Scenarios for New Physics at the LHC

LISHEP 2011

Rio de Janeiro --- July 8, 2011

1. What do we know

- Known matter constituents:

$$\begin{bmatrix} \nu_e & u \\ e^- & d' \end{bmatrix} \qquad \begin{bmatrix} \nu_\mu & c \\ \mu^- & s' \end{bmatrix} \qquad \begin{bmatrix} \nu_\tau & t \\ \tau^- & b' \end{bmatrix}$$

- known interactions:

$$\gamma \qquad W^{\pm} \qquad Z_0 \qquad g$$

neglecting gravity at sub-atomic scales

• The Standard Model

- It is a gauge theory based on the symmetry: $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$
- fermion-fermion-gauge bosons interactions fixed
- gauge boson-gauge boson interactions fixed

$$\mathcal{L} = \mathcal{L}_{\text{kin}} + \mathcal{L}_{ffV} + \mathcal{L}_{VVV} + \mathcal{L}_{VVVV} + \cdots$$

- to be realistic the symmetry must be broken to give mass to fermions and gauge bosons.
- The EWSB sector is connected to flavor physics

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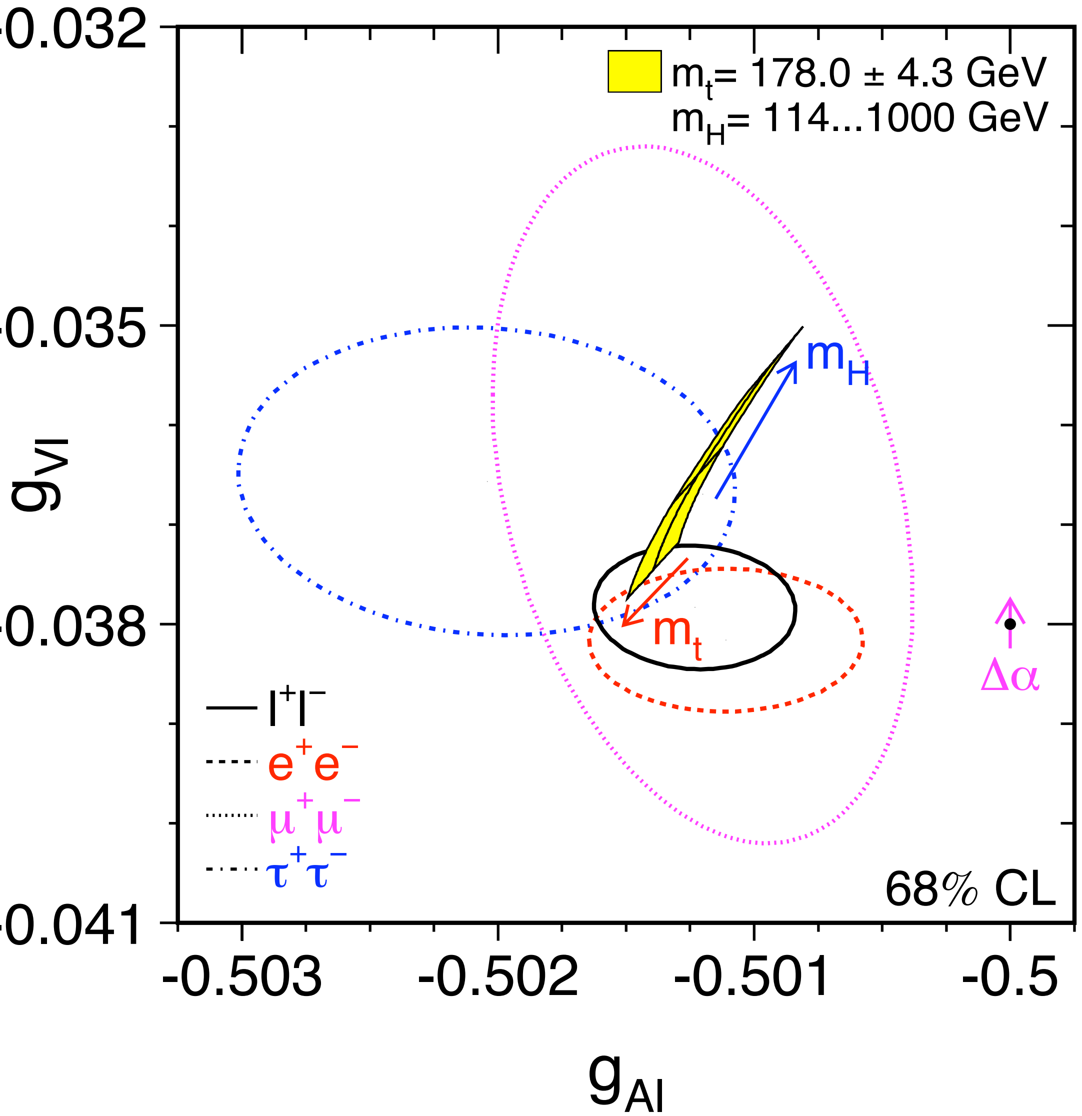
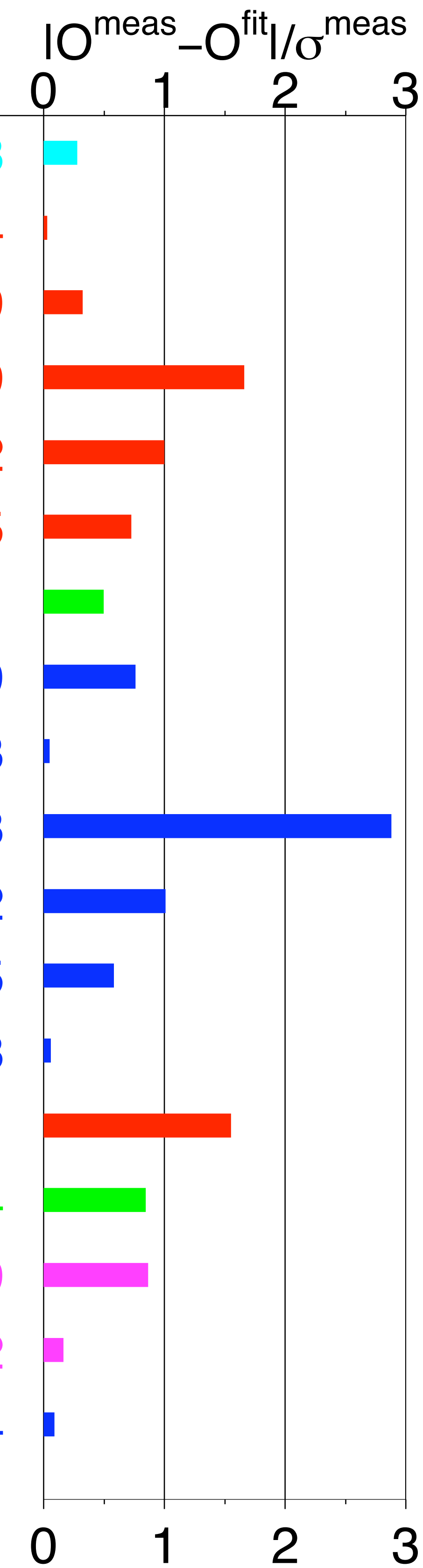
- The fermion interactions have been tested at the 0.1% level



	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^0 [nb]	41.540 ± 0.037	41.479
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.399 ± 0.023	80.379
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.3 ± 1.1	173.4

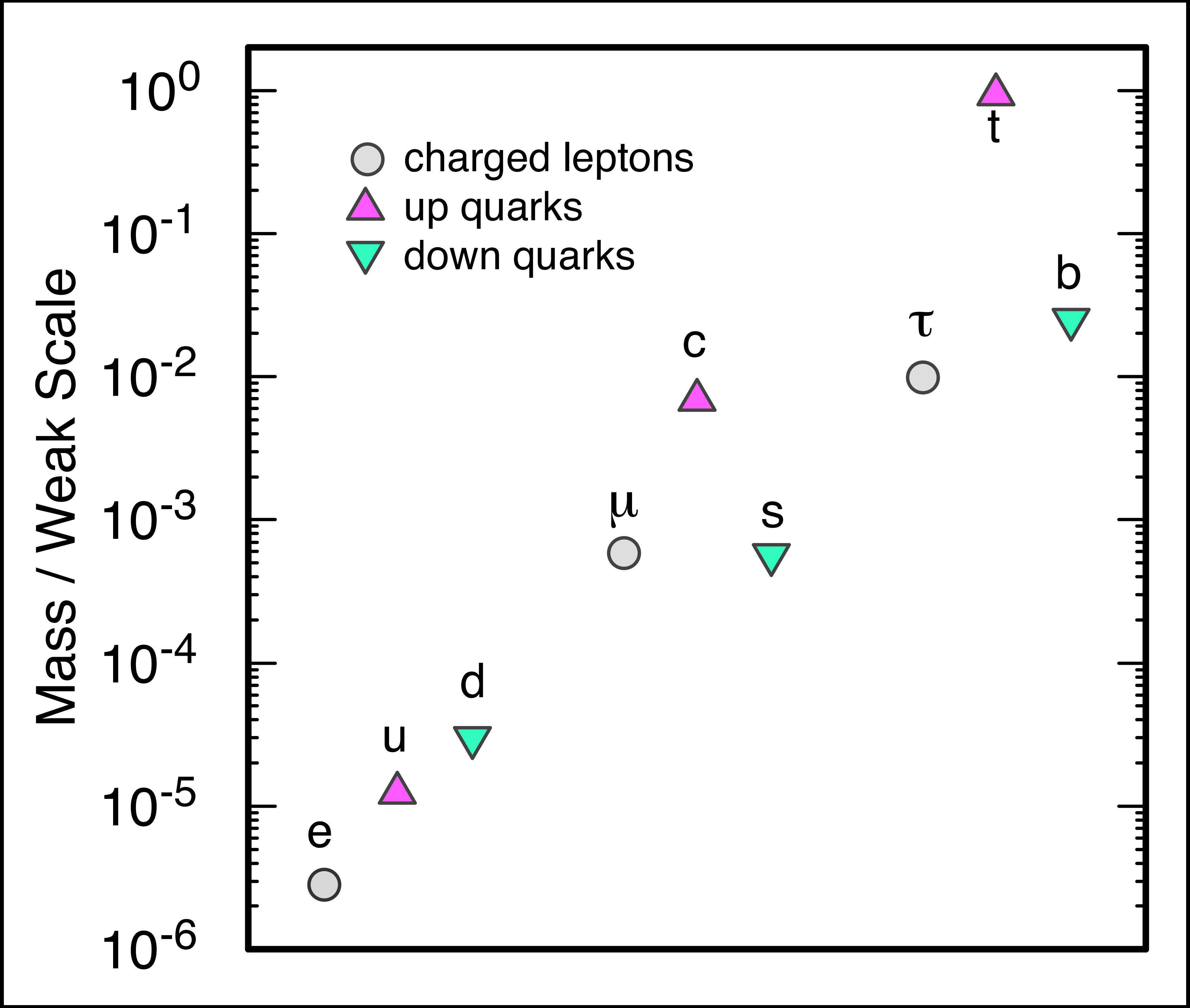


July 2010

- Limitations of the SM: it works. Amazing!

Andreas Hoecker

- Limitations of the SM:
  - what is the origin of fermion masses?



- Limitations of the SM:
  - what is the origin of fermion masses?
  - large number of free parameters (25+)
  - do interaction unify at higher energies?
  - what is dark matter?
  - what is the dark energy?
  - what is the origin of the baryon asymmetry?
  - .....

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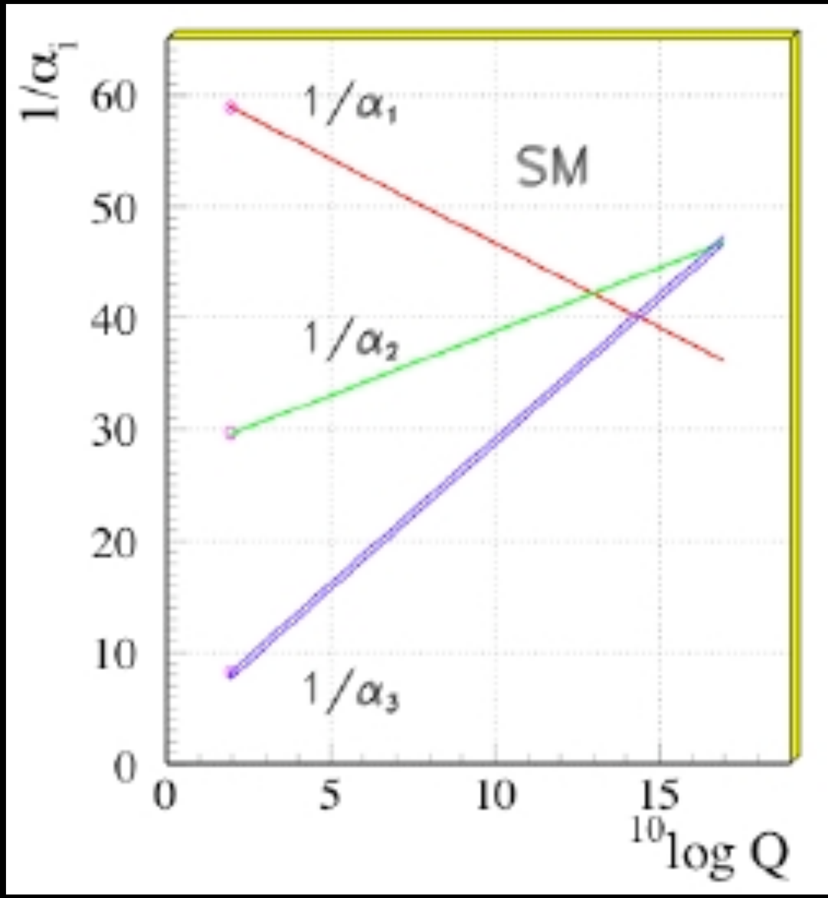
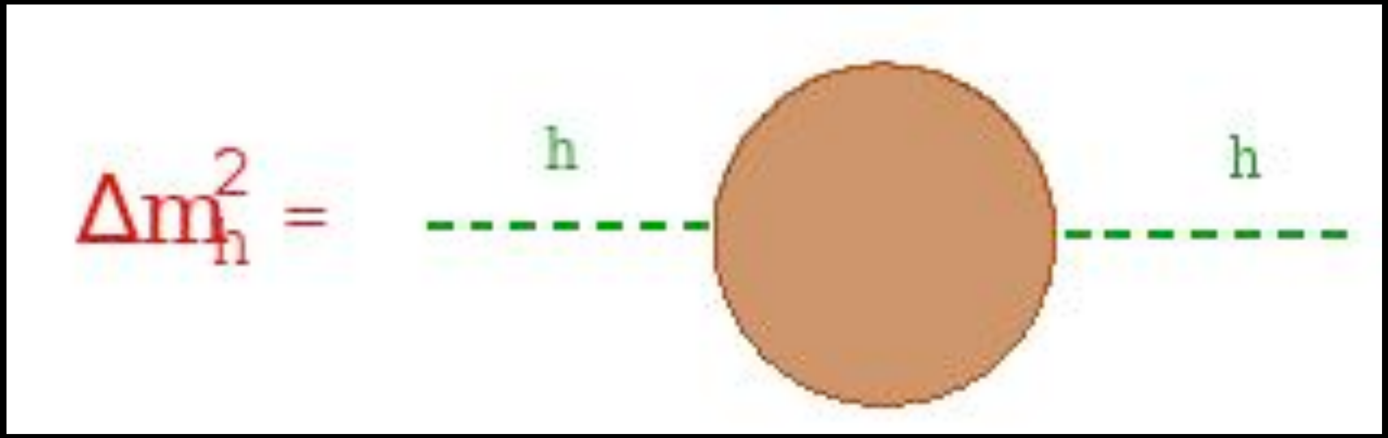


- The SM has also a technical problem (hierarchy problem) :

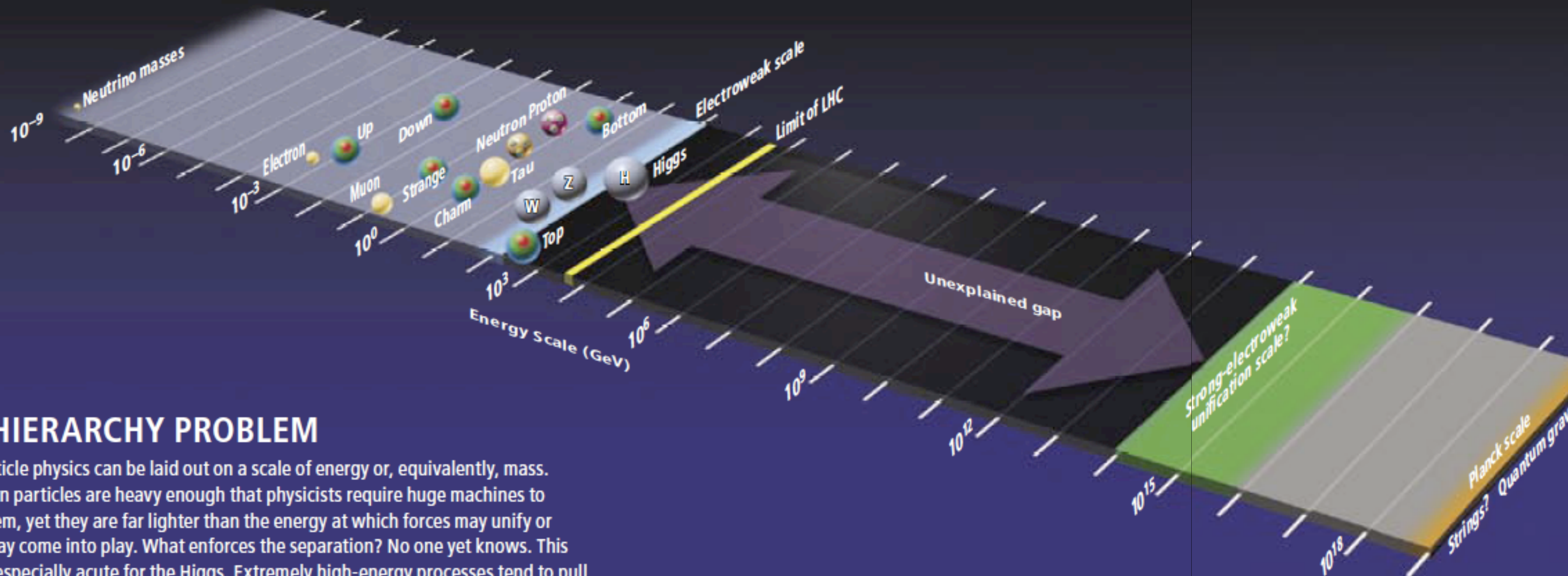
Quantum corrections drive scalar masses to the high energy scale



$$\Delta m_h^2 \propto \Lambda_{UV}^2$$

unlike the fermions and gauge bosons there is no protection mechanism in the SM if $\Lambda_{UV} \simeq M_P \simeq 10^{19}\ \mathrm{GeV}$

$$M_H \simeq 200\ \mathrm{GeV}\ \text{requires}\ \Lambda_{UV} \simeq 1\ \mathrm{TeV}$$



THE HIERARCHY PROBLEM

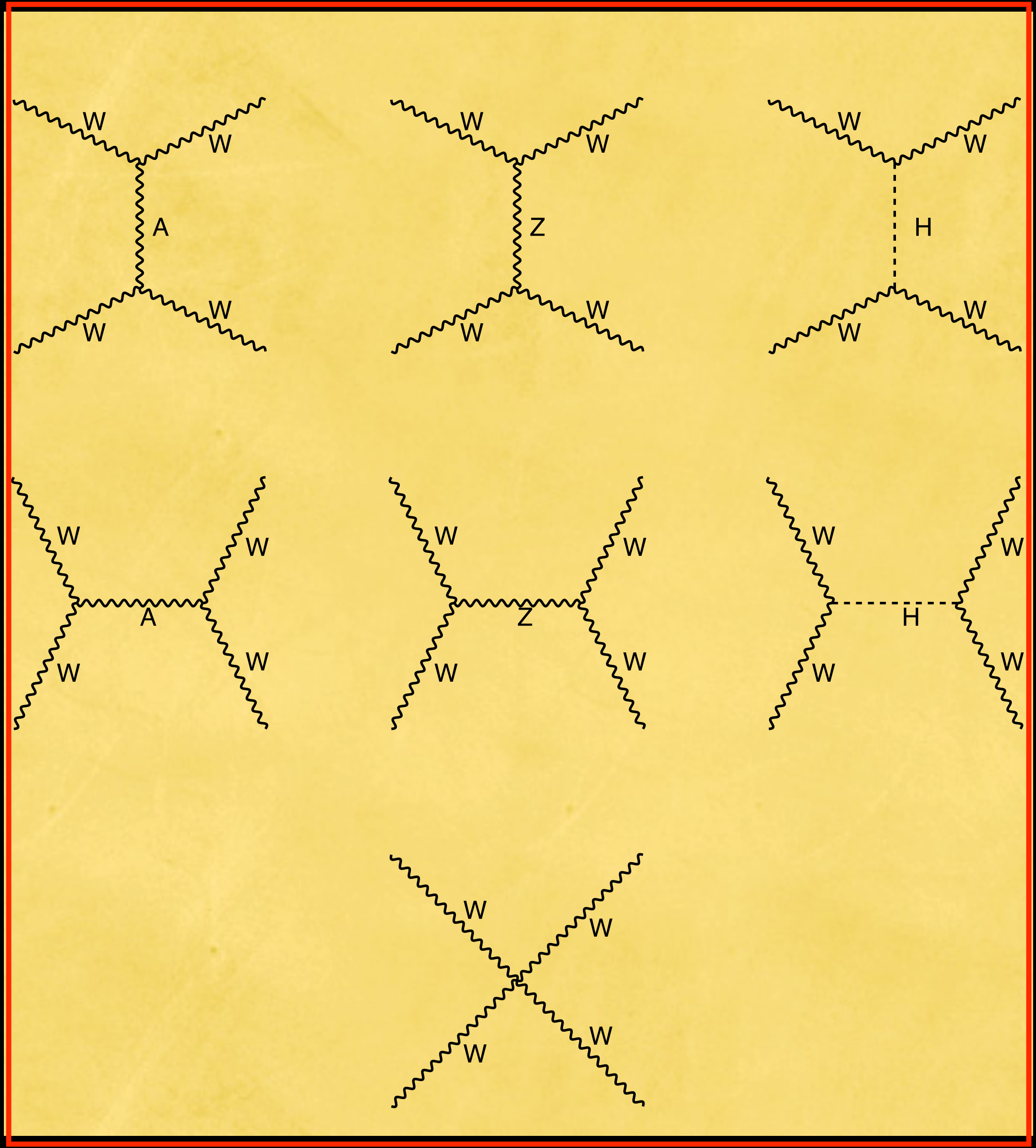
All of particle physics can be laid out on a scale of energy or, equivalently, mass. The known particles are heavy enough that physicists require huge machines to reate them, yet they are far lighter than the energy at which forces may unify or gravity may come into play. What enforces the separation? No one yet knows. This uzzle is especially acute for the Higgs. Extremely high-energy processes tend to pull ts mass far above 1 TeV. What holds it down?

Quigg-Sci.Am.

Importance of the TeV scale (Lee-Quigg-Thacker, Cornwall, etc)

- Without EWSB sector unitarity is violated in the process

$$W_L^+ W_L^- \to W_L^+ W_L^-$$



  - either $M_H < 710 \text{ GeV}$
  - or $\sqrt{s_c} < 1.2\text{TeV}$

II. Hints to go beyond the SM

- We don't know what to expect. We have hints:

  1. hierarchy problem;
  2. number os parameters;
  3. flavor structure (masses, mixings, CP);
  4. dark mass;
  5. baryogenesis;
  6. Tevatron $t\bar{t}$ asymmetry;
  7. deviation in $g-2$;
  8. CDF's Wjj excess;
  9. etc

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- We don't know (now) what is the correct path. There is still time to buy lottery tickets before we have a smoking gun!

Some popular BSM models

- a few models with new physics at the TeV scale

weakly interacting	strongly coupled
Supersymmetry	Technicolor
Little Higgs	Topcolor
Large extra dimensions	Composite Higgs
Universal extra dimensions	Randall-Sundrum

but there are inumerous possibilities: large groups; GUTS; extra fermions; seesaw N; hidden valleys; etc

1.Vanilla BSM: supersymmetry

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- most general extension of Poincaré group
- SUSY can lead to coupling unification
- solves the hierarchy problem
- it is perturbative
- dynamical EWSB
- many free parameters (~150)
- plethora of signals

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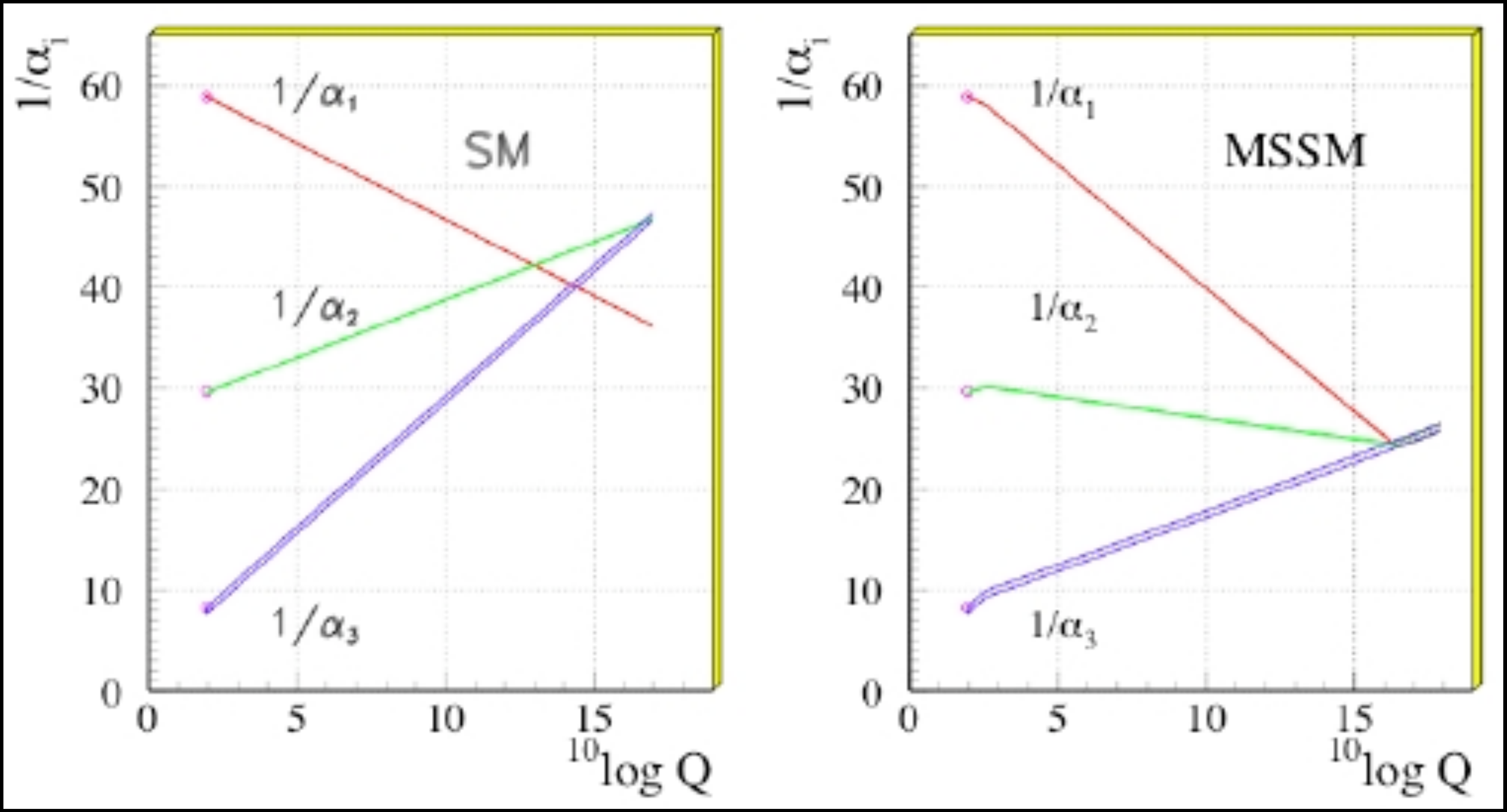

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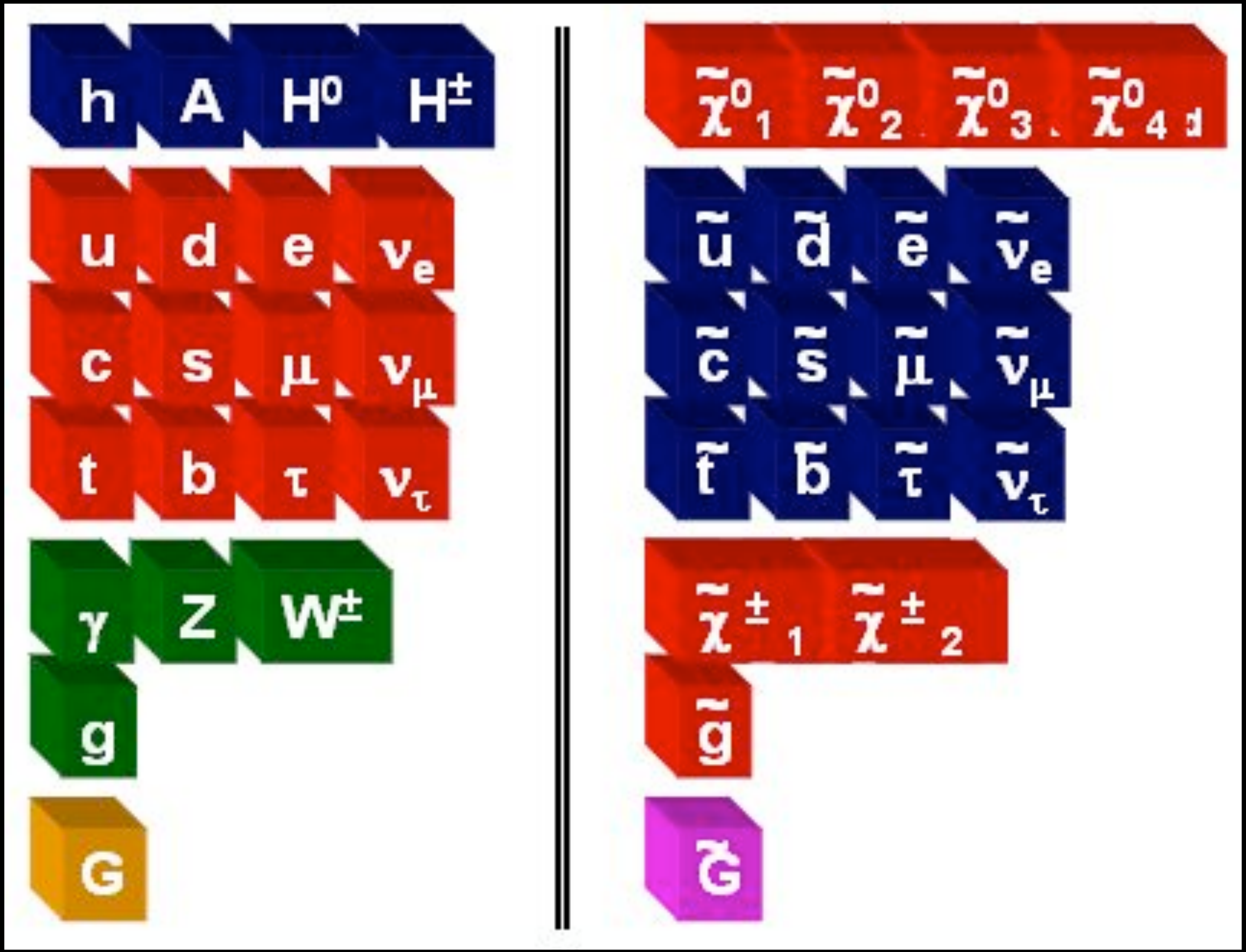
- SUSY relates bosons and fermions
- SUSY introduces to each SM particle a new one with spin differing by 1/2



- SUSY is broken in nature => large number of parameters

- It is popular to impose a discrete symmetry to prevent p decay

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

- The lightest SUSY particle is a candidate for dark matter
- SUSY requires a larger Higgs sector

$$h_0 \qquad H_0 \qquad A_0 \qquad H^\pm$$

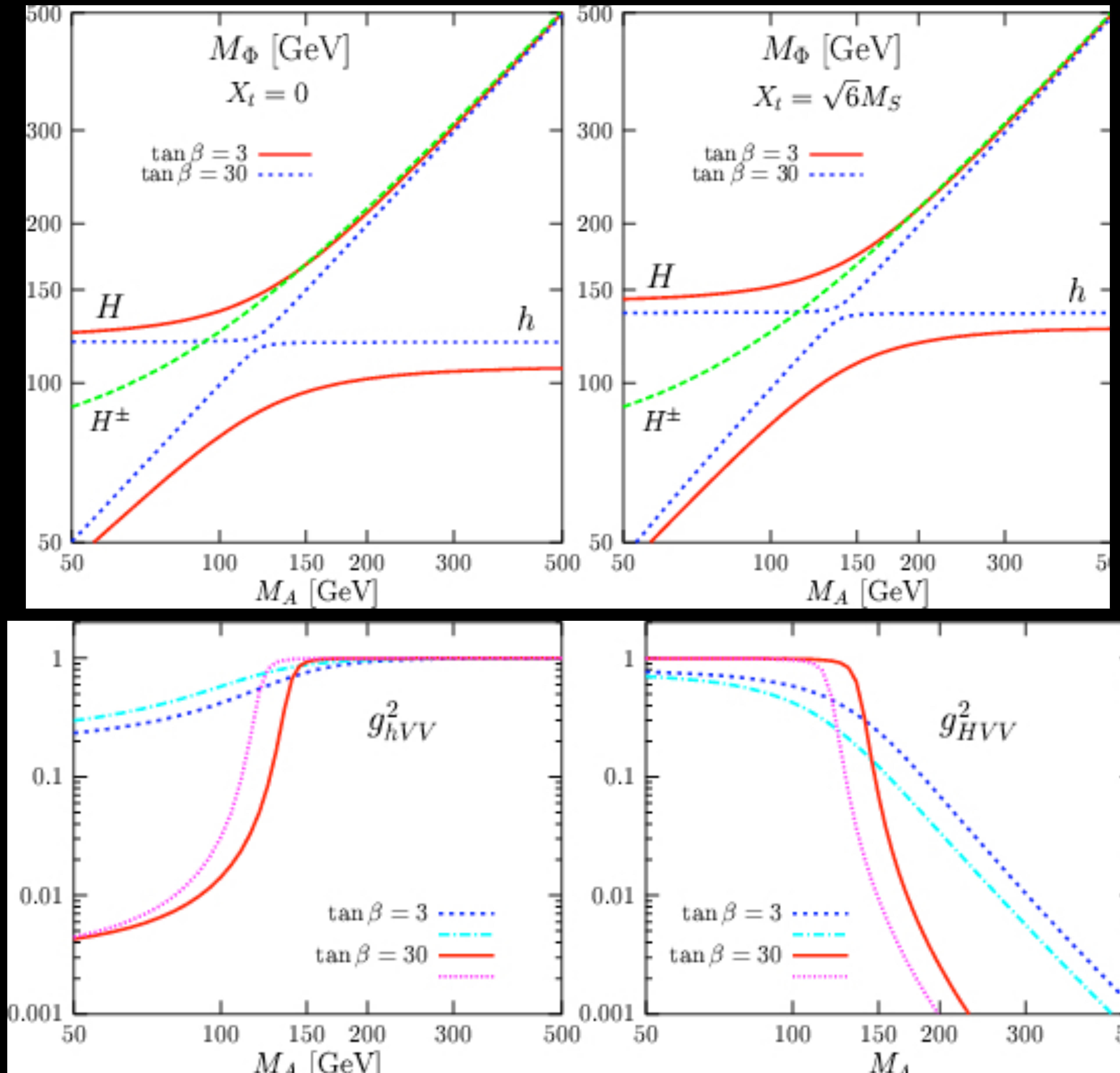
with 2 free parameters M_A and $\tan\beta$

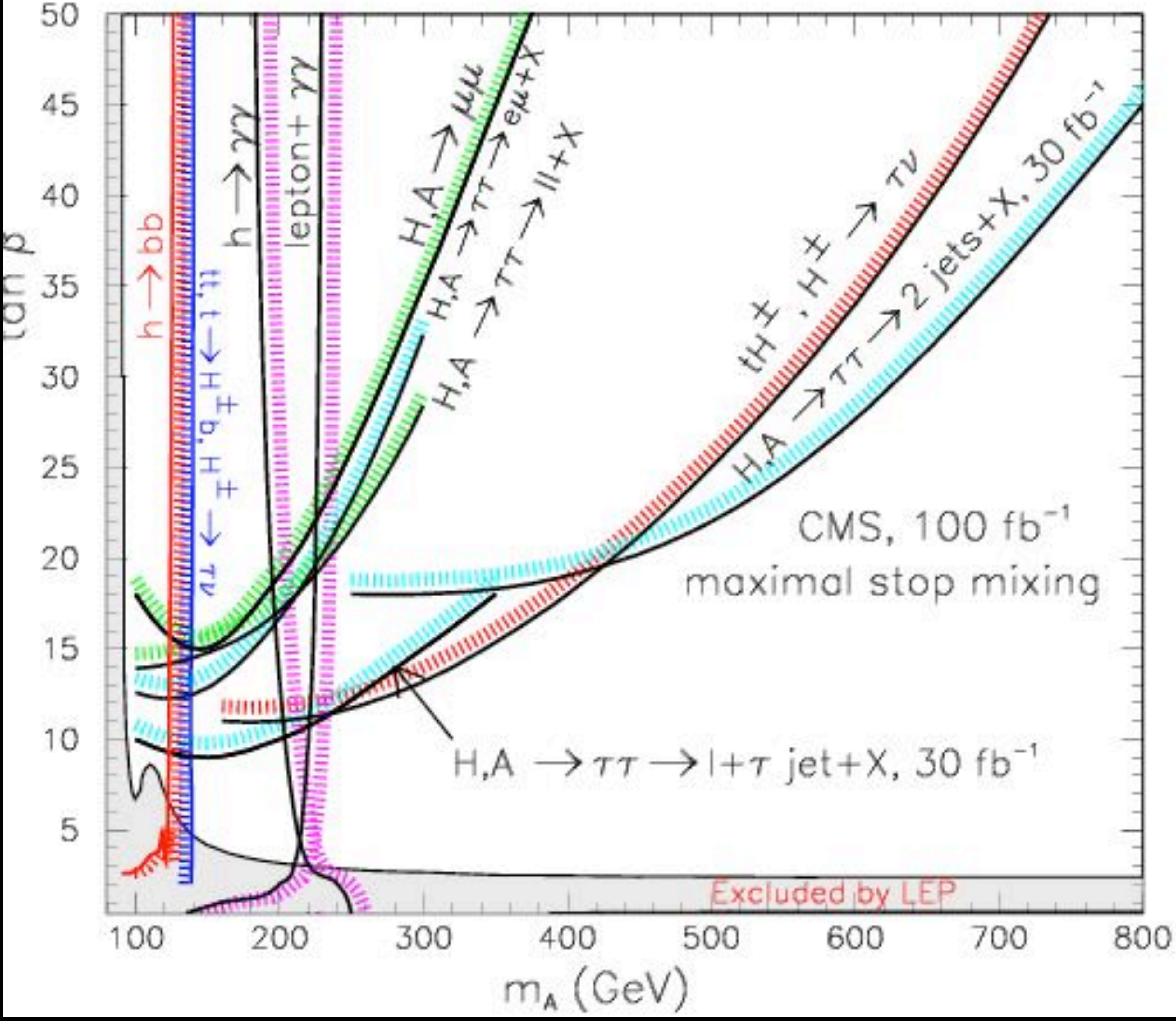
$$\mathbf{M^2_{H^\pm} = M^2_A + M^2_W \quad ; \quad M^2_{H,h} = \frac{1}{2}\Big(M^2_A + M^2_Z \pm ((M^2_A + M^2_Z)^2 - 4M^2_Z M^2_A \cos^2 2\beta)^{1/2}}$$

- At tree level $M_h < M_Z$

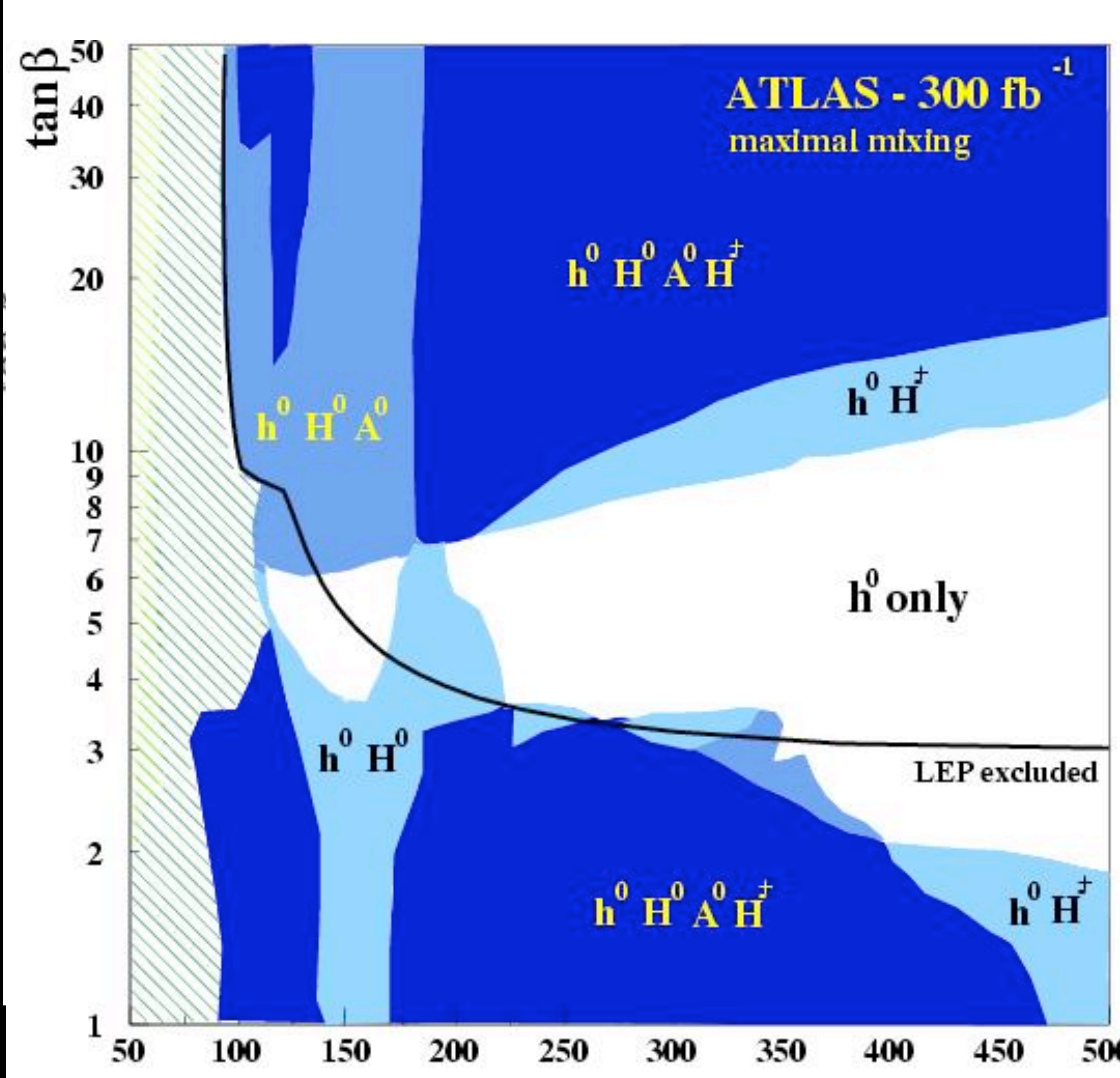
- Radiative corrections help a lot!

- There is a light Higgs similar to the SM one





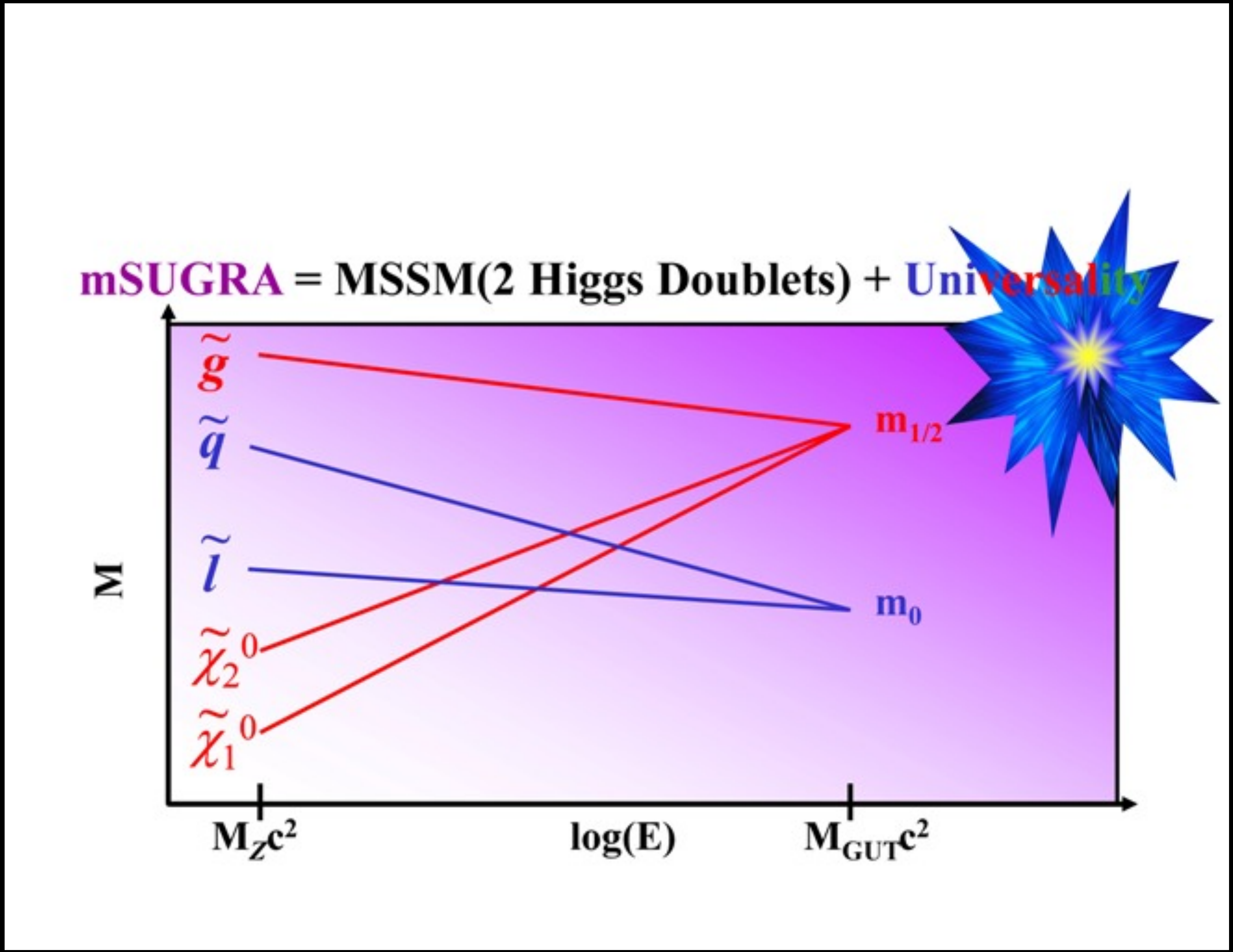
CMS, 100 fb^{-1}
maximal stop mixing
Excluded by LEP
H,A → ττ → l+τ jet+X, 30 fb^{-1}
H,A → ττ → 2 jets+X, 30 fb^{-1}
tH$^\pm$, H$^\pm$ → τν
H,A → μμ
H,A → ττ → eμ+X
H,A → ττ → ll+X
h → γγ
lepton+ γγ
h → bb
tt, H$^\pm$b, H$^\pm$ → τν
tan β
m$_A$ (GeV)


ATLAS - 300 fb-1
maximal mixing
tanβ
h0 H0 A0 H±
h0 H±
h0 H0 A0
h0 only
h0 H0
LEP excluded
h0 H0 A0 H±
h0 H±
50
40
30
20
10
9
8
7
6
5
4
3
2
1
50
100
150
200
250
300
350
400
450
500

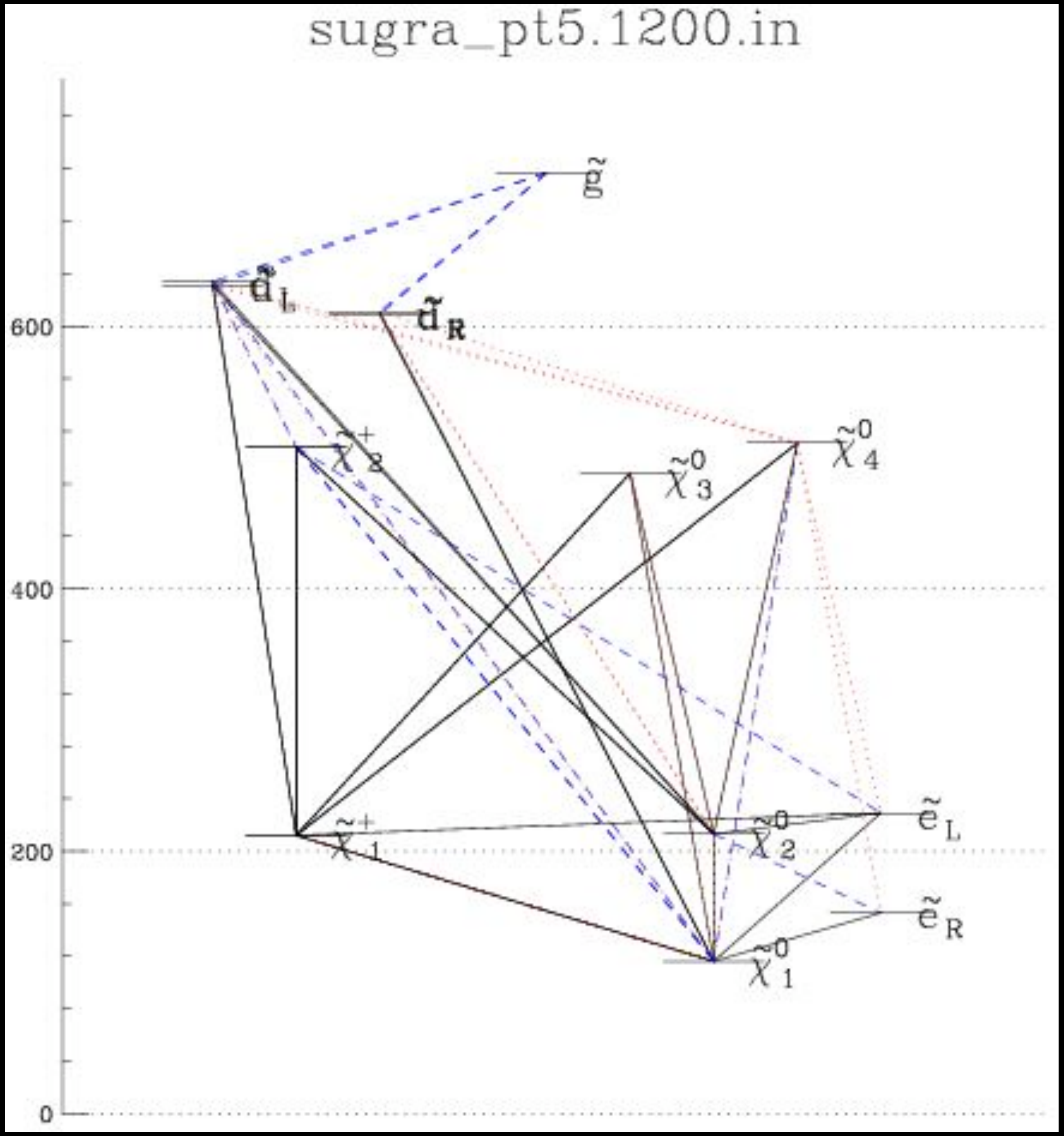
★ Phenomenology strongly depend on the parameters

a popular choice is mSUGRA with 5 parameters

$$m_0 \quad , \quad m_{1/2} \quad , \quad A_0 \quad , \quad \tan\beta \quad , \quad \mathrm{sign}(\mu)$$



“typical” mSUGRA spectrum



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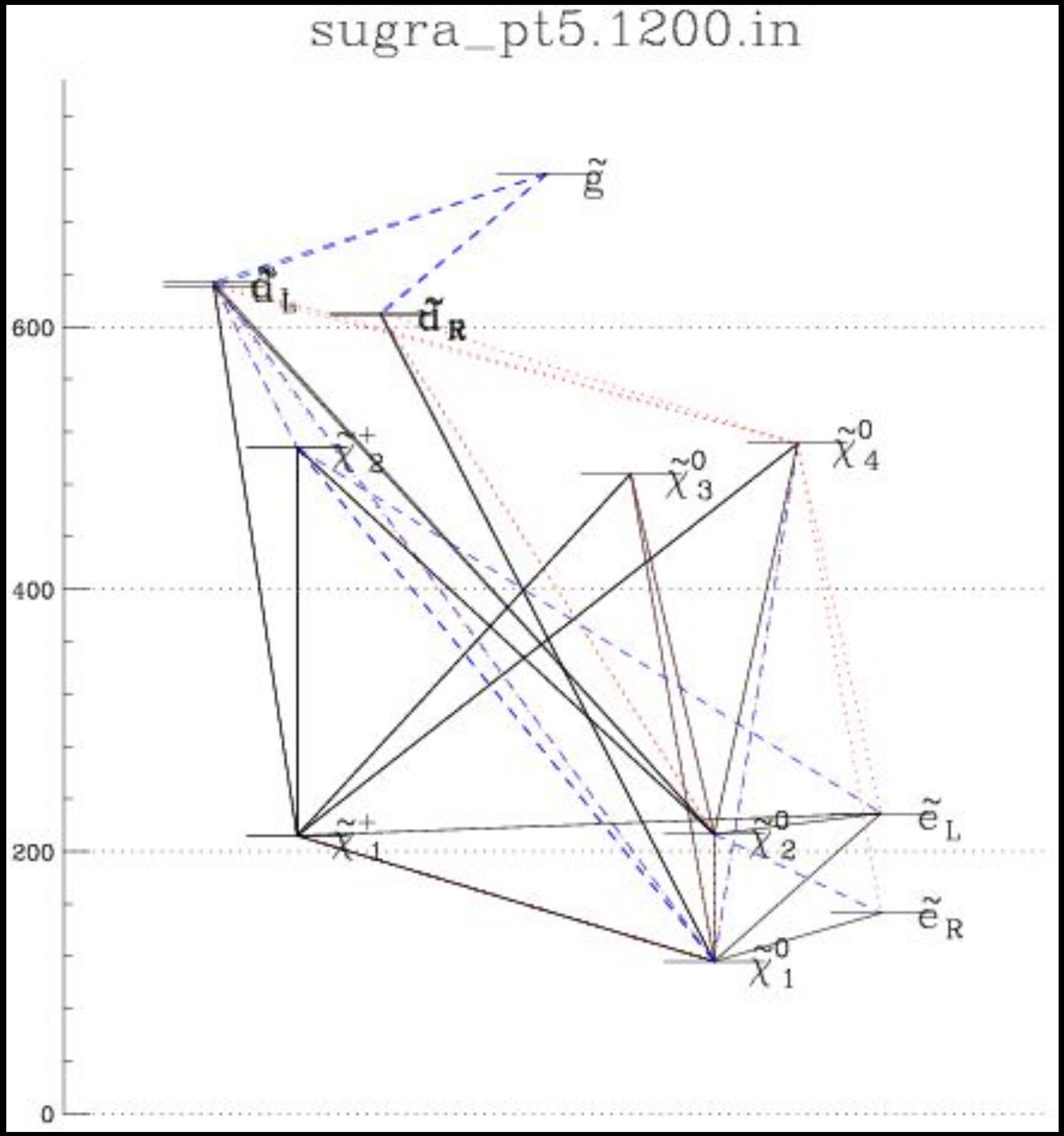
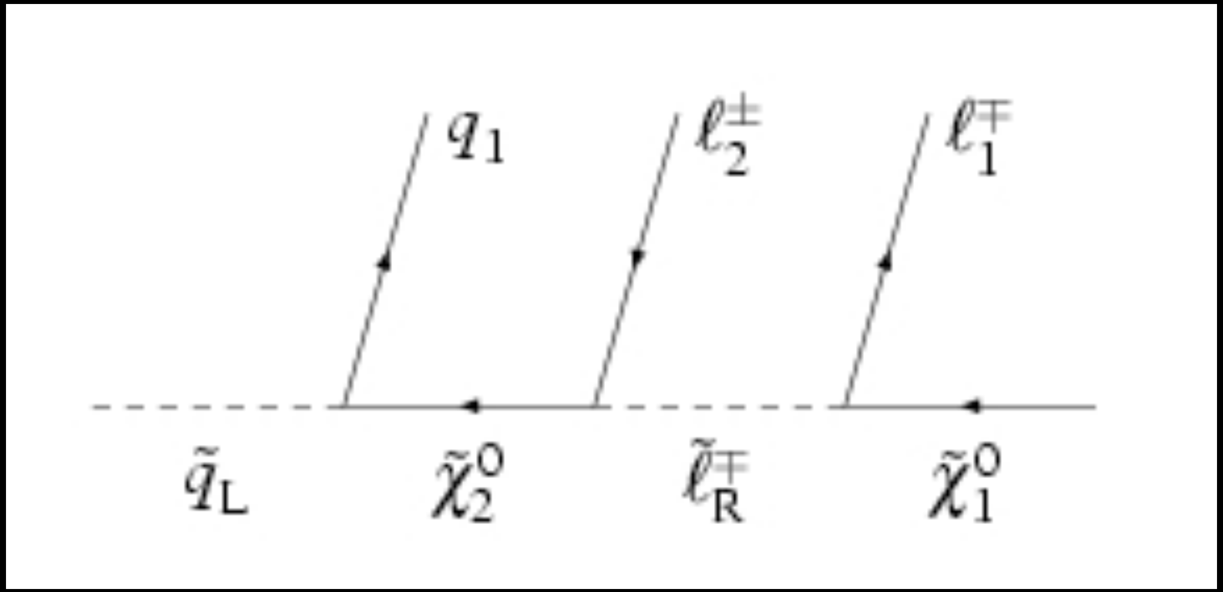
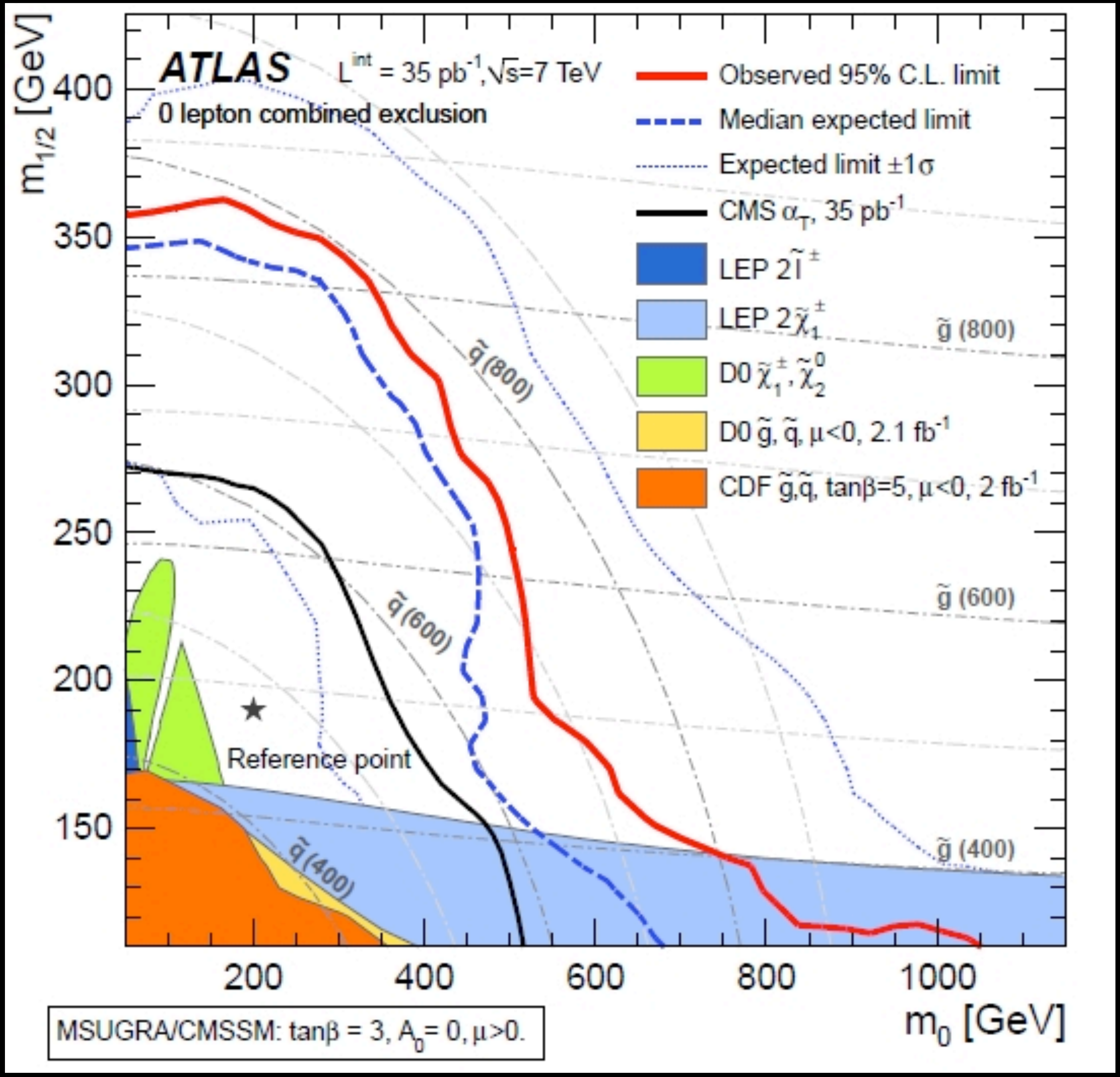


signal characteristics:

- squarks and gluinos : jets
- sleptons and gauginos: leptons
- LSP: missing E_T
- LHC: jets+missing(+leptons)



ATLAS and CMS are searching for SUSY desperately



but we can play with the parameters for some time

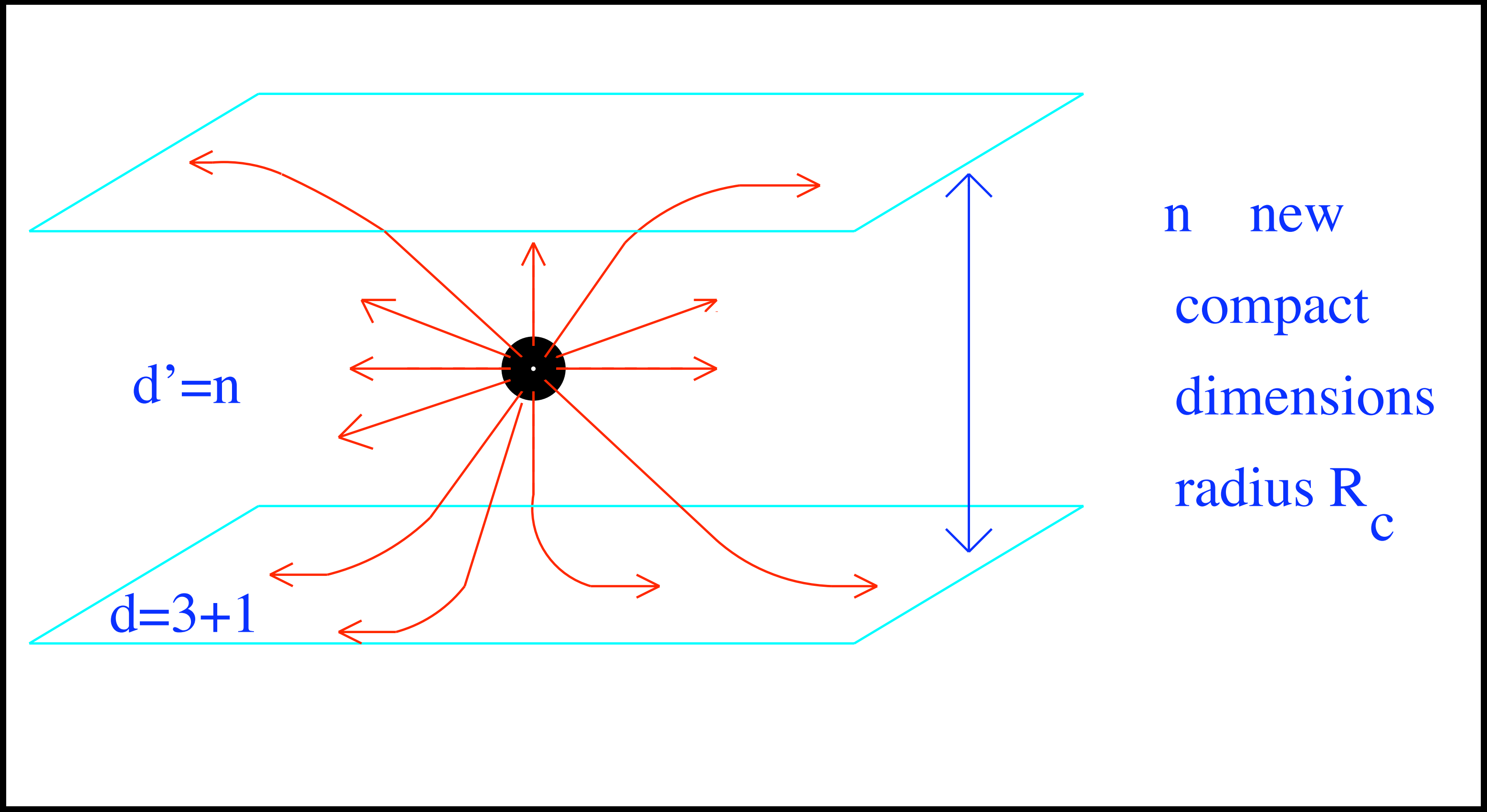
NMSSM: add an extra singlet superfield

$$\lambda \hat{H}_1 \hat{H}_2 \hat{S} + \frac{\kappa}{3}\hat{S}^3 \qquad \lambda A_\lambda H_1 H_2 S + \frac{\kappa}{3} A_\kappa S^3 \qquad \mu_{\text{eff}} = \lambda \langle S \rangle$$

- richer phenomenology: 3 neutral scalar Higgses + 2 pseudoscalars + 5 neutralinos
- For $\langle S \rangle = 0$ it is possible to have invisible Higgs decays $h \to SS$
- It is possible to have $h \to a_1 a_1 \to \tau^+ \tau^- \tau^+ \tau^-$
- This simple modification alter a lot the phenomenology

2. Extra dimensions

- We can also consider 3+n space dimensions
- It is possible to lower/dilute the Planck scale
- For instance, consider n dimensions with radius R



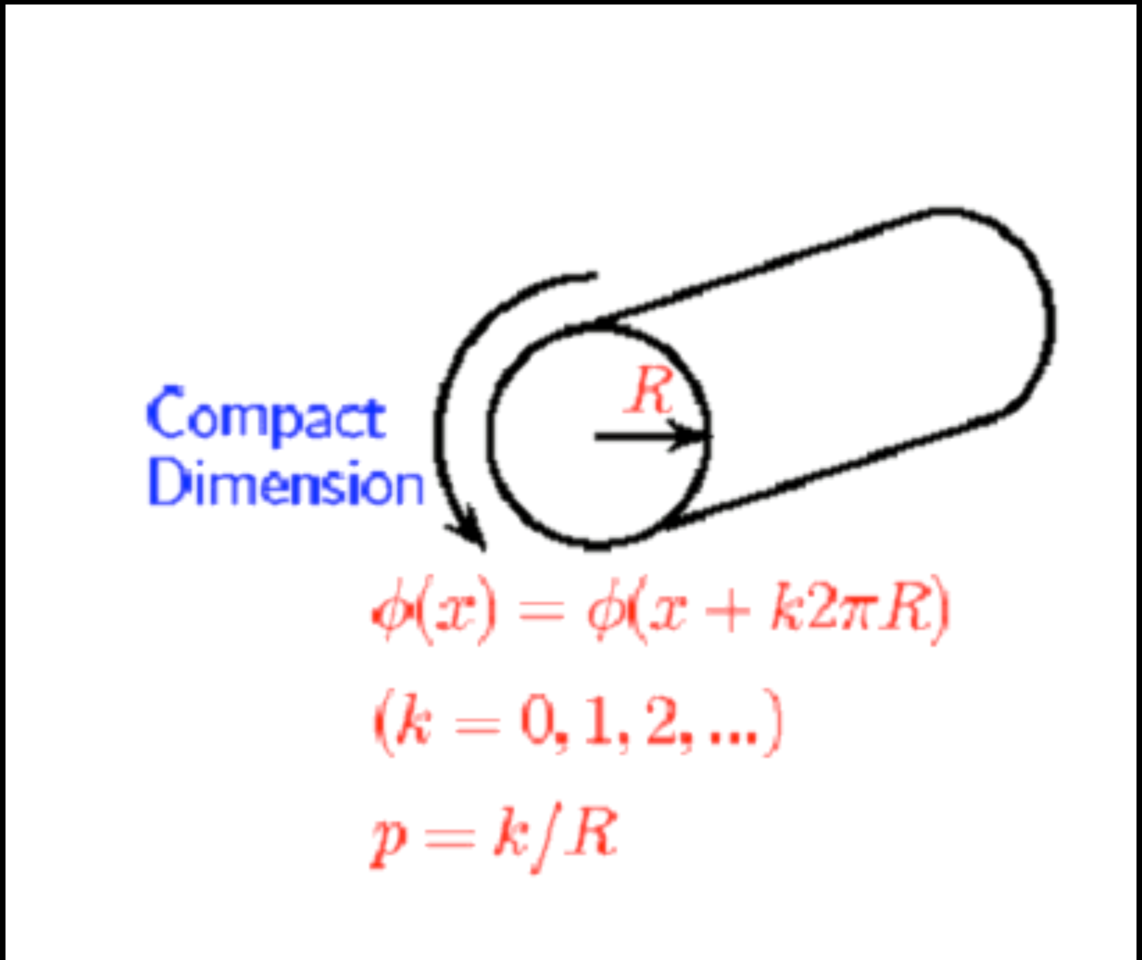
$$M_P^2 \simeq M_S^{2+n} R^n$$

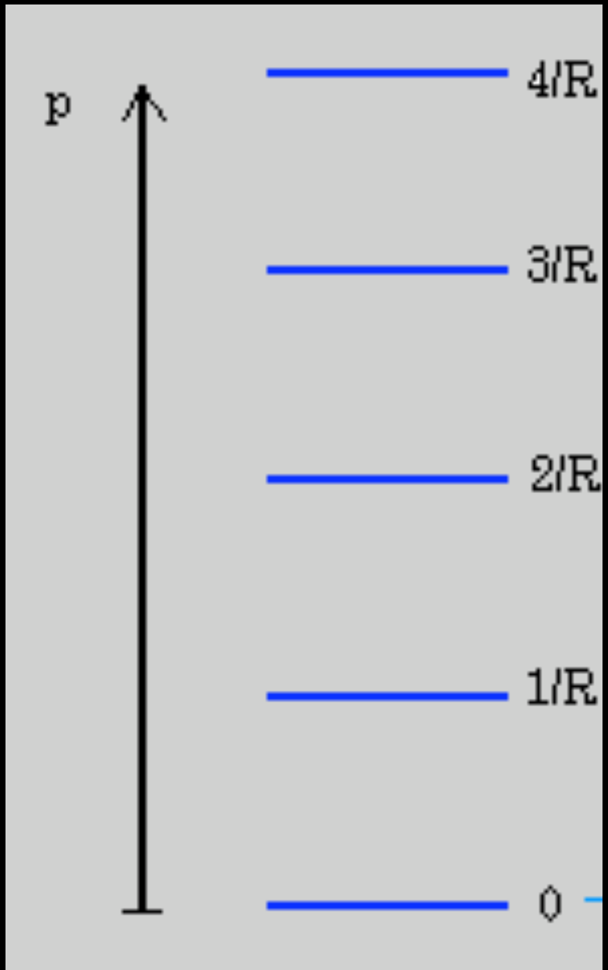
If R is large Ms can be TeV!

(Arkani-Hamed, Dimopoulos, Dvali)

- model building require fixing geometry, particles in ED and b.c.
- what is the signal of particles in the bulk?

$$\varphi(x,y) = \sum A e^{ip_\mu x^\mu} e^{i\frac{2\pi n}{R}y} \qquad \Longrightarrow p_\mu p^\mu - \left(\frac{2\pi n}{R}\right)^2 = 0$$

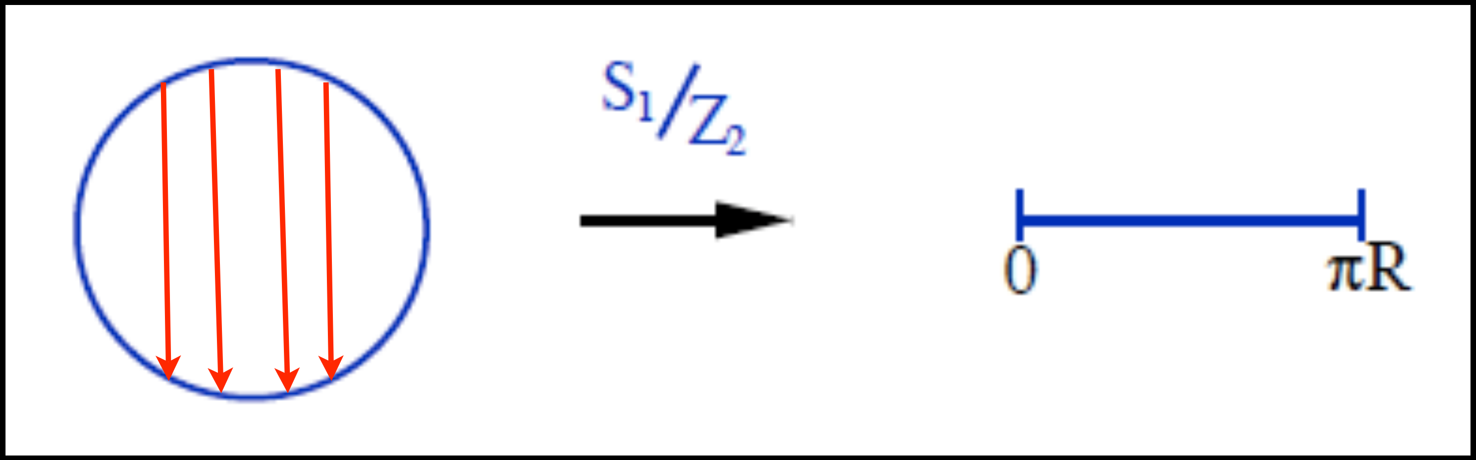




- Allowing gauge fields and matter to propagate in the bulk leads to models of EWSB, flavor, etc

Universal Extra Dimensions (UED)

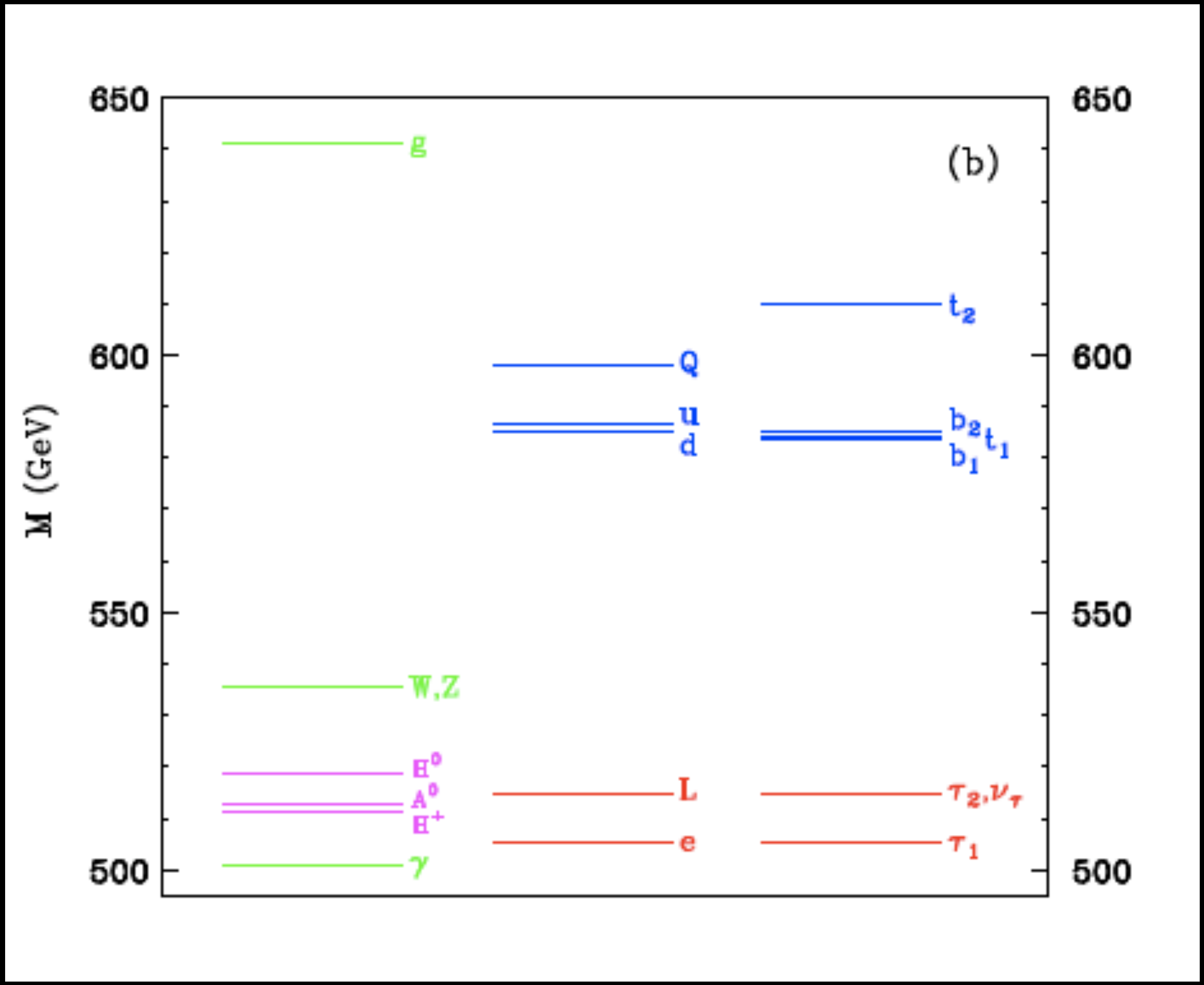
- All SM fields propagate in the 5D bulk
- geometry: orbifold compactification to get chiral fermions



- this breaks KK-number (mom. cons.) to KK parity
- lightest KK particle (LKP) is stable => dark matter candidate
- precison electroweak constraints and direct searches leads to

$$\frac{1}{R} > 300 \text{ GeV}$$

- spectrum after radiative corrections (Cheng, Matchev, Schmaltz)



- LKP stable + pairs production => missing energy

$$pp \to Q_1 Q_1 \to 4\ell + \not{E}_T$$

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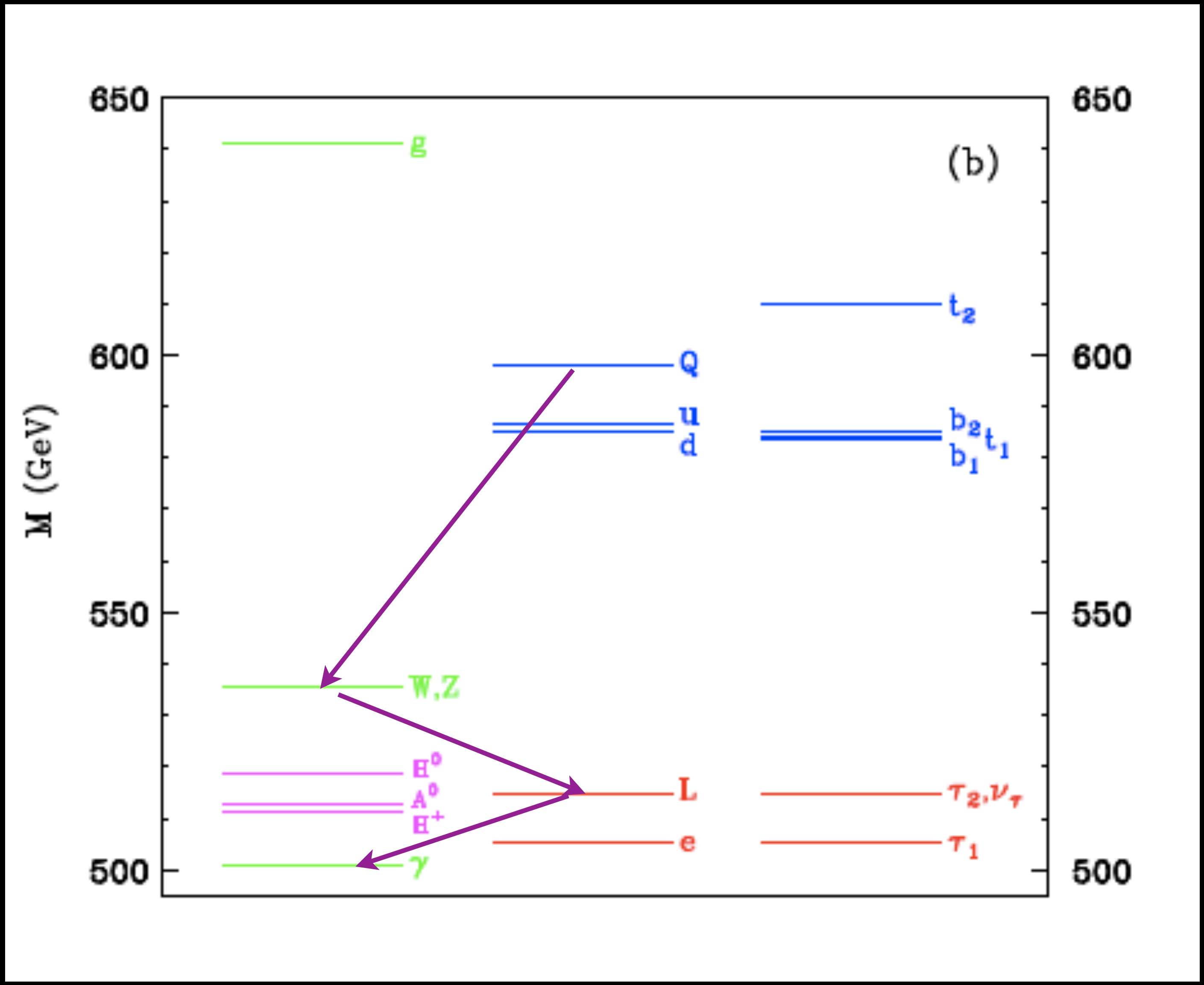

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3. Strongly interacting EWSB

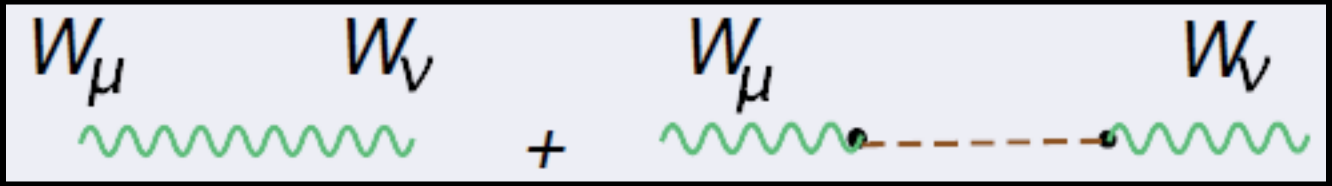
- QCD with 2 massless flavors is invariant under $SU(2)_L \otimes SU(2)_R$

$$\mathcal{L} = \bar{Q}_L i \not{D} Q_L + \bar{Q}_R i \not{D} Q_R \quad \text{with} \quad Q = \begin{pmatrix} u \\ d \end{pmatrix}.$$

- quark condensation $\langle \bar{Q}_L Q_R \rangle \neq 0$ breaks the symmetry to

$$SU(2)_L \otimes SU(2)_R \to SU(2)_V$$

leading to 3 NGB. Notice that this breaks the SM symmetries but at the wrong scale!



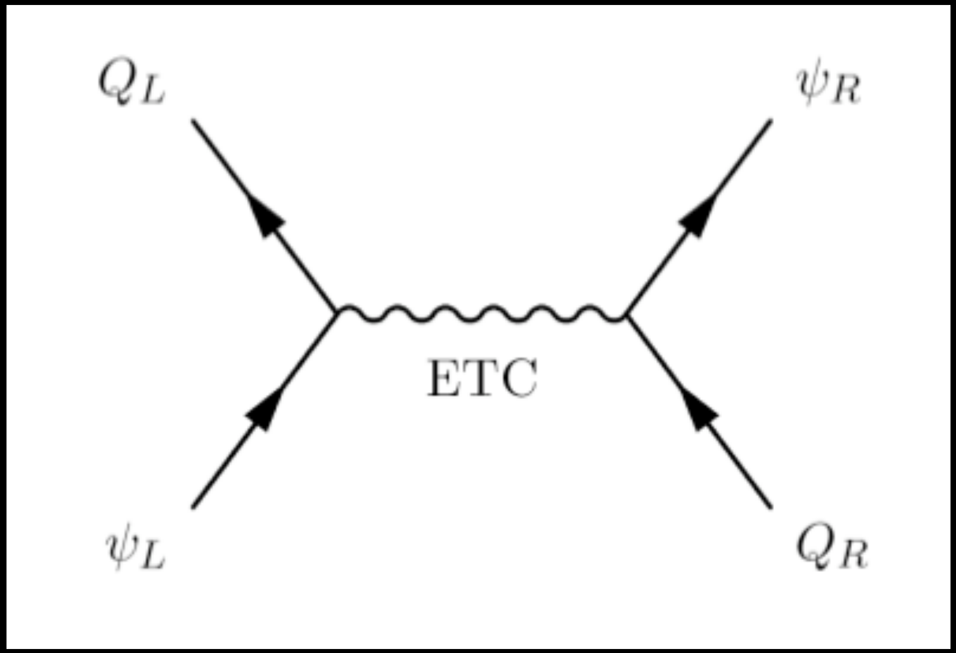
$\langle 0 | j_\mu^{a5} | \pi^b \rangle = i f_\pi p_\mu \delta_{ab}$ $\qquad M_W \simeq g f_\pi$

- The basic idea of technicolor is “copy” QCD but at a higher scale

(Weinberg, Susskind, etc)

$$\Lambda_{\rm QCD} \Longrightarrow \Lambda_{\rm TC} \simeq 1 \ {\rm TeV}$$

- but we still have to generate mass to the SM fermions => extended technicolor



$$m_f \simeq g^2_{\rm ETC} \frac{\Lambda^3_{\rm TC}}{M^2_{\rm ETC}}$$

- much more work is needed to deal with FCNC, top mass: walking technicolor (near conformal behaviour between TC and ETC scales
- also have to face the electroweak precision constraints:

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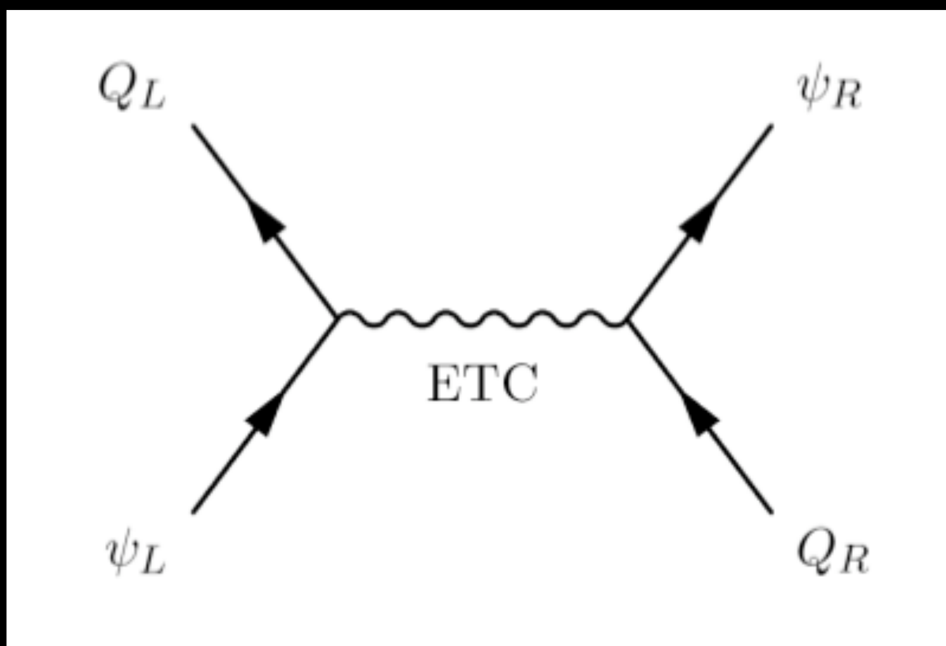

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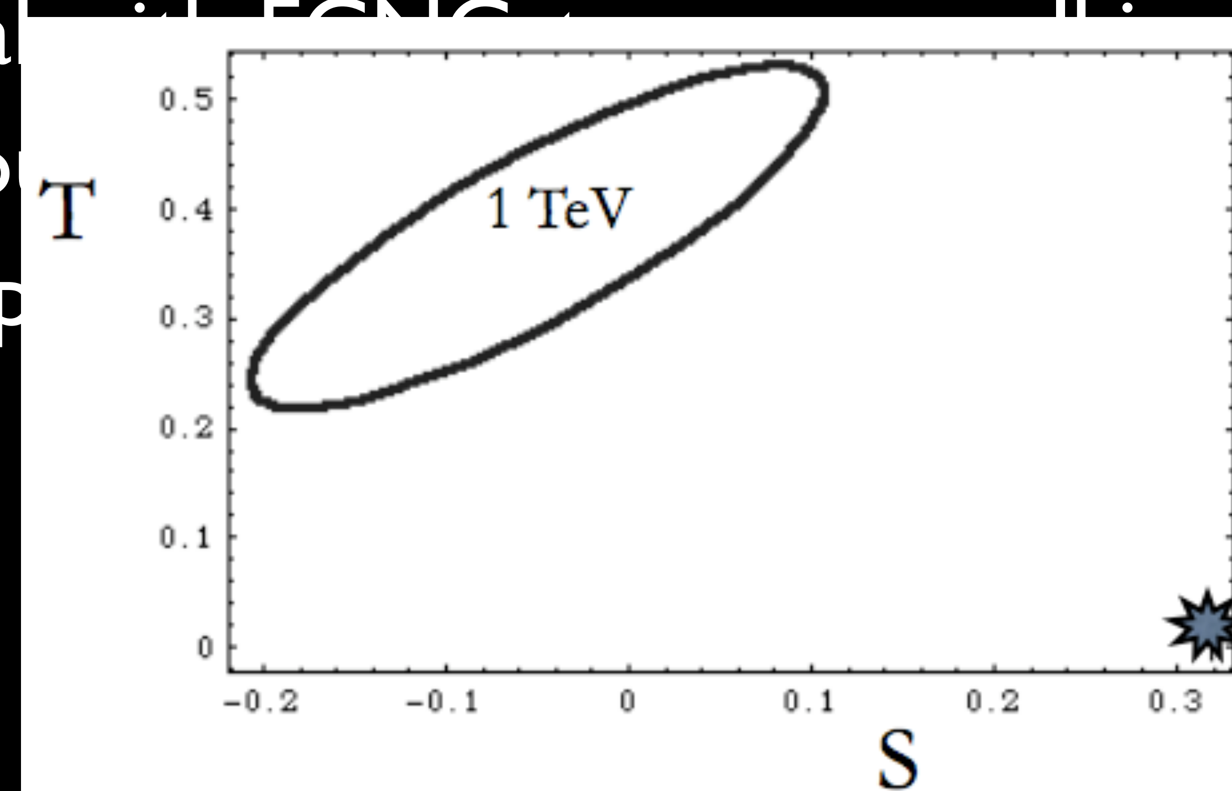
technicolor (near conformal behavio

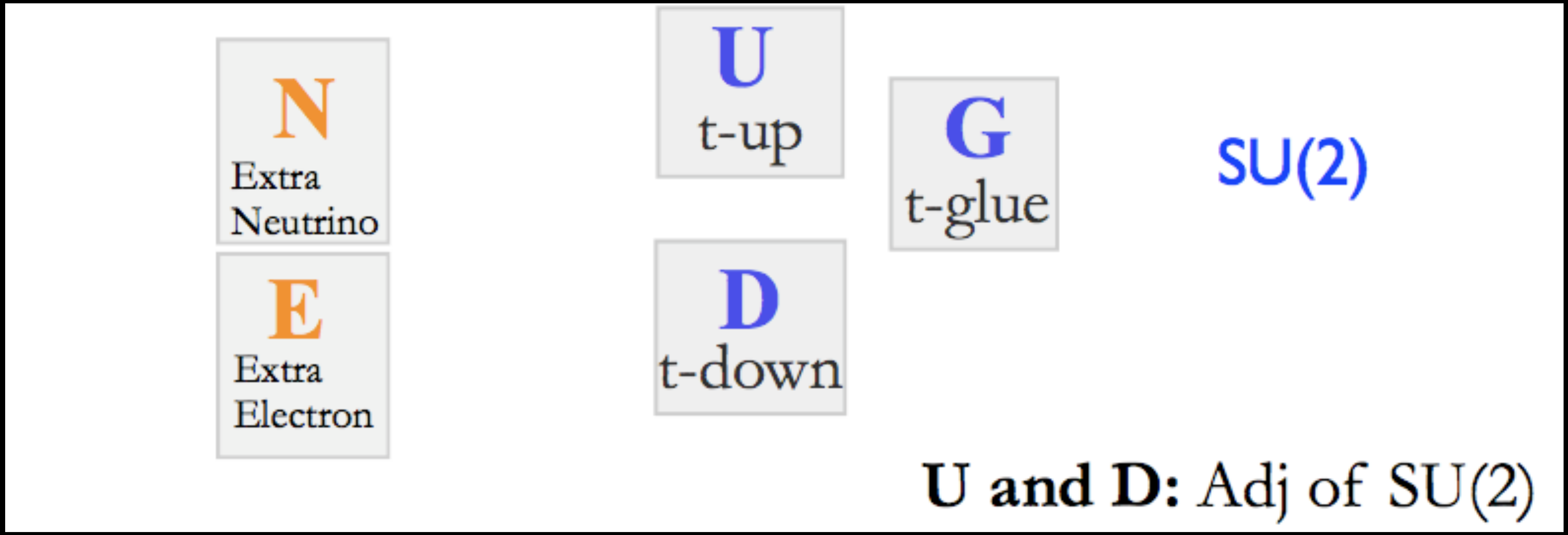
• also have to face the electroweak p

$$S \simeq \frac{N}{6\pi}$$



- In general is not easy to construct a realistic model satisfying FCNC, EWPO.
- surviving models can be tested at LHC through new states: π's, $\rho' s$

- Example: minimal walking technicolor (Sannino, Tuominen, Dietrich,...)



new states include: composite Higgs, composite axial-vectors $R_{1,2}$ ....

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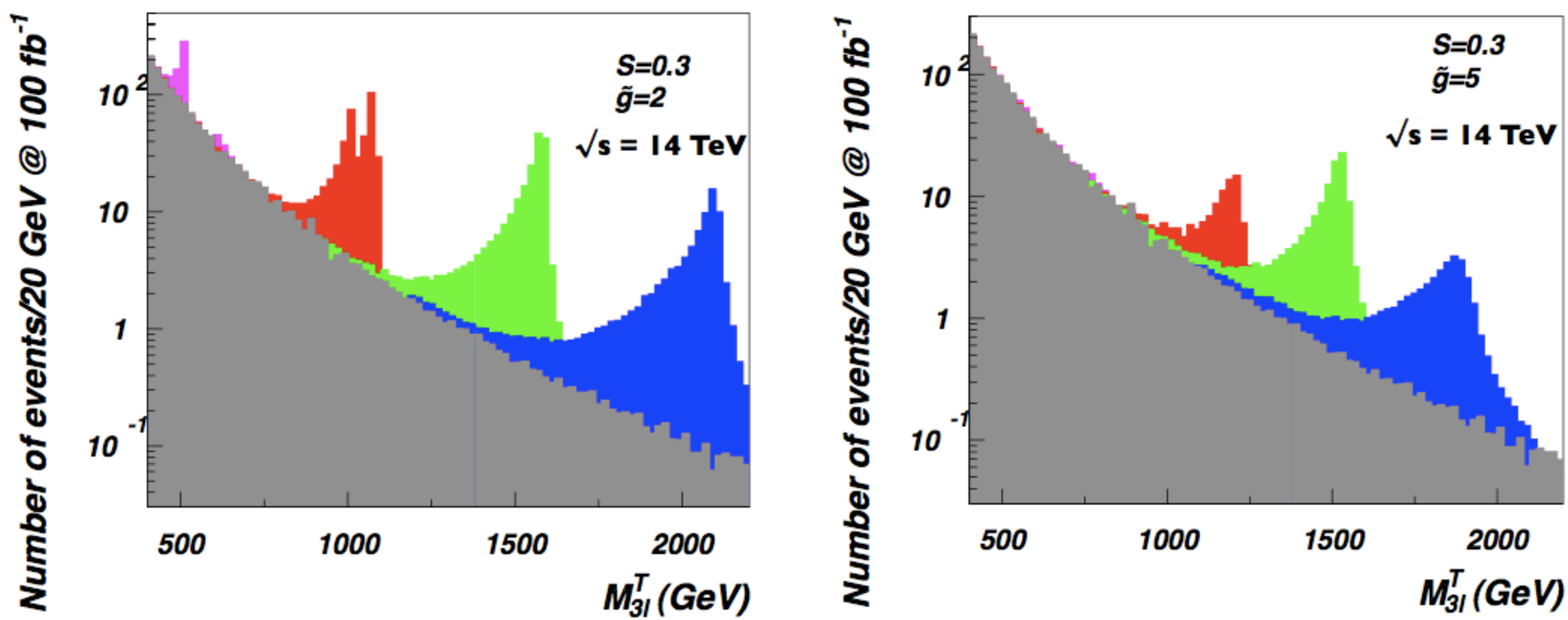
$$pp \to R^{\pm}_{1,2} \to ZW^{\pm} \to 3\ell\nu$$



4. AdS/CFT and Strong dynamics

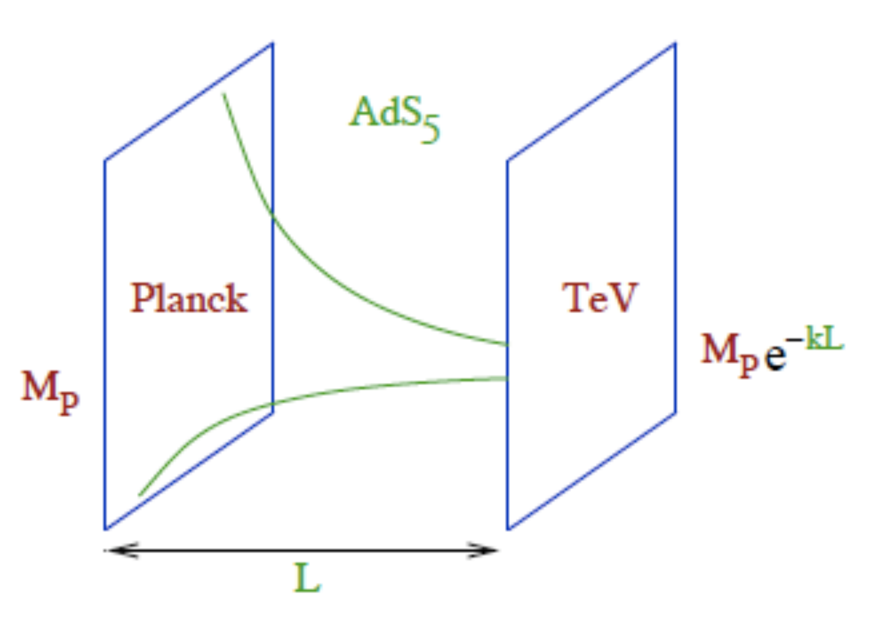
The original correspondence (Maldacena)

$$\mathrm{AdS}_5 \times S^2 \text{ string theory} \iff 4D \quad N = 4 \text{ CFT}$$

is modified to $\mathrm{AdS}_5 \iff 4D$ CFT (strongly coupled)

(Arkani-Hamed,Porrati,Randall)

Warped extra dimensions (Randall-Sundrum)



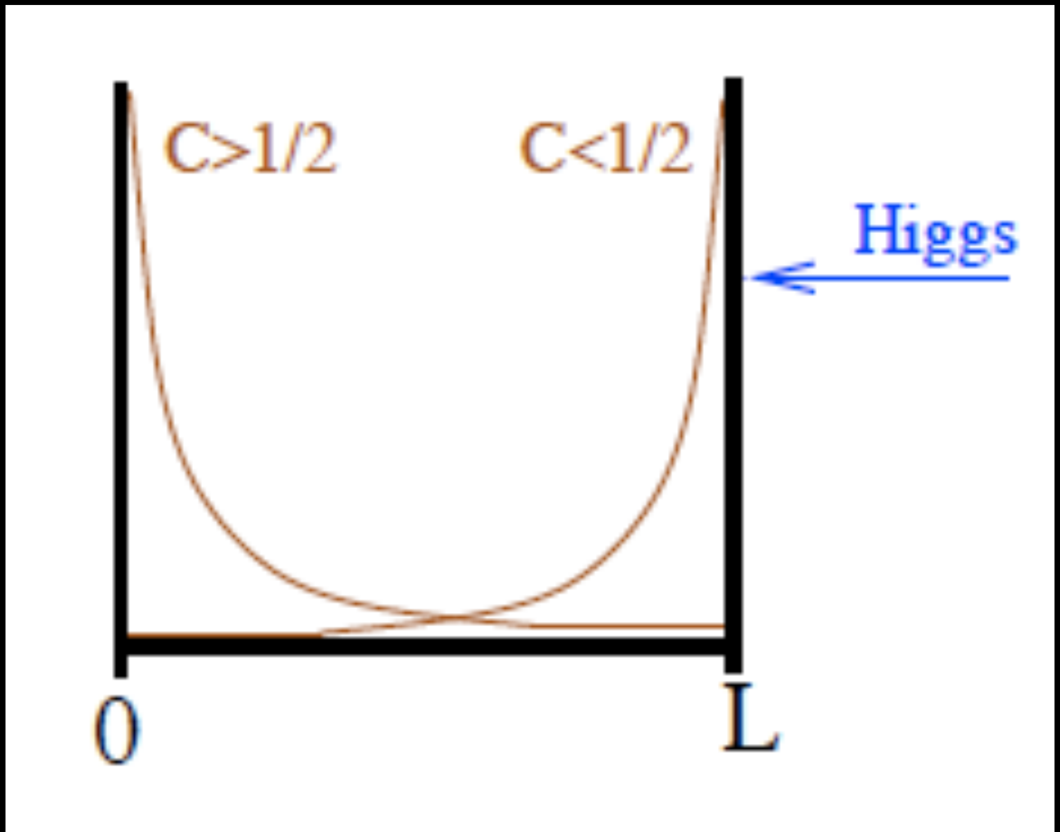
$$ds^2 = e^{-2k|y|}\eta^{\mu\nu}dx_\mu dx_\nu - dy^2$$

a TeV scale comes from $e^{-kL}M_P$

Higgs: hierarchy problem is solved if it is close to TeV brane

- Gauge fields and fermions in the bulk leads to natural flavor model
- 5d fermion mass leads to zero mode localization

$$M_f^{5D} = kc_f \quad \Longrightarrow \quad f_0(y) = \frac{1}{\sqrt{2L}}\, f_0(0)\; e^{(\frac{1}{2}-c_f)ky}$$



- heavy fermions near teV brane
- light fermions near Planck brane
- take the log of Yukawa's!!

- realistic model requires a larger gauge symmetry

$$SU(2)_L \otimes SU(2)_R \otimes U(1)$$

- $Z \to b\bar{b}$ requires a discrete $L \leftrightarrow R$ symmetry (da Rold et al)

- EWPO requires $M_{KK} > (2-3)\ \mathrm{TeV}$
- There is some level of level violation (good/bad)

$$pp \to G^{(1)} \to tc$$

Fermion condensation (Burdman, da Rold)

- Inspired in top condensation models $m_t \simeq 600 \text{ GeV for } \Lambda \simeq O(1) \text{ TeV}$

- Fourth generation in the bulk close to IR brane
- it interacts strongly with KK gauge bosons leading to $\langle \bar{U}U \rangle \neq 0$
- So we have EWSB and

$$m_U \simeq (600 - 700) \text{ GeV and } m_H \simeq (600 - 900) \text{ GeV}$$

- Bulk higher dimensional operators responsible for generating fermion masses:

$$\frac{C^{ijkl}}{M_P^3} \; \bar{\Psi}^i_L \Psi^j_R \bar{\Psi}^k_L \Psi^l_R$$

- A signal from these models is

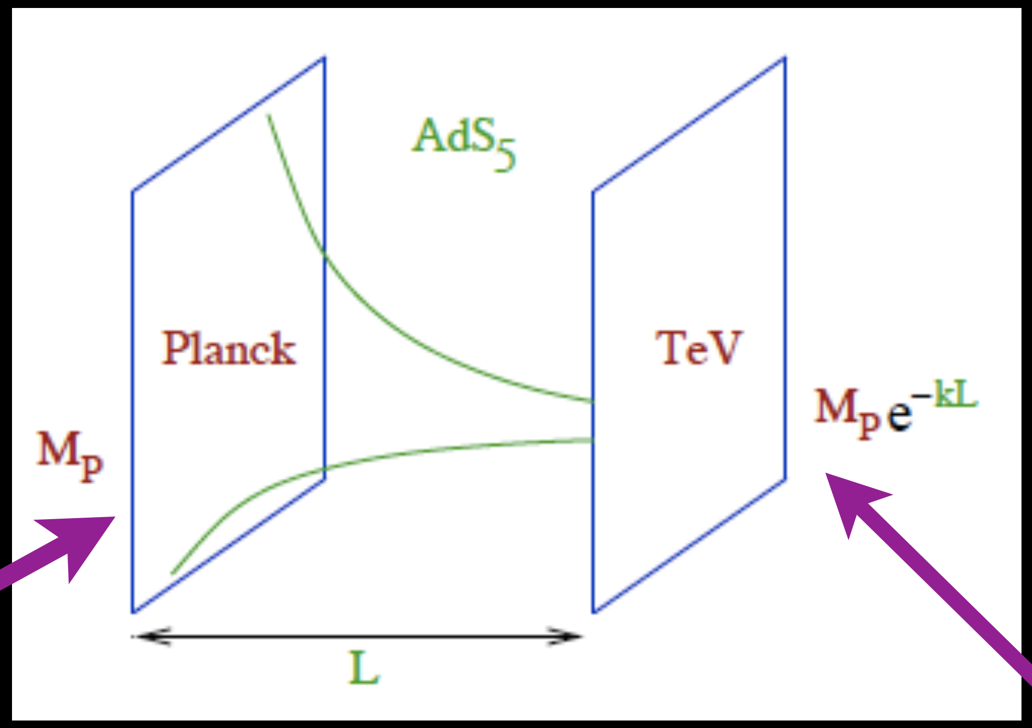
$$pp \to D_4 \bar{D}_4 \to W^- t \;\; W^+ \bar{t} \to W^+ W^- b \;\; W^+ W^- \bar{b}$$

(Burdman et al)

Higgsless models (Csaki, Grojean, Murayama, Pilo, Terning)

- Idea: boundary conditions break

$$SU(2)_L \otimes SU(2)_R \otimes U(1)_X \to U(1)_{\rm em}$$



$$SU(2)_R \otimes U(1)_X \to U(1)_Y \qquad SU(2)_L \otimes SU(2)_R \to SU(2)_V$$

- W and Z are KK modes
- S can be made small delocalizing the fermions
- $Z \to b\bar{b}$ requires further symmetry

- Nice aspect: KK resonances unitarize WW scattering
- Cancelation of E^4 and E^2 terms leads to sum rules

$$g_{WWWW} = g_{WWZ}^2 + g_{WW\gamma}^2 + \sum_n g_{WWV^{(n)}}^2$$

$$4M_W^2 g_{WWWW} = 3g_{WWZ}^2 M_Z^2 + \sum_n g_{WWV^{(n)}}^2 M_{V^{(n)}}^2$$

first KK mode nearly saturates sum rules

$$g_{WWV^1} \simeq g_{WWZ} \ \frac{M_Z}{\sqrt{3}M_{V^{(1)}}}$$

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first KK mode nearly saturates sum rules

$$g_{WWV^1} \simeq g_{WWZ} \, \frac{M_Z}{\sqrt{3} M_{V^{(1)}}}$$

- It is possible to discover Higgsless models at the LHC

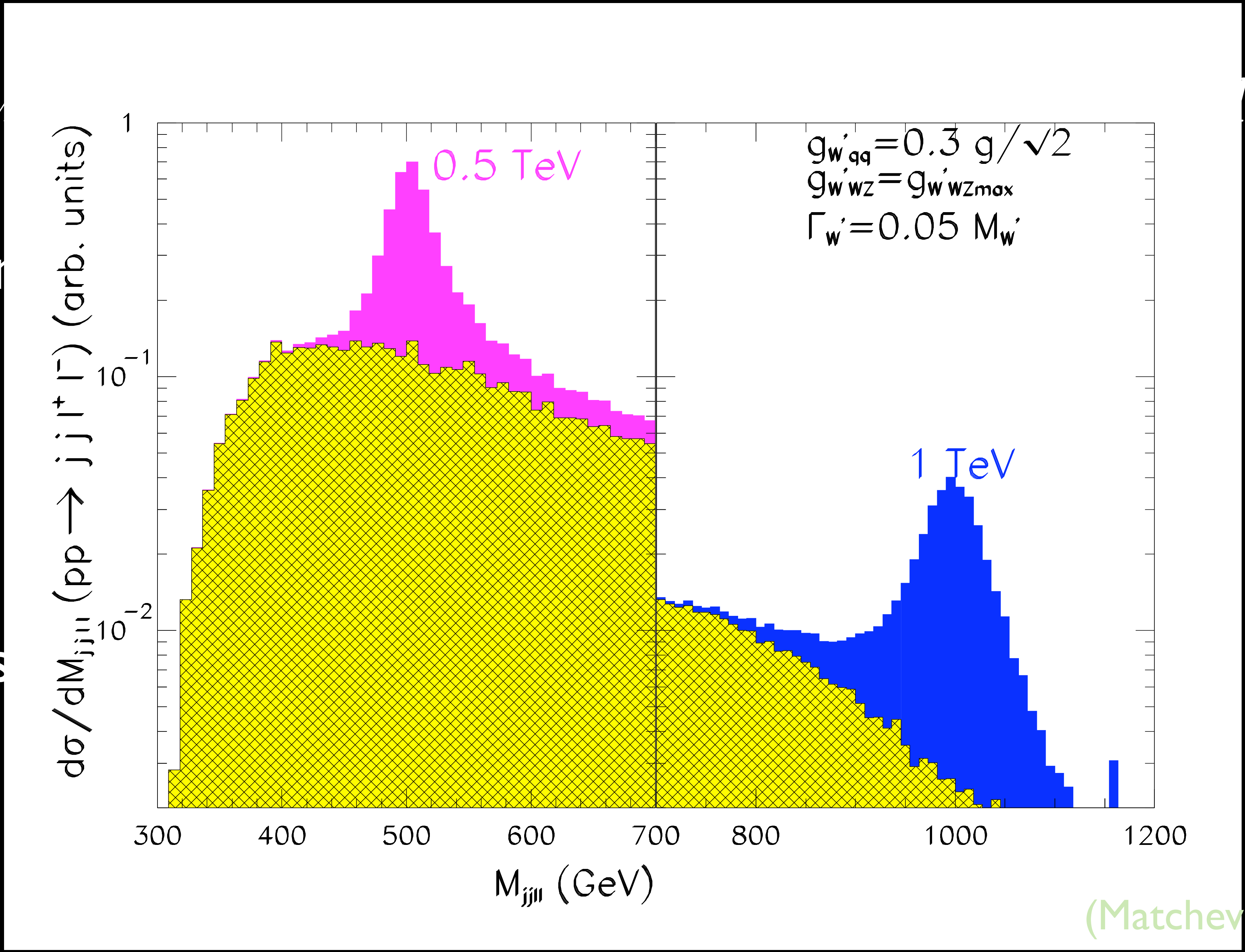
$$pp \to jjV^{\pm}(W^{\pm}Z) \quad \text{or} \quad pp \to V^{\pm} \to W^{\pm}Z$$

- Nice aspect: KK resonances unitarize WW scattering
- Cancelation of E^4 and E^2 terms leads to sum rules

$$g_{WWWW} = g^2_{WWZ} + g^2_{WW\gamma} + \sum_n g^2_{WWV^{(n)}}$$

$4M$ ... $_{V^{(n)}}^{2}$

first KK r



- It is poss

pp

(Matchev et al; Alves et al.)

III. Conclusions

- There are many possible extensions of the SM: extra symmetries; new Higgs systems; strongly interacting EWSB; etc

- At this moment there is no smoking gun where the new physics might show up.

- Very exciting times ahead!

New physics searches at the LHC

Tilman Plehn

	missing energy (p.89)	cascade decays (p.91)	mono-jets/photon (p.15)	lepton resnce (p.109)	di-jet resnce (p.109)	top resnce (p.120)	WW/ZZ resnce (p.15)	W' resnce (p.93)	top partner (p.116)	charged tracks (p.123)	displ. vertex (p.123)	multi-photons (p.29)	spherical events (p.47,76)
SUSY (heavy grav.) (p.17,26)	✓✓	✓✓							✓				
SUSY (light grav.) (p.17,27)	✓	✓	✓						✓	✓	✓		
large extra dim (p.39)	✓✓		✓✓										✓
universal extra dim (p.47)	✓✓	✓✓		✓	✓	✓	✓	✓	✓				
technicolor (vanilla) (p.51)				✓	✓	✓	✓	✓✓					
topcolor/top seesaw (p.53,54)					✓	✓✓	✓						
little Higgs (w/o T) (p.55,58)				✓	✓	✓	✓	✓					
little Higgs (w T) (p.55,58)	✓✓	✓✓	✓	✓	✓	✓	✓	✓	✓				
warped extra dim (IR SM) (p.61,63)				✓	✓	✓	✓						
warped extra dim (bulk SM) (p.61,64)				✓	✓	✓✓	✓	✓					
Higgsless/comp. Higgs (p.69,73)				✓	✓	✓✓	✓✓						
hidden valleys (p.75)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

[arXiv:0912.3259, Morrissey, TP, Tait]