$$\begin{aligned}
\mathcal{L}_{EW} &= i\bar{\psi}\gamma^{\mu}D_{\mu}\psi - \frac{1}{4}\mathbf{W}^{\mu\nu}\cdot\mathbf{W}_{\mu\nu} - \frac{1}{4}B^{\mu\nu}B_{\mu\nu} + \mathcal{L}_{\Phi} \\
\mathcal{L}_{\Phi} &= |D_{\mu}\Phi|^{2} - \mu^{2}|\Phi|^{2} - \lambda|\Phi|^{4} + \mathcal{L}_{Yukawa} \\
\mathcal{L}_{QCD} &= i\bar{\psi}_{a}\gamma^{\mu}D_{\mu}^{ab}\psi_{b} - \frac{1}{4}G_{a}^{\mu\nu}G_{\mu\nu}^{a}
\end{aligned}$$

Beyond Standard Model Physics

At the LHC

Piyabut Burikham

The SM

- Quantum gauge theory of 3 “fundamental” interactions, *gravity excluded*.
- Gauge group: SU(3) SU(2) U(1)
- Unitary group of [*color weak hypercharge*]
- Verified only up to 100 GeV energy (Tevatron)
- But dimensional analysis suggests quantum gravity scale ~10^18 GeV
- New Physics inevitable! (but somewhat remote)

$$\mathcal{L} = \mathcal{L}_{EW} + \mathcal{L}_{QCD}$$

Before Symmetry breaking

$$\mathcal{L}_{EW} = i\bar{\psi}\gamma^{\mu}D_{\mu}\psi - \frac{1}{4}\mathbf{W}^{\mu\nu}\cdot\mathbf{W}_{\mu\nu} - \frac{1}{4}B^{\mu\nu}B_{\mu\nu} + \mathcal{L}_{\Phi}$$

$$\mathcal{L}_{\Phi} = |D_{\mu}\Phi|^2 - \mu^2|\Phi|^2 - \lambda|\Phi|^4 + \mathcal{L}_{Yukawa}$$

$$\mathcal{L}_{QCD} = i\bar{\psi}_a\gamma^{\mu}D_{\mu}^{ab}\psi_b - \frac{1}{4}G_a^{\mu\nu}G_{\mu\nu}^a$$

$$\mathbf{W}_{\mu\nu} = \partial_{\mu}\mathbf{W}_{\nu} - \partial_{\nu}\mathbf{W}_{\mu} - g\mathbf{W}_{\mu}\times\mathbf{W}_{\nu}$$

$$G_{\mu\nu}^a = \partial_{\mu}G_{\nu}^a - \partial_{\nu}G_{\mu}^a - igf^{abc}G_{\mu b}G_{\nu c}$$

Gauge fields: B (hypercharge), W (weak), G (gluon)

Cov.Derivative: Dynamics&gauge interactions, generators T, Ts

$$D_{\mu} = \partial_{\mu} + ig\mathbf{W}_{\mu}\cdot\mathbf{T} + ig'\frac{1}{2}B_{\mu}Y$$

$$D_{\mu}^{ab} = \partial_{\mu}\delta^{ab} + ig_s\mathbf{G}_{\mu}\cdot\mathbf{T}_s^{ab}.$$

Representation matters!!

- Fermions in fundamental representations
- Gauge bosons in adjoint representations
- SM Higgs in fundamental representation
- Representation = a way fields group together forming single multi-component field
- Can we have adjoint fermions(SUSY), scalars(SUSY, extraD) in nature? → New Physics

Particle contents

$$\psi_L^j = \begin{pmatrix} \nu_L^j(u_L^j) \\ \ell_L^j(d_L^j) \end{pmatrix}$$

$$\psi_R^j = \nu_R^j(u_R^j) \text{ and } \ell_R^j(d_R^j)$$

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

$$= \exp\left(\frac{i\zeta(x)\cdot \mathrm{T}}{v\sqrt{2}}\right)\begin{pmatrix} 0 \\ (v+H(x))/\sqrt{2} \end{pmatrix}$$

- 3 generations of fermions (all detected) Why??
- Scalar doublet, with Yukawa couplings
- Self-interacting potential selects vacuum

$$\mathcal{L}_{Yukawa} = -\frac{\sqrt{2}}{v}\left[M_{ij}^d \overline{\psi_R^{di}} \Phi^\dagger \psi_L^j + M_{ij}^u \overline{\psi_R^{ui}} (i\tau_2 \Phi^*)^\dagger \psi_L^j\right] + \text{ h.c.}$$

	T	T_3	$\frac{1}{2}Y$	Q
ν_{eL}	$\frac{1}{2}$	$\frac{1}{2}$	$-\frac{1}{2}$	0
e_L	$\frac{1}{2}$	$-\frac{1}{2}$	$-\frac{1}{2}$	-1
u_L	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{6}$	$\frac{2}{3}$
d_L	$\frac{1}{2}$	$-\frac{1}{2}$	$\frac{1}{6}$	$-\frac{1}{3}$
e_R	0	0	-1	-1
u_R	0	0	$\frac{2}{3}$	$\frac{2}{3}$
d_R	0	0	$-\frac{1}{3}$	$-\frac{1}{3}$

	T	T_3	$\frac{1}{2}Y$	Q
ϕ^+	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
ϕ^0	$\frac{1}{2}$	$-\frac{1}{2}$	$\frac{1}{2}$	0

EW Gauge charges

- Left-handed fermions form weak SU(2) doublets.
- Right-handed fermions are weak singlets.
- Left and Right have different gauge charges *T, Y*
- *But same Q* (electric charge)
- $Q = T_3 + Y/2$
- Observe: no right-handed neutrino → extended SM

  includes a number of ν_R *(*first BSM physics at Kamiokande, *"neutrino has masses!")*

EW breaking: $SU(2)_L \quad U(1)_Y \rightarrow U(1)_{em}$

$$\mathcal{L}_{Yukawa} = -\frac{\sqrt{2}}{v}\left[M^d_{ij}\overline{\psi^{di}_R}\Phi^\dagger\psi^j_L + M^u_{ij}\overline{\psi^{ui}_R}(i\tau_2\Phi^*)^\dagger\psi^j_L\right] + \text{h.c.}$$

- Scalar doublet gains vev, breaks $SU(2)_L \times U(1)_Y$ spontaneously (*i.e.* Vacuum breaks symmetry, action still preserving sym) through Yukawa coupling. $V = 246$ GeV.

$$\mathcal{L}_{EW} = \mathcal{L}_{KE} - \frac{m}{v}H\bar{\psi}\psi + \mathcal{L}_{em} + \mathcal{L}_{neutral} + \mathcal{L}_{charged} + \mathcal{L}_{Higgs}$$

After sym breaking, $SU(3)_c$ remains, EW action acquires mass terms.

SM Higgs mechanism(Breaking& Mixings)

$$\begin{aligned}
\mathcal{L}_{em} &= -eQ\bar{\psi}\gamma^{\mu}\psi A_{\mu} \\
\mathcal{L}_{neutral} &= -\frac{g}{\cos\theta_W}\overline{\psi_{\alpha}}\gamma^{\mu}g_{\alpha}\psi_{\alpha}Z_{\mu} \\
\mathcal{L}_{charged} &= -\frac{g}{\sqrt{2}}\overline{\psi_L^i}\gamma^{\mu}(T^+W_{\mu}^+ + T^-W_{\mu}^-)\psi_L^i \\
\mathcal{L}_{Higgs} &= \frac{1}{4}g^2W^+W^-(v+H)^2 + \frac{1}{8}\frac{g^2}{\cos^2\theta_W}ZZ(v+H)^2 - V
\end{aligned}$$

$$V = \frac{\mu^2}{2}(v+H)^2 + \frac{\lambda}{4}(v+H)^4$$

Higgs self-potential

where $g_{\alpha} = T_3 - Q\sin^2\theta_W, -Q\sin^2\theta_W$ for $\alpha = L, R$, and $\tan\theta_W = g'/g$. θ_W is the Weinberg angle, representing the mixing between B and W^3 to form the photon $A = B\cos\theta_W + W^3\sin\theta_W$, and the $Z = -B\sin\theta_W + W^3\cos\theta_W$. $W^{\pm} = (W^1 \mp iW^2)/\sqrt{2}$ are the charged gauge bosons from the mixing of the original $W^{1,2}$.

Gauge boson masses

$$1/g^2 + 1/g'^2 = 1/e^2$$

Coupling mixing

- $m_W = gv/2$, $m_Z = m_W/\cos\theta_W$

  Z is heavier.

$$\rho = M_W^2 / M_Z^2 \cos^2\theta_W$$

Rho parameter = 1
in SM Higgs

If the sym breaking is NOT SM Higgs mechanism,
Rho does NOT have to be 1. → New Physics

Fermion mixing

- weak eigenstates = mixing of mass eigenstates

$$\begin{aligned} u^i &= U_{iq} q \text{ for } q = u, c, t \\ d^i &= D_{iq'} q' \text{ for } q' = d, s, b \end{aligned}$$

- Only *charged* current feels the mixing → effectively CKM(Cabibbo-Kobayashi-Maskawa) matrix applies to *(d,s,b)*. For $V = U_L^\dagger D_L$

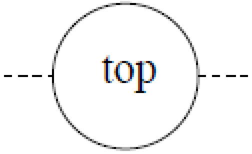
$$\mathcal{L}_{charged} = -\frac{g}{\sqrt{2}} \left(\overline{q_L} \gamma^\mu W_\mu^+ V_{qq'} q_L' + \overline{q_L'} V_{q'q}^* \gamma^\mu W_\mu^- q_L \right)$$

- For neutrinos, called MNS(Maki-Nakagawa-Sakata) matrix.

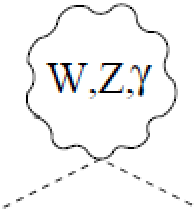
What about Higgs mass?

- At tree level, m_H *α* μ but this means nothing since for the scalar field, quantum corrections are *enormous.* For cutoff scale Λ,

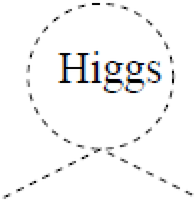
$$-\frac{3}{8\pi^2}\lambda_t^2\Lambda^2$$ from the top



$$\frac{1}{16\pi^2}g^2\Lambda^2$$ from the gauge boson



$$\frac{1}{16\pi^2}\lambda^2\Lambda^2$$ from the Higgs



Cutoff scale 10^16-18 GeV

- Quantum corrections are enormous. Higgs mass cannot be < 1 TeV unless fine tuning occurs. → Fine tuning problem in SM Higgs.
- Several BSM models to address fine tuning problem.
- Among many: Little Higgs models, low-scale SUSY models such as MSSM (Minimal SUSY SM), Technicolour models, Extra-D models
- The most boring possibility = SM Higgs with fine tuning!!

Why needing $m_H < 1$ TeV??

Any 2→2 scattering amplitude can be expanded using partial waves:

$$A(s,t) = 16\pi \sum_{j=M}^{\infty} (2j+1) a_j(s) d^j_{mm'}(\cos\theta)$$

Wigner functions $d^j_{mm'}(\cos\theta)$

- $J = 0, 1$ part of σ $(ZZ, W^+W^- \rightarrow W^+W^-, ZZ)$ proportional to 2nd power of (E_{cm}/m_W) → Will violate unitarity around $E \approx m_W$.
- Higgs exchange in *t*-channel will cancel this contribution iff $m_H < 1$ TeV!!

NP inevitable around 1 TeV ☺!!

- Most boring scenario: SM Higgs with fine tuning of the mass so that $m_H < 1$ TeV. ☹
- OR Other NPs coupling to *W*, *Z* show up around 1 TeV.

Lists: (as well as combinations)

- Non-SM Higgs models (Little Higgs)
- Higgsless models
- Extra-D models (KK, TeV-braneworld)
- Composite models (technicolor, preon)
- SUSY models (top-down, bottom-up)

Motivations for NP models

- In addition to unitarity argument that NP must show up around 1 TeV, *hierarchy problem* or *fine tuning problem* is also a motivation.
- Large mass gap between Planck scale (or GUT scale) and EW breaking scale, 10^18 GeV and 100 GeV. Nothing in between? Really?
- A scalar such as Higgs receives quantum corrections to its mass proportional to cutoff scale square Λ^2 → if Λ huge, *fine tuning* is required for $m_H < 1$ TeV.

EW precision observables (any NPs need to pass.)

- *ρ* parameter: $\rho = M_W^2/M_Z^2\cos^2\theta_W$

  LEP2 results found rho very close to 1.

- 1-loop Higgs contributions to $m_{W,Z}$ *constrain* SM Higgs mass.

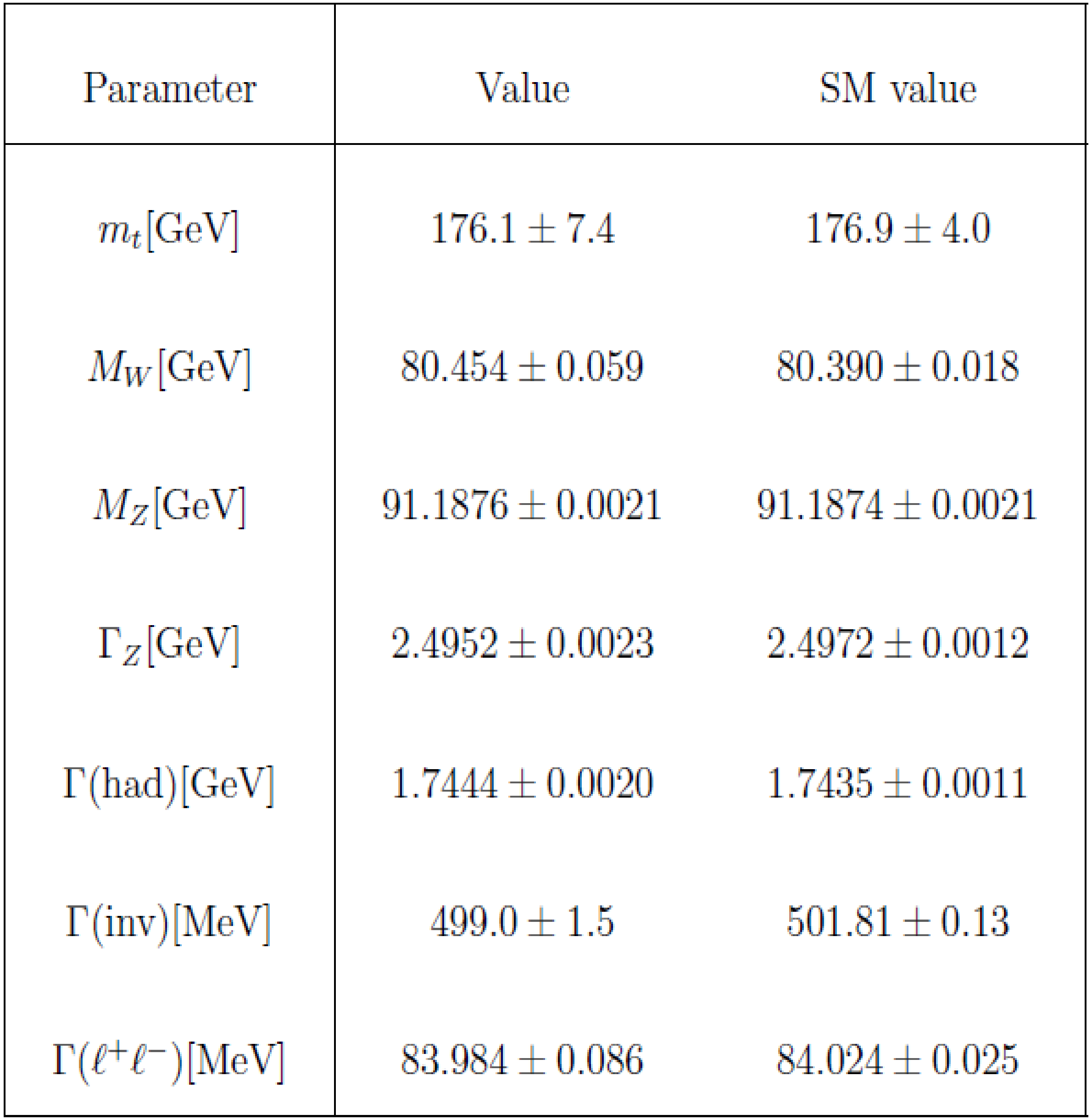
$$\hat{\rho} \approx 1 - \frac{11 G_F M_Z^2 \sin^2\theta_W}{24\sqrt{2}\pi^2} \ln\frac{m_h^2}{M_Z^2}$$

Global fits leading to

$$\rho_0 = 1.0008^{+0.0017}_{-0.0007},$$

$$114.4\ \mathrm{GeV} \le M_H \le 427\ \mathrm{GeV},$$

EW precision measurements



Parameter	Value	SM value
m_t[GeV]	176.1 ± 7.4	176.9 ± 4.0
M_W[GeV]	80.454 ± 0.059	80.390 ± 0.018
M_Z[GeV]	91.1876 ± 0.0021	91.1874 ± 0.0021
Γ_Z[GeV]	2.4952 ± 0.0023	2.4972 ± 0.0012
$\Gamma(\text{had})$[GeV]	1.7444 ± 0.0020	1.7435 ± 0.0011
$\Gamma(\text{inv})$[MeV]	499.0 ± 1.5	501.81 ± 0.13
$\Gamma(\ell^+\ell^-)$[MeV]	83.984 ± 0.086	84.024 ± 0.025

- Some of EW values any NPs cannot violate.
- Strongest constraints usually come from *Z-pole* precision measurements.

*More updated values in PDG.

Extra-D models

- Roughly 3 categories: ADD, RS, Braneworld
- ADD(Antoniadis-Arkani Hamed-Dimopoulos-Dvali): Large compactified flat extra-D
- RS(Randall-Sundrum): infinite curved extra-D (Anti-de Sitter space)
- Braneworld (Witten-Horava-Antoniadis-Dvali): we live on the worldvolume of Dbranes, only gravity can probe extra-D!!

ADD scenario

- Extra-D compactified in a torus (flat) → KK (Kaluza-Klein) modes with nth mode mass: $m_{KK} = nh/2\pi R$.

$$S_E = \frac{\bar{M}_D^{2+\delta}}{2} \int d^4x \; d^\delta y \; \sqrt{-\det \, g} \; \mathcal{R}(g)$$

$$\overline{M}^2_{\rm Pl} = \bar{M}_D^{2+\delta} V_\delta = \bar{M}_D^{2+\delta} (2\pi R)^\delta$$

$$\overline{M}_{\rm Pl} = M_{\rm Pl}/\sqrt{8\pi} = 2.4 \times 10^{18} \; {\rm GeV}$$

$1/R \sim 0.4$ meV – 7 MeV (δ=2 - 6) for M_D =1 TeV

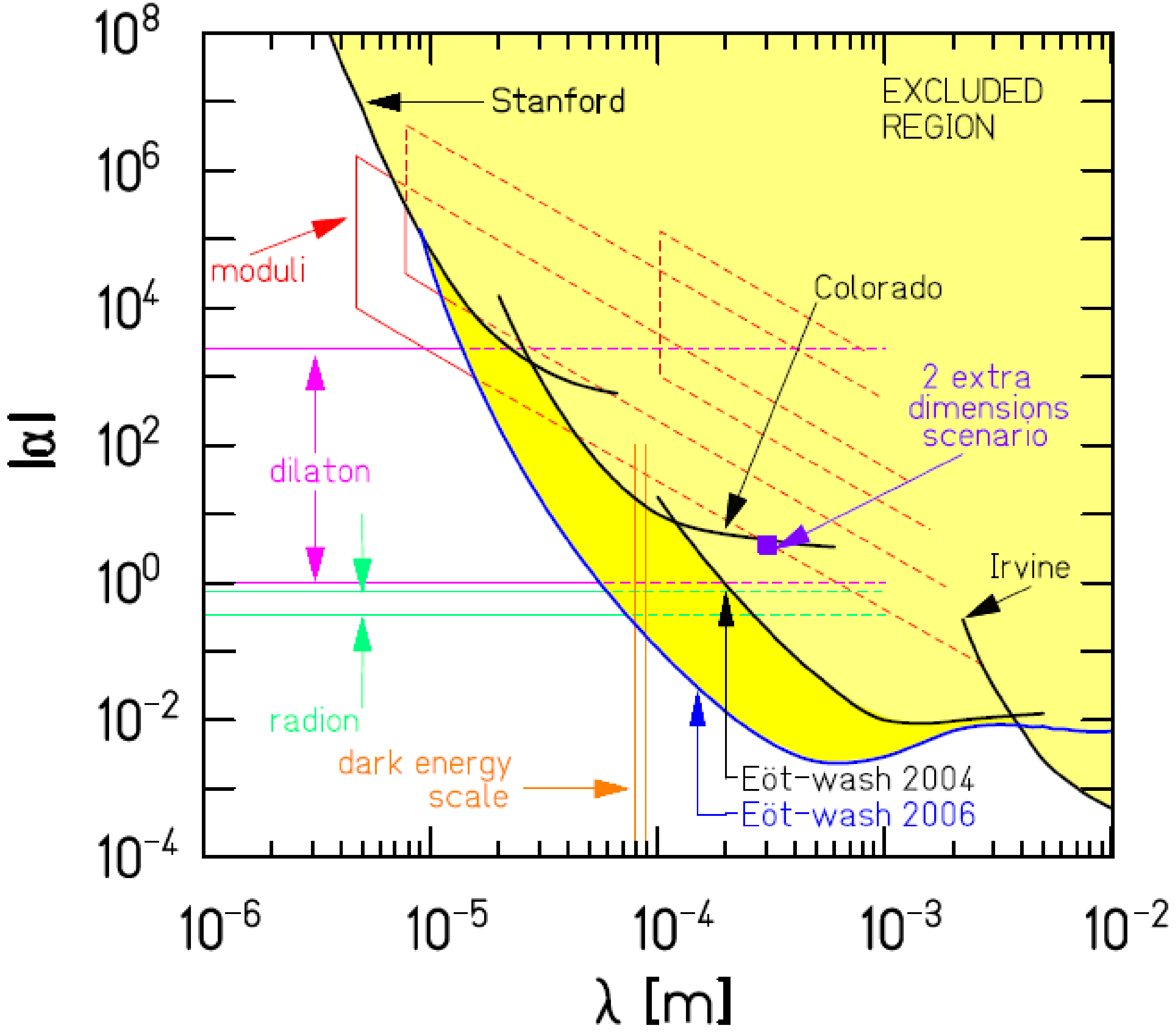
Small KK levels

- Sufficiently large *R* → quite small quantum gravity scale M_D → *low scale quantum gravity!!*
- But how BIG can it be?? Most stringent *universal* constraints from table-top experiments, *e.g.* Eot-wash
- Parametrized as deviation from inverse-square law: KK-graviton in extra-D generates Yukawa potential

$$V(r) = -G_N \frac{m_1 m_2}{r}\left[1 + \alpha \exp\left(-r/\lambda\right)\right]$$

$$\alpha = 8\,\delta/3 \rightarrow R < 37\ (44)\ \mu\mathrm{m\ at\ 95\%\ CL\ for}\ \delta = 2\ (1)$$

$$R^{-1} = M_D\left(M_D/\overline{M}_{\mathrm{Pl}}\right)^{2/\delta}$$ Weaker bound on M_D for $\delta > 2$.



*Stronger bound comes from Supernovae cooling via radiation of extra-D d.o.f. such as KK-gravitons

Plot from PDG http://pdg.lbl.gov/2010/reviews/rpp2010-rev-extra-dimensions.pdf

- Bounds from KK-gauge, radion, dilaton: $M_D > 3.6$ TeV for $\delta = 2$.
- Bounds from KK-gravitons from supernovae cooling: $M_D > 14$ (1.6) TeV for $\delta = 2$ (3).
- Stronger bounds from luminosities of pulsar hit by KK-gravitons: $M_D > 750$ (35) TeV for $\delta = 2$ (3).

ADD open questions:

- Radius stabilization, what mechanism fixing the radius of extra-D? Why this value?
- Still don’t know how to quantize gravity, worse when quantum graviy scale is this small!!

Collider signals

$$\mathcal{L}_{\rm int} = \pm \frac{4\pi}{\Lambda_{\mathcal{T}}^4}\,\mathcal{T}, \qquad \mathcal{T} = \frac{1}{2}\left(T_{\mu\nu}T^{\mu\nu} - \frac{1}{\delta+2}T^{\mu}_{\mu}T^{\nu}_{\nu}\right)$$

Dim.8 operator

$$\mathcal{L}_{\rm int} = \pm \frac{4\pi}{\Lambda_{\Upsilon}^2}\,\Upsilon, \qquad \Upsilon = \frac{1}{2}\left(\sum_{f=q,\ell} \bar{f}\gamma_\mu\gamma_5 f\right)^2$$

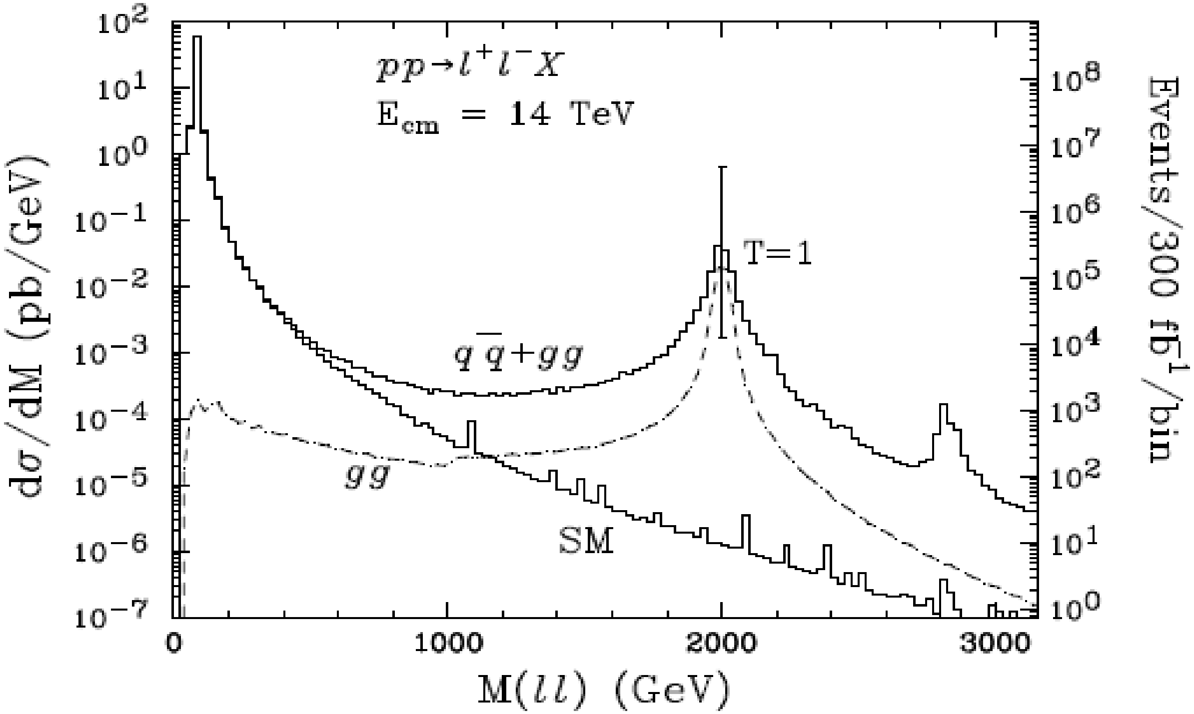
Dim.6 operator

- Effective interactions induced by graviton exchanges, tree-level(dim.8) and loop(dim.6).
- Current lower bound on scales ≈ 1-10 TeV. Still visible at LHC if exists!
- Best channels: lepton pair, diphoton production

TeV-string signals

- If quantum gravity scale is as low as TeVs and if the correct QG theory is string-like, LHC signals are enormous!!
- SR (string resonances)

or stringy excitations could enhance SM scatterings (P. Burikham et. al.).



RS scenario

- Curved or warped extra-D, 5-D space, the 5th compactified on half-circle. S^1/Z_2

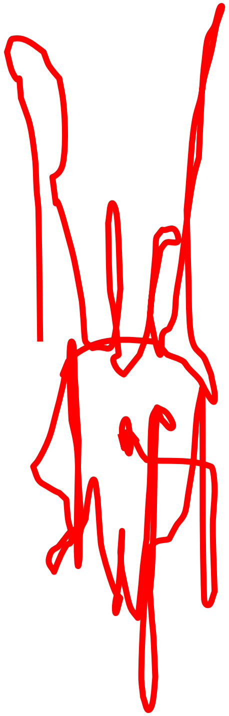
$$ds^2 = \exp\left(-2k|y|\right)\eta_{\mu\nu}dx^\mu dx^\nu - dy^2$$

- 2 branes at opposite ends or *fixed pts,* with negative and positive tension. Negative-tension brane = IR brane *(y=πR)* where SM particles localized, positive-tension brane = UV brane *(y=0).*
- Bulk cosmological constant fine-tuned to exactly cancel apparent 3-D cosmological constant.

$$ds^2 = \exp\left(-2k|y|\right)\eta_{\mu\nu}dx^\mu dx^\nu - dy^2$$

- Spacetime *not* factorized, metric on 4-D exponentiated by 5th coordinate.
- Gravitation redshift by factor $1/g_{00}$^1/2, energies from UV-brane viewed by IR-world redshifted by this factor.

$$m_{IR} = m_{UV}\exp\left(-\pi k R\right)$$



Large hierarchy generated!

- For $kR \approx 12$, M_{UV} = Planck mass (10^18 GeV), M_{IR} = EW mass (100 GeV) can be generated.
- Radius stabilization via Goldberger-Wise mechanism (`99).
- Nth mode KK has mass: $m_n = \frac{x_n}{x_1} m_1$
- x_n is nth zero of Bessel function. m_1 is mass parameter.
- *Interaction:*

$$\mathcal{L} = -\frac{T^{\mu\nu}}{\overline{M}_{\mathrm{Pl}}} h^{(0)}_{\mu\nu} - \frac{T^{\mu\nu}}{\Lambda_\pi} \sum_{n=1}^{\infty} h^{(n)}_{\mu\nu}$$

0-th mode

KK modes

Collider Signals

$$\mathcal{L}_{\rm int} = \pm\frac{4\pi}{\Lambda_\pi^4}\,\mathcal{T}, \qquad \mathcal{T} = \frac{1}{2}\left(T_{\mu\nu}T^{\mu\nu} - \frac{1}{\delta+2}T^{\mu}_{\mu}T^{\nu}_{\nu}\right)\Bigg\}\ \text{Dim.8 operator}$$

- Similar to ADD int. except there is NO dim.6 operator. → cannot tell which model for certain if found.

$$\Lambda_\pi = \overline{M}_{\rm Pl}\exp(-\pi k R)$$

- Again, best channels are dilepton, diphoton.
- Current bounds from D0 and CDF: Λ_π > 4.3(2.6) TeV for m_1 = 500(700) GeV.
- LHC can probe upto 10 TeV for m_n , Λ_π.

Radion

- Size of extra-D determined by radion, radion stabilization is crucial. For a radion *r:*

$$\mathcal{L} = -rT/\Lambda_{\varphi} \qquad \Lambda_{\varphi} = \sqrt{24}\Lambda_{\pi}$$

- Trace anomaly from SM makes gg → *r* large, main channel to be searched at LHC.
- Radion can mix with Higgs through scalar-curvature int. For 4-D induced metric:

$$S_{mix} = -\xi \int d^4x \sqrt{-\det g_{\rm ind}} R(g_{\rm ind}) H^+ H$$

mixing parameter

- Higgs-radion mixing → search for radion is the same as Higgs.
- Radion stabilization requires radion mass less than KK-gravitons.

RS open questions:

- Why 5-D? Gauge and gravity in 5-D are non-renormalizable.
- GUT? How to quantize gravity? String theory at higher scales?
- Other questions remain, cosmological constant, baryogenesis, DM is proposed to be lightest KK-mode.

SM in flat extra-D

- Massive KKs in RGE (Renorm Group Eqn.) → GUT in extra-D at low scales, as low as TeVs!!
- In contrast to ADD, extra-D must be smaller, around TeV^{-1} since we do NOT observe KK SM particles below 1 TeV!
- Typical model: extra-D S/Z_2
- *Varieties:* Gauge bosons in the bulk, fermions&Higgs in the bulk, ALL in bulk (UED).

Gauge bosons in extra-D

- KK masses of gauge bosons: $M_n^2 = M_0^2 + \frac{n^2}{R^2}$
- KK bosons coupling: $(g_n = \sqrt{2}g)$

Shift of observables by factor *V*

$$V = 2\sum_n \left(\frac{g_n^2}{g^2}\right)\frac{M_Z^2 R^2}{n^2} \sim \frac{2}{3}\pi^2 M_Z^2 R^2$$

- Constraints from Precision EW data from Tevatron, HERA, LEP2 → *1/R* > 6.8 TeV.
- LHC at 100 fb^{-1} can probe to *1/R* ~ 16 TeV.

- Fermions at different location in extra-D overlap with Higgs wave function differently → observed mass hierarchy.
- Universal Extra-D(UED)→All SM particles live in bulk with KK parity (discrete sym Z_2 of KK number).
- Conservation of momentum in extra-D → KK-parity conservation → KK particles as DM candidate
- LHC can probe up to $1/R$ ~ 1.5 TeV.

GUT in extra-D

- Scherk-Schwarz mechanism to breaks symmetries such as GUT and SUSY.

$$+ : \quad \cos\frac{n\,y}{R}$$

$$- : \quad \sin\frac{n\,y}{R}$$

- Under S/Z_2 ($y \rightarrow -y$): only even states have 0th mode. Odd states missing at the fixed pts $y=0,\pi R$ where our low E world lives.

- Could have *N=2 SUSY* in bulk and *N=1 for 0th modes* at fixed pt if imposing *A, λ even* and *Φ, ψ odd.*
- Choosing diff boundary conditions for diff fields → *orbifolding* → Z_2 *orbifold.*

GUT in extra-D

- Orbifolding: can project out certain unwanted states by choosing odd b.c. so their 0th modes won’t show up at the fixed pt world.
- Can fudge while proton wont decay according to GUT.
- → Can make unification better at lower scale and yet proton decay is not too fast.

SM in warped extra-D

- In RS scenario, only Higgs need to live on the IR-brane to solve the fine tuning problem of the Higgs mass.← corrections are redshifted.
- But if SM also lives in warped bulk, interesting things happen.
- In 5-D AdS space (AdS/CFT):

  1. motion along 5th D = RG flow of 4D theory
  2. local sym in 5D = global sym in 4D
- RS model ←→ walking technicolor model!!

SM in warped

- Can explain mass hierarchy if locate fermions on diff position along 5th coordinate. Higgs on IR-brane overlap differently with each fermion → diff. masses.
- EW precision observables especially ρ *parameter* excluded basic model → need to enlarge gauge group of EW in bulk to $SU(2)_L$ $SU(2)_R$ $U(1)$ to impose custodial symmetry preserving value of ρ.

Higgsless models

- No Higgs!! Breaks EW using orbifolding. Lightest KK gauge bosons identified with *W, Z* with masses ~ *1/R*.
- Scatterings of SM without Higgs need someth to unitarize the amplitude at $E \sim 4\pi m_W / g \sim 1$ TeV → heavy KK gauge bosons do the job postponing this to 10 TeV!
- Above 10 TeV, strong dynamics take over, bound states expected to form.
- Require warped extra-D, custodial sym, still can*not* predict top-quark mass.

SUSY models

- In a sense, this is extra-D models with Grassmann extra dimensions!
- Poincare sym.→ max'al extension to contain SUSY generators, $Q \sim \sqrt{P}$. ← *theoretical beauty*
- *Motivations (apart from beauty):* fermionic loop contributes the same as bosonic loop but with opposite sign → natural loop cancellations!
- Loop cancellation is promising for many purposes.

Unwanted Loops

- Quantum gravity suffers *loop* complications. Each order of loops is worse than the previous. → unrenormalizable.
- Loops induce anomalies (= breaking of classical sym by quantum effects).
- Pheno level: loop corrections to scalar mass proportional to Λ^2 → *fine tuning problem.*
- *SUSY* ensures loop cancellation at 1-loop order. ← *not only beautiful but also useful*!

SUSY algebra

$$Q|\mathrm{Boson}\rangle = |\mathrm{Fermion}\rangle, \qquad Q|\mathrm{Fermion}\rangle = |\mathrm{Boson}\rangle$$

$$\begin{aligned}
\{Q, Q^\dagger\} &= P^\mu, \\
\{Q, Q\} &= \{Q^\dagger, Q^\dagger\} = 0, \\
[P^\mu, Q] &= [P^\mu, Q^\dagger] = 0,
\end{aligned}$$

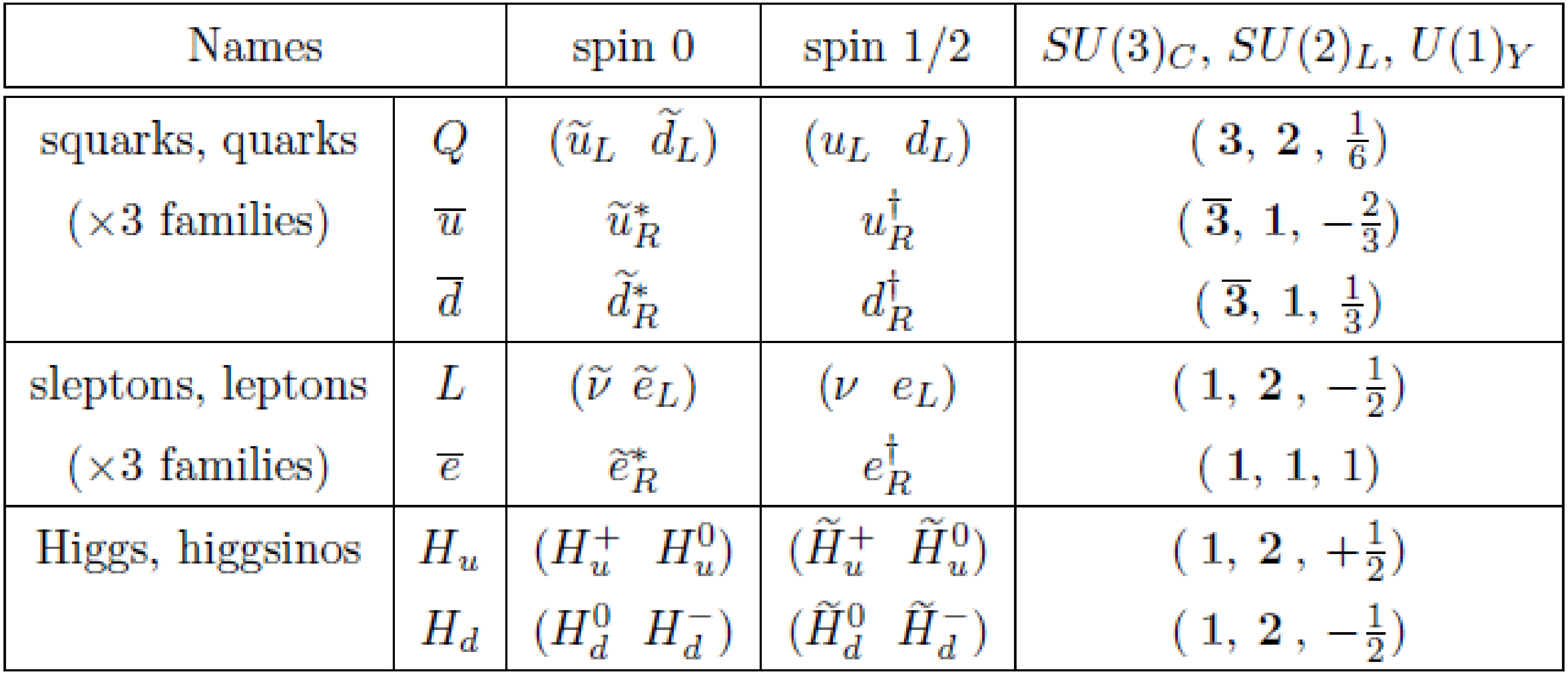
- *Q* transforms boson to fermion and vice versa.
- *P* is a vector with spin 1 → *Q* acts as spin ½.
- *1-particle* states = irreducible rep. of SUSY algebra called *supermultiplets*

- Spin-statistic thm → #bosonic d.o.f. = #fermionic d.o.f. for *each* supermultiplet → Every particle must have its superpartner in SUSY theory.
- *chiral* multiplet = 2-component Weyl fermion
  + 2 real scalars (or 1 complex scalar)
- *vector* multiplet = 2-helicity gauge boson
  + 2-component Weyl fermion
- partners of Weyl in chiral mulp = *sfermions*, partners of gauge bosons in vector mulp = *gauginos*. Same representations in each mulp.

- If including gravity such as sugra: massless graviton (2) + massless gravitino (2),

  graviton has spin 2, gravitino has spin 3/2.
- For *N* = # of SUSY generator *Q's*. Extended SUSY with *N>1* in 4D not allow chiral fermions → unrealistic. But extra-D models *N>1* are realistic if chiral fermions can be obtained, *e.g*. at fixed pts.
- Anomaly free Higgs mulp = at least 2 chiral mulp for Higgs, one for up-type and one for down-type fermion.

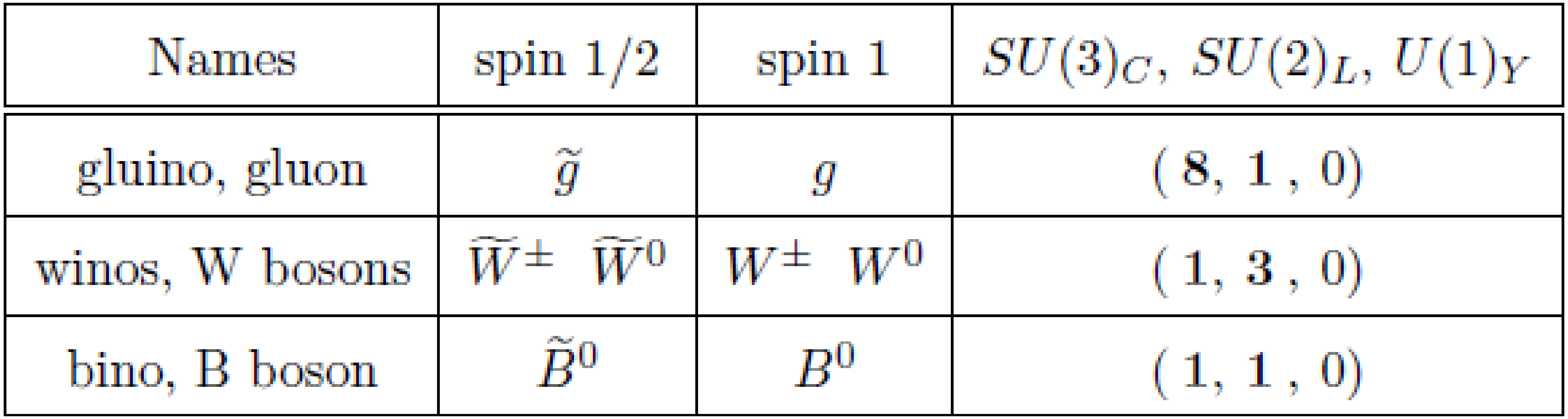
MSSM (minimal supersymmetric SM)



Names		spin 0	spin 1/2	$SU(3)_C, SU(2)_L, U(1)_Y$
squarks, quarks	Q	$(\widetilde{u}_L \;\; \widetilde{d}_L)$	$(u_L \;\; d_L)$	$(\,\mathbf{3},\,\mathbf{2}\,,\,\frac{1}{6})$
(×3 families)	$\overline{u}$	$\widetilde{u}^*_R$	$u^\dagger_R$	$(\,\overline{\mathbf{3}},\,\mathbf{1},\,-\frac{2}{3})$
	$\overline{d}$	$\widetilde{d}^*_R$	$d^\dagger_R$	$(\,\overline{\mathbf{3}},\,\mathbf{1},\,\frac{1}{3})$
sleptons, leptons	L	$(\widetilde{\nu} \;\; \widetilde{e}_L)$	$(\nu \;\; e_L)$	$(\,\mathbf{1},\,\mathbf{2}\,,\,-\frac{1}{2})$
(×3 families)	$\overline{e}$	$\widetilde{e}^*_R$	$e^\dagger_R$	$(\,\mathbf{1},\,\mathbf{1},\,1)$
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	$(H_d^0 \;\; H_d^-)$	$(\widetilde{H}_d^0 \;\; \widetilde{H}_d^-)$	$(\,\mathbf{1},\,\mathbf{2}\,,\,-\frac{1}{2})$

- Chiral supermulp in MSSM, superpartners must have the same gauge charges, reps.
- 2 Higgs multiplets.

MSSM



Names	spin 1/2	spin 1	$SU(3)_C, SU(2)_L, U(1)_Y$
gluino, gluon	$\widetilde{g}$	g	$(\mathbf{8}, \mathbf{1}, 0)$
winos, W bosons	$\widetilde{W}^{\pm}\ \ \widetilde{W}^{0}$	$W^{\pm}\ \ W^{0}$	$(\mathbf{1}, \mathbf{3}, 0)$
bino, B boson	$\widetilde{B}^{0}$	B^{0}	$(\mathbf{1}, \mathbf{1}, 0)$

- Gauge multips in MSSM. Gluino, wino, bino
- After EW breaking: photino, wino, zino
- Apparently, SUSY must be broken since we don’t see partners with exactly the same masses around. → probably spontaneously.

MSSM

- To break SUSY

$$\mathcal{L} = \mathcal{L}_{\rm SUSY} + \mathcal{L}_{\rm soft}$$

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

- Soft terms: mass terms, positive mass dimension coupling terms which violate SUSY.

Breaking MSSM

- Even when SUSY is broken, masses of partners are different. If m_{soft} *= largest scale in soft terms,* then the correction to Higgs mass is

$$\Delta m_H^2 = m_{\rm soft}^2 \left[\frac{\lambda}{16\pi^2} \ln(\Lambda_{\rm UV}/m_{\rm soft}) + \ldots \right]$$

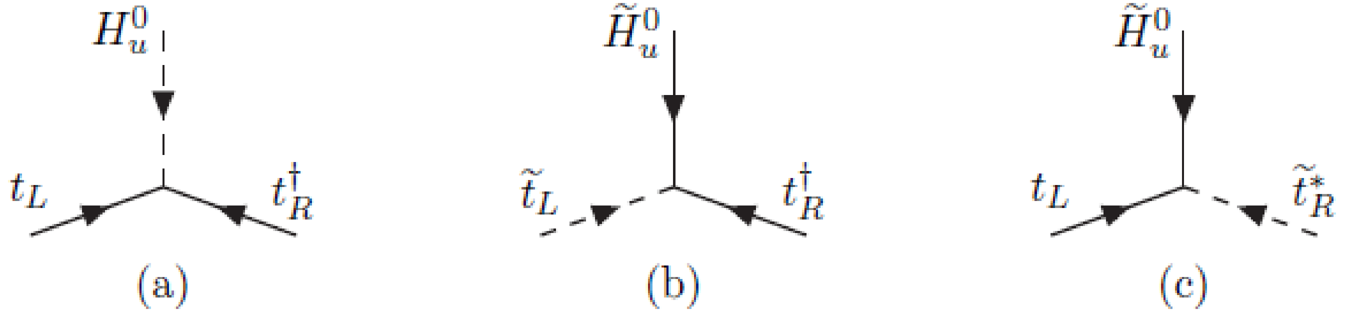
- Only Log divergence with respect to cutoff *Λ,* much better than quadratic divergence in non-SUSY models.
- However, partners masses cannot be too huge to solve fine tuning problem.

- For $\Lambda = M_{Pl}$, m_{soft} should be less than 1 TeV to solve the fine tuning problem.
- Thus if correct, LHC should discover the superpartners.
- Any reasons why only superpartners are not light enough to have already been observed?
- scalars such as sfermions, Higgs can have *gauge-inv*. mass terms $m^2|\phi|^2$ of order of m_{soft}
- Higgsinos, gauginos are in real representation → can also have *gauge-inv*. mass terms of order of m_{soft} as well.

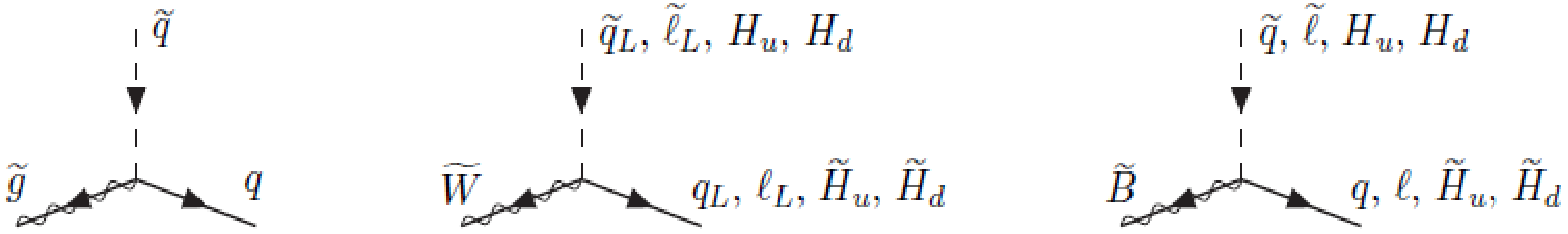
Interactions in MSSM

- Apply SUSY transformation to SM vertices → MSSM vertices! (Higgs sector considered separately)
- Caution: SUSY particles must appear in pairs (*R*-parity conservation).

e.g. top Yukawa, gauge couplings



(a) (b) (c)



Interactions in MSSM

- Some ints. Not determined by gauge int. of SM → Higgs sector. All dimensionful couplings depend on *μ:*

$$-\mathcal{L}_{\text{higgsino mass}} = \mu(\widetilde{H}_u^+\widetilde{H}_d^- - \widetilde{H}_u^0\widetilde{H}_d^0) + \text{c.c.}$$

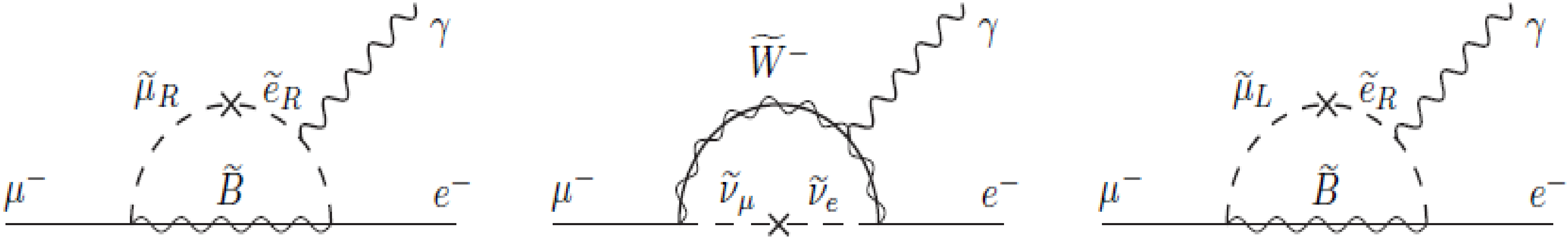
$$-\mathcal{L}_{\text{supersymmetric Higgs mass}} = |\mu|^2(|H_u^0|^2 + |H_u^+|^2 + |H_d^0|^2 + |H_d^-|^2)$$

$$\mathcal{L}_{\text{supersymmetric (scalar)}^3} = \mu^*(\widetilde{\overline{u}}\mathbf{y_u}\widetilde{u}H_d^{0*} + \widetilde{\overline{d}}\mathbf{y_d}\widetilde{d}H_u^{0*} + \widetilde{\overline{e}}\mathbf{y_e}\widetilde{e}H_u^{0*}$$

- *μ* should be about 100 GeV to get right EW scale, but why not the M_{Pl} or M_{GUT} ?? → *μ problem.*

Constraints on MSSM(105 new parameters)

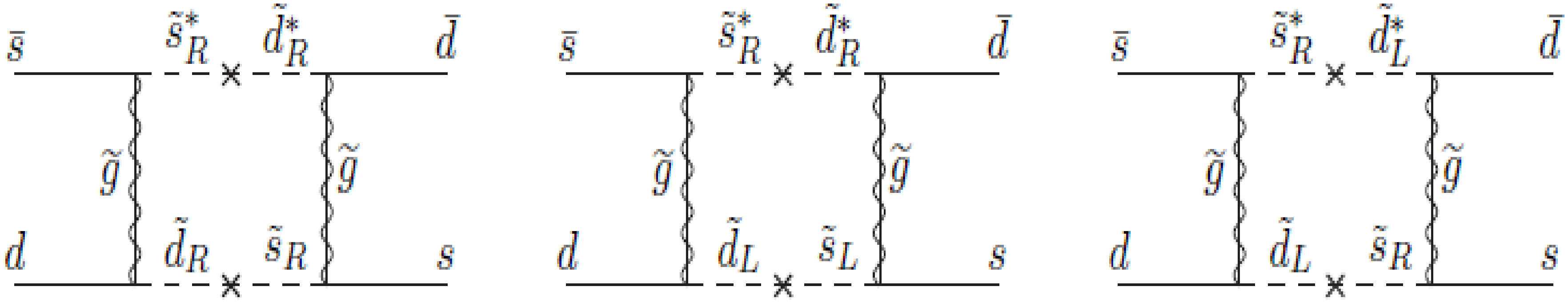
- FCNC (FlavorChangingNeutralCurrent): right-handed slepton can mix, inducing FC processes:



- This process occurs in SM by mixing of *μ*&*e*-neutrinos (SUSY transforms the 2nd diagram).
- $\mathrm{Br}(\mu \to e\gamma)_{\mathrm{exp}} < 1.2 \times 10^{-11}$ → suppressed slepton mixing.

Constraints on MSSM

- Also strong constraints on squark mixing from Kaon mixing: $K^0 \leftrightarrow \overline{K}^0$



- Therefore, MSSM usually assumes NO mixing of squarks, sleptons. ← *flavor-universal* SUSY breaking!

Constraints from SM

- Soft-SUSY breaking *universality*:

  In family space at SUSY breaking scale,

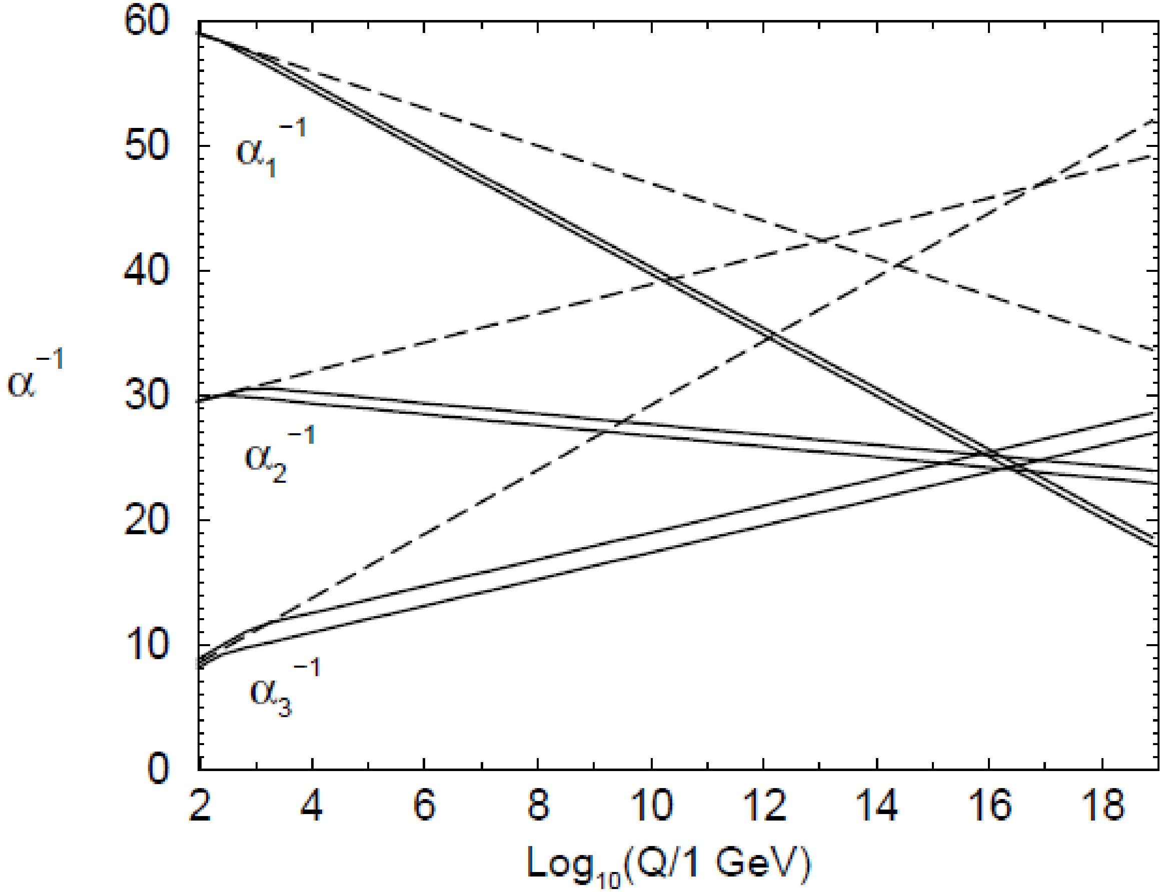
$$\mathbf{m}^2_{\mathbf{Q}} = m^2_{Q}\mathbf{1}, \quad \mathbf{m}^2_{\bar{\mathbf{u}}} = m^2_{\bar{u}}\mathbf{1}, \quad \mathbf{m}^2_{\bar{\mathbf{d}}} = m^2_{\bar{d}}\mathbf{1}, \quad \mathbf{m}^2_{\mathbf{L}} = m^2_{L}\mathbf{1}, \quad \mathbf{m}^2_{\bar{\mathbf{e}}} = m^2_{\bar{e}}\mathbf{1}$$

$$\mathbf{a_u} = A_{u0}\,\mathbf{y_u}, \qquad \mathbf{a_d} = A_{d0}\,\mathbf{y_d}, \qquad \mathbf{a_e} = A_{e0}\,\mathbf{y_e},$$

$$\arg(M_1),\, \arg(M_2),\, \arg(M_3),\, \arg(A_{u0}),\, \arg(A_{d0}),\, \arg(A_{e0}) \;=\; 0 \text{ or } \pi$$

So that only CKM phases break CP.

- This flavor-blind *ad hoc* conditions require theoretical explanations in the top-down approach.



gaugecouplings unified better in MSSM

$$\frac{d}{dt}\alpha_a^{-1} = -\frac{b_a}{2\pi}$$

$$t = \ln(Q/Q_0)$$

*Stephen Martin: The Supersymmetry Primer

$$(b_1, b_2, b_3) = \begin{cases} (41/10,\ -19/6,\ -7) & \text{Standard Model} \\ (33/5,\ 1,\ -3) & \text{MSSM} \end{cases}$$

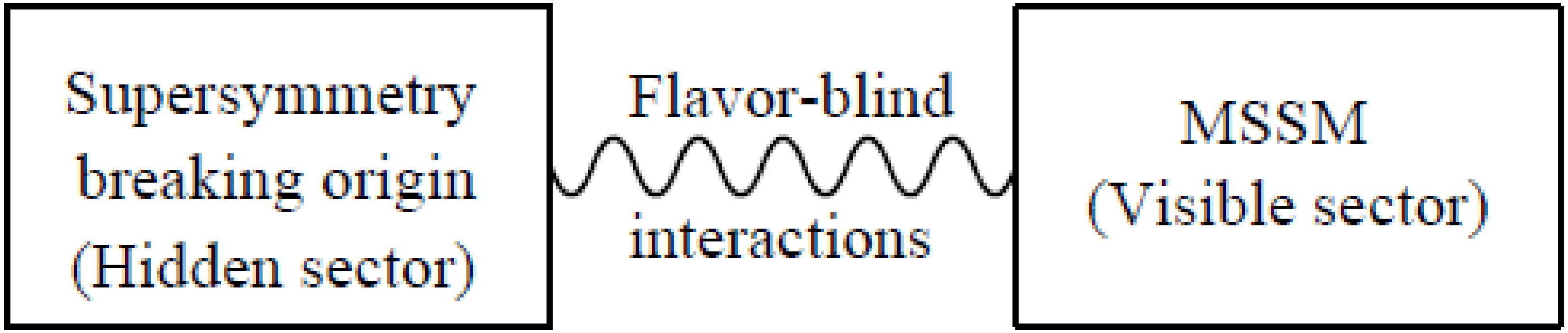
LSP as DM candidate

- MSSM has discrete sym called *R-sym:*

$$R = (-1)^{3(B-L)+2S}$$

- positive for SM particles, negative for superpartners.
- superpartners always created in pairs, LSP cannot into pure SMs.
- LSP with mass few hundred GeVs can serve as cold DM candidate!!

mSUGRA


Supersymmetry breaking origin (Hidden sector)

Flavor-blind interactions

MSSM (Visible sector)

- Hidden sector breaks SUSY, then gravity mediates the breaking to MSSM sector, resulting in flavor-blind or flavor universal breaking.
- Can explain conditions mentioned earlier.

mSUGRA

- In generation space at the SUSY breaking scale:

$$M_3 = M_2 = M_1 = m_{1/2},$$

$$\mathbf{m}^2_{\mathbf{Q}} = \mathbf{m}^2_{\bar{\mathbf{u}}} = \mathbf{m}^2_{\bar{\mathbf{d}}} = \mathbf{m}^2_{\mathbf{L}} = \mathbf{m}^2_{\bar{\mathbf{e}}} = m_0^2\,\mathbf{1}, \qquad m^2_{H_u} = m^2_{H_d} = m_0^2,$$

$$\mathbf{a_u} = A_0\mathbf{y_u}, \qquad \mathbf{a_d} = A_0\mathbf{y_d}, \qquad \mathbf{a_e} = A_0\mathbf{y_e},$$

$$b = B_0\mu,$$

- Remaining parameters :

$$m_{1/2},\ m_0^2,\ A_0,\ B_0,\ \text{and}\ \mu$$

mSUGRA

- Remaining parameters after EW breaking : for v_u, v_d = vev of H_u, H_d,

$$m_0\,,\; A_0\,,\; m_{1/2}\,,\; \tan\beta\,,\ \text{and}\ \ \text{sgn}(\mu)$$

$$\tan\beta = v_u/v_d \qquad v_d^2 + v_u^2 = 4m_W^2/g^2 \simeq (246\ \text{GeV})^2$$

$$\begin{aligned} \sin(2\beta) &= \frac{2b}{m_{H_u}^2 + m_{H_d}^2 + 2|\mu|^2}, \\ m_Z^2 &= \frac{|m_{H_d}^2 - m_{H_u}^2|}{\sqrt{1-\sin^2(2\beta)}} - m_{H_u}^2 - m_{H_d}^2 - 2|\mu|^2 \end{aligned}$$

Masses at EW scale

- All mass spectrum determined by SM parameters plus these additional 5.

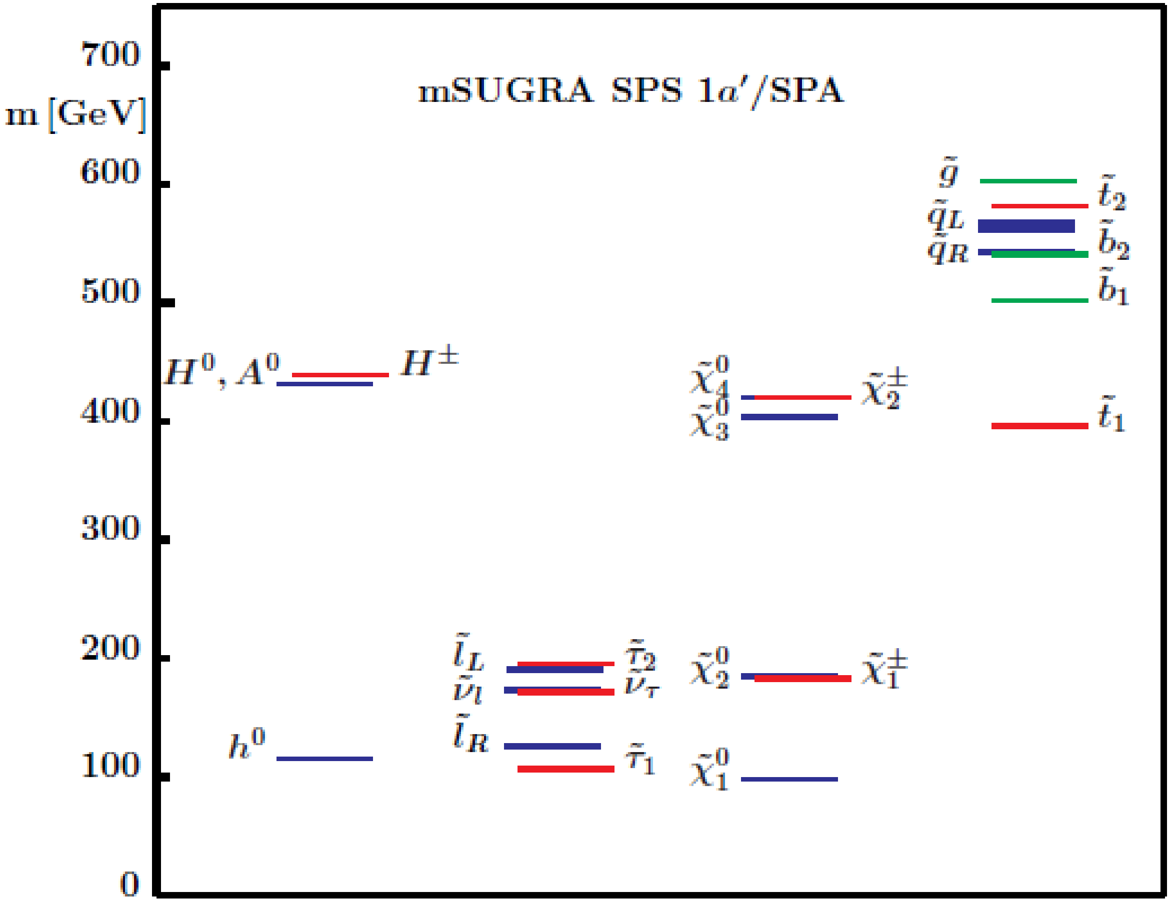
mSUGRA

$$y_b/y_t = (m_b/m_t)\tan\beta$$

- For natural Yukawa coupling, $y_b \sim y_t$ → large tanβ is prefered. ← But upper bound from EW breaking conditions exists.
- *Reference points* or benchmark points: SPA=SUSY Parameter Analysis, points in parameter space with realistic values consistent with LSP as CDM and EW precision.

mSUGRA mass spectrum at SPS 1a'/SPA reference point (SUSY scale 1 TeV)

$$\begin{array}{llll} M_{1/2} = & 250\ \mathrm{GeV} & \mathrm{sign}(\mu) & = +1 \\ M_0 \ = & 70\ \mathrm{GeV} & \tan\beta(\tilde{M}) & = \ 10 \\ A_0 \ = & -300\ \mathrm{GeV} & & \end{array}$$



http://arxiv.org/PS_cache/hep-ph/pdf/0511/0511344v2.pdf for details.

- Squarks heavier than sleptons and gauginos
- LSP=lightest neutralino
- Higgs light enough to be found at LHC.

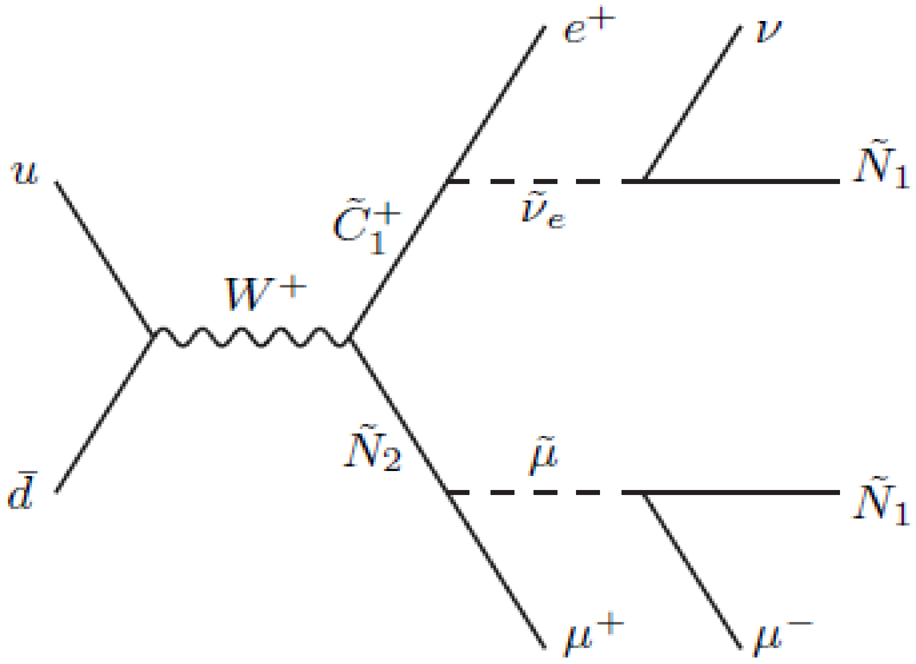
Experimental signatures

- Constraints from $\mu \rightarrow e\gamma$, $b \rightarrow s\gamma$, neutral meson mixing, electric dipole moment for *e, n,* anomalous magnetic moment of muon.
- Collider signatures:
- Superpartners produced in pairs then decay to SM particles and invisible LSPs (Lightest superpartners). *e.g.* at hadron colliders

$$u\bar{d} \rightarrow \tilde{C}_i^+ \tilde{N}_j, \qquad d\bar{u} \rightarrow \tilde{C}_i^- \tilde{N}_j, \qquad gg \longrightarrow \tilde{g}\tilde{g}, \quad \tilde{q}_i \tilde{q}_j^*,$$

$$u\bar{d} \rightarrow \tilde{\ell}_L^+ \tilde{\nu}_\ell \qquad d\bar{u} \rightarrow \tilde{\ell}_L^- \tilde{\nu}_\ell^*, \qquad gq \longrightarrow \tilde{g}\tilde{q}_i,$$

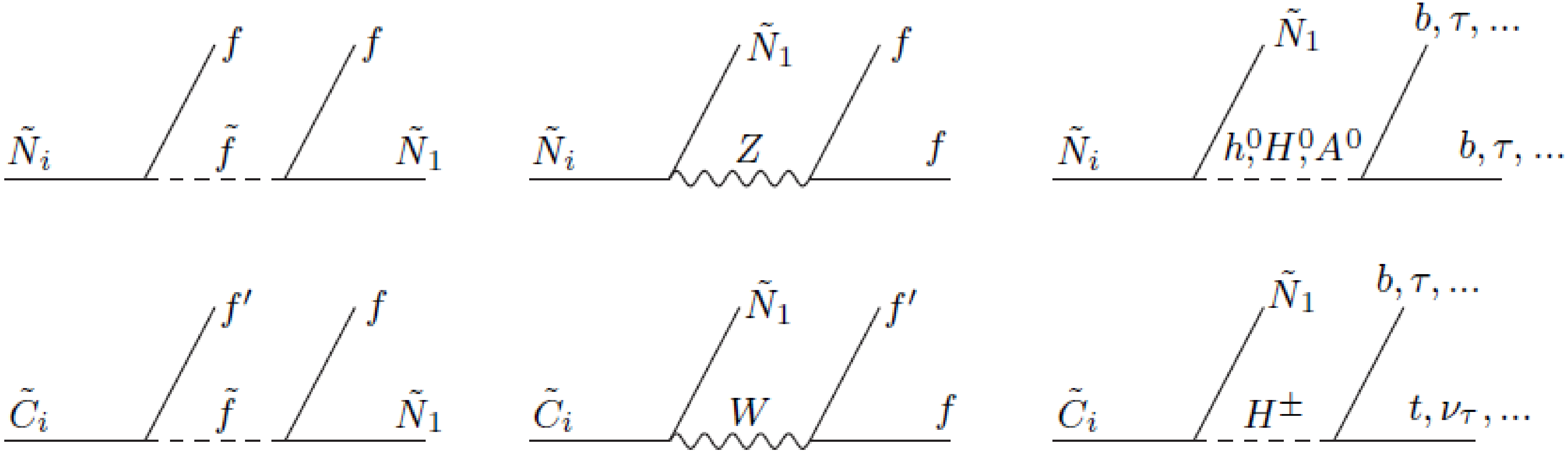
Collider signatures



- Example of charginos, neutralino production. They will finally decay into LSP, assumed to be the lightest neutralinno here.
- Looking for $\mu^+\mu^-e^+ + \not{E}_T$ with no jets. (*trilepton* signals)

Collider signatures

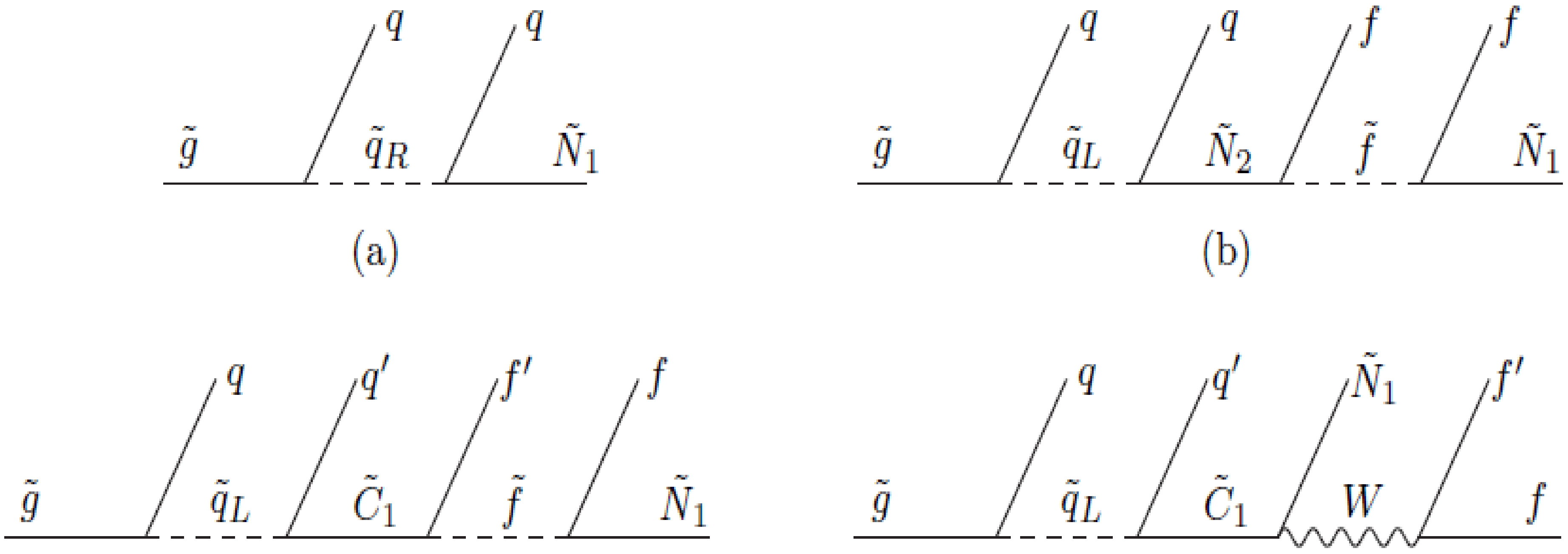
- Many decay channels: chargino, neutralino



- slepton decays:

$$\widetilde{\ell} \to \ell \widetilde{N}_i, \quad \widetilde{\ell} \to \nu \widetilde{C}_i, \quad \widetilde{\nu} \to \nu \widetilde{N}_i, \quad \widetilde{\nu} \to \ell \widetilde{C}_i$$

- Gluino decays:



(a) (b)

- Lightest Higgs possible to be discovered at LHC:

Very large Gluon fusion $gg \to h^0$

$$h^0 \to \gamma\gamma$$
$$h^0 \to ZZ^{(*)} \to \ell^+\ell^-\ell'^+\ell'^-$$
$$h^0 \to WW^{(*)} \to \ell^+\nu\ell'^-\bar{\nu}.$$

MSSM Higgs at LHC

- Other channels: weak bosons fusion, *W, Z radiated* from quarks (forward jets):

$$W^+W^- \to h^0 \text{ and } ZZ \to \bar{h}^0$$

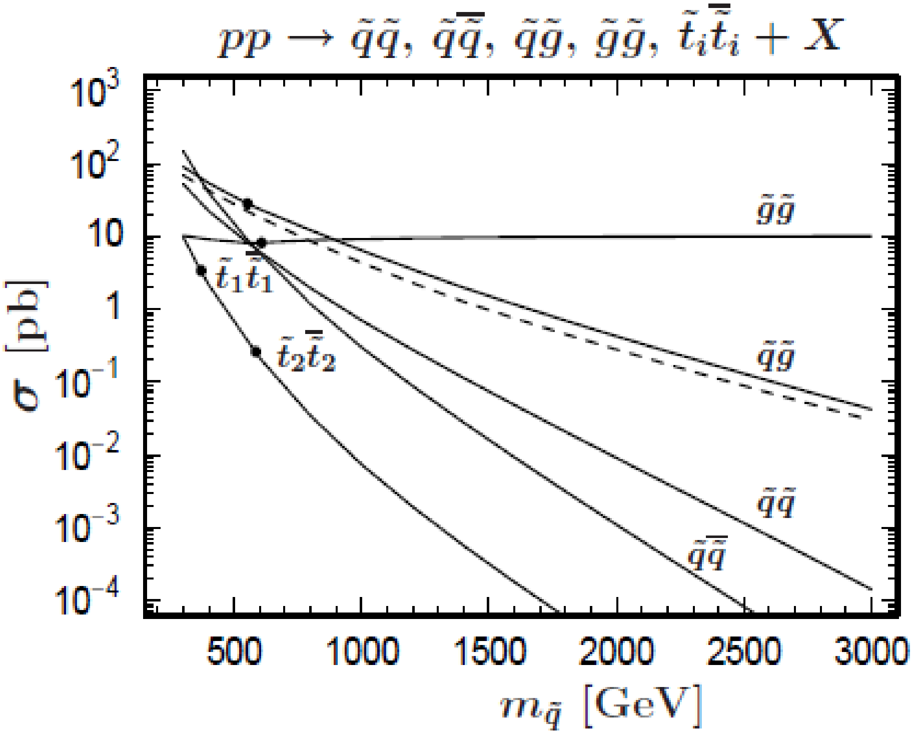
$$pp \to h^0 jj \to \tau^+\tau^- jj \text{ or } WW^{(*)} jj$$

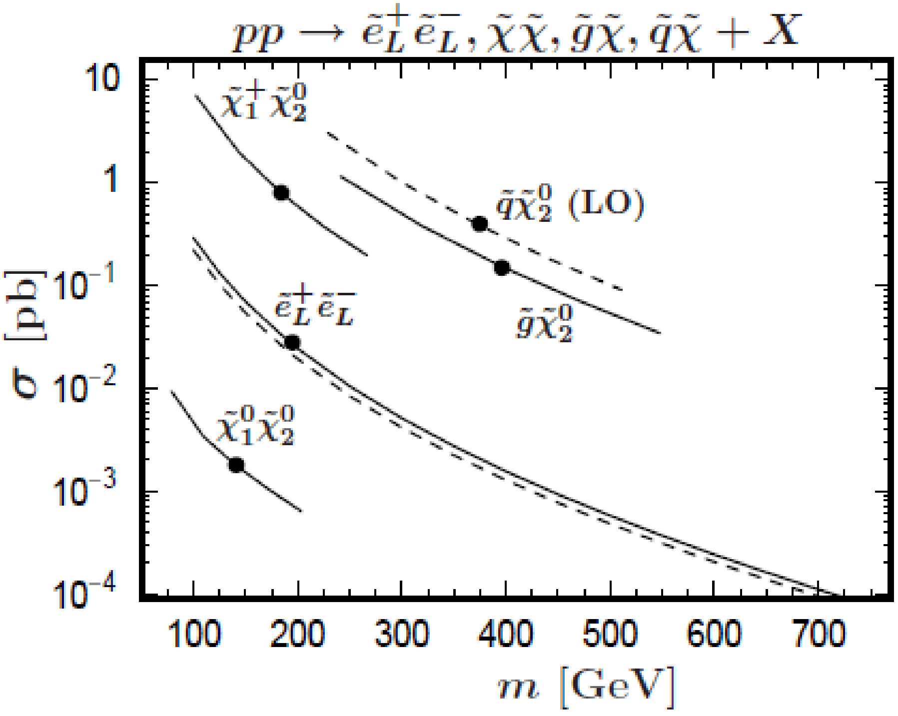
- Also because of large Yukawa coupling:

Higss radiated from a top

$$pp \to t\bar{t}h^0 \to t\bar{t}b\bar{b}.$$

Some hypothetical plots at LHC





http://arxiv.org/PS_cache/hep-ph/pdf/0511/0511344v2.pdf
for details.

NP lists

More and more and much more.

- Little Higgs, Fat Higgs, SUSY in extra-D
- Strong dynamics: technicolor models, preons
- Flavor gauge theories, horizontal symmetries
- NMSSM, mmSUGRA (gravitino variations), GMSB, AMSB → more parameters!
- String models, low-scale string pheno (e.g. P. Burikham et. al. ☺) TeV-scale BH, string balls etc.
- LHC Pb-Pb collision → Quark-Gluon Plasma*

References

- PDG (Particle Data Group) and references therein, http://pdg.lbl.gov/
- SPIRES, http://www.slac.stanford.edu/spires/

  to search for articles and references.