Strong Signatures of Right-Handed Compositeness

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work in collaboration with

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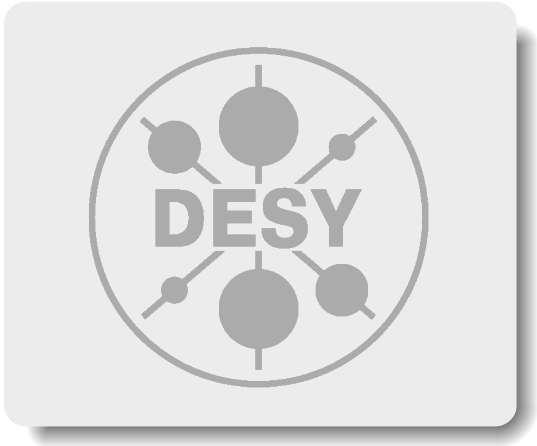


Introduction

Nature of the Higgs?

The Higgs may very well be composite

- How do we satisfy EWPT and flavour?
- Which additional particles show up?

Motivation

Hierarchy Problem & Dynamical Origin of EWSB

two big questions in particle physics

Weakly coupled solutions

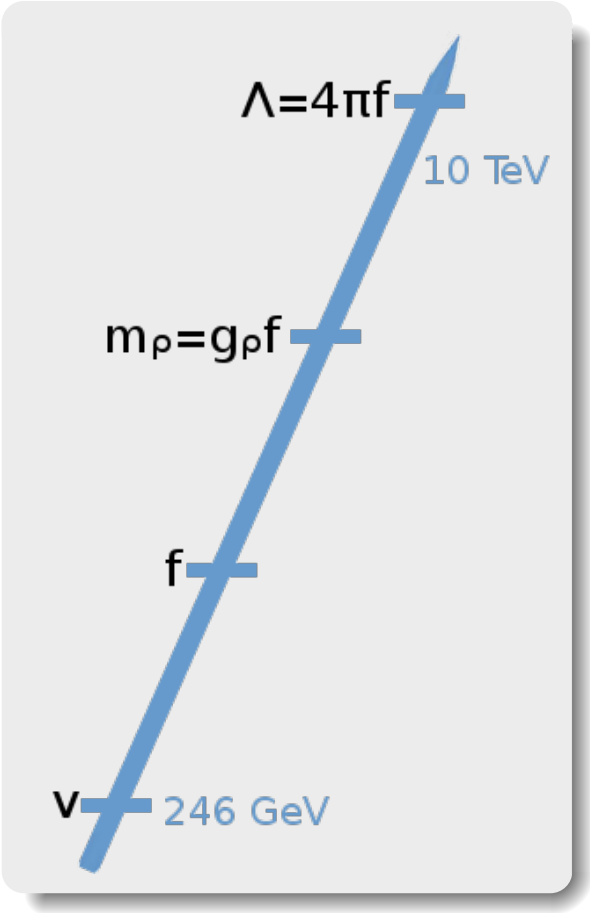
- example: low energy Supersymmetry

Strongly coupled solutions

- examples: Technicolor, Little Higgs, Composite Higgs

Composite Higgs

- Naturally describes a light Higgs without any further resonances at the weak scale, corresponding to LHC results so far



Composite Higgs

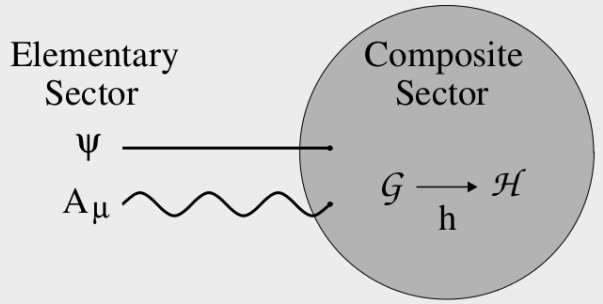
Higgs is a GB from the strong sector

[Georgi, Kaplan]

Global symmetry $\mathcal{G}$ spontaneously broken to $\mathcal{H}$

simplest custodial example

$SO(5)/SO(4) \Rightarrow 4$ GB's $\Leftrightarrow$ Higgs doublet



- Couplings between elementary and strong sector break G slightly
- Higgs is a **pseudo Goldstone boson**, like the pions in QCD
- Makes the Higgs naturally lighter than other resonances

- Electroweak symmetry breaking is radiatively induced
- Corrections to EW observables are suppressed by $\xi = (v/f)^2$
- Strong sector usually contains a towers of resonances

Flavour Problems

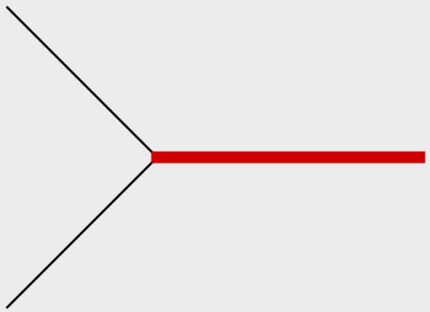
Scaling of Operators

- **Higgs:** $\Lambda^2 H^\dagger H$
- **Yukawa:** $\frac{1}{\Lambda^{\dim H-1}} y_{ij} \bar{\psi}_i H \psi_j$
- **Flavour:** $\frac{1}{\Lambda^2} c_{ijkl} \bar{\psi}_i \psi_j \bar{\psi}_k \psi_l$

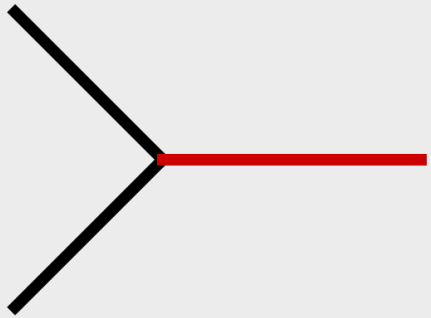
Possible Tension

- **Natural SM:** $\Lambda \approx 1\ \mathrm{TeV}$ flavour is problematic
- **Technicolor:** $\dim \langle \bar{\psi}\psi \rangle \approx 3$ tension with top mass
- **Composite Higgs:** $\dim H \gtrsim 1$

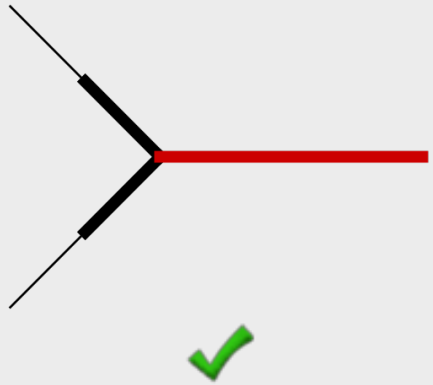
Technicolor



Total Compositeness



Partial Compositeness



Partial Compositeness

Partial Compositeness

[Kaplan; Gerghetta et al.; Contino et al.; ...]

Combine the elementary and the strong sector via mass mixing

Elementary Sector

Massless SM Lagrangian (only gauge bosons and fermions)

Composite Sector

EFT of strong sector (lightest SM resonances + Higgs)

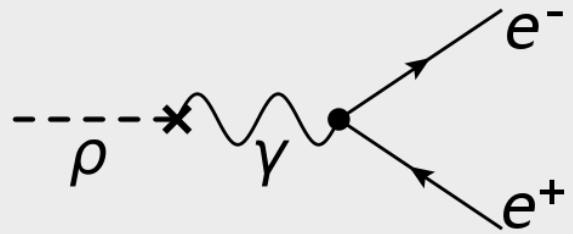
Mixing Sector

Linear mixing: $\mathcal{L}_{\text{mix}} \supset -M^2 \, \frac{g_{\text{el}}}{g_\rho} \, A_\mu \rho_\mu + (\bar{q}_L \Delta Q_R + \text{h.c.})$

Mixing & Flavour

Photon-ρ Mixing

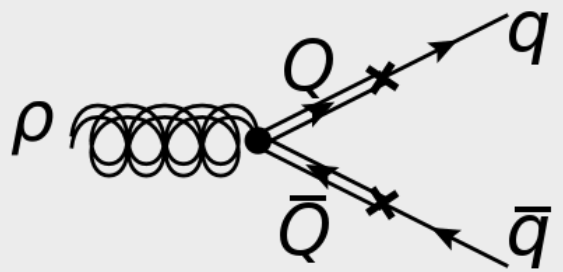
Analogous to QCD, where the photon remains massless



Fermion mixing

$$\begin{pmatrix} q_L^{\mathrm{SM}} \\ Q_L^{\mathrm{par}} \end{pmatrix} = \begin{pmatrix} \cos\varphi & -\sin\varphi \\ \sin\varphi & \cos\varphi \end{pmatrix} \begin{pmatrix} q_L^{\mathrm{el}} \\ Q_L^{\mathrm{co}} \end{pmatrix}$$

Leads to light SM fermions and heavy partners



Naive Partial Compositeness almost works

- CP observables push $m_\rho \gtrsim 10\ \mathrm{TeV}$
- What can we do to make it work completely?

Right-Handed Compositeness

Implement MFV to comply with flavour constraints

[Redi, Weiler arXiv:1106.6357]

- Both the elementary and the composite sector are flavour degenerate
- Then generate the Standard Model flavour through the mixings

Fermion Mixing

$$\mathcal{L}_{\rm mix} = m_\rho \left[\lambda_{Lu}\bar{q}_L Q_{Ru} + \lambda_{Ld}\bar{q}_L Q_{Rd} + \lambda_{Ru} u_R \bar{U}_L + \lambda_{Rd} d_R \bar{D}_L + \text{h.c.}\right]$$

Left-Handed Compositeness: $\lambda_{Lu}, \lambda_{Ld} \propto I_3$ and $\lambda_{Ru}, \lambda_{Rd} \propto y_u, y_d$

EWPT (in particular $Z\bar{b}b$ branching ratio) imply $m_\rho \gtrsim m_t \frac{35}{\sin\varphi_{tR}}$

Right-Handed Compositeness: $\lambda_{Lu}, \lambda_{Ld} \propto y_u, y_d$ and $\lambda_{Ru}, \lambda_{Rd} \propto I_3$

EWPT are O.K. and predicts strong signatures at LHC, because light quarks can be highly composite

RH Compositeness Phenomenology

LHC Strategy

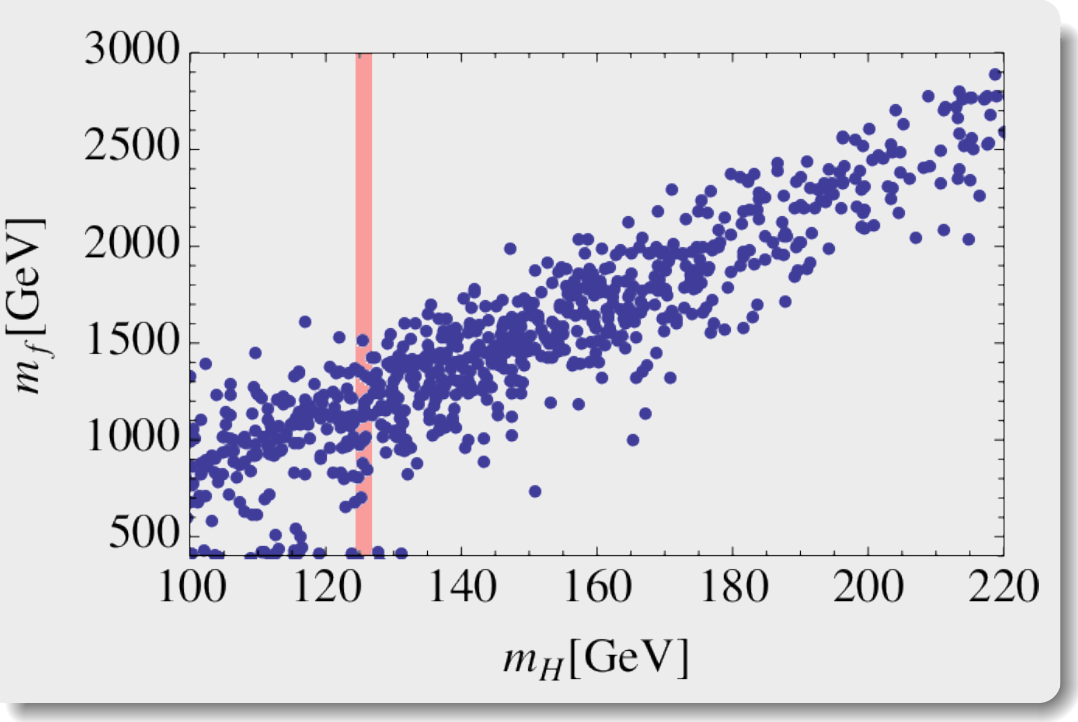
- Rotate to the mass basis
- Every SM particle has a heavy partner
- Reduce number of parameters to do analysis

Phenomenology Overview

- g_ρ: Coupling of the strong sector $1 < g_\rho < 4\pi$
- m_ρ: Generic mass of strong gauge resonances
- m_Q: Generic mass of strong fermionic resonances
- $\sin\varphi_{uR/dR}$: Mixing angles for the RH up/down type quarks

Implications of a Light Higgs

- Like in supersymmetry the absence of fine-tuning and a light Higgs have consequences for the spectrum of the theory
- For general and natural composite Higgs models a **light Higgs** implies **light fermionic partners** [Contino, Da Rold, Pomarol; Serone et al.; ...]

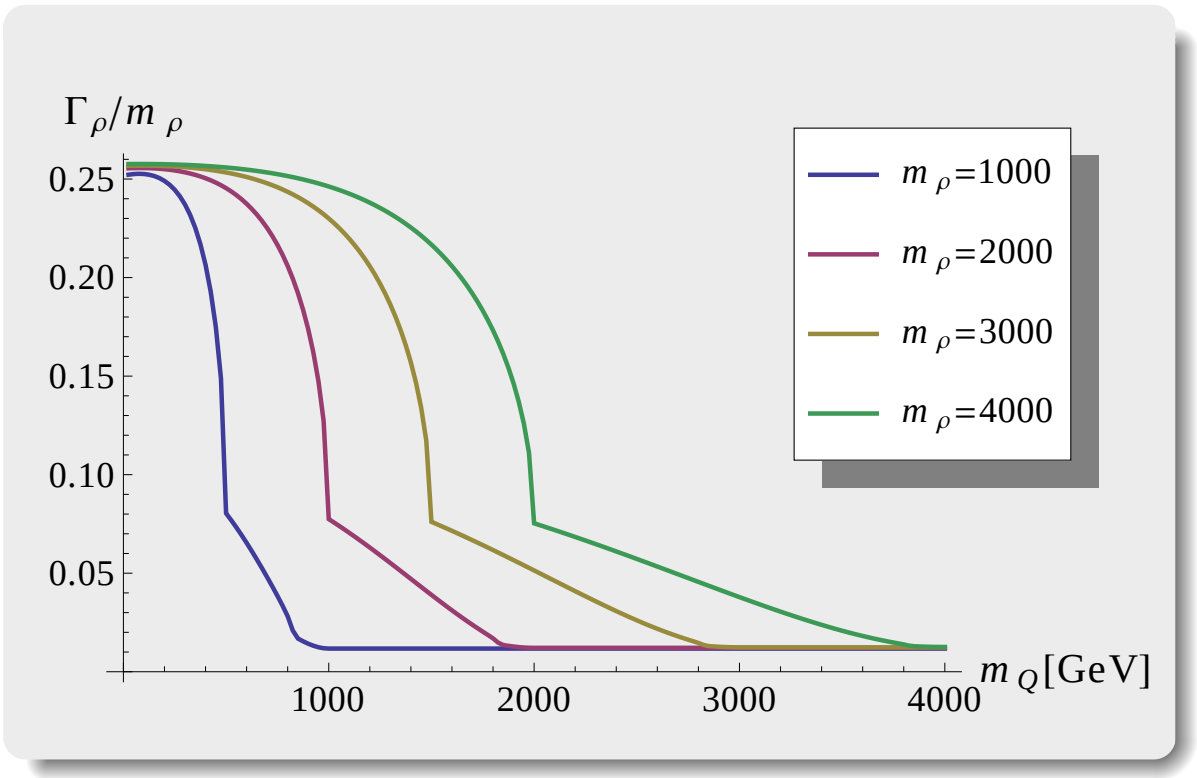


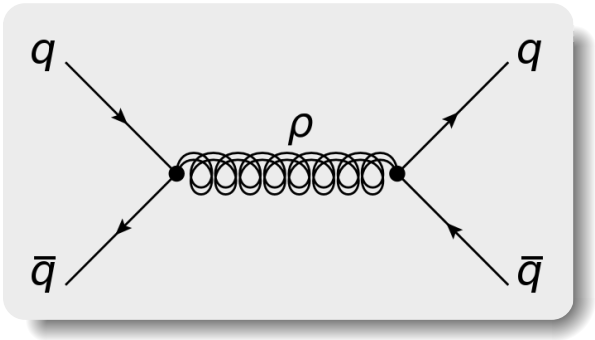
- Analysis for the **MFV partial compositeness** scenario [Redi, Tesi arXiv:1205.0232]
- These arguments **constrain the fermionic partner masses** as

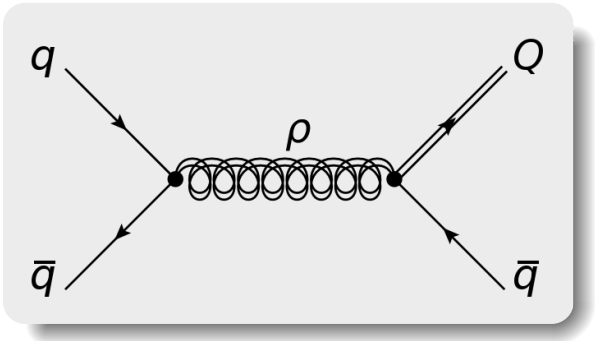
$$m_Q \lesssim 1500 \text{ GeV}$$

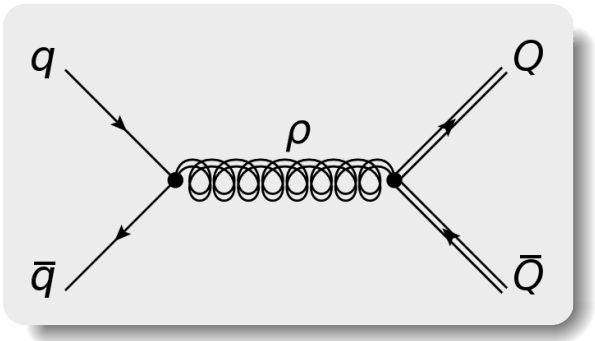
Heavy Colour Octet

- Heavy partner of the gluon
- Couples strongly to coloured fermions
- Dijet resonance search ($pp \to \rho \to jj$)
- First analyze decay modes and width

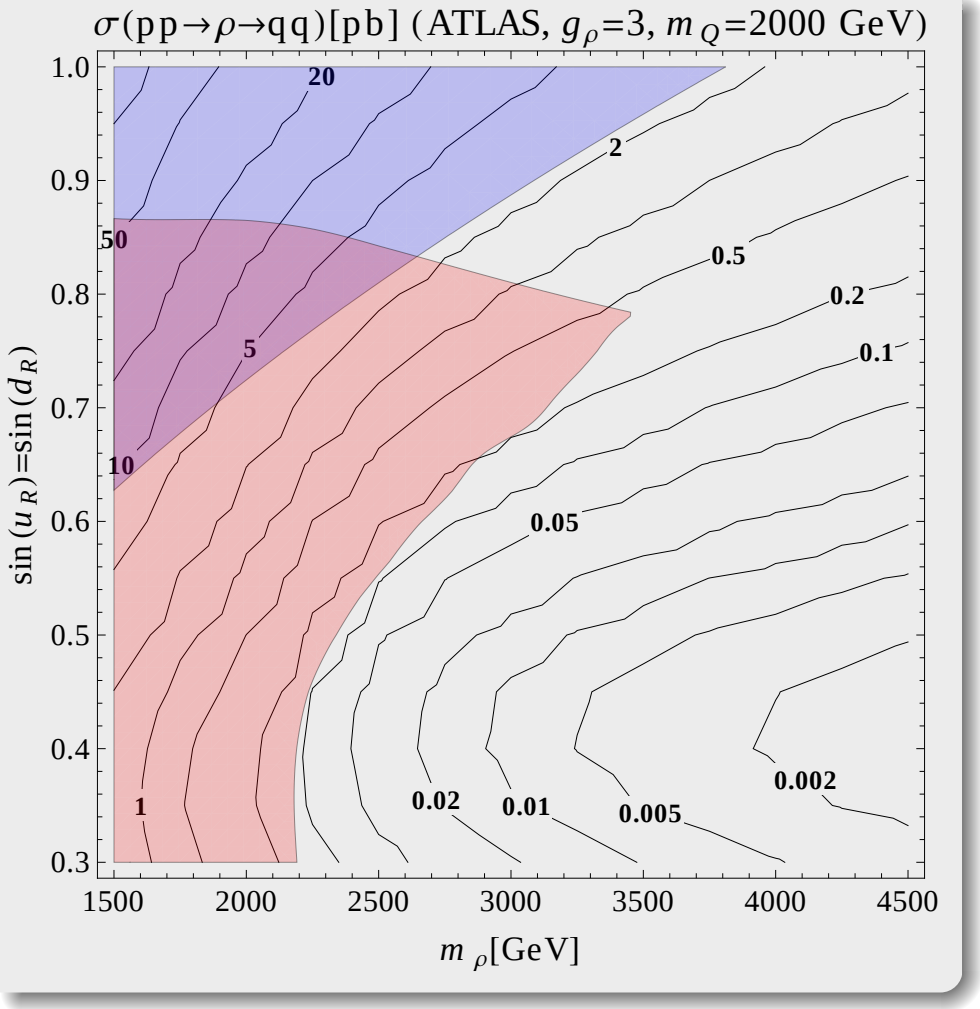






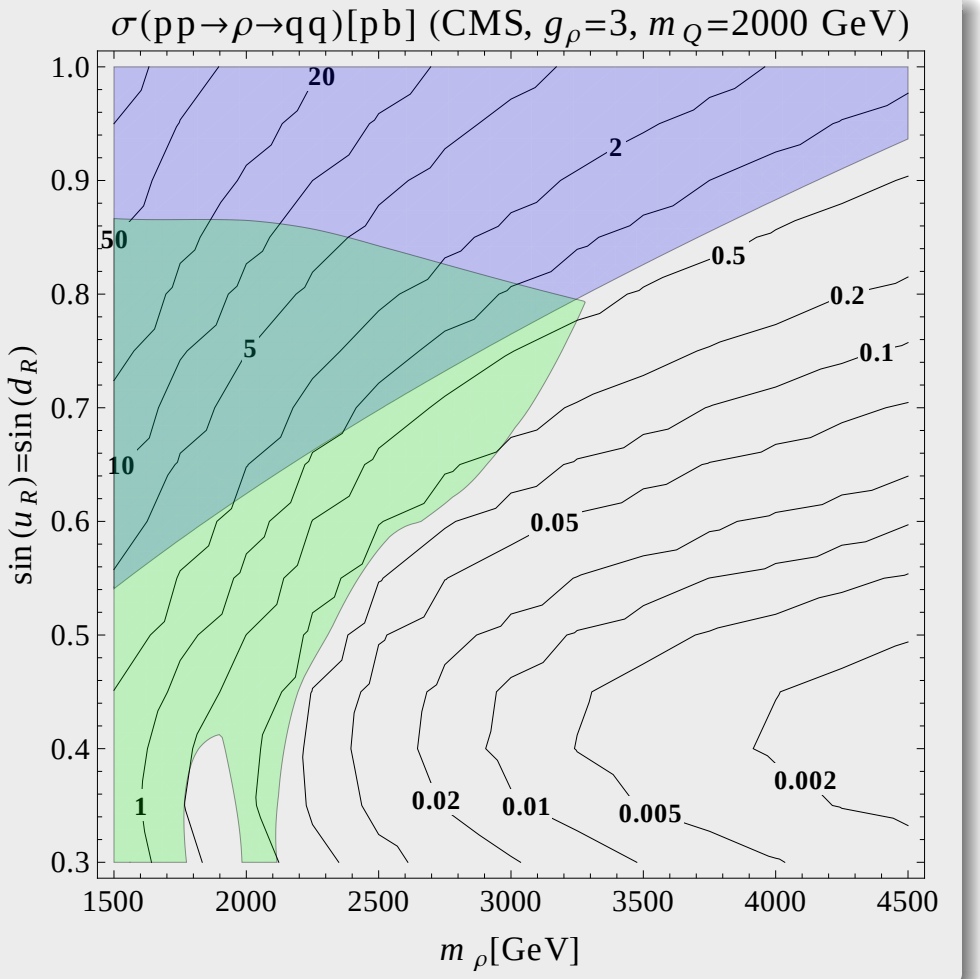


ATLAS Exlusion Limits



- Compositeness operator bounds
- $\mathcal{L} = \frac{2\pi}{\Lambda^2} \left(\bar{q}_{L,R}\gamma^\mu q_{L,R}\right)^2$
  L/R is the same for pp collisions
- ATLAS dijet angular searches [ATLAS-CONF-2012-038]
  $\Rightarrow \Lambda = 7.8\ \mathrm{TeV}$
- Dijet resonance search bounds
- ATLAS 8 TeV 5.8 fb^{-1} [ATLAS-CONF-2012-088]
- Only valid for narrow resonances
  $\Gamma_\rho / m_\rho < 0.15$
- Mixing angles constrained by top mass: $\sin\varphi_{uR} \gtrsim \frac{\lambda_t}{Y} \approx \frac{1}{3}$

CMS Exlusion Limits



- Compositeness operator bounds
- $\mathcal{L} = \pm\frac{2\pi}{\Lambda^2}\left(\bar{q}_{L,R}\gamma^\mu q_{L,R}\right)^2$
- CMS dijet angular searches [CMS-EXO-11-017]

  $\Rightarrow \Lambda^+ = 7.5\ \mathrm{TeV}$ "destructive"

  $\Rightarrow \Lambda^- = 10.5\ \mathrm{TeV}$ "constructive"
- Dijet resonance search bounds
- CMS 8 TeV 4 fb^{-1} [CMS PAS EXO-12-016]
- Rough exclusion limit:

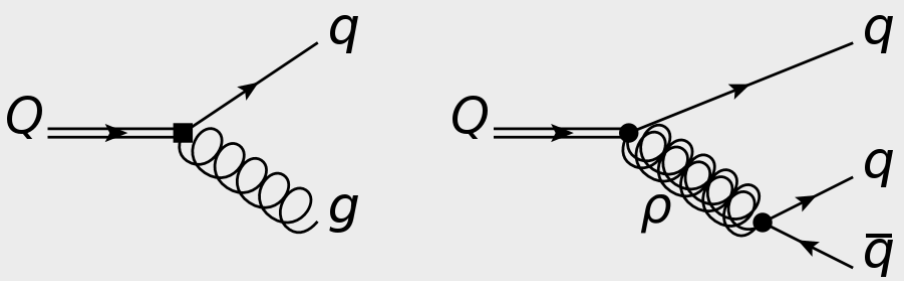
  $m_\rho \gtrsim 2\ \mathrm{TeV}$ @ 95% CL

Heavy Fermions Partners

Interesting at the LHC

- A light Higgs implies light fermion partners: $m_Q \lesssim 1500\ \mathrm{GeV}$
- Various production modes and decay into multijet channels
- Light fermion partners should be visible soon at the LHC

Two decay modes

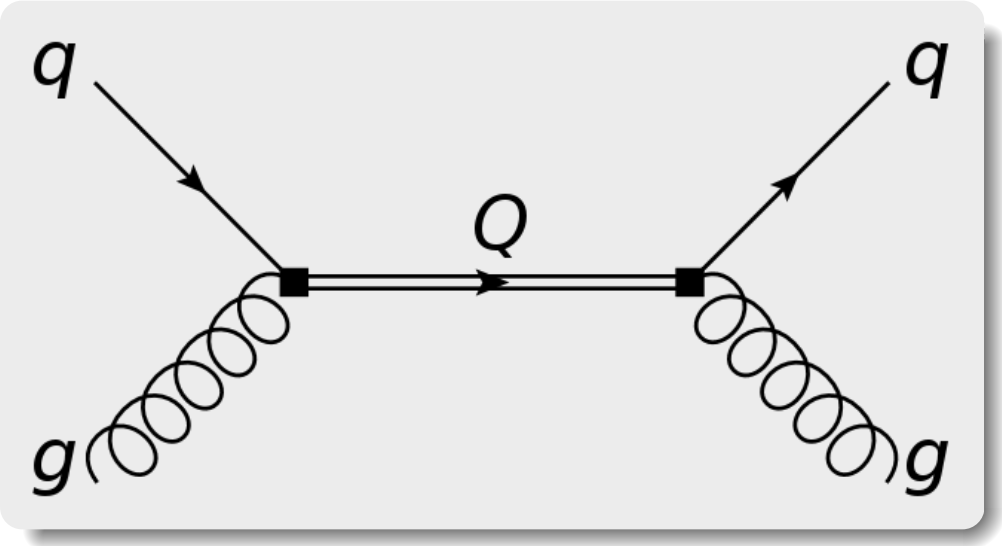


- Chromomagnetic operator $\mathcal{L} = \frac{g_s \kappa}{m_Q} \bar{Q} \sigma^{\mu\nu} T^a q G^a_{\mu\nu}$
- Three body decay through a colour octet

Both decay modes are suppressed and result in a narrow width

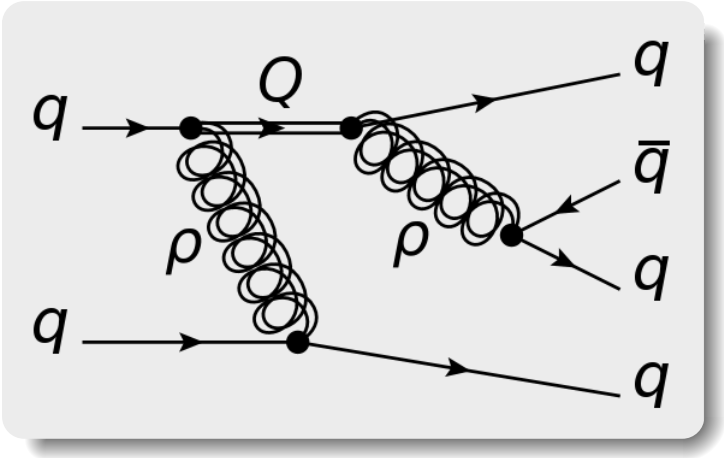
Chromomagnetic Dijet

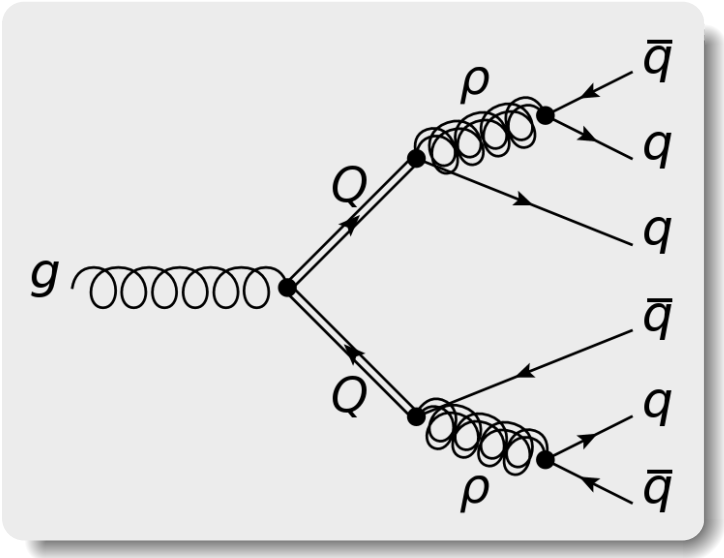
- Chromomagnetic introduces coupling between gluon, light and heavy quark
- Coupling too much suppressed for normal dijet resonance searches to be constraining



- **Dijet angular search**
- Experiments define an angular variable $\chi = e^{|y_1 - y_2|}$
- QCD background flat in $d\sigma/d\chi$
- However, new physics generally predicts higher rates for small χ
- Interesting analysis for the chromomagnetic production, but production cross section might be too small
- Therefore fruitful to look at other production mechanisms than just s-channel

Production Modes





- **Four jet** analysis by CMS 7 TeV 2.2 fb^{-1} [CMS PAS EXO-11-016]
- However, optimized for pair production of two heavy resonances
- Hence, needs a dedicated search for this topology
- **Six jet** analysis by CMS 7 TeV 5.0 fb^{-1} [CMS-EXO-11-060]
- Looks at the invariant mass of three jets to find resonances, but six jets are hard to analyze
- Our paper will contain more detailed analyses and suggestions for dedicated experimental searches

Conclusion

Composite Higgs with partial compositeness is an appealing solution to the hierarchy problem without flavour problems, still consistent with LHC results.

Strongly coupled resonances, i.e. the **colour octet**, are already **constrained** with current LHC data $m_\rho \gtrsim 2000\ \mathrm{GeV}$. However, these are allowed to be heavy without inducing sizable tuning.

Relatively **light fermionic partners** $m_Q \lesssim 1500\ \mathrm{GeV}$ are implied by a light Higgs. These provide immediate discovery opportunities at the LHC, however, there are no dedicated experimental searches yet.

Thank you for your attention!

Higgs might be composite

Partial Compositeness Lagrangian

- Massless Standard Model without Higgs

$$\mathcal{L}_{\text{elementary}} = -\frac{1}{4}F_{\mu\nu}^2 + \bar{\psi}_L i\not{D}\psi_L + \bar{\tilde{\psi}}_R i\not{D}\tilde{\psi}_R$$

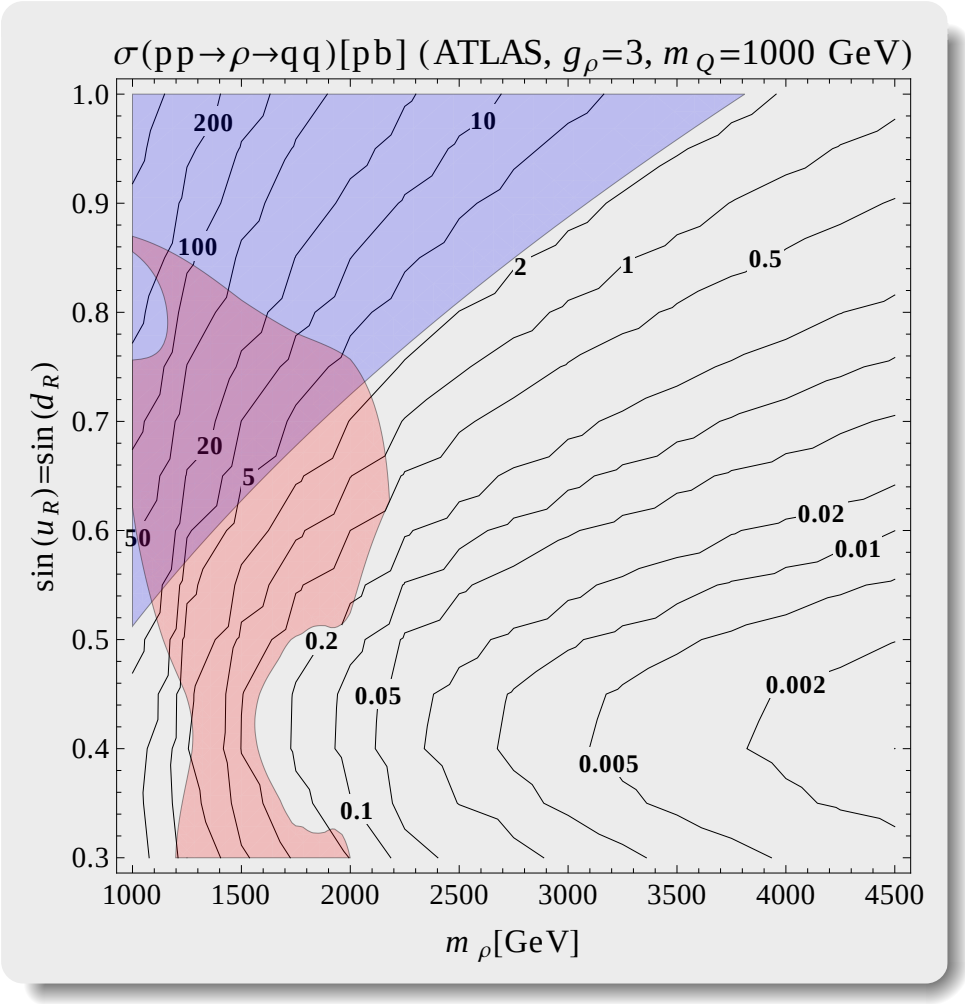
- Strongly coupled theory

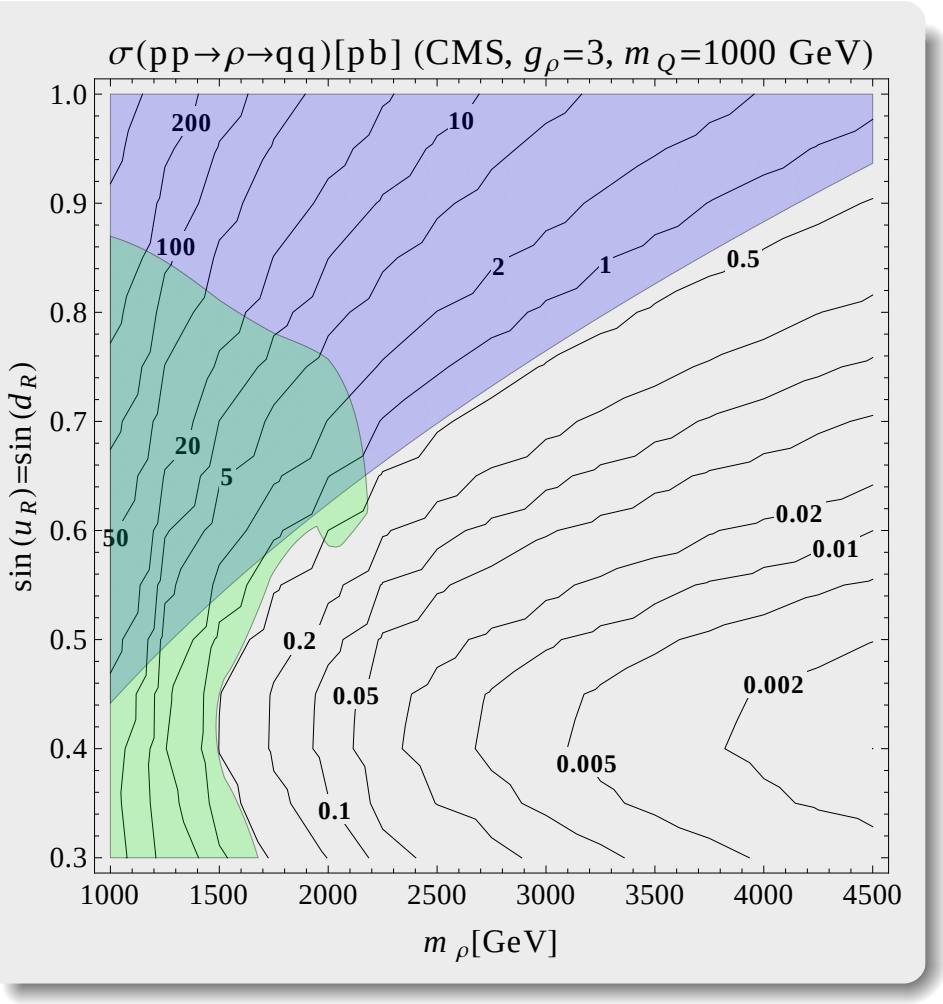
$$\begin{aligned}\mathcal{L}_{\text{comp}} = &-\frac{1}{4}\rho_{\mu\nu}^2 + \frac{M_*^2}{2}\rho_\mu^2 + |D_\mu H|^2 - V(H) \\ &+ \bar{\chi}(i\not{D} - m)\chi + \bar{\tilde{\chi}}(i\not{D} - \tilde{m})\tilde{\chi} \\ &- \bar{\chi}\left(Y_{*u}\tilde{H}\tilde{\chi}^u + Y_{*d}H\tilde{\chi}^d\right) + \text{h.c.}\end{aligned}$$

- Mass mixing between fermionic and gauge states of both sectors

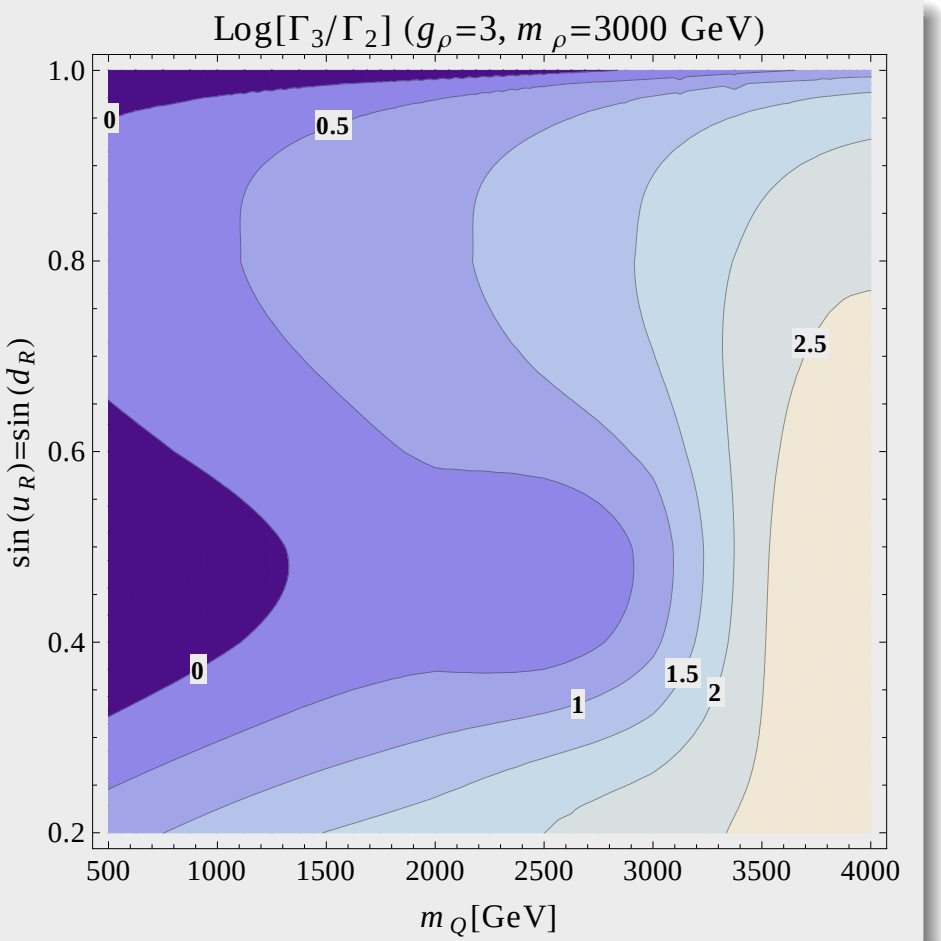
$$\begin{aligned}\mathcal{L}_{\text{mix}} = &-M_*^2\,\frac{g_{\text{el}}}{g_*}\,A_\mu\rho_\mu^* + \frac{M_*^2}{2}\left(\frac{g_{\text{el}}}{g_*}A_\mu\right)^2 \\ &+ \left(\bar{\psi}_L\Delta\chi_R + \bar{\tilde{\psi}}_R\tilde{\Delta}\tilde{\chi}_L + \text{h.c.}\right)\end{aligned}$$

Dijet Exclusion Limits for $m_Q = 1000$ GeV

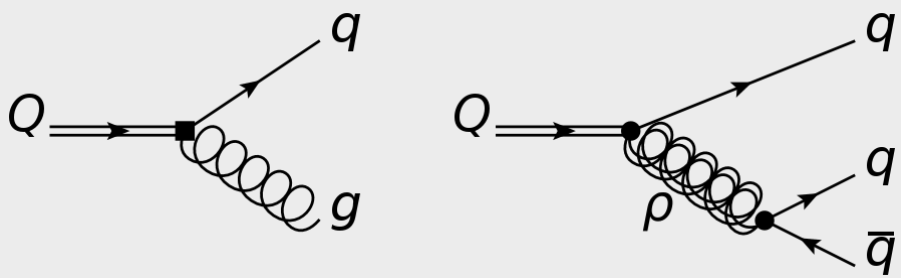




Heavy Fermion Decays



Heavy Fermion Decay Modes



- Three body decay dominant almost everywhere
- $\Gamma_2 > \Gamma_3$ only in small region of low m_Q