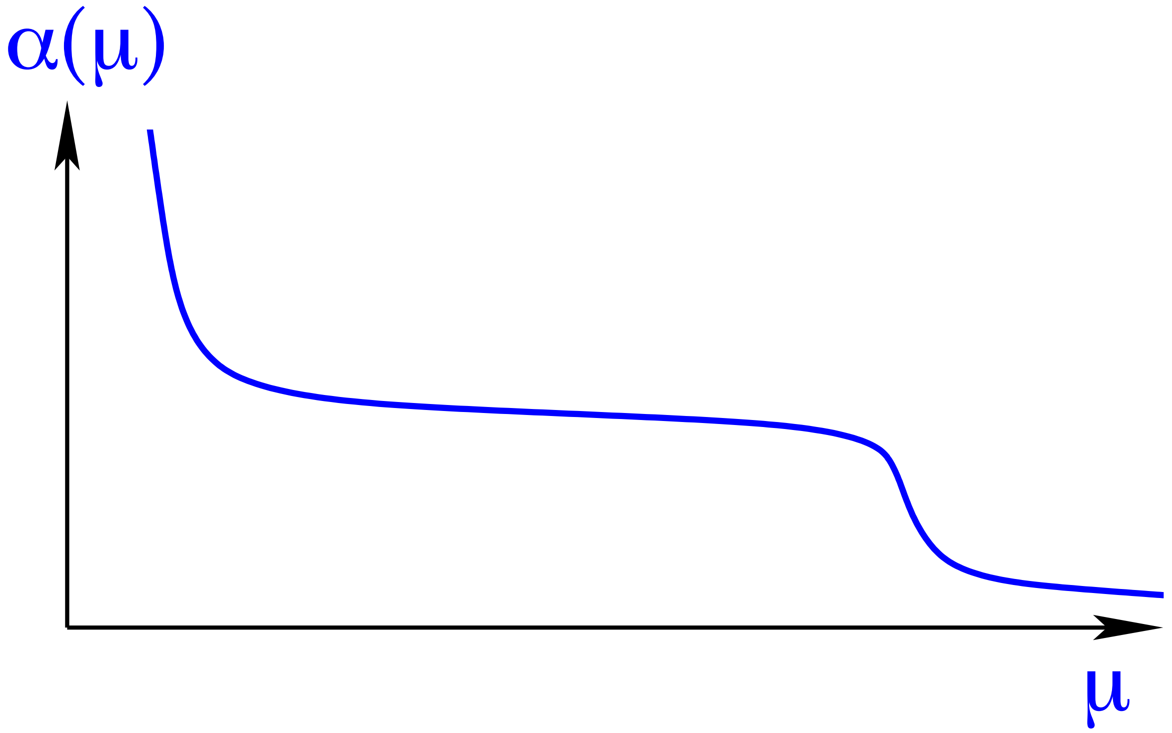

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126 GeV Higgs
= Composite Higgs
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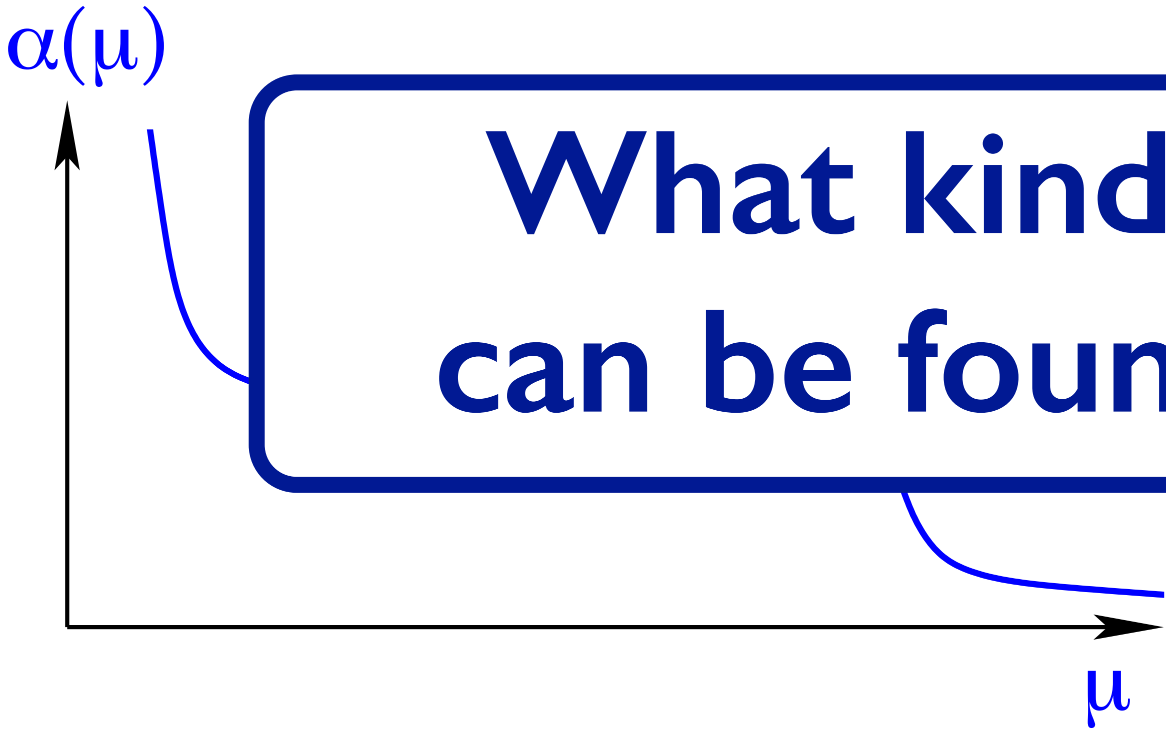

What kind of signatures can be found at the LHC?

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lar

boundstate (Techni-Dilaton)

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2. Effective Lagrangian

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We want to add something extra as typical resonances arising from strong dynamics

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- Techni-Dilaton: (Higgs) NG bosons associated with the scale symmetry breaking

- Techni-Rho mesons: analogue of rho mesons in QCD

Techni-Pion

analogue of pions in QCD

$$\frac{\mathrm{SU}(2)_\mathrm{L} \otimes \mathrm{SU}(2)_\mathrm{R}}{\mathrm{SU}(2)_\mathrm{V}} \Rightarrow$$

3 NG bosons

$$\pi^0, \ \pi^+, \ \pi^-$$

Techni-Pion

in One-Family model

$$\frac{\mathrm{SU}(8)_{\mathrm{L}} \otimes \mathrm{SU}(8)_{\mathrm{R}}}{\mathrm{SU}(8)_{\mathrm{V}}} \Rightarrow$$

63 NG bosons

$$\pi^{A} \quad (A = 1 \sim 63)$$

Techni-Pion

$$\sum_{A=1}^{63} \pi^A(x) X^A = \sum_{i=1}^{3} \pi^i_{\text{eaten}}(x) X^i_{\text{eaten}} + \sum_{i=1}^{3} P^i(x) X^i_P + P^0(x) X_P$$

$$+ \sum_{i=1}^{3}\sum_{a=1}^{8} \theta^i_a(x) X^i_{\theta a} + \sum_{a=1}^{8} \theta^0_a(x) X_{\theta a}$$

$$+ \sum_{c=r,g,b}\sum_{i=1}^{3}\left[T^{(1)i}_c(x) X^{(1)i}_{Tc} + T^{(1)i}_c(x) X^{(2)i}_{Tc}\right] + \sum_{c=r,g,b}\left[T^{(1)}_c(x) X^{(1)}_{Tc} + T^{(1)}_c(x) X^{(2)}_{Tc}\right]$$

$$X^i_{\text{eaten}} = \frac{1}{2}\left(\begin{array}{c|c} \tau^i \otimes 1_{3\times 3} & \\ \hline & \tau^i \end{array}\right), \quad X^i_P = \frac{1}{2\sqrt{3}}\left(\begin{array}{c|c} \tau^i \otimes 1_{3\times 3} & \\ \hline & -3\cdot\tau^i \end{array}\right), \quad X_P = \frac{1}{4\sqrt{3}}\left(\begin{array}{c|c} 1_{6\times 6} & \\ \hline & -3\cdot 1_{2\times 2} \end{array}\right),$$

$$X^i_{\theta a} = \frac{1}{\sqrt{2}}\left(\begin{array}{c|c} \tau^i \otimes \lambda_a & \\ \hline & 0 \end{array}\right), \quad X_{\theta_a} = \frac{1}{2\sqrt{2}}\left(\begin{array}{c|c} 1_{2\times 2} \otimes \lambda_a & \\ \hline & 0 \end{array}\right),$$

$$X^{(1)i}_{Tc} = \frac{1}{\sqrt{2}}\left(\begin{array}{c|c} & \tau^i \otimes \xi_c \\ \hline \tau^i \otimes \xi^\dagger_c & \end{array}\right), \quad X^{(2)i}_{Tc} = \frac{1}{\sqrt{2}}\left(\begin{array}{c|c} & -i\tau^i \otimes \xi_c \\ \hline i\tau^i \otimes \xi^\dagger_c & \end{array}\right),$$

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τ^i : Pauli matrix, λ^a : Gell − Mann matrix

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Color-singlet, Iso-triplet
(eaten by W and Z)

$$X^i_{\text{eaten}} = \frac{1}{2}\left(\begin{array}{c|c} \tau^i \otimes 1_{3\times 3} & \\ \hline & \tau \ldots \end{array}\right) \text{[illegible]}, \quad X_P = \frac{1}{4\sqrt{3}}\left(\begin{array}{c|c} 1_{6\times 6} & \\ \hline & -3\cdot 1_{2\times 2} \end{array}\right),$$

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Color-singlet, Iso-singlet

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Color-octet, Iso-triplet

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Color-octet, Iso-singlet

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$$X^i_{\theta a} = \frac{1}{\sqrt{2}}\left(\begin{array}{c|c} \tau^i\otimes\lambda_a & \\ \hline & 0 \end{array}\right), \qquad X_{\theta_a} = \frac{1}{2\sqrt{2}}\left(\begin{array}{c|c} 1_{2\times2}\otimes\lambda_a & \\ \hline & 0 \end{array}\right),$$

$$X^{(1)i}_{Tc} = \frac{1}{\sqrt{2}}\left(\begin{array}{c|c} & \tau^i\otimes\xi_c \\ \hline \tau^i\otimes\xi_c^\dagger & \end{array}\right), \qquad X^{(2)i}_{Tc} = \frac{1}{\sqrt{2}}\left(\begin{array}{c|c} & -i\tau^i\otimes\xi_c \\ \hline i\tau^i\otimes\xi_c^\dagger & \end{array}\right),$$

$$X^{(1)}_{Tc} = \frac{1}{2\sqrt{2}}\left(\begin{array}{c|c} & 1_{2\times2}\otimes\xi_c \\ \hline 1_{2\times2}\otimes\xi_c^\dagger & \end{array}\right), \qquad X^{(2)}_{Tc} = \frac{1}{2\sqrt{2}}\left(\begin{array}{c|c} & -i\cdot 1_{2\times2}\otimes\xi_c \\ \hline i\cdot 1_{2\times2}\otimes\xi_c^\dagger & \end{array}\right),$$

τ^i : Pauli matrix, λ^a : Gell – Mann matrix

Techni-Pion

$$\sum_{A=1}^{63}\pi^A(x)X^A = \sum_{i=1}^{3}\pi^i_{\rm eaten}(x)X^i_{\rm eaten}+\sum_{i=1}^{3}P^i(x)X^i_P+P^0(x)X_P$$
$$+\sum_{i=1}^{3}\sum_{a=1}^{8}\theta^i_a(x)X^i_{\theta a}+\sum_{a=1}^{8}\theta^0_a(x)X_{\theta a}$$
$$+\sum_{c=r,g,b}\sum_{i=1}^{3}\left[T_c^{(1)i}(x)X_{Tc}^{(1)i}+T_c^{(1)i}(x)X_{Tc}^{(2)i}\right]+\sum_{c=r,g,b}\left[T_c^{(1)}(x)X_{Tc}^{(1)}+T_c^{(1)}(x)X_{Tc}^{(2)}\right]$$

Color-triplet, Iso-triplet

$$X^i_{\rm eaten} = \frac{1}{2}\left(\begin{array}{c|c}\tau^i\otimes 1_{3\times 3} & \\ \hline & \tau^i\end{array}\right),\qquad X^i_P=\frac{1}{2\sqrt{3}}\left(\begin{array}{c|c}\tau^i\otimes 1_{3\times 3} & \\ \hline & -3\cdot\tau^i\end{array}\right),\qquad X_P=\frac{1}{4\sqrt{3}}\left(\begin{array}{c|c}1_{6\times 6} & \\ \hline & -3\cdot 1_{2\times 2}\end{array}\right),$$

$$X^i_{\theta a} = \frac{1}{\sqrt{2}}\left(\tau^i\otimes \ldots\right.$$

$$X^{(1)i}_{Tc} = \frac{1}{\sqrt{2}}\left(\begin{array}{c|c} & \tau^i\otimes\xi_c \\ \hline \tau^i\otimes\xi_c^\dagger & \end{array}\right),\qquad X^{(2)i}_{Tc}=\frac{1}{\sqrt{2}}\left(\begin{array}{c|c} & -i\tau^i\otimes\xi_c \\ \hline i\tau^i\otimes\xi_c^\dagger & \end{array}\right),$$

$$X^{(1)}_{Tc} = \frac{1}{2\sqrt{2}}\left(\begin{array}{c|c} & 1_{2\times 2}\otimes\xi_c \\ \hline 1_{2\times 2}\otimes\xi_c^\dagger & \end{array}\right),\qquad X^{(2)}_{Tc}=\frac{1}{2\sqrt{2}}\left(\begin{array}{c|c} & -i\cdot 1_{2\times 2}\otimes\xi_c \\ \hline i\cdot 1_{2\times 2}\otimes\xi_c^\dagger & \end{array}\right),$$

τ^i : Pauli matrix, λ^a : Gell − Mann matrix

Techni-Pion

$$
\begin{aligned}
\sum_{A=1}^{63} \pi^A(x) X^A \;=\; & \sum_{i=1}^{3} \pi^i_{\text{eaten}}(x) X^i_{\text{eaten}} + \sum_{i=1}^{3} P^i(x) X^i_P + P^0(x) X_P \\
& + \sum_{i=1}^{3} \sum_{a=1}^{8} \theta^i_a(x) X^i_{\theta a} + \sum_{a=1}^{8} \theta^0_a(x) X_{\theta a} \\
& + \sum_{c=r,g,b} \sum_{i=1}^{3} \left[T^{(1)i}_c(x) X^{(1)i}_{Tc} + T^{(1)i}_c(x) X^{(2)i}_{Tc} \right] + \sum_{c=r,g,b} \left[T^{(1)}_c(x) X^{(1)}_{Tc} + T^{(1)}_c(x) X^{(2)}_{Tc} \right]
\end{aligned}
$$

Color-triplet, Iso-singlet

$$
X^i_{\text{eaten}} = \frac{1}{2} \left(\begin{array}{c|c} \tau^i \otimes 1_{3\times 3} & \\ \hline & \tau^i \end{array} \right), \quad
X^i_P = \frac{1}{2\sqrt{3}} \left(\begin{array}{c|c} \tau^i \otimes 1_{3\times 3} & \\ \hline & -3\cdot\tau^i \end{array} \right), \quad
X_P = \frac{1}{4\sqrt{3}} \left(\begin{array}{c|c} 1_{6\times 6} & \\ \hline & -3\cdot 1_{2\times 2} \end{array} \right),
$$

$$
X^i_{\theta a} = \frac{1}{\sqrt{2}} \left(\begin{array}{c|c} \tau^i \otimes \lambda_a & \\ \hline & 0 \end{array} \right), \quad
X_{\theta_a} = \frac{1}{2\sqrt{2}} \left(\begin{array}{c|c} 1_{2\times 2} \otimes \lambda_a & \\ \hline & 0 \end{array} \right),
$$

$$
X^{(1)i}_{Tc} = \frac{1}{\sqrt{2}} \left(\begin{array}{c|c} & \tau^i \otimes \xi_c \\ \hline \tau^i \otimes \xi_c^\dagger & \end{array} \right), \quad
X^{(2)i}_{Tc} = \frac{1}{\sqrt{2}} \left(\begin{array}{c|c} & -i\tau^i \otimes \xi_c \\ \hline i\tau^i \otimes \xi_c^\dagger & \end{array} \right),
$$

$$
X^{(1)}_{Tc} = \frac{1}{2\sqrt{2}} \left(\begin{array}{c|c} & 1_{2\times 2} \otimes \xi_c \\ \hline 1_{2\times 2} \otimes \xi_c^\dagger & \end{array} \right), \quad
X^{(2)}_{Tc} = \frac{1}{2\sqrt{2}} \left(\begin{array}{c|c} & -i\cdot 1_{2\times 2} \otimes \xi_c \\ \hline i\cdot 1_{2\times 2} \otimes \xi_c^\dagger & \end{array} \right),
$$

τ^i : Pauli matrix, λ^a : Gell – Mann matrix

Techni-Pion

$$\sum_{A=1}^{63} \pi^A(x) X^A = \sum_{i=1}^{3} \pi^i_{\rm eaten}(x) X^i_{\rm eaten} + \sum_{i=1}^{3} P^i(x) X^i_P + P^0(x) X_P$$
$$+ \sum_{i=1}^{3}\sum_{a=1}^{8} \theta^i_a(x) X^i_{\theta a} + \sum_{a=1}^{8} \theta^0_a(x) X_{\theta a}$$
$$+ \sum_{c=r,g,b}\sum_{i=1}^{3} \left[T_c^{(1)i}(x) X_{Tc}^{(1)i} + T_c^{(1)i}(x) X_{Tc}^{(2)i} \right] + \sum_{c=r,g,b} \left[T_c^{(1)}(x) X_{Tc}^{(1)} + T_c^{(1)}(x) X_{Tc}^{(2)} \right]$$

$$X^i_{\rm eaten} = \frac{1}{2}\left(\begin{array}{c|c} \tau^i \otimes 1_{3\times 3} & \\ \hline & \tau^i \end{array}\right), \quad X^i_P = \frac{1}{2\sqrt{3}}\left(\begin{array}{c|c} \tau^i \otimes 1_{3\times 3} & \\ \hline & -3\cdot\tau^i \end{array}\right), \quad X_P = \frac{1}{4\sqrt{3}}\left(\begin{array}{c|c} 1_{6\times 6} & \\ \hline & -3\cdot 1_{2\times 2} \end{array}\right),$$

$$X^i_{\theta a} = \frac{1}{\sqrt{2}}\left(\begin{array}{c|c} \tau^i \otimes \lambda_a & \\ \hline & \end{array}\right. \ldots$$

$$X_{Tc}^{(1)i} = \frac{1}{\sqrt{2}}\left(\begin{array}{c|c} & \tau^i \otimes \xi_c \\ \hline \tau^i \otimes \xi_c^\dagger & \end{array}\right), \quad X_{Tc}^{(2)i} = \frac{1}{\sqrt{2}}\left(\begin{array}{c|c} & \ldots \otimes \xi_c \\ \hline i\tau^i \otimes \xi_c^\dagger & \end{array}\right),$$

$$X_{Tc}^{(1)} = \frac{1}{2\sqrt{2}}\left(\begin{array}{c|c} & 1_{2\times 2} \otimes \xi_c \\ \hline 1_{2\times 2} \otimes \xi_c^\dagger & \end{array}\right), \quad X_{Tc}^{(2)} = \frac{1}{2\sqrt{2}}\left(\begin{array}{c|c} & -i\cdot 1_{2\times 2} \otimes \xi_c \\ \hline i\cdot 1_{2\times 2} \otimes \xi_c^\dagger & \end{array}\right),$$

Rich spectrum!!

τ^i : Pauli matrix, λ^a : Gell – Mann matrix

Techni-Pion

$$
\begin{aligned}
\sum_{A=1}^{63} \pi^A(x) X^A \;=\; & \sum_{i=1}^{3} \pi^i_{\rm eaten}(x) X^i_{\rm eaten} + \sum_{i=1}^{3} P^i(x) X^i_P + P^0(x) X_P \\
& + \sum_{i=1}^{3}\sum_{a=1}^{8} \theta^i_a(x) X^i_{\theta a} + \sum_{a=1}^{8} \theta^0_a(x) X_{\theta a} \\
& + \sum_{c=r,g,b}\sum_{i=1}^{3} \left[T_c^{(1)i}(x) X_{Tc}^{(1)i} + T_c^{(1)i}(x) X_{Tc}^{(2)i} \right] + \sum_{c=r,g,b} \left[T_c^{(1)}(x) X_{Tc}^{(1)} + T_c^{(1)}(x) X_{Tc}^{(2)} \right]
\end{aligned}
$$

$$
X^i_{\rm eaten} = \frac{1}{2}\left(\begin{array}{c|c} \tau^i \otimes 1_{3\times3} & \\ \hline & \tau^i \end{array}\right), \quad X^i_P = \frac{1}{2\sqrt{3}}\left(\begin{array}{c|c} \tau^i \otimes 1_{3\times3} & \\ \hline & -3\cdot\tau^i \end{array}\right), \quad X_P = \frac{1}{4\sqrt{3}}\left(\begin{array}{c|c} 1_{6\times6} & \\ \hline & -3\cdot 1_{2\times2} \end{array}\right),
$$

Similarly for Techni-Rho mesons

$$
X_{Tc}^{(1)i} = \frac{1}{\sqrt{2}}\left(\begin{array}{c|c} & \tau^i \otimes \xi_c \\ \hline \tau^i \otimes \xi_c^\dagger & \end{array}\right), \quad X_{Tc}^{(2)i} = \frac{1}{\sqrt{2}}\left(\begin{array}{c|c} & -i\tau^i \otimes \xi_c \\ \hline i\tau^i \otimes \xi_c^\dagger & \end{array}\right),
$$

$$
X_{Tc}^{(1)} = \frac{1}{2\sqrt{2}}\left(\begin{array}{c|c} & 1_{2\times2} \otimes \xi_c \\ \hline 1_{2\times2} \otimes \xi_c^\dagger & \end{array}\right), \quad X_{Tc}^{(2)} = \frac{1}{2\sqrt{2}}\left(\begin{array}{c|c} & -i\cdot 1_{2\times2} \otimes \xi_c \\ \hline i\cdot 1_{2\times2} \otimes \xi_c^\dagger & \end{array}\right),
$$

τ^i : Pauli matrix, λ^a : Gell − Mann matrix

Low-energy Effective Lagrangian

Techni-Pions

Low-energy Effective Lagrangian

Techni-Pions

$$\frac{\mathrm{SU}(8)_{\mathrm{L}} \otimes \mathrm{SU}(8)_{\mathrm{R}}}{\mathrm{SU}(8)_{\mathrm{V}}}$$ chiral Lagrangian

Low-energy Effective Lagrangian

Techni-Pions

$$\frac{\mathrm{SU}(8)_\mathrm{L} \otimes \mathrm{SU}(8)_\mathrm{R}}{\mathrm{SU}(8)_\mathrm{V}}$$ chiral Lagrangian

$$\mathcal{L} = \quad F_\pi^2 \mathrm{tr}[\hat{\alpha}_{\mu\perp}^2]$$

$$\hat{\alpha}_{\mu\perp} = \frac{(D_\mu \xi_R)\xi_R^\dagger - (D_\mu \xi_L)\xi_L^\dagger}{2i}$$

$$D_\mu \xi_L = \partial_\mu \xi_L + i\xi_L \mathcal{L}_\mu$$

$$D_\mu \xi_R = \partial_\mu \xi_R + i\xi_R \mathcal{R}_\mu$$

SM gauge fields

Techni-Pions

$$\xi_{L,R} = \quad e^{\mp \frac{i\pi}{F_\pi}}, \quad \pi = \pi^A X^A$$

Low-energy Effective Lagrangian

Techni-Pions

$$\frac{\mathrm{SU}(8)_{\mathrm{L}} \otimes \mathrm{SU}(8)_{\mathrm{R}}}{\mathrm{SU}(8)_{\mathrm{V}}}$$ chiral Lagrangian

$$\mathcal{L} = F_\pi^2 \mathrm{tr}[\hat{\alpha}_{\mu\perp}^2]$$

$$\hat{\alpha}_{\mu\perp} = \frac{(D_\mu \xi_{R} \ldots}{2i}$$

Techni-Pions obtain their masses from explicit breaking effects

J. Jia, S. Matsuzaki, K. Yamawaki (2012)

$$D_\mu \xi_L = \partial_\mu \xi_L + i\xi_L \mathcal{L}_\mu$$

$$D_\mu \xi_R = \partial_\mu \xi_R + i\xi_R \mathcal{R}_\mu$$

SM gauge fields

Techni-Pions

$$\xi_{L,R} = e^{\mp \frac{i\pi}{F_\pi}}, \quad \pi = \pi^A X^A$$

Low-energy Effective Lagrangian

Techni-Pions

$$\frac{\mathrm{SU(8)_L} \otimes \mathrm{SU(8)_R}}{\mathrm{SU(8)_V}}$$ chiral Lagrangian

$$\mathcal{L} = \quad F_\pi^2 \mathrm{tr}[\hat{\alpha}^2_{\mu\perp}$$

$$\hat{\alpha}_{\mu\perp} \quad = \quad \frac{(\ \ }{2i}$$

Holographic estimate shows Techni-pions are rather heavy:

$$m_\pi > O(1)\ \mathrm{TeV}$$

M.K., S. Matsuzaki, K. Yamawaki, arXiv:1403.0467

$$D_\mu \xi_L = \partial_\mu \xi_L + i \xi_L \mathcal{L}_\mu$$

$$D_\mu \xi_R = \partial_\mu \xi_R + i \xi_R \mathcal{R}_\mu$$

SM gauge fields ($\mathcal{L}_\mu$, $\mathcal{R}_\mu$)

$$\xi_{L,R} = \quad e^{\mp \frac{i\pi}{F_\pi}}, \quad \pi = \pi^A X^A$$

Techni-Pions (π^A)

Low-energy Effective Lagrangian

Techni-Pions + Techni-Dilaton
(Composite Higgs)

$$\mathcal{L} = F_\pi^2 \mathrm{tr}[\hat{\alpha}_{\mu\perp}^2]$$

$$\hat{\alpha}_{\mu\perp} = \frac{(D_\mu \xi_R)\xi_R^\dagger - (D_\mu \xi_L)\xi_L^\dagger}{2i}$$

$$D_\mu \xi_L = \partial_\mu \xi_L + i\xi_L \mathcal{L}_\mu$$

$$D_\mu \xi_R = \partial_\mu \xi_R + i\xi_R \mathcal{R}_\mu$$

$$\xi_{L,R} = e^{\mp \frac{i\pi}{F_\pi}}, \quad \pi = \pi^A X^A$$

Low-energy Effective Lagrangian

Techni-Pions + Techni-Dilaton
(Composite Higgs)

requiring scale invariance

$$\mathcal{L} = \qquad F_\pi^2 \mathrm{tr}[\hat{\alpha}_{\mu\perp}^2]$$

$$\hat{\alpha}_{\mu\perp} \quad = \frac{(D_\mu \xi_R)\xi_R^\dagger \text{ - } (D_\mu \xi_L)\xi_L^\dagger}{2i}$$

$$D_\mu \xi_L = \partial_\mu \xi_L + i\xi_L \mathcal{L}_\mu$$

$$D_\mu \xi_R = \partial_\mu \xi_R + i\xi_R \mathcal{R}_\mu$$

$$\xi_{L,R} = \qquad e^{\mp \frac{i\pi}{F_\pi}}, \quad \pi = \pi^A X^A$$

Low-energy Effective Lagrangian

Higgs

Techni-Pions + Techni-Dilaton

(Composite Higgs)

$$\chi = e^{\frac{\phi}{F_\phi}}$$

requiring scale invariance

$$\mathcal{L} = \chi^2 \quad F_\pi^2 \mathrm{tr}[\hat{\alpha}_{\mu\perp}^2]$$

$$\hat{\alpha}_{\mu\perp} = \frac{(D_\mu \xi_R)\xi_R^\dagger - (D_\mu \xi_L)\xi_L^\dagger}{2i}$$

$$D_\mu \xi_L = \partial_\mu \xi_L + i\xi_L \mathcal{L}_\mu$$

$$D_\mu \xi_R = \partial_\mu \xi_R + i\xi_R \mathcal{R}_\mu$$

$$\xi_{L,R} = e^{\mp \frac{i\pi}{F_\pi}}, \quad \pi = \pi^A X^A$$

Low-energy Effective Lagrangian

Higgs

Techni-Pions + Techni-Dilaton

(Composite Higgs)

requiring scale invariance

$$\chi = e^{\frac{\phi}{F_\phi}}$$

$$\mathcal{L} = \chi^2 \quad F_\pi^2 \mathrm{tr}[\hat{\alpha}_{\mu\perp}^2]$$

Consistent with LHC data

S. Matsuzaki, K. Yamawaki (2012), (2013)

Best fit: $\frac{v_{\mathrm{EW}}}{F_\phi} = 0.22 \quad (\text{for } N_{\mathrm{TC}} = 4)$

$$\hat{\alpha}_{\mu\perp} = \frac{(D}{}$$

$$D_\mu \xi_L = \partial_\mu \xi_L + i\xi_L \mathcal{L}_\mu$$

$$D_\mu \xi_R = \partial_\mu \xi_R + i\xi_R \mathcal{R}_\mu$$

$$\xi_{L,R} = e^{\mp \frac{i\pi}{F_\pi}}, \quad \pi = \pi^A X^A$$

Low-energy Effective Lagrangian

Higgs

Techni-Pions + Techni-Dilaton

(Composite Higgs)

$\chi = e^{\frac{\phi}{F_\phi}}$

requiring scale invariance

$\mathcal{L} = \chi^2 \quad F_\pi^2 \mathrm{tr}[\hat{\alpha}_{\mu\perp}^2]$

Consistent with LHC data

S. Matsuzaki, K. Yamawaki (2012), (2013)

Best fit: $\frac{v_{\rm EW}}{F_\phi} = 0.22 \quad (\text{for } N_{\rm TC} = 4)$

$\hat{\alpha}_{\mu\perp} \quad = \frac{(D}{}$

$D_\mu \xi_L = \partial_\mu \xi$

$D_\mu \xi_R = \partial_\mu \xi$

More details in the talk
by S. Matsuzaki

$\xi_{L,R} = \quad e^{\mp \frac{i\pi}{F_\pi}}, \quad \pi = \pi^A X^A$

Low-energy Effective Lagrangian

Techni-Pions + Techni-Dilaton

+ Techni-Rho mesons
(Hidden Local Symmetry)

$$\chi = e^{\frac{\phi}{F_\phi}}$$

$$\mathcal{L} = \chi^2 \quad F_\pi^2 \mathrm{tr}[\hat{\alpha}_{\mu\perp}^2]$$

$$\hat{\alpha}_{\mu\perp} \quad = \frac{(D_\mu \xi_R)\xi_R^\dagger - (D_\mu \xi_L)\xi_L^\dagger}{2i}$$

$$D_\mu \xi_L = \partial_\mu \xi_L + i\xi_L \mathcal{L}_\mu$$

$$D_\mu \xi_R = \partial_\mu \xi_R + i\xi_R \mathcal{R}_\mu$$

$$\xi_{L,R} = \quad e^{\mp \frac{i\pi}{F_\pi}}, \quad \pi = \pi^A X^A$$

Low-energy Effective Lagrangian

Techni-Pions + Techni-Dilaton

+ Techni-Rho mesons
(Hidden Local Symmetry)

$$\chi = e^{\frac{\phi}{F_\phi}}$$

$$\mathcal{L} = \chi^2 \left(F_\pi^2 \mathrm{tr}[\hat{\alpha}_{\mu\perp}^2] + F_\sigma^2 \mathrm{tr}[\hat{\alpha}_{\mu\parallel}^2] \right) - \frac{1}{2g^2} \mathrm{tr}\left[V_{\mu\nu}^2 \right]$$

$$\hat{\alpha}_{\mu\perp,\parallel} = \frac{(D_\mu \xi_R)\xi_R^\dagger \mp (D_\mu \xi_L)\xi_L^\dagger}{2i}$$

Techni-Rho mesons

$$D_\mu \xi_L = \partial_\mu \xi_L + i\xi_L \mathcal{L}_\mu - iV_\mu \xi_L$$

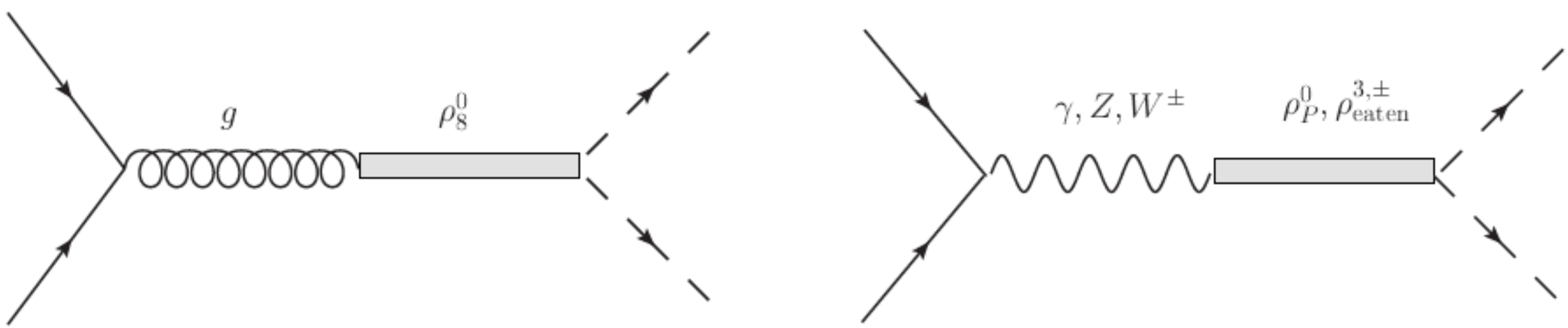
$$D_\mu \xi_R = \partial_\mu \xi_R + i\xi_R \mathcal{R}_\mu - iV_\mu \xi_R$$

$$\xi_{L,R} = e^{\frac{i\sigma}{F_\sigma}} e^{\mp \frac{i\pi}{F_\pi}}, \quad \pi = \pi^A X^A, \; \sigma = \sigma^A X^A$$

3. Collider phenomenology

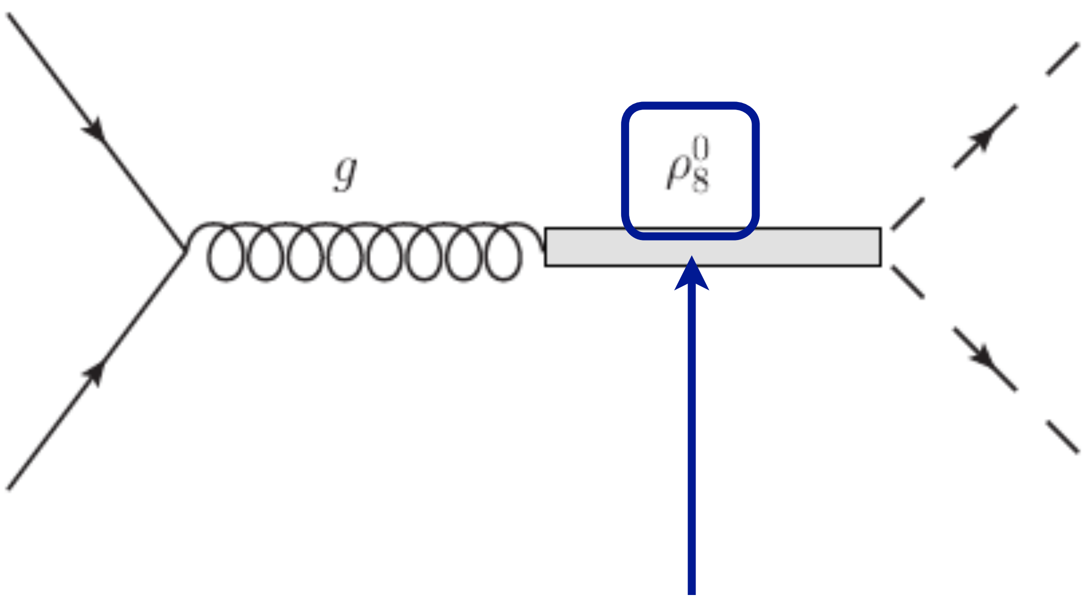
Techni-Rho productions

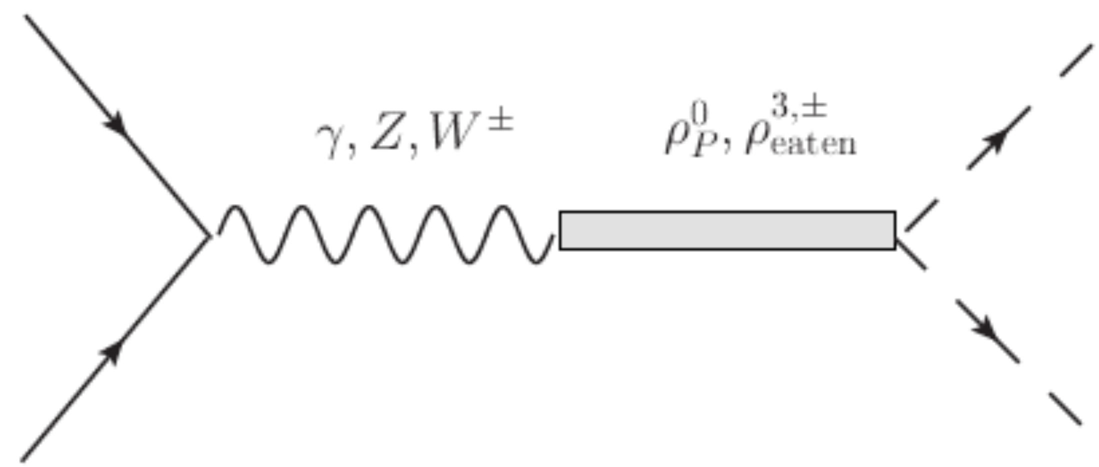
Ones that mix with SM gauge bosons are produced through the Drell-Yan process



Techni-Rho productions

Ones that mix with SM gauge bosons are produced through the Drell-Yan process

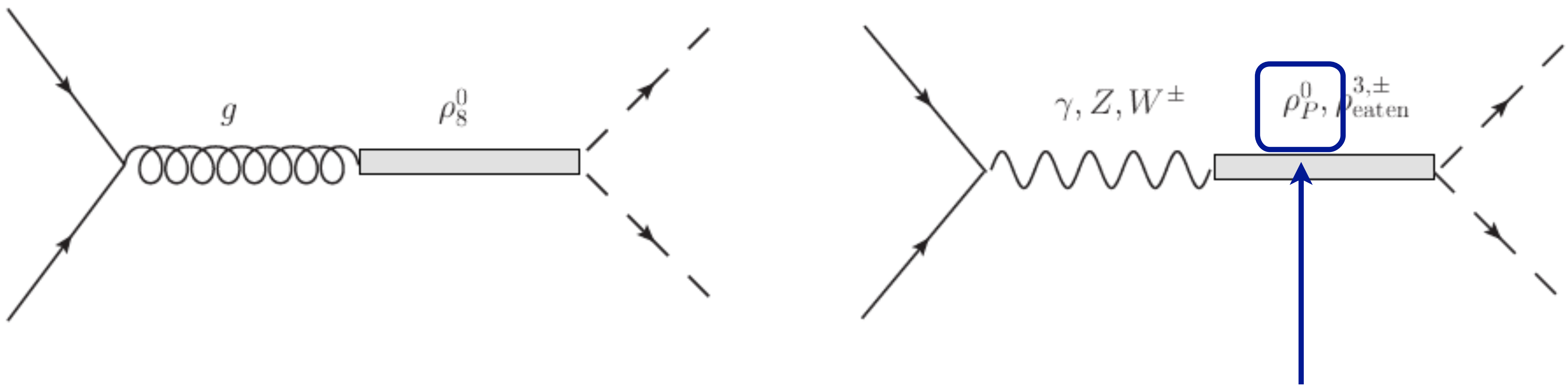




Color-octet, Iso-singlet Techni-Rho meson

Techni-Rho productions

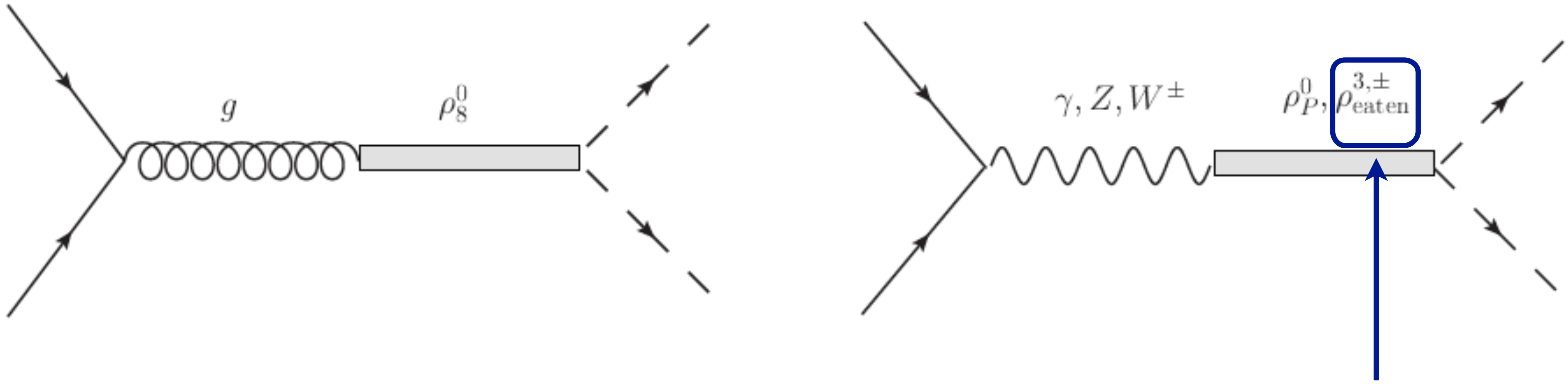
Ones that mix with SM gauge bosons are produced through the Drell-Yan process



Color-singlet, Iso-singlet
Techni-Rho meson

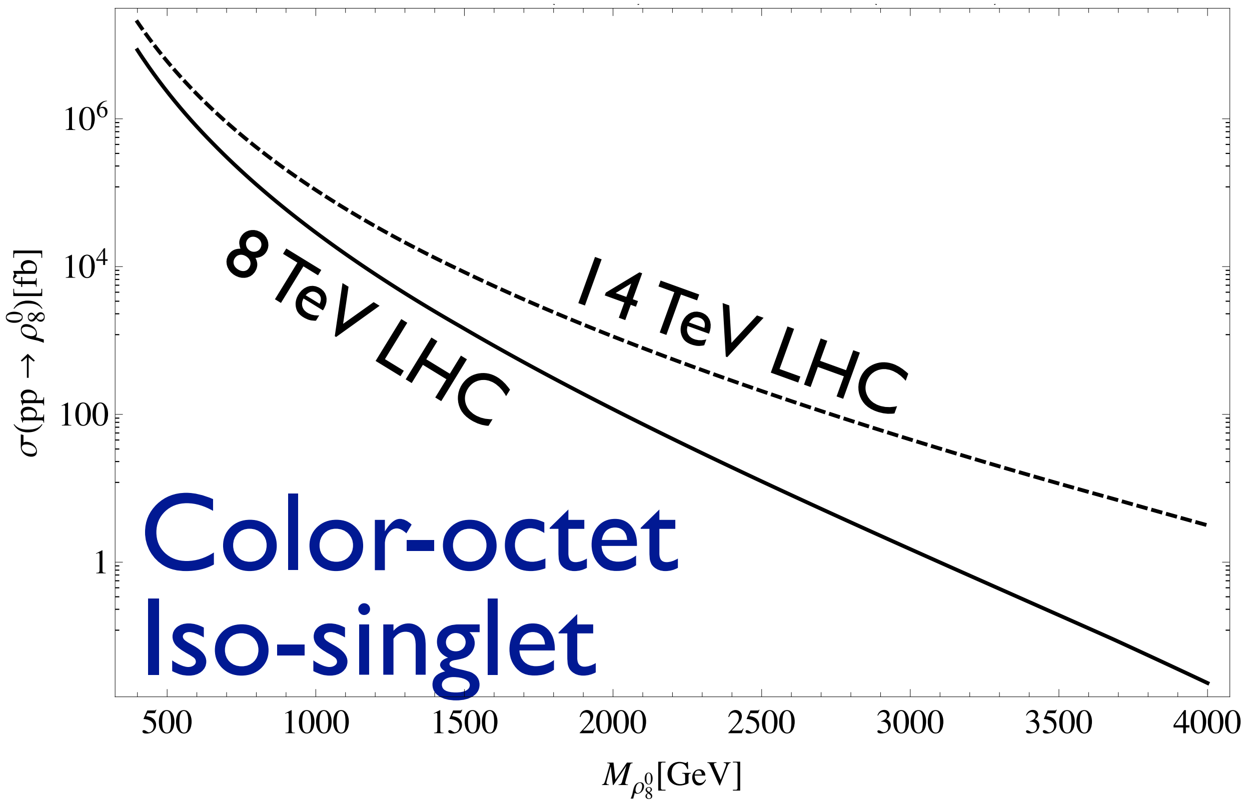
Techni-Rho productions

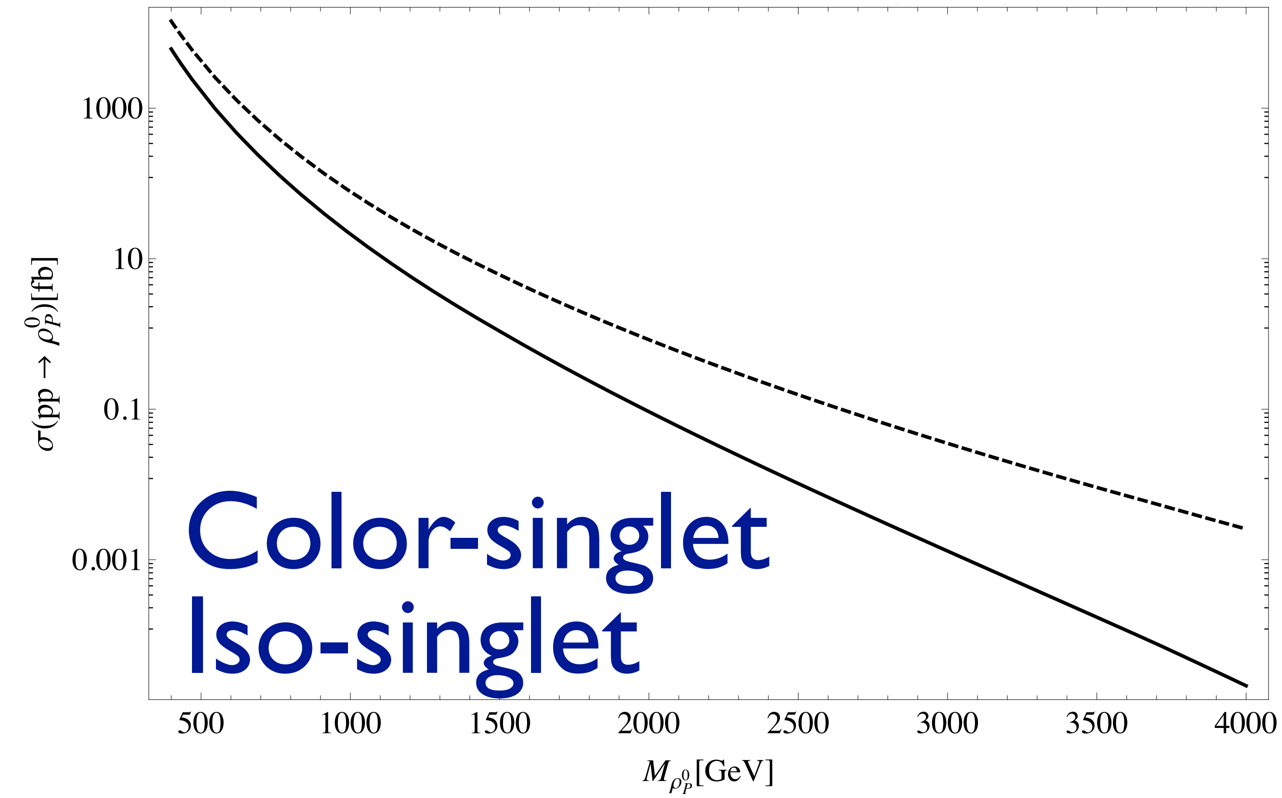
Ones that mix with SM gauge bosons are produced through the Drell-Yan process

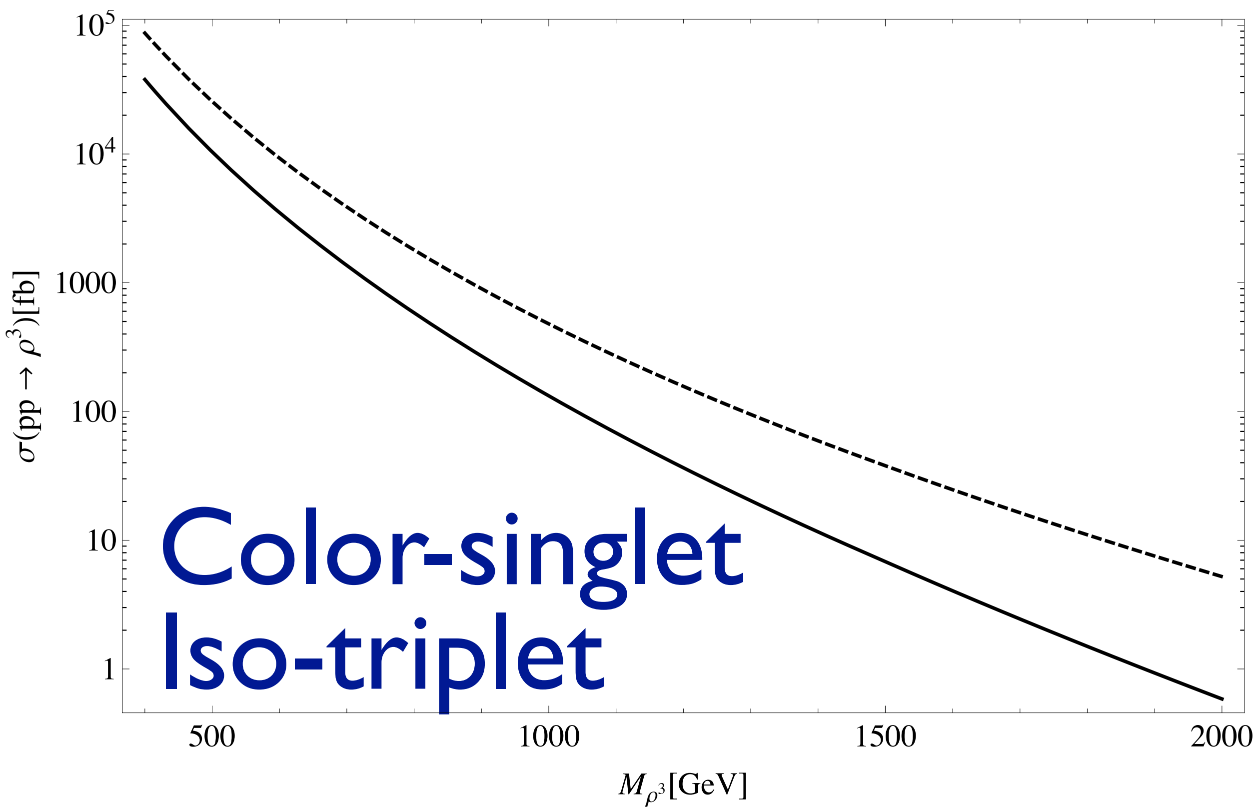


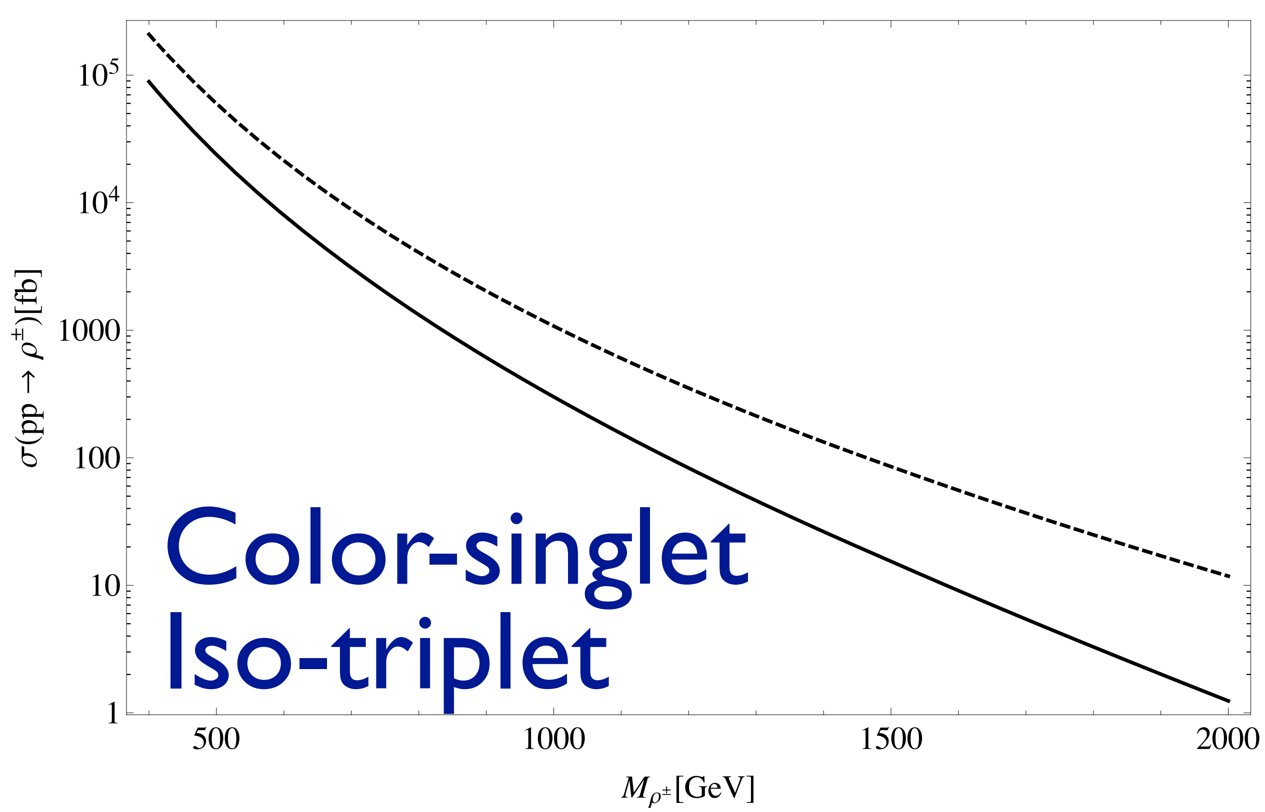
Color-singlet, Iso-triplet
Techni-Rho meson

Techni-Rho productions cross section







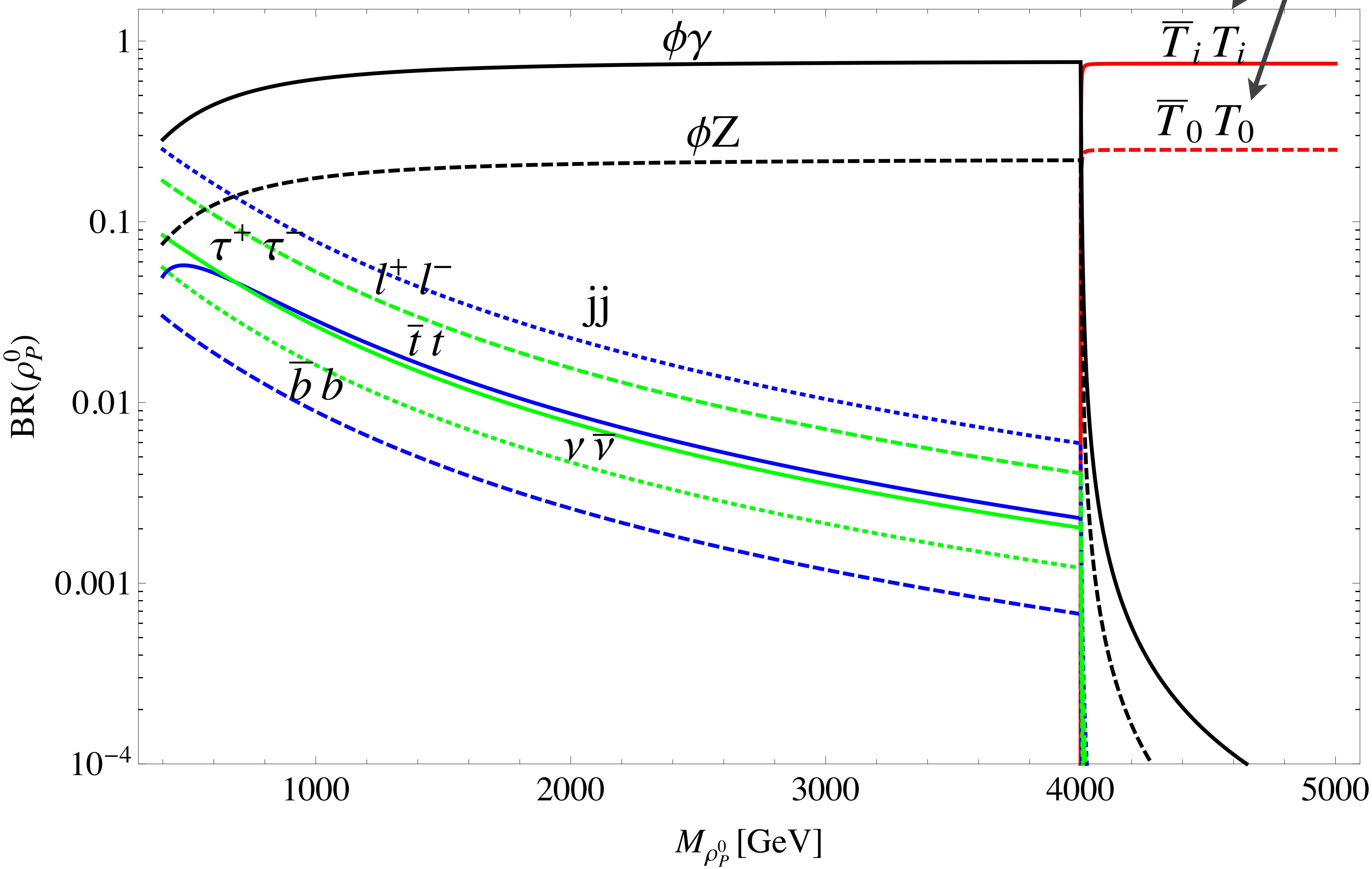


ρ_P^0 Color-singlet Iso-singlet

Branching ratio

Color-triplet Techni-Pions

$(M_T = 2\ \text{TeV})$

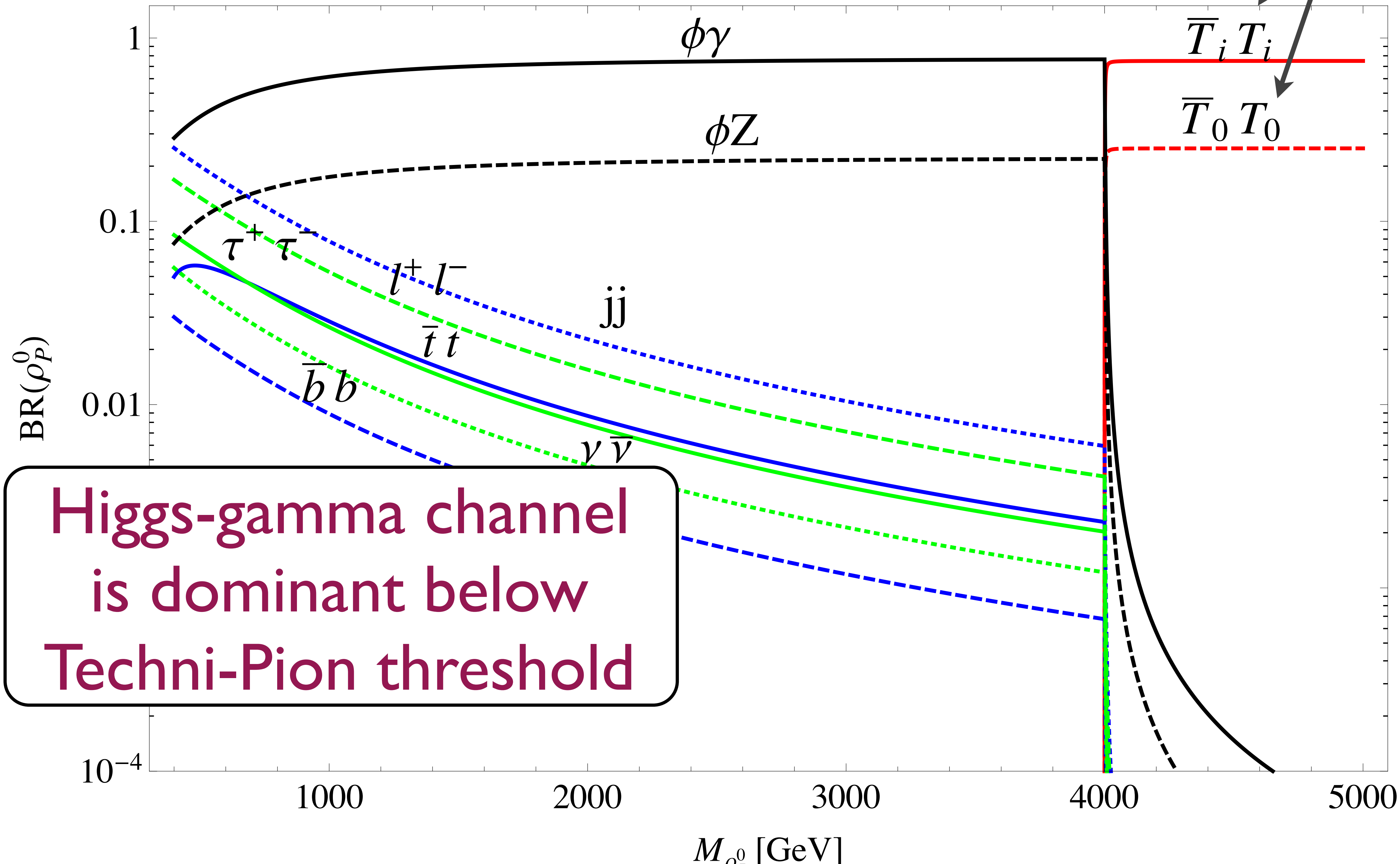


ρ_P^0 Color-singlet Iso-singlet

Branching ratio

Color-triplet Techni-Pions

$(M_T = 2\ \text{TeV})$



Higgs-gamma channel is dominant below Techni-Pion threshold

ρ_P^0 Color-singlet Iso-singlet

Branching ratio

Constraint from LHC?

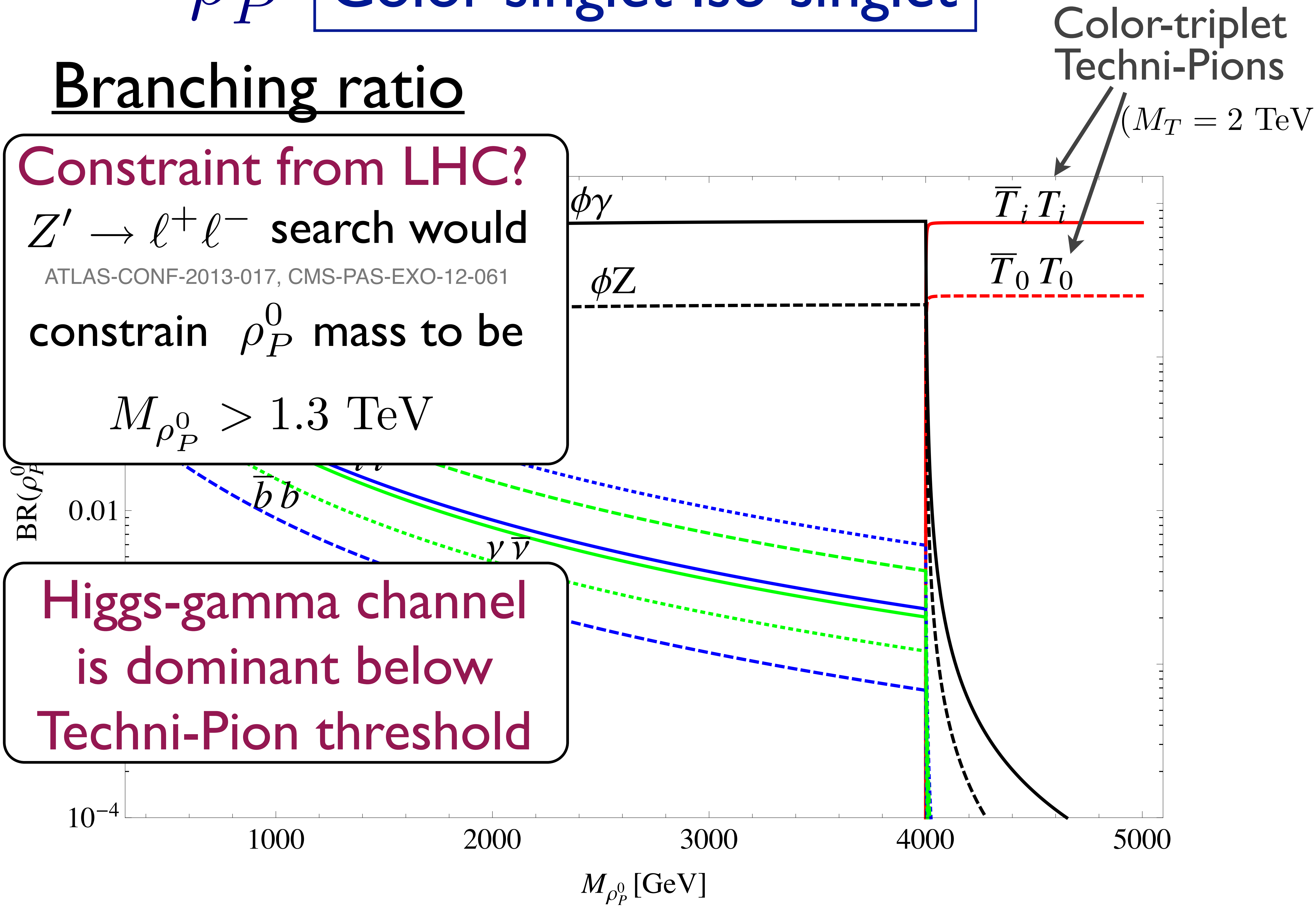
$Z' \to \ell^+\ell^-$ search would

ATLAS-CONF-2013-017, CMS-PAS-EXO-12-061

constrain ρ_P^0 mass to be

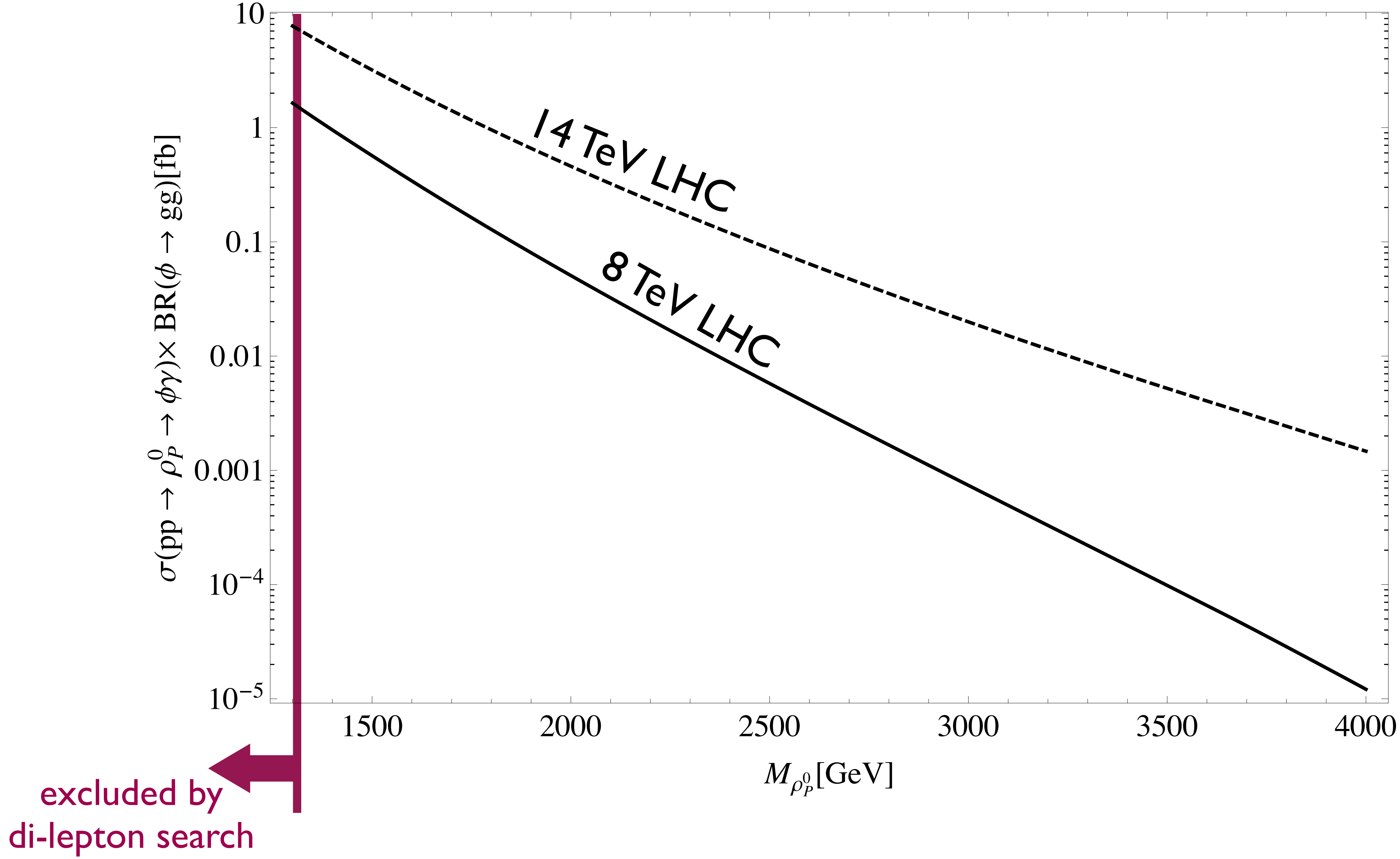
$$M_{\rho_P^0} > 1.3 \text{ TeV}$$

Higgs-gamma channel is dominant below Techni-Pion threshold



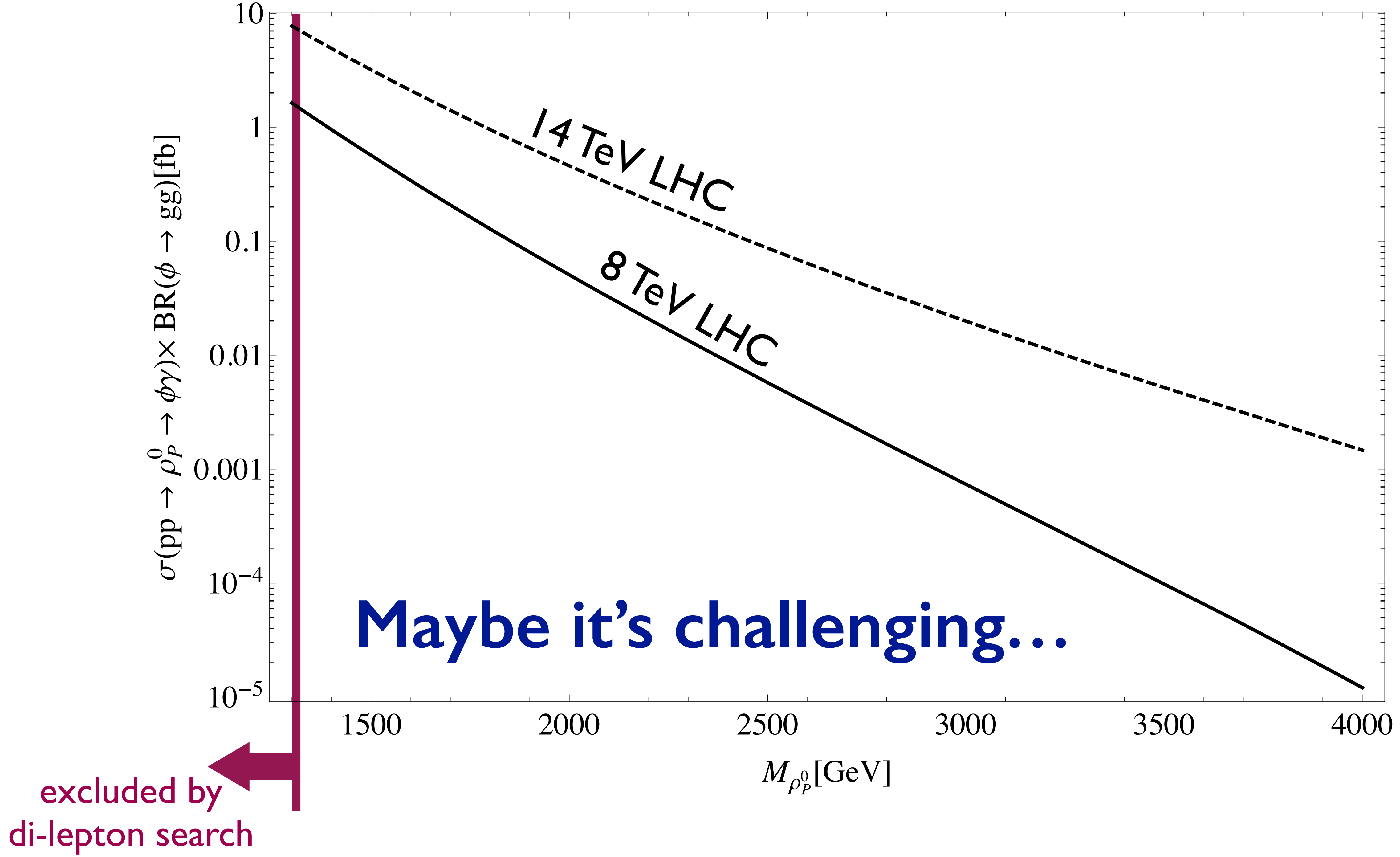
ρ_P^0 Color-singlet Iso-singlet

$$\sigma(pp \to \rho_P^0 \to \phi\,\gamma) \times \mathrm{BR}(\phi \to \overset{\sim 75\%}{gg})$$



ρ_P^0 Color-singlet Iso-singlet

$$\underline{\sigma(pp \to \rho_P^0 \to \phi\,\gamma) \times \mathrm{BR}(\phi \to \overbrace{gg}^{\sim 75\%})}$$

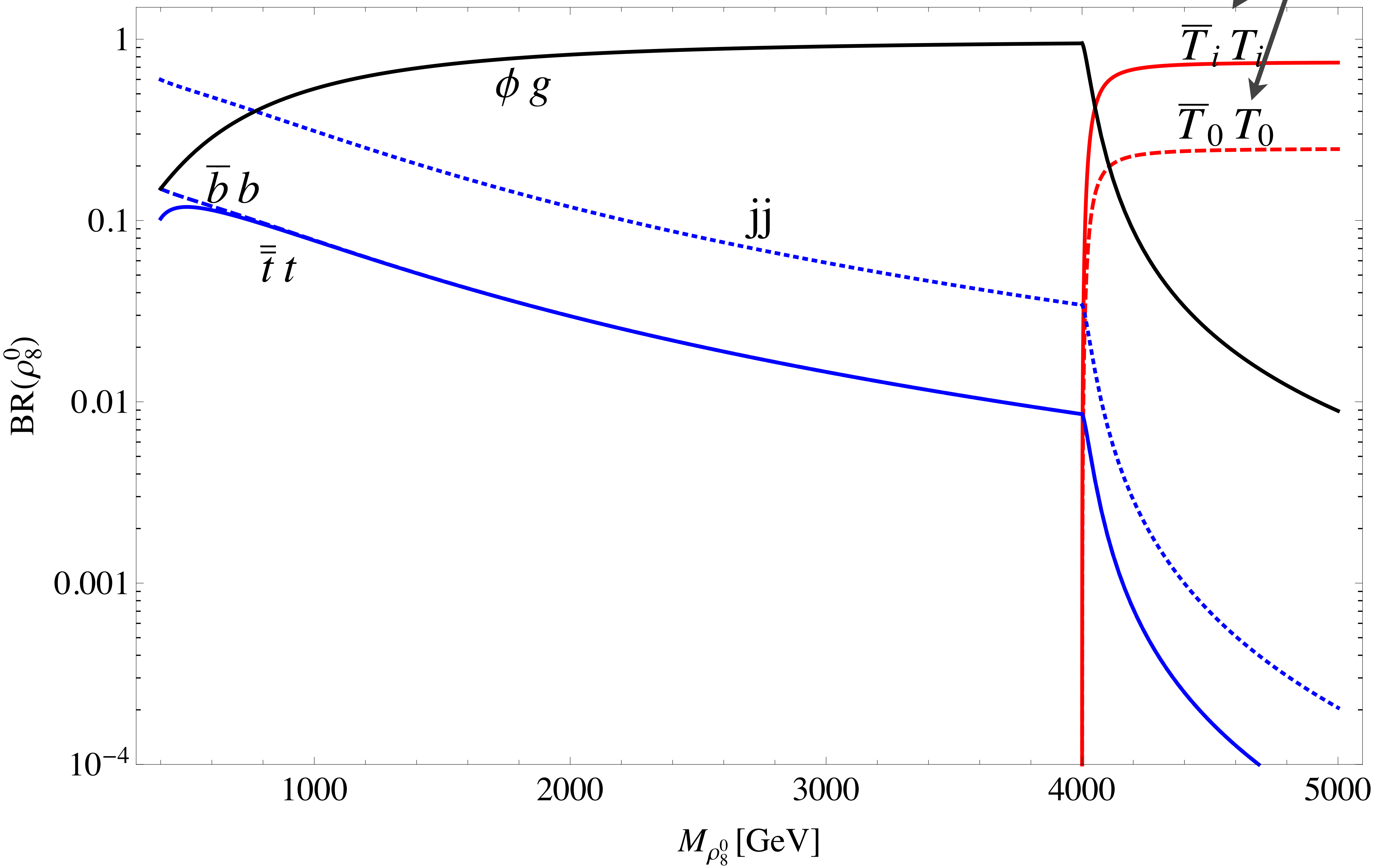


ρ_8^0 Color-octet Iso-singlet

Branching ratio

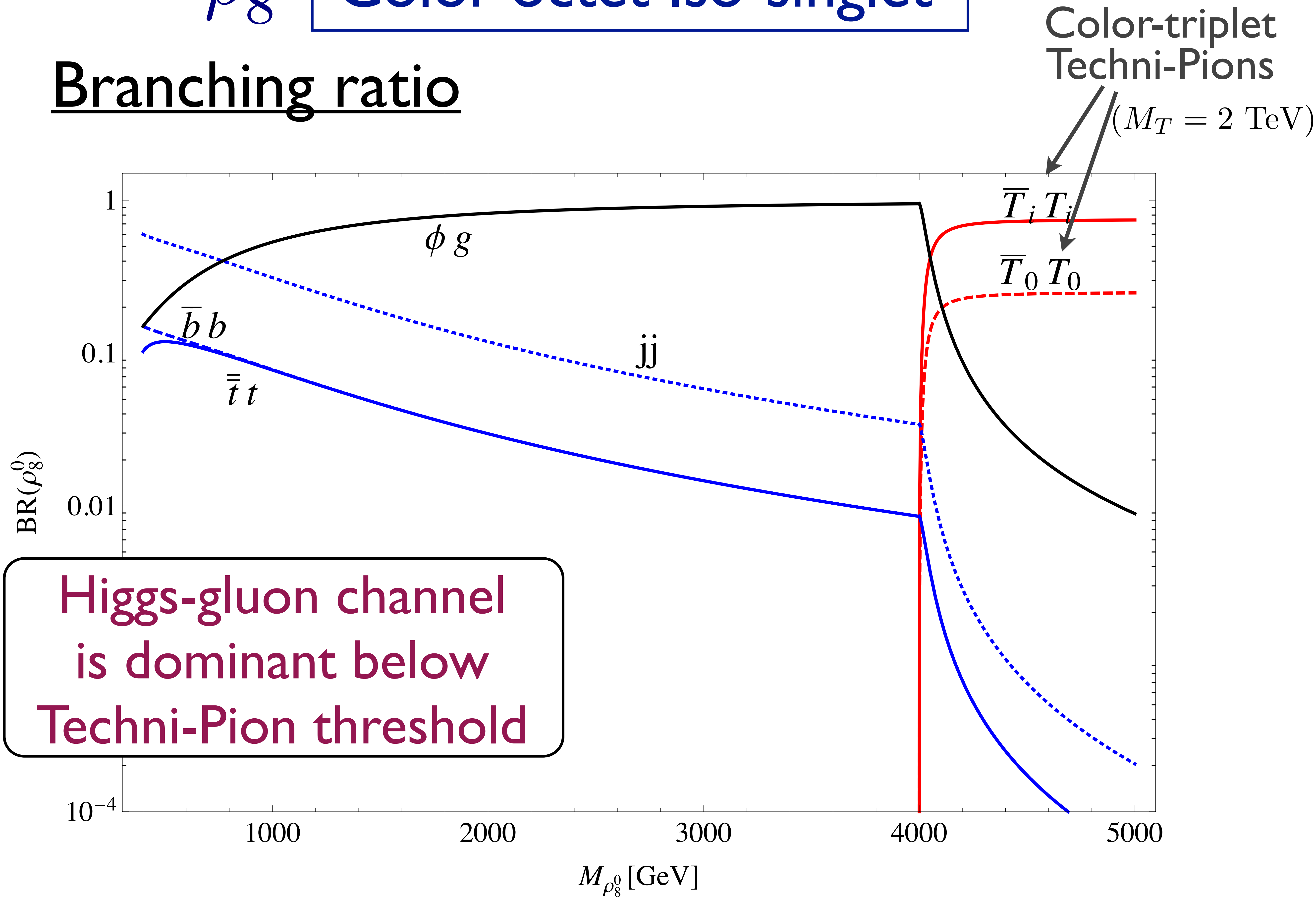
Color-triplet Techni-Pions

$(M_T = 2\ \mathrm{TeV})$



ρ_8^0 Color-octet Iso-singlet

Branching ratio



Higgs-gluon channel is dominant below Techni-Pion threshold

ρ_8^0 Color-octet Iso-singlet

Branching ratio

Constraint from LHC?

dijet resonance search would

CMS-PAS-EXO-12-016

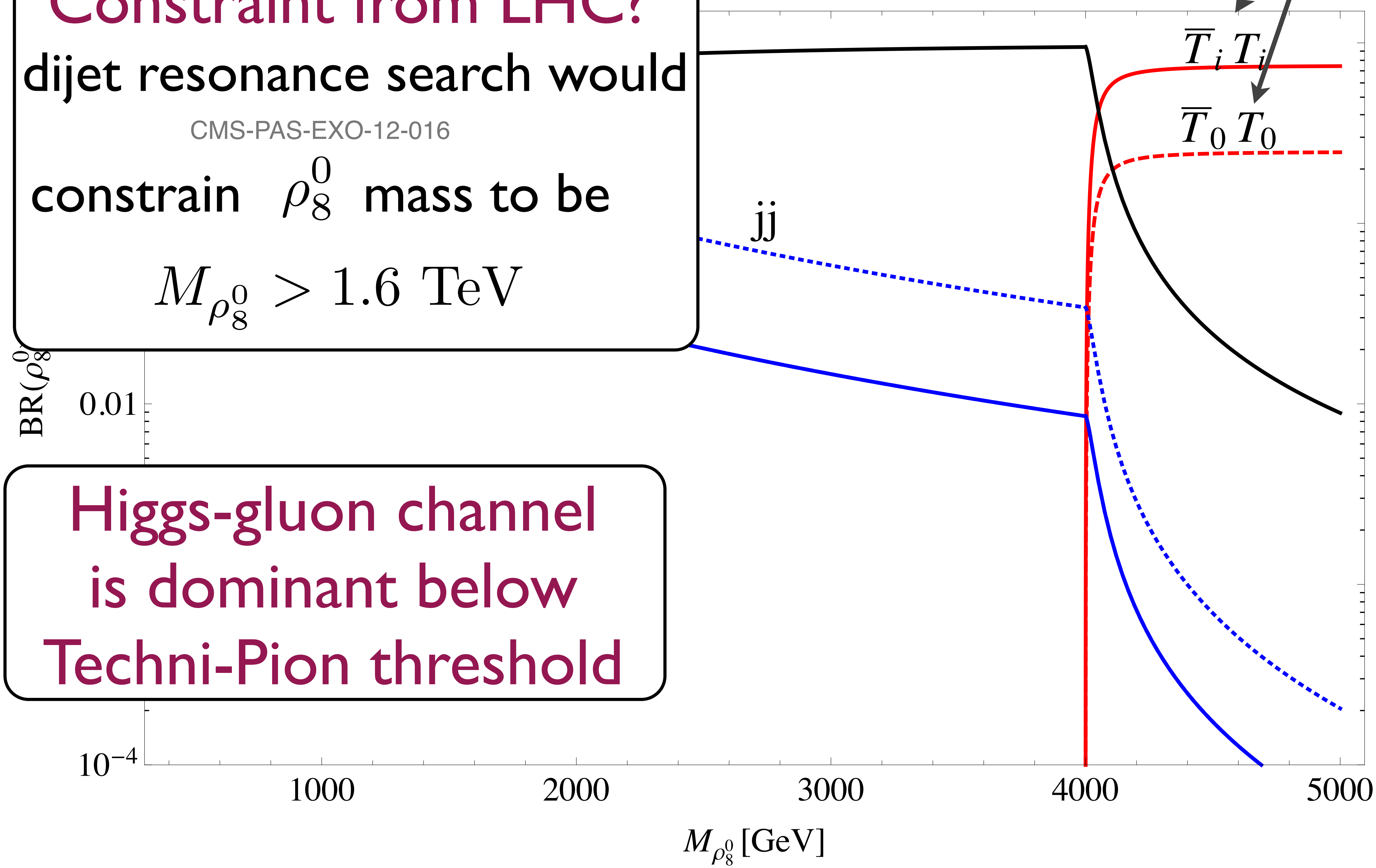
constrain ρ_8^0 mass to be

$$M_{\rho_8^0} > 1.6\ \text{TeV}$$

Higgs-gluon channel is dominant below Techni-Pion threshold

Color-triplet Techni-Pions

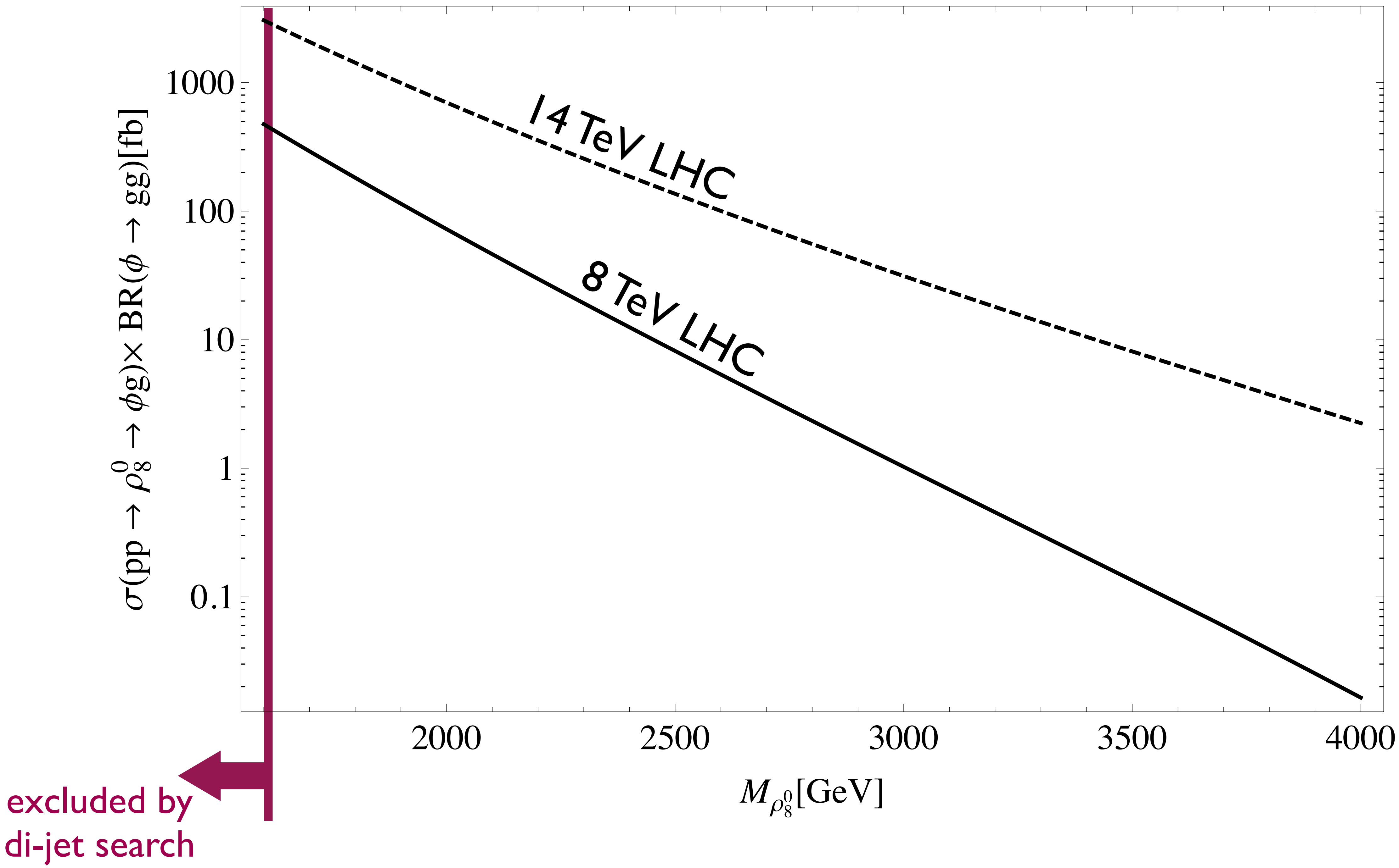
$(M_T = 2\ \text{TeV})$



ρ_8^0 Color-octet Iso-singlet

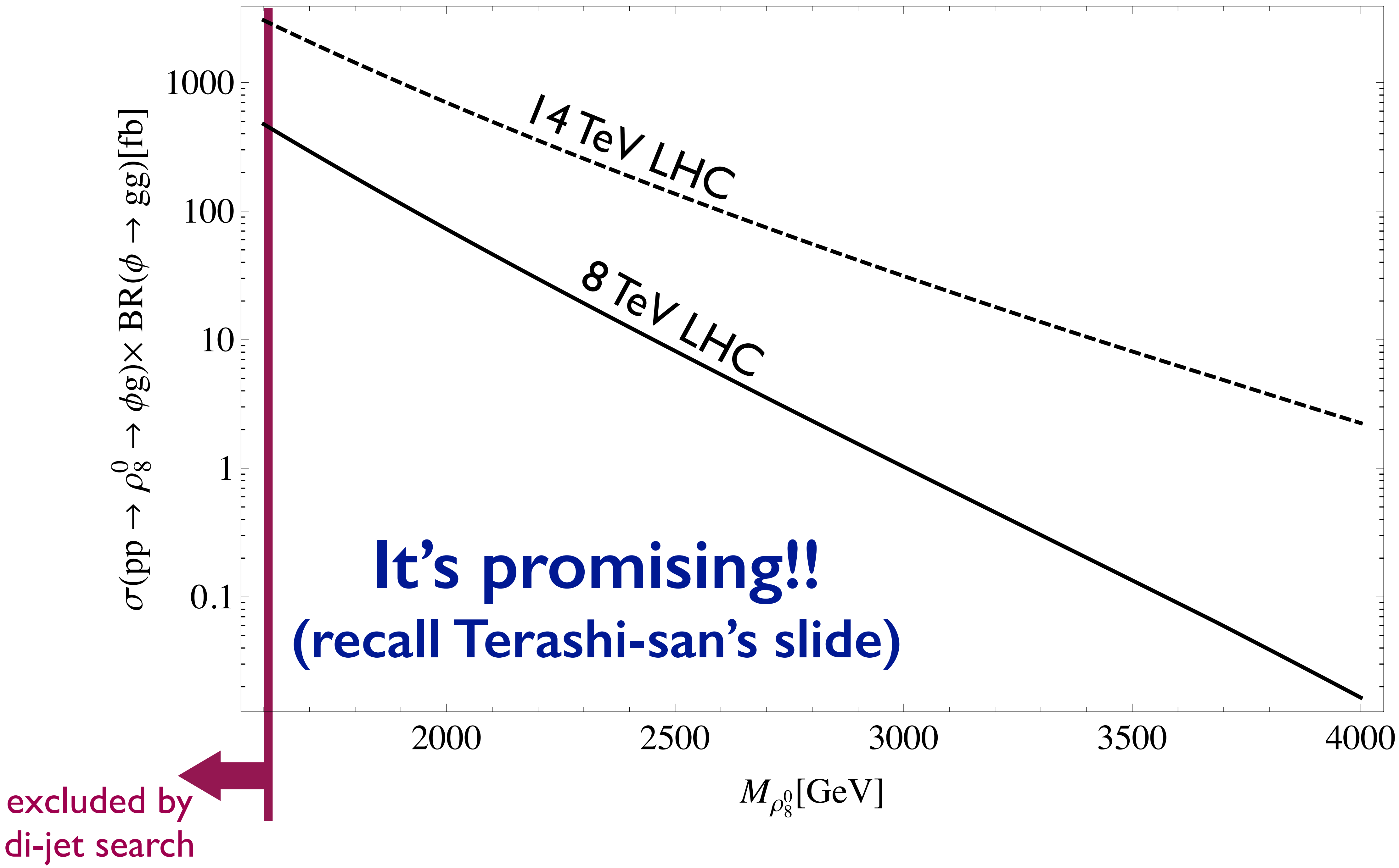
$$\sigma(pp \to \rho_8^0 \to \phi\, g) \times \mathrm{BR}(\phi \to gg)$$

$\sim 75\%$



ρ_8^0 Color-octet Iso-singlet

$$\sigma(pp \to \rho_8^0 \to \phi\, g) \times \mathrm{BR}(\phi \to \underset{\sim 75\%}{gg})$$

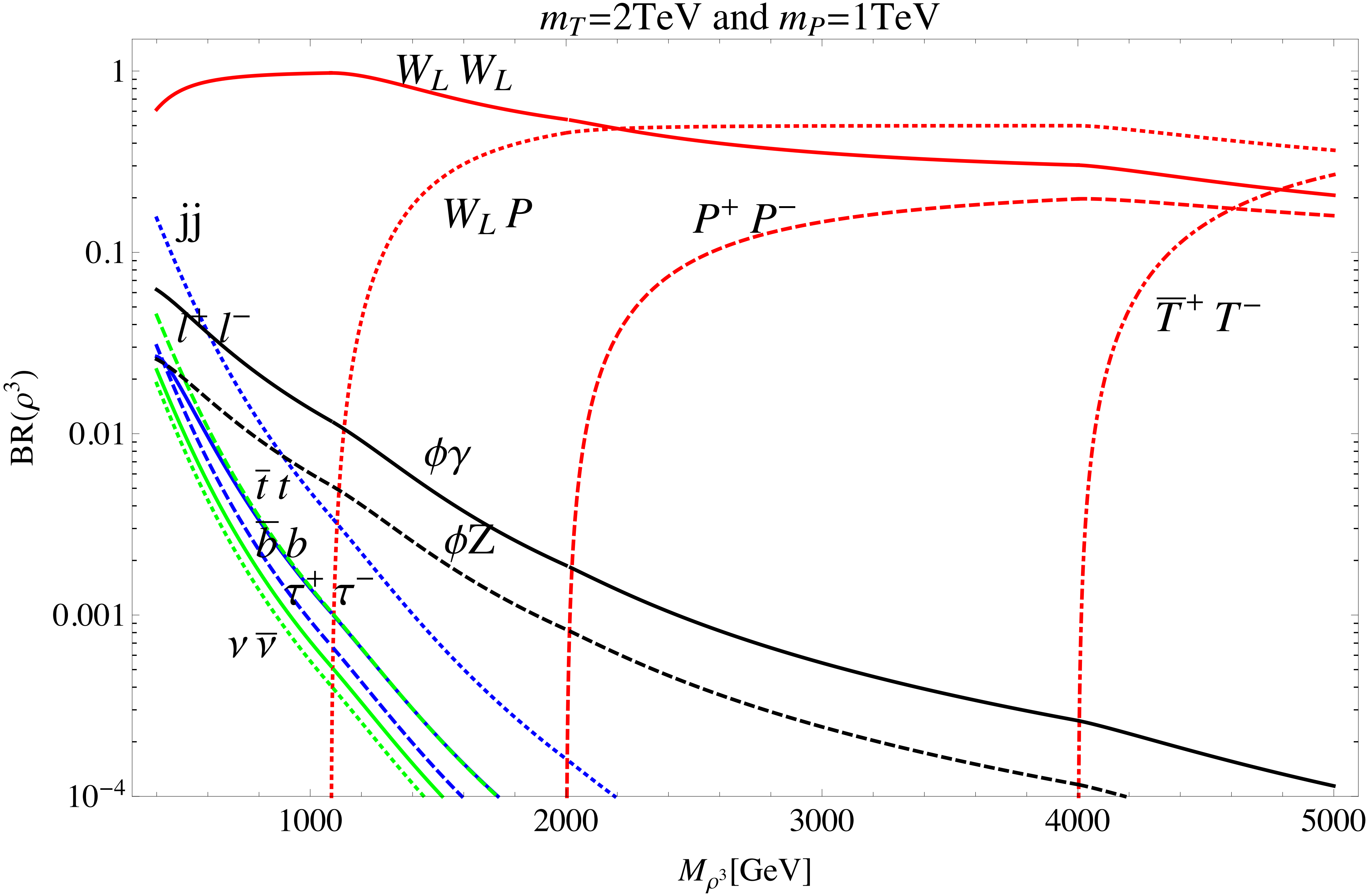


4. Summary

- Techni-Pions, Techni-dilaton, and Techni-Rho mesons as Low-energy spectrum of the one-family TC
- Scale-invariant chiral Lagrangian with the HLS
- Techni-Dilaton production through Techni-Rho decay
- Color-octet technirho decaying into the Higgs (Techni-dilaton) and gluon is promising channel
- Detailed collider study is in progress

Backups

Branching ratio (ρ^3)



Branching ratio $(\rho^{\pm})$