New Physics Beyond the Standard Model

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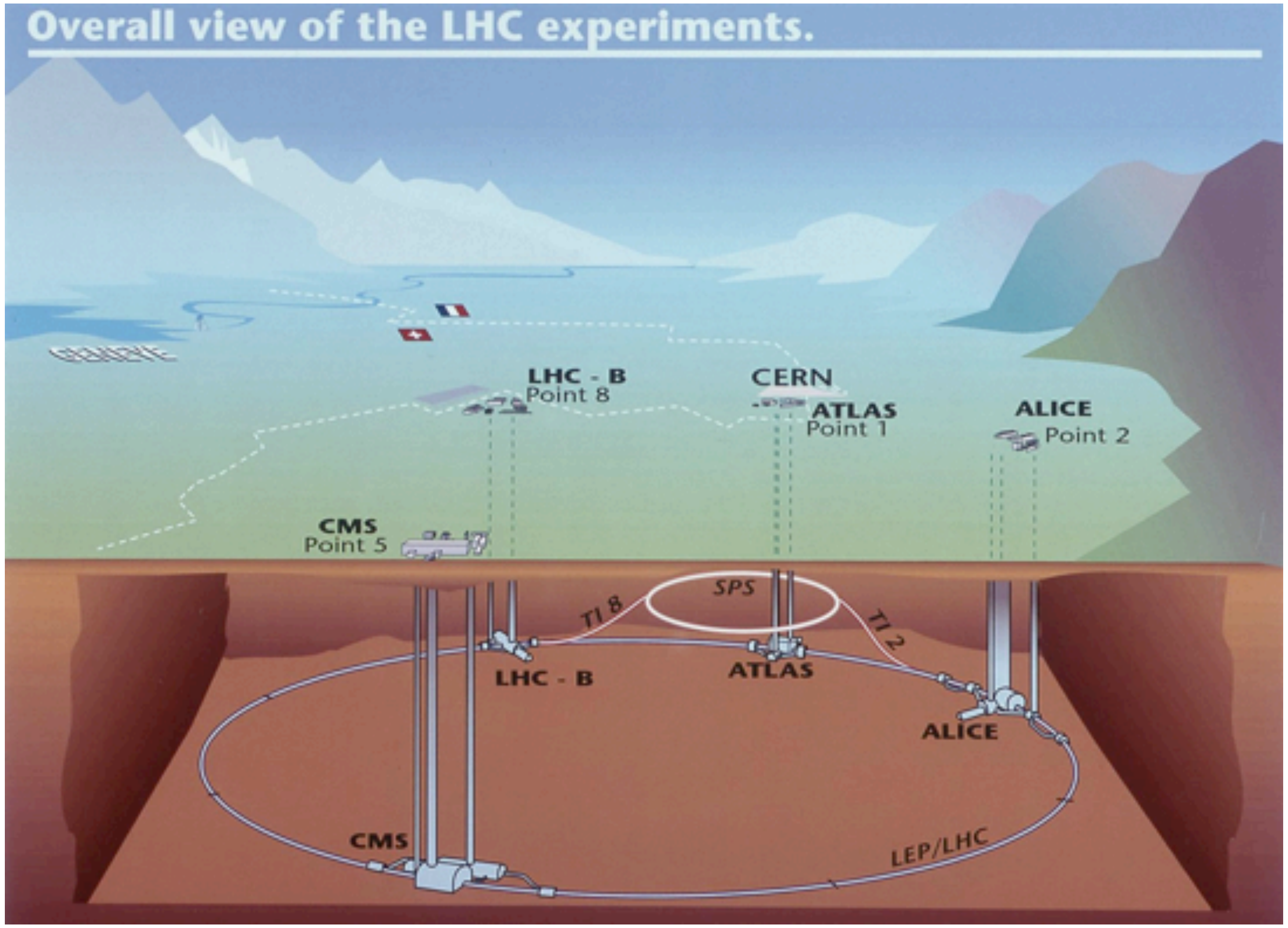
Fermilab, HCPSS 2012, August 2012

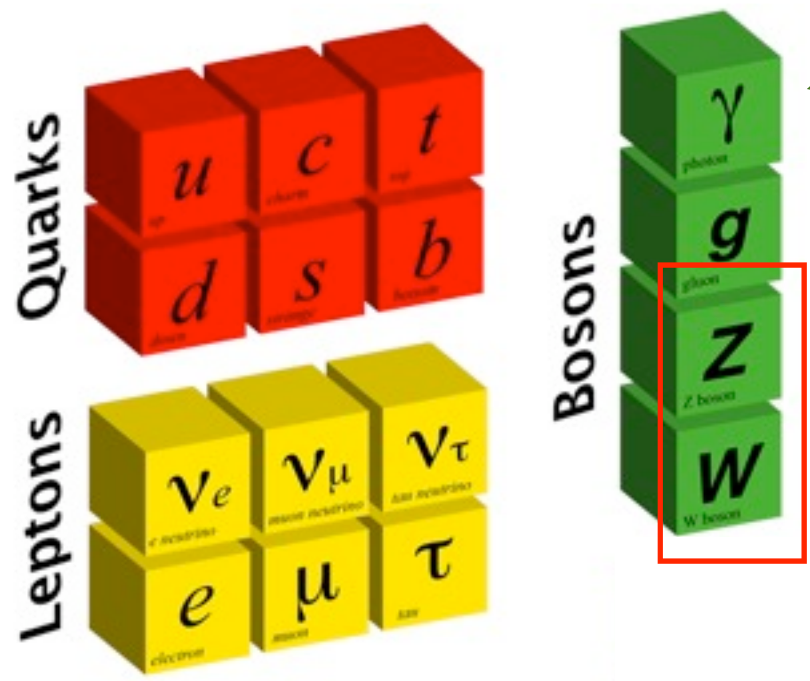
TeV frontier at the LHC



- Search is on for new physics beyond the Standard Model.

The Standard Model

Force carriers



		Interaction strength
Electromagnetic		e
Strong		g_{strong}
Weak		g_{W}

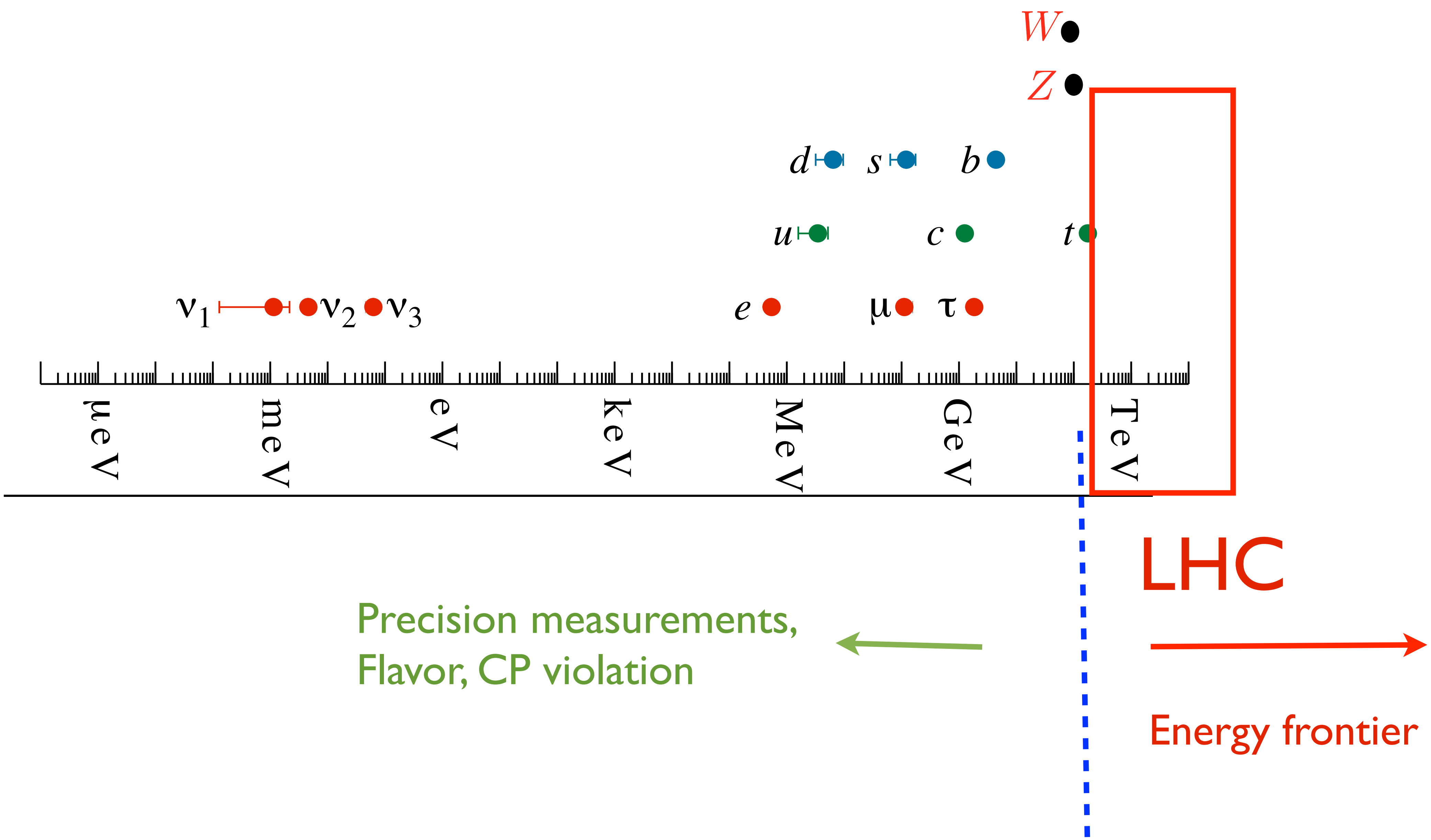
$$m_{\text{W,Z}} \simeq 10^2 \text{ GeV}$$

- Electroweak symmetry breaking: weak interaction has finite range

$$V_{\text{weak}}(r) \approx \frac{e^{-r/r_{\text{W}}}}{r}, \; r_{\text{W}} \approx m^{-1}_{\text{W,Z}} \approx 10^{-17} \text{ m}$$

Fermi, 1934

Expanding the horizon:



- What do we expect at the energy frontier?

New physics beyond the SM?

- Why not?
  - Sure. But we may want to have better arguments, and we do (main goal of these lectures).
- At Hadron colliders, such as the LHC, we need to anticipate what may be there.

Scenarios, frameworks, models...

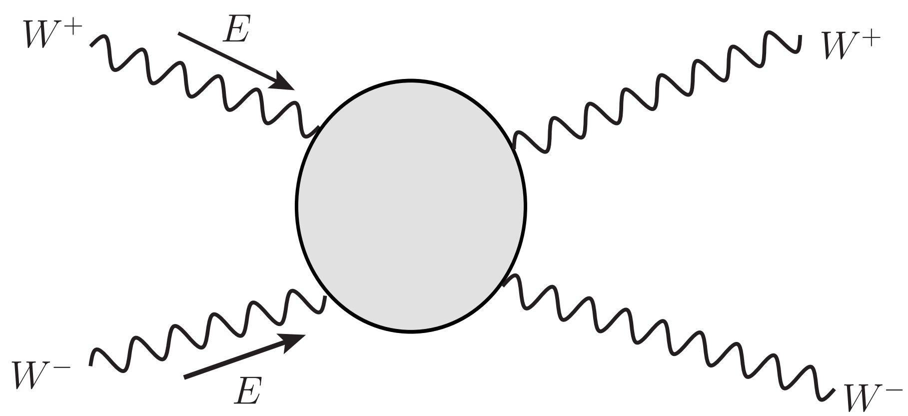
- BSM: beyond the SM, besides the SM, below the SM, ...

These lectures

- A quick survey of BSM new physics.
- Focus on
  - Motivation.
  - Basic ideas, interesting scenarios.
  - Signals at hadron colliders (mainly LHC).
- Would not cover all technical details.
  - See excellent lectures in previous schools.
- Related lectures in this school
  - Sally Dawson: Electroweak theory
  - Roni Harnik: Dark Matter

Standard Model needs to be extended.

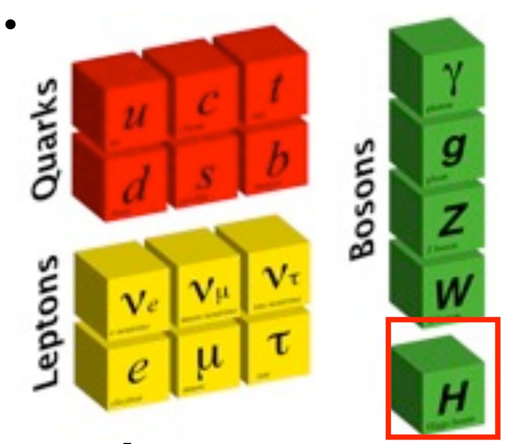
Consider:



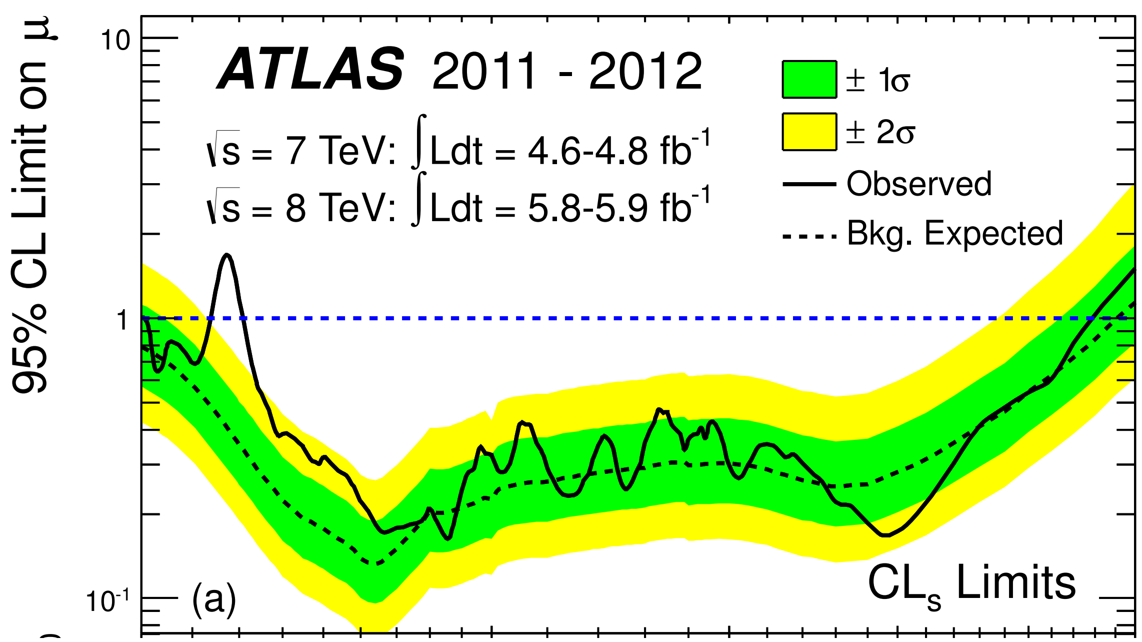
$$\text{Amplitude} \approx g_{\mathrm{W}}^2 \frac{E^2}{m_{\mathrm{W}}^2}$$

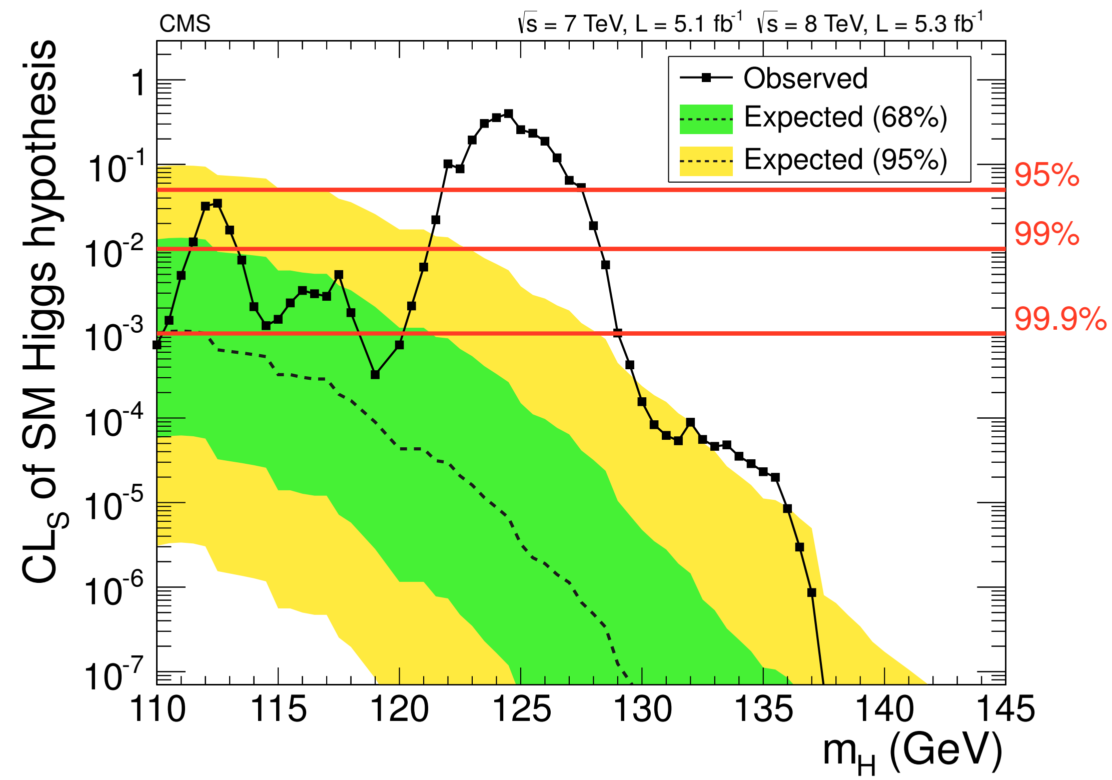
Growing stronger at higher energy.
Perturbative unitarity breaks down.

- Therefore, this picture is not valid at $E \sim 4\pi m_{\mathrm{W}}/g_{\mathrm{W}} \simeq \ \text{TeV}$
- Something new must happen before TeV scale.
- Simplest new physics:
  - The Higgs boson, a spin-0 neutral particle.
  - Higgs field can give mass to both electrons and gauge bosons (W, Z).



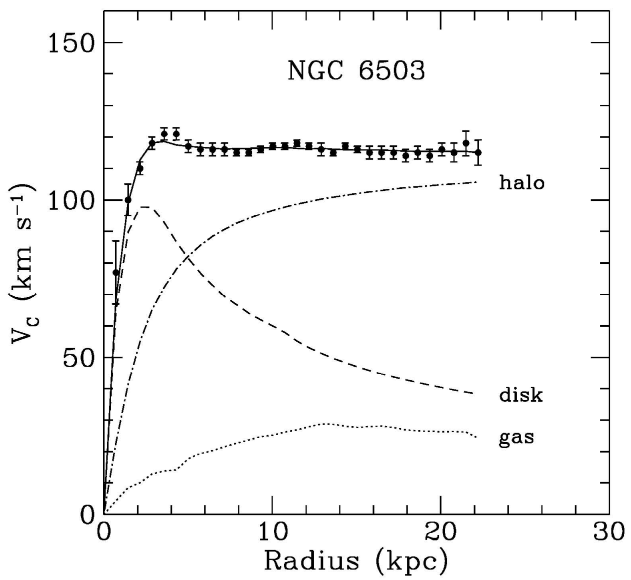
Higgs discovered! (likely)

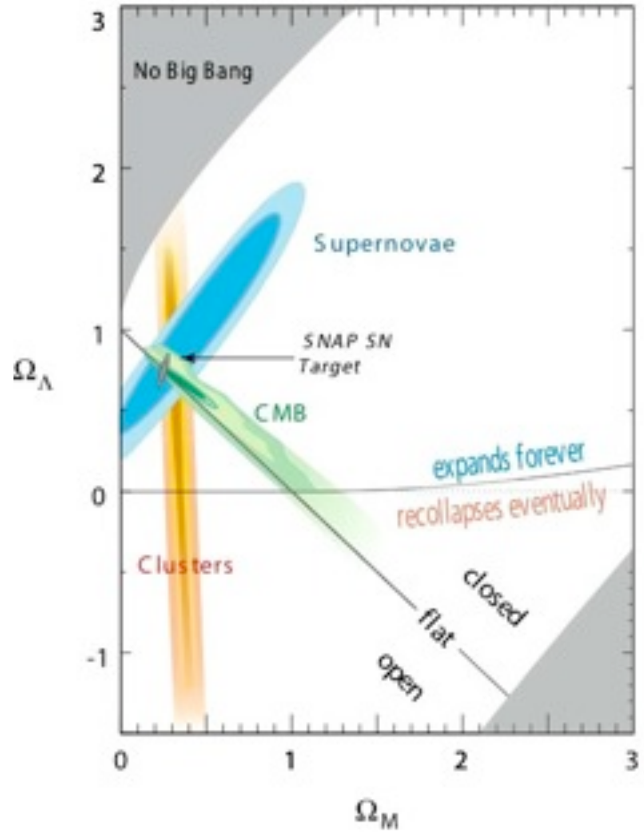


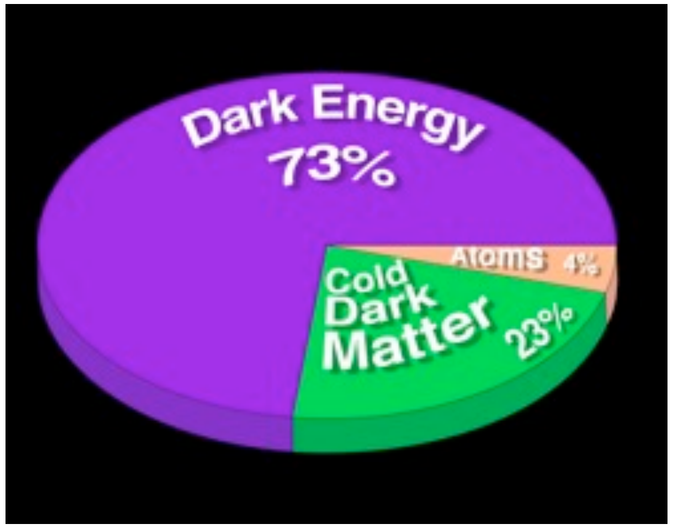


- We have discovered something looks like a Higgs.
  - We need to test whether it is the Higgs boson.

We have solid evidence that dark matter:







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- gravitates.
- is dark.

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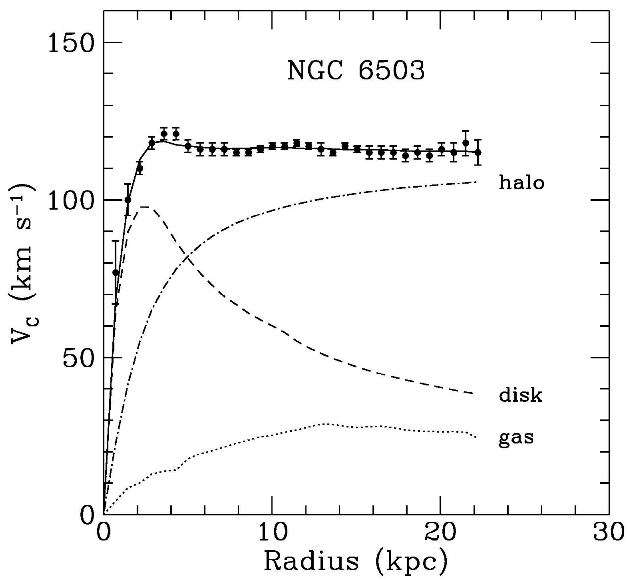

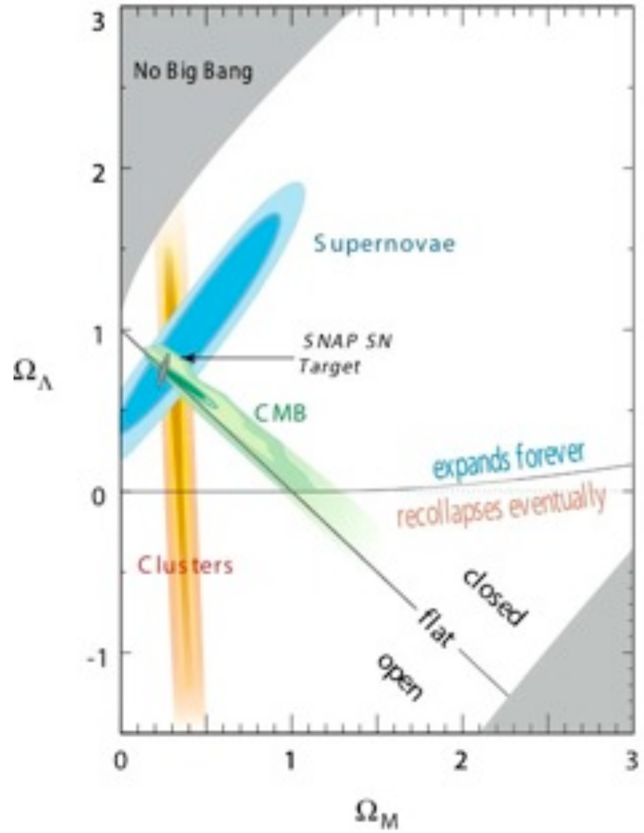

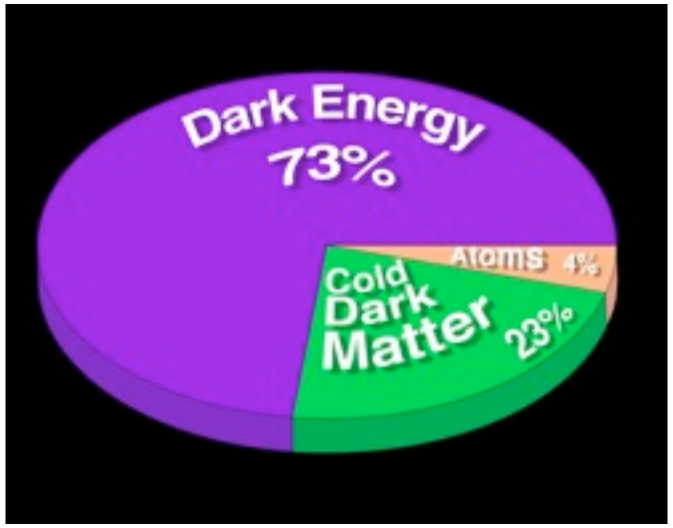

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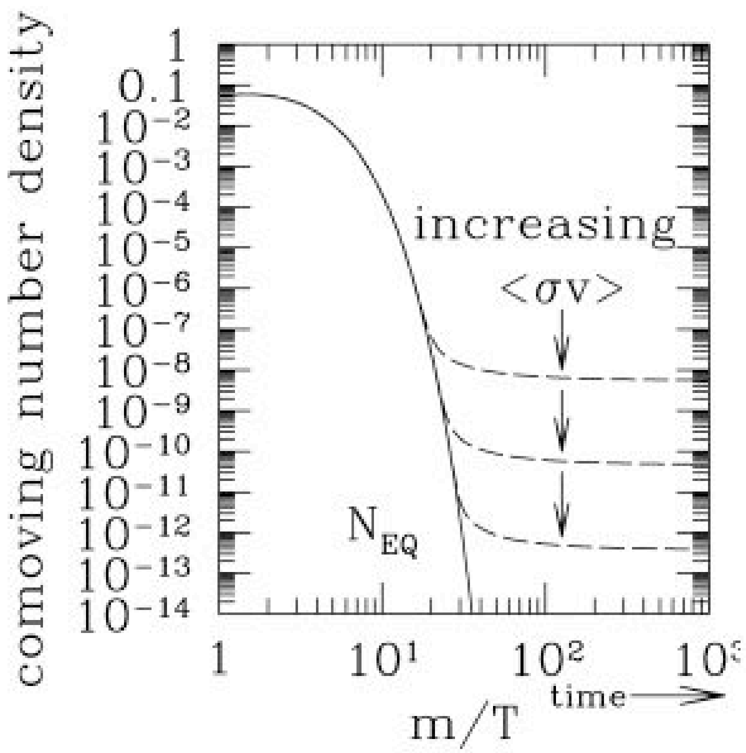
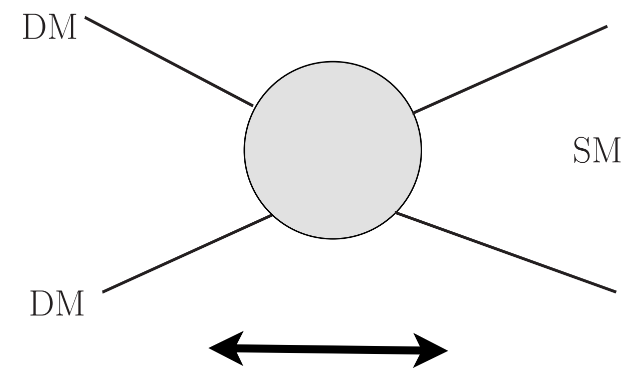
Cannot be SM particle !

TeV dark matter: WIMP miracle.





Rate in thermal eq. $\langle \sigma v \rangle \sim \frac{g_{\rm D}^4}{m_{\rm DM}^2}$

Freeze out: dropping out of thermal eq.

Stronger coupling, lower abundance.

- If dark matter is
  - Weakly interacting: $g_{\rm D} \sim 0.1$
  - Weakscale: $m_{\rm DM} \sim 100{\rm s~GeV} - 1~{\rm TeV}$
  - We get the right relic abundance of dark matter.
- A major hint of TeV scale new physics.
  - We can produce and study them at the LHC!

Naturalness puzzle.

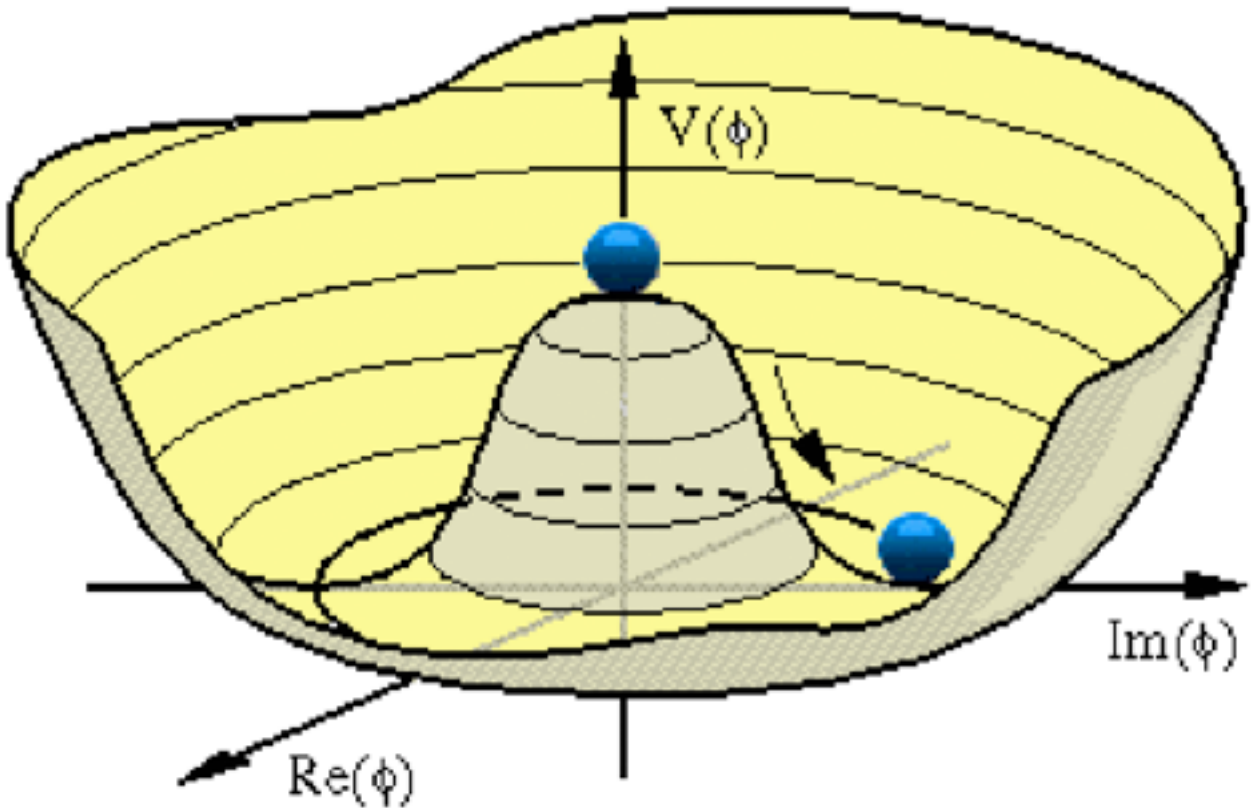
- The masses of W, Z gauge bosons are very different from any known scale. For example, the quantum gravity scale:

$$m_{\rm W,Z} \ll M_{\rm Planck} \simeq 10^{19}\ {\rm GeV}$$

- The question is more serious than just this apparent disparity between scales.
  - Is this generic or plausible in a quantum theory? No.

Weak scale in the SM

Simplest implementation



$$V(\phi) = \frac{1}{2}\mu_h^2\phi^2 + \frac{\lambda}{4}\phi^4$$

ϕ : Charged under weak interaction. Order parameter of EW phase transition.

$$\phi \to \frac{1}{\sqrt{2}}(v + h(x)) \quad m_h = \sqrt{2\lambda}v = \sqrt{\lambda}\left(2\sqrt{2}\frac{m_W}{g_W}\right)$$

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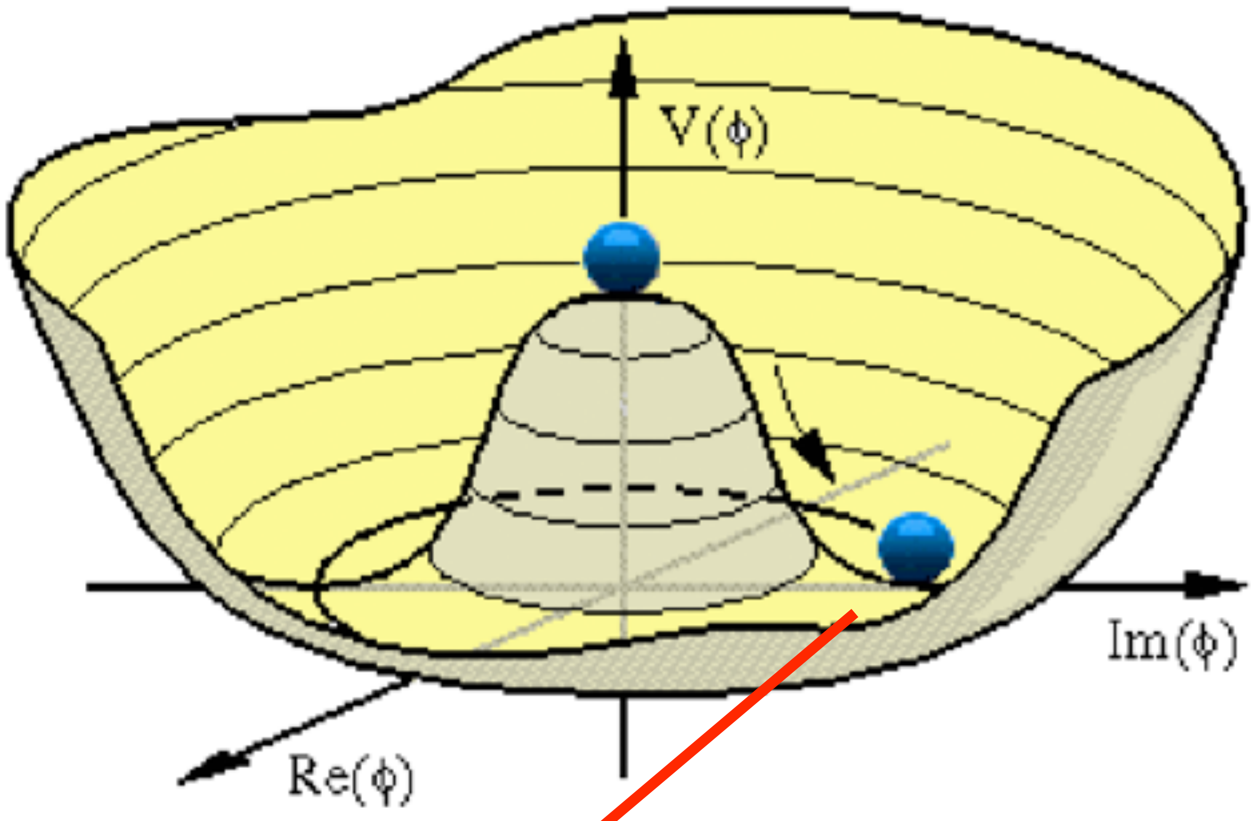

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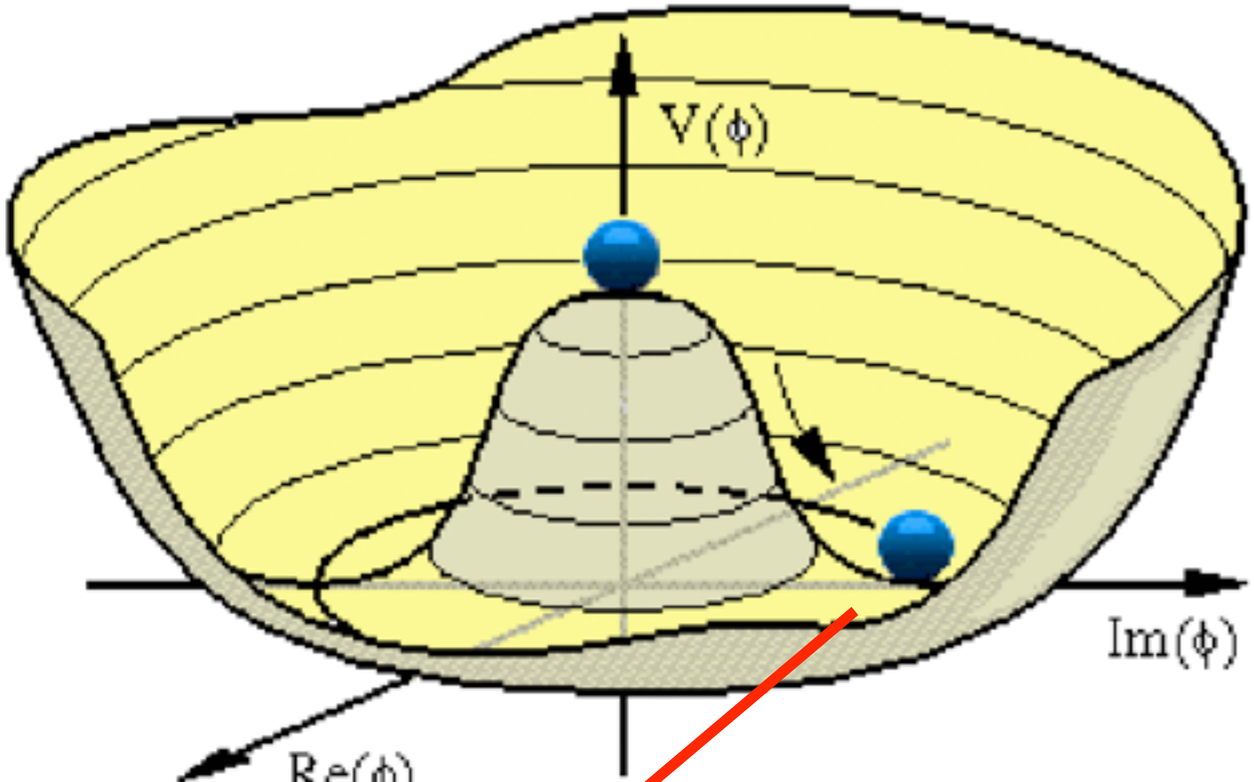

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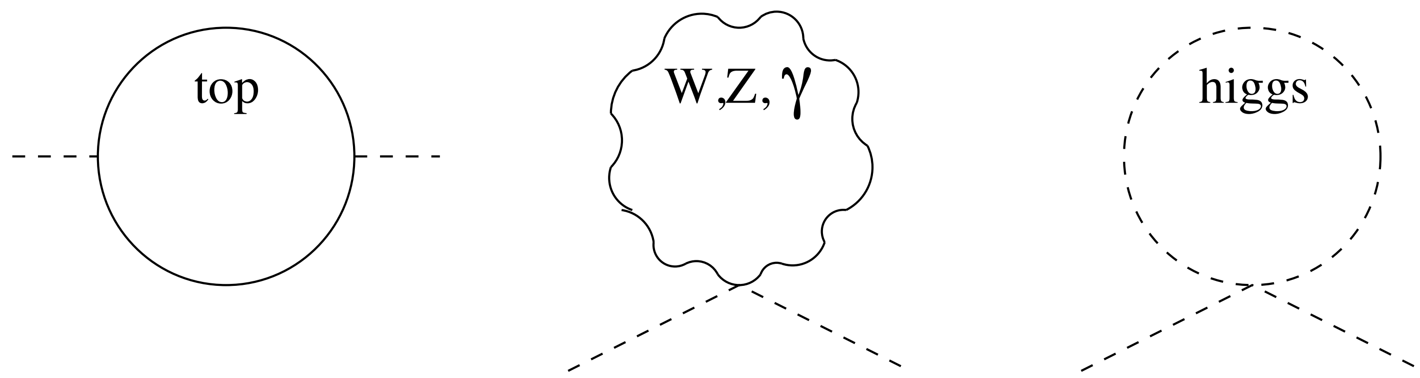
Higgs boson

$m_h \sim m_{W/Z}$!

Scalar (Higgs) mass in quantum theory



$$-\frac{3}{8\pi^2}\lambda_t^2\Lambda^2 \qquad \frac{9}{64\pi^2}g^2\Lambda^2 \qquad \frac{1}{16\pi^2}\lambda^2\Lambda^2$$

Λ: cut-off, limit of validity of theory
scale at which new physics enters

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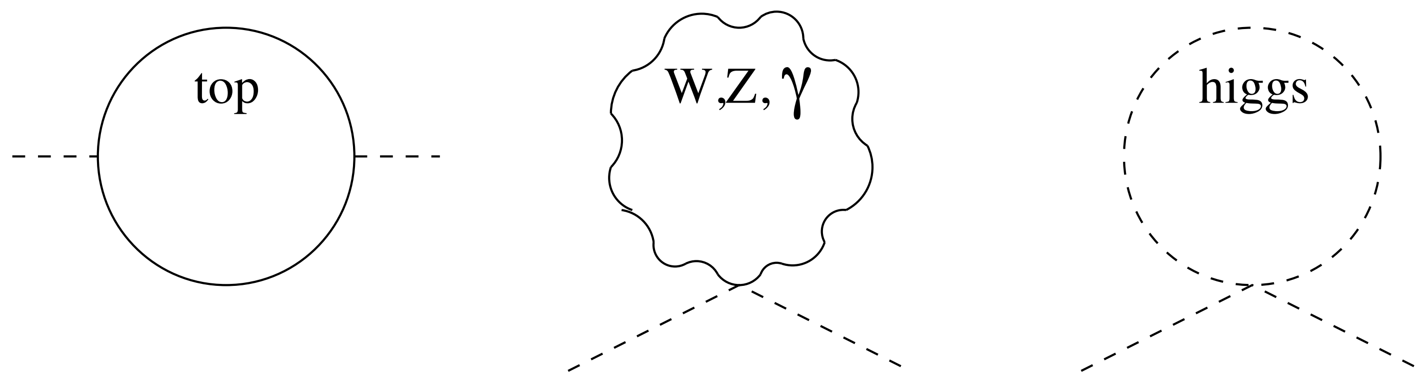

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Λ: cut-off, limit of validity of theory
scale at which new physics enters

- Renormalization
  - m_h^2 (physical) = $m_0^2 + c\ \Lambda^2$
- Counter term m_0^2 can always be adjusted to give correct m_h^2 (physical).

The problem is

- m_h^2 (physical) = $m_0^2 + c\,\Lambda^2$, c some O(0.01) number
- What is Λ?
  - Some fundamental scale beyond the Standard Mode.
  - $\Lambda \approx M_{Pl}$?
- $\Lambda^2 \approx M_{Pl}^2$, m_0^2 must be very close to M_{Pl}^2 . At the same time, they must cancel to the precision of 10^{-32} to have m_h^2 (physical) $\approx$ (100 GeV)^2, fine-tuning.
- Other cut offs? $\Lambda_{GUT} \approx 10^{16}$ GeV, ...

Is this plausible?

- m_h^2 (physical) = $m_0^2 + c\,\Lambda^2$
- In Quantum field theory, we understood this as
  - m_h^2 (physical): mass at weak scale $\sim$ 100 GeV.
  - Counter term m_0^2 : mass for theory at scale Λ
  - $c\,\Lambda^2$: correction to mass due to physics between Λ and weak scale.
- m_0^2 and $c\,\Lambda^2$ come from very different physical origins. Why should they cancel so precisely?

The lesson

The lesson

- Maybe Quantum Field Theory is wrong.
  - Maybe. However, the predictions of QFT, in particular "those loops", are the most precisely tested scientific predictions ever made.
  - "those loops" are among the greatest successes of the Standard Model of particle physics.

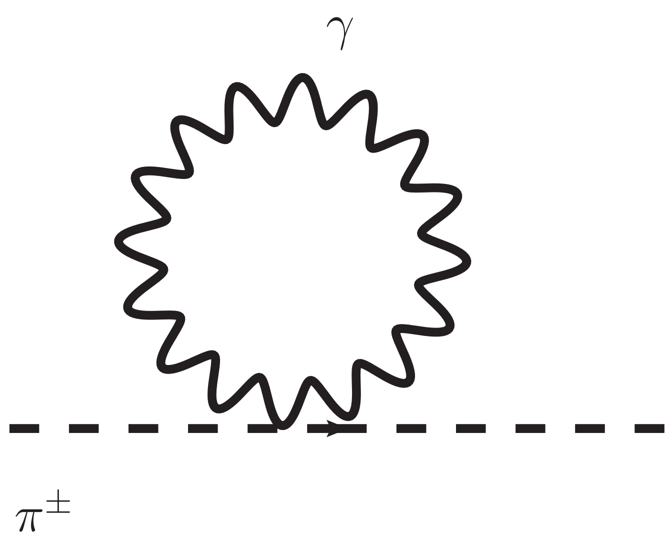
The lesson

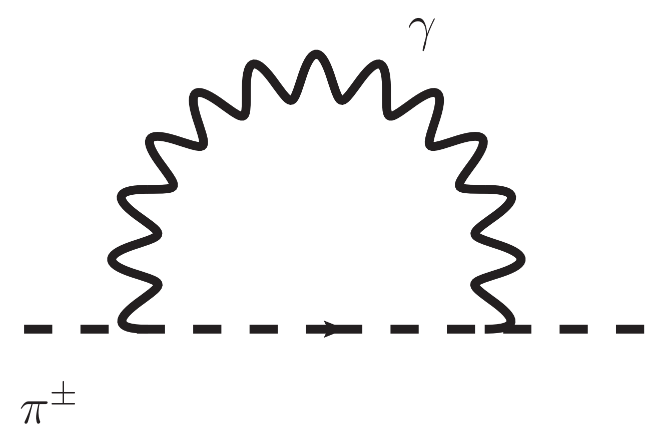
- Maybe Quantum Field Theory is wrong.
  - Maybe. However, the predictions of QFT, in particular "those loops", are the most precisely tested scientific predictions ever made.
  - "those loops" are among the greatest successes of the Standard Model of particle physics.
- So, we take it seriously.
  - m_h^2 (physical) $= m_0^2 + c\,\Lambda^2$
  - No fine-tuning: m_h^2 (physical) $\sim m_0^2 \sim c\,\Lambda^2$

  $\Lambda \approx$ 100s GeV - TeV

  Naturalness criterion leads to a prediction of the mass scale of new physics!!

Does this work?

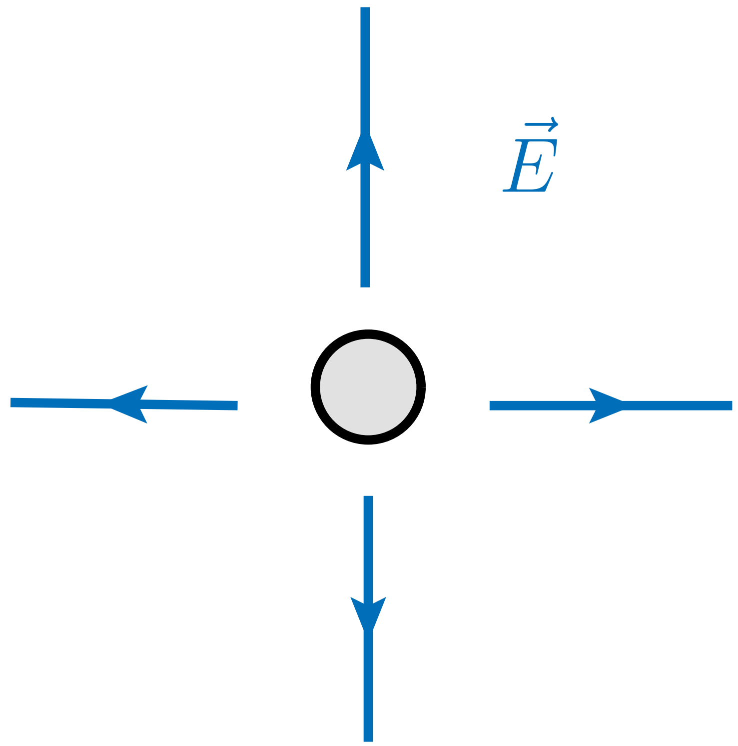




$$\delta m^2_{\pi^{\pm}} \simeq \frac{e^2}{16\pi^2}\Lambda^2$$

- Example: low energy QCD resonances: pion ....
- m_π ~ 100 MeV.
- Naturalness requires $\Lambda \approx$ GeV.
  - Indeed, at GeV, QCD $\Rightarrow$ theory of quark and gluon
  - Pion is not elementary.

Another example: electron mass



Classically:

$$\int_{r=\Lambda^{-1}} d^3r\vec{E}^2 \simeq \alpha\Lambda$$

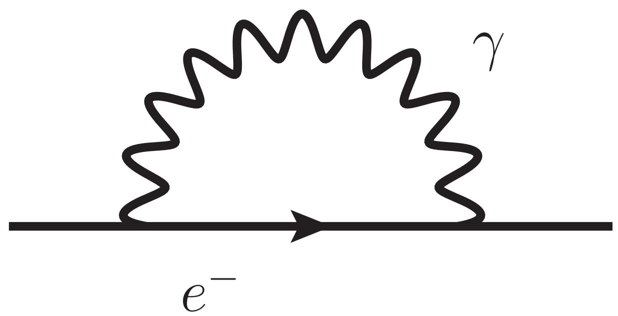
- Linearly divergent.
- Need new physics below $\Lambda \sim \alpha^{-1} m_e$

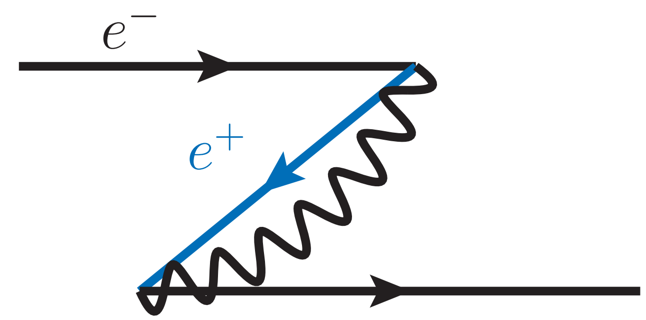
New physics: the positron

$$\delta m_e \simeq \frac{\alpha}{\pi} m_e \log\left(\frac{\Lambda}{m_e}\right)$$

- Extension of spacetime symmetry:
  - Lorentz symmetry + quantum mechanics $\Rightarrow$ positron, doubling the spectrum!
- Log divergence (very mild).
- Proportional to m_e .

New physics: the positron





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    $\Rightarrow$ positron, doubling the spectrum!

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Fermion mass is natural!

Scale of new physics

- m(positron) = m(electron) (CPT).
- New physics can come in at a lower scale then necessary, for a natural theory.

Does not always work

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- Cosmological constant: CC ≈ $(10^{-3}\text{ eV })^4$

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- Computing quantum field theory, most divergent
  - CC$\propto \Lambda^4$
  - New physics at 10^{-3} eV, or at about 1 mm!
  - We have not seen them!

Does not always work

- Cosmological constant: CC $\approx$ (10^{-3} eV $)^4$
- Computing quantum field theory, most divergent
  - CC$\propto$ Λ^4
  - New physics at 10^{-3} eV, or at about 1 mm!
  - We have not seen them!
- Doesn't mean it is not a problem. Instead, We are missing something big!
  - Missing dynamics of gravity?
  - Multiverse?

Naturalness of the weak scale.
Example 1: Supersymmetry

References:

S. Martin, "A supersymmetry primer", hep-ph/9709356
M. Drees, R. Godbole, P. Roy "Sparticles" World Scientific.
And many more...

Supersymmetry (SUSY)

- Supersymmetry: $|\mathrm{boson}\rangle \Leftrightarrow |\mathrm{fermion}\rangle$
- A different kind of symmetry
  - boson, spin-0, does not transform under rotation.
  - Fermion, spin-1/2, transforms non-trivially under rotation.
  - Therefore, a symmetry which transforms boson to fermion must be a space-time symmetry, an extension of known spacetime symmetry (Poincare).

Supermultiplets.

- In writing down interactions invariant under some symmetry, it is convenient to group all states which transform into each other under the symmetry transformation together, called a **multiplet**.

- In supersymmetry, we use supermultiplet.
  - Will have fermionic and bosonic components, same mass.
  - SUSY commute with other global or gauge symmetries.
    - Within a supermultiplet, states have the same gauge (or global) quantum numbers (i.e., representation, charge).

Supermultiplets

- Chiral multiplet
  - On-shell: free particles.
  - complex scalar: ϕ, two on-shell degrees of freedom
  - Weyl fermion (2-component): ψ, two on-shell degrees of freedom.
- Examples of chiral multiplet
  - Starting from SM model quark (left or right handed), $q_{L,R}$
  - Adding scalar partner: squark. $\tilde{q}_{L,R}$
  - Form a chiral multiplet.

Supermultiplets

- Vector multiplet (on-shell).
  - Spin-1: vector A_μ (massless, 2 degrees of freedom)
  - Weyl fermion: λ (2 d.o.f.)
- Example:
  - Starting with SM gauge bosons, such as the 8 gluons $G^a{}_\mu$ (a=1, ..., 8)
  - Adding their partners, $\tilde{g}^a$ 8 gluinos.

SUSY and naturalness

- Remember (an important part of) the problem is that scalar mass in a generic theory requires fine-tuning.
- We have also seen that fermion mass (such as electron mass) is natural.
- SUSY makes scalar mass natural by relating it to fermion mass!
- SUSY extends the spacetime symmetry, doubles the spectrum, and delivers naturalness.
  - Similar to the electron story (extending to Lorentz symmetry, introducing positron.)

First consequence of SUSY

- Each known elementary particles must belong to a supermultiplet, has a superpartner.

SM int.	gauge boson, spin-1	Super-partner, spin-1/2
$SU(3)_C$	g^a, $a = 1, 2, ..., 8$	gluino: $\tilde{g}^a$
$SU(2)_L$	$W_{1,2,3}$	wino: $\tilde{W}_{1,2,3}$
$U(1)_Y$	B_μ	bino: $\tilde{B}$

squarks, quarks	Q	$(\widetilde{u}_L \ \ \widetilde{d}_L)$	$(u_L \ \ d_L)$	$(\mathbf{3}, \mathbf{2}, \frac{1}{6})$
($\times 3$ families)	$\overline{u}$	$\widetilde{u}_R^*$	$u_R^\dagger$	$(\overline{\mathbf{3}}, \mathbf{1}, -\frac{2}{3})$
	$\overline{d}$	$\widetilde{d}_R^*$	$d_R^\dagger$	$(\overline{\mathbf{3}}, \mathbf{1}, \frac{1}{3})$
sleptons, leptons	L	$(\widetilde{\nu} \ \widetilde{e}_L)$	$(\nu \ \ e_L)$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$
($\times 3$ families)	$\overline{e}$	$\widetilde{e}_R^*$	$e_R^\dagger$	$(\mathbf{1}, \mathbf{1}, 1)$
Higgs, higgsinos	H_u	$(H_u^+ \ \ H_u^0)$	$(\widetilde{H}_u^+ \ \ \widetilde{H}_u^0)$	$(\mathbf{1}, \mathbf{2}, +\frac{1}{2})$
	H_d	$(H_d^0 \ \ H_d^-)$	$(\widetilde{H}_d^0 \ \ \widetilde{H}_d^-)$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$

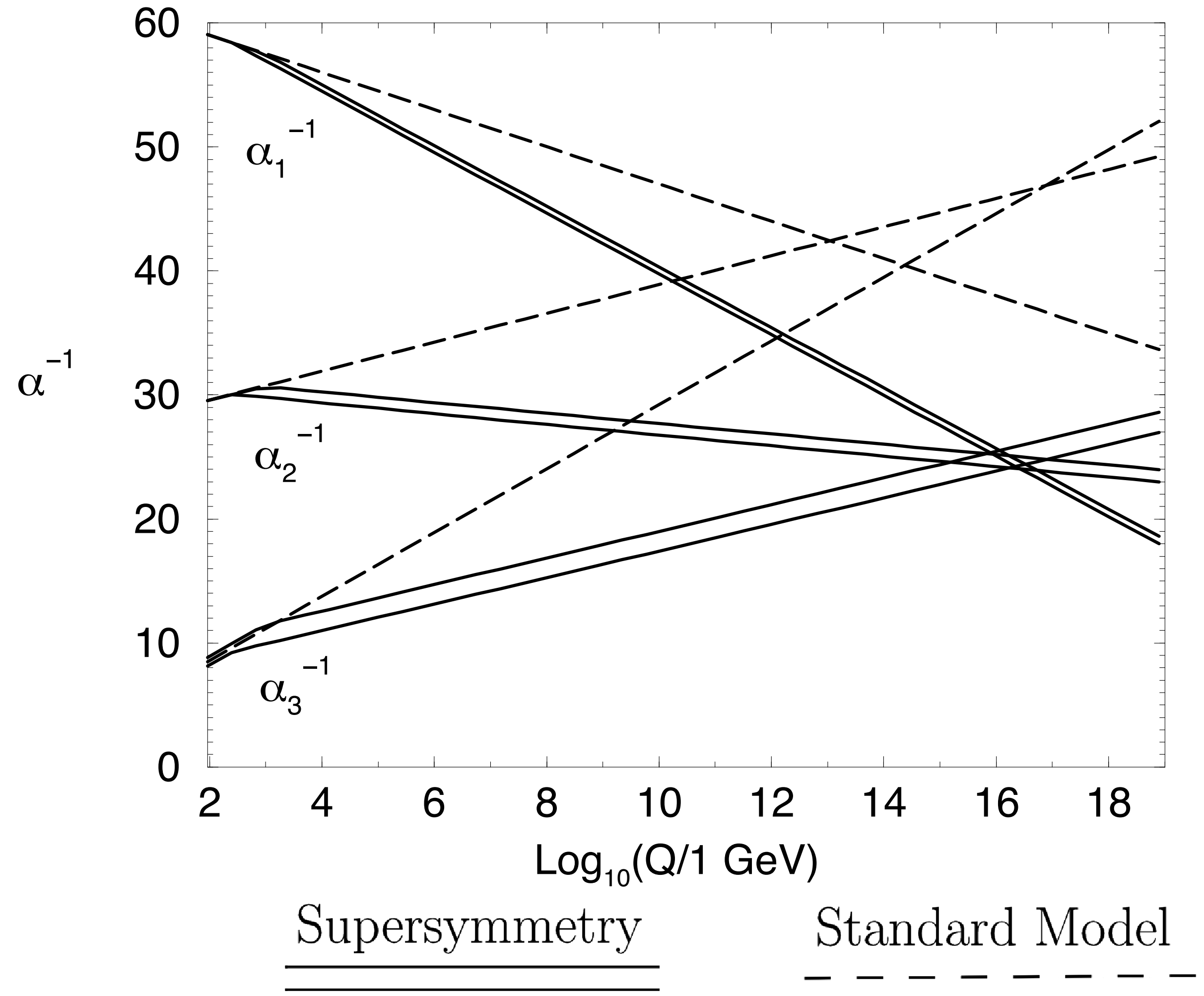
Minimal Supersymmetric Standard Model (MSSM)

Supersymmetry: a theorist's dream

- A new paradigm. First extension of spacetime symmetry since Einstein.

From 3 SM gauge couplings,

define: $\alpha_{1,2,3} = \dfrac{g_{1,2,3}^2}{4\pi}$



- Gauge coupling unification!
  - An unintended and amazing consequence of SUSY.

Interactions.

More details: for example, S. Martin "Supersymmmetry Primer"

- Superpartners have the same gauge quantum numbers as their SM counter parts.
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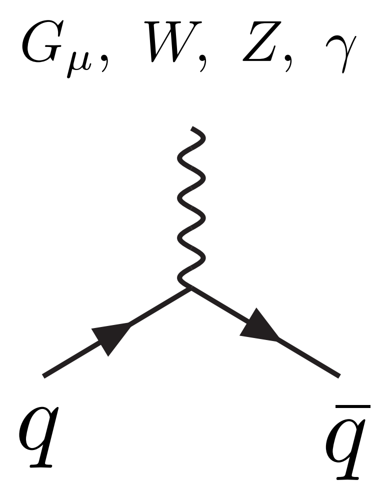

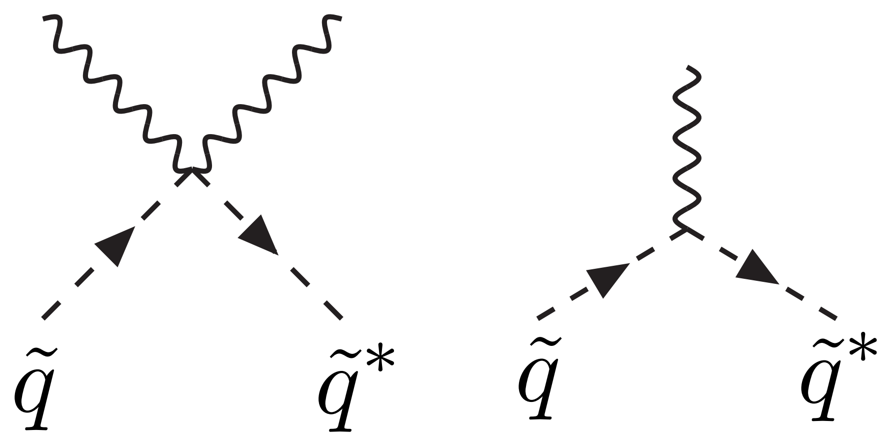

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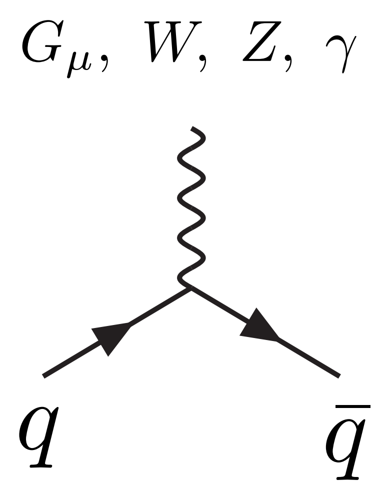
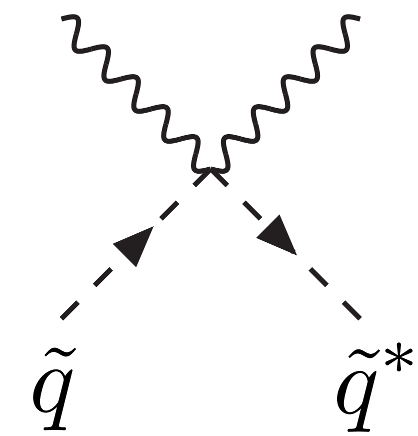
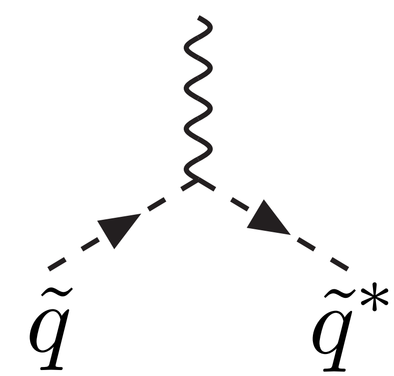
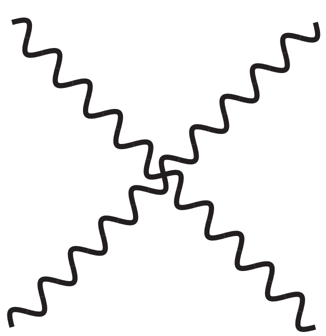
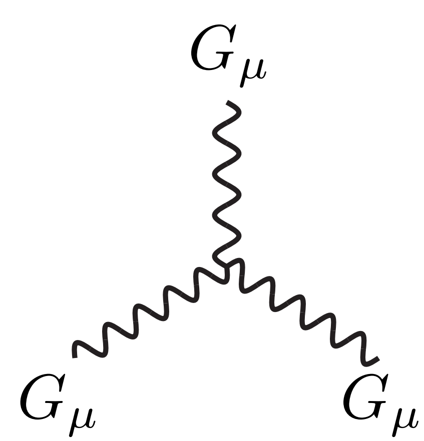


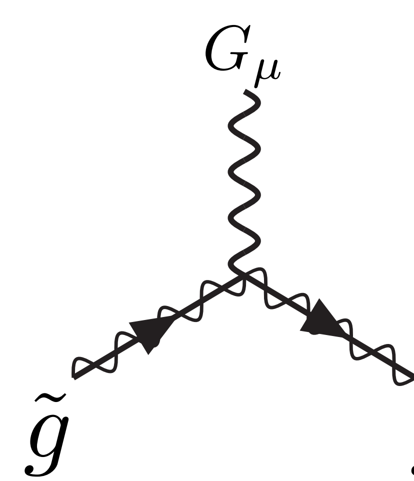




non-Abelian







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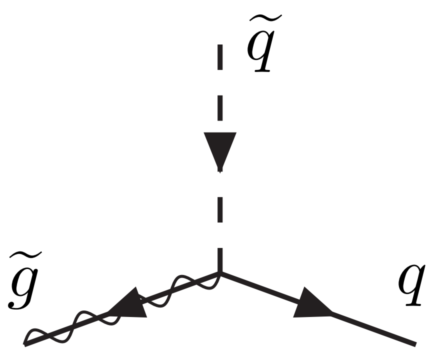

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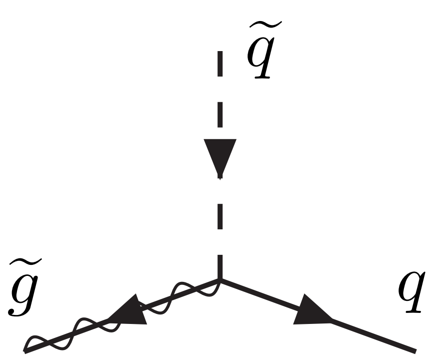
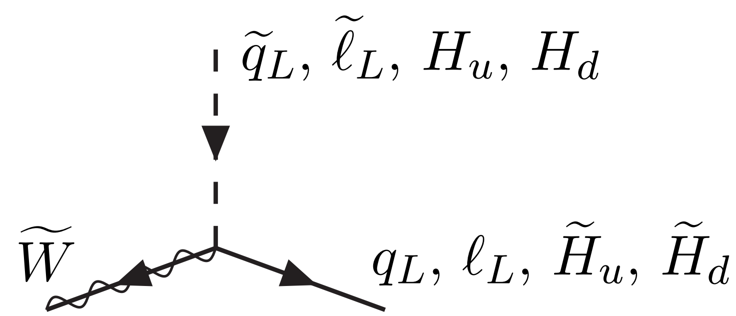


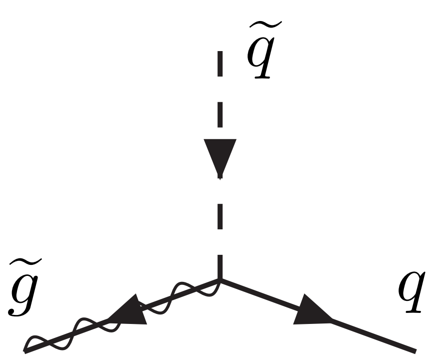
SU(2)$_{\text{L}}$



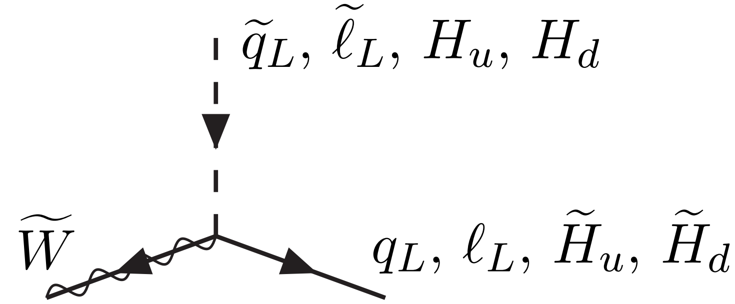
Interactions.

- SUSY$\Rightarrow$ additional couplings
  - strength fixed by corresponding gauge couplings.

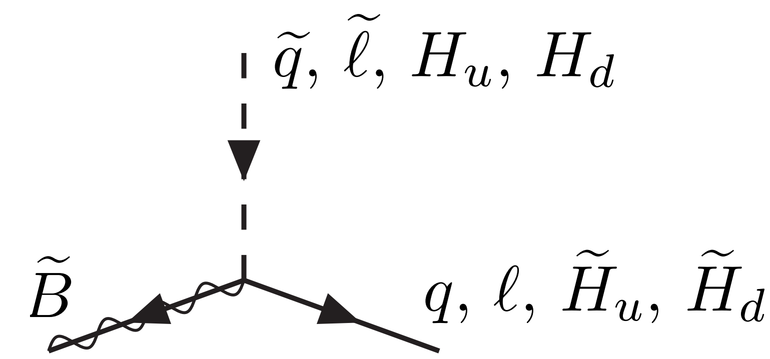
$SU(3)_{color}$



$SU(2)_L$



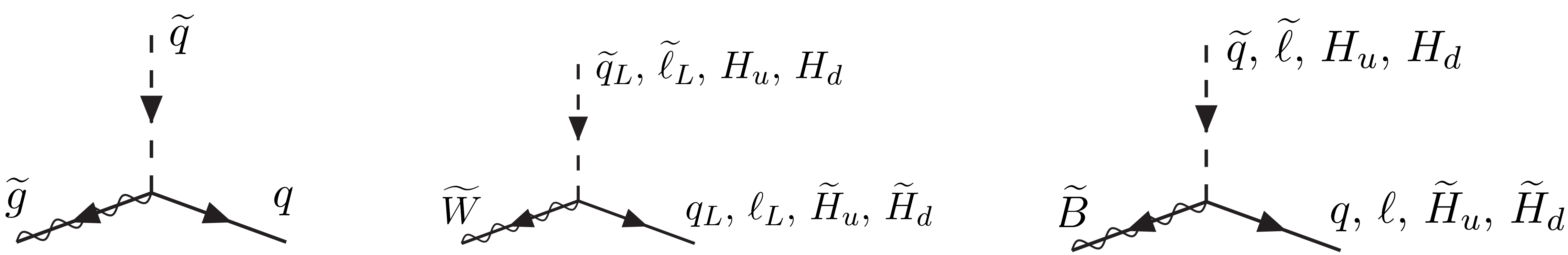
$U(1)_Y$



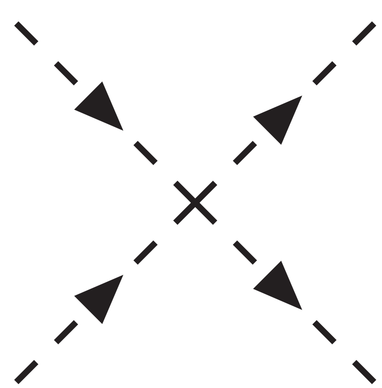
Interactions.

- SUSY$\Rightarrow$ additional couplings
  - strength fixed by corresponding gauge couplings.

$SU(3)_{color}$ $SU(2)_L$ $U(1)_Y$

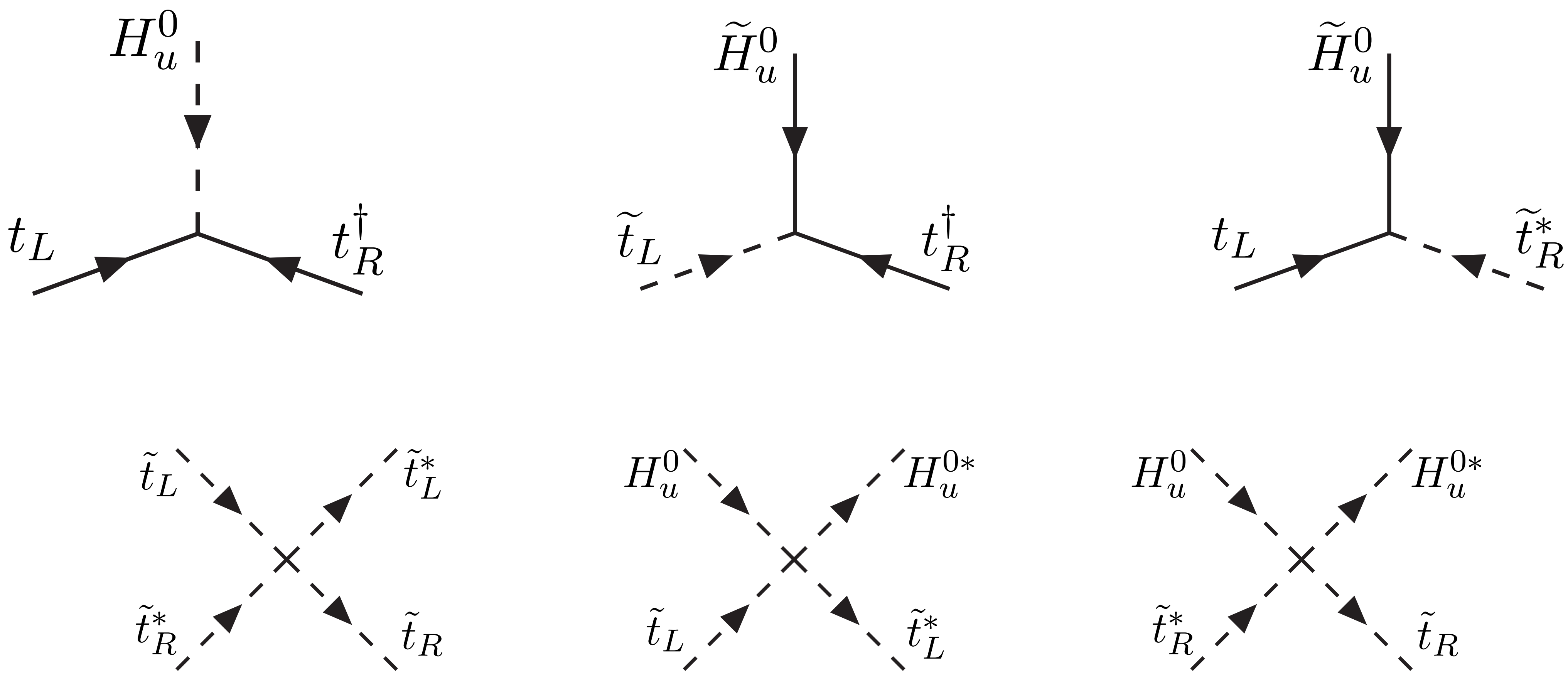


D-term: $\propto$ **g^2**



Interactions.

- SM fermions (such as the top quark) receive masses by coupling to the Higgs boson.
  - Yukawa couplings ⇒ SUSY counter parts.



Superpartners.

- We have not seen any of the superpartner yet.
  - They must be heavier than the SM particles.
- Therefore, SUSY must be a broken symmetry.
- Are we back to the beginning?
  - No.
  - SUSY can be broken in a controlled way so that the theory stays natural, soft SUSY breaking.

Superpartner mass and naturalness

- m_h^2 (physical) = $m_0^2 + c\,\Lambda^2$, c some O(0.01) number.

- New physics needed at $\Lambda \approx$ 100s GeV - TeV
  - This should be the superpartner mass for a natural theory.

- At higher energies, the theory is approximately supersymmetric. Therefore, scalar mass would be be sensitive to what happens at higher energy scales.
  - m_h^2 (physical) = $m_0^2 + c\, m(\text{superpartner})^2$

The masses of the superpartners

$$\begin{aligned}
\mathcal{L}_{\text{soft}}^{\text{MSSM}} \quad = \quad & -\frac{1}{2}\left(M_3\widetilde{g}\widetilde{g} + M_2\widetilde{W}\widetilde{W} + M_1\widetilde{B}\widetilde{B} + \text{c.c.}\right) \\
& - \left(\widetilde{\overline{u}}\,\mathbf{a_u}\,\widetilde{Q}H_u - \widetilde{\overline{d}}\,\mathbf{a_d}\,\widetilde{Q}H_d - \widetilde{\overline{e}}\,\mathbf{a_e}\,\widetilde{L}H_d + \text{c.c.}\right) \\
& - \widetilde{Q}^\dagger\,\mathbf{m_Q^2}\,\widetilde{Q} - \widetilde{L}^\dagger\,\mathbf{m_L^2}\,\widetilde{L} - \widetilde{\overline{u}}\,\mathbf{m_{\overline{u}}^2}\,\widetilde{\overline{u}}^\dagger - \widetilde{\overline{d}}\,\mathbf{m_{\overline{d}}^2}\,\widetilde{\overline{d}}^\dagger - \widetilde{\overline{e}}\,\mathbf{m_{\overline{e}}^2}\,\widetilde{\overline{e}}^\dagger \\
& - m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d - \left(bH_uH_d + \text{c.c.}\right).
\end{aligned}$$

The masses of the superpartners

$$\begin{aligned}
\mathcal{L}_{\rm soft}^{\rm MSSM} = & \boxed{-\frac{1}{2}\left(M_3\widetilde{g}\widetilde{g} + M_2\widetilde{W}\widetilde{W} + M_1\widetilde{B}\widetilde{B} + \text{c.c.}\right)} \\
& -\left(\widetilde{\overline{u}}\,\mathbf{a_u}\,\widetilde{Q}H_u - \widetilde{\overline{d}}\,\mathbf{a_d}\,\widetilde{Q}H_d - \widetilde{\overline{e}}\,\mathbf{a_e}\,\widetilde{L}H_d + \text{c.c.}\right) \\
& -\widetilde{Q}^\dagger\,\mathbf{m^2_Q}\,\widetilde{Q} - \widetilde{L}^\dagger\,\mathbf{m^2_L}\,\widetilde{L} - \widetilde{\overline{u}}\,\mathbf{m^2_{\overline{u}}}\,\widetilde{\overline{u}}^\dagger - \widetilde{\overline{d}}\,\mathbf{m^2_{\overline{d}}}\,\widetilde{\overline{d}}^\dagger - \widetilde{\overline{e}}\,\mathbf{m^2_{\overline{e}}}\,\widetilde{\overline{e}}^\dagger \\
& - m^2_{H_u}H_u^*H_u - m^2_{H_d}H_d^*H_d - (bH_uH_d + \text{c.c.})\,.
\end{aligned}$$

Gaugino masses

The masses of the superpartners

$$
\begin{aligned}
\mathcal{L}_{\text{soft}}^{\text{MSSM}} \;=\; & -\frac{1}{2}\left(M_3\widetilde{g}\widetilde{g} + M_2\widetilde{W}\widetilde{W} + M_1\widetilde{B}\widetilde{B} + \text{c.c.}\right) \\
& \boxed{-\left(\widetilde{\overline{u}}\,\mathbf{a_u}\,\widetilde{Q}H_u - \widetilde{\overline{d}}\,\mathbf{a_d}\,\widetilde{Q}H_d - \widetilde{\overline{e}}\,\mathbf{a_e}\,\widetilde{L}H_d + \text{c.c.}\right)} \\
& -\widetilde{Q}^\dagger\,\mathbf{m_Q^2}\,\widetilde{Q} - \widetilde{L}^\dagger\,\mathbf{m_L^2}\,\widetilde{L} - \widetilde{\overline{u}}\,\mathbf{m_{\overline{u}}^2}\,\widetilde{\overline{u}}^\dagger - \widetilde{\overline{d}}\,\mathbf{m_{\overline{d}}^2}\,\widetilde{\overline{d}}^\dagger - \widetilde{\overline{e}}\,\mathbf{m_{\overline{e}}^2}\,\widetilde{\overline{e}}^\dagger \\
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\end{aligned}
$$

trilinear,
similar to Yukawa

The masses of the superpartners

$$
\begin{aligned}
\mathcal{L}_{\rm soft}^{\rm MSSM} \;=\; & -\frac{1}{2}\left(M_3\widetilde{g}\widetilde{g} + M_2\widetilde{W}\widetilde{W} + M_1\widetilde{B}\widetilde{B} + {\rm c.c.}\right) \\
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& - m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d - (bH_uH_d + {\rm c.c.})\,.
\end{aligned}
$$

sfermion masses

The masses of the superpartners

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& - m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d - (bH_uH_d + \text{c.c.})\,.
\end{aligned}$$

General parameterization

$$
\begin{aligned}
\mathcal{L}_{\rm soft}^{\rm MSSM} \;=\;& -\frac{1}{2}\left(M_3 \widetilde{g}\widetilde{g} + M_2 \widetilde{W}\widetilde{W} + M_1 \widetilde{B}\widetilde{B} + {\rm c.c.} \right) \\
& - \left(\widetilde{\overline{u}}\, \mathbf{a_u}\, \widetilde{Q} H_u - \widetilde{\overline{d}}\, \mathbf{a_d}\, \widetilde{Q} H_d - \widetilde{\overline{e}}\, \mathbf{a_e}\, \widetilde{L} H_d + {\rm c.c.} \right) \\
& - \widetilde{Q}^\dagger\, \mathbf{m^2_Q}\, \widetilde{Q} - \widetilde{L}^\dagger\, \mathbf{m^2_L}\, \widetilde{L} - \widetilde{\overline{u}}\, \mathbf{m^2_{\overline{u}}}\, \widetilde{\overline{u}}^\dagger - \widetilde{\overline{d}}\, \mathbf{m^2_{\overline{d}}}\, \widetilde{\overline{d}}^\dagger - \widetilde{\overline{e}}\, \mathbf{m^2_{\overline{e}}}\, \widetilde{\overline{e}}^\dagger \\
& - m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d - (b H_u H_d + {\rm c.c.}) \, .
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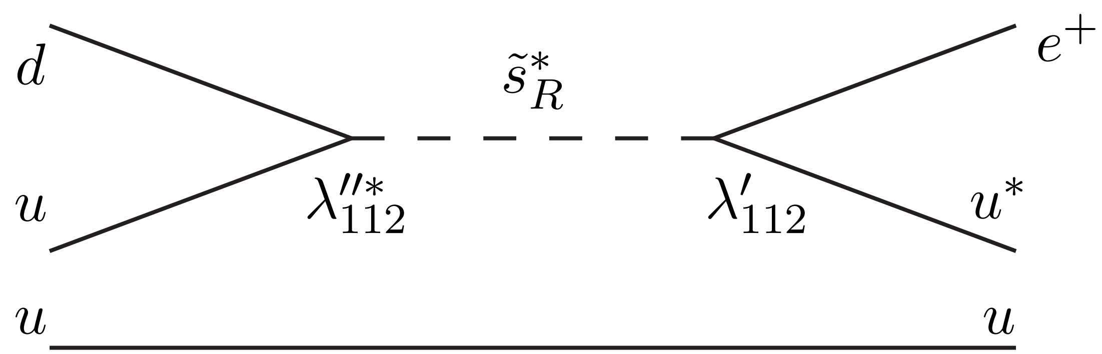
& - m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d - (bH_uH_d + \text{c.c.})\,.
\end{aligned}
$$

- > 100 parameters.
  - Too many? Have to include all of them in the most general theory.
  - Most of them, flavor mixing, CP phases, are strongly constrained to vanish.
  - A theory of SUSY breaking typically contain much less (< 10-ish) parameters.

More couplings?

- Gauge invariance and SUSY allows for more couplings. For example



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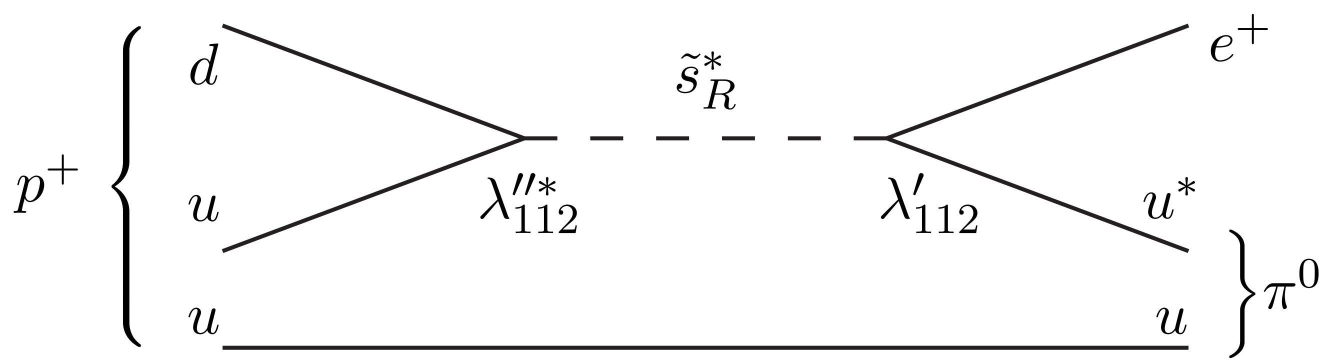

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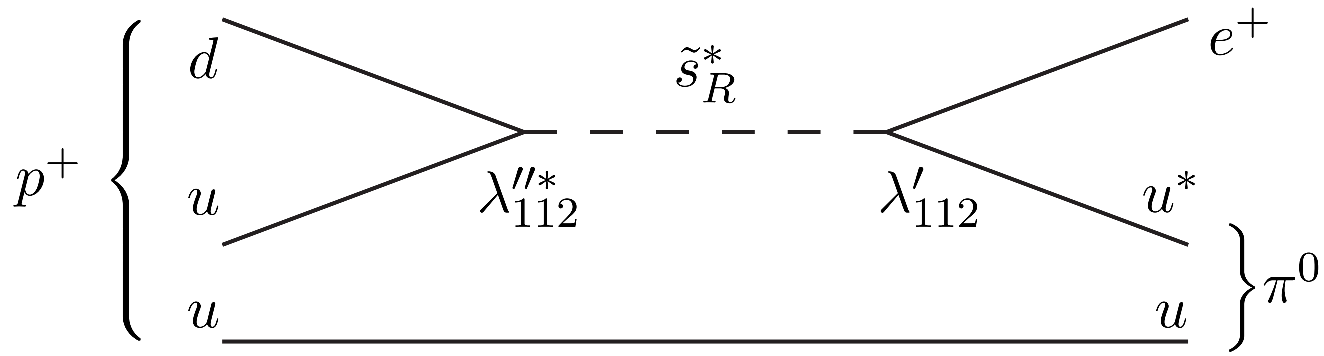

Proton decay: $$\Gamma_{p\to e^+\pi^0} \sim m^5_{\text{proton}} \sum_{i=2,3} |\lambda'^{11i}\lambda''^{11i}|^2 / m^4_{\tilde{d}_i}$$

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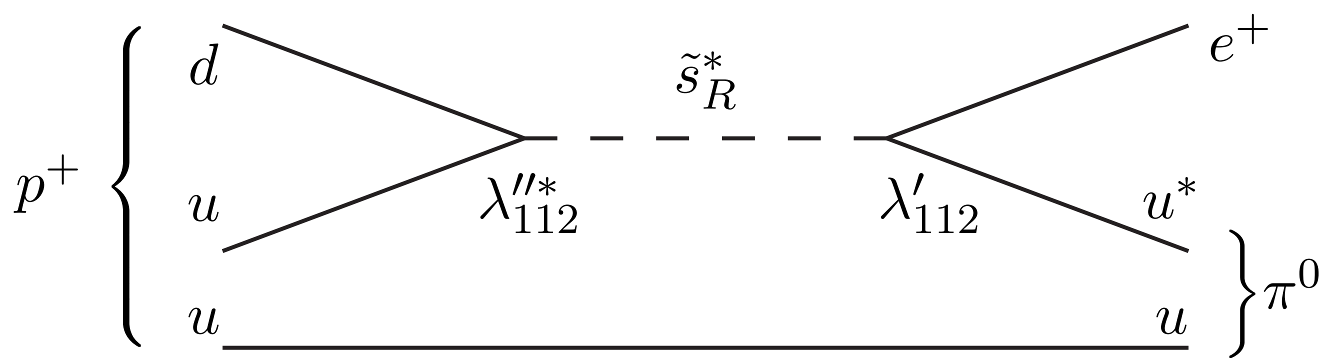


Proton decay: $$\Gamma_{p\to e^+\pi^0} \sim m_{\text{proton}}^5 \sum_{i=2,3} |\lambda'^{11i}\lambda''^{11i}|^2 / m_{\tilde{d}_i}^4$$

These couplings must be extremely tiny!

A symmetry:

- Vanishing couplings usually come from a symmetry principle.
- Could impose B (B_{quark} = 1/3) or L (L_{lepton} = 1) symmetry. Slightly uncomfortable
  - Not exact symmetries in the SM.
- An interesting choice: R-parity

$$P_R = (-1)^{3(\mathrm{B}-\mathrm{L})+2s}$$

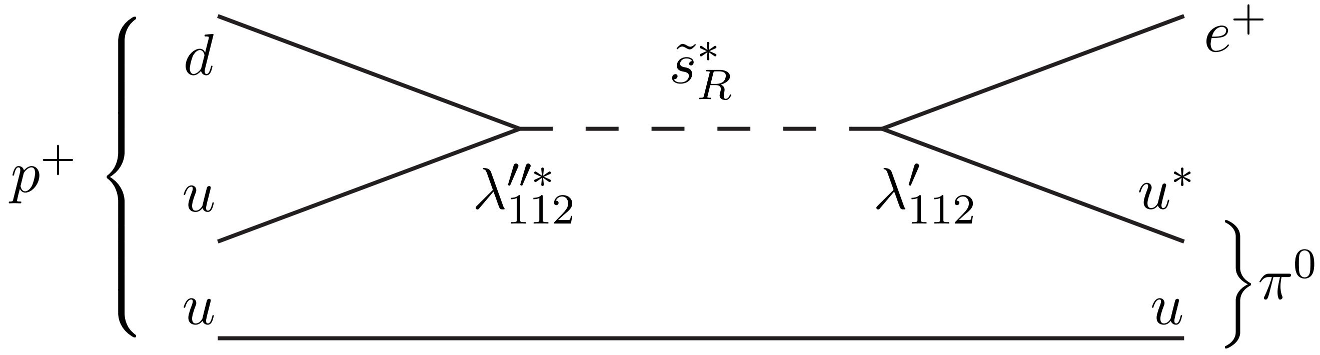
R-parity

$$P_R = (-1)^{3(\mathrm{B}-\mathrm{L})+2s}$$

SM	spin	(super)partner	spin
gluon, g	1	gluino: $\tilde{g}$	1/2
$W^{\pm}, Z$	1	gaugino: $\tilde{W}^{\pm}, \tilde{Z}$	1/2
quark: q	1/2	squark: $\tilde{q}$	0
...		...	

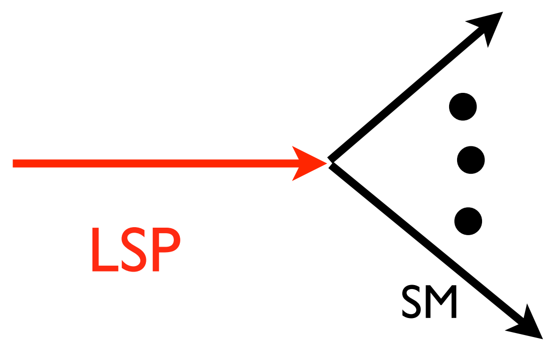
– All superpartners are odd under R-parity.

R-parity



forbidden!

Lightest SuperPartner (LSP) is stable



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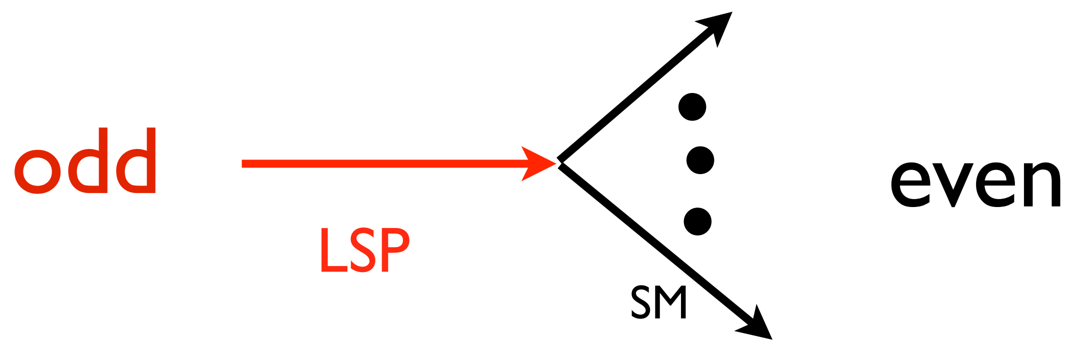

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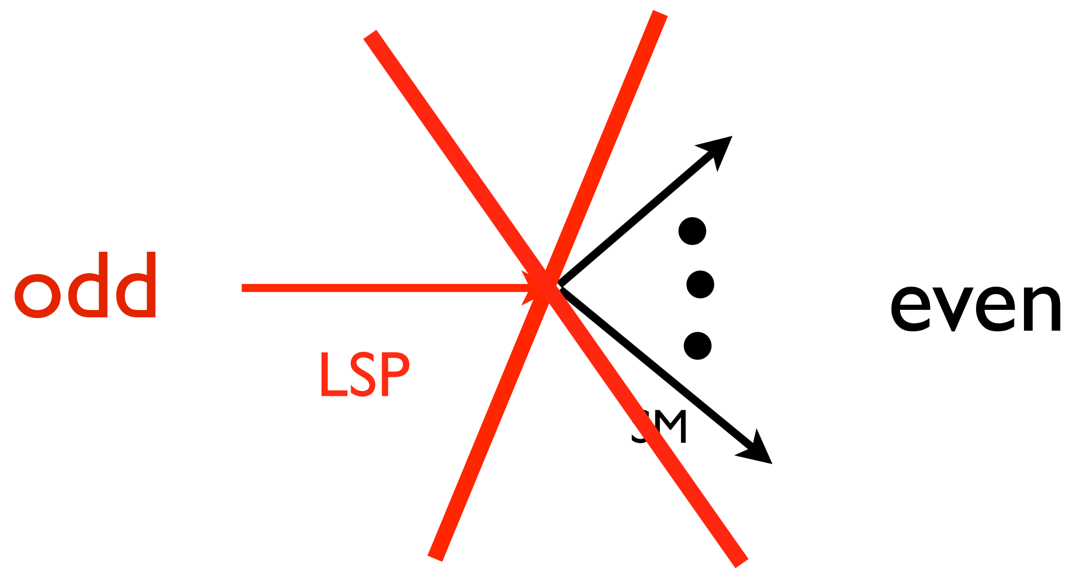

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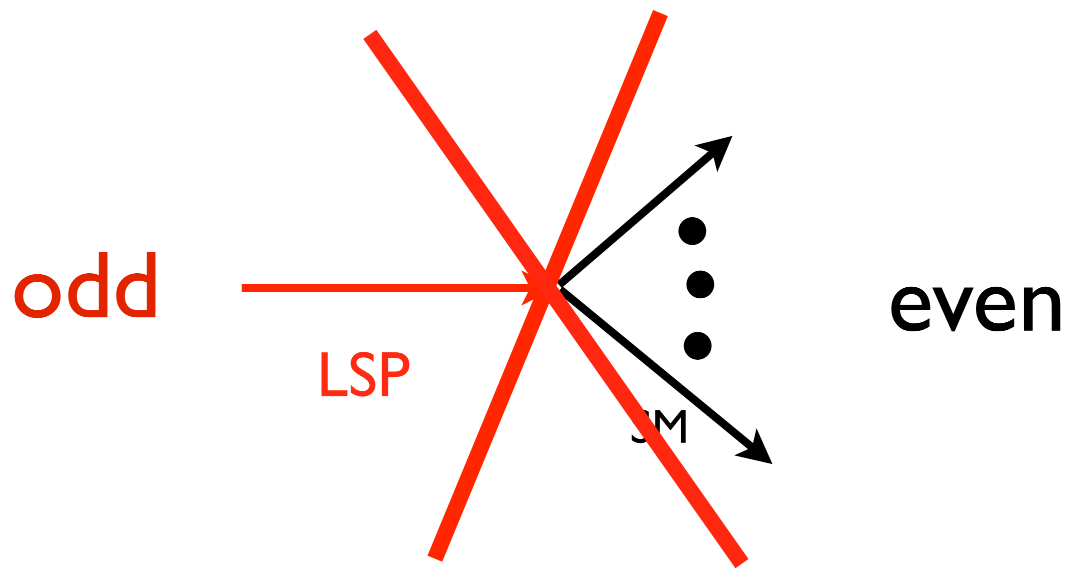
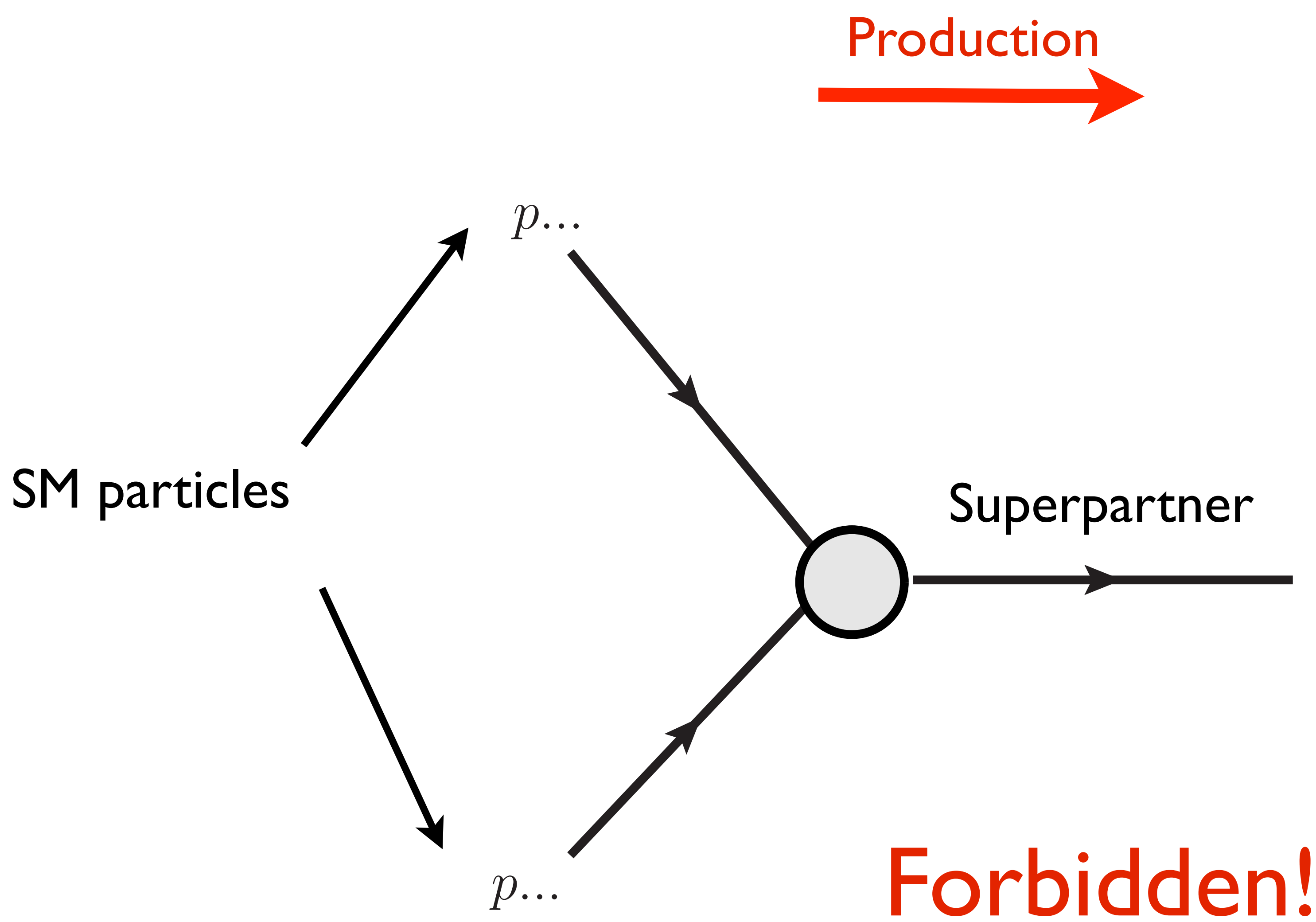


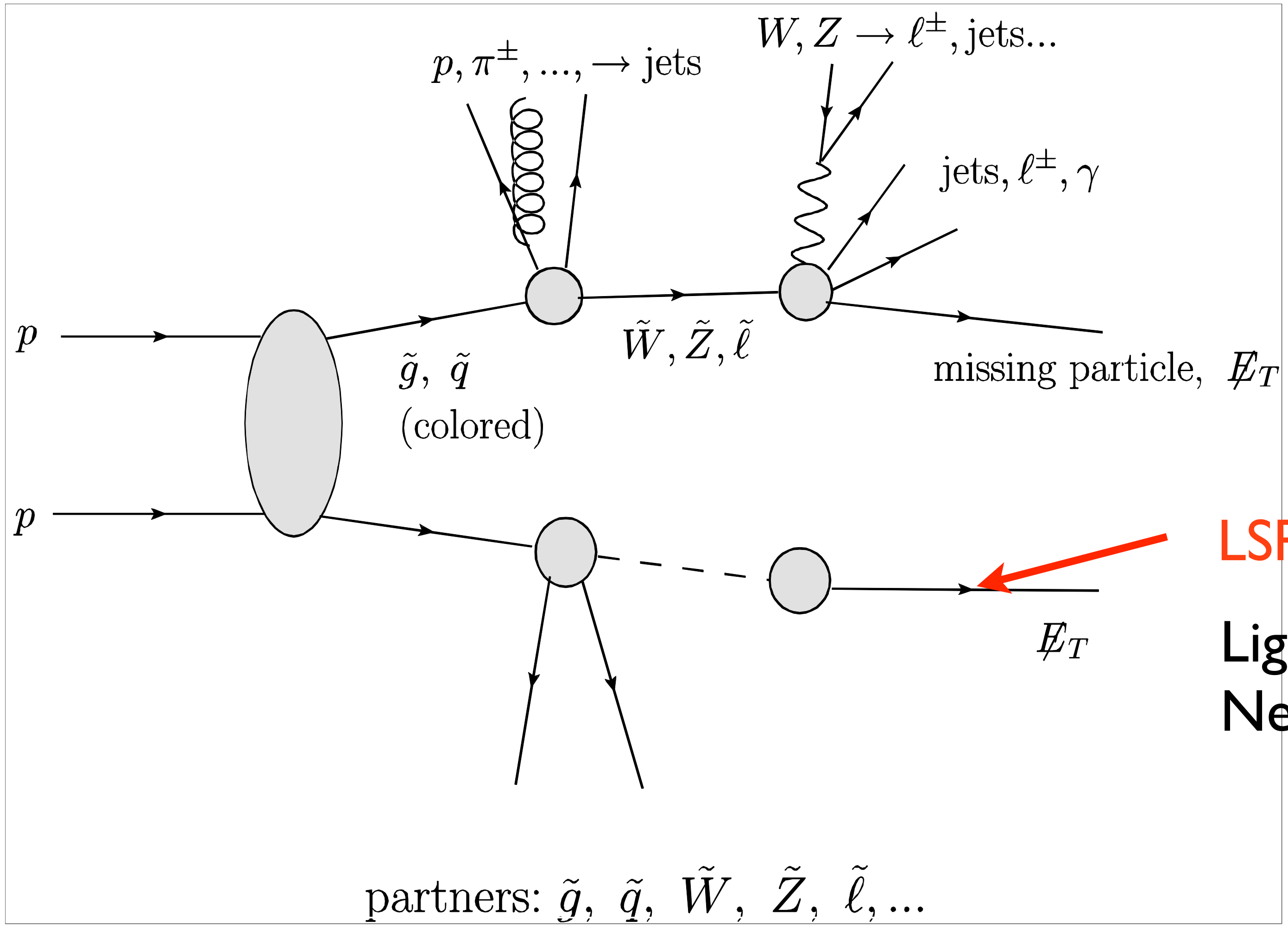
- Neutral LSP a natural candidate for WIMP dark matter.
  - $O(\Lambda_{EW})$
  - Weakly coupled.
  - Can have Similar states in other new physics scenario. With SUSY, a consequence of forbidding proton decay.

SUSY at colliders

- Superpartners must be pair produced!



SUSY at colliders



LSP, DM candidate

Lightest superpartner (LSP)
Neutral and stable.

- long decay chain.
- jets, leptons, missing E_T ....
- Nice signal, good discovery potential.