BEYOND THE SM (I)

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Outline

Lecture 1

- Review of SM (see also Sullivan's lectures)
- Motivation to go beyond...
- SUSY

Lecture 2

- Extra dimensions

Review of SM

Particle content

- Spin-1/2 matter (LH Weyl fermions: e^c is anti-particle of RH positron)
- Spin-1 gauge bosons (force carriers)

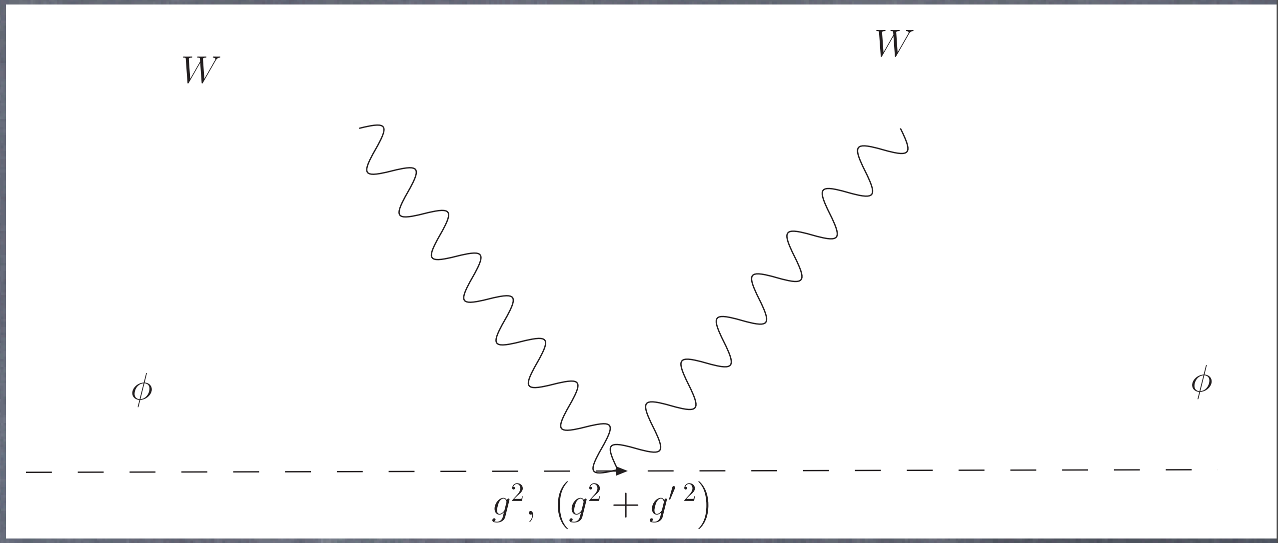
  (Sullivan's lectures: A instead of W)

- Spin-0 Higgs (gives mass to others)

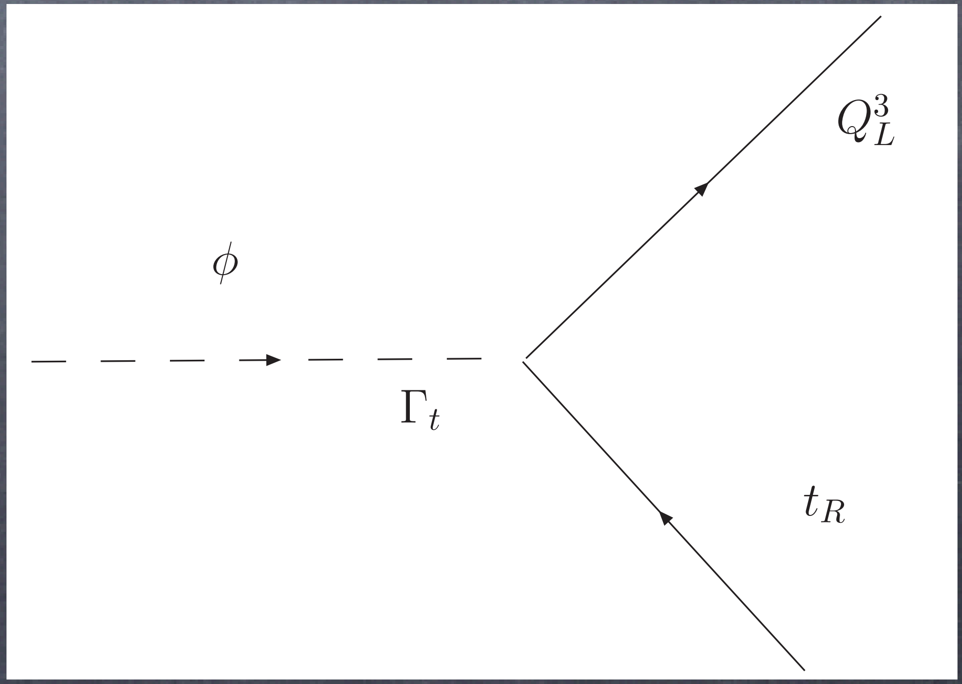
particle	$SU(3)_c$	$SU(2)_w$	$U(1)_Y$
$\begin{pmatrix} u \\ d \end{pmatrix}_i$	$\mathbf{3}$	$\mathbf{2}$	$\frac{1}{6}$
u_i^c	$\bar{\mathbf{3}}$	$\mathbf{1}$	$-\frac{2}{3}$
d_i^c	$\bar{\mathbf{3}}$	$\mathbf{1}$	$\frac{1}{3}$
$\begin{pmatrix} \nu \\ e \end{pmatrix}_i$	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$
e_i^c	$\mathbf{1}$	$\mathbf{1}$	1
W	$\mathbf{1}$	$\mathbf{3}$	0
G	$\mathbf{8}$	$\mathbf{1}$	0
B	$\mathbf{1}$	$\mathbf{1}$	0
$\begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$	$\mathbf{1}$	$\mathbf{2}$	$\frac{1}{2}$

Electroweak symmetry breaking via Higgs VEV

- W, Z masses (not for photon):



- Quark, e.g., top, (and lepton) masses:



(return to these vertices for motivation to go beyond SM)

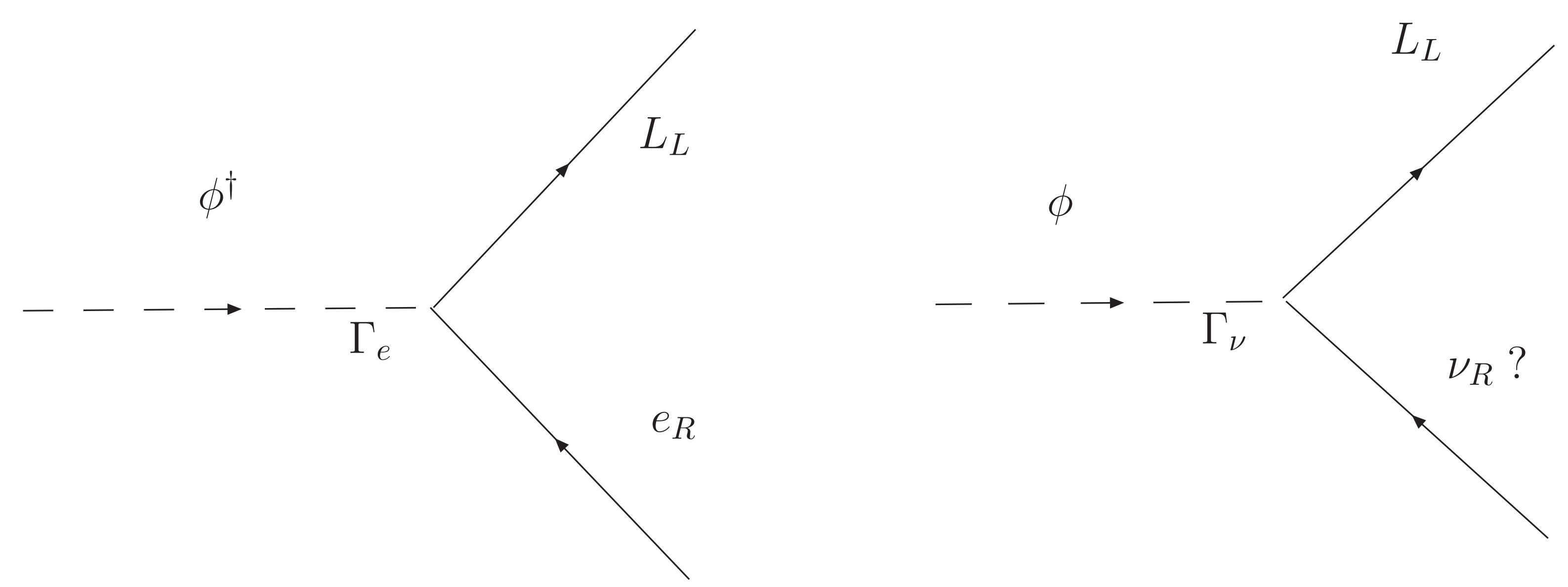
“Disclaimer” for beyond SM (I)

- numerous motivations, ideas...
- focus on a couple (instead of overview of many)

"Experimental" motivations

- Dark Matter (20 %) of universe:
  only observed gravitationally so far;
  no reliable guiding principles for theory (cf. SM)
  (return during SUSY)

- Neutrino mass
  (see Sullivan's lectures):
  absence of ν_R in SM
  just add it ("ν"SM):
  "wierd": no SM gauge couplings +
  why mass/Yukawa coupling so much smaller than
  charged fermions
  (return during extra dimensions)



- a few "anomalies": e.g., (g-2) of muon...

“Theoretical/aesthetic” motivations

(no theoretical inconsistency)

Hierarchy problems

- Planck-weak hierarchy problem: radiatively unstable
- Flavor (hierarchy) puzzle: radiatively stable

SM: effective theory below M_{Pl}

- Gravitational coupling $\sim G_N \times E_1 E_2$
- ...becomes strong at energy $M_{Pl} \sim \sqrt{hc^5 G_N^{-1}} \sim 10^{18}$ GeV
- new physics at M_{Pl}, not a QFT (non-renormalizable)
- cannot extrapolate rest of SM beyond M_{Pl}
- Instead of $\Lambda_{UV} \to \infty$ in SM (QFT), use $\Lambda_{UV} \sim M_{Pl}$

"Revisit" renormalization

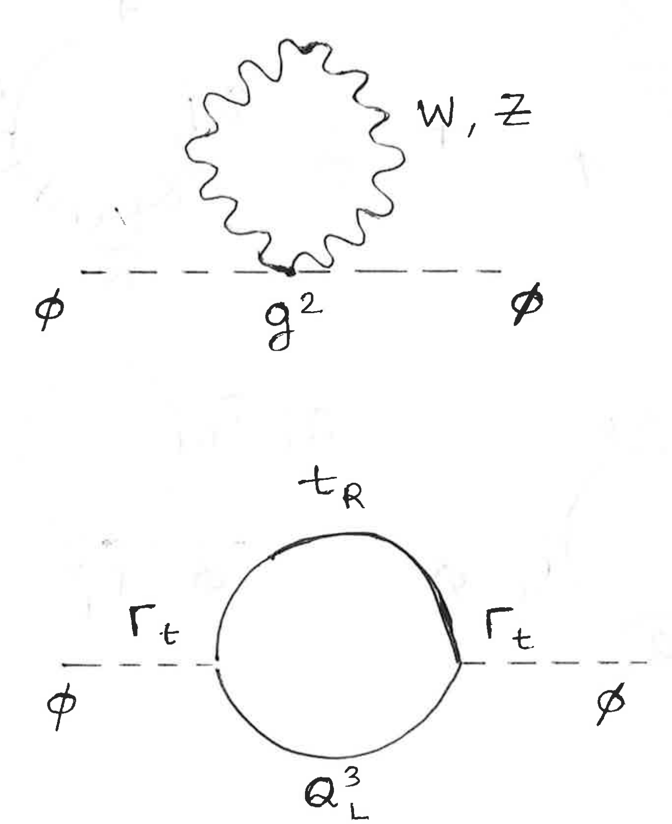
- (finite) observed = (infinite) bare + (infinite) loop
  vs.
- (finite) observed = ("finite") bare + finite (large) loop
- Is there tuning? ("meaningless" when $\Lambda_{UV} \to \infty$)

Quantum correction to Higgs mass term/vev (I)

- same vertices which give mass to top and W, Z
- quadratic divergence (dimensional analysis + no symmetry):

$$\delta\mu^2 \sim \frac{(g, \Gamma_t)^2}{16\pi^2}\Lambda_{UV}^2$$

(problem so severe that estimate suffices)

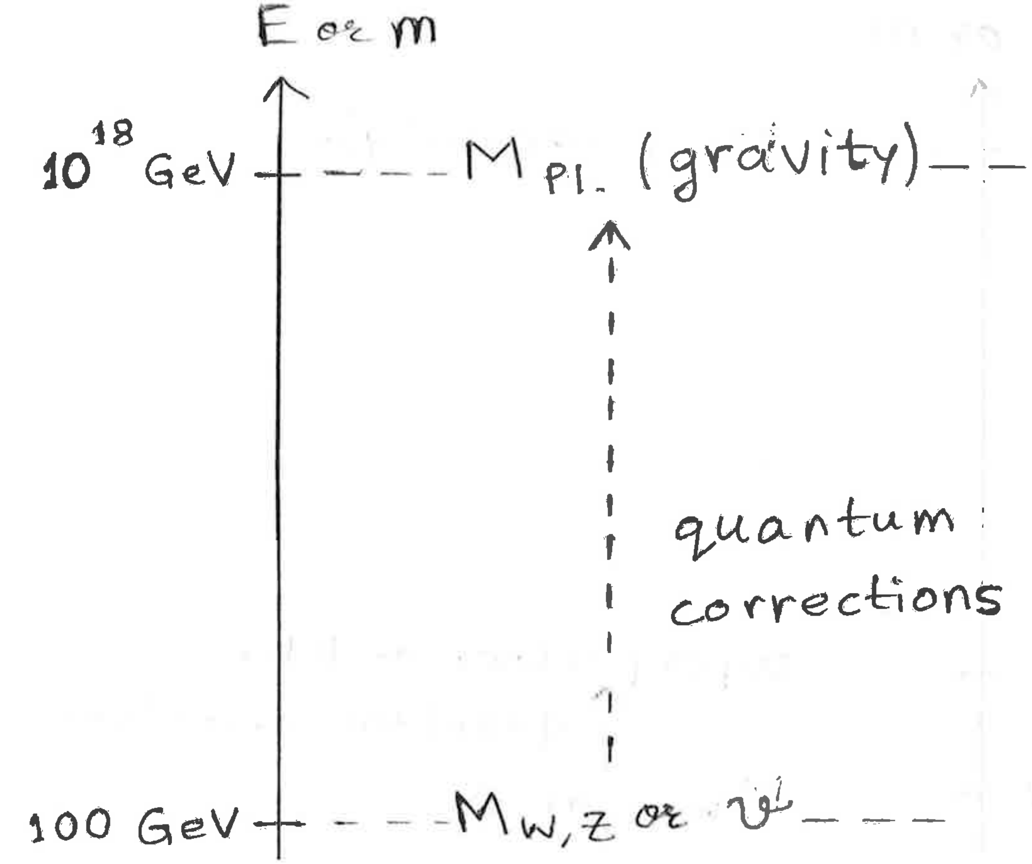


Quantum correction to Higgs mass term/vev (II)

- Naturally:

$$\mu^2_{obs.} = \mu^2_{bare} + \delta\mu^2 \rightarrow \Lambda^2_{UV} \sim M^2_{Pl}$$

- huge (~1 part in 10^{30}) tuning between μ^2_{bare} and $\delta\mu^2$ to obtain observed Higgs mass term/vev ~100 GeV



Aside...

- Even if we ignore gravity, new particles at very high scales for GUT/neutrino mass:
  Higgs mass naturally up there...

("seesaw" for neutrino mass: see Sullivan's lecture)

(GUTs: strength of 3 forces of SM RG evolve to unify at $\sim 10^{15}$ GeV)

cf. Quantum correction to fermion mass

- logarithmic divergence due to chiral symmetry

$$\mathcal{L} \ni M_e \overline{e_L} e_R \Rightarrow$$
$$\text{IF } M_e \to 0, \text{ then } e_{L,R} \to e^{i\alpha_{L,R}} e_{L,R} \Rightarrow$$
$$\delta M_e \propto M_{e\ bare} \text{ (both sides break symmetry)} \Rightarrow$$
$$\text{can}\mathit{not} \text{ have } \Lambda_{UV}^{>0}$$

- Even if $\Lambda_{UV} \sim M_{Pl}$, log $\sim$ O(40)

- no tuning: $M_{e\ obs.} \sim M_{e\ bare} \sim \delta M_e$

(cf. $\delta\mu^2 \neq 0$ even if $\mu^2_{bare} = 0$: no symmetry)

...really quantum correction to Yukawa coupling (to Higgs)

- similar symmetry argument:

$$M_e = \Gamma_e v/\sqrt{2} \text{ with } \delta\Gamma_e \sim \Gamma_e \times \frac{g^2}{16\pi^2} \log \Lambda_{UV} \ldots$$

Flavor (hierarchy) "puzzle"

- If M_e or Γ_e starts small, then stays small (radiatively stable)...

- ...but why starts small (vs. large for top quark)?

(return during extra dimensions)

Supersymmetry (theory)

“Disclaimer” for beyond SM (II)

- skip technical details (see references)
- focus on:
  “principle” behind solution
  who are new particles
  interactions of/signals for new particles

SUSY: basic idea

- symmetry relating fermions to bosons

⇒

every fermion has bosonic partner and vice versa
+ interactions invariant under exchange

SUSY solves Planck-weak hierarchy problem (Ia)

- (chiral) symmetry "protection" for fermion "extends" to scalar
- that's the "one liner": more in a bit...

Minimal supersymmetric SM (MSSM)

see Martin's review:hep-ph/9709356)

2 Higgs doublets: anomaly cancellation (See Sullivan's lectures) ⟶

particle	sparticle	$SU(3)_c$	$SU(2)_w$	$U(1)_Y$
$\begin{pmatrix} u \\ d \end{pmatrix}_i$	$\begin{pmatrix} \tilde{u} \\ \tilde{d} \end{pmatrix}_i$	$\mathbf{3}$	$\mathbf{2}$	$\frac{1}{6}$
u_i^c	$\tilde{u}_i^c$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$-\frac{2}{3}$
d_i^c	$\tilde{d}_i^c$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$\frac{1}{3}$
$\begin{pmatrix} \nu \\ e \end{pmatrix}_i$	$\begin{pmatrix} \tilde{\nu} \\ \tilde{e} \end{pmatrix}_i$	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$
e_i^c	$\tilde{e}_i^c$	$\mathbf{1}$	$\mathbf{1}$	1
W	$\tilde{W}$	$\mathbf{1}$	$\mathbf{3}$	0
G	$\tilde{G}$	$\mathbf{8}$	$\mathbf{1}$	0
B	$\tilde{B}$	$\mathbf{1}$	$\mathbf{1}$	0
$\begin{pmatrix} \phi_u^+ \\ \phi_u^0 \end{pmatrix}$	$\begin{pmatrix} \tilde{\phi}_u^+ \\ \tilde{\phi}_u^0 \end{pmatrix}$	$\mathbf{1}$	$\mathbf{2}$	$\frac{1}{2}$
$\begin{pmatrix} \phi_d^0 \\ \phi_d^- \end{pmatrix}$	$\begin{pmatrix} \tilde{\phi}_d^0 \\ \tilde{\phi}_d^- \end{pmatrix}$	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$

Sparticle/superpartner interactions

- "Replace" particles (2 in order to conserve angular momentum) in SM interactions by sparticles
- Gauge-related interactions:
  $g_s\ \bar{q}\ \tilde{q}\ \tilde{G}$ (as above)
  $g_s\ \tilde{q}^\dagger\ G^\mu\ \partial_\mu \tilde{q} \ldots$ (a la scalar QED)

(Similarly, other gauge groups...)

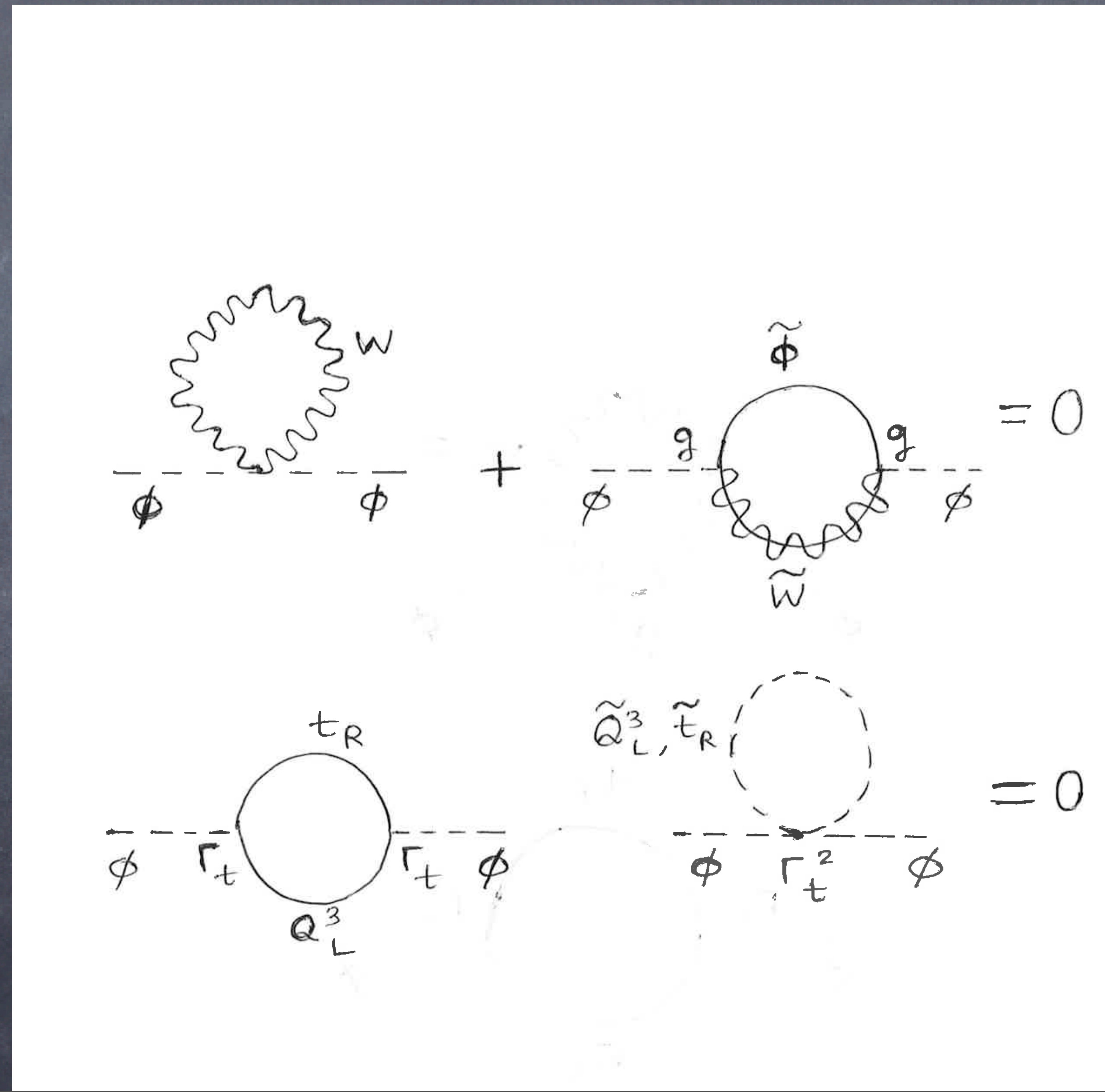
- Yukawa-related interactions:

$\Gamma_t\ \overline{Q_L^3}\ \tilde{t_R}\ \tilde{\phi}_u$ (as above)

$(\Gamma_t)^2\ \phi_u^\dagger \phi_u\ \tilde{Q_L^3}^\dagger\ \tilde{Q_L^3} \ldots$(see review)

SUSY: solves Planck-weak hierarchy problem (Ib)

- Cancellation in $\delta\mu^2$ (-1 for fermion loops vs. boson loops)



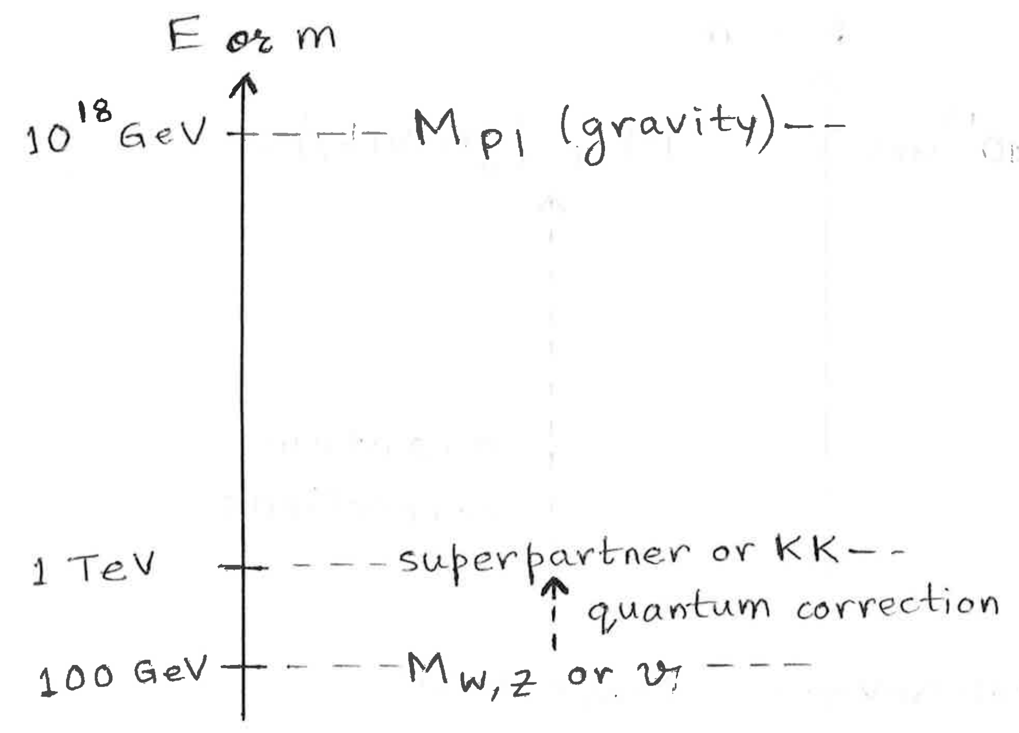
SUSY: solves Planck-weak hierarchy problem (IIa)

- Real world: SUSY broken (haven't seen selectron degenerate with electron)
- cancellation not exact:

$$\delta\mu^2 \sim \frac{\Gamma_t^2}{16\pi^2} M_{\tilde{t}}^2 \ldots$$

← SUSY breaking mass

- ...still natural if SUSY breaking mass <∼ TeV



SUSY: solves Planck-weak hierarchy problem (IIb)

- "New" hierarchy problem: SUSY breaking scale $\ll M_{Pl}$?
- Solution: dynamical SUSY breaking (by gauge coupling becoming strong at scale naturally $\ll M_{Pl}$ a la QCD...)

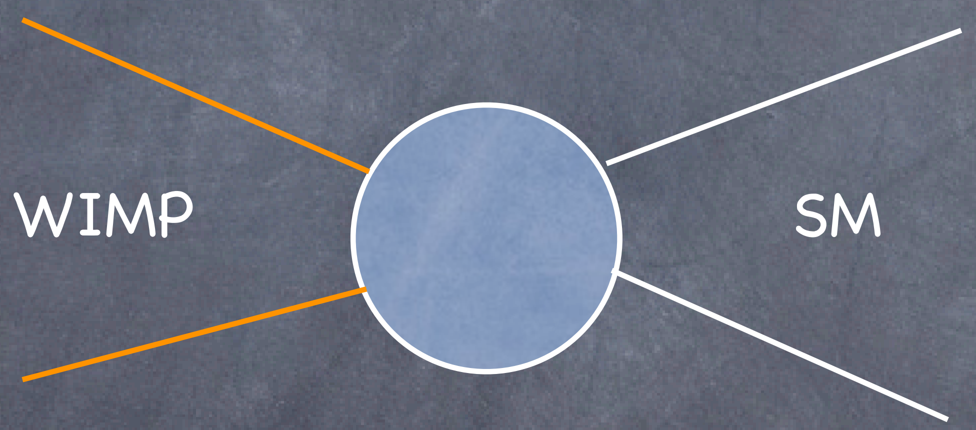
Supersymmetry phenomenology

R-parity

- Minimal model:
  interactions have even number of superpartners
- lightest supersymmetric particle (LSP) stable
  (cannot decay into SM)
- R-parity:
  SM particles even, superpartners odd

R-parity → (LSP) Dark matter

- ...if LSP (weak scale mass by construction) is electrically/color neutral (WIMP)
- Detour: (stable) particle pair annihilation into SM cannot catch up with expanding universe



- thermal freeze-out:
correct relic density for dark matter if WIMP...
- candidates: $\tilde{W^3}$, $\tilde{B}$, $\tilde{\phi}_{u,d}$
($\tilde{\nu}$ disfavored by direct detection via Z exchange)
- ...mix (neutralinos): $\tilde{\chi}^0_{i=1\ldots4}$ ($\tilde{\chi}^0_1$ is LSP)

(R-parity →) Collider signals (general)

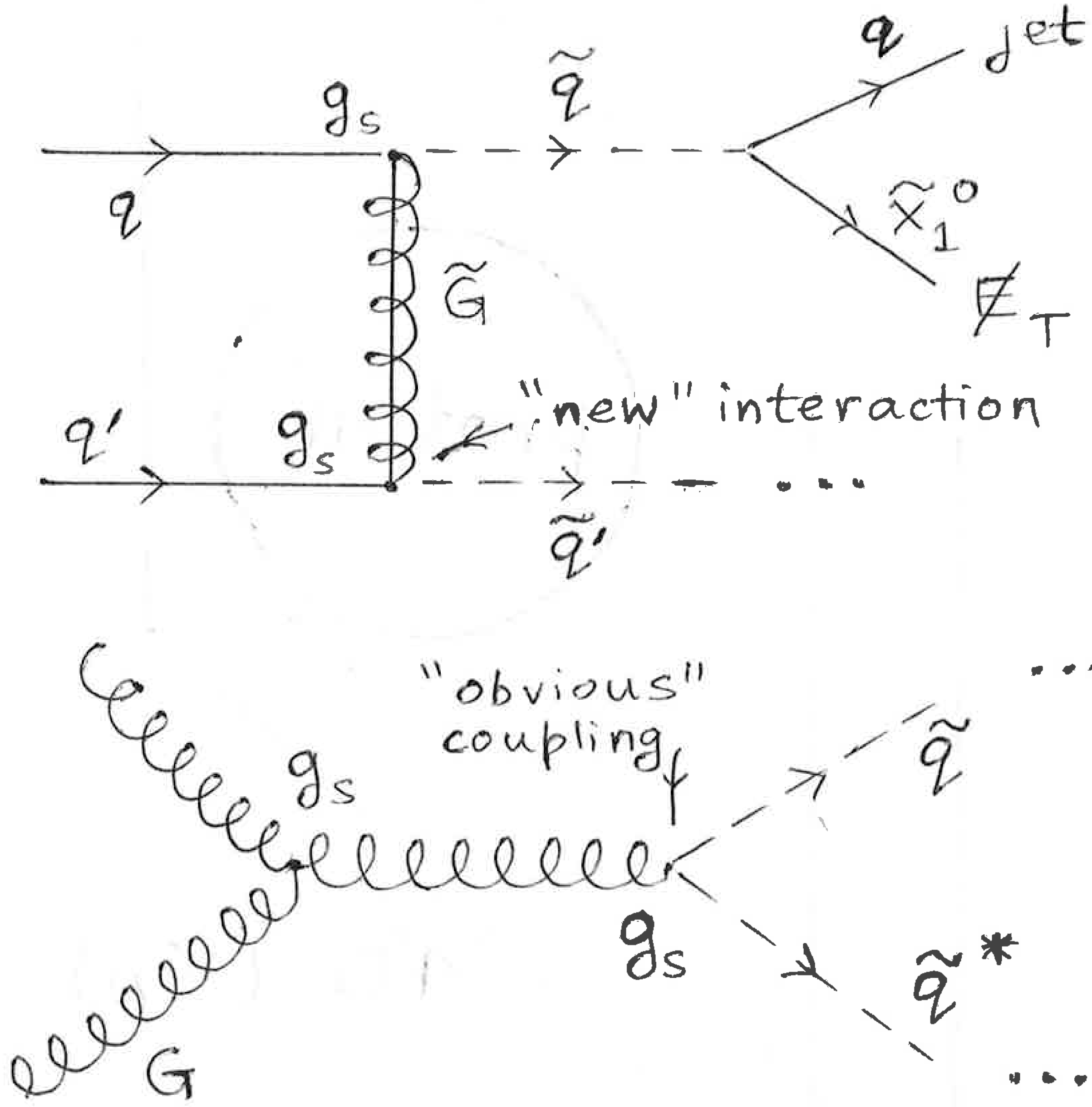
- (Must) pair produce superpartner
- ...each of which decays into LSP + SM

→

- missing transverse momentum + leptons/jets/photons

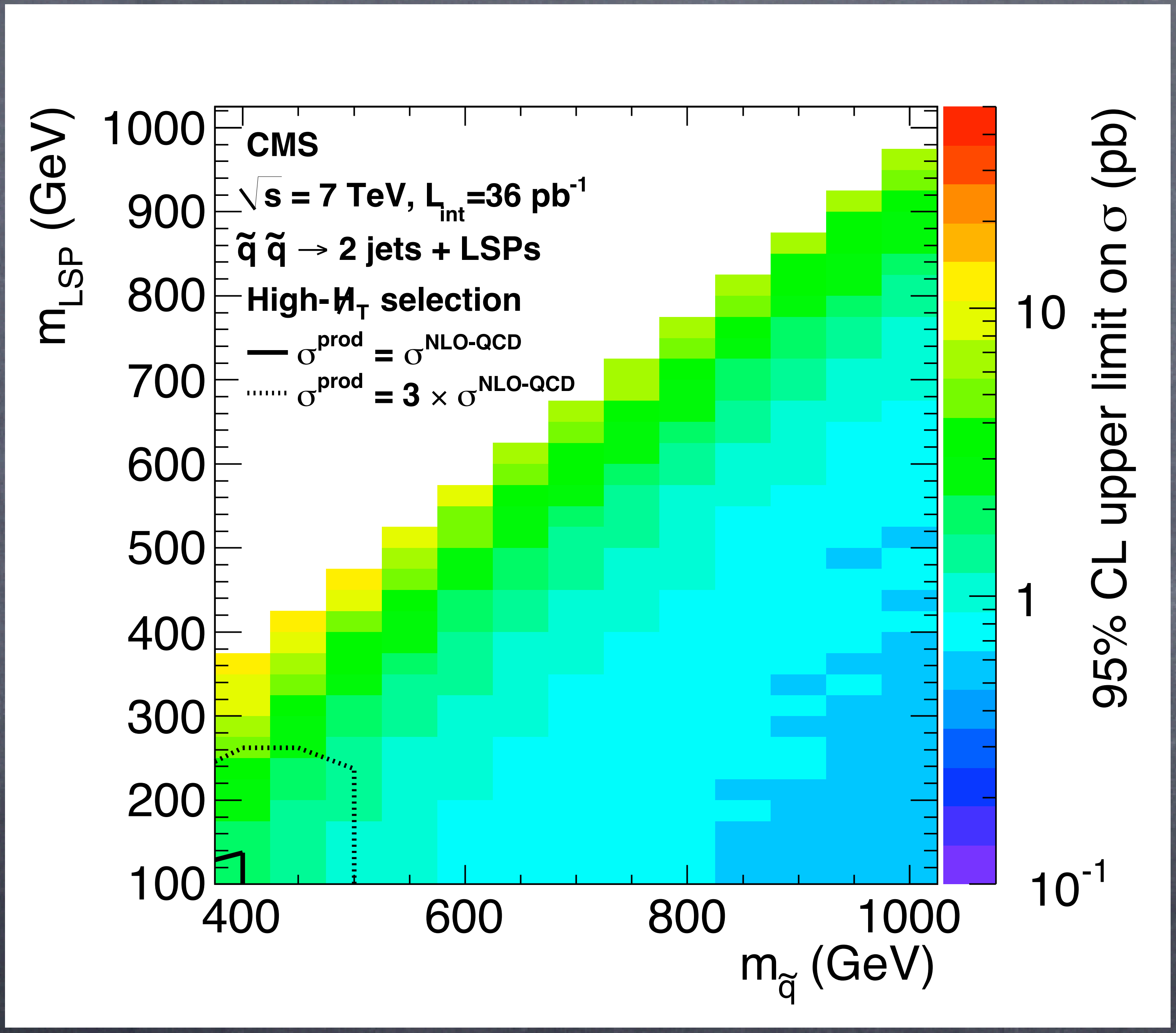
Collider signals: example 1

- Squark production



Collider signals: limits

- 1106.4503 (based on jets + $\not{p}_T$): update at EPS in a few days!



(SM background: Z+jets...

need accurate calculations: see Reina's lectures?)

Collider signals: example 2

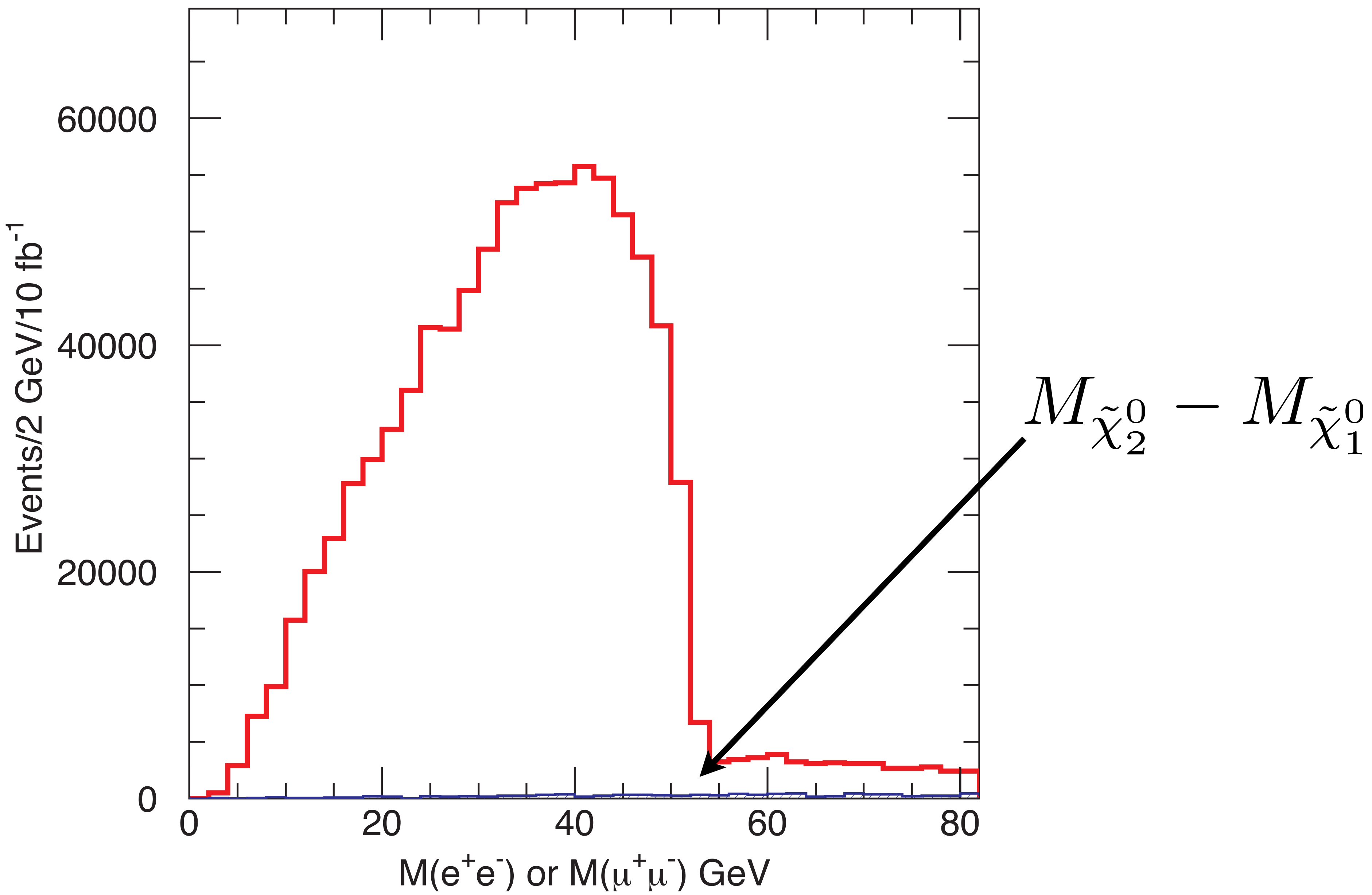
- cascade decay of squark to LSP (vs. direct decay earlier):

$$\tilde{q} \rightarrow \tilde{\chi}_2^0 + q$$
$$\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 + l^+ l^-$$

- invariant mass of lepton pair, then adding jet...contains information about masses

Collider signal: future

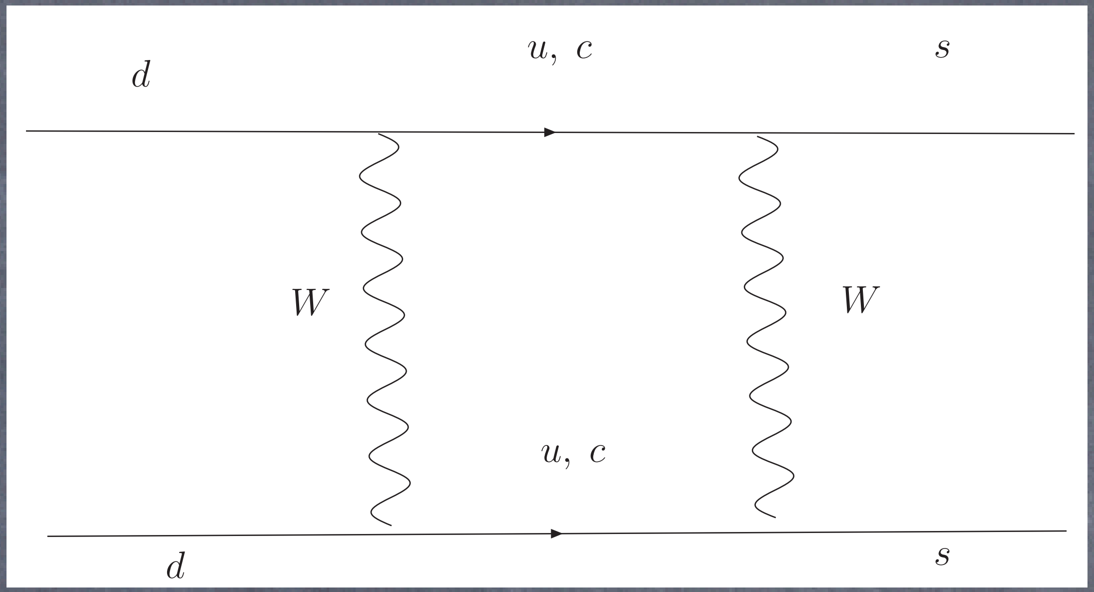
- ...from chapter 20 of ATLAS Detector and Physics Performance Technical Design Report LHCC 99-14/15
- 1st step:



Virtual effects of superpartners

No flavor problem in SM

- Review of SM box diagram for $K^0 - \bar{K^0}$ mixing

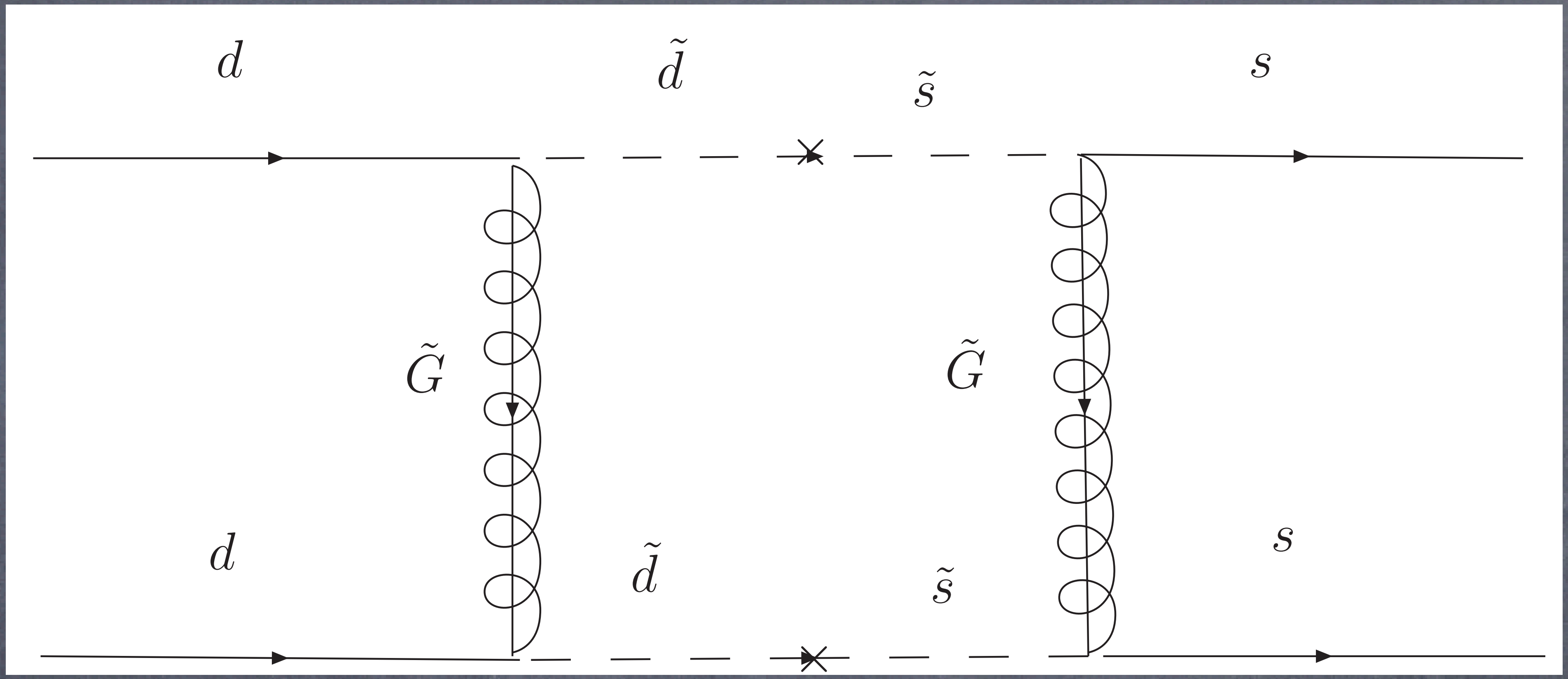


- Glashow-Illiopoulos-Maini (GIM) mechanism:

$$\text{suppression} \propto \frac{m_c^2 - m_u^2}{M_W^2}$$

SUSY flavor problem

- loop due to R-parity (each interaction has 2 sparicles)



- Generic SUSY breaking ($\tilde{d}, \tilde{s}$ mix) ⇒ too large effect

Solution to SUSY flavor problem

- "SUSY-GIM": squarks degenerate/don't mix
- Realization: gauge (flavor-blind) mediation of SUSY breaking
- ...predict superpartner spectrum:
  squarks heavier than sleptons