Hidden interactions of quarks

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$$\begin{pmatrix} u_L \\ d_L \end{pmatrix} \quad \begin{pmatrix} c_L \\ s_L \end{pmatrix} \quad \begin{pmatrix} t_L \\ b_L \end{pmatrix}$$

$$\begin{matrix} u_R & c_R & t_R \\ d_R & s_R & b_R \end{matrix}$$

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“Everything” around—and in—us is built of ***up*** **and** ***down*** **quarks (plus gluons and electrons).**

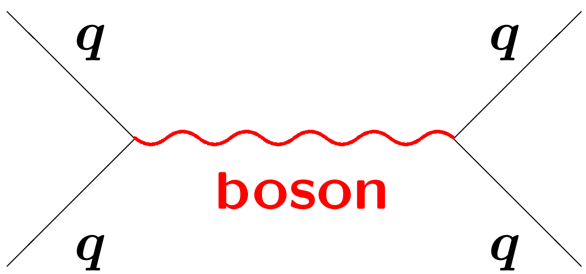
- **What are the known interactions of the quarks?**

- **What additional interactions could the quarks feel?**

Particles are manifestations of quantum fields.

Local quantum field theory:
interactions at a distance mediated by particle exchange.

One-boson exchange:



Quarks are fermions (spin 1/2).

1. Electromagnetic interaction

Coulomb force: $\sim \frac{1}{r^2}$ *(massless spin-1 particle exchange: photon)*

Laws of physics have a $U(1)$ gauge symmetry if the Lagrangian is invariant under a gauge transformation:

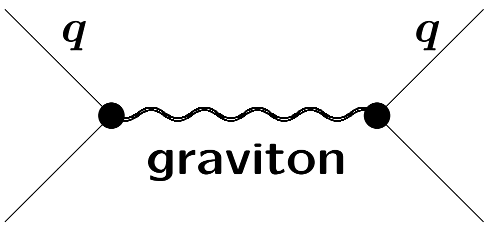
spin 1/2 (quark) field: $u(x^\mu) \rightarrow e^{2/3\, i\, \alpha(x^\mu)} u(x^\mu)$

spin-1 (photon) field: $A_\mu(x) \rightarrow A_\mu(x) - \partial_\mu \alpha(x^\mu)$

Photon mass term, $A_\mu A^\mu$, is not gauge invariant
$\Rightarrow U(1)_{\mathrm{e.m.}}$ symmetry keeps the photon massless!

2. Gravitational interaction

Newton's law: $\sim \frac{1}{r^2}$ *(massless spin-2 exchange: "graviton")*



Classical limit is identical to General Relativity!

Graviton-quark interaction is a dimension-5 operator suppressed by the Planck scale

$\Rightarrow$ **theory is valid at energies** $\ll 10^{18}$ **GeV**

3. Strong interaction

One-gluon-exchange force: $$\frac{1}{r^2}\left[1 - b\ln\left(\frac{r}{10^{-14}\,\mathrm{cm}}\right)\right]^{-1}$$

Approximation breaks down at distances $\gtrsim 10^{-14}$ cm,

bound states form: proton, neutron, pions, ...

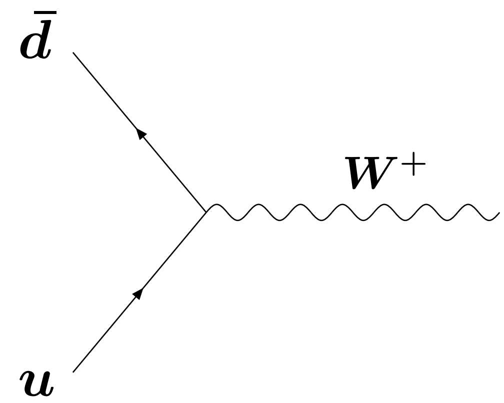
Short-range interaction due to confinement!

4. Weak interaction

"Z^0-exchange force": $\sim \frac{1}{r^2} \exp\left[-2r/(10^{-16}\text{cm})\right]$

Short-range interaction due to the Z^0 mass.

$W^{\pm}$ interaction changes the quark flavor:



Weak & electromagnetic interactions require $SU(2)_W \times U(1)_Y$ gauge symmetry: 4 gauge bosons $\rightarrow$ $W^{\pm}$, Z^0, γ

If the laws of physics are gauge invariant,

where are the $W^{\pm}$ and Z^0 masses coming from?

Vacuum = the ground state of a quantum field theory.

Lagrangian has an $SU(2)_W \times U(1)_Y$ gauge symmetry,

vacuum has only a $U(1)_{\mathrm{e.m.}}$ gauge symmetry.

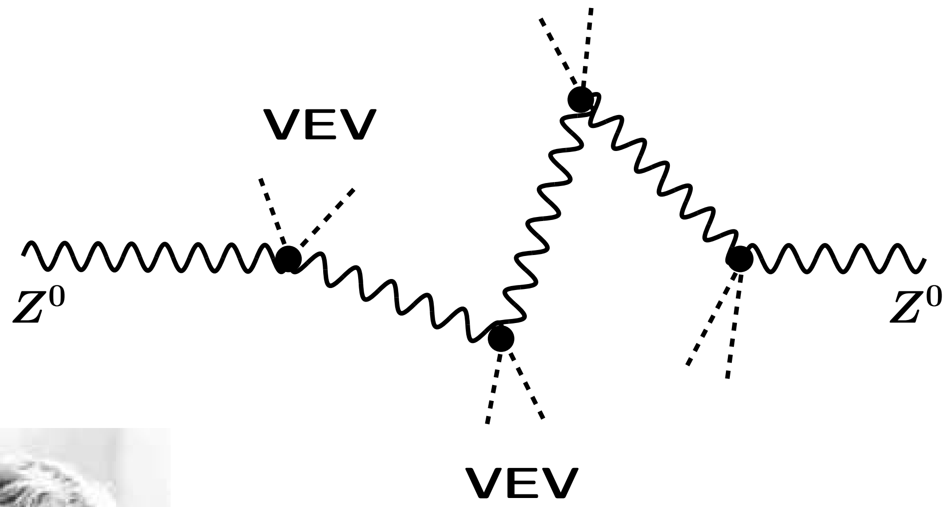
Similar to superconductivity: photon is massive inside superconductors.

Need something to populate the vacuum ...

FloridaMemory.com

Higgs field 'condenses', has a Vacuum Expectation Value:

$v_H = (\sqrt{2}/g)M_W \approx 174$ **GeV**



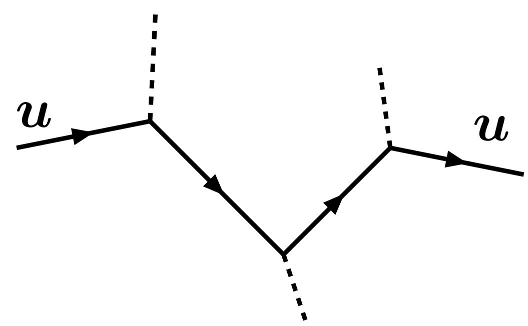
Z^0 **acquires a mass!**

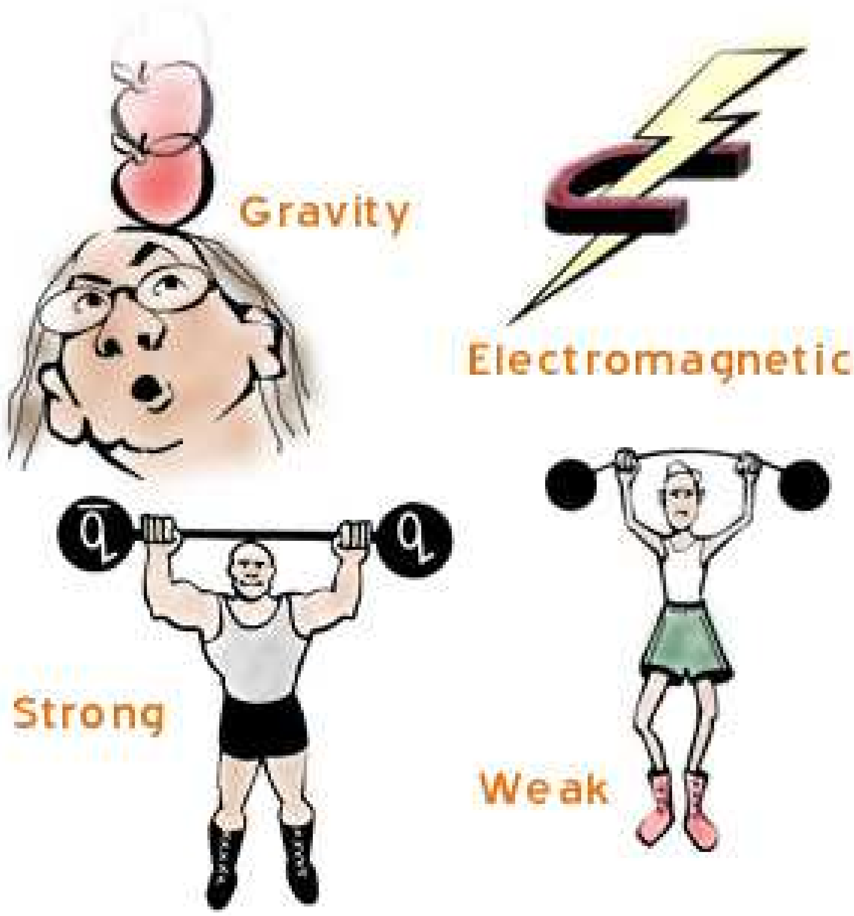
Steven Weinberg

"A Theory of Leptons"

1967

Quark masses also arise due to the Higgs field:




Gravity
Electromagnetic
Strong
Weak

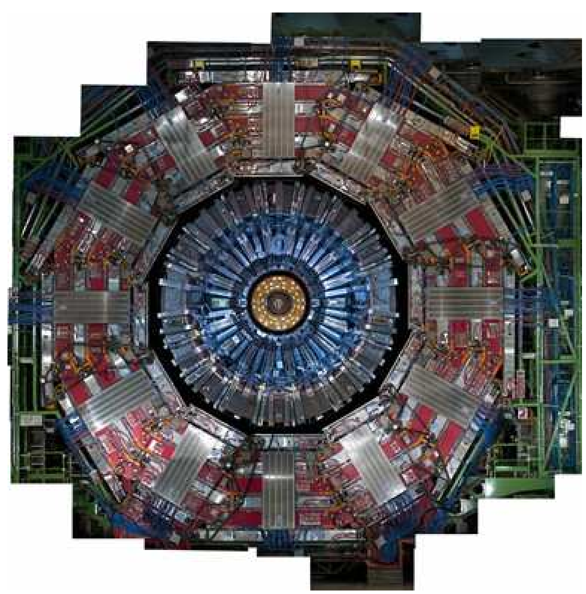
+ ?

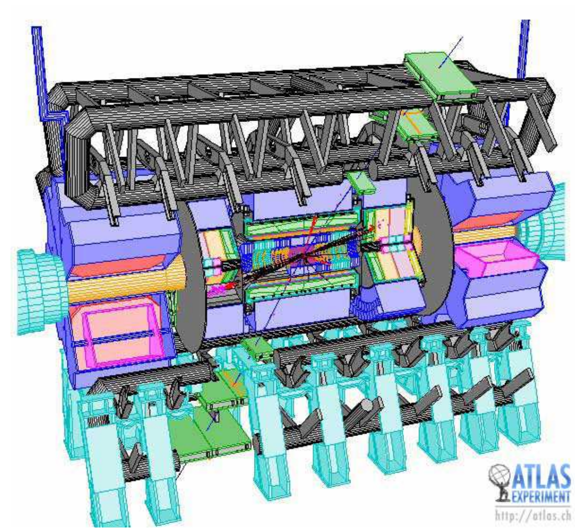
Higgs field implies the existence of a particle carrying the same quantum numbers as the vacuum:

the Higgs boson (h^0) is a particle of spin 0 that couples to W, Z, quarks and leptons, proportional to their mass:

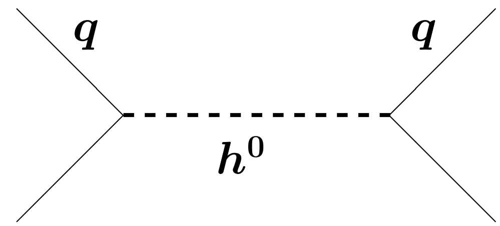
$$\frac{\sqrt{2}}{v_H}\, h^0 \left(M_W^2 W^\mu W_\mu + \frac{M_Z^2}{2} Z^\mu Z_\mu + \sum_q m_q\, \bar{q}_L q_R + \cdots \right)$$

Discovered in 2012 with the CMS and ATLAS detectors:





Fifth "force": Higgs exchange!



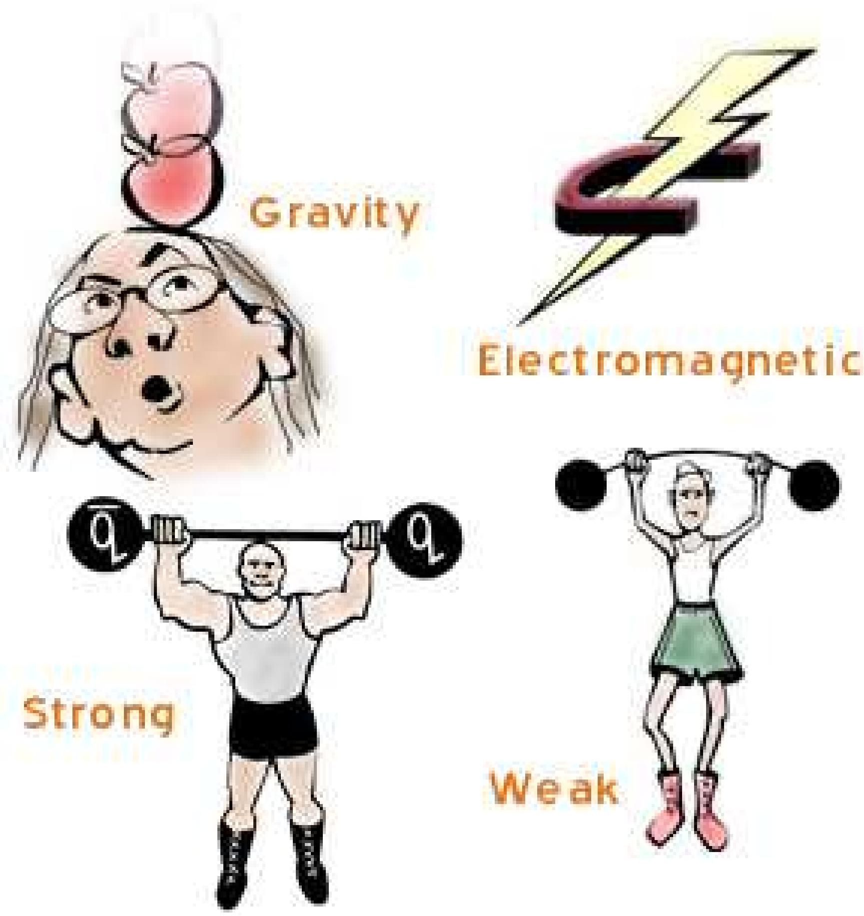
$$F \approx \left(\frac{m_q}{174\ \mathrm{GeV}}\right)^2 \frac{1}{r^2} \exp\left[-2.5r/(10^{-16}\mathrm{cm})\right]$$

↓

tiny for ordinary stable matter... ($m_d \approx 5$ MeV, $m_u \approx 3$ MeV)

There is also a momentum-dependent interaction induced at two loops (involving a top quark and a gluon).

Scalar exchange → spin-independent force.



$+ \; h^0 \; + \; ?$

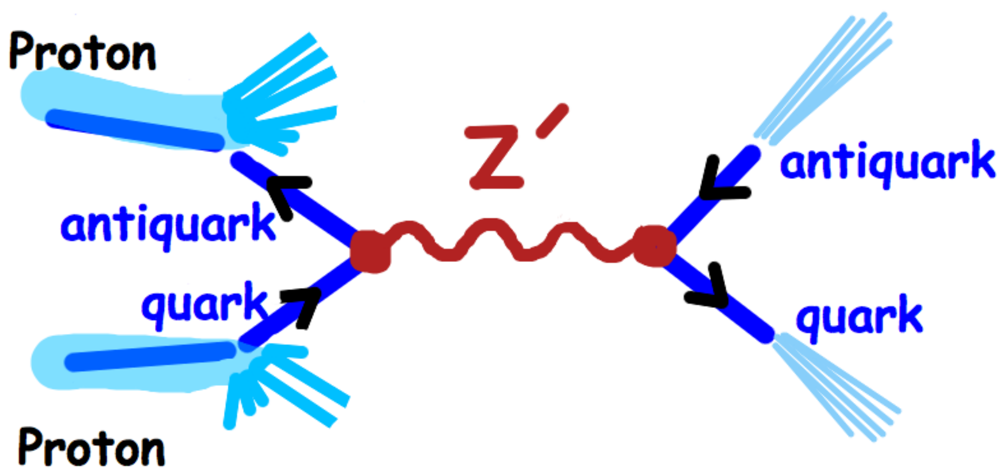
Could there exist additional quark interactions?

Yes, if the new bosons are sufficiently heavy,

or sufficiently weakly coupled.

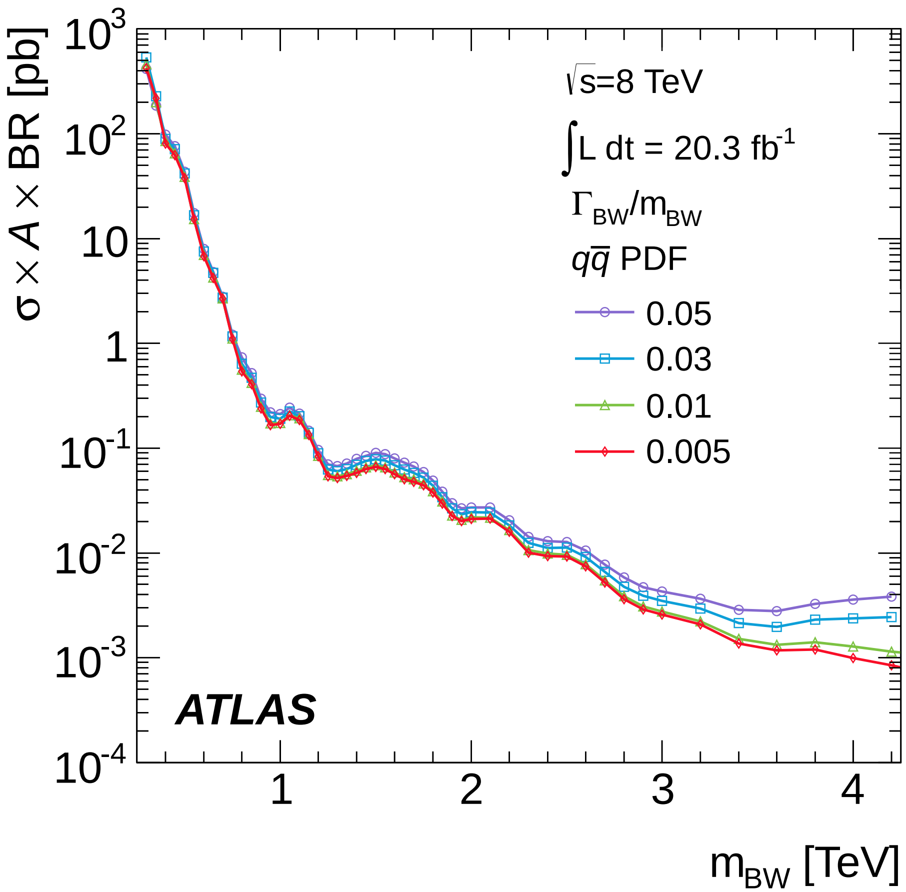
Hypothetical heavy particle of spin 1 and charge 0: Z' boson.

If Z' couples only to quarks ("leptophobic"), then it can be produced at hadron colliders (SpS, Tevatron, LHC) and decays back to quark-antiquark pairs, which give rise to jets of hadrons:



Two final-state jets, hard to separate from the background ...

However, the two hadronic jets form a resonance that can show up above the background if $M_{Z'}$ is large enough.

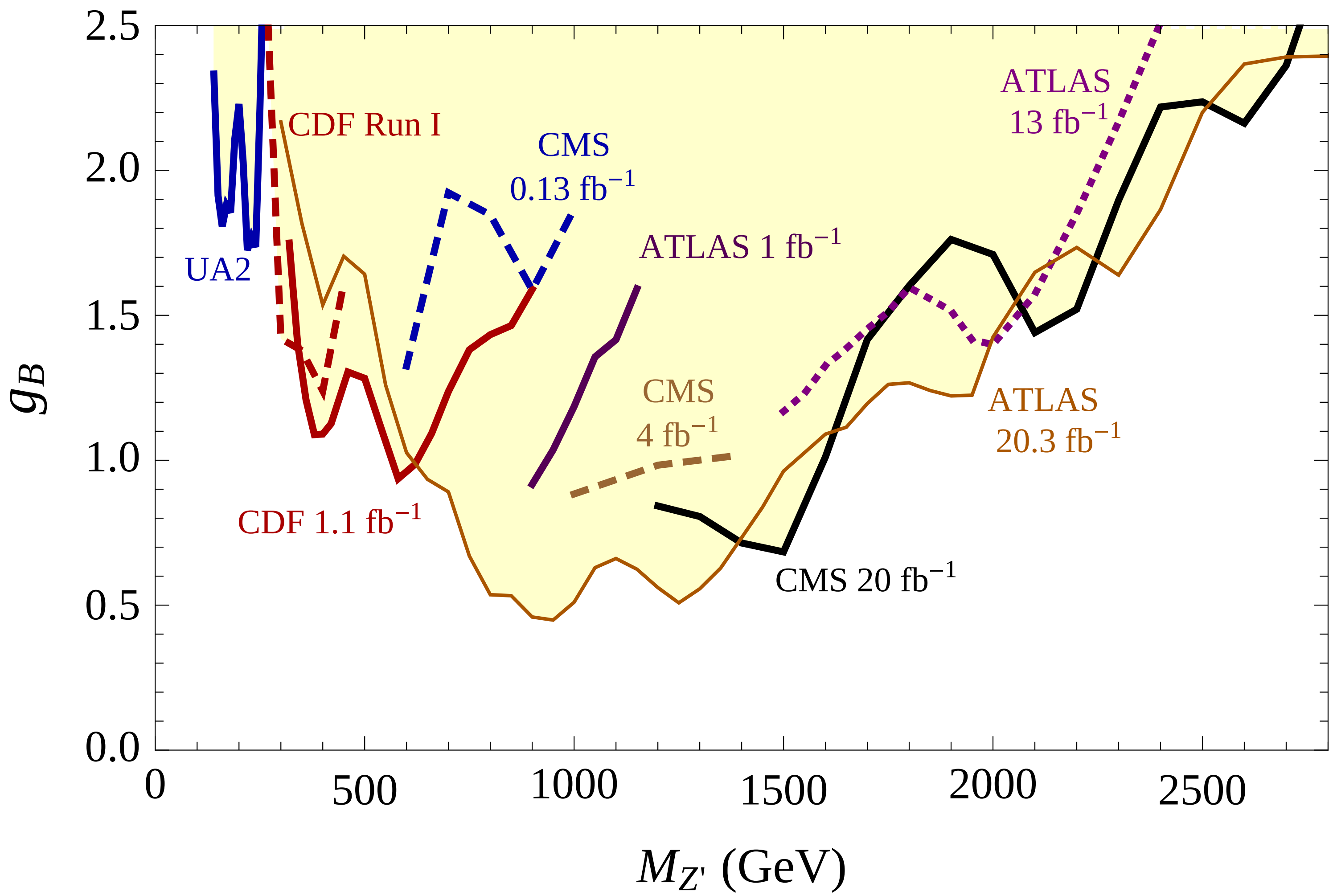


Limits on the production of a Gaussian resonance ... (1407.1376)

Dijet resonances are not Gaussian (have a long tail due to final state radiation)

What are the limits on the Z' couplings to quarks?

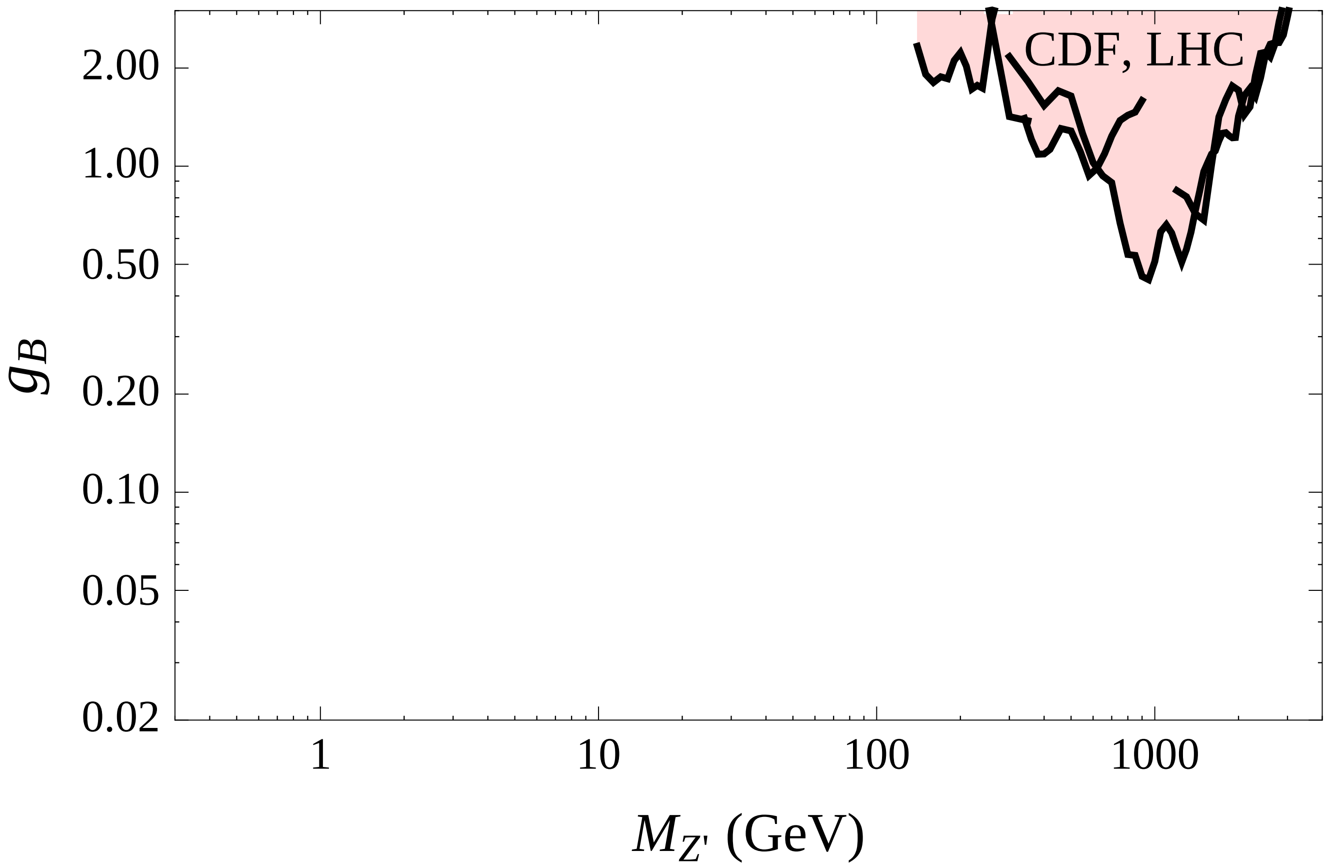
"Baryonic" Z'_B: same coupling (g_B) to all six quark flavors.



$$\mathcal{L}_q = \frac{g_B}{2} Z'_\mu \sum_q \left(\frac{1}{3} \overline{q}_L \gamma^\mu q_L + \frac{1}{3} \overline{q}_R \gamma^\mu q_R \right)$$

with Felix Yu: 1306.2629

What are the limits on g_B for $M_{Z'} < 140$ GeV?



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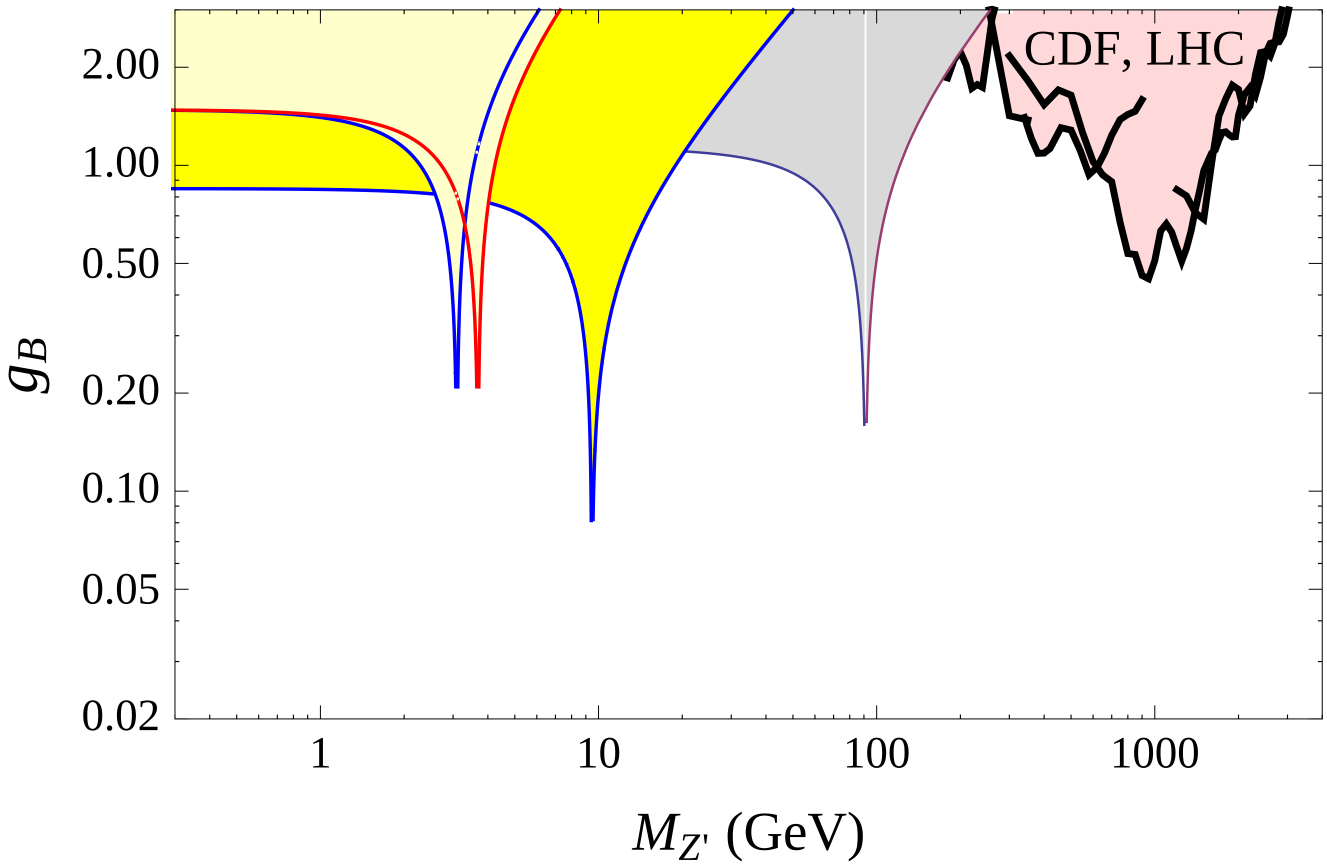

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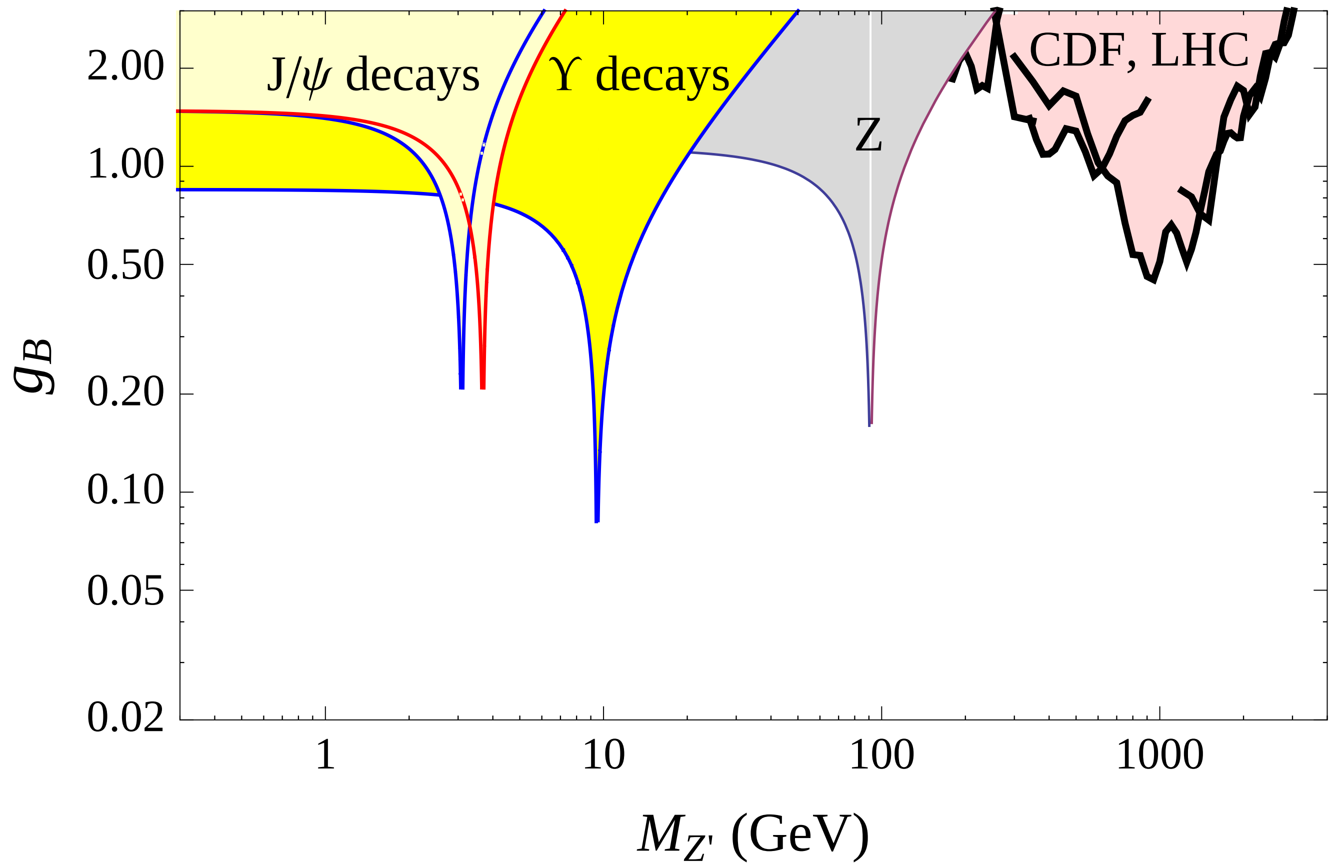
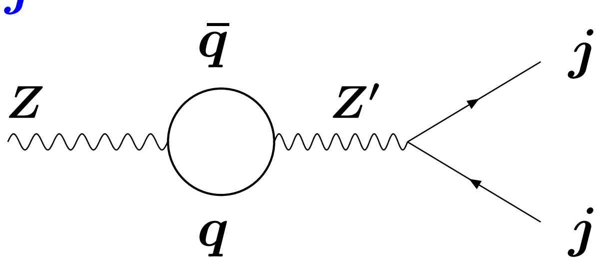


Υ are $b\bar{b}$ mesons, masses $\sim O(10)$ GeV.

ARGUS experiment, 1986: limit on $\Upsilon \to Z'^* \to jj$

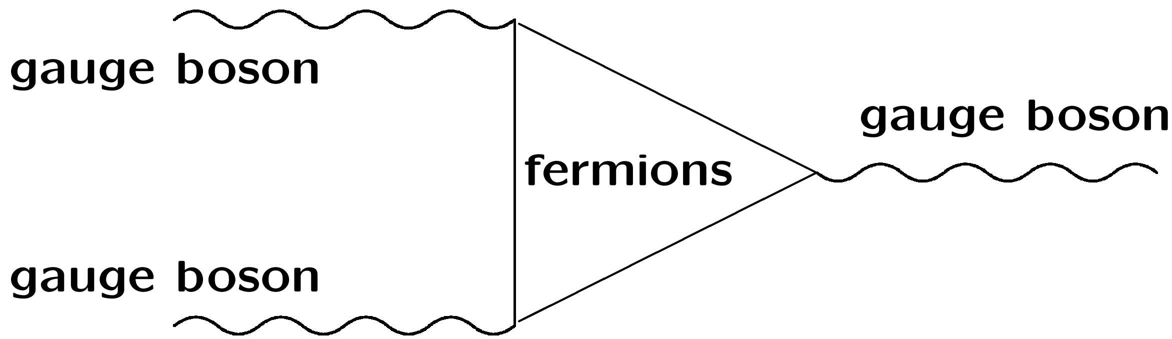
Small $Z - Z'$ mixing induced at one loop:



Gauge anomaly cancellation

Gauge symmetries may be broken by quantum effects.

Cure: sums over fermion triangle diagrams must vanish.



Standard Model – anomalies cancel within each fermion generation:

$[SU(3)_c]^2 U(1)_Y$: $\quad 2(1/6) + (-2/3) + (1/3) = 0$

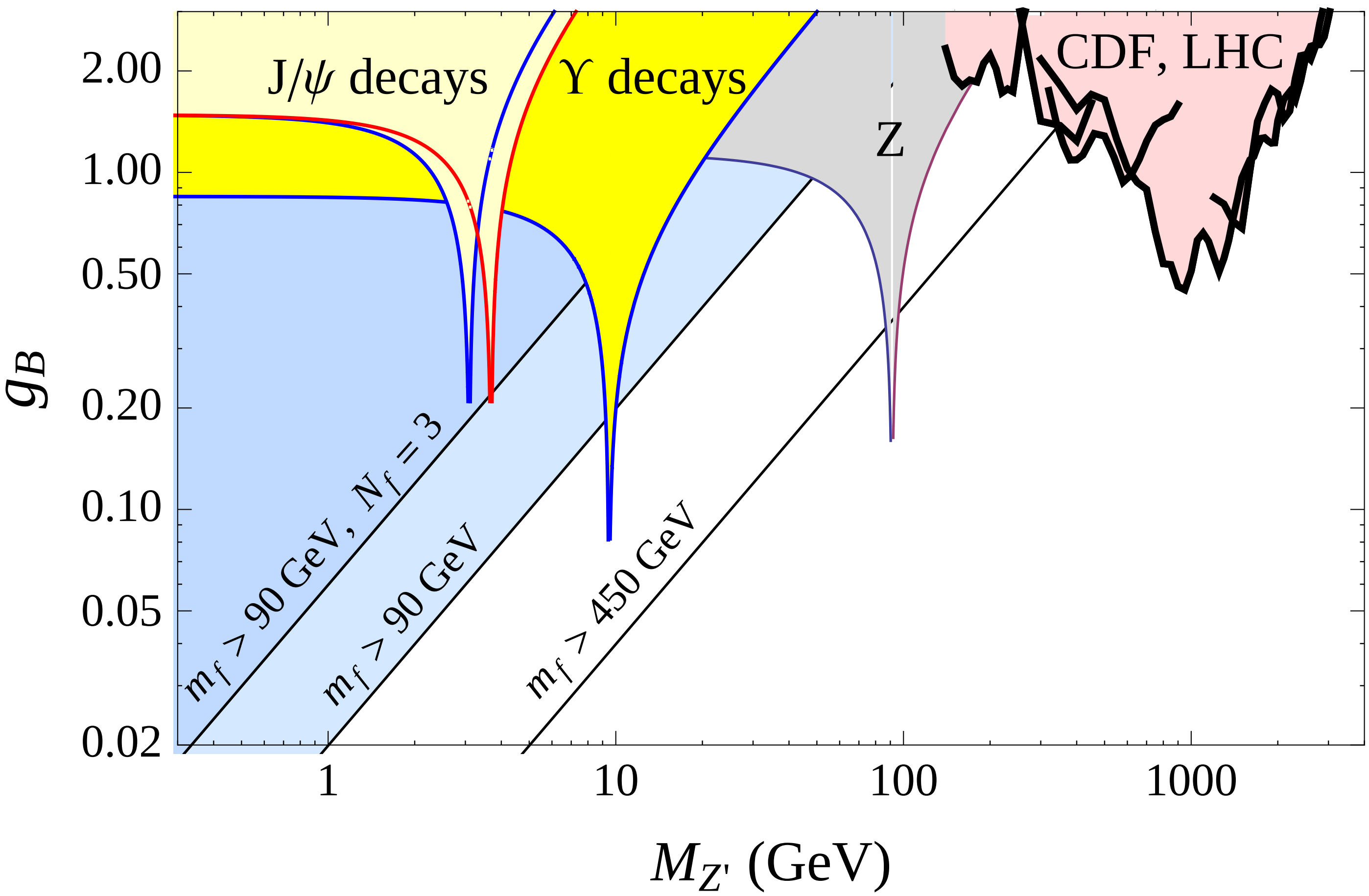
$[SU(2)_W]^2 U(1)_Y$: $\quad 3(1/6) + (-1/2) = 0$

$[U(1)_Y]^3$: $\quad 3\left[2(1/6)^3 + (-2/3)^3 + (1/3)^3\right] + 2(-1/2)^3 + (-1)^3 = 0$

... $\quad (u_L, d_L) \quad u_R \quad d_R \quad (\nu_L, e_L) \quad e_R$

Z' *requires a new gauge symmetry:* $SU(3)_c \times SU(2)_W \times U(1)_Y \times U(1)_B$

$U(1)_Y [U(1)_B]^2$ anomaly cancelation $\Rightarrow$ charged vector-like fermions
$\Rightarrow$ colliders limits on fermion masses lead to a limit on g_B:



$U(1)_B$ is spontaneously broken
by the VEV of a new scalar field φ.

with Claudia Frugiuele:
PRL 113, 061801 (2014)

A leptophobic Z' model with relaxed constraints:

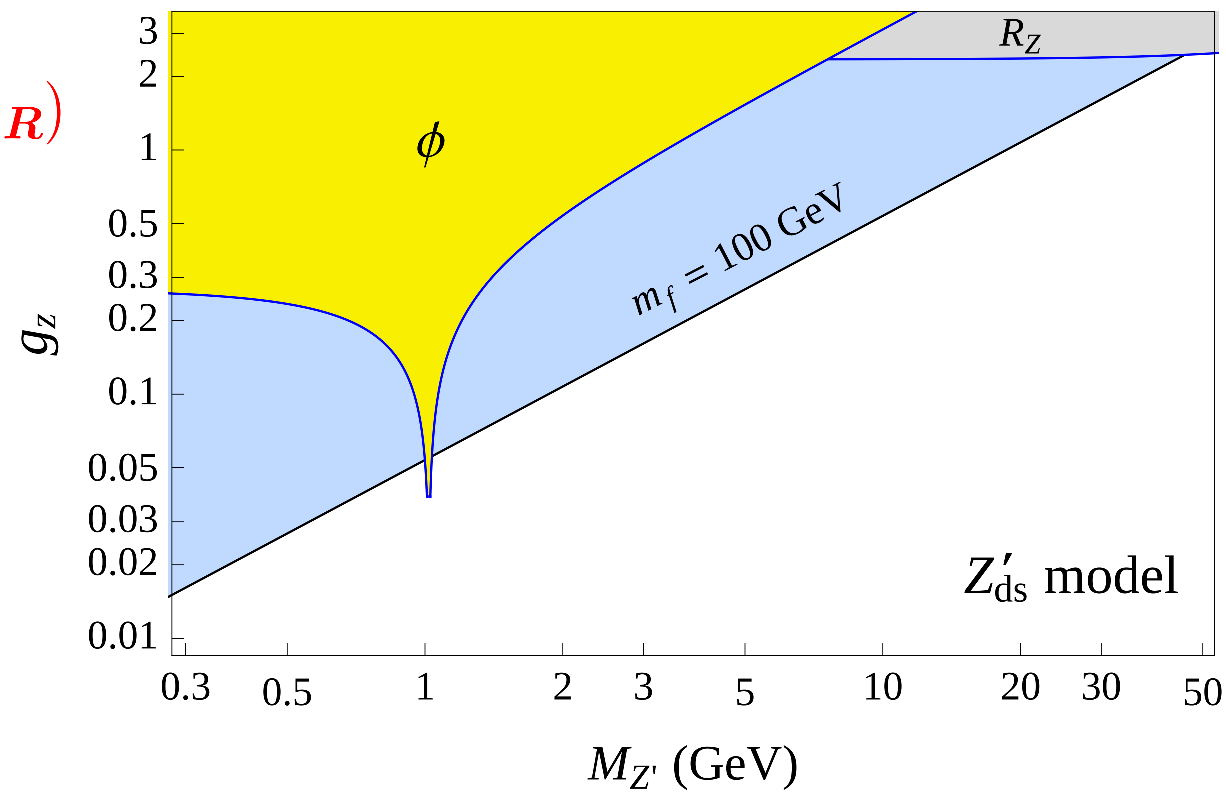
field	$SU(3)_C$	$SU(2)_W$	$U(1)_Y$	$U(1)_{ds}$
d_R	3	1	$+1/3$	$+1/3$
s_R	3	1	$-1/3$	$-1/3$
f_L, f'_L	1	1	$+1$	$+2/3$, $-2/3$
f_R, f'_R	1	1	$+1$	$+1/3$, $-1/3$
φ	1	1	0	1

$$\mathcal{L}_q = \frac{g_z}{2} Z'_\mu \left(\overline{d}_R \gamma^\mu d_R - \overline{s}_R \gamma^\mu s_R \right)$$

no coupling to q_L

$\rightarrow$ no flavor-changing Z' couplings.

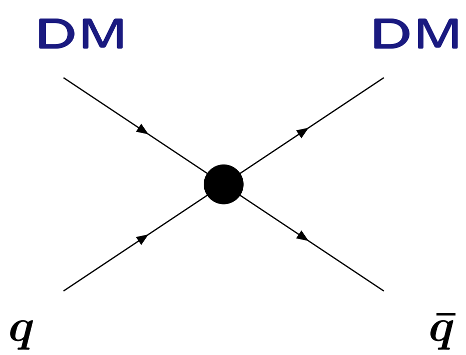
s, d masses from dimension-5 operators.



Dark matter requires particle(s) beyond the SM

DM particle may be part of a large hidden sector.

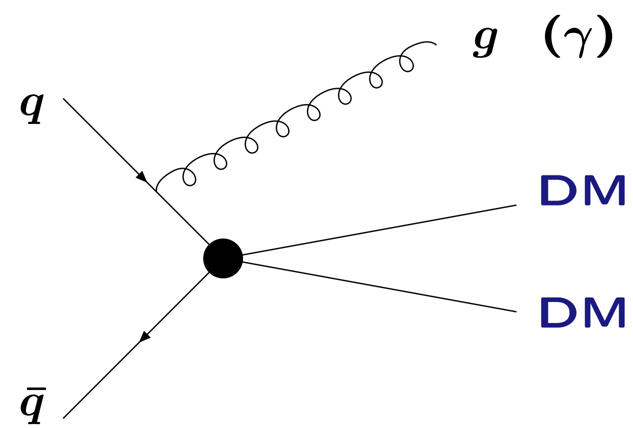
There can be several particles contributing to the DM density.



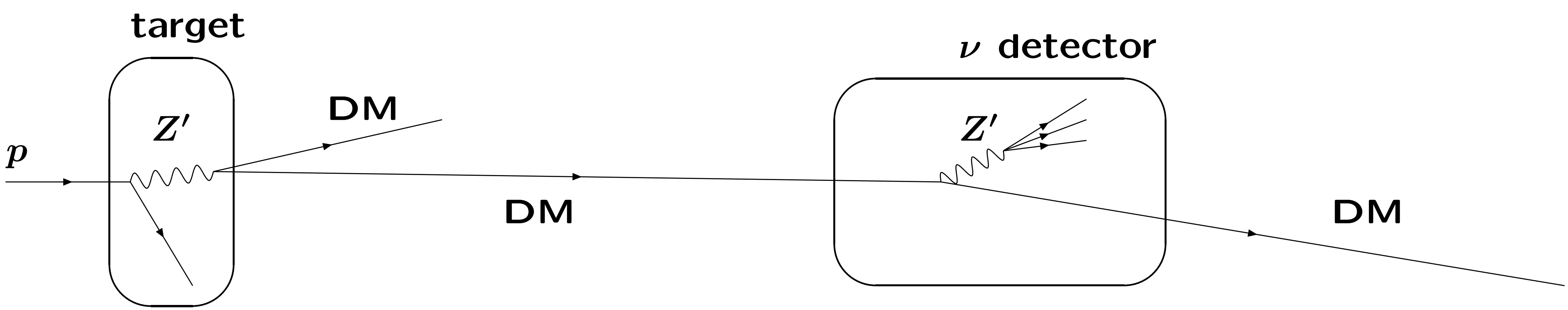
DM direct detection relies on DM interaction with nuclei (*i.e.*, quarks or gluons), and $m_{\rm DM} \gtrsim$ 5 GeV

If DM interacts with quarks, it may be produced at the LHC. *(Bai, Fox, Harnik, Tait, ...)*

Current limit: $g_B \lesssim 0.2$



Quark – DM interaction: fixed target experiments → DM beam



Neutral-current events → background: ν beam!

DM events have higher energy, can separate the signal from background.

Main Injector: $> 10^{21}$ protons (of 120 GeV) on target.

Presence of DM particles can be probed with the NOνA, MINOS, LBNF, ..., detectors.

Similar search for lighter Z' at MiniBoone – B. Batell et al, 1405.7049

Even when quarks are neutral under the new gauge group, they can interact with Z':

$$\frac{1}{M^2} Z'_{\mu\nu} \left(C_u \, \overline{Q}_L \sigma^{\mu\nu} u_R H + \mathrm{h.c.} \right)$$

$Z'_{\mu\nu} = \partial_\mu Z'_\nu - \partial_\nu Z'_\mu$ **(field strength)**

C_u: **dimensionless parameters**

$\rightarrow$ **magnetic- and electric-like dipole moments**

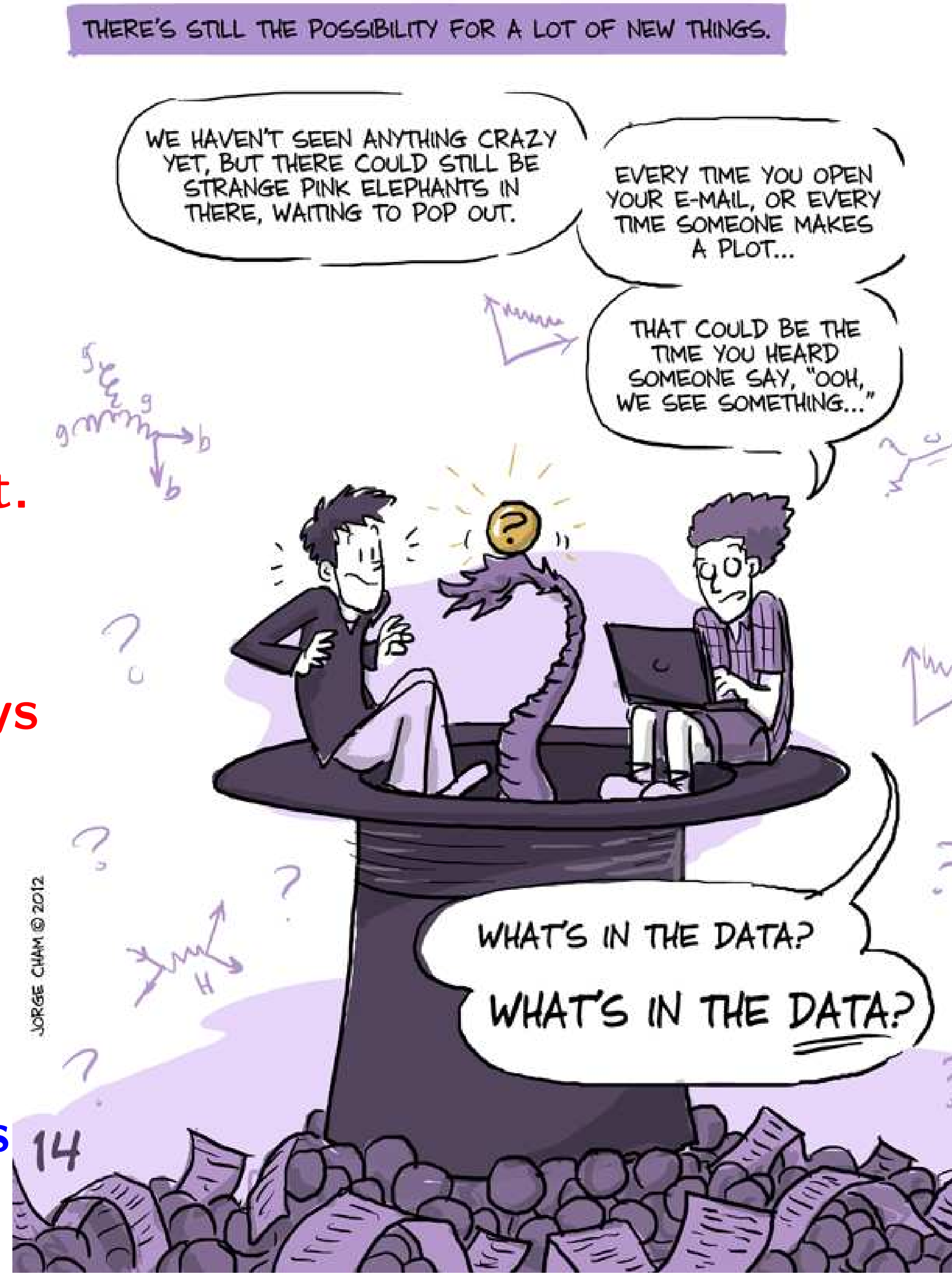
Interaction strength increases with the energy of the production process!

Conclusions

- 5 known interactions of quarks:
  - electromagnetic; gravitational
  - strong; weak; Higgs

- Additional interactions may exist. Leptophobic Z' — mass:
  - $\gtrsim 100$ GeV: probed at colliders
  - $\lesssim 10$ GeV: probed in meson decays
  - $\lesssim 50$ GeV: "theoretical" limits

- Many interesting possibilities:
  - interactions with DM (use ν detectors ...)
  - momentum-dependent couplings
  - ...



phdcomics.com/higgs