The Composite Nambu-Goldstone Higgs

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Natural or Unnatural ?

One sure goal of the LHC is to answer the question:
"Is EWSB scale Natural of Fine-tuned?"

$$\Delta \geq \frac{\delta m_H^2}{m_H^2} \simeq \left(\frac{126\ \mathrm{GeV}}{m_h}\right)^2 \left(\frac{M_P}{500\ \mathrm{GeV}}\right)^2$$

M_P = New Physics (Top Partners) scale

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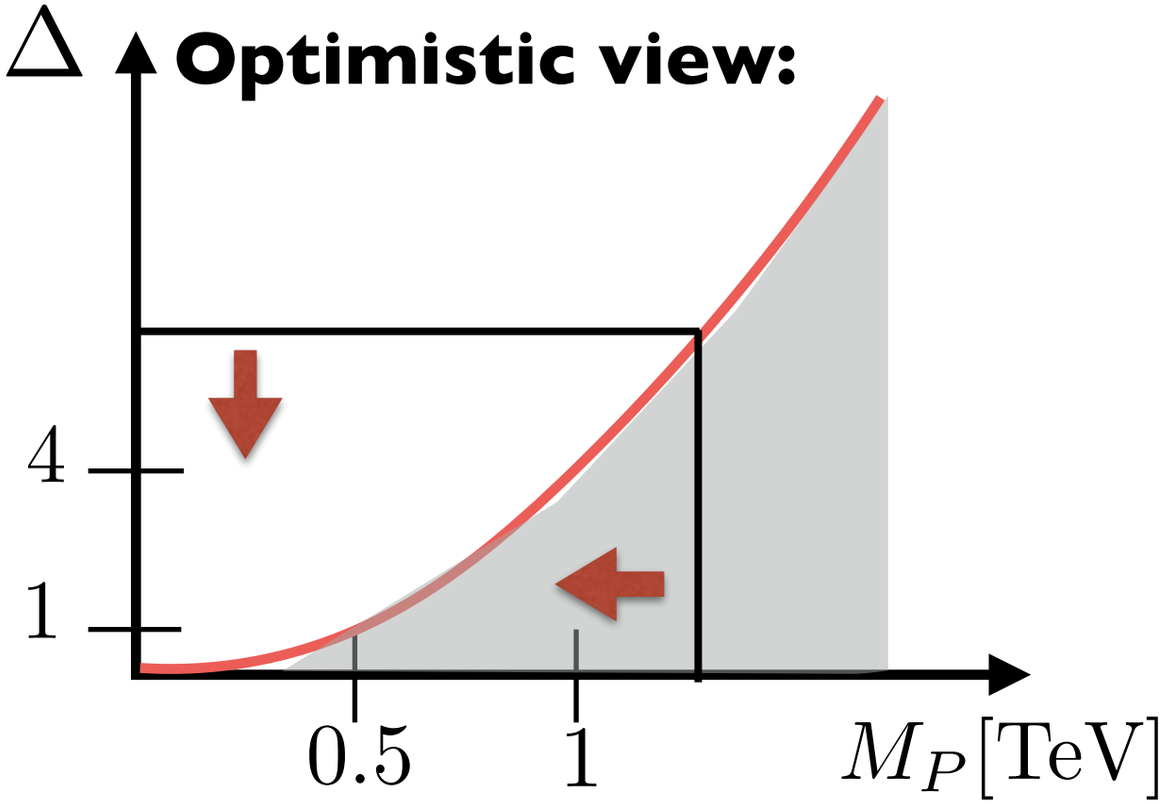

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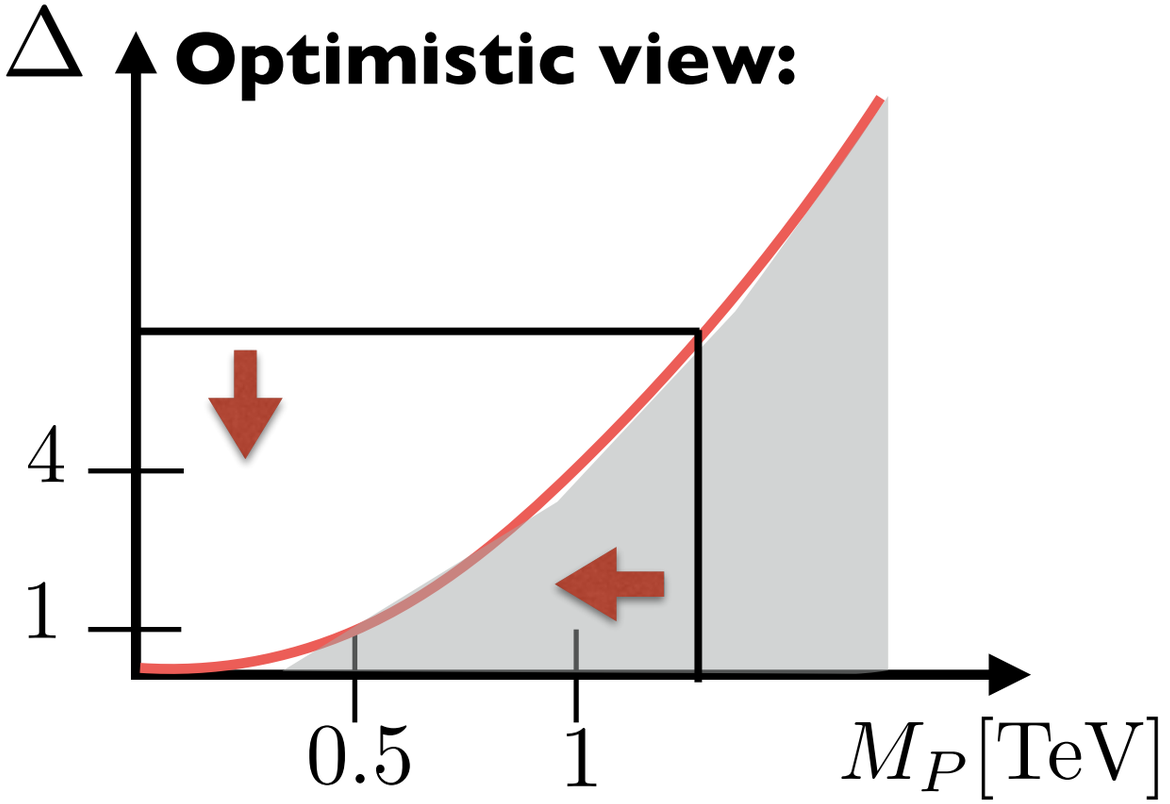

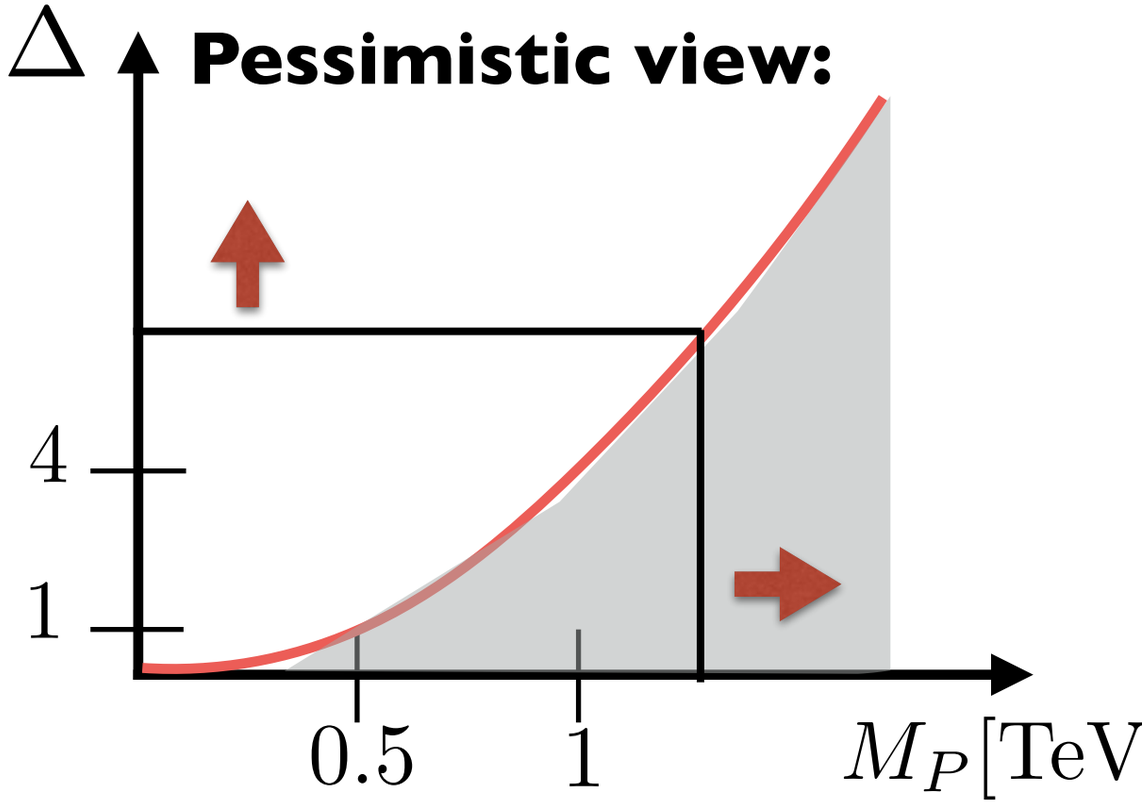

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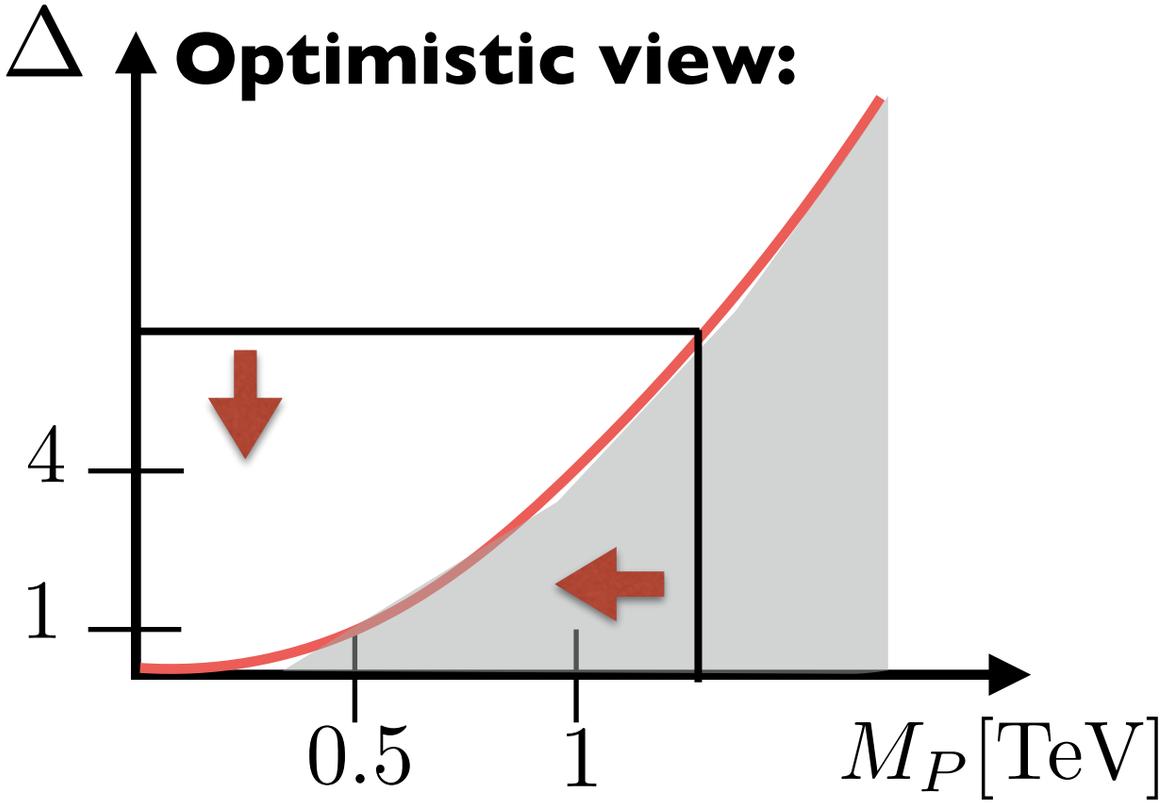
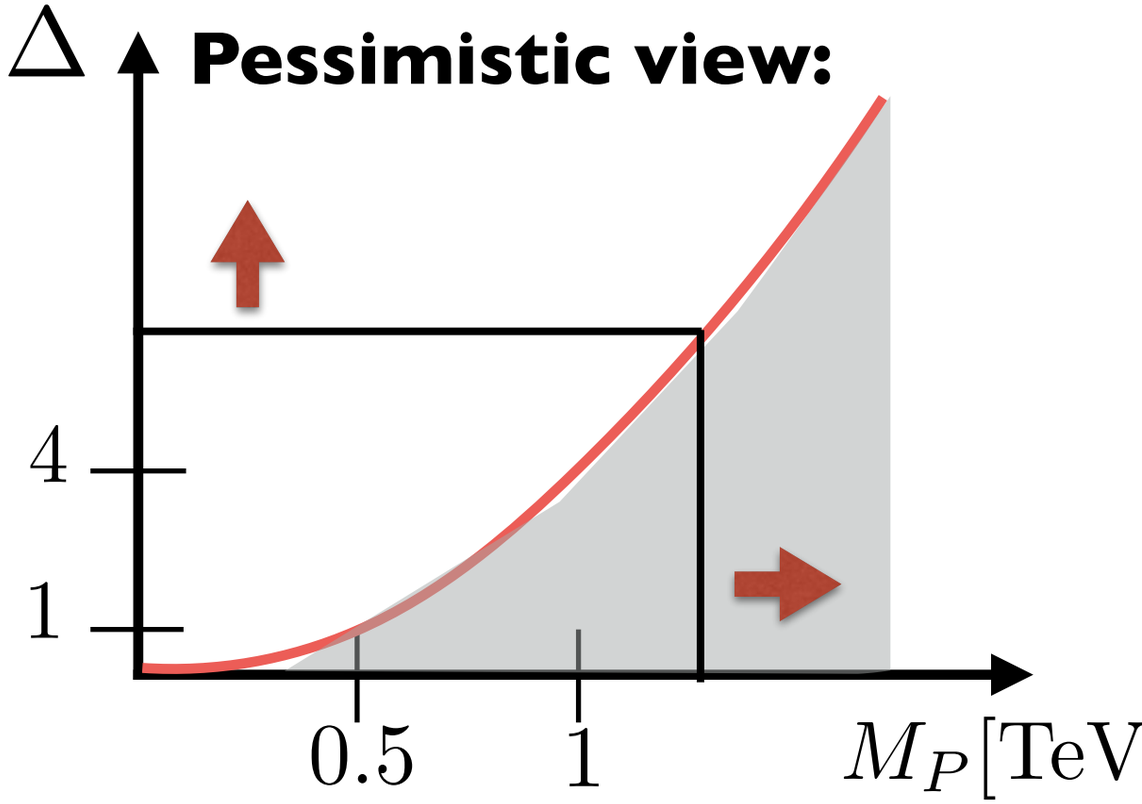




In both cases we will learn something!

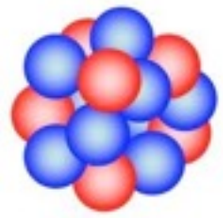
Composite Higgs

Composite Higgs scenario:

1. Higgs is **hadron** of **new strong force**

Corrections to m_H screened above $1/l_H$

The **Hierarchy Problem** is **solved**



l_H

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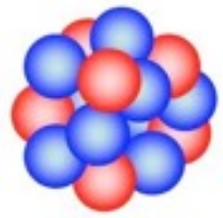

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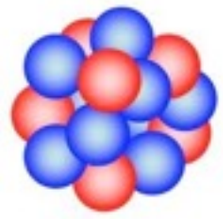

l_H

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Indirect effects from sigma-model couplings

A) Corrections to SM:

$[\mathcal{O}(v^2/f^2) \lesssim 20\%]$

- Higgs Br. Ratios
- Higgs Production

B) New Non-ren. Couplings:

- e.g. $gg \to hh$

Indirect, but "direct" (robust) signature of compositeness

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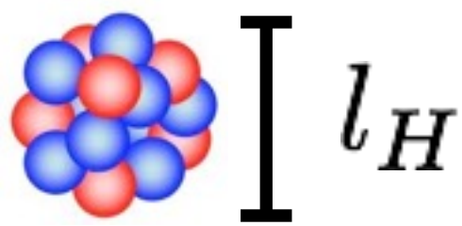

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3. Partial Fermion Compositeness: linear coupling to strong sector

Composite Sector

$$\mathrm{SO}(5) \to \mathrm{SO}(4)$$

$$H \in \mathrm{SO}(5)/\mathrm{SO}(4)$$

$\mathcal{L}_{\rm int}$

Elementary Sector

$$W_\mu^{1,2,3},\ B_\mu$$

$$f_L,\ f_R$$

gauge: $\mathcal{L}_{\rm int} = g J_\mu W^\mu$

fermions: $\mathcal{L}_{\rm int} = y_L q_L \mathcal{O}_L + y_R q_R \mathcal{O}_R$

Composite Higgs

Low energy Higgs physics from **symmetries**

$$\mathcal{L}_\pi = \frac{f^2}{4} d^i_\mu d^\mu_i = \frac{1}{2}(\partial h)^2 + \frac{g^2}{4} f^2 \sin^2 \frac{h}{f} \left(|W|^2 + \frac{1}{2c_w^2} Z^2 \right)$$

$$g_{HVV} = i \frac{g^2}{4} v \sqrt{1-\xi} \qquad \xi \equiv \frac{v^2}{f^2} = \sin^2 \frac{\langle h \rangle}{f}$$

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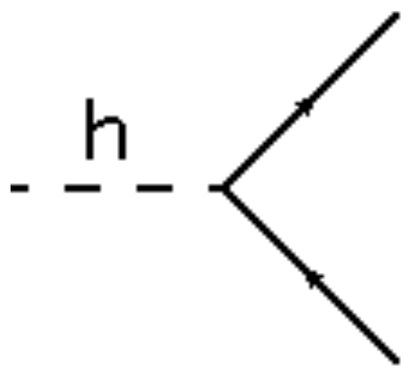
Fermion couplings are less sharply predicted.



$$= i \frac{m_f}{v} c$$

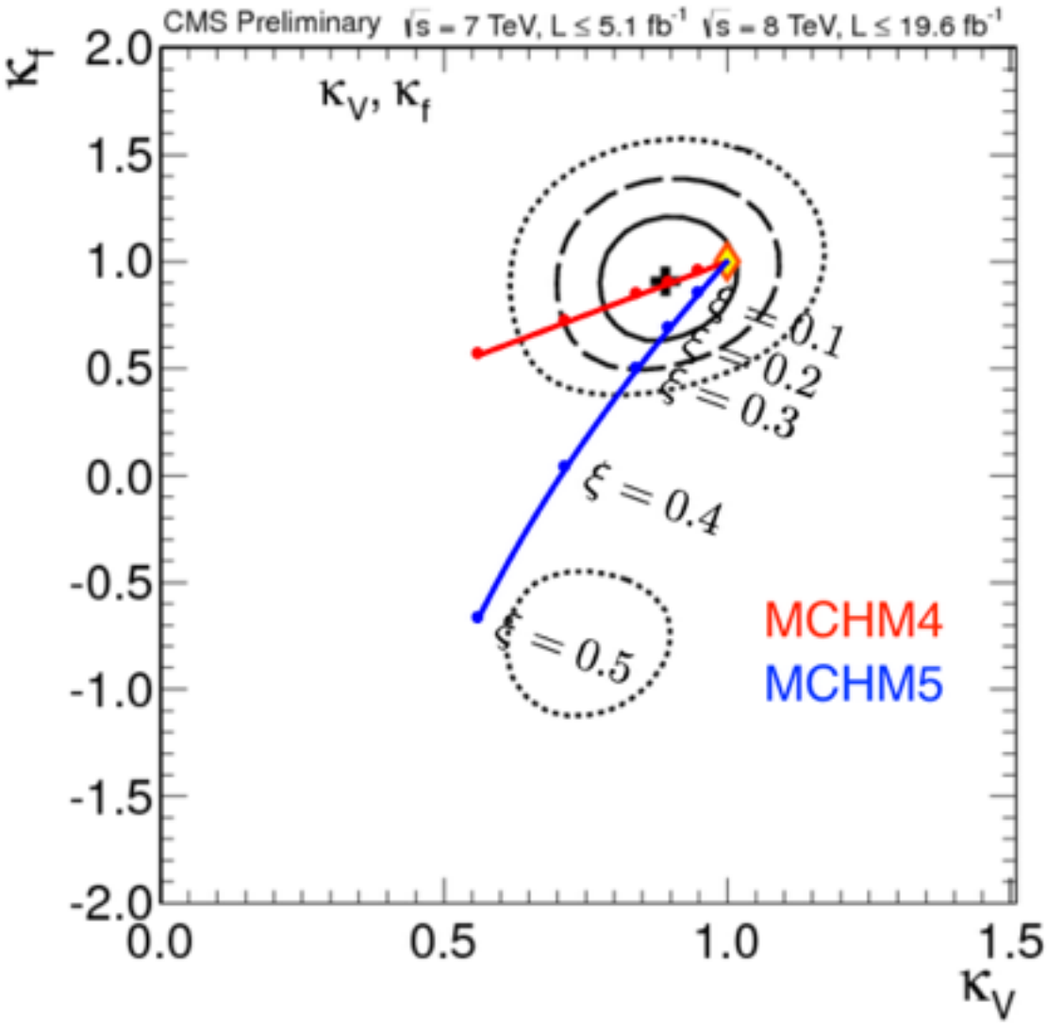
MCHM_5	$c = \dfrac{1-2\xi}{\sqrt{1-\xi}}$
MCHM_4	$c = \sqrt{1-\xi}$
MCHM_{10}	$\cdots$

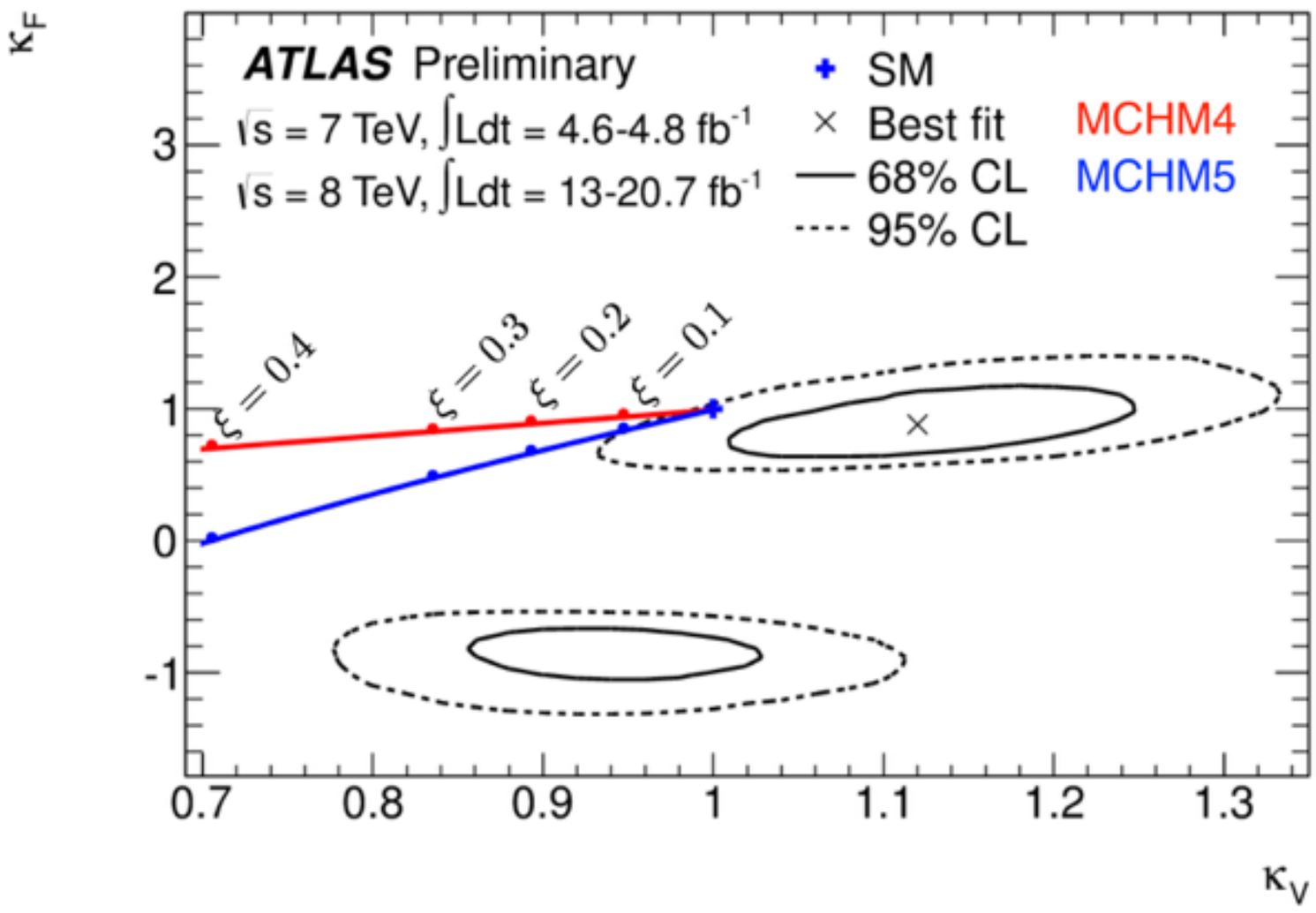
Do depend on fermionic operator representations

Composite Higgs

courtesy of R. Torre

A rough comparison with data:





Higher order effects, from resonances exchange, should be also taken into account

Top Partners

In the IR, fermionic operators correspond to particles:

$$\langle 0|\mathcal{O}|Q\rangle \neq 0 \qquad \mathcal{O}_{L,R} \leftrightarrow Q_{L,R}$$

$\mathcal{O}$ and Q **carry color !**

$Q =$ "vector-like colored fermions" (partners)

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$\mathcal{L}_{\rm int} = y_L q_L \mathcal{O}_L + y_R q_R \mathcal{O}_R$ gives a **mass-mixing** in the IR:

$$\mathcal{L}_{mass} = m_Q^* \overline{Q} Q + y\, f \bar{q} Q$$

physical particles are **partially composite**

$$|SM_n\rangle = \cos\phi_n |elementary_n\rangle + \sin\phi_n |composite_n\rangle$$
$$|BSM_n\rangle = \cos\phi_n |composite_n\rangle - \sin\phi_n |elementary_n\rangle$$

$$\tan\phi_n = \frac{yf}{m_Q^*}$$

Top Partners

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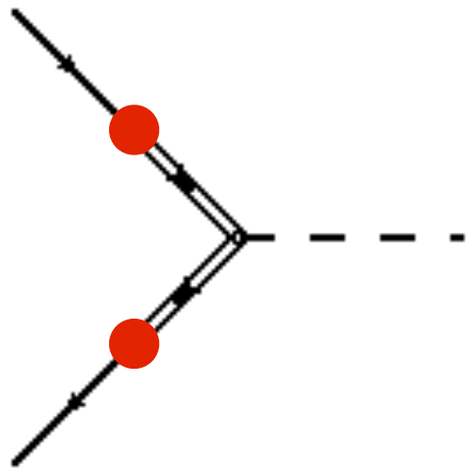
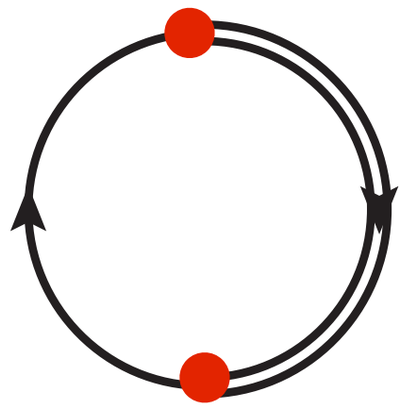
P.C. generates **Yukawas** ...

$y_f =$



... and the **Higgs Potential**



Top loop dominate because the top is largely composite.

Top Partners

Top partners cancel m_H divergence, thus are **directly bounded** by Naturalness

$$\Delta \geq \frac{\delta m_H^2}{m_H^2} \simeq \left(\frac{125\ \mathrm{GeV}}{m_H}\right)^2 \left(\frac{M_P}{400\ \mathrm{GeV}}\right)^2$$

SUSY:

light stops

Composite Higgs:

light fermionic partners

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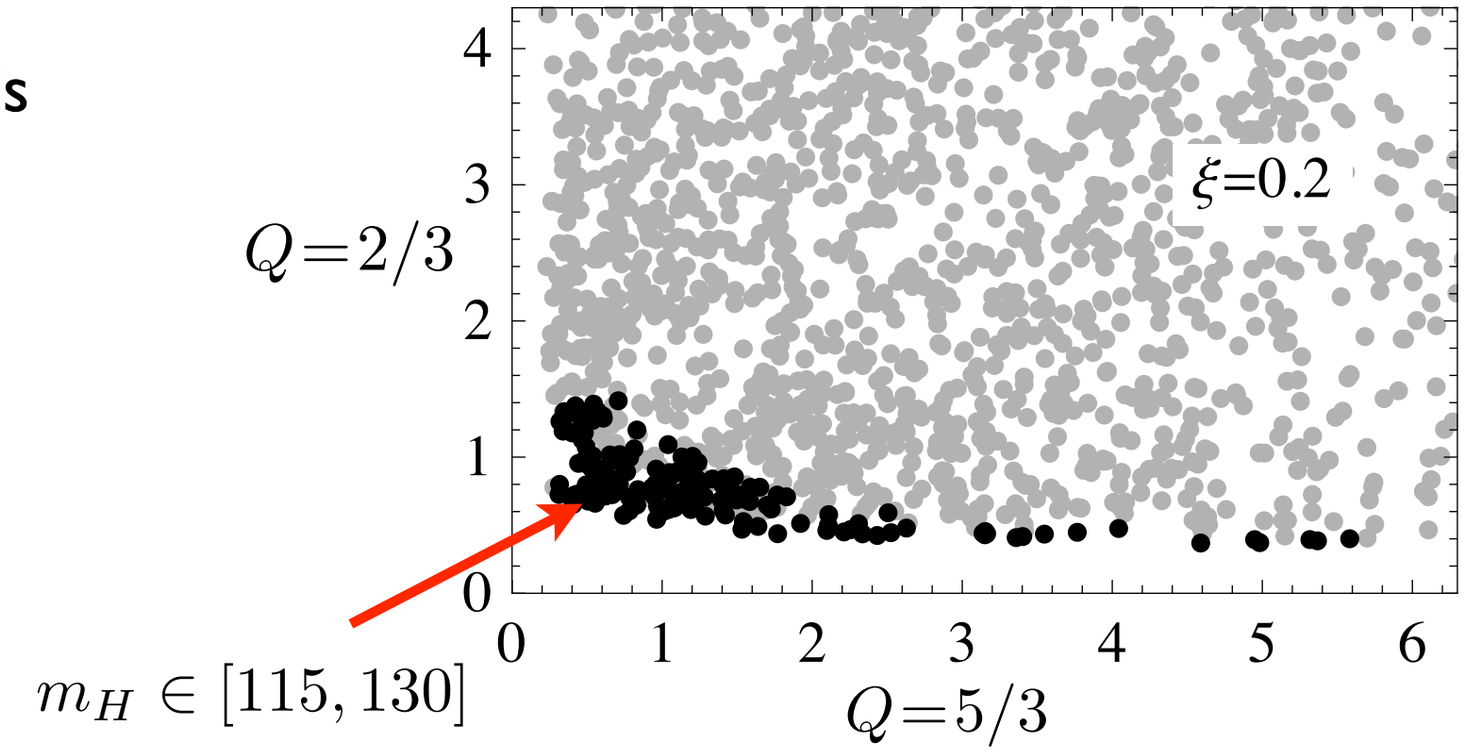
In a class of explicit CH models

$$\text{MCHM}_{4,5,10}$$

$\xi = 0.2$: (low tuning)



Light Higgs plus **Low Tuning** need **Light Partners**

(Matsedonsky,i Panico, AW 2012)

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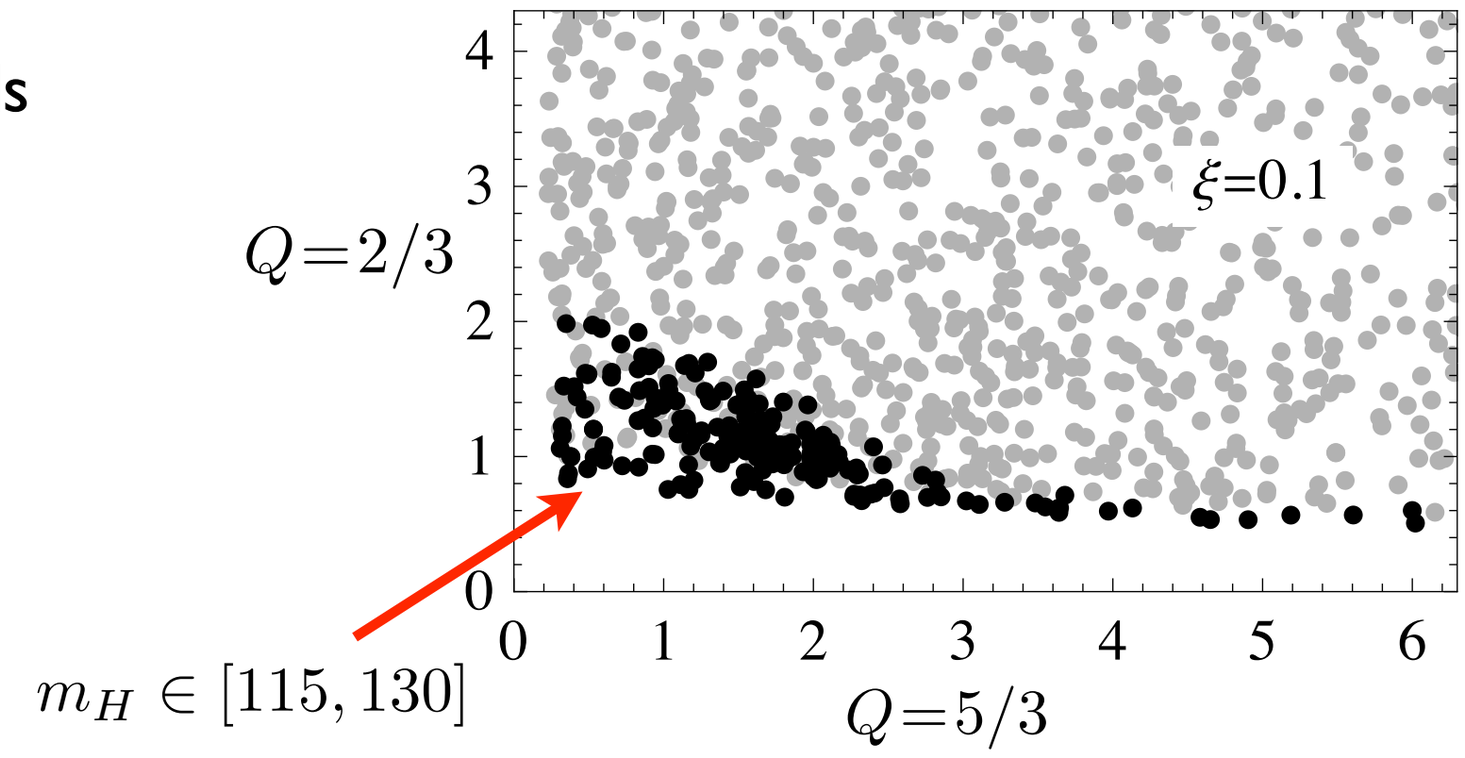
In a class of explicit CH models

$\text{MCHM}_{4,5,10}$

$\xi = 0.1$: (larger tuning)



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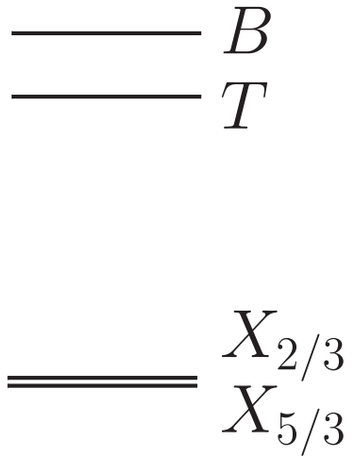
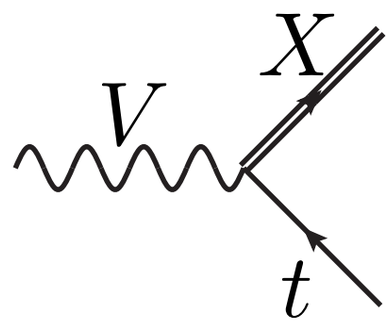
Top Partners

Fourplet of custodial $\mathrm{SO}(4)$ $\begin{pmatrix} T & X_{5/3} \\ B & X_{2/3} \end{pmatrix}$

Spectrum:



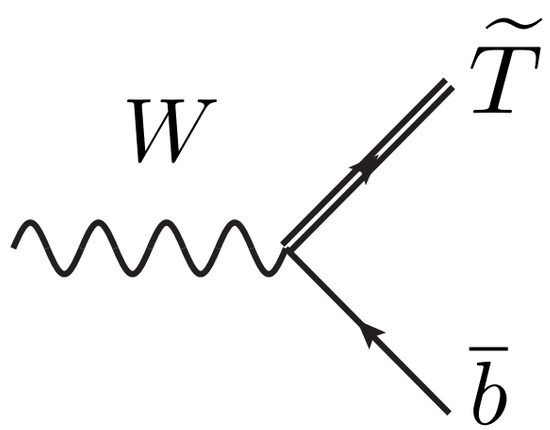
Couplings:



$\sim M_X/f$

because Goldstones are derivatively coupled

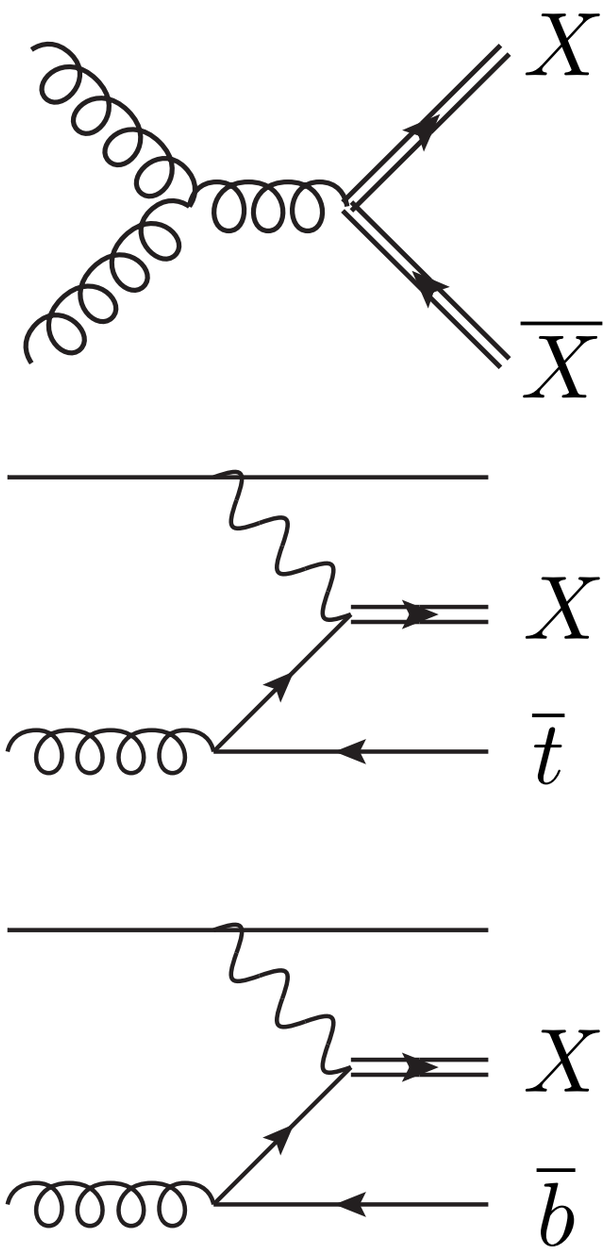
Singlet of custodial $\mathrm{SO}(4)$ $\widetilde{T}$



sizeable coupling to bottom quark

Top Partners

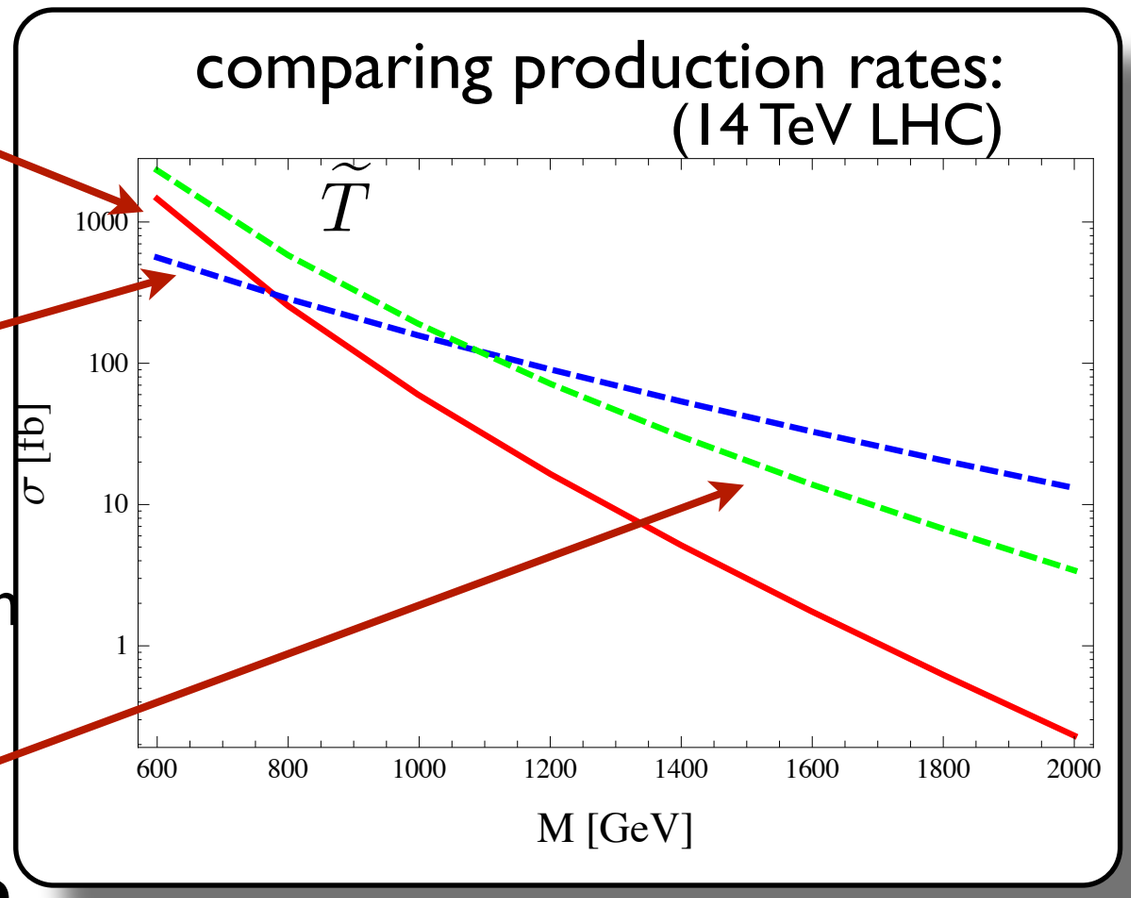
Three possible production mechanisms



QCD **pair prod**.
model indep.,
relevant at low mass

single prod. with **t**
model dep. coupling
pdf-favoured at high m

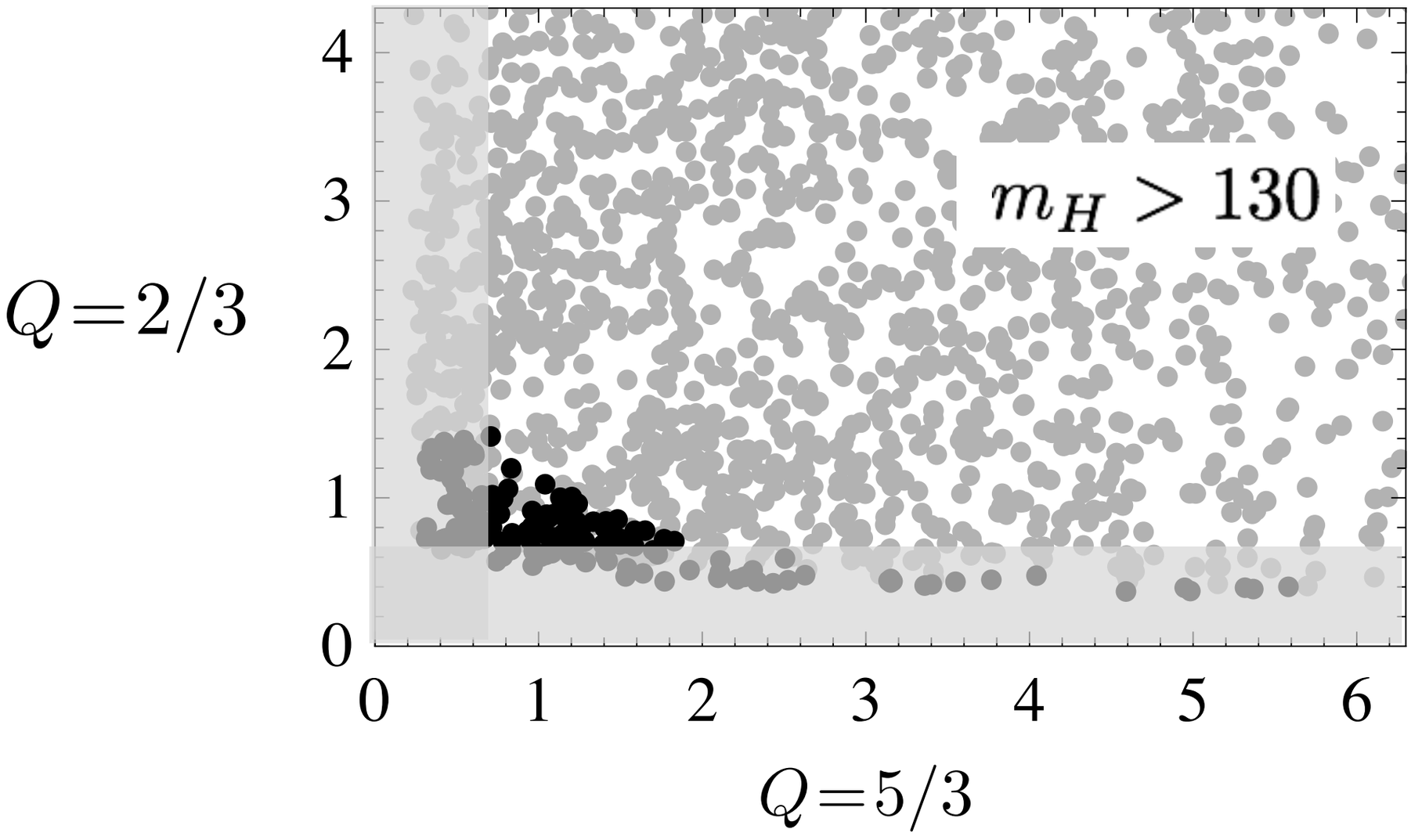
single prod. with **b**
favoured by small b mass
dominant when allowed



Top Partners

Current limits (rough):

$\xi = 0.2$



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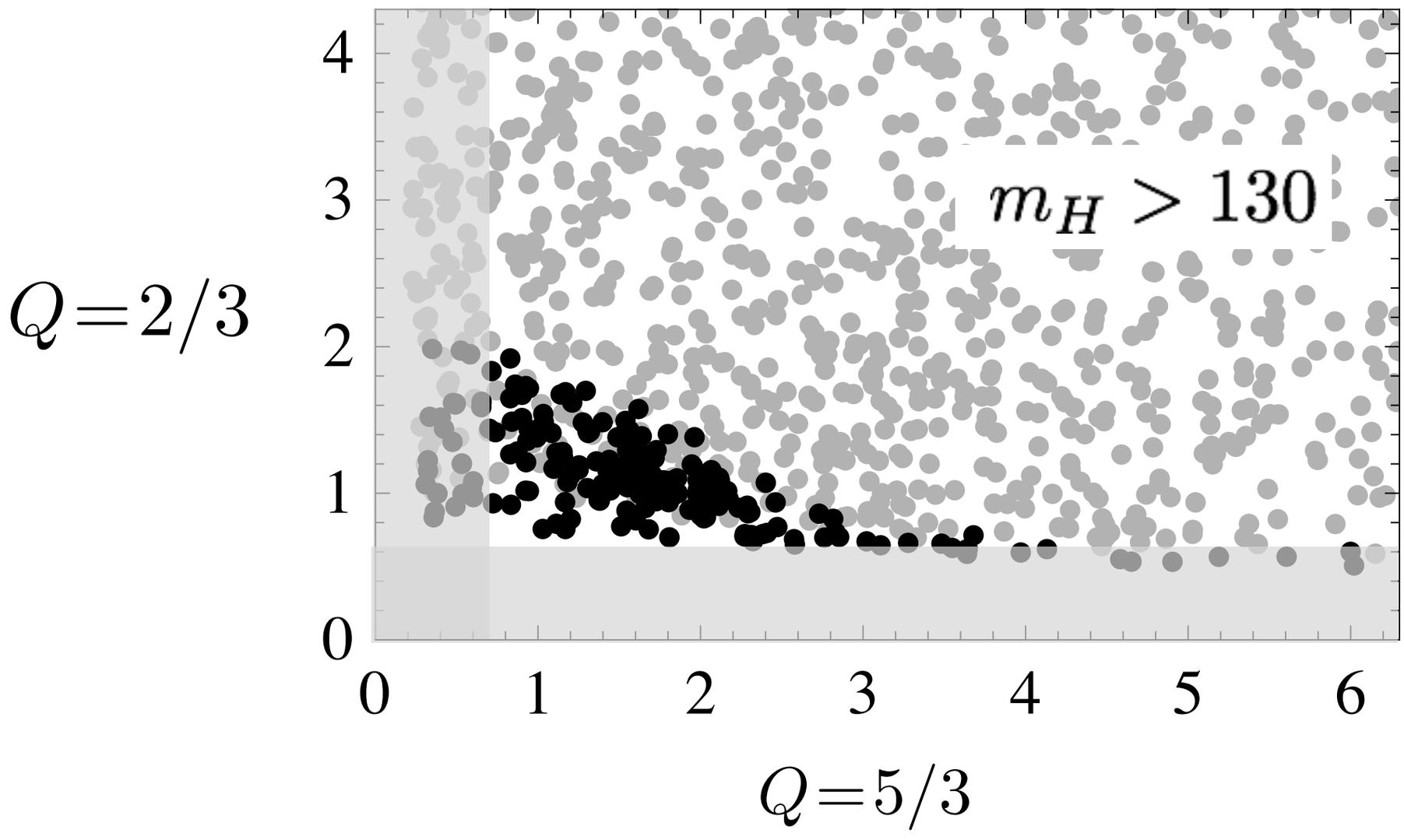

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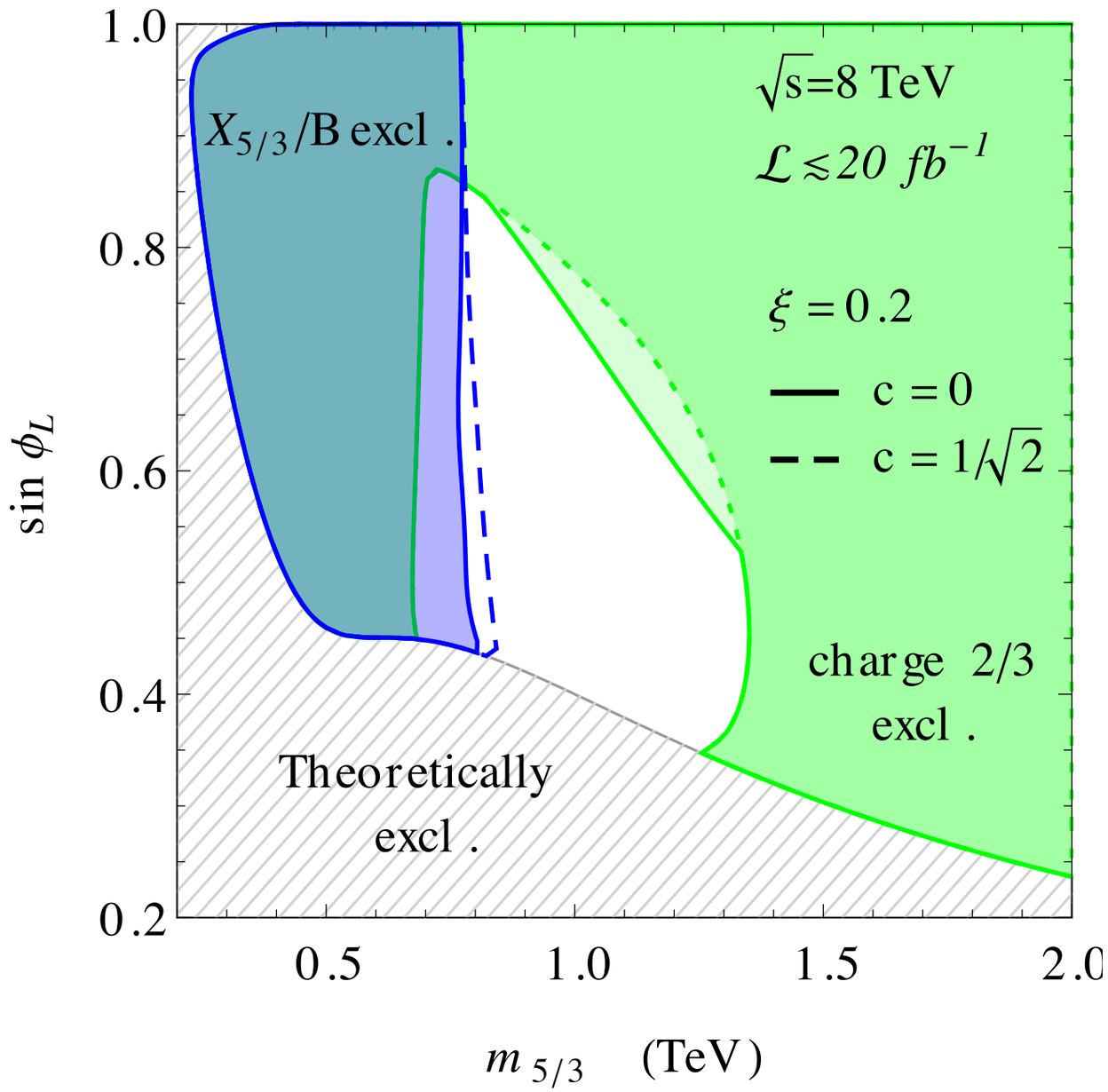
Current limits, simplified model approach:



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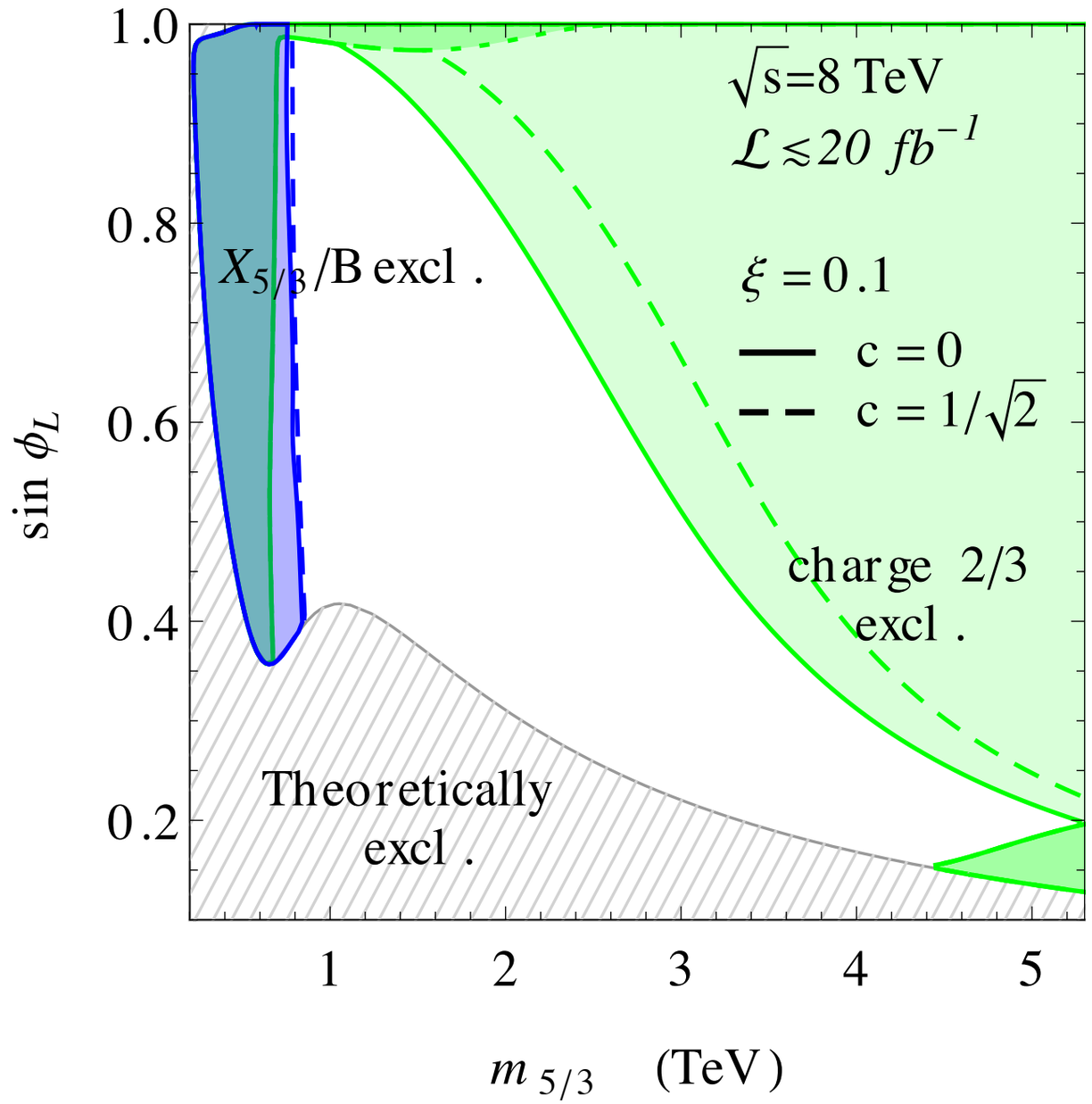

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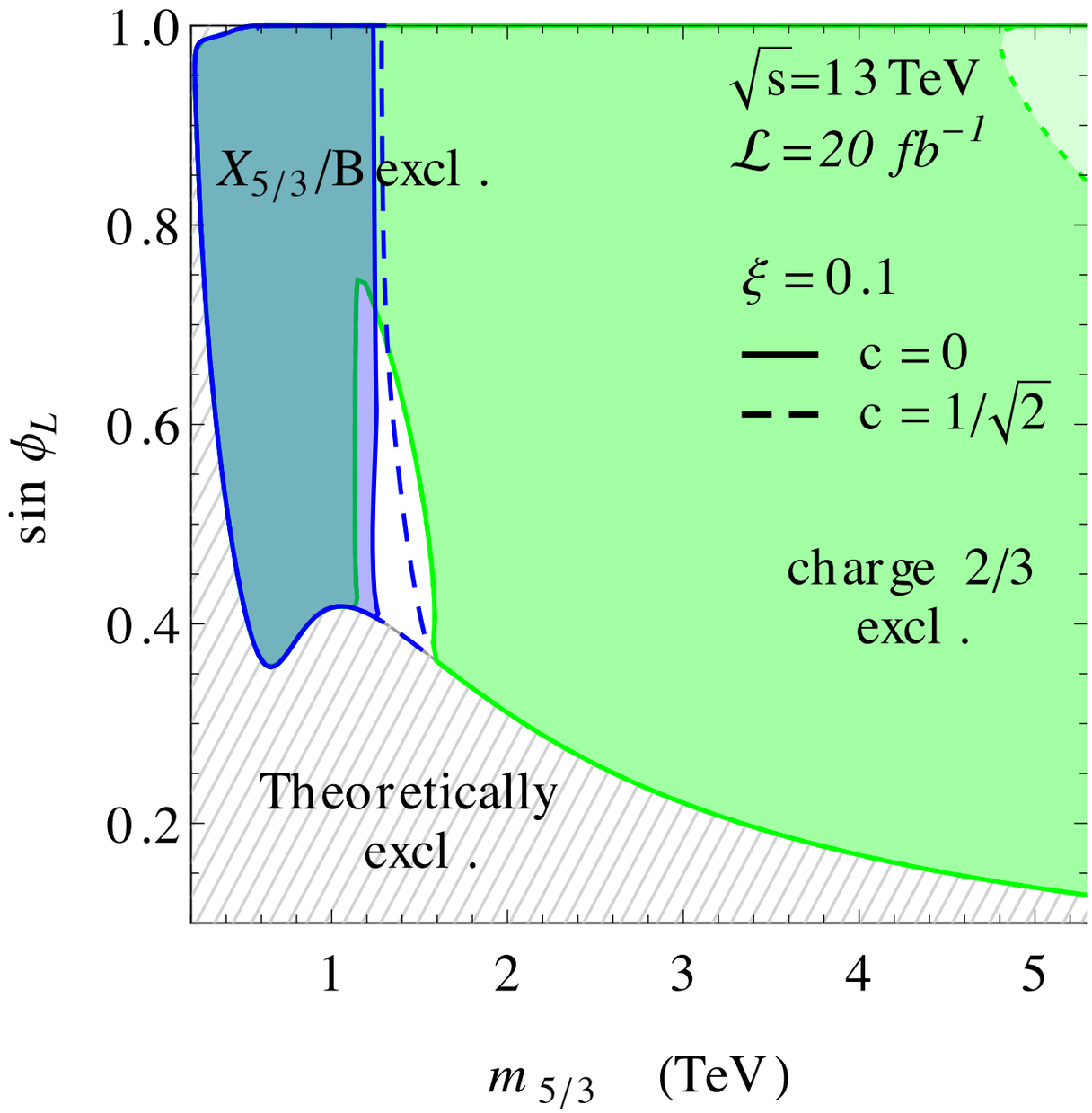

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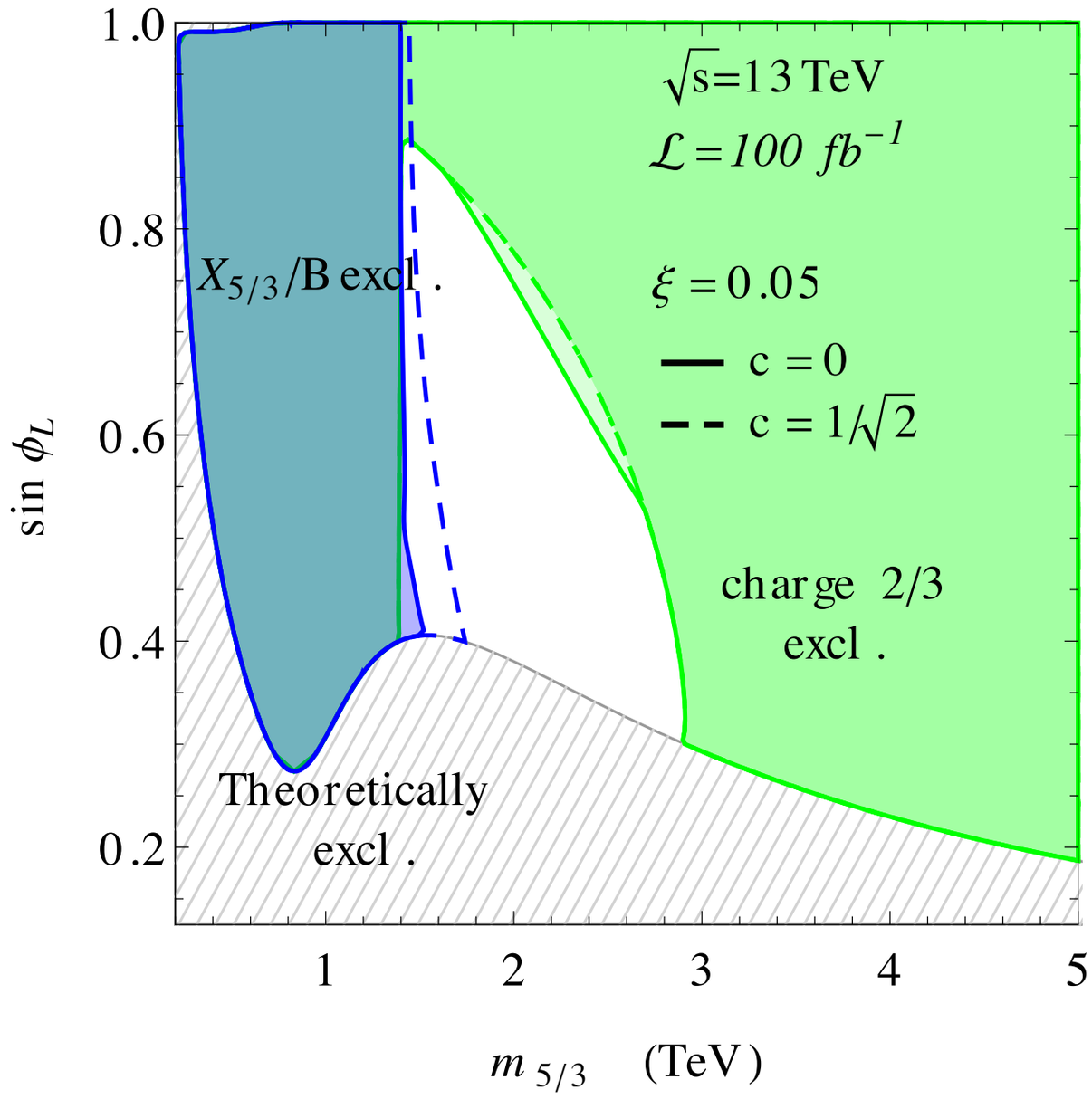

Conclusions and Outlook

- Composite Higgs is the perfect benchmark for present and future studies of Higgs couplings modifications

- Important playground for (Un-)Naturalness tests from fermionic Top Partner searches

- Direct searches win over coupling determinations

- Much to be learned (on both) from the 13 TeV run!

Backup

Reach on CH vectors