Collider Signatures of a Light Scalar

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arXiv:0803.2040 [hep-ph]

Outline

1. Motivation

   approximate scale invariance of EWSB scenarios, low energy EFT

2. Setup

   SM embedded in spontaneously broken CFT, dilaton + its couplings

3. Collider signatures

   new production and discovery channels, Tevatron + LHC

4. Conclusion

Motivation

- LHC will hopefully shed light on EWSB
- EWSB sector of SM with Higgs doublet suffers from the hierarchy problem
- many BSM scenarios of EWSB which address shortcomings of SM Higgs mechanism
- large class of scenarios has a light scalar in spectrum due to an approximate scale invariance which is spontaneously broken at some scale $f \geq v$

Motivation

- light scalar arises as pseudo-Goldstone boson of spontaneously broken conformal symmetry
- (pseudo-)dilaton with $m_\chi^2 = \epsilon f^2$
- a <u>light</u> SM Higgs can be regarded as such a dilaton with $f = v, \quad \epsilon = (m_H/v)^2$
- dilaton can arise in other EWSB scenarios beyond the SM with an approximate conformal symmetry such as walking technicolor or models with extra dimensions where $f > v$

Motivation

- dilaton potentially the only light state to be seen at the LHC
- use conformal symmetry to construct an effective low energy description of dilaton dynamics and its couplings to SM particles
- how does a generic dilaton differ from a Higgs?

Setup

- start with SM where EWSB parameterized by EW chiral Lagrangian written as

$$\mathcal{L}_{SM} = \sum c_i(\mu)\mathcal{O}_i(x)$$

- under scale transformation $x^\mu \longrightarrow e^\lambda x^\mu$

$$\mathcal{O}_i(x) \longrightarrow e^{\lambda d_i}\mathcal{O}_i(e^\lambda x)$$

$$\mu \longrightarrow e^{-\lambda}\mu$$

- introduce conformal compensator field $\chi(x)$ which transforms as $\chi(x) \longrightarrow e^\lambda \chi(e^\lambda x)$

Setup

$$\mathcal{L}_{SM} = \sum c_i(\mu)\mathcal{O}_i(x)$$

- make Lagrangian invariant by replacing

$$c_i(\mu) \to c_i\left(\mu\frac{\chi}{f}\right)\left(\frac{\chi}{f}\right)^{4-d_i}$$

- expanding $\chi = f + \bar{\chi}$ find dilaton couplings

$$\begin{aligned}\mathcal{L}_\chi &= \left(\frac{2\bar{\chi}}{f} + \frac{\bar{\chi}^2}{f^2}\right)\left(m_W^2 W_\mu^+ W^{-\mu} + \frac{1}{2}m_Z^2 Z_\mu Z^\mu\right) \\ &\quad - \frac{\bar{\chi}}{f}\sum_\psi m_\psi \bar{\psi}\psi + \cdots\end{aligned}$$

Setup

- need explicit scale symmetry breaking

$$\mathcal{L}_{CFT} \to \mathcal{L}_{CFT} + \lambda \mathcal{O}$$

  with operator of scaling dimension $\Delta \neq 4$
- this explicit breaking gives dilaton mass and non-derivative self-couplings
- small breaking if either $\lambda \ll 1$ in units of f or if the operator is nearly marginal with $|\Delta - 4| \ll 1$
- incorporate by treating λ as a spurion

see also Goldberger, Grinstein + Skiba, PRL 100:111802,2008

Setup

- explicit scale symmetry breaking also modifies couplings to SM fields, e.g.

$$\mathcal{L}_Y = -\frac{\chi}{f}\sum_\psi m(z)\bar{\psi}\psi$$

where $m(z) = c_0 + c_1 z + c_2 z^2 + \cdots \quad z = \hat{\lambda}(\chi/f)^{\Delta-4}$

- expand up to linear order in the dilaton

$$\mathcal{L}_Y = -\sum_\psi m_\psi \bar{\psi}\psi - \bar{\chi}\sum_\psi Y_\psi \bar{\psi}\psi + \cdots$$

Setup

$$\mathcal{L}_Y = -\frac{\chi}{f}\sum_\psi m(z)\bar{\psi}\psi \qquad z = \hat{\lambda}(\chi/f)^{\Delta-4}$$

- for $|\Delta - 4| \ll 1$ we have

$$\begin{aligned} m_\psi &= m(\hat{\lambda}) \\ Y_\psi &= \frac{1}{f}\left[m_\psi + (\Delta-4)m'(\hat{\lambda})\right] \end{aligned}$$

- Yukawa couplings not proportional to mass!
- extra piece proportional to small explicit symmetry breaking parameter

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$$\mathcal{L}_\chi = -\frac{\bar{\chi}}{f}\sum_\psi \left(m_\psi + \epsilon y_\psi^{(1)} v\right)\bar{\psi}\psi$$
$$+\left(\frac{2\bar{\chi}}{f}+\frac{\bar{\chi}^2}{f^2}\right)\left(m_W^2 W_\mu^+ W^{-\mu} + \frac{1}{2}m_Z^2 Z_\mu Z^\mu\right)$$
$$+\frac{\bar{\chi}}{f}\left[\frac{\alpha_{EM}}{8\pi}c_{EM}(F_{\mu\nu})^2 + \frac{\alpha_s}{8\pi}c_G(G_{\mu\nu})^2\right]$$

- effects of explicit symmetry breaking could be most dramatic for light fermions where $m_\psi \ll v$
- new production channels $u\bar{u},\ d\bar{d} \to \chi$
- new clean signatures $\chi \to \mu^+\mu^-,\ e^+e^-$

Collider Signatures

$$\mathcal{L}_\chi = -\frac{\bar{\chi}}{f}\sum_\psi \left(m_\psi + \epsilon y_\psi^{(1)} v\right)\bar{\psi}\psi$$
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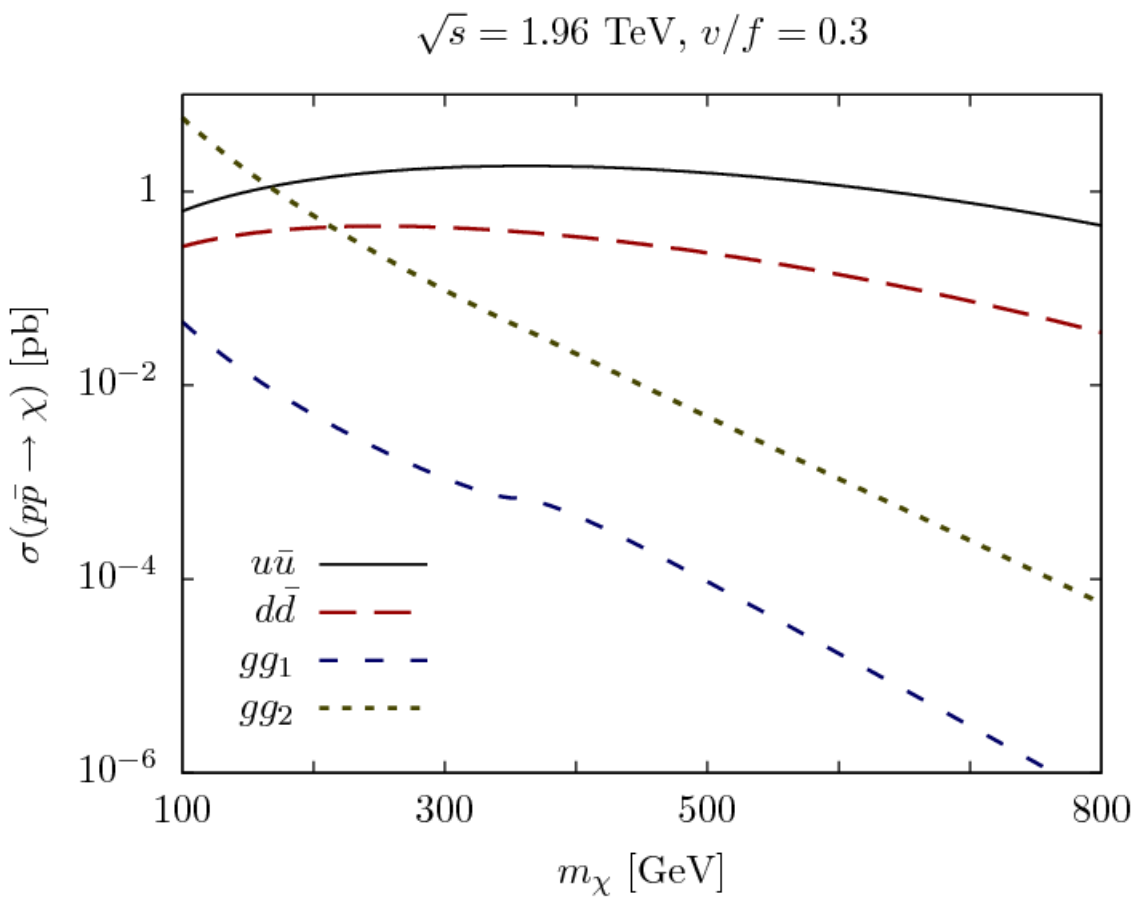
$$+\frac{\bar{\chi}}{f}\left[\frac{\alpha_{EM}}{8\pi}c_{EM}(F_{\mu\nu})^2 + \frac{\alpha_s}{8\pi}c_G(G_{\mu\nu})^2\right]$$

- loop induced couplings to photons and gluons with model-dependent coefficients, possible enhancement for gluons by $\sim$10 over SM Higgs
- here define small breaking parameter $\epsilon \equiv m_\chi^2/f^2$

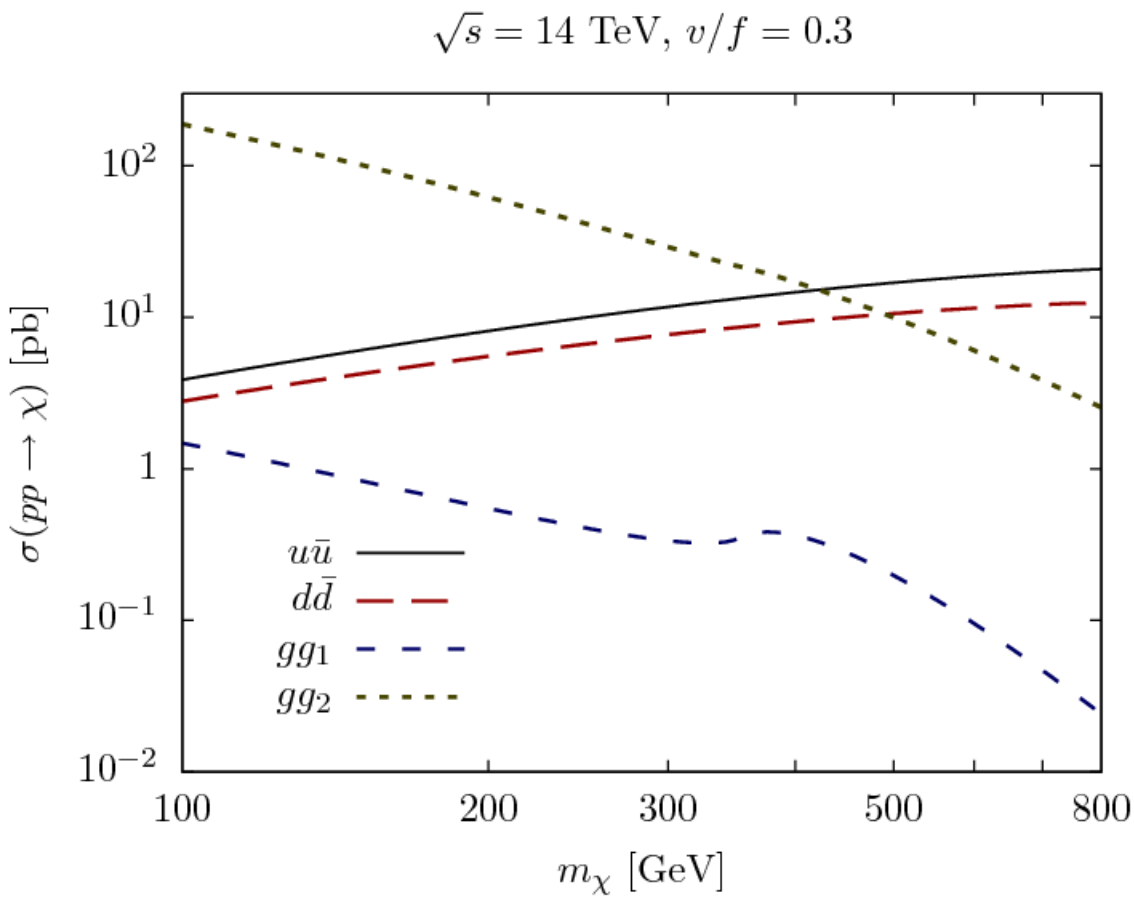
Collider Signatures

- Production cross section at Tevatron



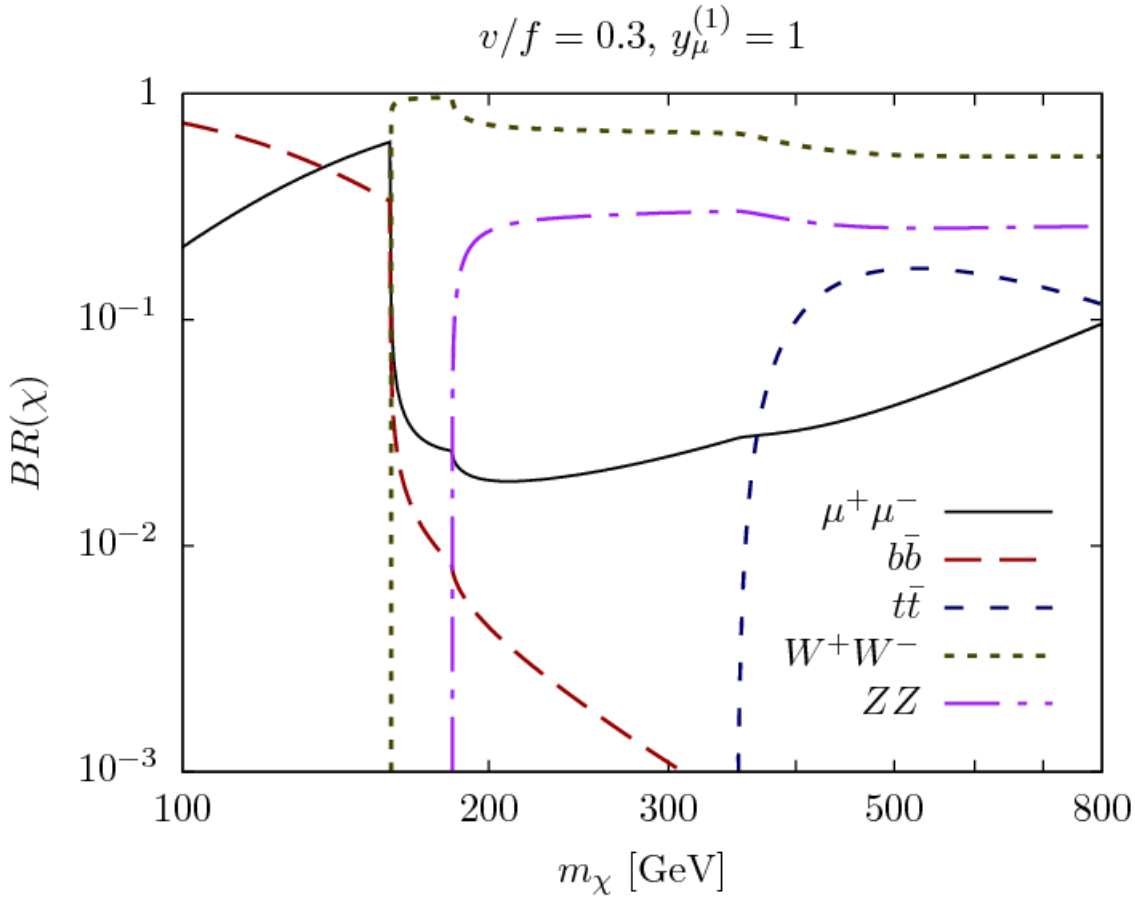
Collider Signatures

- Production cross section at LHC



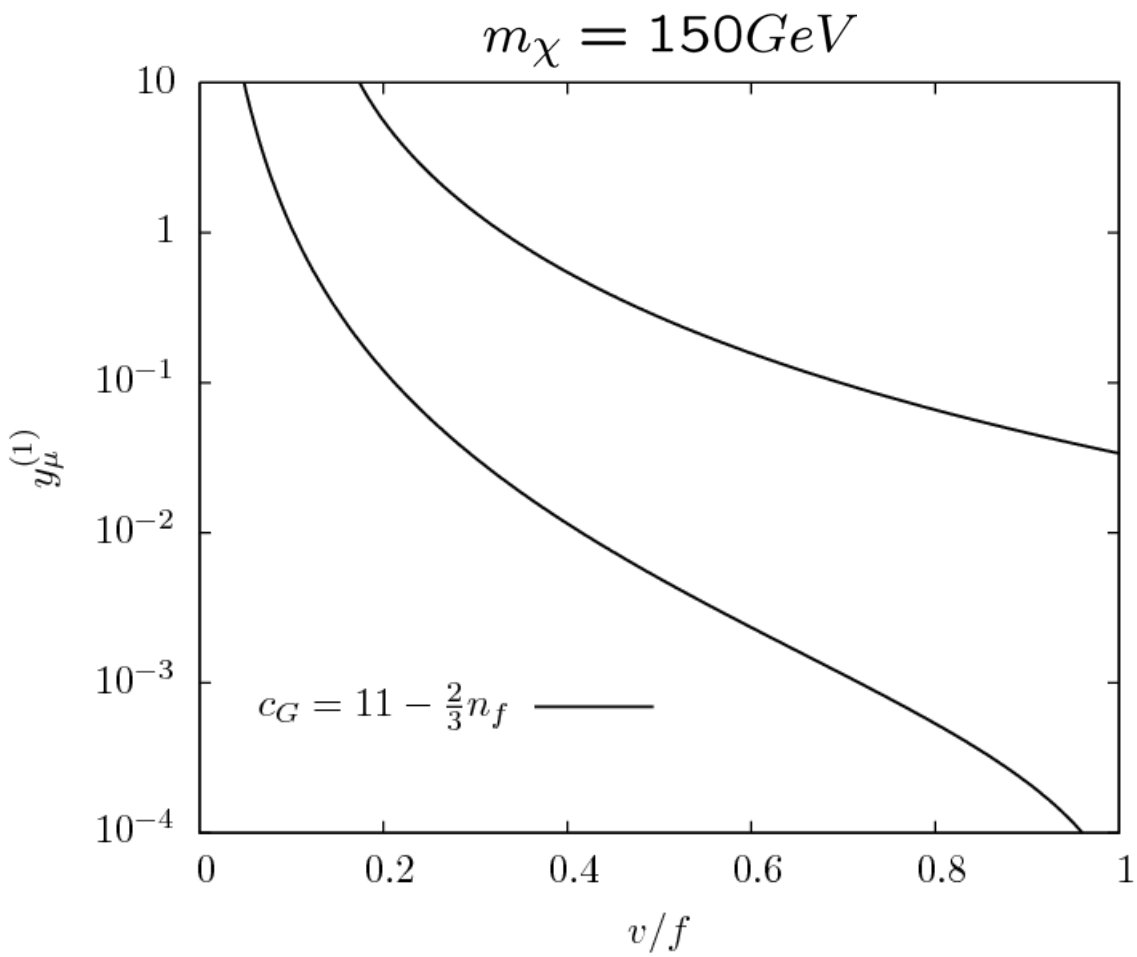
Collider Signatures

- Branching fractions for enhanced muon coupling



Collider Signatures

- Prospect for $gg \to \chi \to \mu^+\mu^-$ detection at LHC



Collider Signatures

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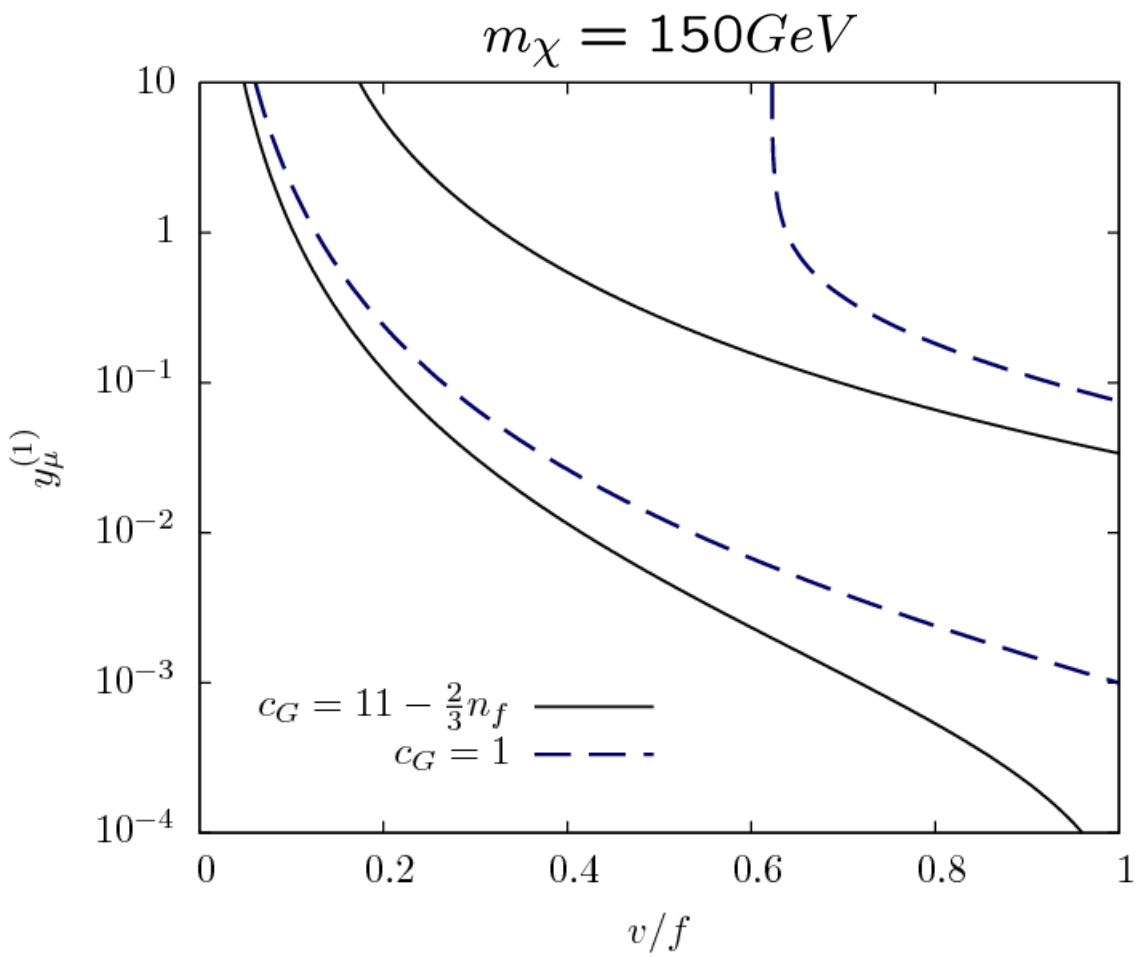


Conclusion

- EWSB from nearly conformal physics is likely to have a light CP-even scalar in spectrum which arises as a pseudo-Goldstone boson of spontaneous breaking of conformal symmetry
- in symmetry limit, dilaton couplings to fermions same as SM Higgs rescaled by v/f
- explicit breaking can significantly change the game for light fermions
- new production channels $u\bar{u},\ d\bar{d} \to \chi$
- new clean signatures $\chi \to \mu^+\mu^-,\ e^+e^-$

Setup Backup

- more on spurion λ
- procedure analogous to introduction of explicit symmetry breaking due to quark masses in χPT

$$\mathcal{L}_{CFT} \to \mathcal{L}_{CFT} + \lambda \mathcal{O}$$

- assign scaling transformation to spurion λ such that symmetry breaking becomes formally invariant: $\lambda \to e^{(4-\Delta)\lambda}\lambda$
- now can form invariant $\lambda\chi^{\Delta-4} = \hat{\lambda}(\chi/f)^{\Delta-4}$ which we can insert to any powers in couplings

Collider Signatures Backup

- Han & McElrath, Phys.Lett.B528:81-85,2002

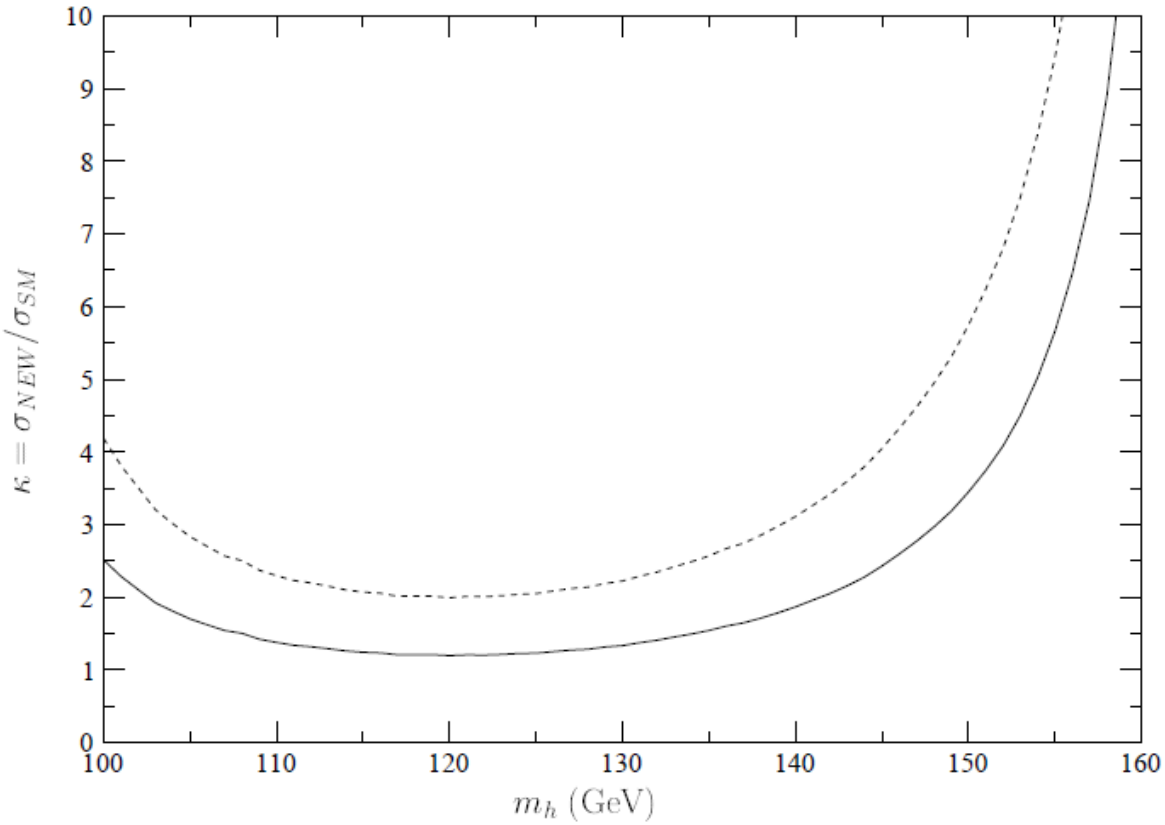
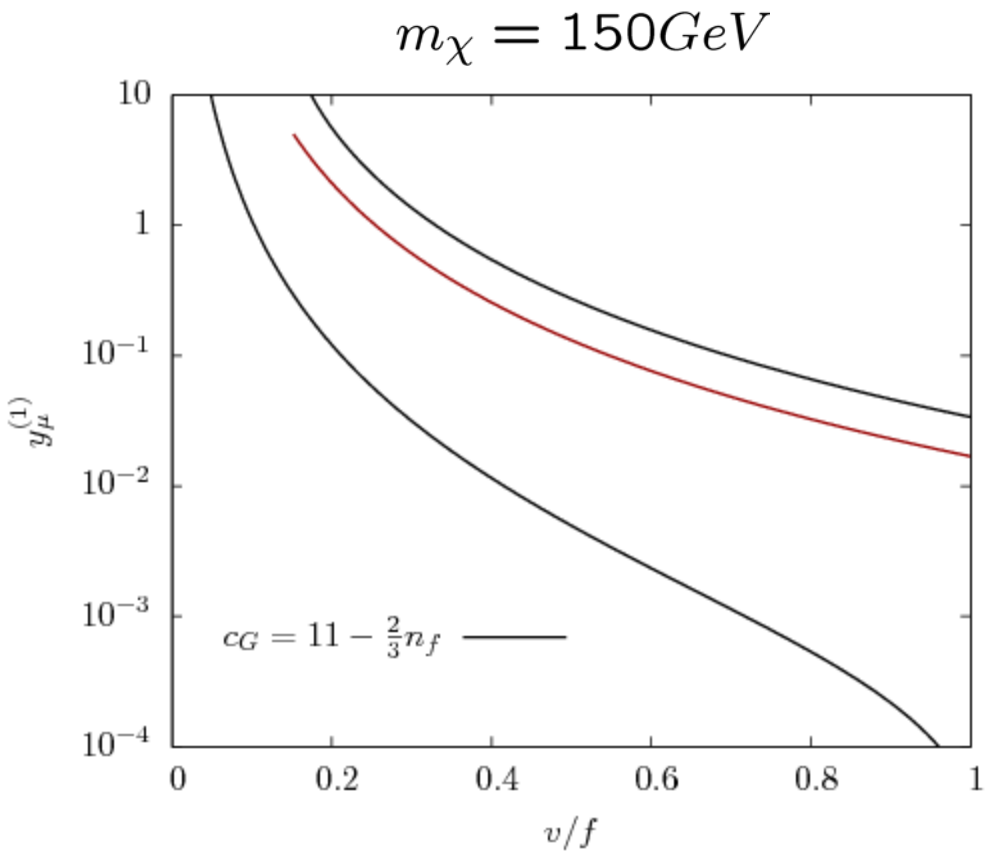


FIG. 1: The enhancement factor κ over the SM rate required to observe the $gg \to h \to \mu^+\mu^-$ signal at the 3σ (solid) and 5σ (dashed) level with 300 fb^{-1} delivered luminosity, including both the ATLAS and CMS detectors.

Collider Signatures Backup

- Updated CDF dimuon data arXiv:0811.0053



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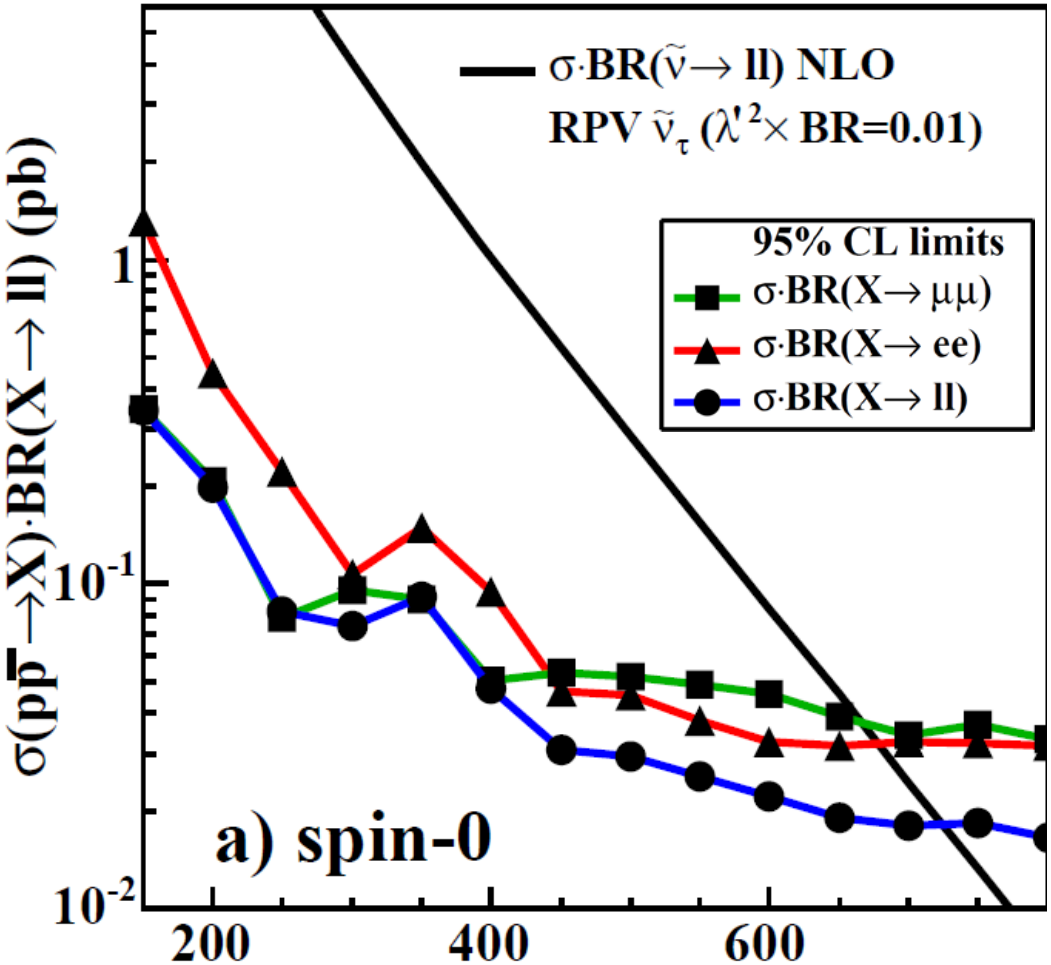
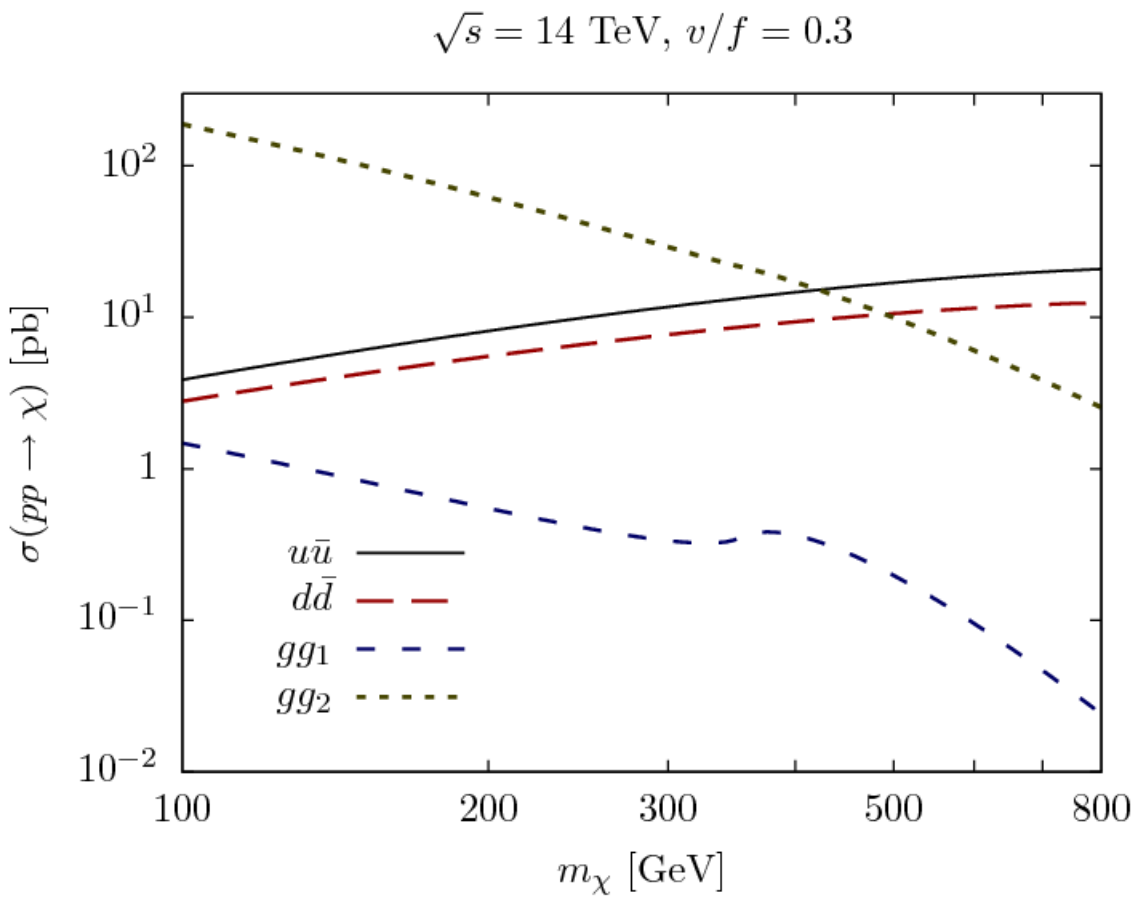
- CDF Collaboration, PRL 95 (2005) 25200



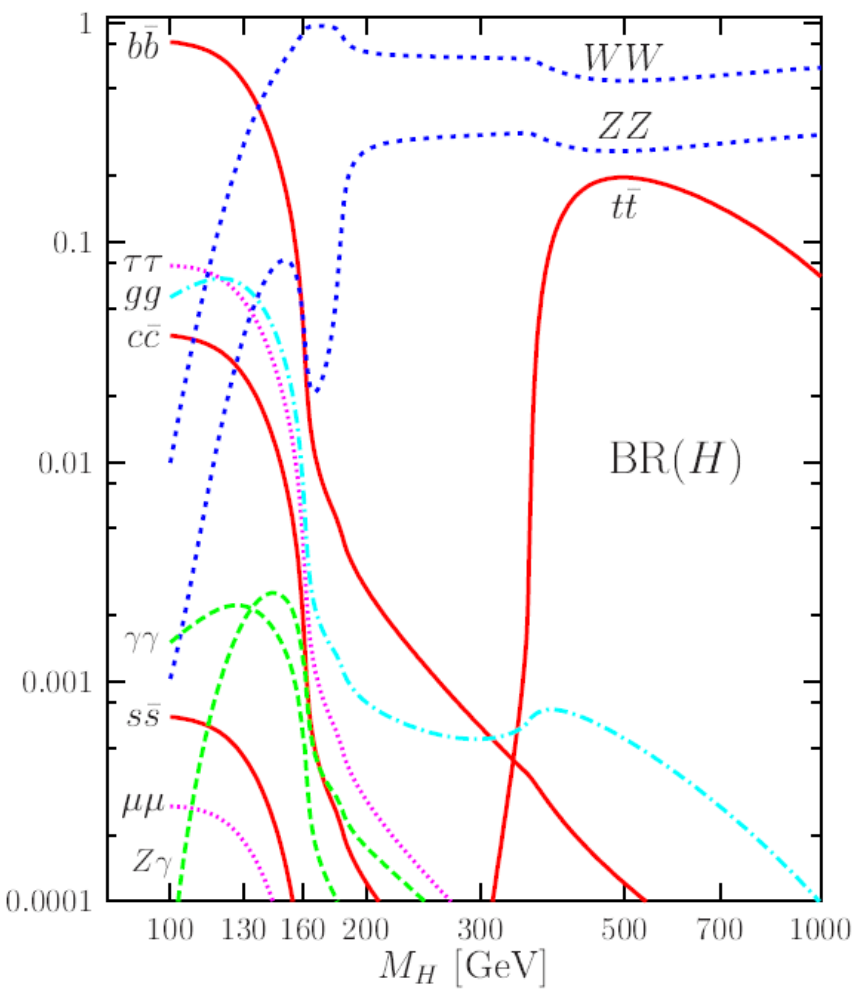
Collider Signatures Backup

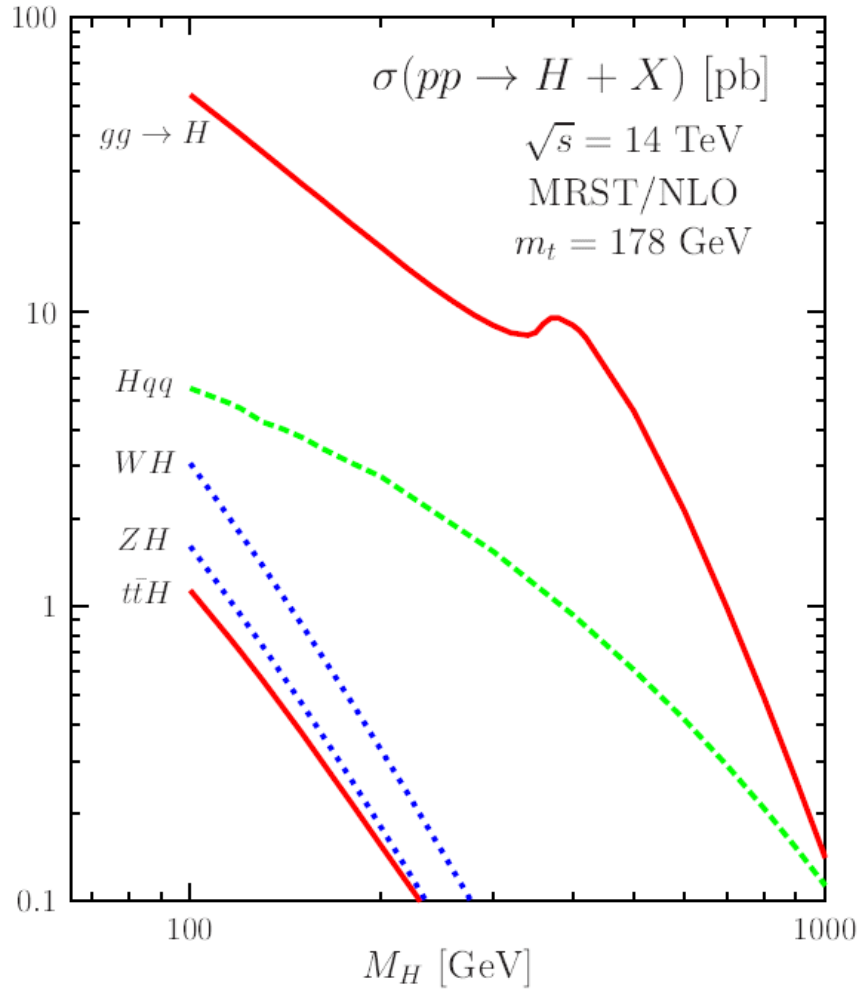
- Production cross section at LHC



Collider Signatures Backup

- Higgs for comparison





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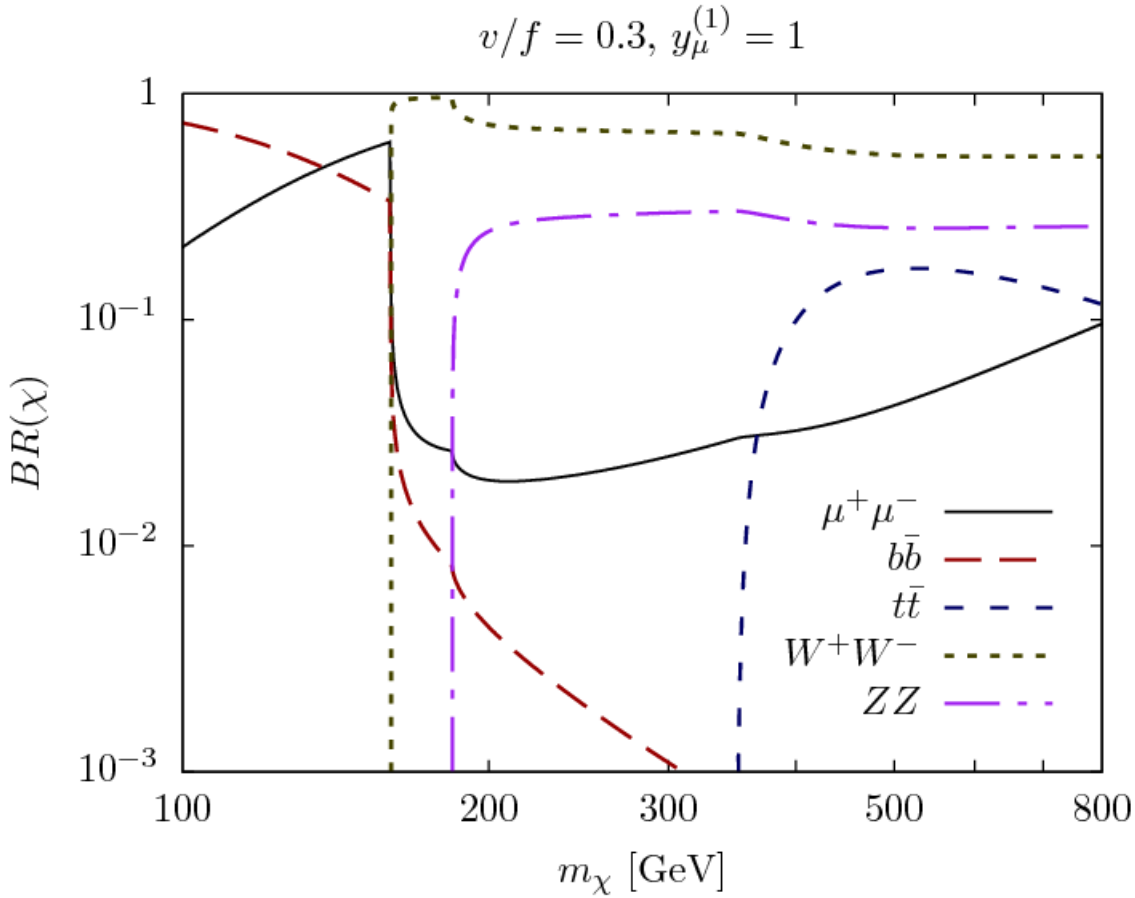
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