BEYOND THE SM (BSM)

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Outline

- Review of SM (see also previous lectures)
- Motivation to go beyond
- SUSY
- Extra dimensions

} (Prime) Illustrations of BSM

Review of SM

Particle content

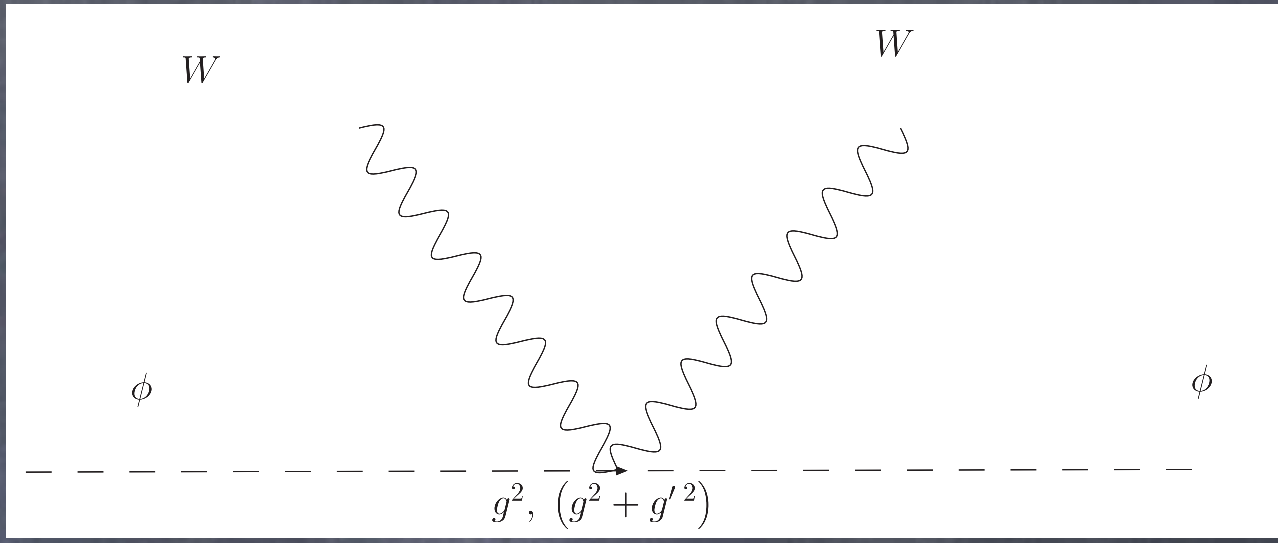
- Spin-1/2 matter (LH Weyl fermions: e^c is anti-particle of RH electron)
- Spin-1 gauge bosons (force carriers)
- Spin-0 Higgs (gives mass to others)

generation

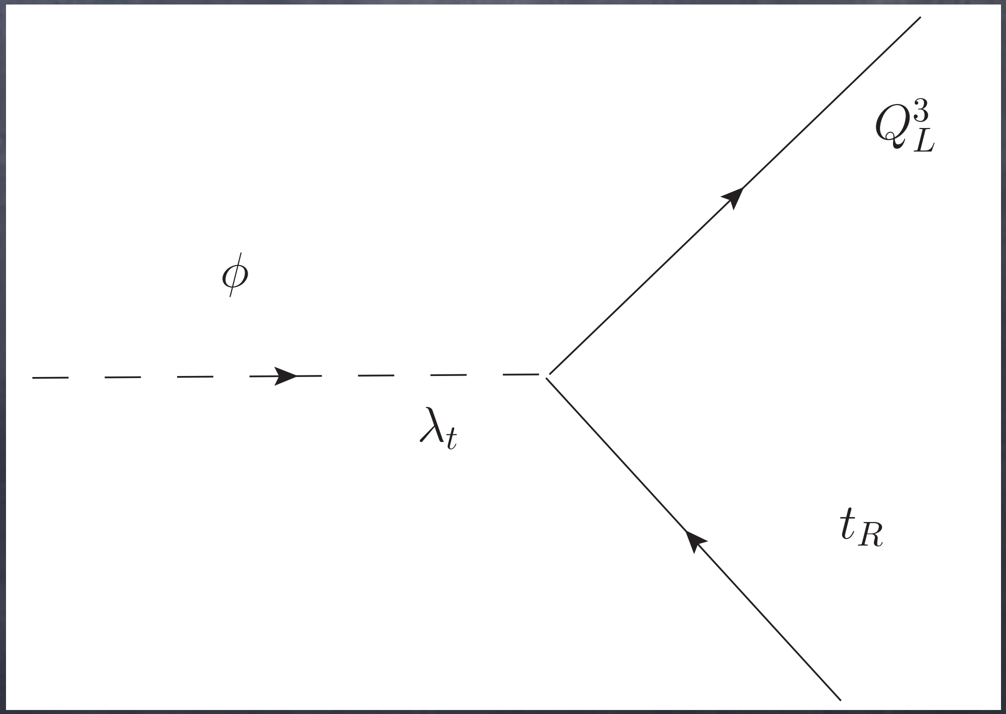
particle	$SU(3)_c$	$SU(2)_w$	$U(1)_Y$
$\begin{pmatrix} u \\ d \end{pmatrix}_i$	$\mathbf{3}$	$\mathbf{2}$	$\frac{1}{6}$
u_i^c	$\bar{\mathbf{3}}$	$\mathbf{1}$	$-\frac{2}{3}$
d_i^c	$\bar{\mathbf{3}}$	$\mathbf{1}$	$\frac{1}{3}$
$\begin{pmatrix} \nu \\ e \end{pmatrix}_i$	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$
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 (see Williams lectures)

- W, Z masses (not for photon):



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



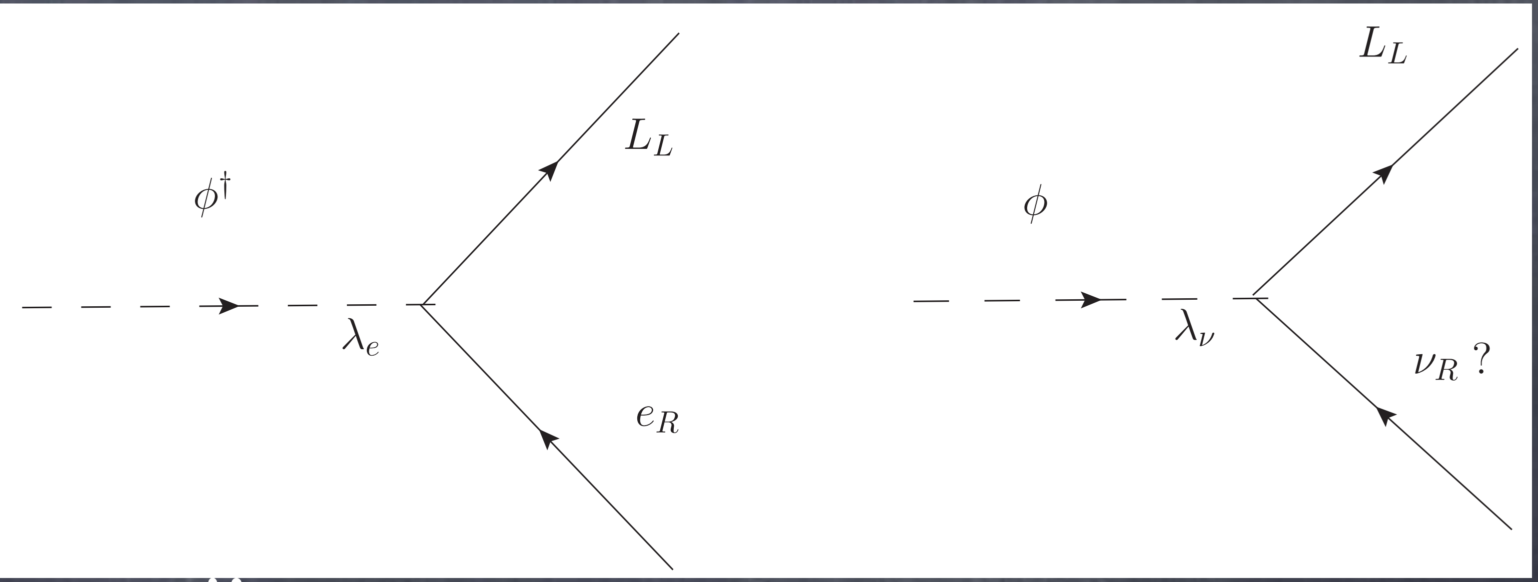
(return to these vertices for motivation to go beyond SM)

Disclaimer (I) for BSM

- 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 unique guiding principle for theory (cf. SM) (although WIMP miracle, return during SUSY)



- Neutrino mass (see Parke/Paley lectures): absence of ν_R in SM just add it ("ν"SM): "weird": no SM gauge couplings + why mass/Yukawa coupling so much smaller than charged fermions (see back-up on 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

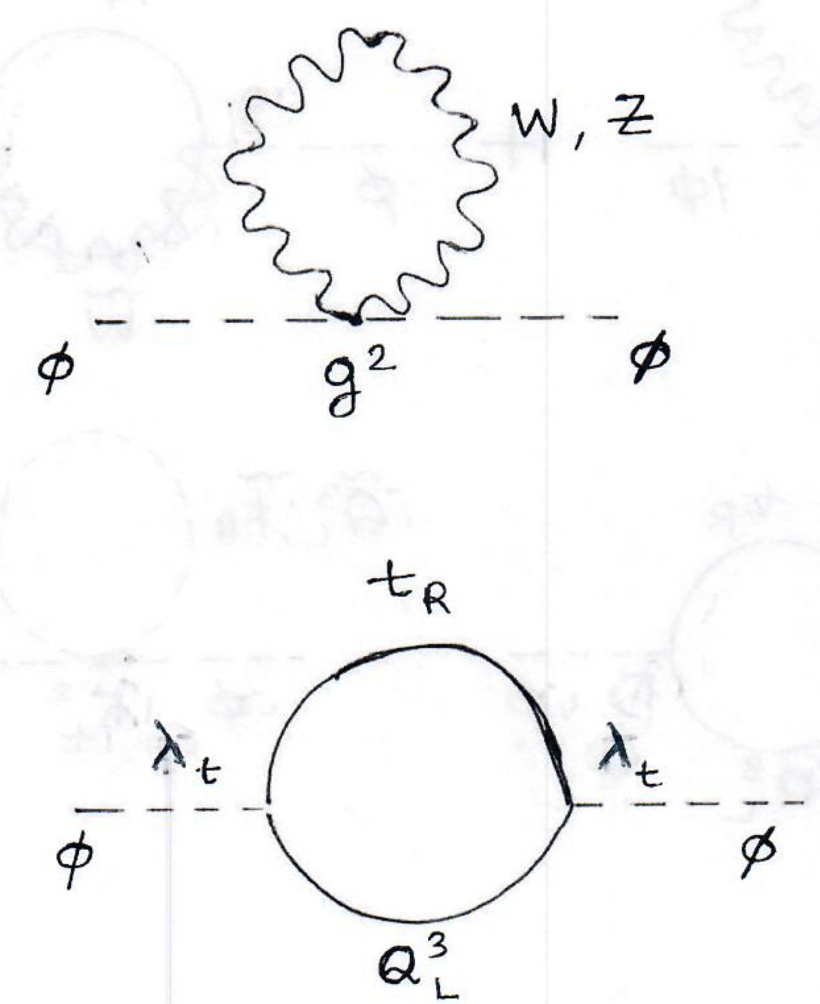
- (finite) observed = (infinite) bare + (infinite) loop, with $\Lambda_{UV} \to \infty$ vs.
- (finite) observed = (finite) bare + finite (even if large) loop, with $\Lambda_{UV} \sim M_{Pl}$
- Is there tuning? (meaningless when $\Lambda_{UV} \to \infty$)

Quantum correction to Higgs mass term/VEV (I)

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

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

(problem so severe that estimate suffices)

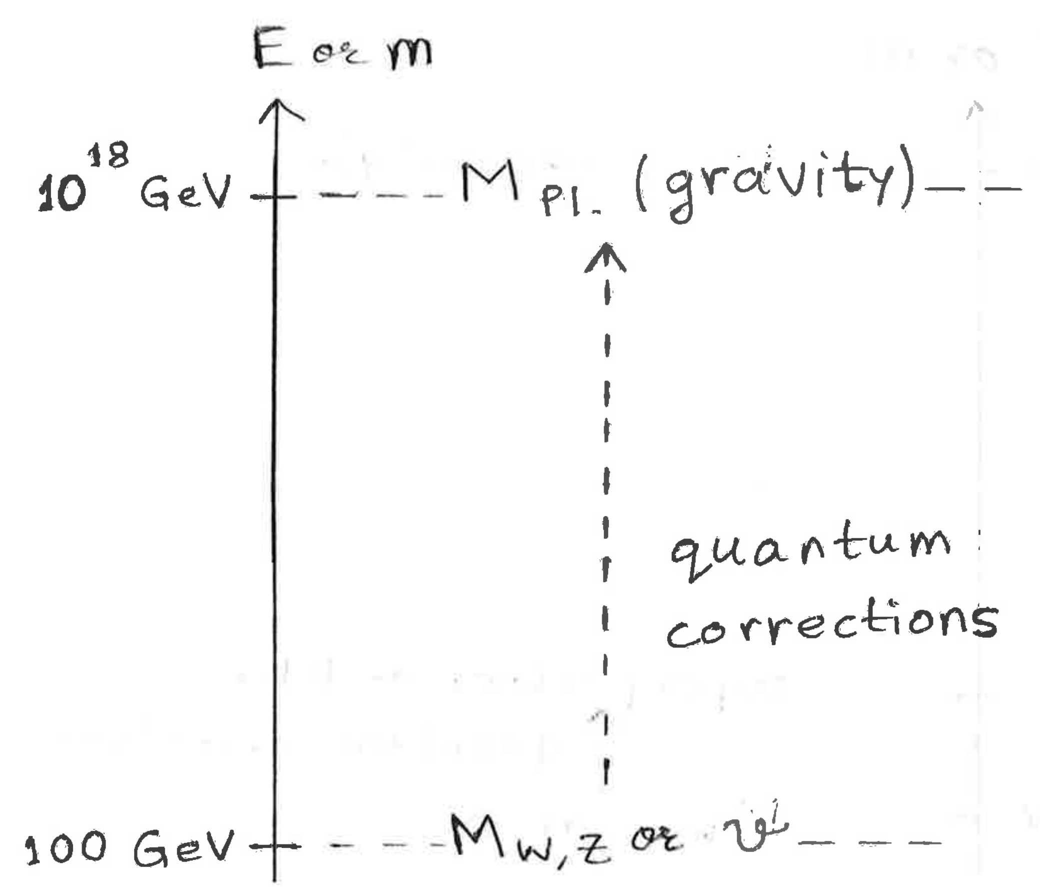


Quantum correction to Higgs (scalar) mass term/VEV (II)

- Naturally

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

- 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 mechanism for neutrino mass: see Parke 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

  $\mathcal{L} \ni M_e \overline{e_L} e_R \Rightarrow$

  IF $M_e \rightarrow 0$, then (chiral) symmetry:

  invariance under $e_{L,R} \rightarrow e^{i\alpha_{L,R}} e_{L,R} \Rightarrow$

  $\delta M_e \propto M_{e\ bare}$ (both sides break symmetry) $\Rightarrow$

  can*not* have $\Lambda_{UV}^{>0} \Rightarrow$

  $\delta M_e \sim M_{e\ bare} \times \frac{e^2}{16\pi^2} \log \Lambda_{UV} \ldots$

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

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

- similar symmetry argument:

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

[Even if $\lambda_e = 0$, electron does couples to W, Z which couple to Higgs...⇒electron couples via gauge loop to Higgs?...No (due to symmetry)!]

Flavor (hierarchy) puzzle

- If M_e or λ_e starts small, then stays small (radiatively stable)...
- ...but why starts small (vs. large for top quark)?

(return during extra dimensions)

Supersymmetry (SUSY)

(BSM I)

Disclaimer for beyond SM (II)

- skip technical details (see references)
- focus on (for both SUSY and extra dimensions):
  principle behind idea/solution to hierarchy
  who are new particles (dictated by principle)
  interactions of/signals for new particles

SUSY (theory)

(Solution to Planck-weak hierarchy problem)

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 (discussed earlier) "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

SM particle spin $= S$	sparticle spin $= \left\lvert S - \frac{1}{2} \right\rvert$	$SU(3)_c$	$SU(2)_w$	$U(1)_Y$
$\begin{pmatrix} u \\ d \end{pmatrix}_i$	$\begin{pmatrix} \tilde{u} \\ \tilde{d} \end{pmatrix}_i$	$\mathbf{3}$	$\mathbf{2}$	$\frac{1}{6}$
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 (two 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...)

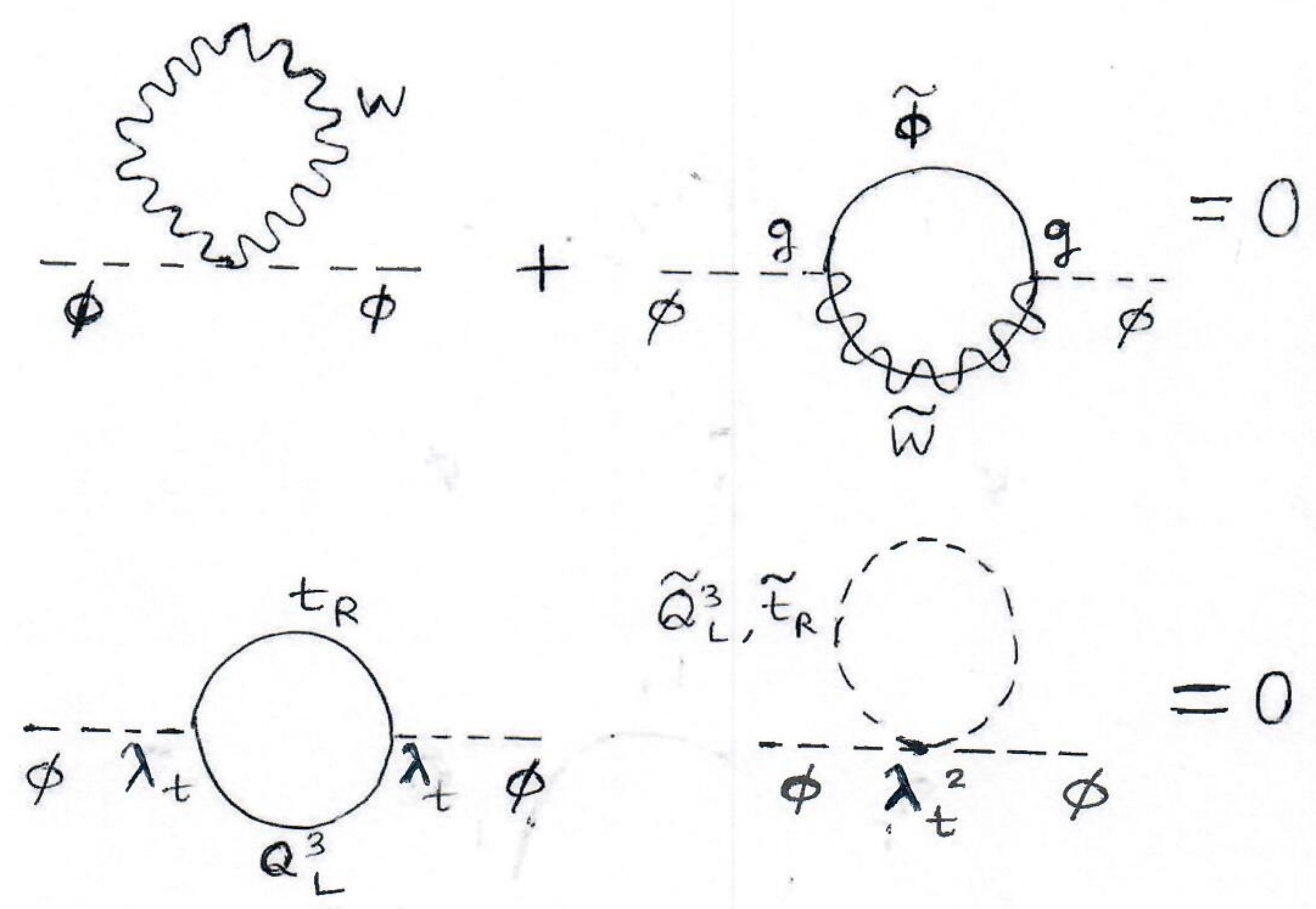
- Yukawa-related interactions:

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

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

SUSY: solves Planck-weak hierarchy problem (Ib)

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



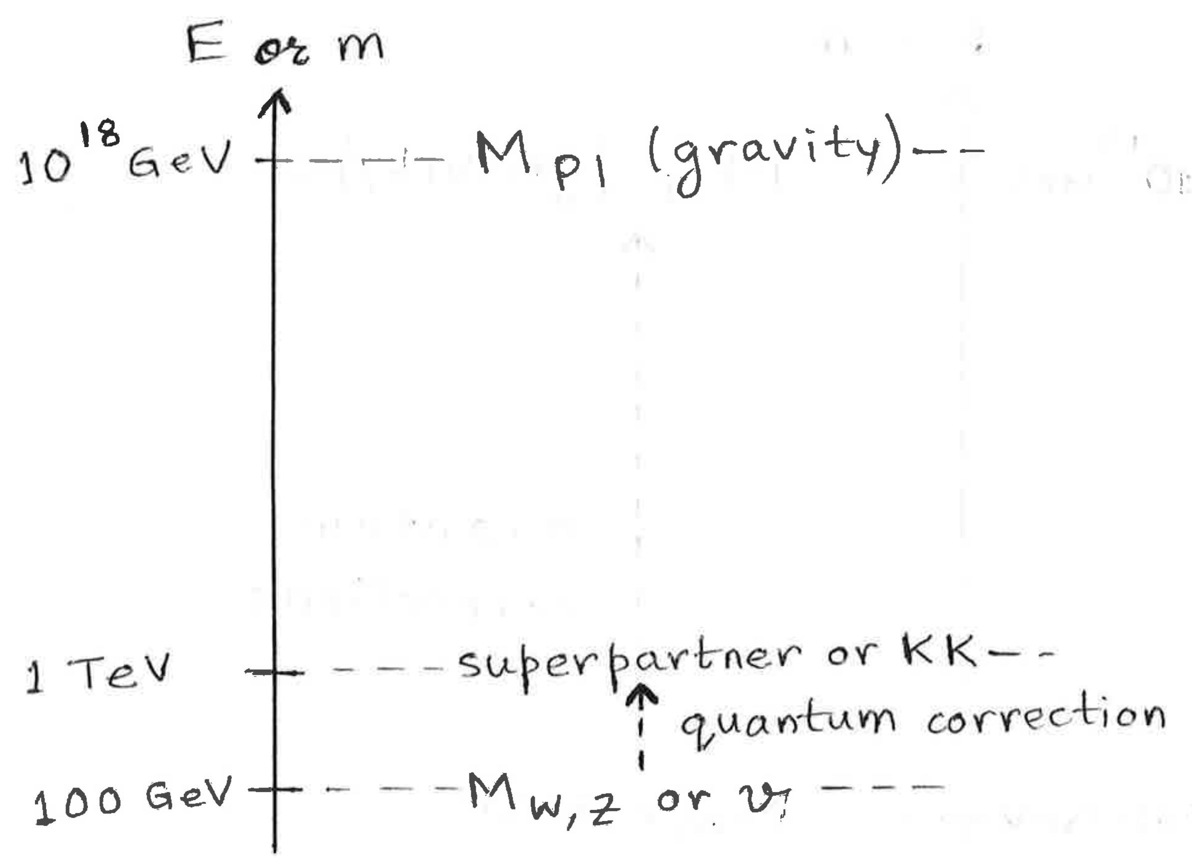
SUSY: solves Planck-weak hierarchy problem (IIa)

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

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

SUSY breaking mass

- ...still natural if SUSY breaking mass $<\sim$ 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)

Summary

- SUSY solves Planck-weak hierarchy problem...
- ...if superpartners have mass <∼TeV ⇒
- LHC is SUSY "factory"

SUSY phenomenology

(DM candidate and LHC signals)

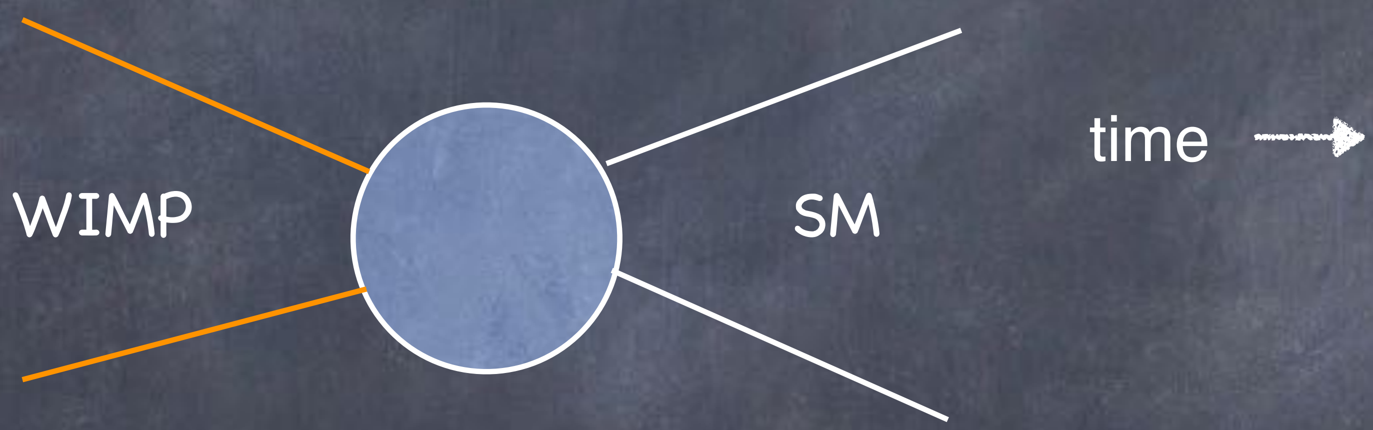
R-parity

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

- candidates: $\tilde{W}^3,\ \tilde{B},\ \tilde{\phi}^0_{u,d}$
($\tilde{\nu}$ 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)

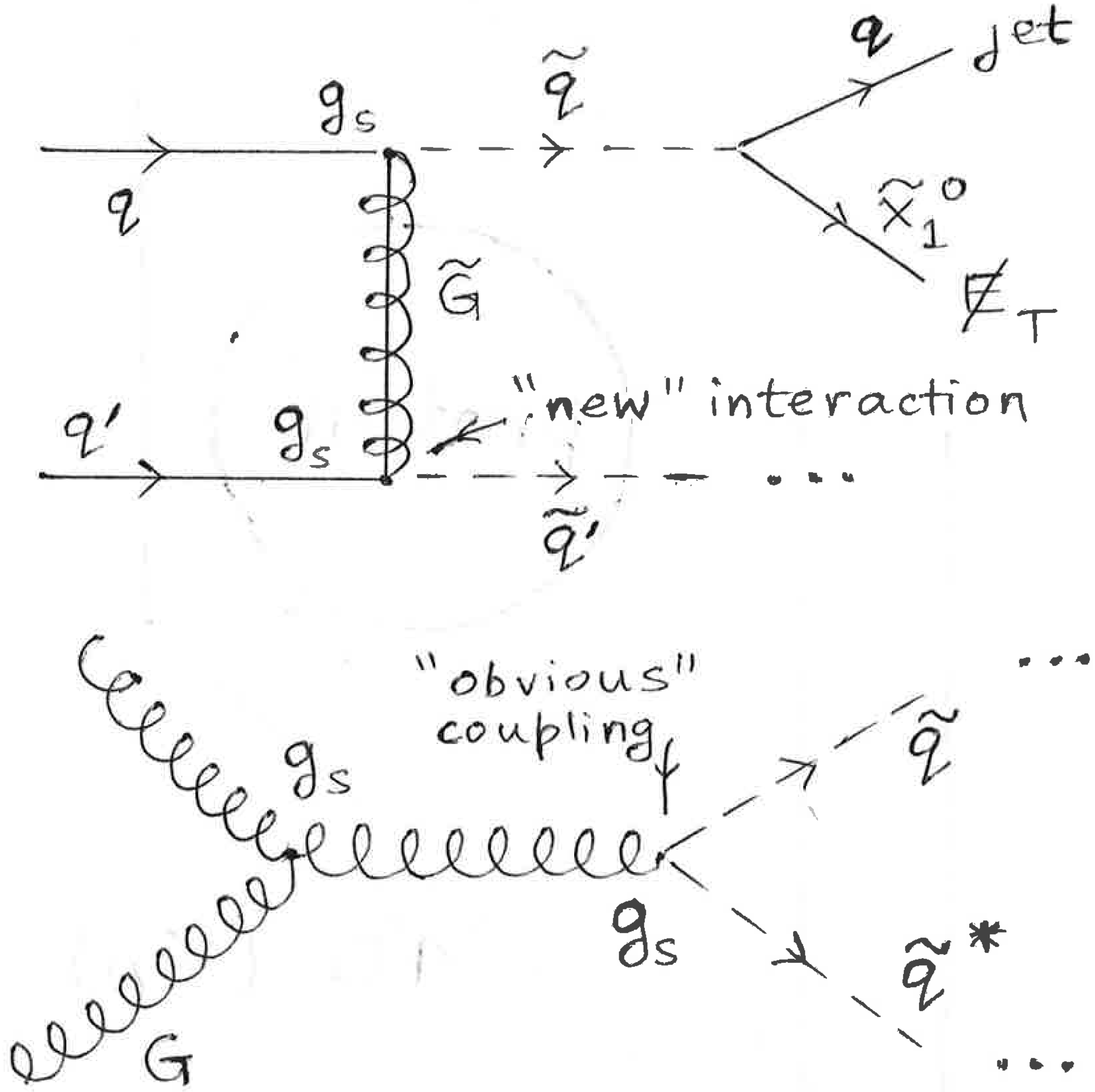
- (Must) pair produce superpartner
- ...each of which decays into LSP + SM

→

- missing transverse momentum + leptons/jets/photons

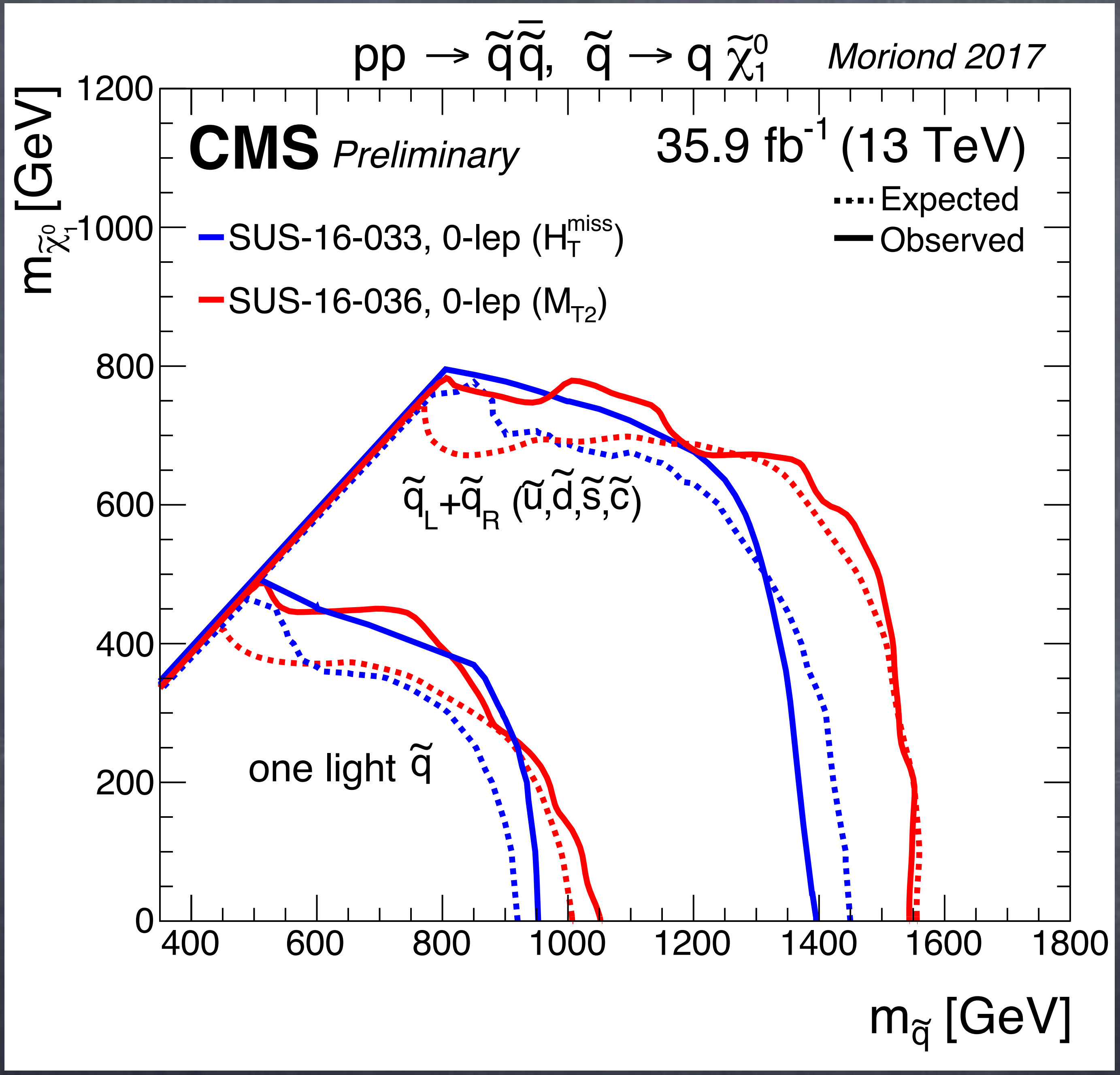
Collider signals: example 1

- Squark production



Collider signals: limits

- based on jets + $\not{p}_T$



(SM background: Z+jets…need accurate calculations: see Boughezal lecture)

Extra Dimensions

(Solutions to both Planck-weak and flavor hierarchy problems)

(BSM II)

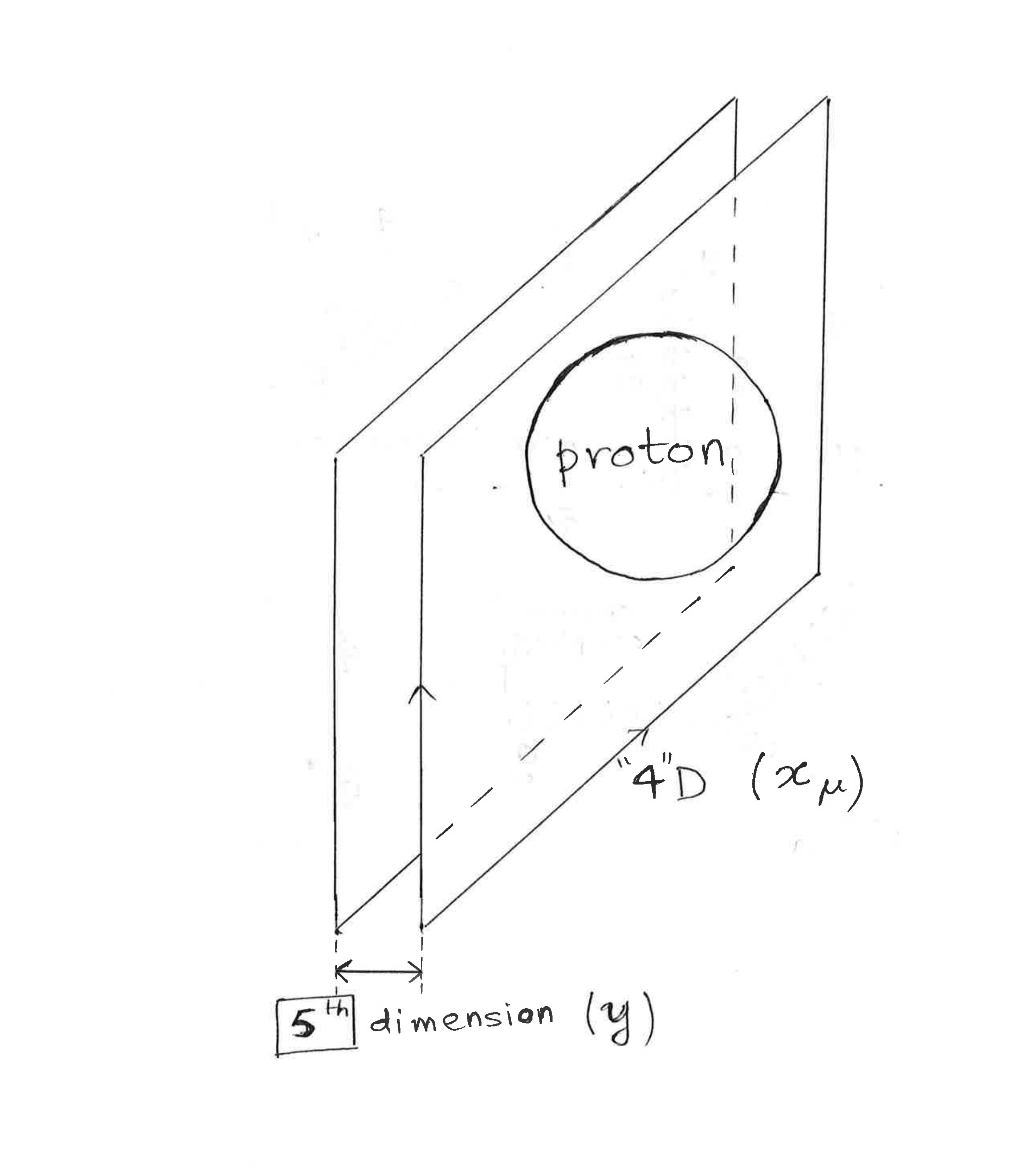
Extra dimensions:
basic idea

(reviews in hep-ph/0404096,hep-ph/0510275,

hep-th/0508134, hep-ph/0605325,...)

Why haven't we "seen" it?

- It's small!



Why should it be compact/"small"?

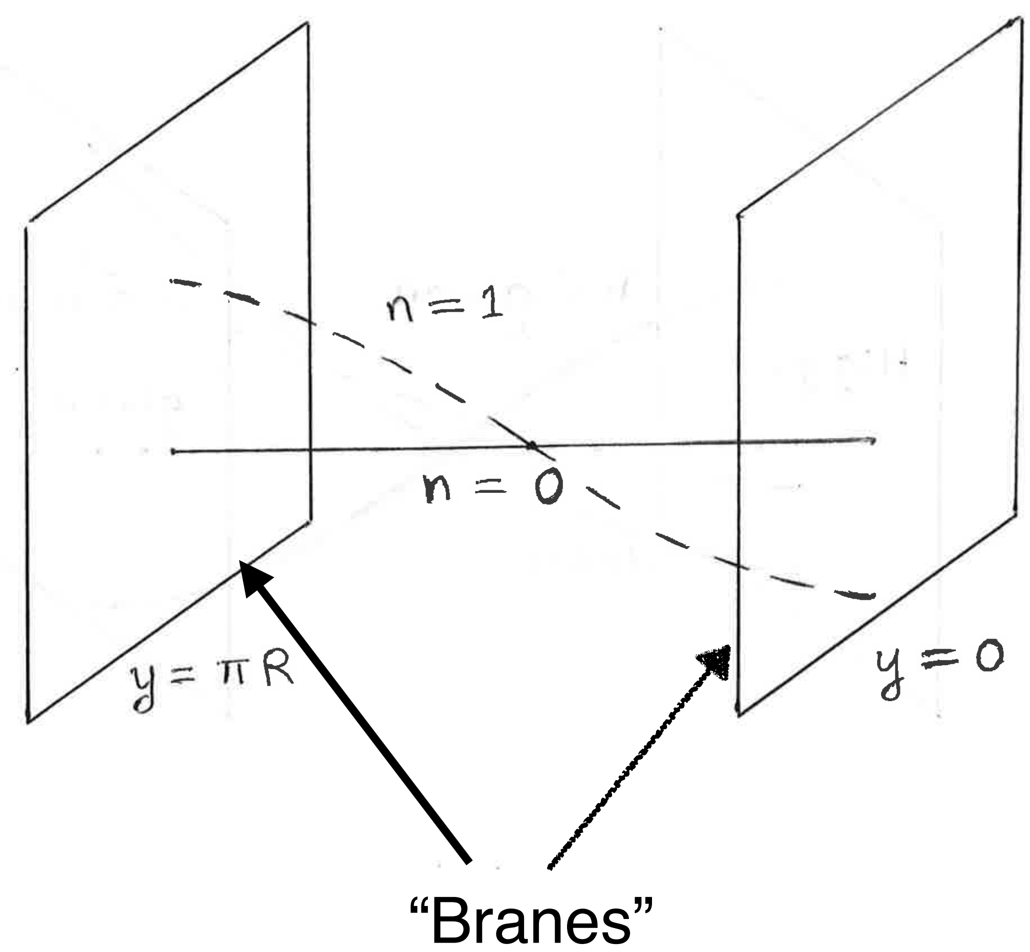
- If 5th dimension was infinite, Newton's law $\propto 1/r^3$ (Gauss' law)
- we have measured it to be $\propto 1/r^2$ down to 100 μ m

What can we see in future (I)?

- SM field (x_μ, y):
  "Fourier" expand (compact) y

- From 4D viewpoint, dynamics in y similar to quantum mechanics of particle in 1D infinite potential well

- Kaluza-Klein (KK) modes (still function of x) with profile in y and quantized $p_5 \sim n/R$



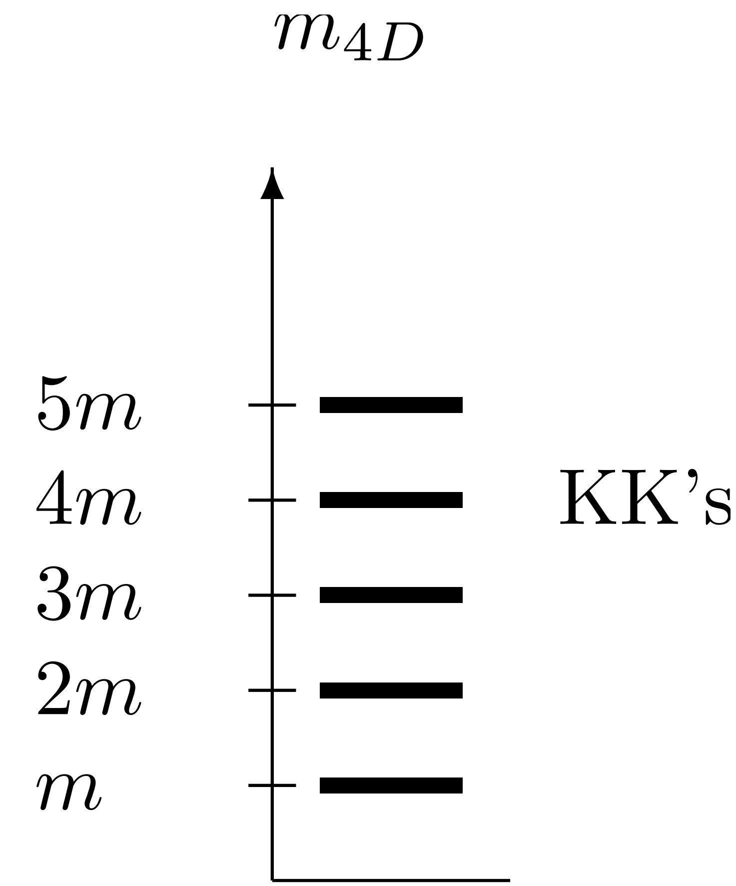
What can we see in future (II)?

- Each KK mode like massive field (particle upon quantization) from 4D viewpoint:

set to 0 (→ M_{5D})

$$E^2 = |\bar{p}|^2 + p_5^2 + M_{5D}^2 \Rightarrow$$

$\bar{p} = 0$ mode (at rest in 3D): $E \sim n/R \Rightarrow$
(rest) mass, $m_{4D} \sim n/R$



- p_5 "converted" to 4D mass

- lightest mode ($n = 0$) identified with observed/SM

- heavier (KK) modes ($n \neq 0$):
  new particles (signals + solve problems)

- KK mass scale >~TeV, haven't seen it yet!

4D particle content

- Assume **all** SM fields propagate in extra dimensional "bulk" (some fields localized on brane also possible: **no** KK modes for these)

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

Simplest case: scalar field on circle (with 5D mass term only)

Summary (see back-up for technical details)

- Profiles:

$$n = 0 \text{ (zero-mode): constant in } y$$
$$n = 1, 2... \text{ (KK modes): } \sin / \cos ...$$

- Masses: $m^2_{4D\ n} = M^2_{5D} + n^2/R^2$

Fermion on "orbifold" (semi-circle)

(Solve general wave equation, with 5D and brane-localized mass/kinetic terms to obtain modes)

- exponential profile for fermion zero-modes (massless) (cf. flat for scalar earlier)

not m_{4D}

$$\sim e^{-M_{5D\ L} y},\ e^{+M_{5D\ R} y}$$

- can get exponential profile for zero-mode even for scalar

Technically: gauge field...

$$\mathcal{A}_M = \mathcal{A}_{\mu=0,1,2,3} + \mathcal{A}_5$$

- $\mathcal{A}_\mu$ modes behaves as vectors (spin-1) from 4D viewpoint
- $\mathcal{A}_5$ modes behaves as scalars from 4D viewpoint (Higgs?...see later)
- zero-mode flat; KK sin/cos...

Interactions of 4D modes...

5D Dirac matrices

$$\int d^4x \; dy \; g_{5D} \bar{\Psi} \Gamma^M \mathcal{A}_M \Psi \Rightarrow$$

$$\int d^4x \; g_{4D\;mnp} \psi_L^{(m)} A_\mu^{(n)} \gamma^\mu \psi_L^{(p)} :$$

$$g_{4D\;mnp} \sim g_{5D} \int dy \; (m^{th}\text{profile}) \times (n^{th}\text{profile}) \times (p^{th}...)$$

- coupling between modes $\propto$ overlap of profiles

Summary

- 5D field → tower of (massive) KK modes (from 4D viewpoint)
- profiles from (generalized) wave equation in 5D space-time
- Coupling of particles $\propto$ overlap of profiles

Extra dimensions: "application"

Solution to flavor (hierarchy) puzzle

Yukawa coupling: $\lambda_{4D} \sim \lambda_{5D} \times \int dy \, e^{(-M_{5D\ L} + M_{5D\ R} + M_{5D\ \phi})y}$

- choose M's so that overlap near Higgs brane dominates

→

- $m_d \ll m_s$ due to (exponential) hierarchical fermion profiles at Higgs brane:

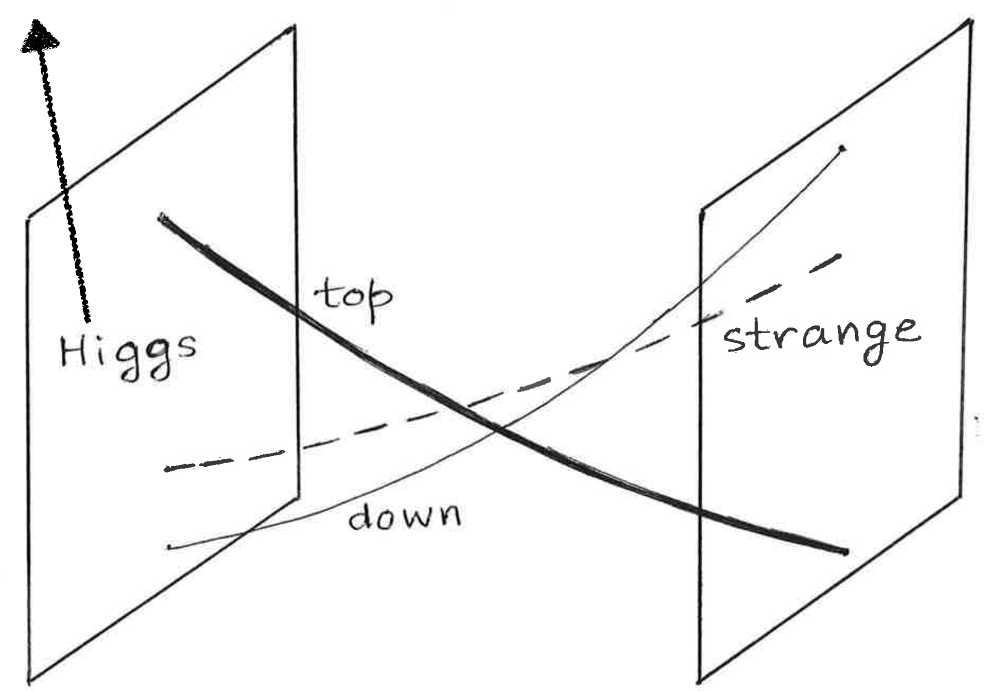
  $\lambda_{4D} \sim \lambda_{5D} \, e^{(-M_{5D\ L} + M_{5D\ R})\pi R}$

  (do not need hierarchies in 5D Yukawa or M_{5D} for fermions)

- 1-2 (Cabbibo) mixing also small:

$$\lambda_d^{22} \gg \lambda_d^{12} \gg \lambda_d^{11}$$

For simplicity, shown localized (in general, peaked near brane)



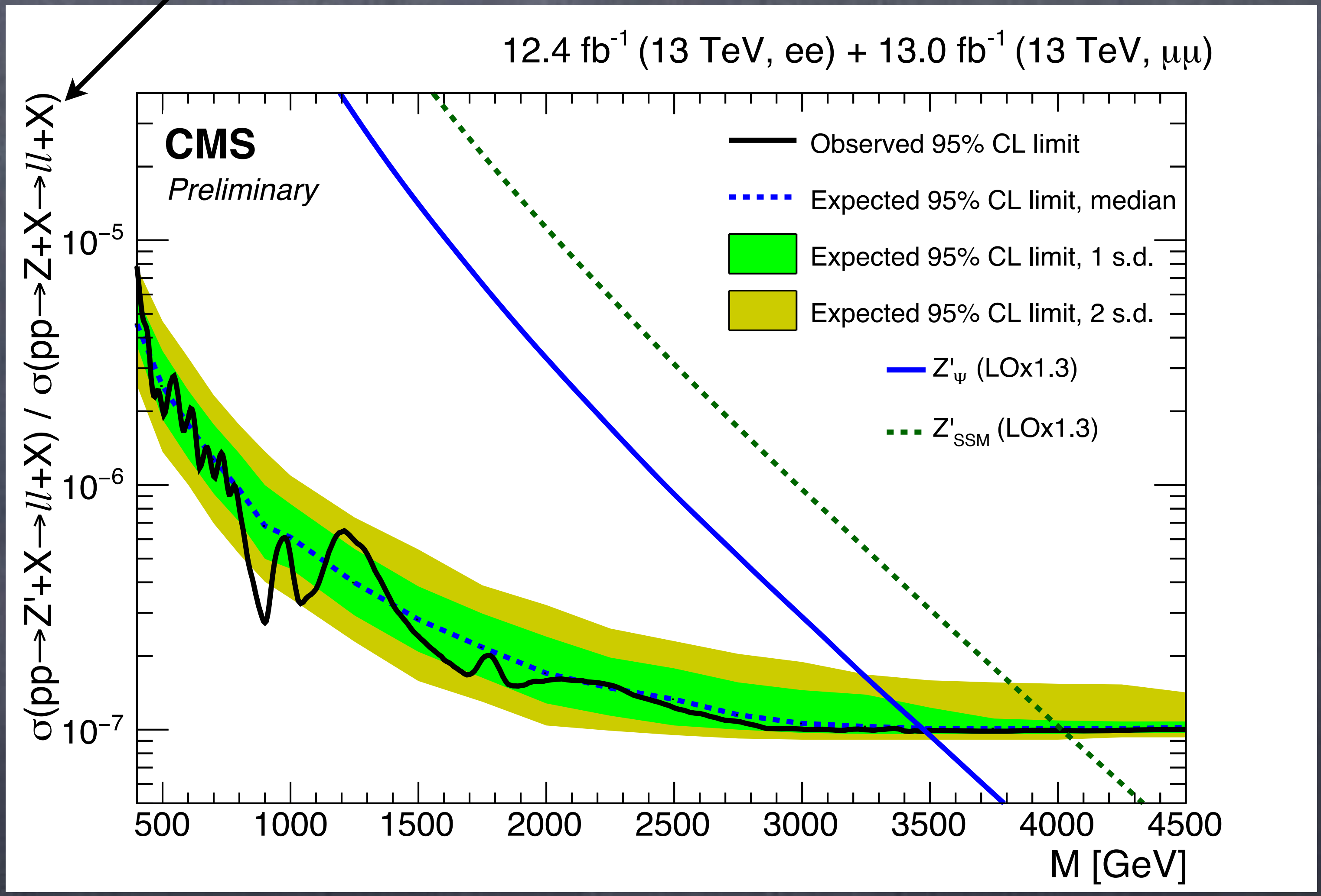
Signals for KK modes I (general)

- resonant production of single KK gauge mode a la SM Z:

$$q\bar{q} \to \text{KK } Z \to l^+l^-$$

- peak in dilepton invariant mass
- adapt LHC Z′ search (include appropriate couplings)

ratio of Z′ and SM Z cross-section x BR

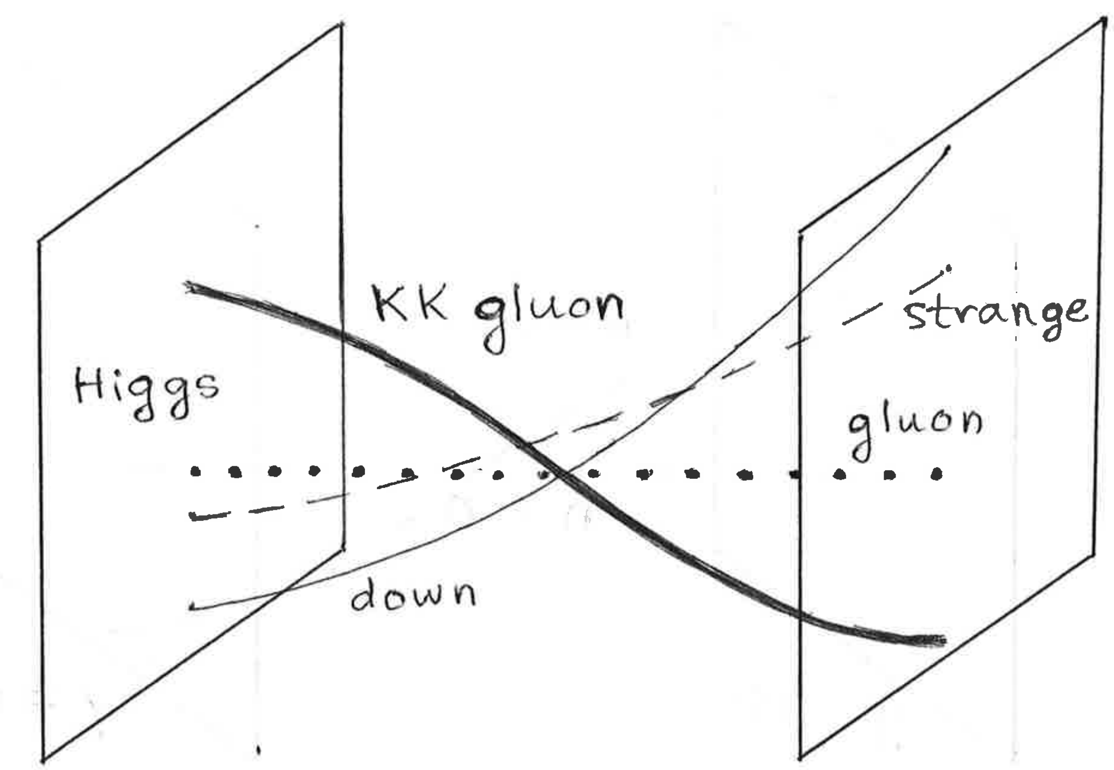


(from CMS-PAS-EXO-16-031)

Signals for KK modes (II)

- Coupling to KK gauge mode is flavor-dependent: in overlap, KK common, but fermion varies
- cf. coupling to gauge zero-mode (flat) is universal

(see later/back-up: flavor problem; KK gluon decays mostly to top quarks)



Summary

- solution to flavor (hierarchy) puzzle based on fermion profiles in extra dimension...
- → KK/massive gluon, Z... resonances
- LHC sensitive only if KK mass scale $\sim$ TeV
- ...but (so far) can be (much) heavier (smaller ruled out by current limits)
- ...it has to be TeV if use extra dimension to also solve Planck-weak hierarchy problem

Extra dimensions: “complete” model

Extra dimension solves Planck-weak hierarchy problem (I)

- KK particles cut-off Higgs mass divergence...like superpartners, KK's must be <~TeV

- Principle: Higgs is A_5 mode ("extra" component of 5D gauge field)

- no quadratic divergence from $E \gtrsim$ KK mass scale $(5D$ regime$)$: (5D) gauge invariance protection "extended" from spin-1 to 0 (these two 4D spins are related via 5th dimension)

...cf. SUSY...

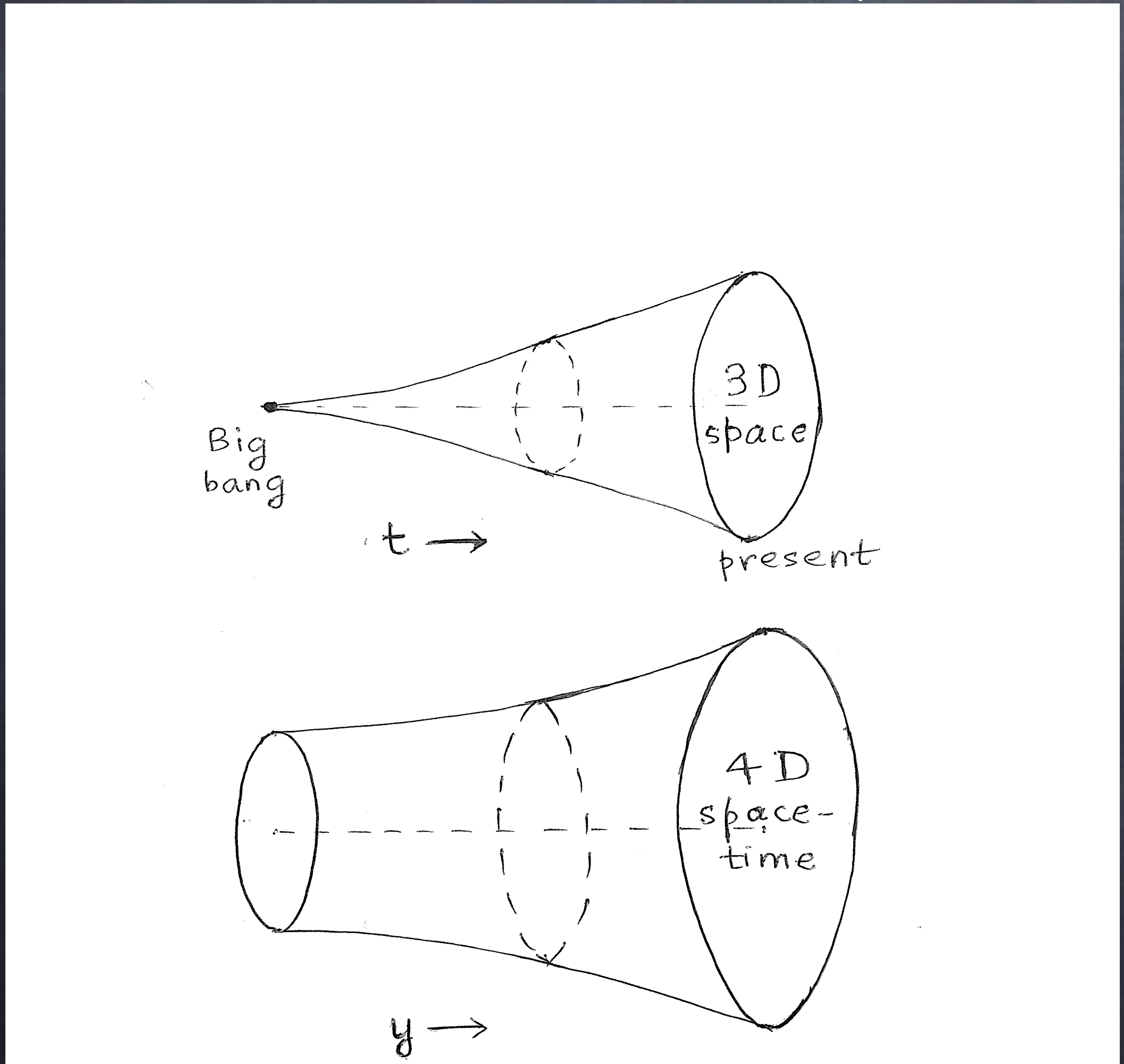
- (chiral) symmetry protection for fermion: extended to scalar...
- ...the two spins (differing by 1/2) related by SUSY

Extra dimension solves Planck-weak hierarchy problem (II)

- Like SUSY, "new" hierarchy problem: KK mass scale $\ll M_{Pl}$?
- Solution: warped extra dimension

Warped extra dimension intuitively
(see back-up for technically)

- Analogy with expanding universe
- gravitational red-shift generates hierarchies in mass scale between different positions in 5th dimension



3D space expands with time

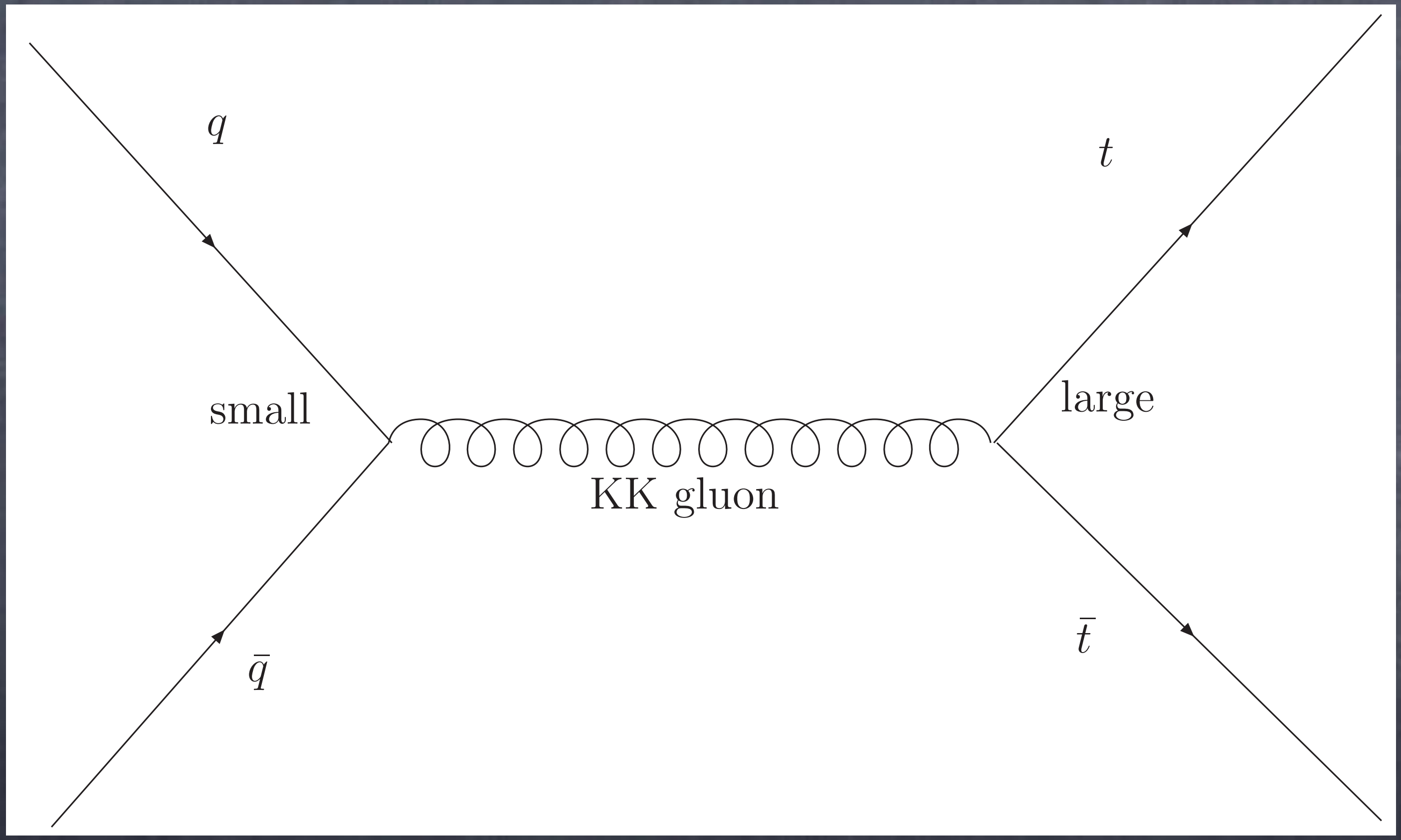
vs.

4D space-time expands with moving along 5th dimension

A bottomline: KK gluon signal (decays to top)

(see back-up for details)

- production suppressed due to small coupling to proton
- decay dominated by top quark with stronger coupling



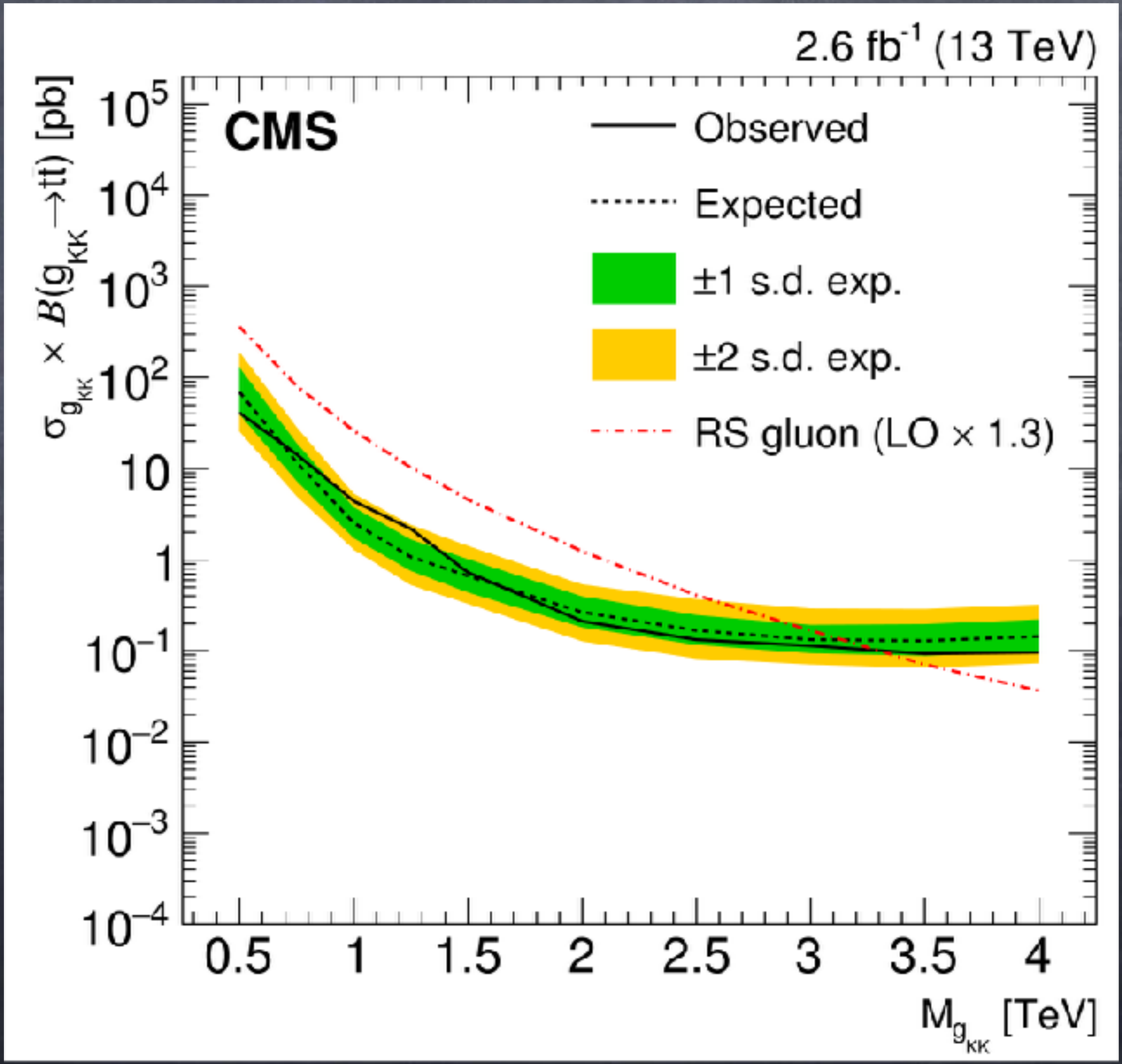
- mass >∼3 TeV due to constraints from virtual effects (see back-up)

KK gluon signal: decays to boosted top

- Energy of each top quark is 1.5 TeV
- top decay products (bW, $W \to l\nu$ or $q\bar{q}$) collimated
- looks like QCD jet at 0th order
- jet substructure (see Larkoski lecture)to distinguish the two

...already there!

- **CMS-B2G-16-015**



Outlook (personal opinion!)

- natural region [$O(10)\%$ fine-tuning] of both SUSY and extra dimensions ($\sim$TeV mass new particles) disfavored by LHC null results

- naturalness is a “slippery slope”: $O(0.1)\%$ fine-tuning ($\sim$10 TeV mass new particles) clearly out of reach of LHC, but still (much, much) better than SM ($1 \text{ part in } 10^{30}$)

→

keep looking at LHC (especially hidden signals) +
100 TeV collider

Back-ups

SUSY collider signals: example 2

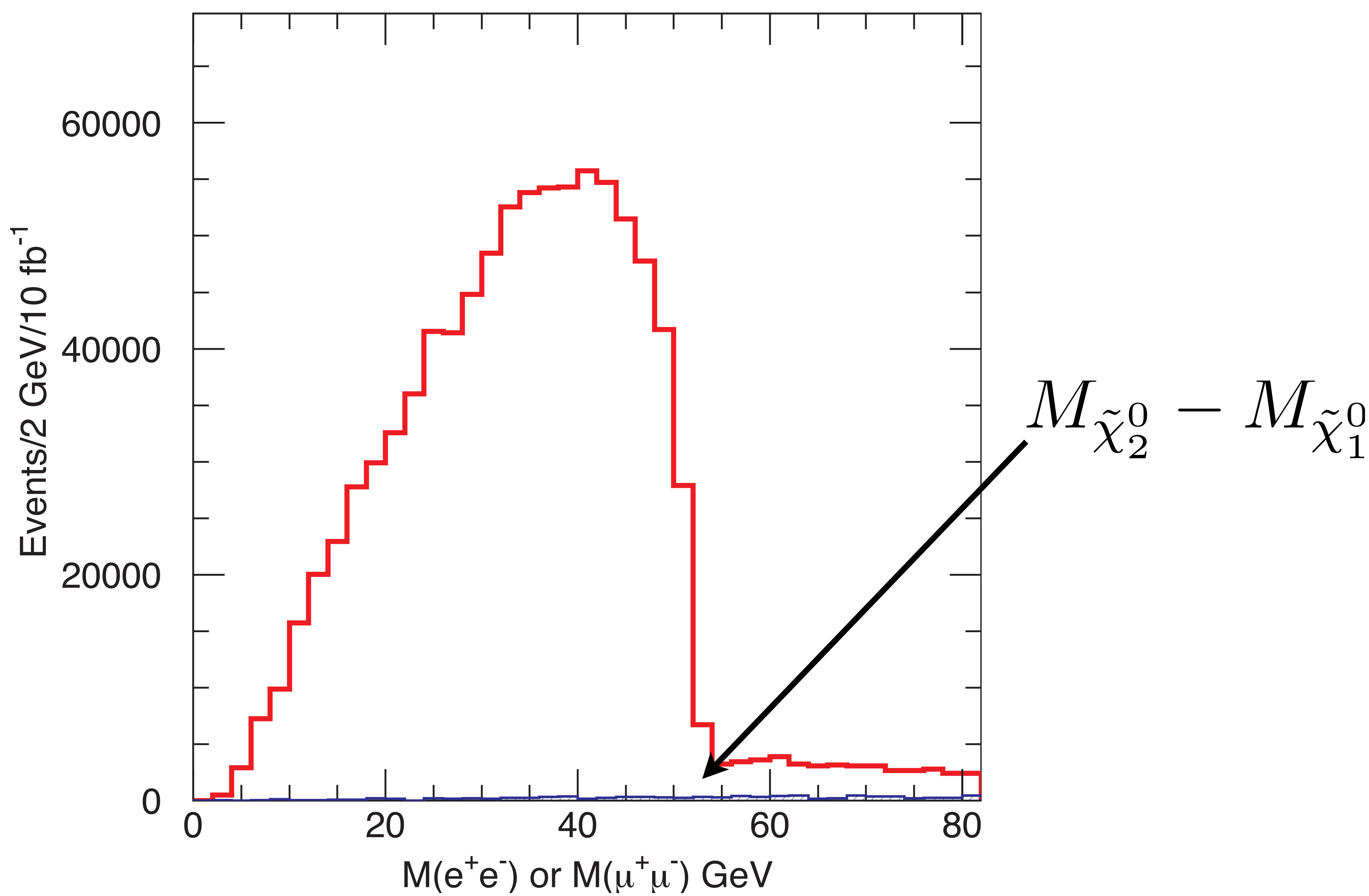
- cascade decay of squark to LSP (vs. direct decay earlier):

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

- 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:

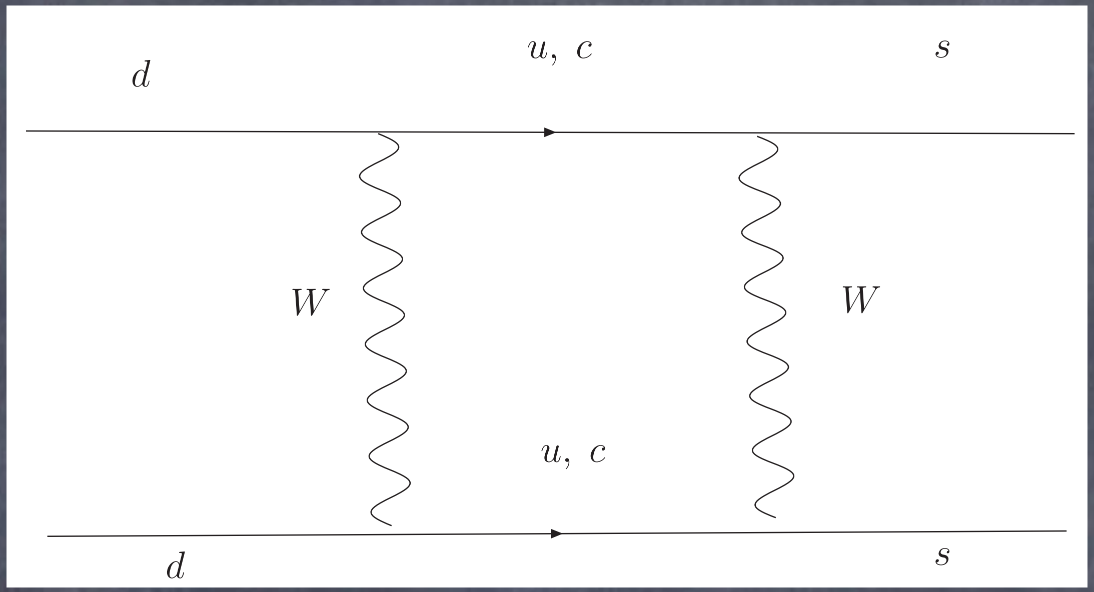


Virtual effects of superpartners

(see , e.g.,pages 25, 26 of hep-ph/9612389)

No flavor problem in SM

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

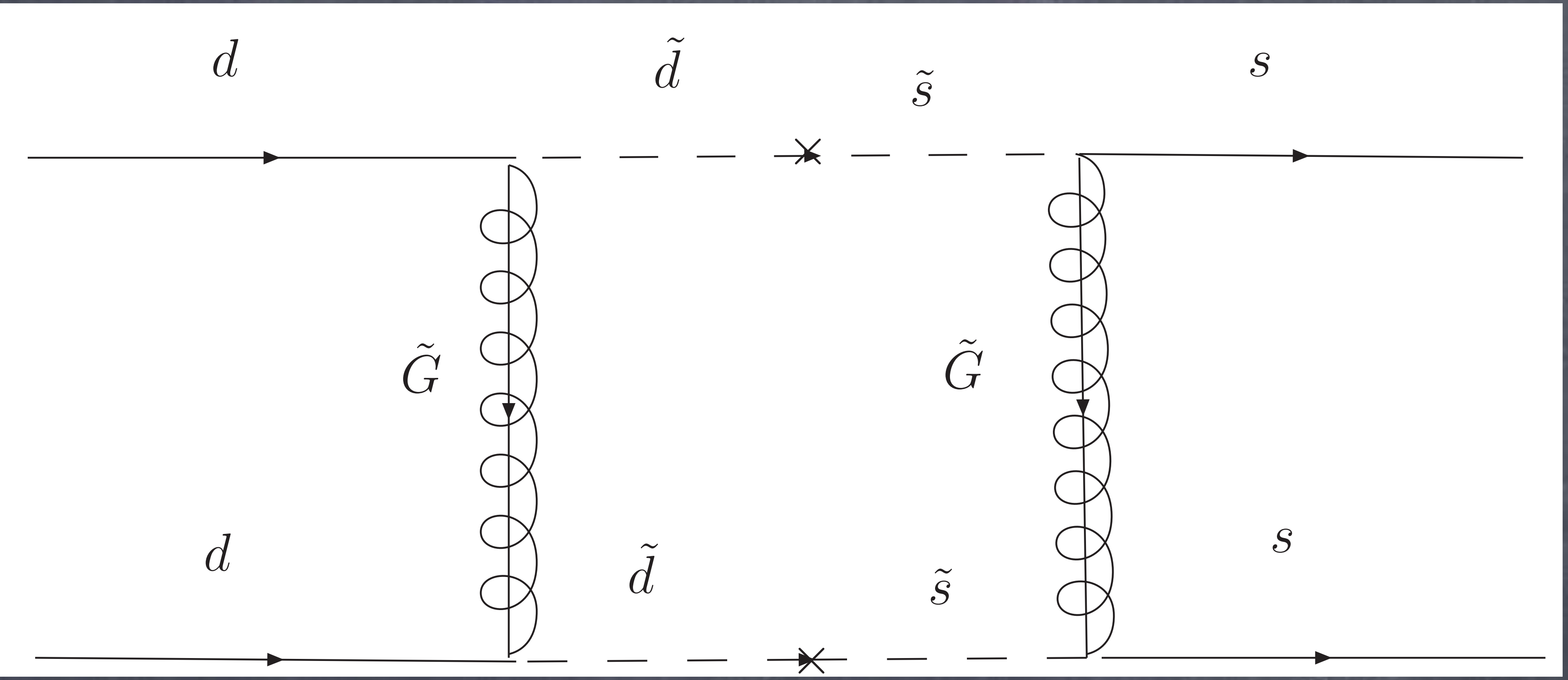


- Glashow-Illiopoulos-Maini (GIM) mechanism:

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

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

Technically: (real) scalar field on circle (with 5D mass term only)

$$S_{5D} = \int d^4x \int dy \Big[\left(\partial^M \Phi\right) \left(\partial_M \Phi\right) - M_{5D}^2 \Phi\Phi \Big]$$

- Compacfity on a circle (S^1):
  $-\infty < y < \infty$ with $y \equiv y + 2\pi R$

Periodic boundary condition: $\Phi(y = 2\pi R) = \Phi(y) \Rightarrow$

$$\Phi = \frac{1}{\sqrt{2\pi R}} \sum_{n=-\infty}^{n=+\infty} \phi^{(n)}(x) e^{iny/R}$$

$n = 0$ (zero-mode): constant in y
$n = 1, 2...$ (KK modes): sin / cos ...

Substitute into S_{5D}, use orthogonality of profiles:

$$S_{4D} = \int d^4x \sum_n \Big[\left(\partial_\mu \phi^{(n)}\right) \left(\partial^\mu \phi^{(n)}\right) - \left(M^2 + \frac{n^2}{R^2} \right) \phi^{(n)} \phi^{(n)} \Big]$$

- 4D viewpoint: Tower of $4D$ fields (KK modes),
  $\phi^{(n)}$ with mass^2: $m_{4D\ n}^2 = M_{5D}^2 + n^2/R^2$ (n^2/R^2 from ∂_5 acting on profile)

Technically: Fermion field on orbifold

- on circle: fermion zero-modes not chiral (both LH and RH) (unlike SM: LH doublet, RH singlet) →
- go to orbifold to project out one zero-mode:

$$S^1/Z_2\text{: } y \leftrightarrow -y \text{ in addition to } y \equiv y + 2\pi R$$

- exponential profile for fermion zero-modes (cf. flat for scalar earlier) due to 5D mass term:

not m_{4D}

$$\sim e^{-M_{5D\ L} y},\ e^{+M_{5D\ R} y}$$

(Solve general wave equation/boundary conditions to obtain modes: can get exponential profile for zero-mode even for scalar)

Extra dimensions: What about neutrino mass?

- Add ν_R with profile...similar to quarks?
- ...but neutrino masses VERY small and mixing large!
- choose $M_{5D\ \nu_R}$ so that overlap near other brane dominates:

$$\lambda_{4D} \sim \lambda_{5D}\ e^{(-M_{5D\ \phi})\pi R}$$

- very small neutrino mass due to Higgs tail:

NOT due to smallness of ν profiles at Higgs brane: cf. quarks and charged leptons

- mixing large since all 3 profiles similar near other brane:

$$\lambda_\nu^{33} \sim \lambda_\nu^{23} \sim \lambda_\nu^{22}$$

Warped extra dimension technically (I)

- Bulk + brane cosmological constants $\Rightarrow$

flat 4D

$$(ds)^2 \quad = \quad e^{-2ky}\eta_{\mu\nu}(dx)^\mu(dx)^\nu + (dy)^2$$

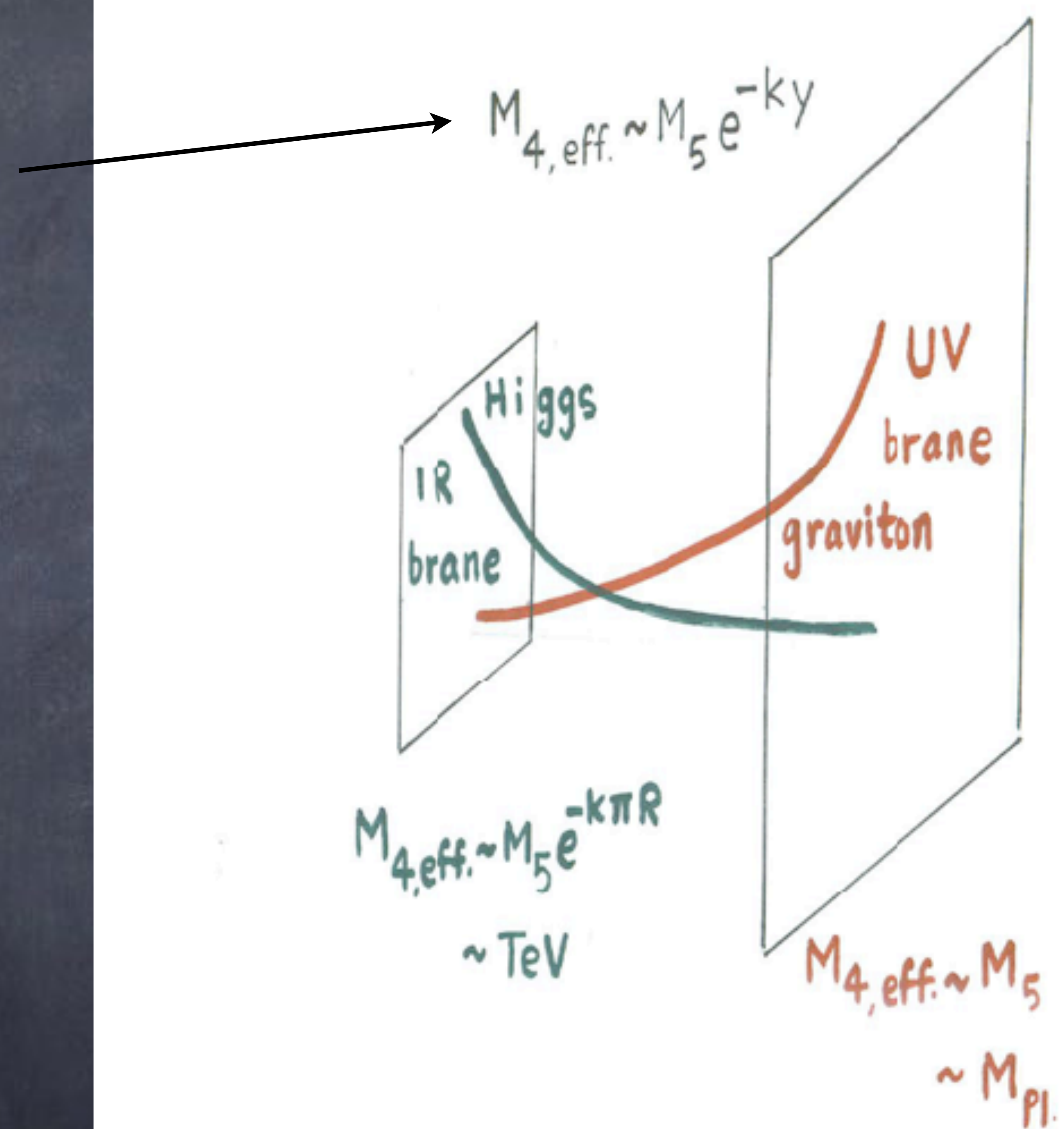
- Master equation:

$$M_{4D,\,\mathrm{eff.}}(y) \quad \sim \quad M_{5D,\,\mathrm{fund.}} \times e^{-ky} \text{ (warp factor)}$$

Warped extra dimension technically (II)

- Gravity and Higgs: Randall-Sundrum (RS1) model

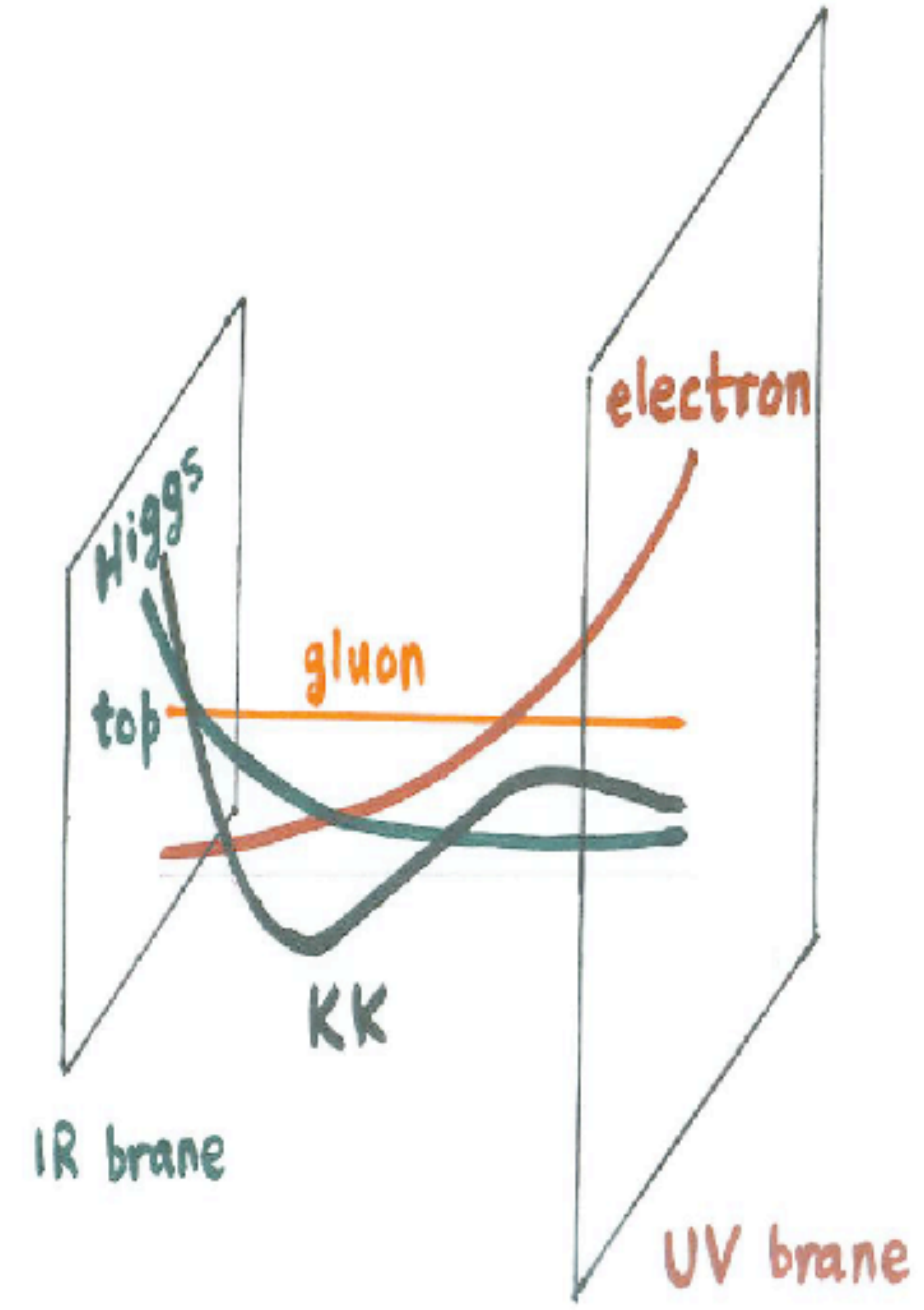
apply master...at 2 ends...



Need $kR \sim \log\left(M_{Pl}/\text{TeV}\right)/\pi \sim 10$:
Exponential $4D$ hierarchy
from $O(10)$ hierarchy in $5D$ theory!

KK's localized near Higgs/TeV brane

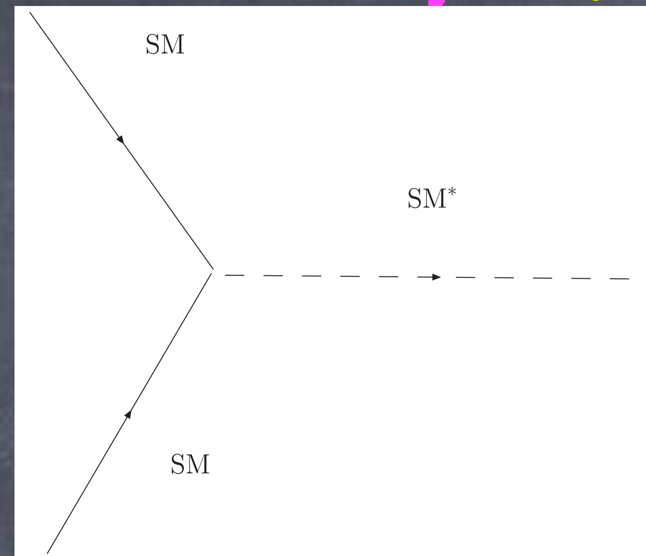
- ...due to curvature (cf. flat extra dimension earlier)
- KK mass $\sim$ Higgs brane scale ($\sim$ TeV)
- KK's couple strongly to Higgs, top (weakly to light fermions): based on overlap of profiles



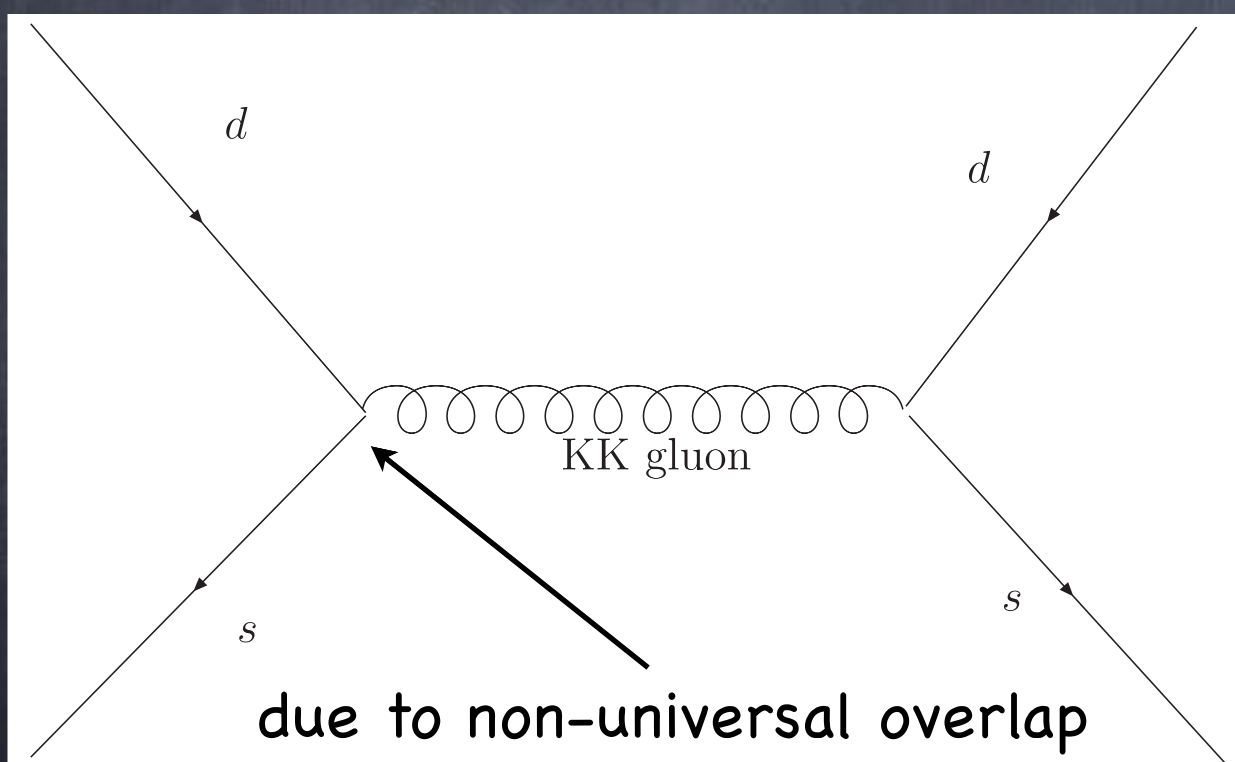
Virtual effects of (extra-dimensional) KK modes

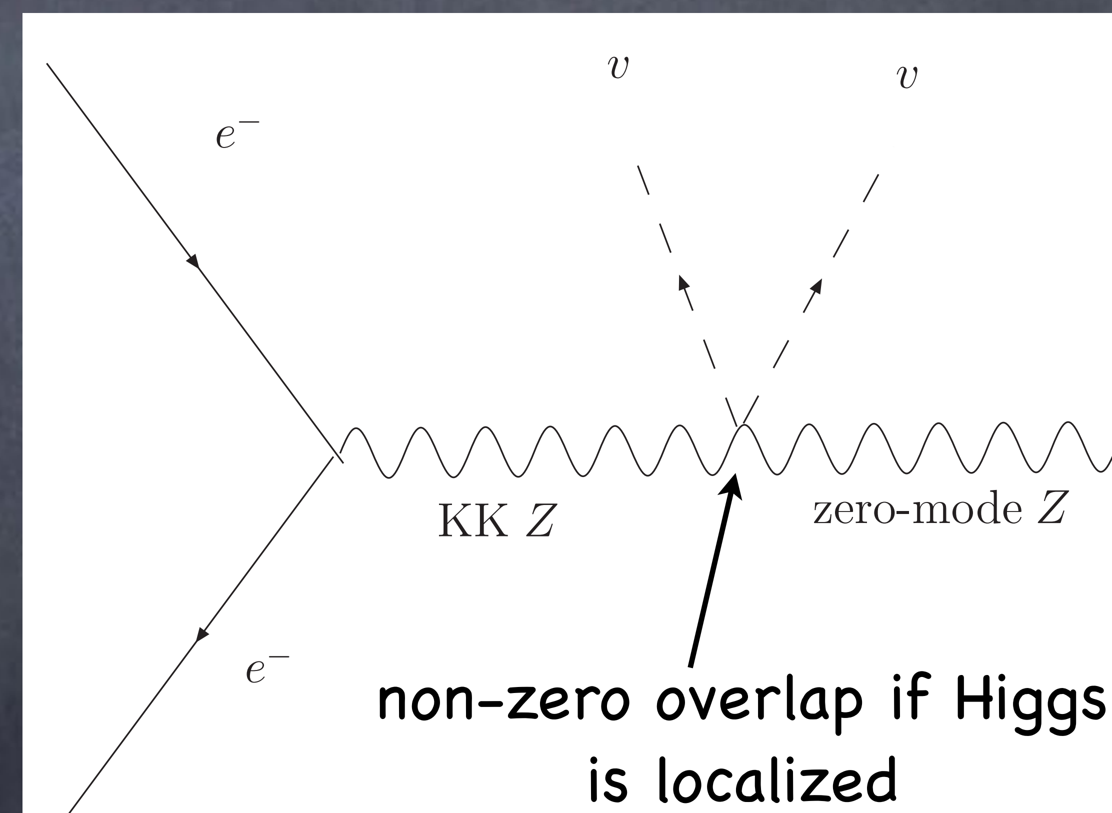
Summary (rough)

- no parity



- tree-level contributions to flavor and EW precision tests





- limit on KK scale: ~O(10) TeV [built-in mechanism: cf. O(1000) TeV in SUSY] $\rightarrow$ O(3) TeV model-building/mild tuning

AdS/CFT “duality”

- tower of KK’s like tower of hadrons from (purely) 4D strong dynamics
- warped extra dimension solution dual to Higgs compositeness at TeV scale