Beyond the Standard Model

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High Energy Physics

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- Amir Rezaeian (Coordinator)
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The Plan of BSM Lectures

- Lecture I: Beauty and Problems of the Standard Model
- Lecture II: Effective Field Theory and Supersymmetry
- Lecture III: Extra-dimensions and Technicolor/Composite Higgs models

About these BSM lectures

- Inspired by many different collaborators and lecturers

  [Dmitri Kazakov, Ben Gripaios, Veronica Sasnz, Hitoshi Murayama...]

- These lectures are more kind of **review** - time limit

- You must ~~Do not hesitate to~~ ask questions **during** the lectures

- There are **exercises** for you

Lecture I: Beauty and Problems of the Standard Model

Notations

- natural units $\hbar = c = 1$
- metric $\eta^{\mu\nu} = diag(1, -1 - 1, -1)$
- assuming you are familiar with Dirac (4-component) spinors and Dirac gamma-matrices

$$\gamma^\mu = \begin{pmatrix} 0 & \sigma^\mu \\ \overline{\sigma}^\mu & 0 \end{pmatrix}$$ where $$\overline{\sigma}^\mu = (1, -\sigma^i)$$ $$\sigma^\mu = (1, \sigma^i)$$

and σ^i are usual 2x2 Pauli matrices:

$$\sigma^1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \sigma^2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \sigma^3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

Notations

- Properties: $\{\gamma^\mu, \gamma^\nu\} \equiv \gamma^\mu\gamma^\nu + \gamma^\nu\gamma^\mu = 2\eta^{\mu\nu}$
- Definition: $\gamma^5 \equiv i\gamma^0\gamma^1\gamma^2\gamma^3 = \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix}$

- Representation:
- Dirac fermion carries 4-dim reducible representation (1/2; 0) x (0; 1/2) of the Lorentz group which is the product of two irreducible ones for 2-component Weyl spinors

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→ Fermion masses and mixings

→ Higgs boson
- scalar kinetic term and potential

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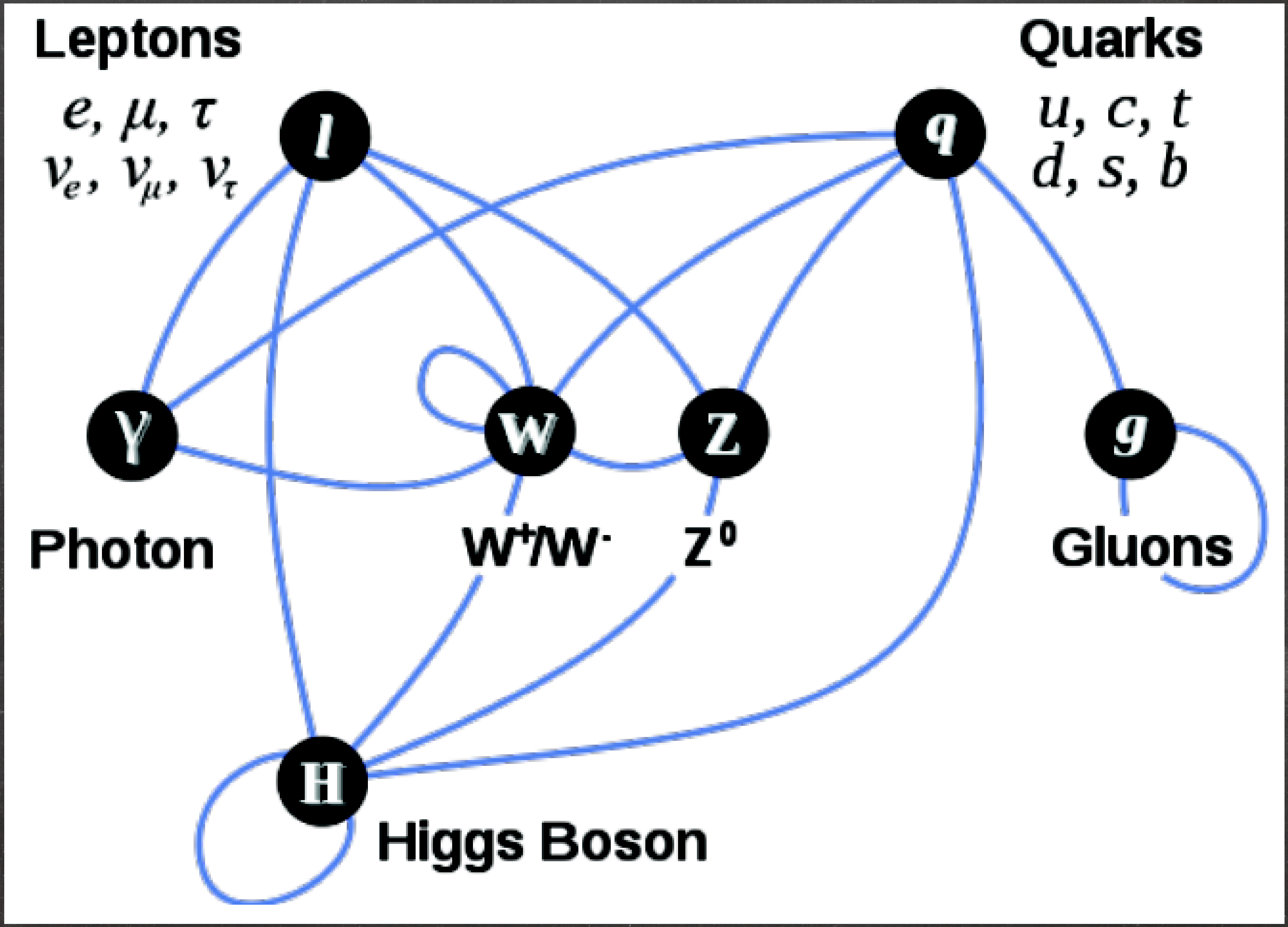

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$$SU(3) \times SU(2) \times U(1)$$

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together with matter fields - 15 Weyl fermions

and one complex scalar, carrying irreps of the gauge groups above

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- The lagrangian should contain all terms up to dimension four, such that it is renormalizable.

Gauge-Matter sector of the SM

- Lagrangian $$\mathcal{L} = i\overline{\psi}_i \overline{\sigma}^\mu D_\mu \psi_i - \frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu}$$
- 12 gauge fields:
  8 in an adjoint of SU(3)
  3 in an adjoint of SU(2)
  1 for U(1)
- The covariant derivative D_μ contains the three gauge couplings with the gauge group generators in the appropriate reps

The Flavour sector of the SM

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- The λs are three 3x3 complex matrices (in flavour space) - quite a few free parameters and the possibility of CP-violation (since a CP transformation is equivalent to interchanging the λs with their complex conjugates).

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$$\lambda^u q H^c u^c + \lambda^d V q H d^c + \lambda^e l H e^c + \text{h. c.}$$

- where now all λs the are diagonal, and V is a 3x3 CKM matrix. This is the only off-diagonal object in the Lagrangian, so it must contain all the information about mixing of flavours in the SM. Very roughly

$$V \sim \begin{pmatrix} 1 & \epsilon & \epsilon^3 \\ \epsilon & 1 & \epsilon^2 \\ \epsilon^3 & \epsilon^2 & 1 \end{pmatrix}$$

with $\epsilon \simeq 0.2$

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  - If we look back for the Lagrangian, we see that **6** of the real parameters are the quark masses, so there must be **3 physical angles** in the CKM matrix, and **a single phase**. This phase is a source of CP-violation.

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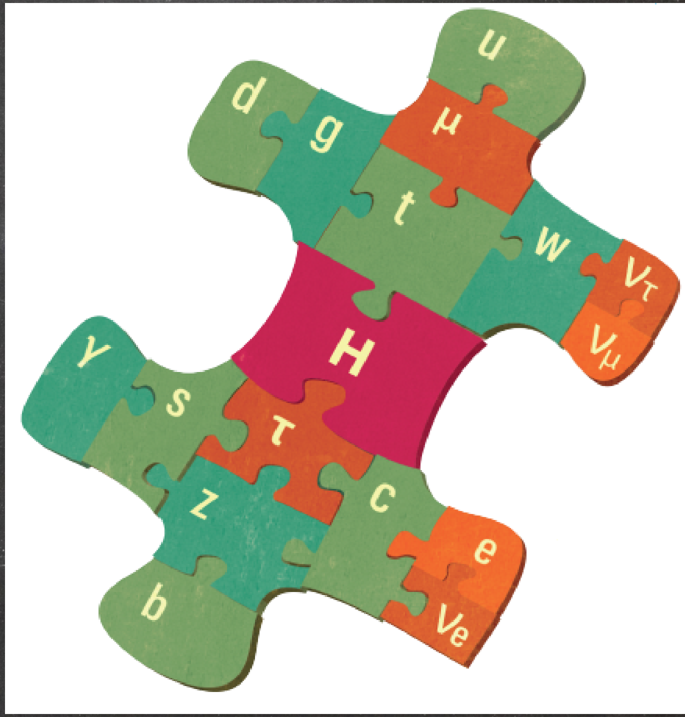

Miracles of the Standard Model

There certain features of the SM that are very special, and are vital clues in our quest for the form of physics BSM

No Flavour Changing Neutral Currents (FCNC) at tree-level

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- Not necessarily true in a theory with more than one Higgs doublet, where there are extra Yukawa coupling matrices in general, and the VEV is shared between the doublets (**exercise: show explicitly that tree-level FCNC exists in a 2 Higgs doublet model. How is this avoided in the MSSM?**).

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- If not the case -> the different irreps would have different couplings to the Z -> the matrix of couplings to the Z would then be diagonal in the interaction basis, but not proportional to the identity matrix -> The matrix would then acquire off-diagonal entries when we rotate to the mass basis.

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- For example, the d and s are both colour anti-triplets with charge -1/3 and can mix, but they also all come from SU(2) doublets with hypercharge +1/6, so there are no FCNC.
(**exercise: before the charm quark was invented, it was thought that the s- quark lived in an SU(2) singlet. Show that this leads to tree-level FCNC.**)

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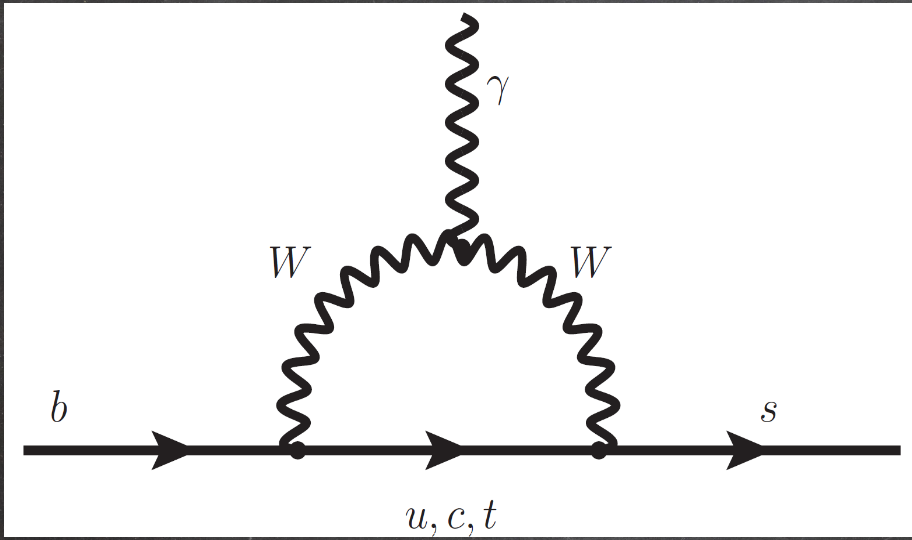

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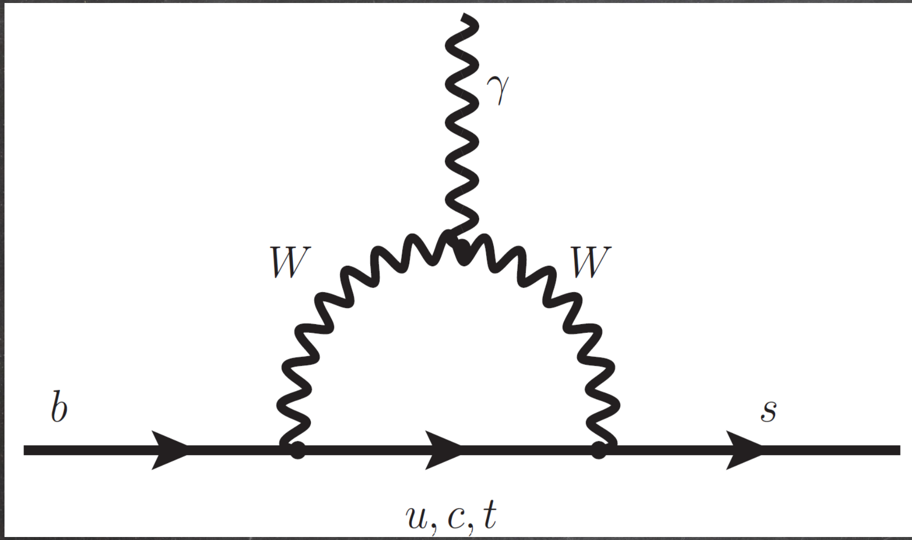

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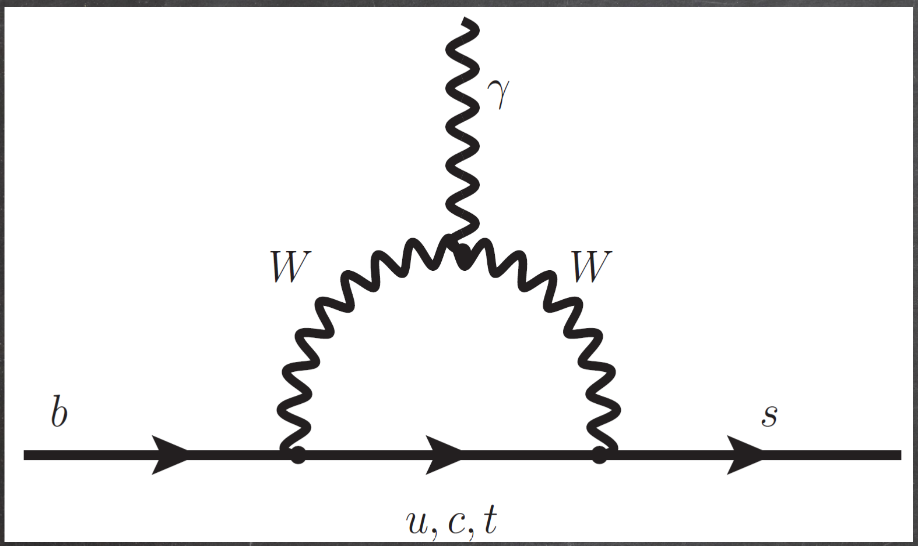

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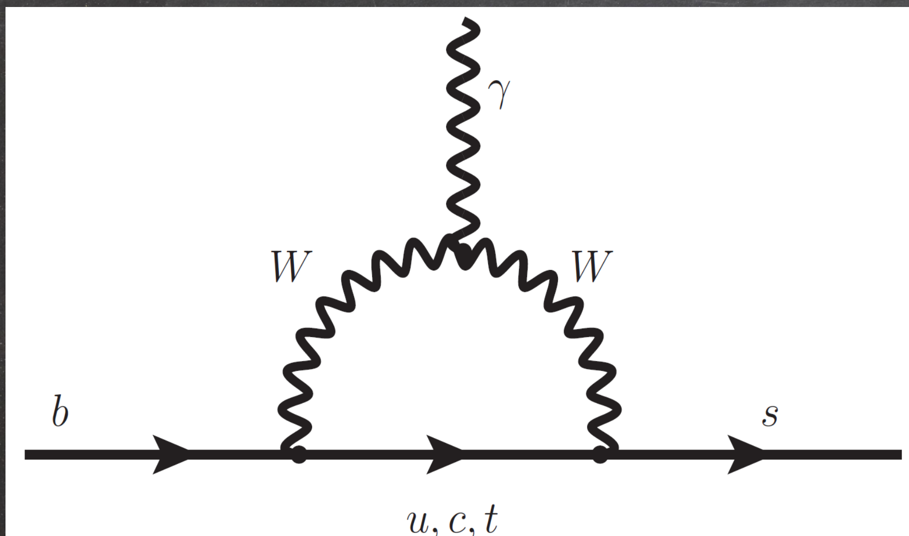

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- Additional factor of $(1/4\pi)^2$ from the loop integral leads to the overall contribution of

$$\frac{1}{(4\pi)^2}\frac{m_c^2}{m_W^2}\frac{1}{m_W^2}\simeq 1/(60\mathrm{TeV})^2(!)$$

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- But many of the SM quark masses are roughly degenerate, and many mixings in CKM are small, so again there is a huge suppression. For the mixings, for example, we get a factor of $\varepsilon^6 \sim 10^{-3}$

Miracles of the Standard Model

CP-violation (CPV)

- The structure of the flavour sector and the fact that CPV resides in the CKM matrix, imply suppressions of CPV processes.
- Note that in case of two generations of quarks in the SM, there would be no physical CPV parameter in the flavour sector (**exercise**).
- This means that any process which violates CP in the SM must involve all three quark generations. For similar reasons, CPV cannot occur if
  - any of the masses are degenerate in either the up or down sector
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Again, these properties do not hold for generic BSM physics, and so the constraints thereon are strong.

Miracles of the Standard Model

Electroweak precision tests and custodial symmetry

- There is suppression in EW precision tests - not a generic feature for BSMs. For the complex SU(2) there are four real fields and the respective O(4) symmetry. V(H) has the same feature – the function of $|H|^2 = h_1^2 + h_2^2 + h_3^2 + h_4^2$ – manifestly invariant under O(4), with the Lie algebra the same as that of SU(2)xSU(2) (**exercise**).
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  This (approximate, $g' \to 0$, $\lambda^t \to 0$) symmetry is called `custodial SU(2)'
- Consider the Lagrangian for the gauge bosons after EWSB. The most general Lagrangian consistent with U(1). At quadratic level, in momentum space

$$\mathcal{L} = \Pi_{+-}W^+W^- + \Pi_{33}W^3W^3 + \Pi_{3B}W^3B + \Pi_{BB}BB$$

where $\Pi_{ab}(p^2)$ are functions of momentum generated by the currents to which W and B couple: $\Pi_{ab} \sim \langle J_a J_b \rangle$

Miracles of the Standard Model

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- But since $SU(2)_V$ is a symmetry of the vacuum, only singlets of $SU(2)_V$ can have non-vanishing VEVs. This implies that $\mathrm{T}=0$, which in turn implies a definite relation for, say, m_W/m_Z

Miracles of the Standard Model

Electroweak precision tests and custodial symmetry

- This derivation applies to any theory with $SU(2)_L \times SU(2)_R$ broken to the diagonal $SU(2)_V$ in the vacuum. Any such theory will naturally come out with the right value for the measured T- parameter

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- Even if we add only an additional Higgs doublet, we will get in to trouble, because the theory remains $SU(2)_L x SU(2)_R$ symmetric, but $SU(2)_V$ is now broken in the vacuum: a second complex Higgs doublet will break this even further to just electromagnetism. The vacuum is no longer $SU(2)_V$ symmetric

Miracles of the Standard Model

Accidental symmetries and proton decay

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$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + iaF_{\mu\nu}\tilde{F}^{\mu\nu} + i\overline{\Psi}D\Psi + \overline{\Psi}(m + i\gamma^5 m_5)\Psi$$

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- Note that if we had not insisted on renormalizability, we could write dimension-six terms e.g. $\overline{\Psi}\gamma^\mu\gamma^5\Psi\overline{\Psi}\gamma_\mu\Psi$, which do violate parity (**exercise**)

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Accidental symmetries and proton decay

- As already discussed, the SM Lagrangian is accidentally invariant
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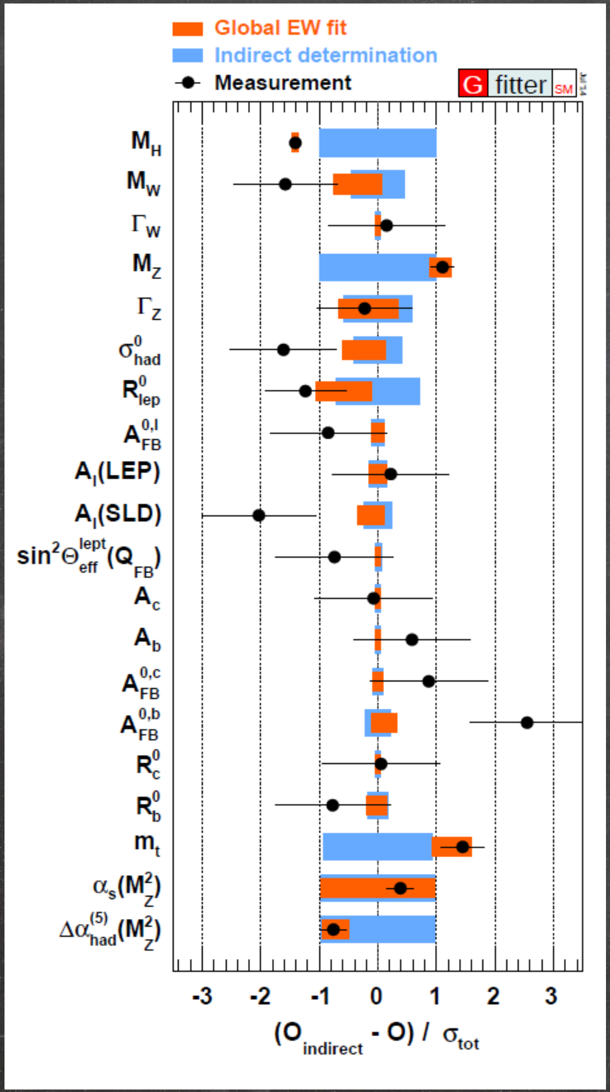
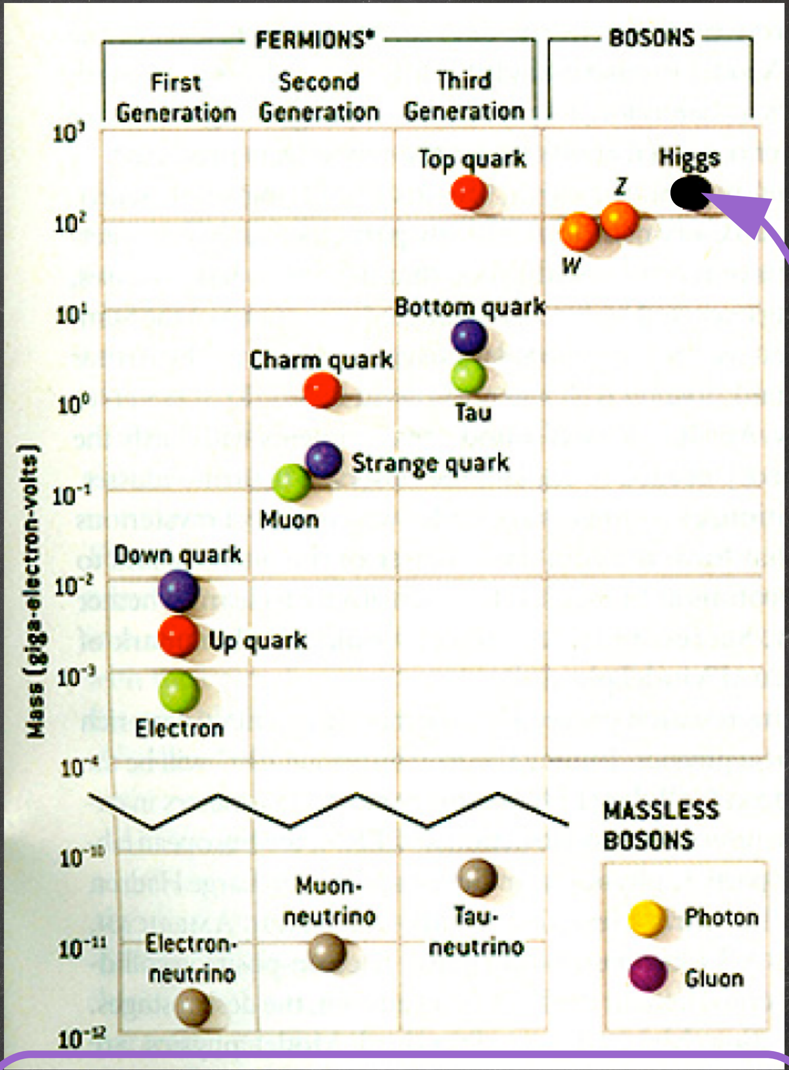
- Again, once we allow higher dimension operators, we will find that lepton and baryon number are violated (by operators of dimension five or six, respectively), meaning that the proton can decay. Similarly, generic theories of physics BSM will violate them and hence will be subject to strong constraints. (**exercise: consider just the Higgs sector coupled to the W-boson. Show that $SU(2)_L \times SU(2)_R$ is an accidental symmetry, and find a dimension-six operator that violates it**)

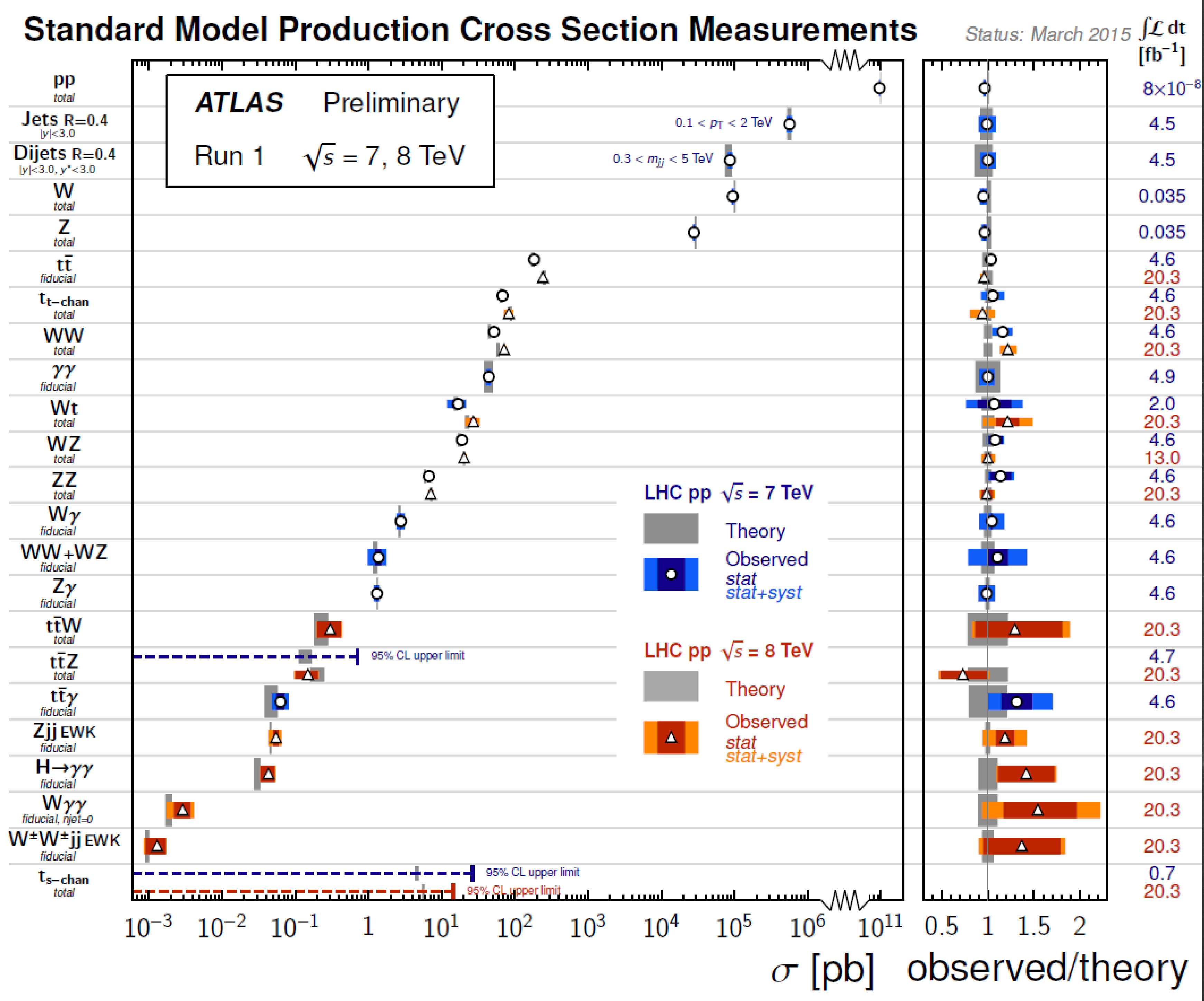
The the Standard Model is very successful !





Confirmed to better than 1% precision by 100's of precision measurements

The last missing particle – Higgs boson with ~125 GeV mass is discovered on the 4th of July 2012


Standard Model Production Cross Section Measurements
Status: March 2015
ATLAS Preliminary
Run 1 √s = 7, 8 TeV
LHC pp √s = 7 TeV
Theory
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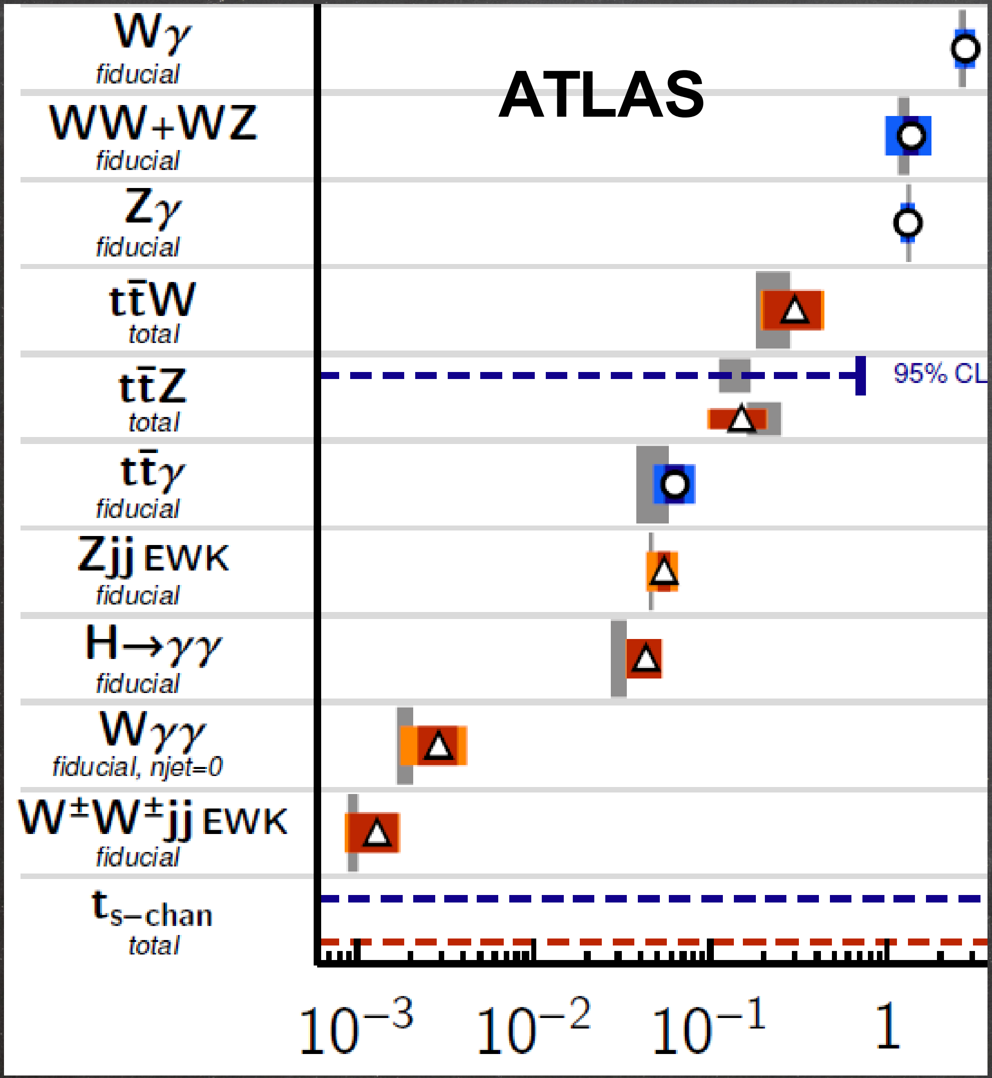

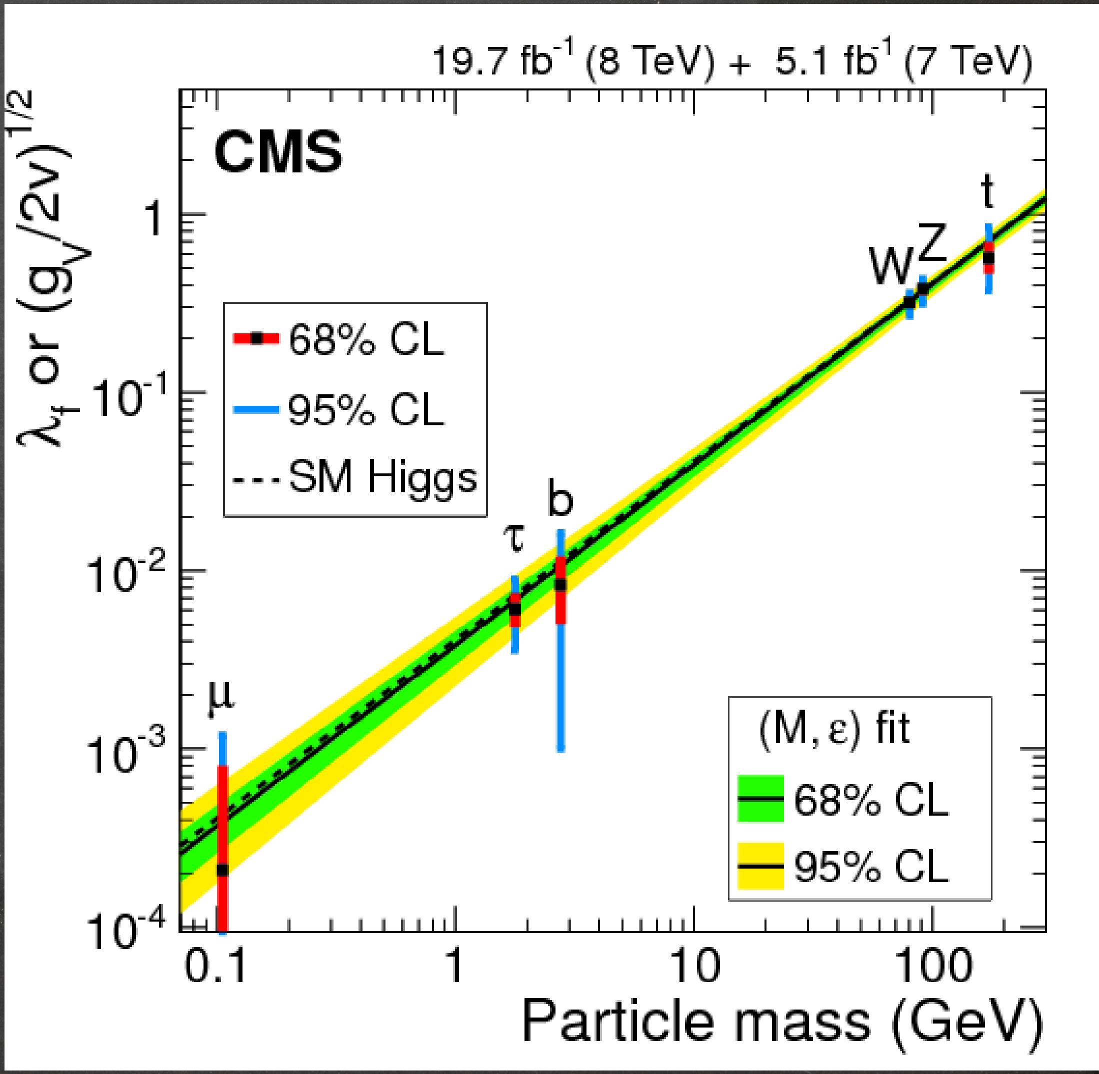

So, if SM works so good, why we are looking beyond?!

SM is empirically incomplete

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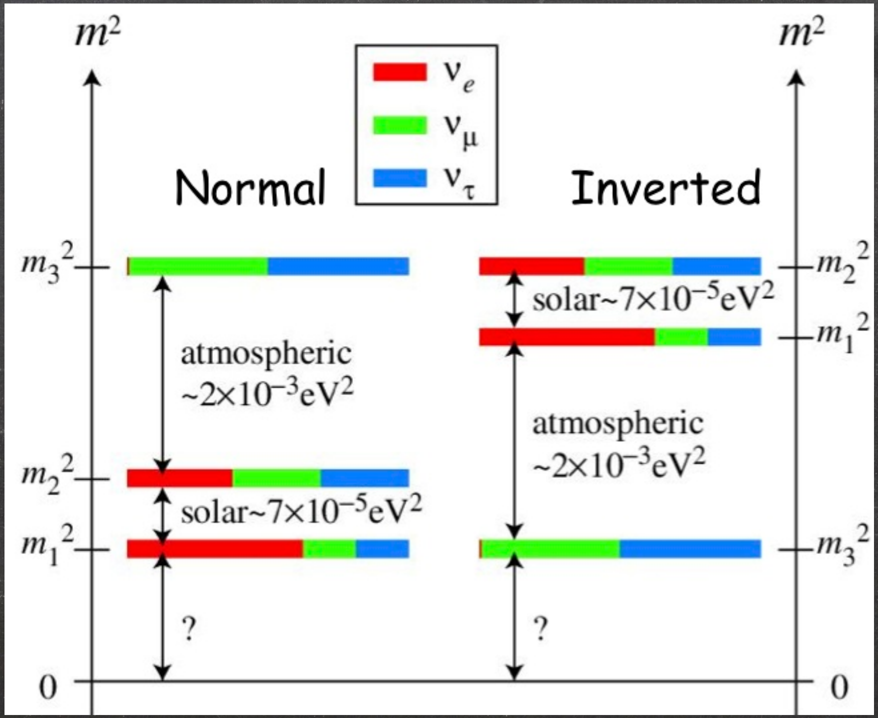
But there are, by now, also **plenty of data that the SM cannot describe**:

- **neutrino masses and mixings: no term in SM Lagrangian yields these**



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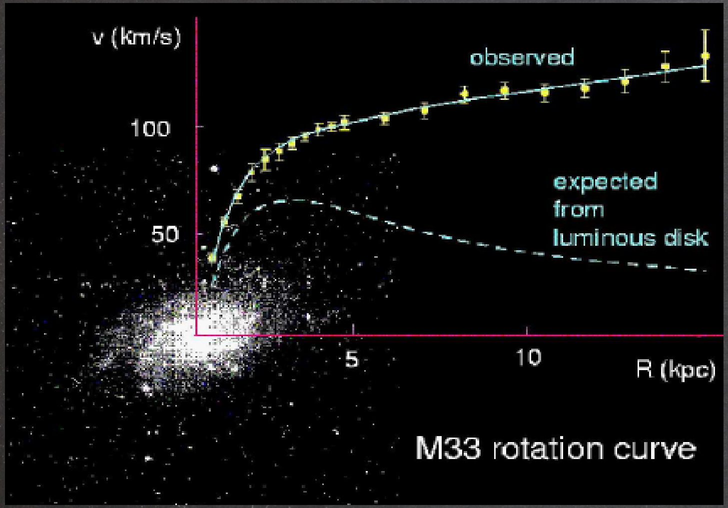
Galactic rotation curves



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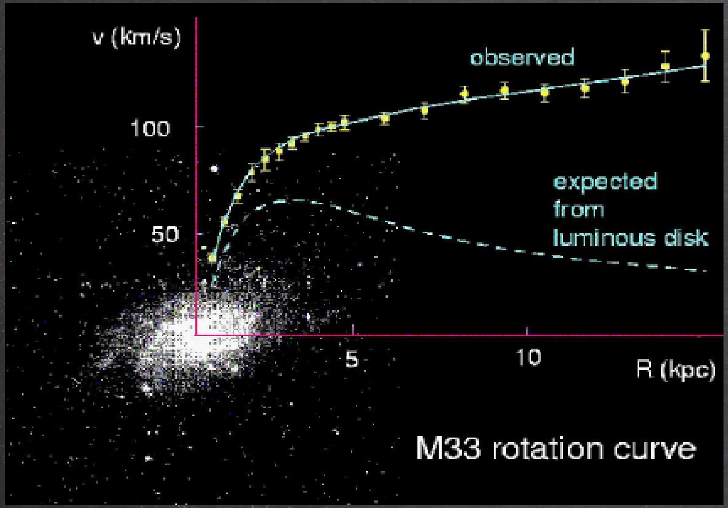
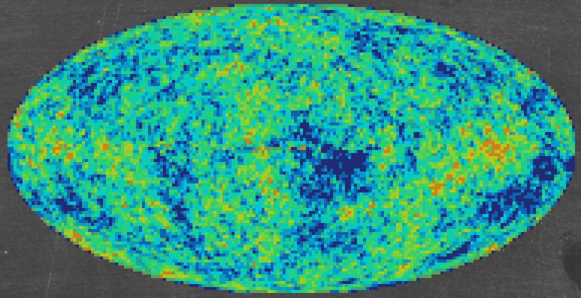


CMB: WMAP and PLANCK



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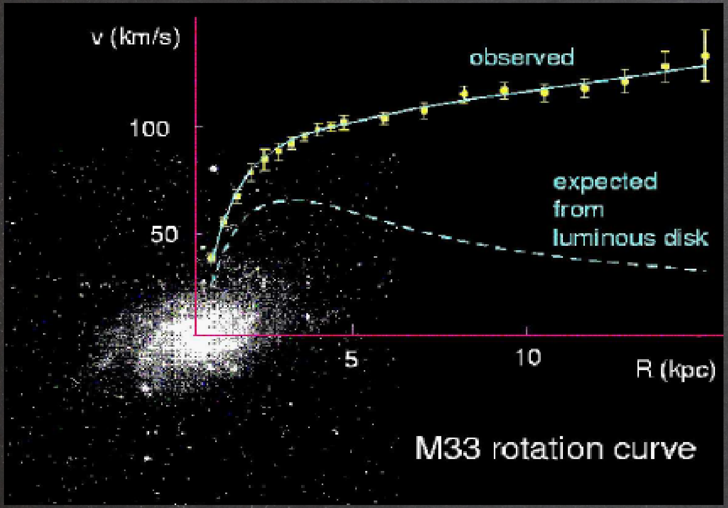

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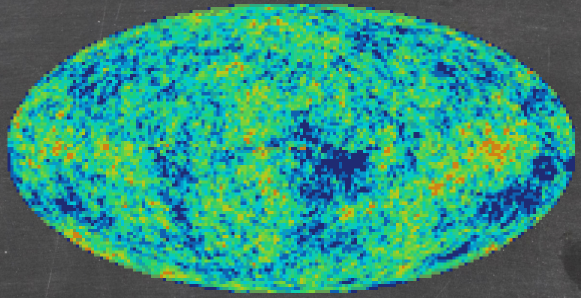
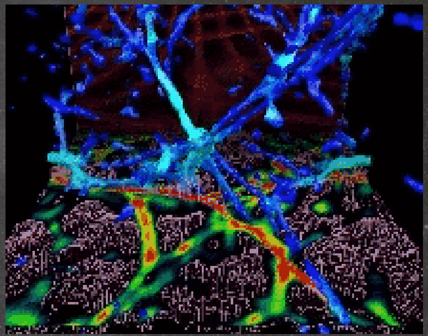


Large Scale Structures



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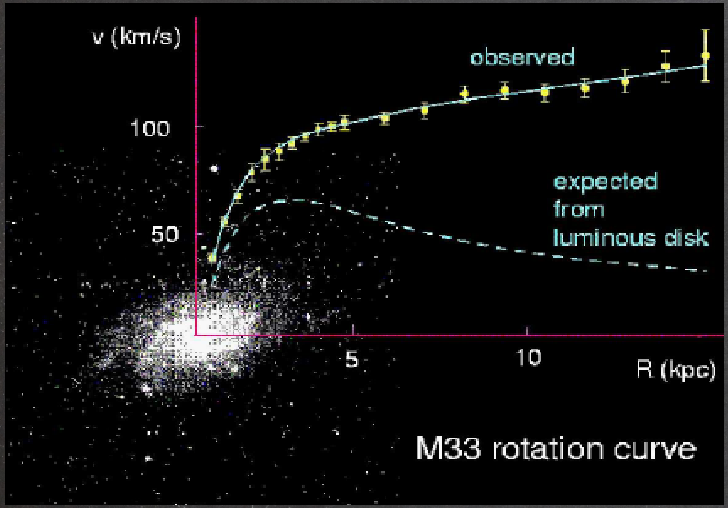

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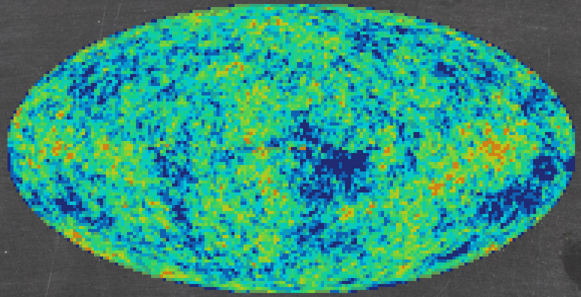

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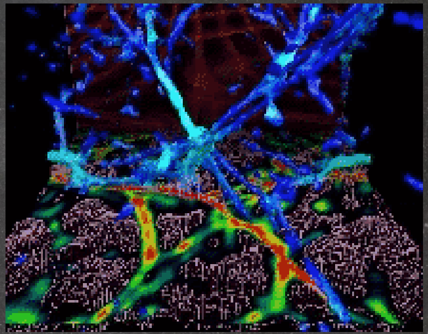
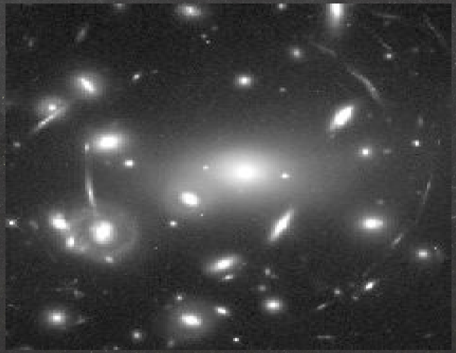


Gravitational lensing



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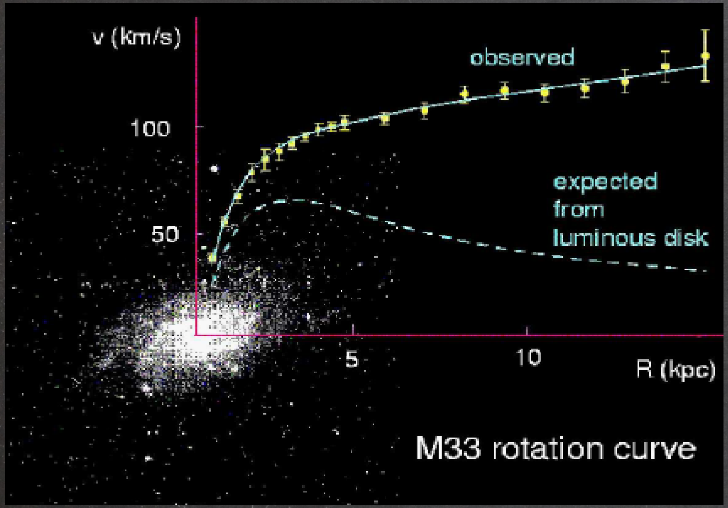

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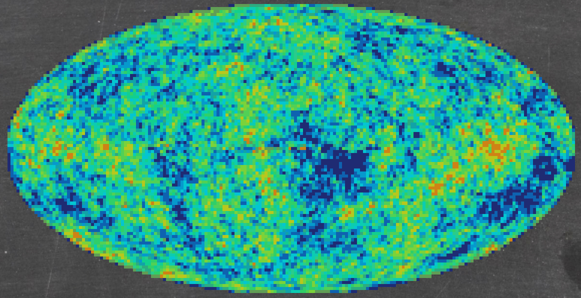

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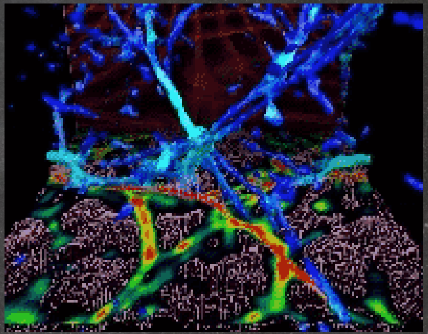

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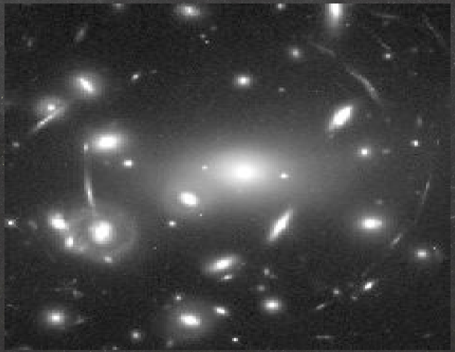

Bullet cluster

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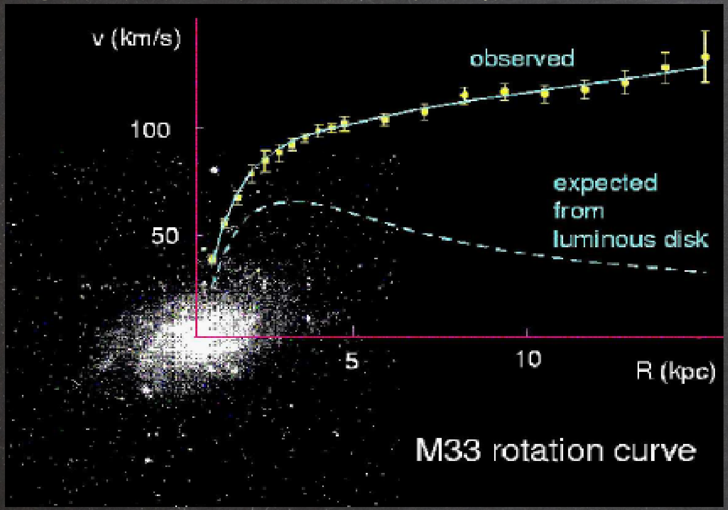

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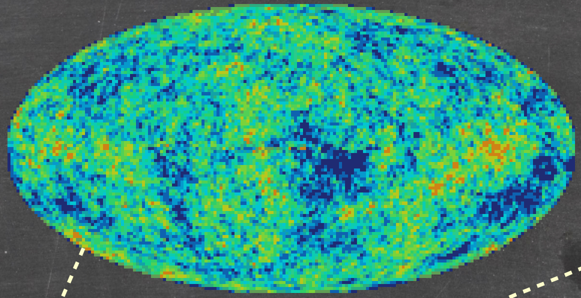

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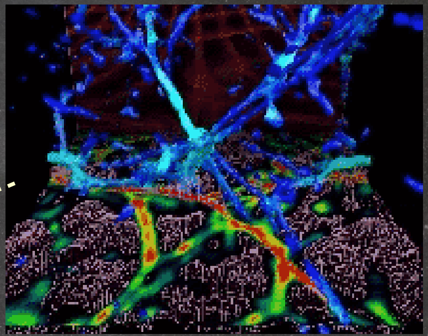

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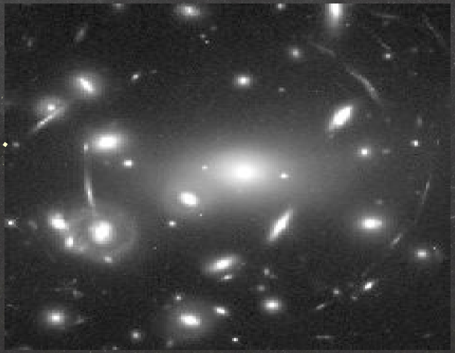

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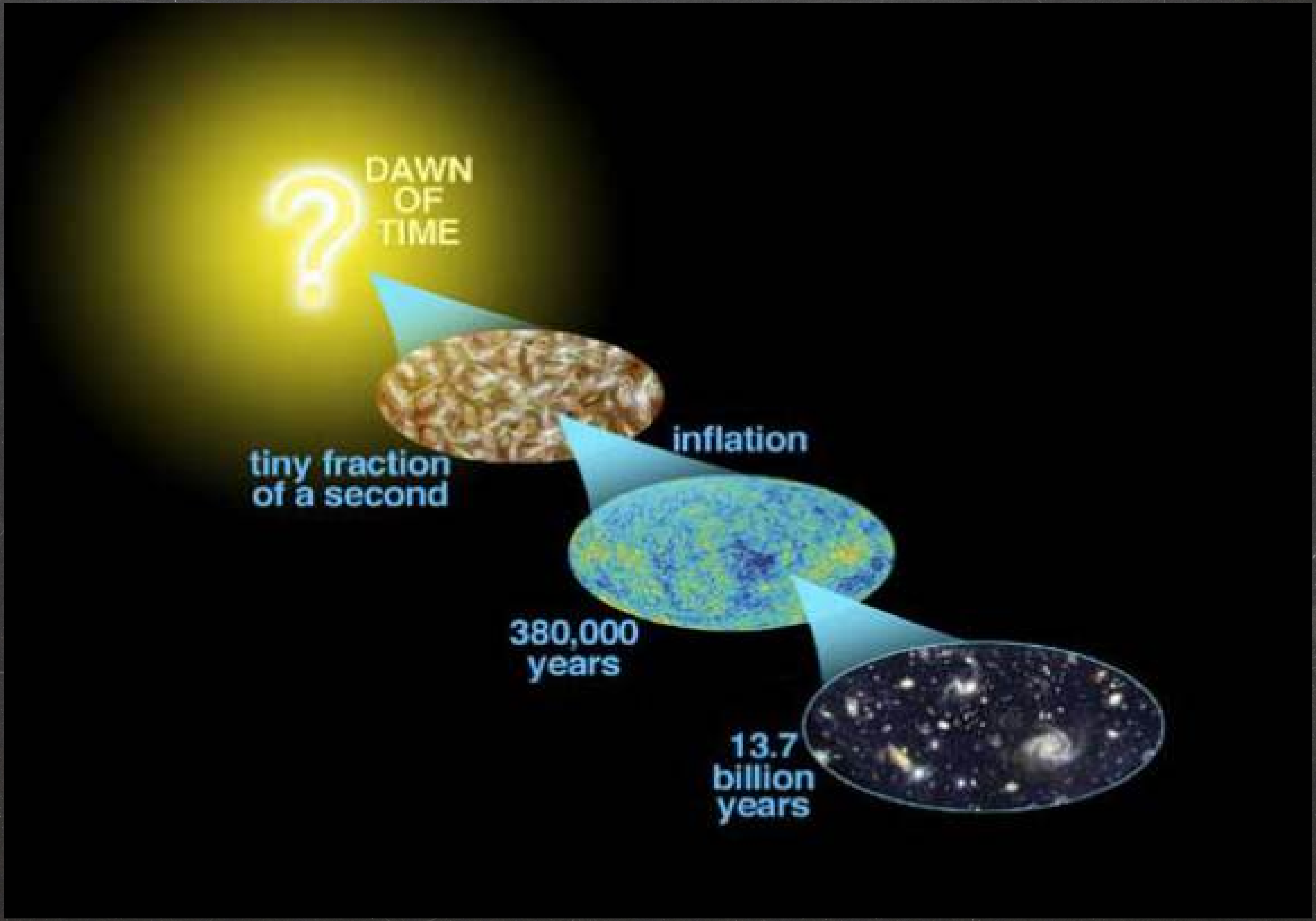
- **the presence of scale-invariant, Gaussian, and apparently acausal density perturbations:** consistent with a period of inflation at early times



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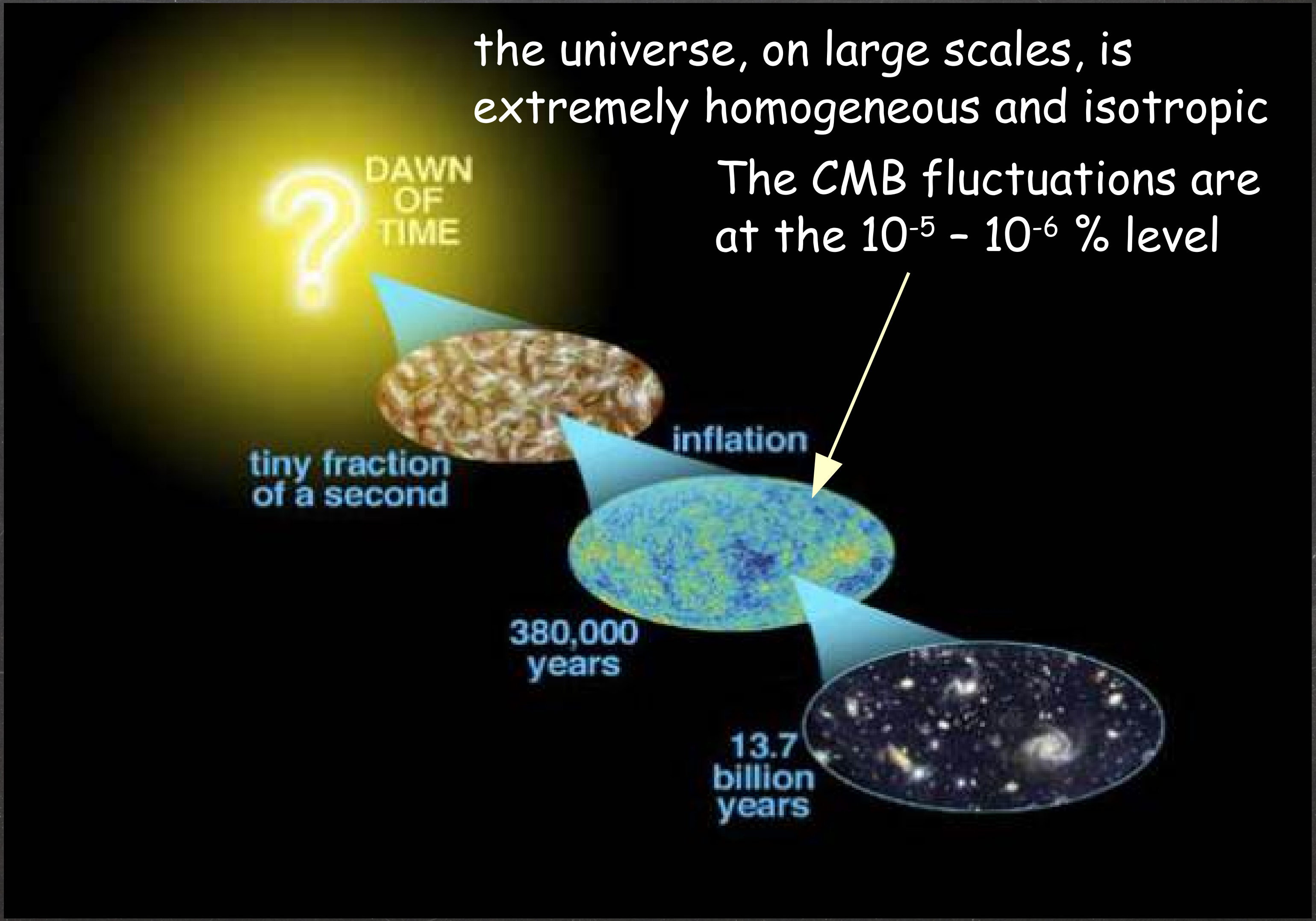

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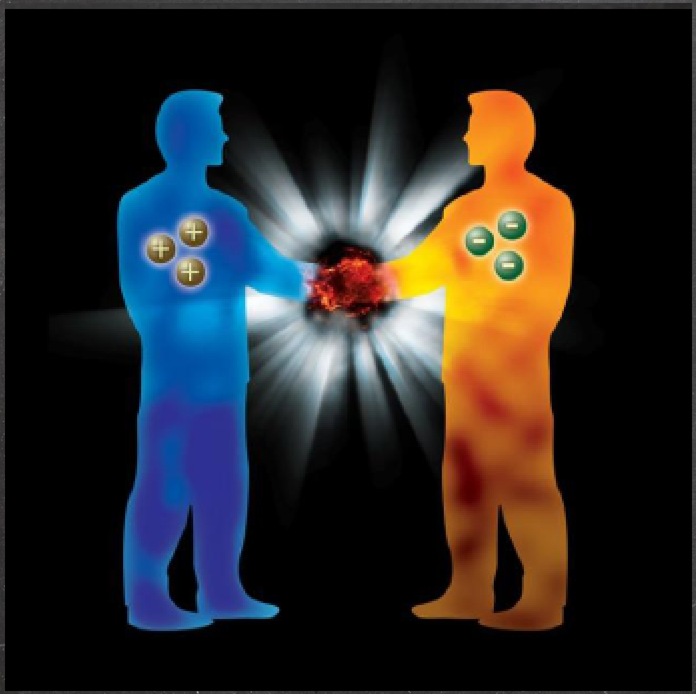

The amount of CP violation in the SM which could lead to baryon-antibaryon asymmetry is too small (would lprovide BAU ~10 orders of magnitude below the observed one)

$$\frac{n_B}{n_\gamma} = (6.1^{+0.3}_{-0.2}) \times 10^{-10}$$

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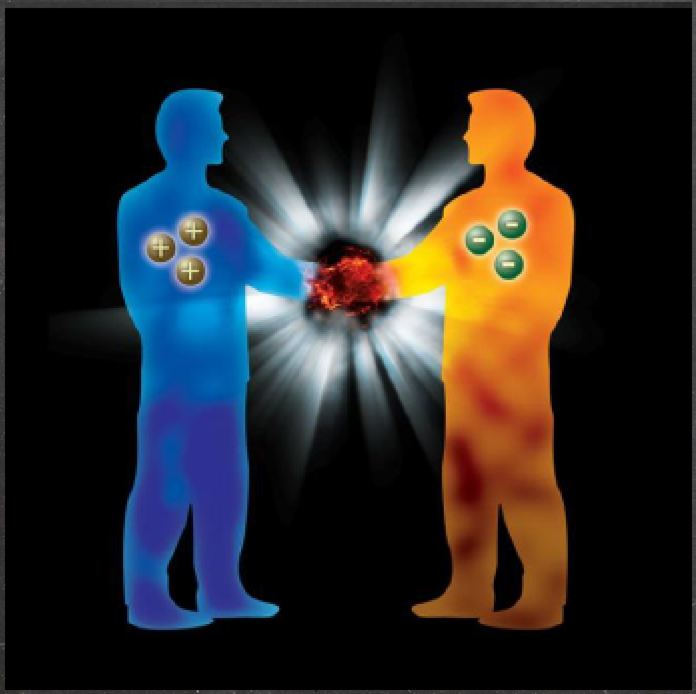
- **the observed abundance of matter over anti-matter:** note, moreover, that inflation would destroy any asymmetry imposed as an initial condition.



The amount of CP violation in the SM which could lead to baryon-antibaryon asymmetry is too small (would lprovide BAU ~10 orders of magnitude below the observed one)

$$\frac{n_B}{n_\gamma} = (6.1^{+0.3}_{-0.2}) \times 10^{-10}$$

Empirical problems of the SM stated above have been established beyond reasonable doubt.

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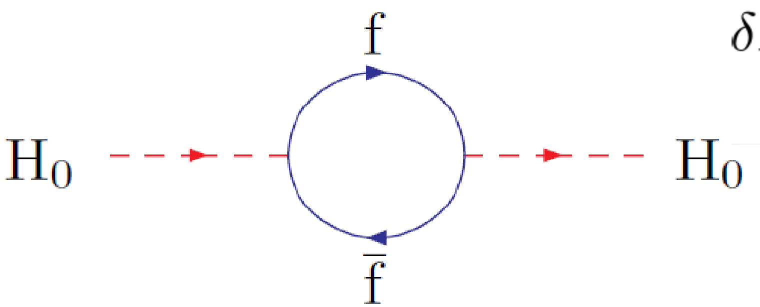

$$\delta M^2_{H\,f} = i\frac{|g_f|^2}{4}\int\frac{d^4k}{(2\pi)^4}\frac{\mathrm{tr}\ [(k+p+m_f)(k+m_f)]}{\left[(k+p)^2-m_f^2\right]\left[k^2-m_f^2\right]}$$

$$= \frac{|g_f|^2}{16\pi^2}\left[-2\Lambda^2+6m_f^2\ln\left(\Lambda/m_f\right)\right]$$

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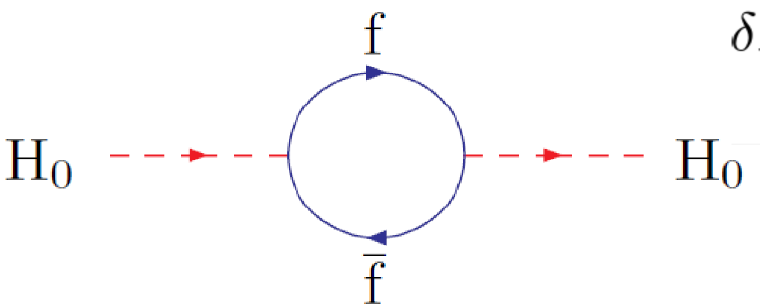

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there is a cancellation of over 30 orders of magnitude to have 125 GeV Higgs

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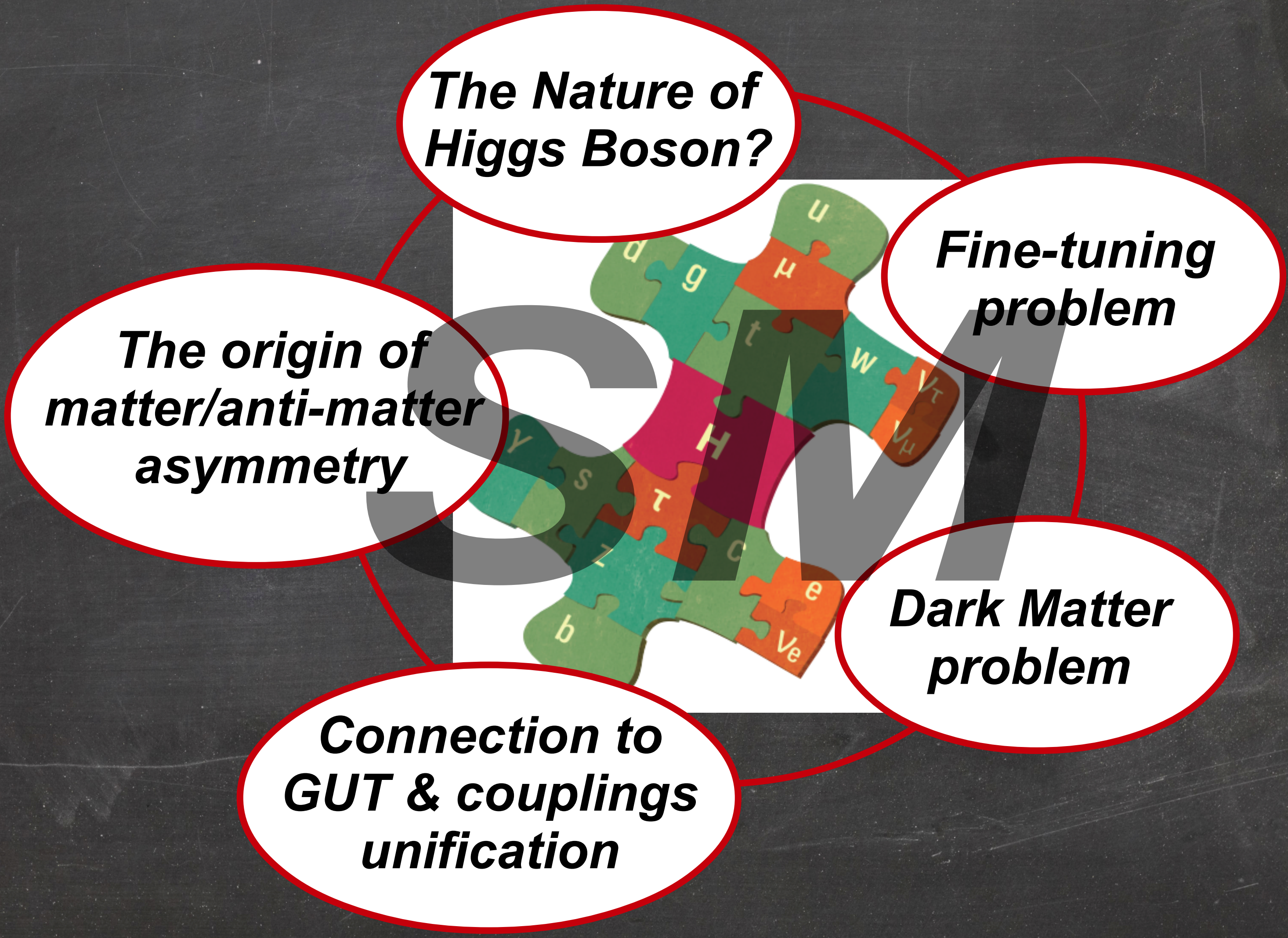
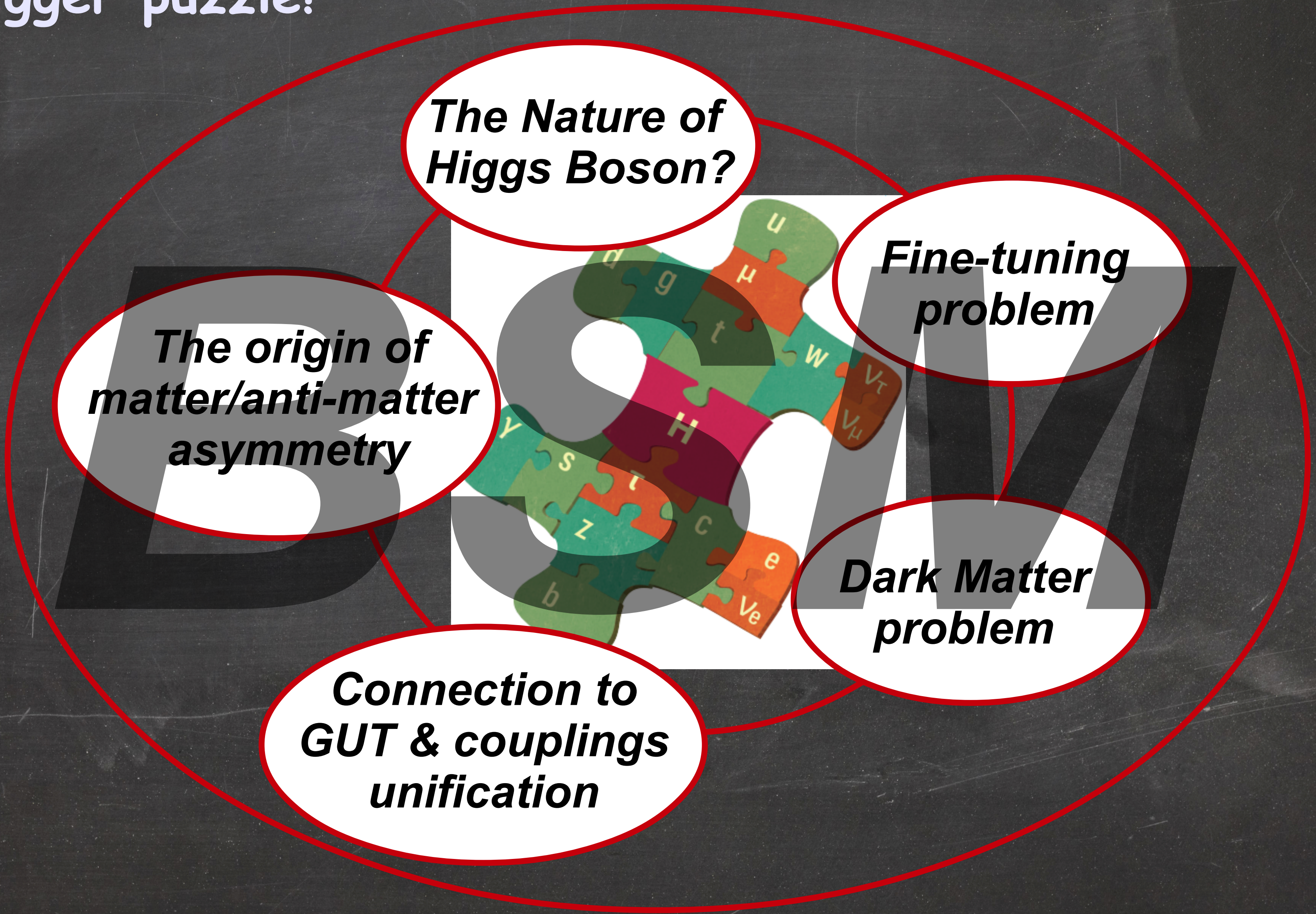
Explanation & exp confirmation of any of these merit a Nobel prize!

So, while Higgs Boson Discovery has completed the puzzle of the Standard model ...

But it has raised even more questions than the number of answers it has given!



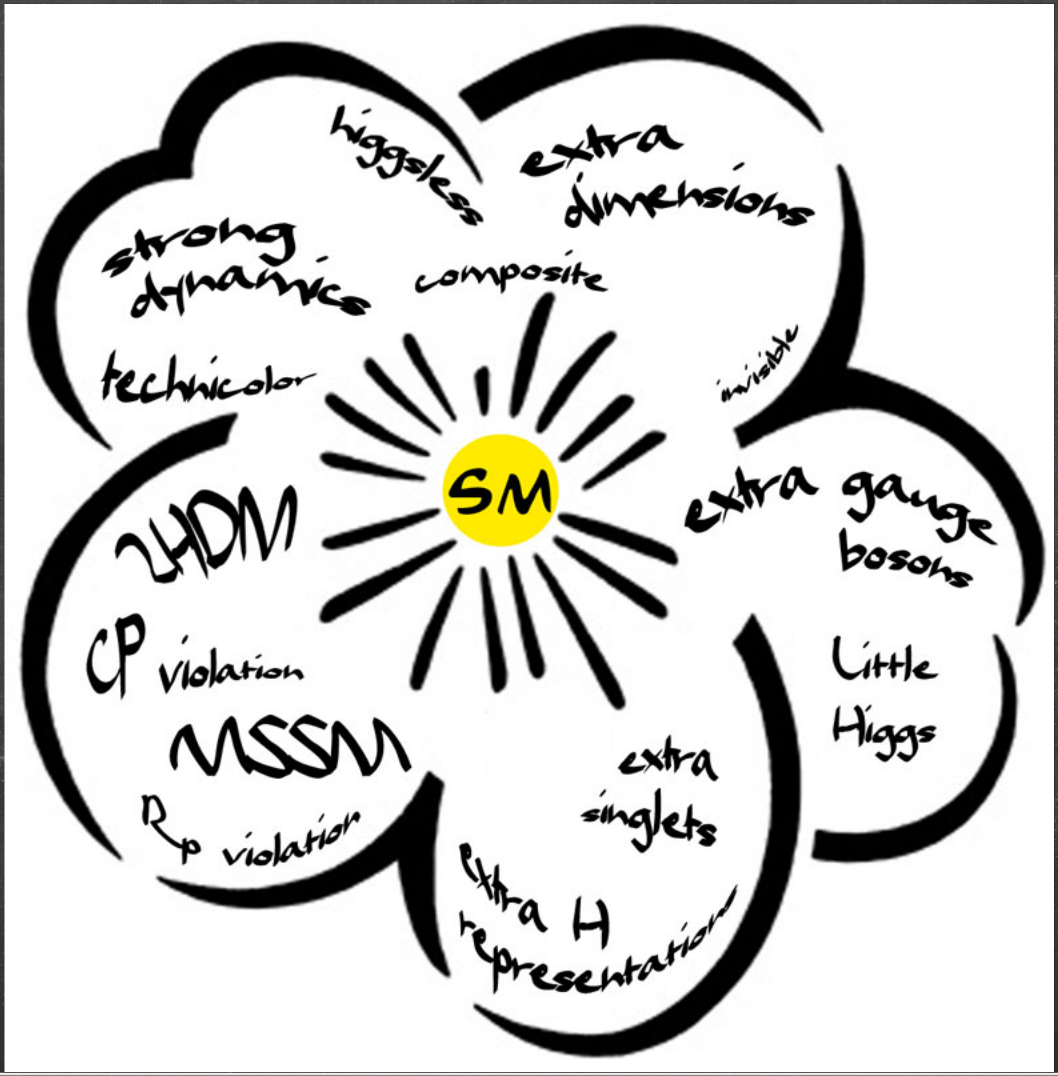
Higgs boson properties are consistent with main compelling BSM theories, so the pattern we have is just a piece of a much bigger puzzle!



Lecture II:
Effective Field Theory and Supersymmetry

Beyond the Higgs discovery

- Higgs properties are amazingly consistent with all main compelling underlying theories (except higgsless ones!) Some parameter space of BSM theories was eventually excluded.



CPNSH workshop
CERN 2006-009

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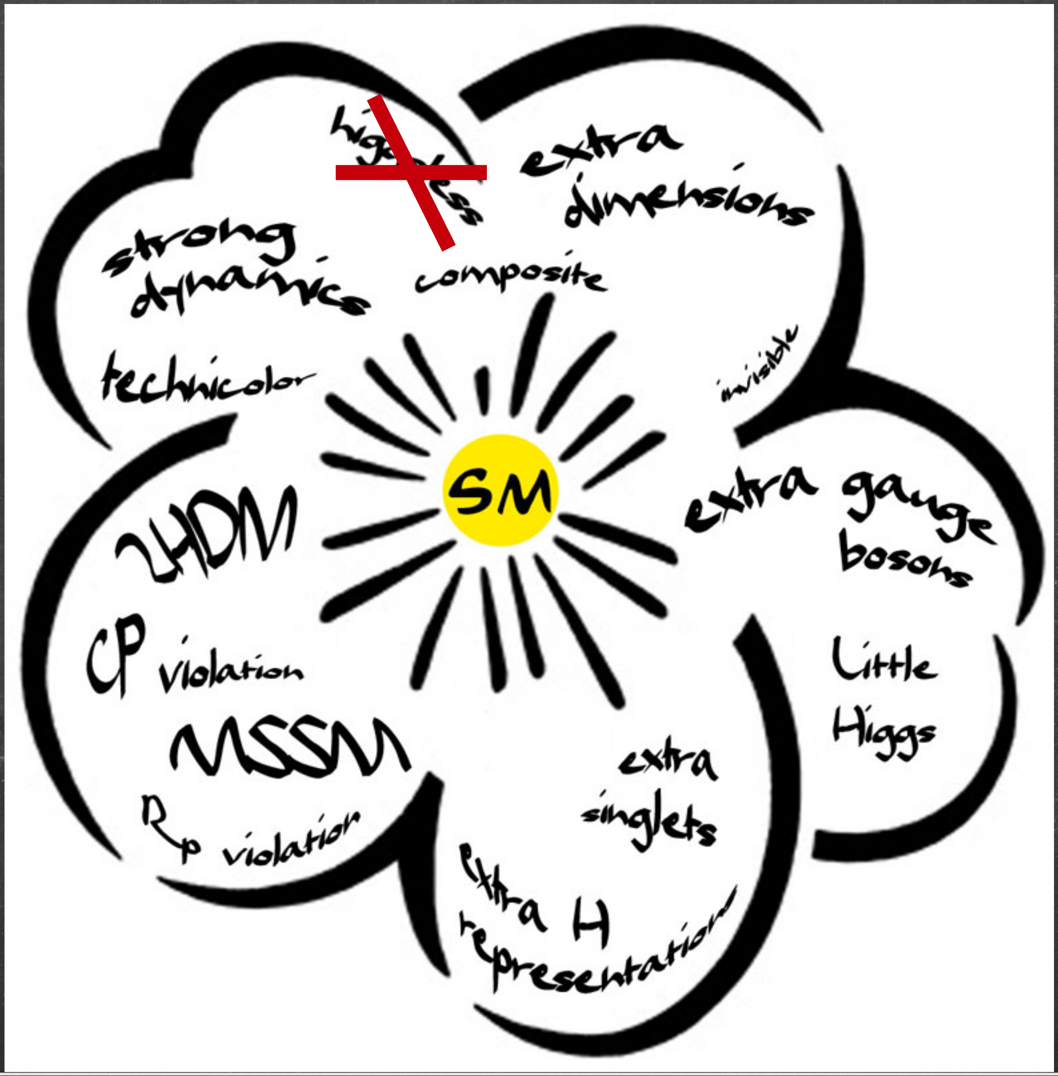

Present Status

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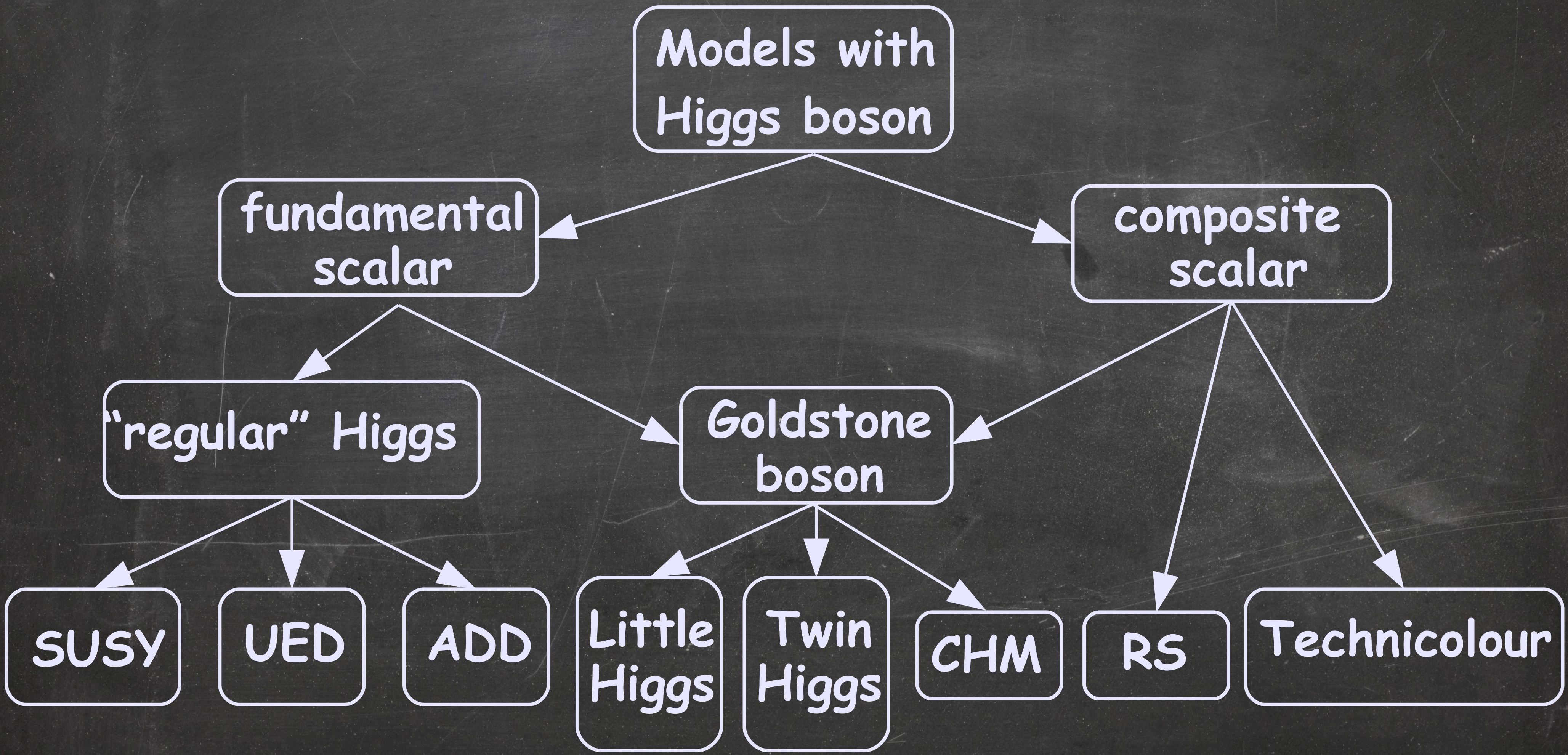

Remarks on the fine-tuning problem

- Actually the problem cannot be strictly formulated in the strict context of the Standard Model – the Higgs mass is not calculable
- However the this problem is related to yet unknown mechanism of underlying theory where Higgs mass is calculable! In this BSM theory Higgs mass should not have tremendous fine-tuing.
- There is no hint yet about such a mechanism – and this is the main source of our worries about fine-tuning

Effective Field Theory
useful reviews

- J. Polchinski “Effective field theory and the Fermi surface” hep-th/9210046
- A. V. Manohar “Effective field theories” hep-ph/9606222
- I. Z. Rothstein, “TASI lectures on effective field theories” hep-ph/0308266
- D. B. Kaplan “Five lectures on effective field theory” nucl-th/0510023
- B. Gripaios “Lectures on Effective Field Theory” arXiv:1506.05039

Effective Field Theory (EFT)

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- We start with the renormalizable SM, and consider only energies and momenta well below the weak scale ~ 100 GeV.
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$$\frac{-1}{q^2 - m_W^2} = \frac{1}{m_W^2} + \frac{q^2}{m_W^4} + \dots$$

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  - Expansion breaks down for momenta ~ m_W and theory is naturally equipped with a cut-off scale.

Main Principles of EFT

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- So, let us imagine that the SM itself is really just an effective, low-energy description of some more complete BSM theory. Thus, the fields and the (gauge) symmetries of the theory are exactly the same as in the SM, but we no longer insist on renormalizability.

SM as an Effective Field Theory

- For operators up to dimension 4, we simply recover the SM. But at dimensions higher than 4, we obtain new operators, with new physical effects.
- As a striking example of these, we expect that the accidental baryon and lepton number symmetries of the SM will be violated at some order in the expansion, and protons will decay!
- We don't know what the BSM theory – need to write down all possible operators - infinitely many! Predictivity is lost?! (infinitely many measurements to fix all the coeff).
- No! Once we truncate the theory at a given order in the operator/momentum expansion – the number of coefficients is finite - can make predictions

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- **If EFT make sense, why did we ever insist on renormalizability of SM?** Actually, it can now be thought of as a special case of a non-renormalizable theory, in which Λ to be very large.
  - **DIM>4** operators become completely negligible (**`irrelevant'**)
  - **DIM=4** operators stay the same (**`marginal'**)
  - **DIM <4** dominate (and are called **`relevant'**) - actually has problem since m ~ Λ (from din analysis) – so theory needs dynamical mechanism or tuning

SM extension to EFT

D=0: the cosmological constant

- adds an arbitrary constant, to the Lagrangian; no dependence on any fields & derivatives, can be interpreted as the energy density of the vacuum

- the vacuum energy is measurable - is equivalent to including of Einstein's "cosmological constant" ρ_{cc} **~ $(10^{-3}$ev$)^4$** into the gravitational field equation
  - good news, on one hand - Universe is observed to accelerate
  - bad news, on the other hand - the size of this operator coefficient Λ^4:
    for Planck scale we need **$(10^{19}$ GeV$/10^{-3}$eV$)^4 = (10^{31})^4 = 10^{124}$ tuning!**
    for SUSY scale we need **$(10^{3}$ GeV$/10^{-3}$eV$)^4 = (10^{15})^4 = 10^{60}$ tuning!**
    many attempts - no satisfactory dynamical solution has been suggested
  - an alternative is to argue that we live in a multiverse in which the constant takes many different values in different corners, and we happen to live in one which is conducive to life (Weinberg, 1988)

SM extension to EFT

- **D=2: the Higgs mass parameter**
  the SM is the Higgs mass parameter, the natural size is Λ, while we measure $v \sim 100$ GeV -> two options: a) the natural cut-off of the SM is not far above the weak scale (LHC will tell) ; b) the cut-off is much larger, and the weak scale is tuned (anthropics etc)

- **D=4: marginal operators** – renormalisable SM – discussed at previous lecture

SM extension to EFT

- **D=5: neutrino masses and mixings**
there is precisely one (**exercise**) operator $\frac{\lambda^{ll}}{\Lambda}(lH)^2$ where λ^{ll} is a dimensionless 3x3 matrix in flavour space
  - this operator violates the individual and total lepton numbers
  - it gives masses to neutrinos after EWSB, just as we observe
- given the observed $\Delta m^2 = 10^{-3}$ **eV^2** for neutrinos, $\Lambda \sim 10^{14}$ **GeV**
  - one could argue that while neutrino masses are evidence for physics BSM
  - Alternatively one can add three ν^c, singlets under SU(3)x SU(2) xU(1) for each SM family replacing D=5 operator renormalizable Yukawa term

    $\lambda^\nu \; lH^c \; \nu^c$ (Dirac mass term after EWSB)

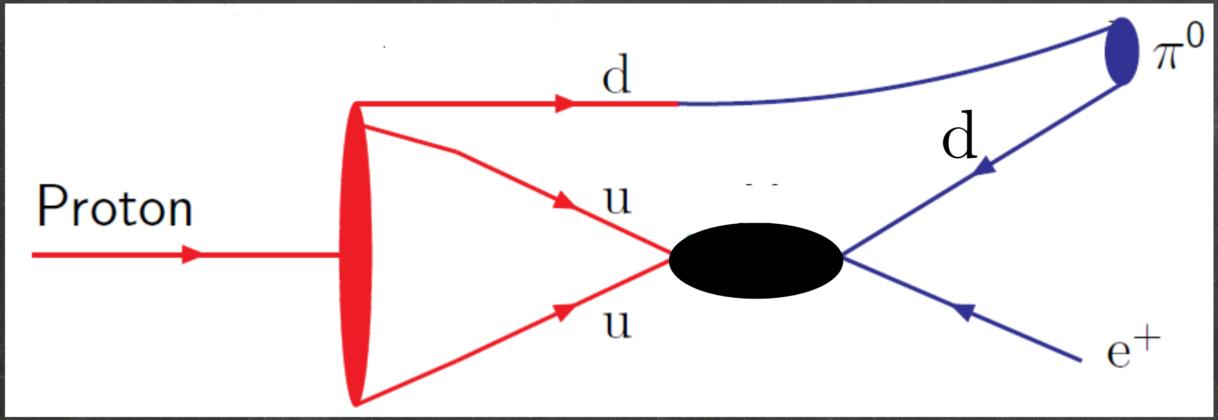
    and/or

    $m^\nu \nu^c \nu^c$ (Majorana mass term)

    (**exercise**: how λ^{ll} is related to λ^ν and m^ν ?)
  - neutrino mass eigenstates in this renormalizable model need not be heavy, but very weakly coupled to SM states!
One can **redefine SM** to include these terms

SM extension to EFT

- **D=6: mbaryon-number violation**
  many operators appear, including baryon and lepton number violating ones
  $$\frac{qqq\ell}{\Lambda^2} \quad \text{and} \quad \frac{u^c u^c d^c e^c}{\Lambda^2}$$
  (**exercise:** check these are invariants)
- cause the proton decay $\mathrm{p} \to e^+\pi^0$.
  Λ > 10^{15} GeV comes the exp bounds on the proton lifetime, **τ^p > 10^{33} yr**:
- new physics either respects baryon or lepton number, or is a long way away



$$\Gamma(p \to \pi^0 e^+) \propto \frac{M_p^5}{\Lambda^4}$$

- Operators that give corrections to FCNC are highly suppressed in the SM
  e.g. $(\mathrm{s}^c d)(d^c s)/\Lambda^2$ contributes to Kaon mixing, **Λ > 10^8 GeV**

Grand Unification

- The basic idea is that the Standard model gauge group SU(3)xSU(2)xU(1) is a subgroup of a larger gauge symmetry group
- The simplest is SU(5)
- Another example is SO(10): SU(5)xU(1) $\subset$ SO(10) comes with RH neutrinos!

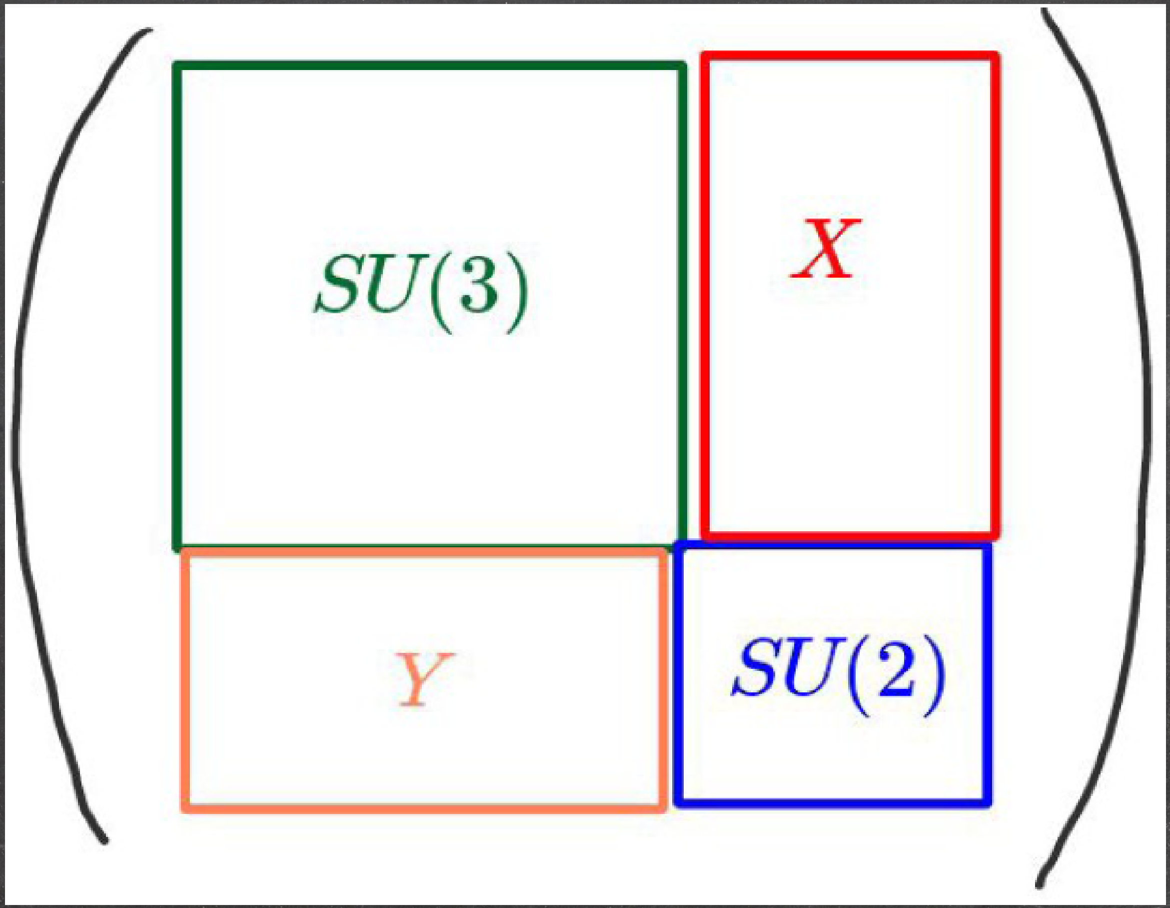
SU(5)

- SU(3) has 3^2-1=8 generators, they correspond to
  - the 8 gluons
  - The quarks are in the fundamental representation of SU(3)

- SU(5) has 5^2-1=24 generators, which means that
  - we have 24 gauge bosons
    - 8 gluons and 4 electroweak bosons
    - so we get 12 new gauge bosons

SU(5)

- Generators of SU(5)



SU(5)

- The right handed down type quarks and left-handed leptons form a 5 representation of SU(5)
- The rest forms a 10 representation

$$\begin{pmatrix} d \\ d \\ d \\ e^c \\ \bar{\nu}_e \end{pmatrix} \qquad \begin{pmatrix} 0 & u^c & -u^c & -u & -d \\ u^c & 0 & u^c & -u & -d \\ u^c & -u^c & 0 & -u & -d \\ u & u & u & 0 & -e^c \\ d & d & d & e^c & 0 \end{pmatrix}$$

Simplest rep:

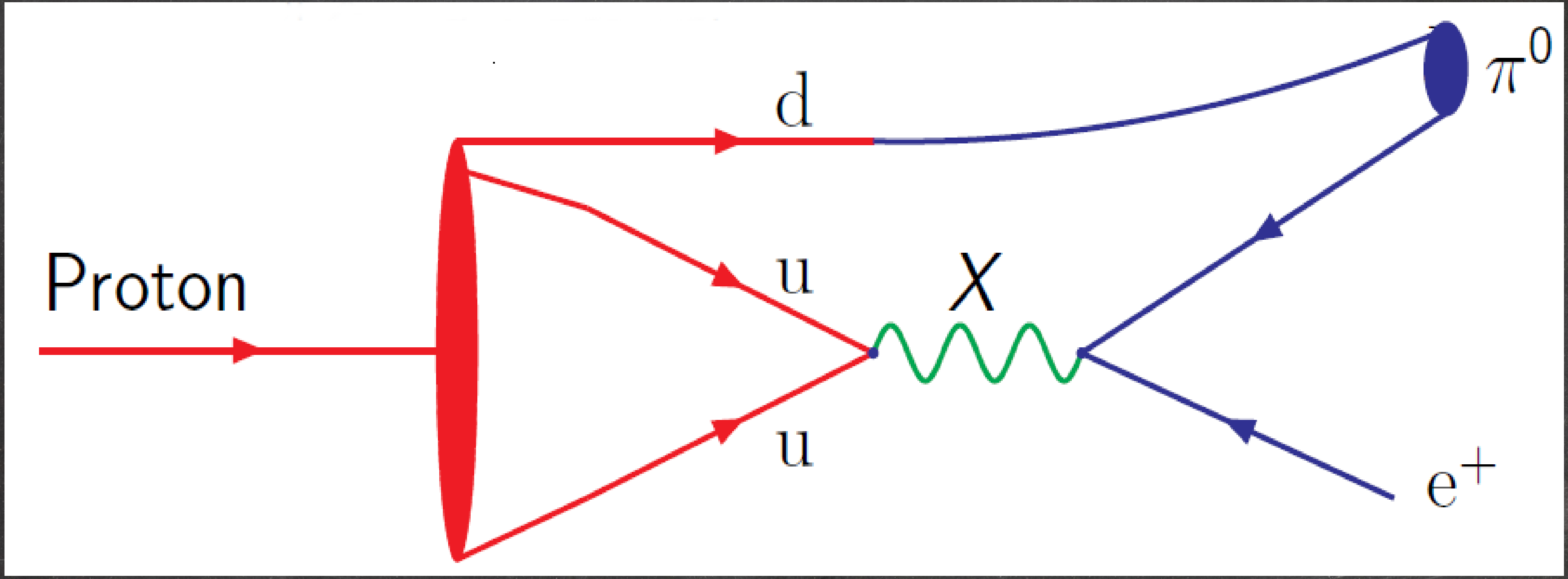
$$\overline{5} = (\overline{3}, 1)_{+2/3} \oplus (1, 2)_{-1} \qquad 10 = (\overline{3}, 1)_{-4/3} \oplus (3, 2)_{+1/3} \oplus (1, 1)_{+2}$$

Grand Unified Theories

- In this model there are two stages of symmetry breaking
- At the GUT scale the SU(5) symmetry is broken and the X and Y bosons get masses
- At the electroweak scale the SU(2)xU(1) symmetry is broken as before
- Problems with this theory
  - The couplings don't meet at the GUT scale
  - Proton decay

Proton Decay

- Since in Grand Unified theories we have the X/Y bosons which couple quarks and leptons, they predict the decay of the proton



- The expected rate would be $$\Gamma(p \to \pi^0 e^+) \propto \frac{M_p^5}{M_X^4}$$

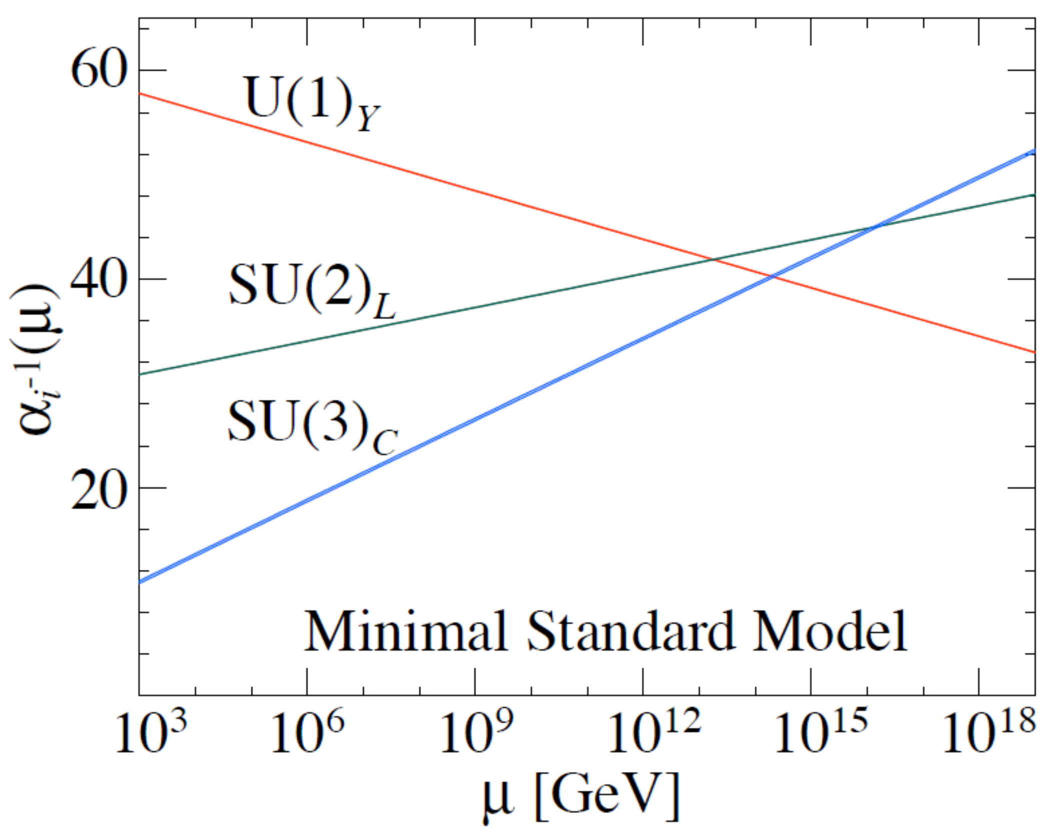
The hint about GUT scale and couplings unification

We ignore threshold corrections and assume desert! Then 1-loop RGEs for $SU(N)$:

$$\frac{1}{g_i^2(\mu)} = \frac{1}{g_i^2(Q)} + b_i \log\left(Q^2/\mu^2\right) \quad b_N = \frac{1}{(4\pi)^2}\left[-\frac{11}{3}N + \frac{4}{3}n_g\right]$$

$$b_1 = \frac{1}{4\pi^2} \quad b_2 = -\frac{5}{24\pi^2} \quad b_3 = -\frac{7}{16\pi^2}$$

The hint about GUT scale and couplings unification



- There is a clear hing about couplings unification
- Couplings do not unify exactly
- GUT scale can be roughly estimated to be in the 10^{14} -10^{17} GeV range

Hints on Supersymmetry

From Hitoshi Murayama, 2007

Once upon a time, there was a hierarchy problem...

- At the end of 19th century: a "crisis" about electron
  - Like charges repel: hard to keep electric charge in a small pack
  - Electron is point-like
  - At least smaller than 10^{-17}cm
- Need a lot of energy to keep it small!

$$\Delta m_e c^2 \sim \frac{e^2}{r_e} \sim \mathrm{GeV}\frac{10^{-17}\mathrm{cm}}{r_e}$$

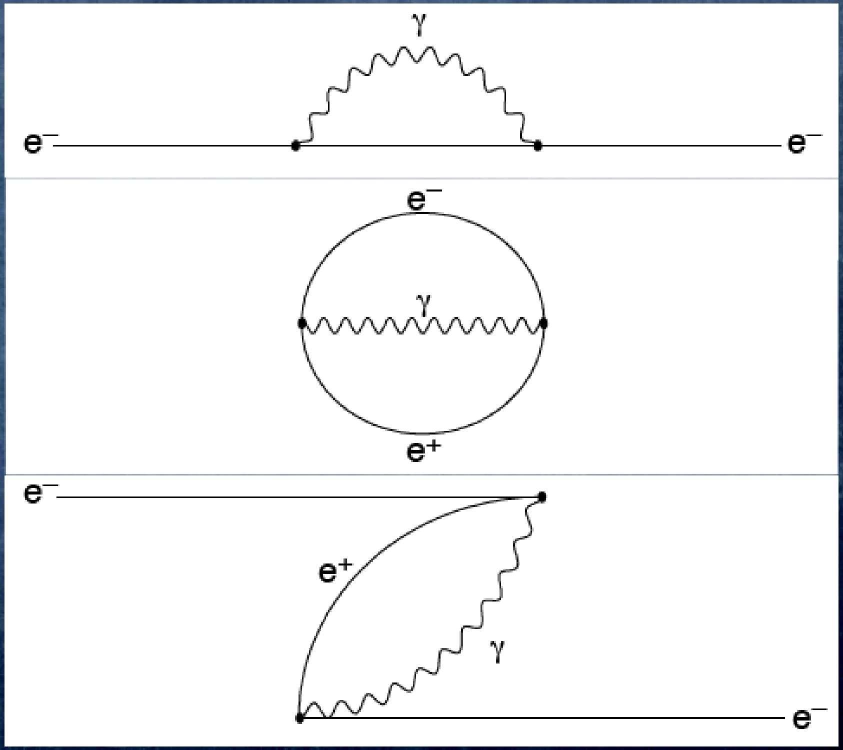
- Correction $\Delta m_e c^2 > m_e c^2$ for $r_e < 10^{-13}$cm
- Breakdown of theory of electromagnetism
  $\Rightarrow$ Can't discuss physics below 10^{-13}cm

From Hitoshi Murayama, 2007

Anti-Matter Comes to Rescue by Doubling of #Particles

- Electron creates a force to repel itself
- Vacuum bubble of matter anti-matter creation/annihilation
- Electron annihilates the positron in the bubble

$\Rightarrow$ only 10% of mass even for Planck-size $r_e \sim 10^{-33}$cm



$$\Delta m_e \sim m_e \frac{\alpha}{4\pi} \log(m_e r_e)$$

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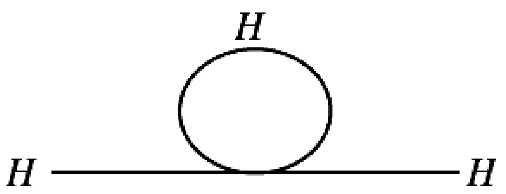
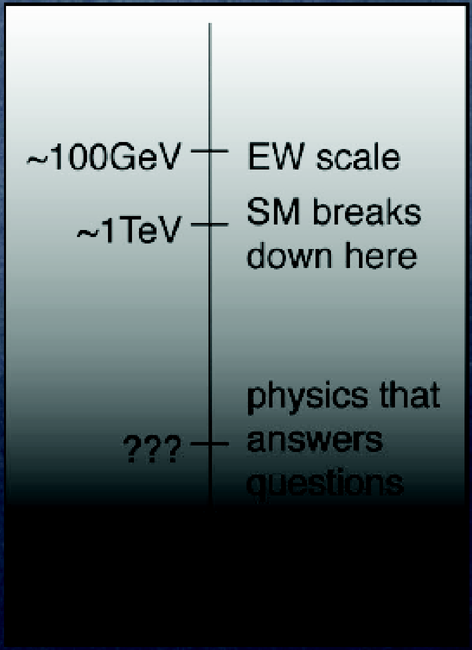
Higgs repels itself, too



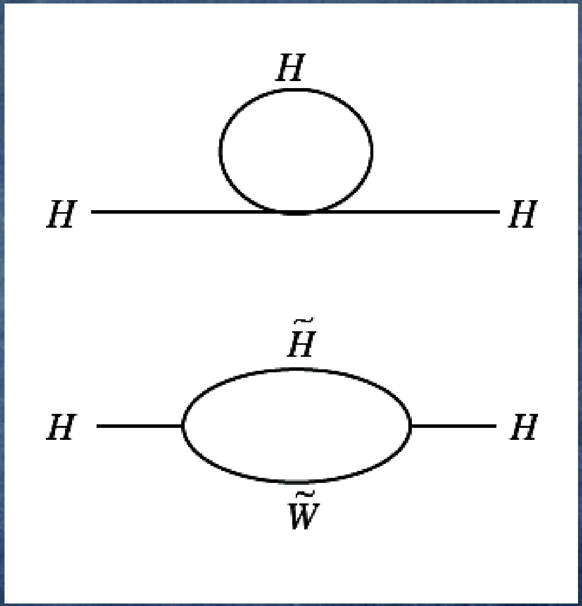
$$\Delta m_H^2 c^4 \sim \left(\frac{\hbar c}{r_H}\right)^2$$

- Just like electron repelling itself because of its charge, Higgs boson also repels itself
- Requires a lot of energy to contain itself in its point-like size!
- Breakdown of theory of weak force
- Can't get started!



History repeats itself?

- Double #particles again ⇒ superpartners
- "Vacuum bubbles" of superpartners cancel the energy required to contain Higgs boson in itself
- Standard Model made consistent with whatever physics at shorter distances



$$\Delta m_H^2 \sim \frac{\alpha}{4\pi} m_{SUSY}^2 \log(m_H r_H)$$

Supersymmetry

Supersymmetry (SUSY)

boson-fermion symmetry aimed to unify all forces in nature

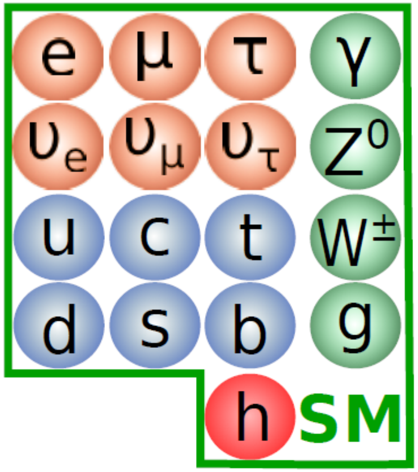
$$Q|\text{BOSON}\rangle = |\text{FERMION}\rangle, \quad Q|\text{FERMION}\rangle = |\text{BOSON}\rangle$$

extends Poincare algebra to Super-Poincare Algebra:

the most general set of space-time symmetries! (1971-74)

$$\{f,f\}=0, \quad [B,B]=0, \quad \{Q_\alpha,\bar{Q}_\beta\}=2\gamma^\mu_{\alpha\beta}P_\mu$$

Golfand and Likhtman'71; Ramond'71; Neveu,Schwarz'71; Volkov and Akulov'73; Wess and Zumino'74



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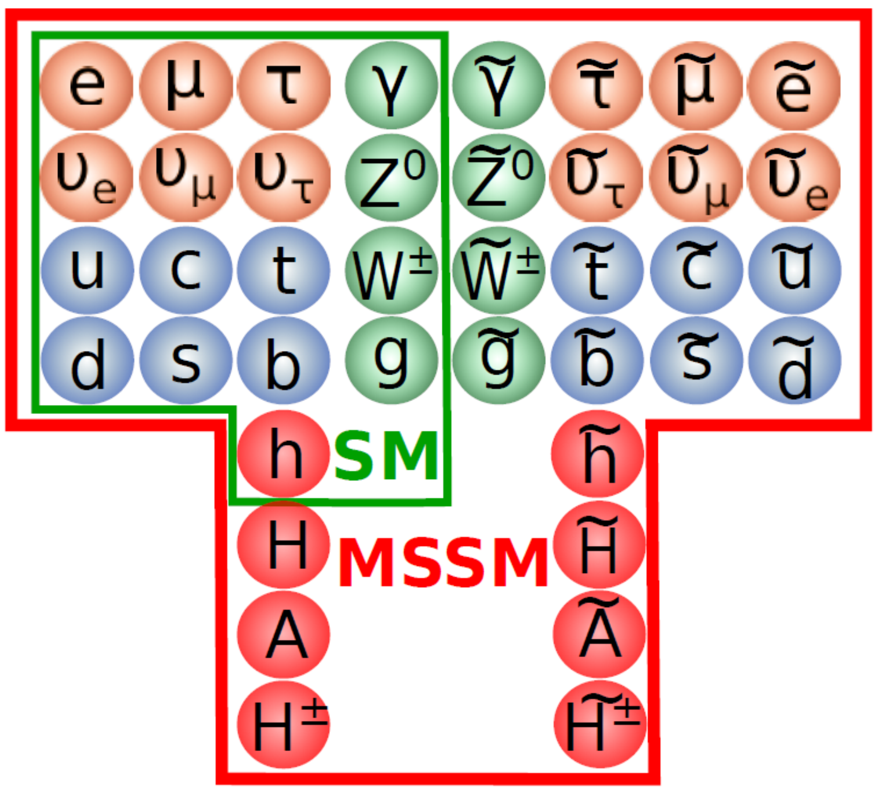

SUSY principles

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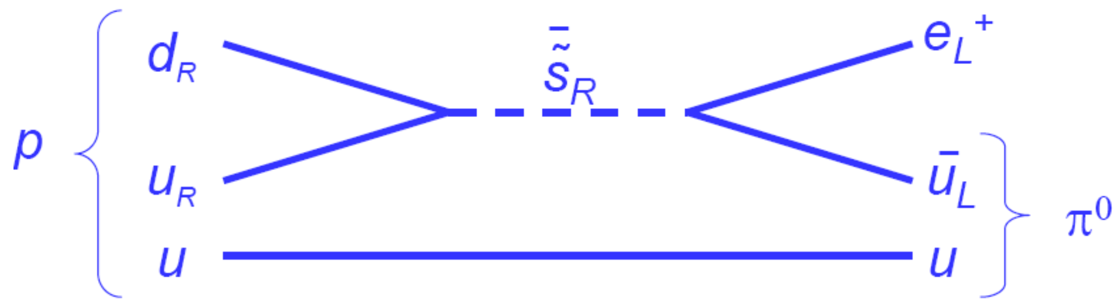
Particle	SUSY partner
e,ν,u,d *spin 1/2*	$\tilde{e},\tilde{\nu},\tilde{u},\tilde{d}$ *spin 0*
γ,W,Z h,H,A,H$^\pm$ *spin 1 and 0*	$\tilde{\chi}_1^\pm,\tilde{\chi}_2^\pm$ $\tilde{\chi}_1^0\cdots\tilde{\chi}_4^0$ *spin 1/2*



could give rise the proton decay!

SUSY principles

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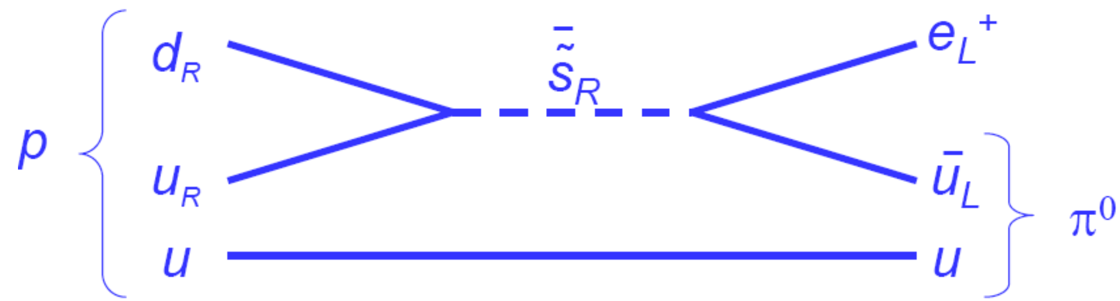
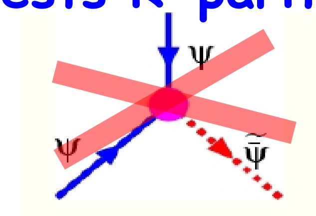


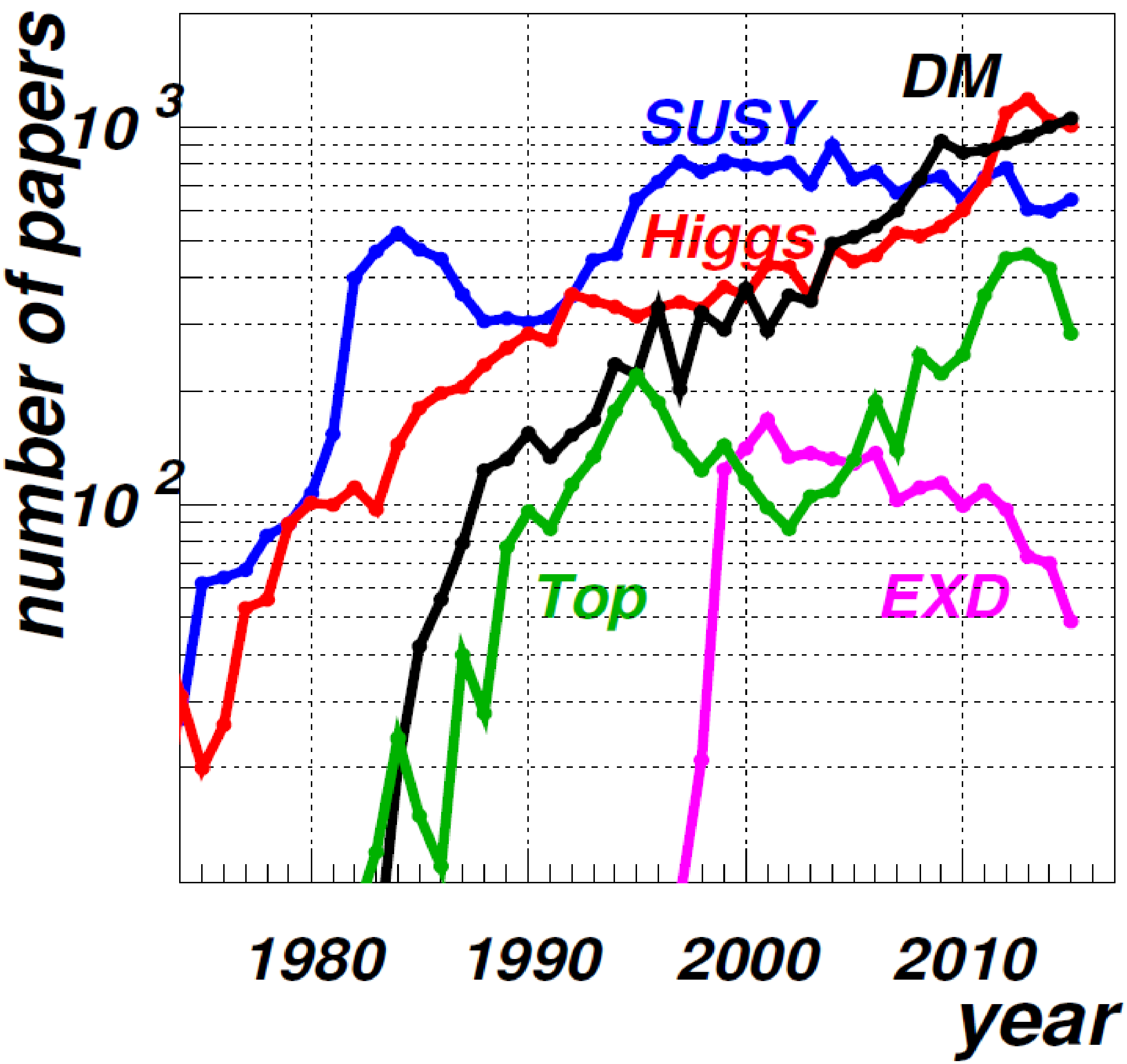
the absence of proton decay suggests R-parity

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



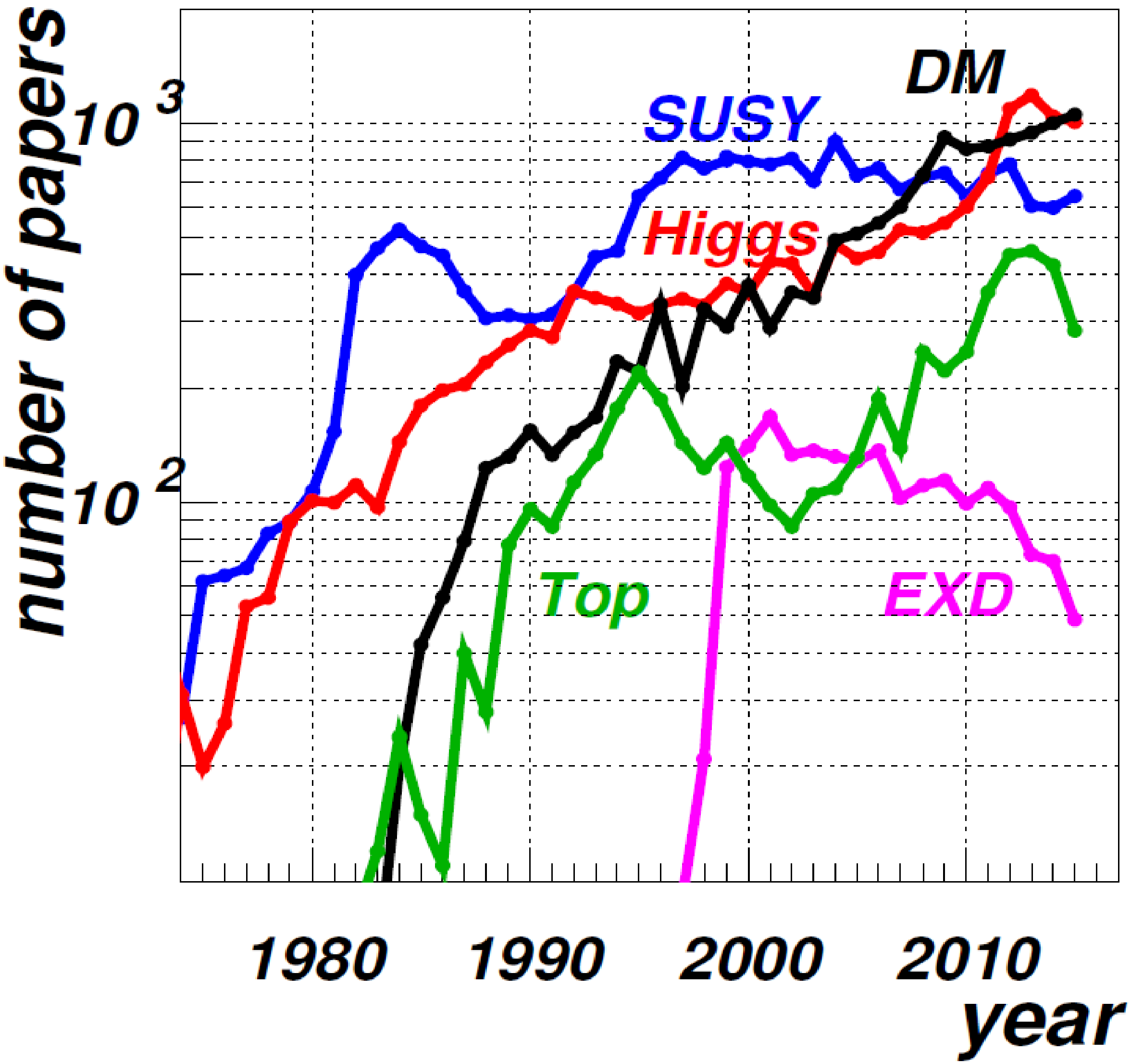
R-parity guarantees Lightest SUSY particle (LSP) is stable – DM candidate!

We are still inspired by this beauty ...



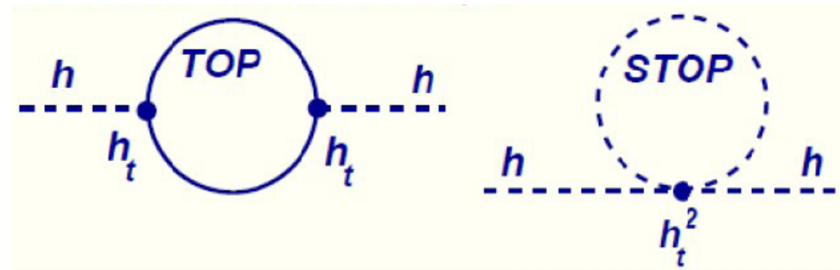
We are still inspired by this beauty ...

after more than 30 year unsuccessful searches ...

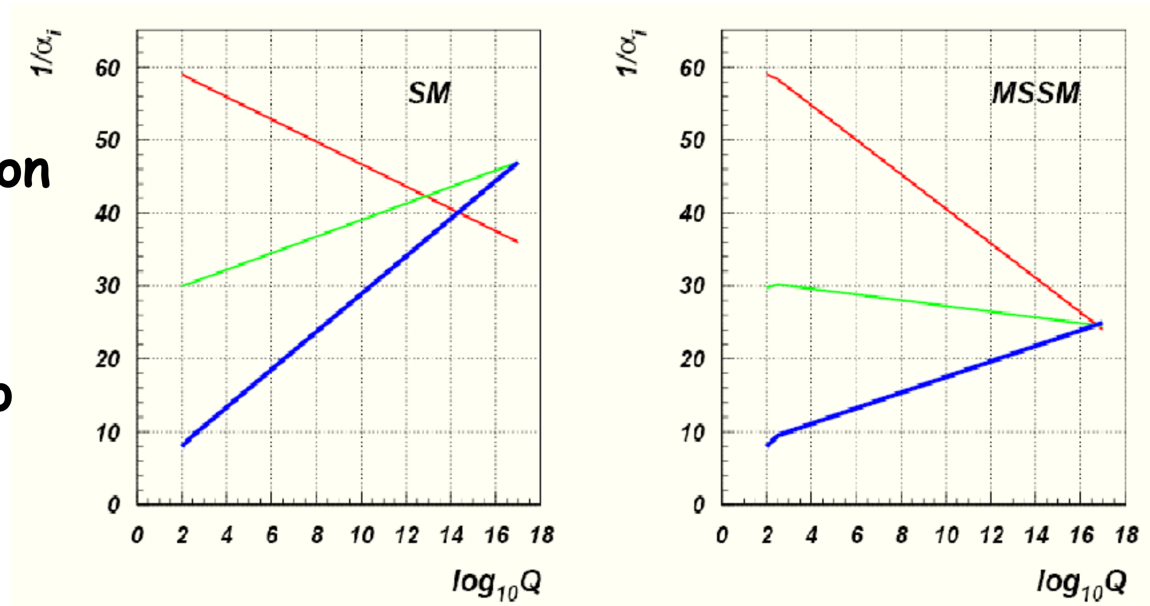


Beauty of SUSY

- Provides good DM candidate – LSP
- CP violation can be incorporated - baryogenesis via leptogenesis
- Radiative EWSB
- Solves fine-tuning problem
- Provides gauge coupling unification
- local supersymmetry requires spin 2 boson – graviton!
- allows to introduce fermions into string theories



$$\Delta M_H^2 \sim M_{SUSY}^2 \log(\Lambda/M_{SUSY})$$



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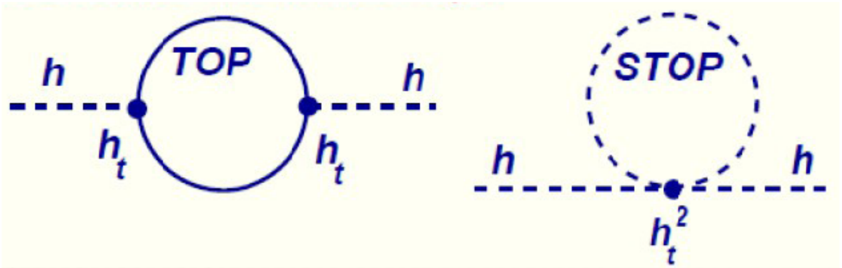

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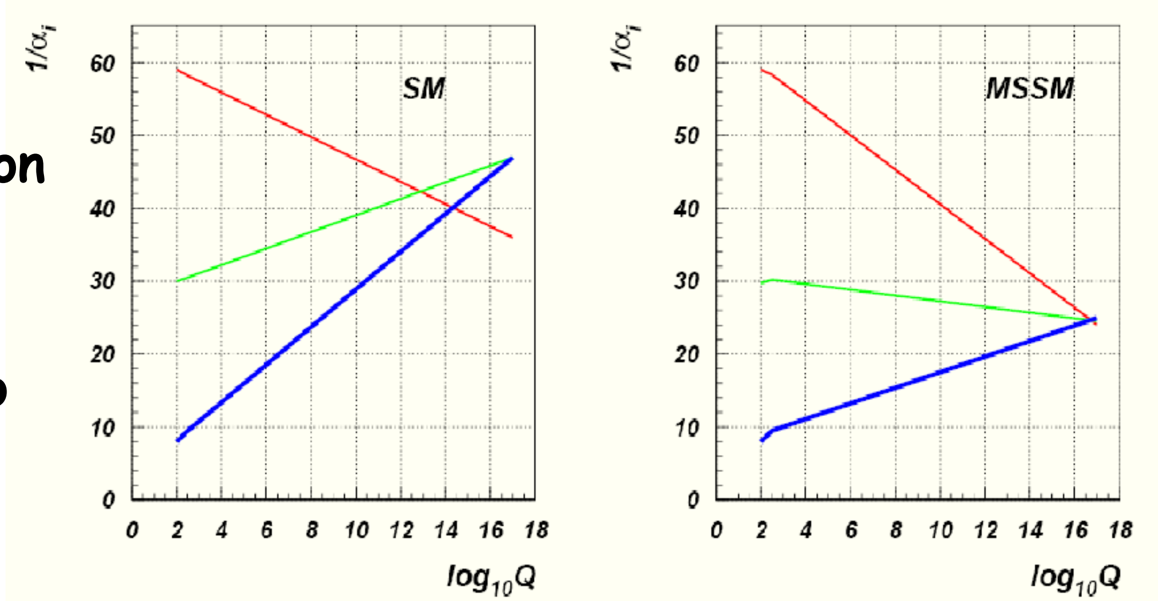
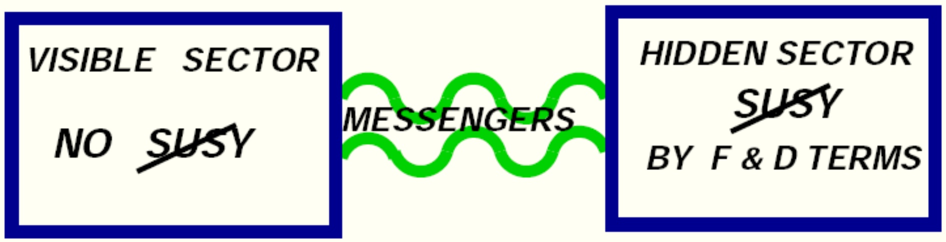


But the real beauty of SUSY is that

It was not deliberately designed to solve the SM problems!

SUSY breaking and mSUGRA scenario

- *SUSY is not observed $\Rightarrow$ must be broken*



Gravity mediation
Gauge mediation
Anomaly mediation
Gaugino mediation

$$\mathcal{L}^{MSSM}_{soft} = \underbrace{\sum_{i,j} B_{ij}\mu_{ij} S_i S_j}_{\text{bilinear terms}} + \underbrace{\sum_{ij} m^2_{ij} S_i S_j^{\dagger}}_{\text{scalar mass terms}} + \underbrace{\sum_{i,j,k} A_{ijk} f_{ijk} S_i S_j S_k}_{\text{trilinear scalar interactions}} + \underbrace{\sum_{A,\alpha} M_{A\alpha} \bar{\lambda}_{A\alpha} \lambda_{A\alpha}}_{\text{gaugino mass terms}}$$

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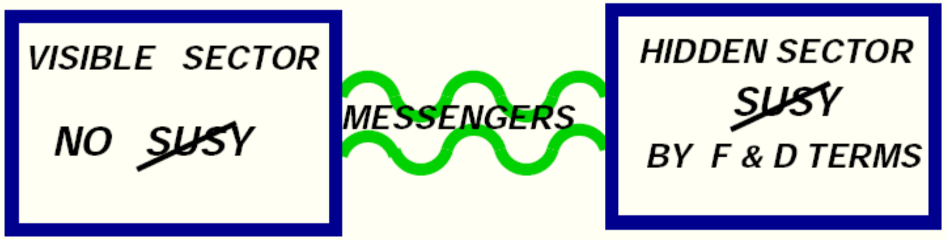

Gravity mediation
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- SUGRA: *the hidden sector communicates with visible one via gravity*
  – all soft terms are non-zero in general($\sim m_{3/2}$ -gravitino mass)

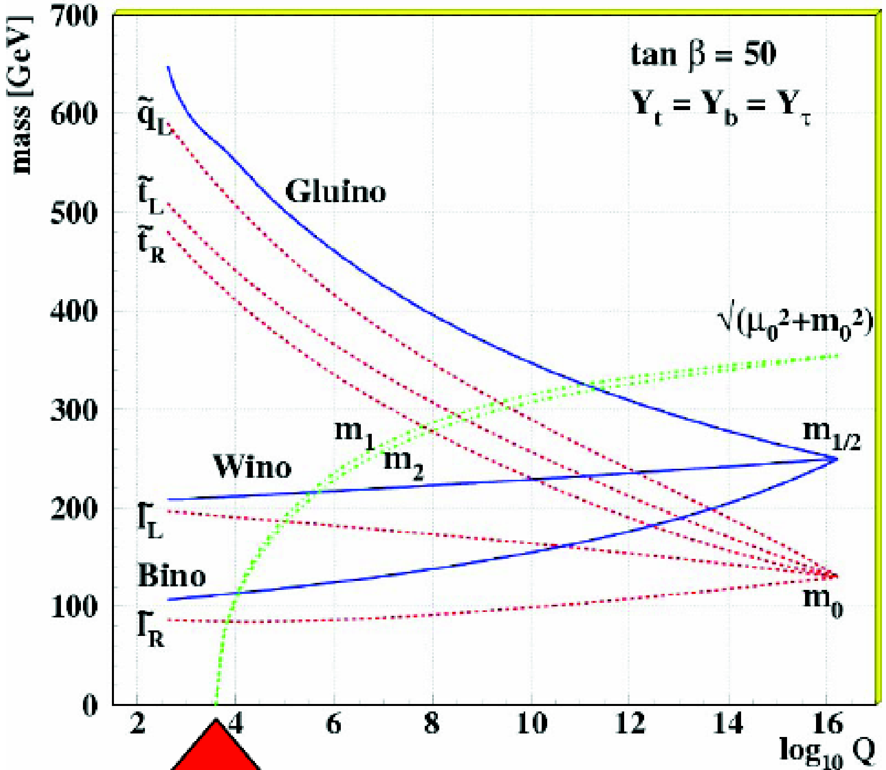
SUGRA: $M_a = f_a\frac{\langle F\rangle}{M_P}$ $\quad m^2_{ij} = k_{ij}\frac{|\langle F\rangle|^2}{M_P^2}$ $\quad A_{ijk} = y_{ijk}\frac{\langle F\rangle}{M_P}$

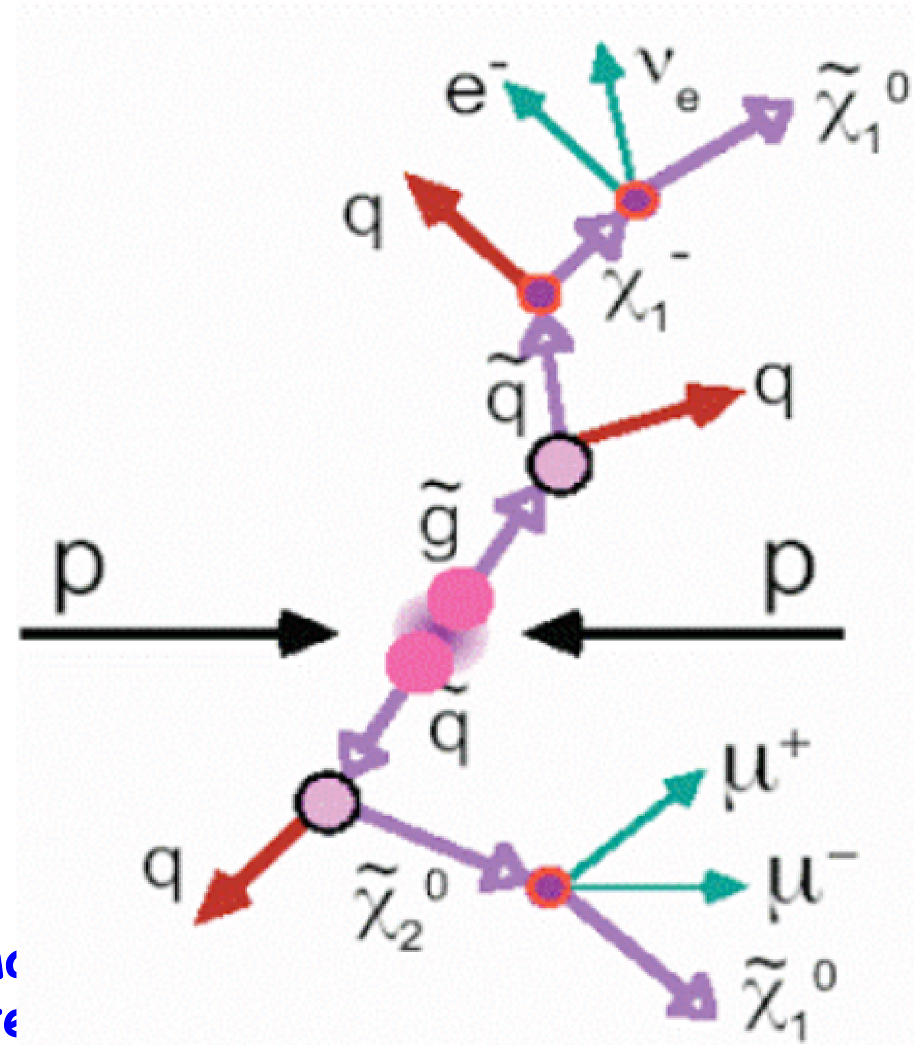
mSUGRA: $\Longrightarrow m_{1/2}$ $\quad \Longrightarrow m_0^2$ $\quad \Longrightarrow A_0$

flat Kähler metric takes care of constraining of Flavor violating processes

- $sign(\mu)$, μ^2 *value is fixed by the minim condition for Higgs potential*
- B - *parameter – usually expressed via* $\tan\beta$
- $\Rightarrow$ *mSUGRA parameters:* $m_0, m_{1/2}, A_0, \tan\beta, sign(\mu)$

Limits from LHC for mSUGRA scenario





independent parameters:

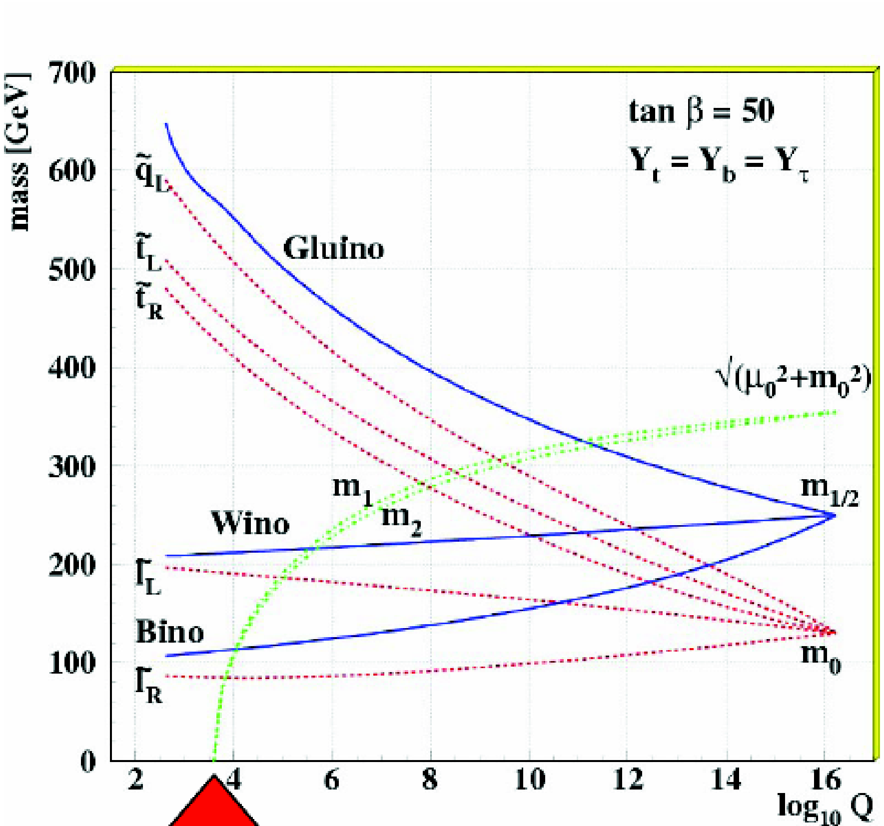
m0 - universal scalar mass

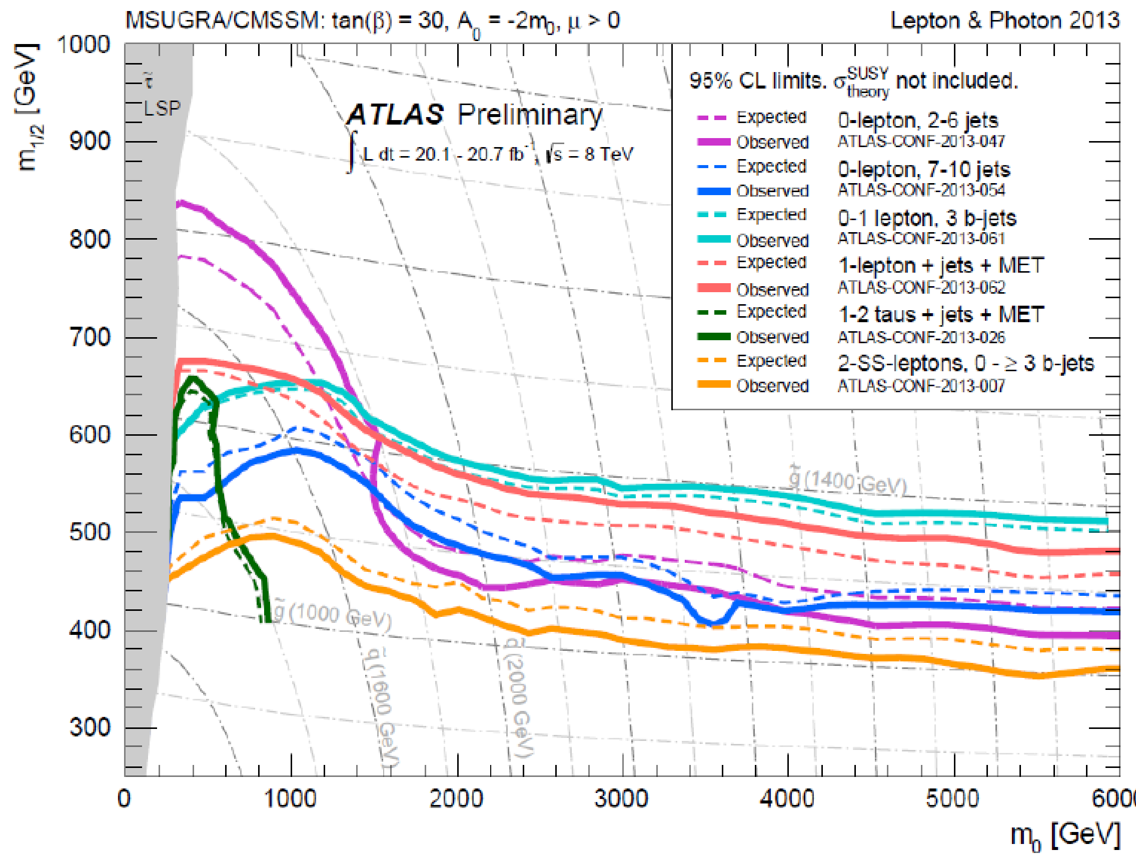
m1/2 - universal gaugino m

A - trilinear soft paramete

tan(beta) - v1/v2

Limits from LHC for mSUGRA scenario





independent parameter

m0 – universal scalar mass

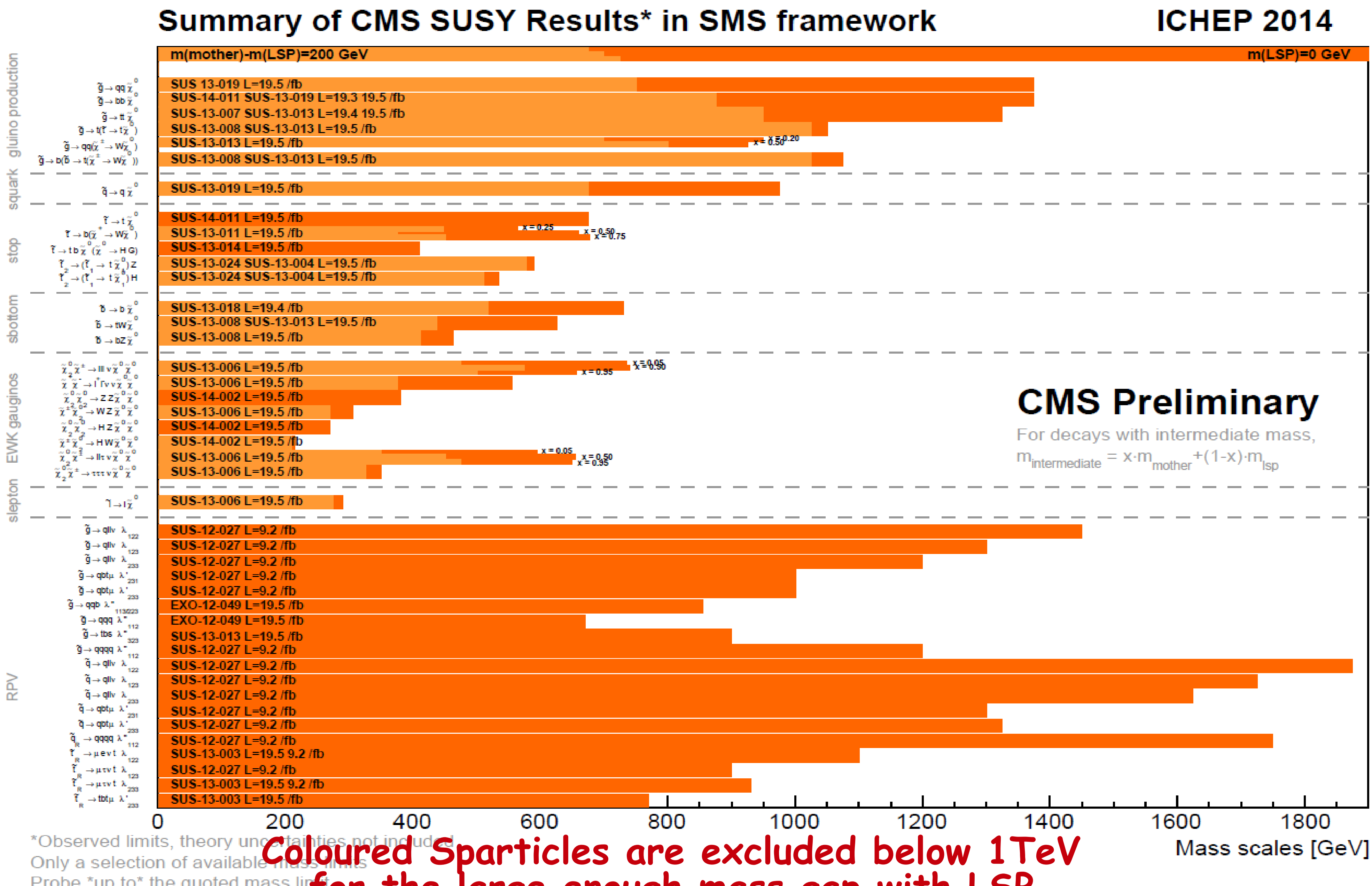
m1/2 – universal gaugino masses

$\tilde{A}$ -trilinear soft parameter

tan(beta) - v1/v2

jets + missing transverse momentum signature

SUSY, where are you?!



Coloured Sparticles are excluded below 1TeV for the large enough mass gap with LSP

The MSSM Higgs Sector

Comparison with SM case:

$$\mathcal{L}_{\mathrm{SM}} = \underbrace{m_d \bar{Q}_L \Phi d_R}_{\text{d-quark mass}} + \underbrace{m_u \bar{Q}_L \Phi_c u_R}_{\text{u-quark mass}}$$

$$Q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L, \quad \Phi_c = i\sigma_2 \Phi^*, \quad \Phi \to \begin{pmatrix} 0 \\ v \end{pmatrix}, \quad \Phi_c \to \begin{pmatrix} v \\ 0 \end{pmatrix}$$

In SUSY: term $\bar{Q}_L \Phi^*$ not allowed

Superpotential is holomorphic function of chiral superfields, i.e. depends only on φ_i, not on φ_i^*

No soft SUSY-breaking terms allowed for chiral fermions

$\Rightarrow$ $H_d (\equiv H_1)$ and $H_u (\equiv H_2)$ needed to give masses to down- and up-type fermions

Furthermore: two doublets also needed for cancellation of anomalies, quadratic divergences

Enlarged Higgs sector: Two Higgs doublets

$$H_1 = \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix}$$

$$H_2 = \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix}$$

$$V = m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2(\epsilon_{ab} H_1^a H_2^b + \text{h.c.})$$

$$+ \underbrace{\frac{g'^2 + g^2}{8}}(H_1\bar{H}_1 - H_2\bar{H}_2)^2 + \underbrace{\frac{g^2}{2}}|H_1\bar{H}_2|^2$$

gauge couplings, in contrast to SM

physical states: $h^0, H^0, A^0, H^\pm$

Goldstone bosons: $G^0, G^\pm$

Input parameters: (to be determined experimentally)

$$\tan\beta = \frac{v_2}{v_1}, \qquad M_A^2 = -m_{12}^2(\tan\beta + \cot\beta)$$

Rotation to physical basis:

$$\begin{pmatrix} H^0 \\ h^0 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \phi_1^0 \\ \phi_2^0 \end{pmatrix} \qquad \tan(2\alpha) = \tan(2\beta)\frac{M_A^2 + M_Z^2}{M_A^2 - M_Z^2}$$

$$\begin{pmatrix} G^0 \\ A^0 \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \chi_1^0 \\ \chi_2^0 \end{pmatrix}, \qquad \begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \phi_1^\pm \\ \phi_2^\pm \end{pmatrix}$$

Three Goldstone bosons (as in SM): G^0, $G^\pm$

$\longrightarrow$ longitudinal components of $W^\pm$, Z

$\Rightarrow$ Five physical states: $h^0, H^0, A^0, H^\pm$

h, H: neutral, $\mathcal{CP}$-even, A^0: neutral, $\mathcal{CP}$-odd, $H^\pm$: charged

Gauge-boson masses:

$$M_W^2 = \frac{1}{2}g'^2(v_1^2 + v_2^2), \quad M_Z^2 = \frac{1}{2}(g^2 + g'^2)(v_1^2 + v_2^2), \quad M_\gamma = 0$$

Parameters in MSSM Higgs potential V (besides g, g'):

$$v_1,\ v_2,\ m_1,\ m_2,\ m_{12}$$

relation for M_W^2, $M_Z^2 \Rightarrow$ 1 condition

minimization of V w.r.t. neutral Higgs fields H_1^1, $H_2^2 \Rightarrow$ 2 conditions

$\Rightarrow$ only two free parameters remain in V, conventionally chosen as

$$\tan\beta = \frac{v_2}{v_1}, \qquad M_A^2 = -m_{12}^2(\tan\beta + \cot\beta)$$

$\Rightarrow$ m_h, m_H, mixing angle α, $m_{\mathrm{H}^\pm}$: no free parameters, can be predicted

In lowest order:

$$m_{\mathrm{H}^\pm}^2 = M_A^2 + M_W^2$$

Predictions for m_h, m_H from diagonalization of tree-level mass matrix:

$\phi_1 - \phi_2$ basis:

$$M^{2,\text{tree}}_{\text{Higgs}} = \begin{pmatrix} m^2_{\phi_1} & m^2_{\phi_1\phi_2} \\ m^2_{\phi_1\phi_2} & m^2_{\phi_2} \end{pmatrix} =$$

$$\begin{pmatrix} M_A^2 \sin^2\beta + M_Z^2\cos^2\beta & -(M_A^2 + M_Z^2)\sin\beta\cos\beta \\ -(M_A^2 + M_Z^2)\sin\beta\cos\beta & M_A^2\cos^2\beta + M_Z^2\sin^2\beta \end{pmatrix}$$

$$\Big\Downarrow \quad \leftarrow \ \text{Diagonalization}, \alpha$$

$$\begin{pmatrix} m_H^{2,\text{tree}} & 0 \\ 0 & m_h^{2,\text{tree}} \end{pmatrix}$$

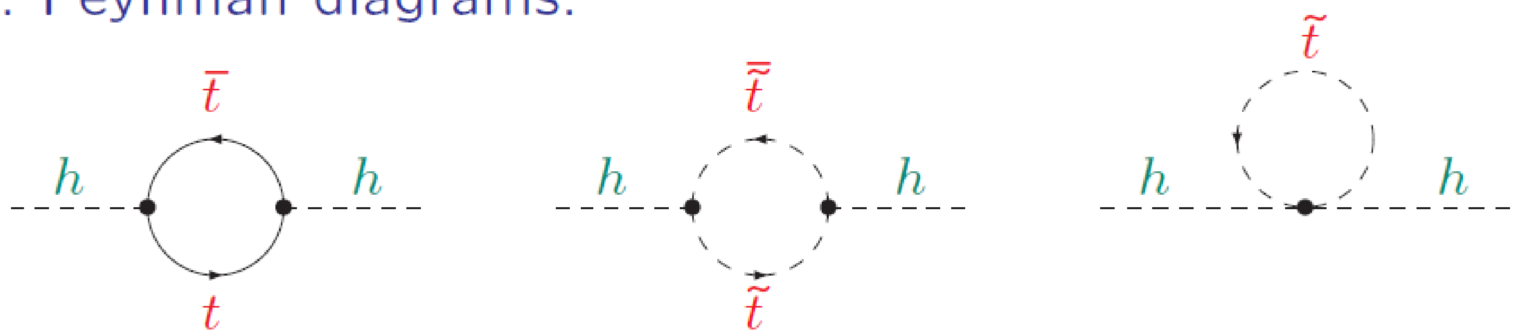
Tree-level result for m_h, m_H:

$$m^2_{H,h} = \frac{1}{2}\left[M_A^2 + M_Z^2 \pm \sqrt{(M_A^2 + M_Z^2)^2 - 4M_Z^2 M_A^2 \cos^2 2\beta}\right]$$

$\Rightarrow m_h \leq M_Z$ at tree level

$\Rightarrow$ Light Higgs boson h required in SUSY

1-Loop: Feynman diagrams:



Dominant 1-loop corrections: $\Delta m_h^2 \sim G_\mu m_t^4 \log\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right)$

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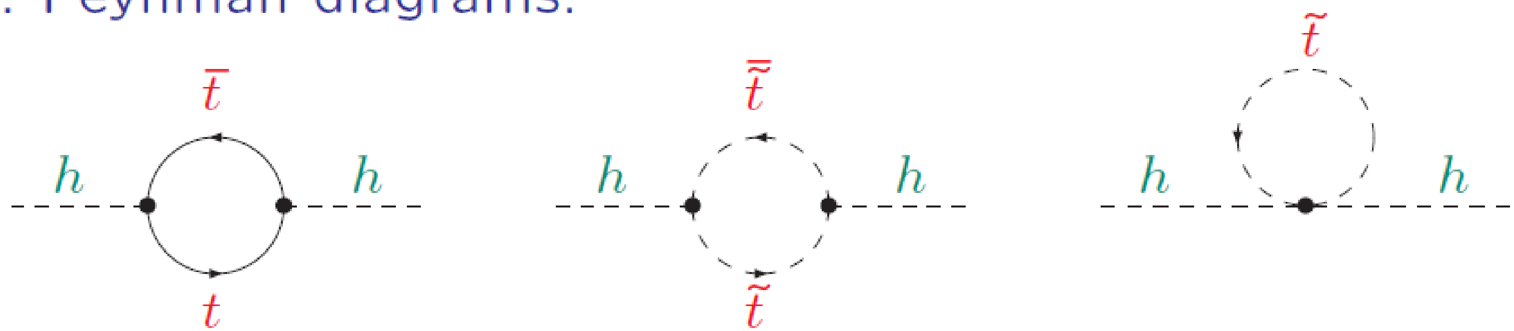

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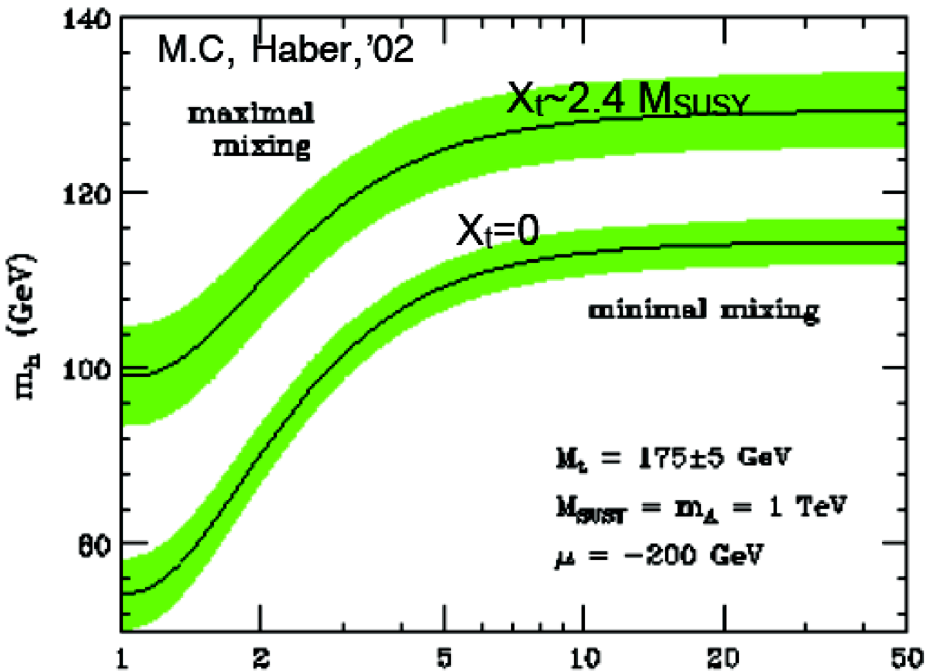
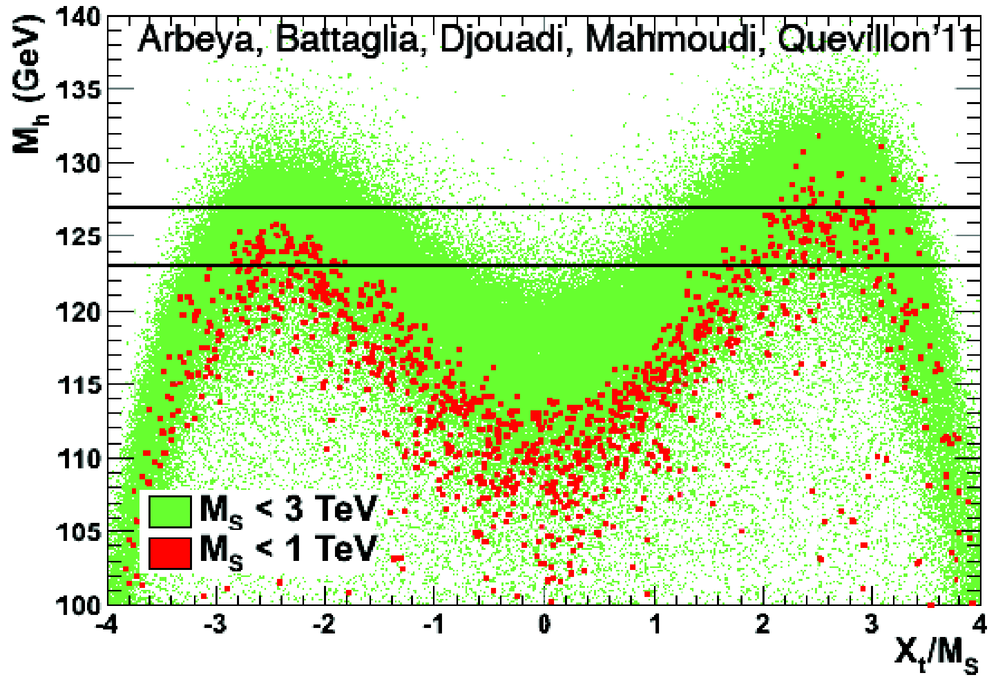
Stop, sbottom mass matrices ($X_t = A_t - \mu/\tan\beta$, $X_b = A_b - \mu\tan\beta$):

$$\mathcal{M}^2_{\tilde{t}} = \begin{pmatrix} M^2_{\tilde{t}_L} + m_t^2 + DT_{t_1} & m_t X_t \\ m_t X_t & M^2_{\tilde{t}_R} + m_t^2 + DT_{t_2} \end{pmatrix} \xrightarrow{\theta_{\tilde{t}}} \begin{pmatrix} m^2_{\tilde{t}_1} & 0 \\ 0 & m^2_{\tilde{t}_2} \end{pmatrix}$$

$$\mathcal{M}^2_{\tilde{b}} = \begin{pmatrix} M^2_{\tilde{b}_L} + m_b^2 + DT_{b_1} & m_b X_b \\ m_b X_b & M^2_{\tilde{b}_R} + m_b^2 + DT_{b_2} \end{pmatrix} \xrightarrow{\theta_{\tilde{b}}} \begin{pmatrix} m^2_{\tilde{b}_1} & 0 \\ 0 & m^2_{\tilde{b}_2} \end{pmatrix}$$





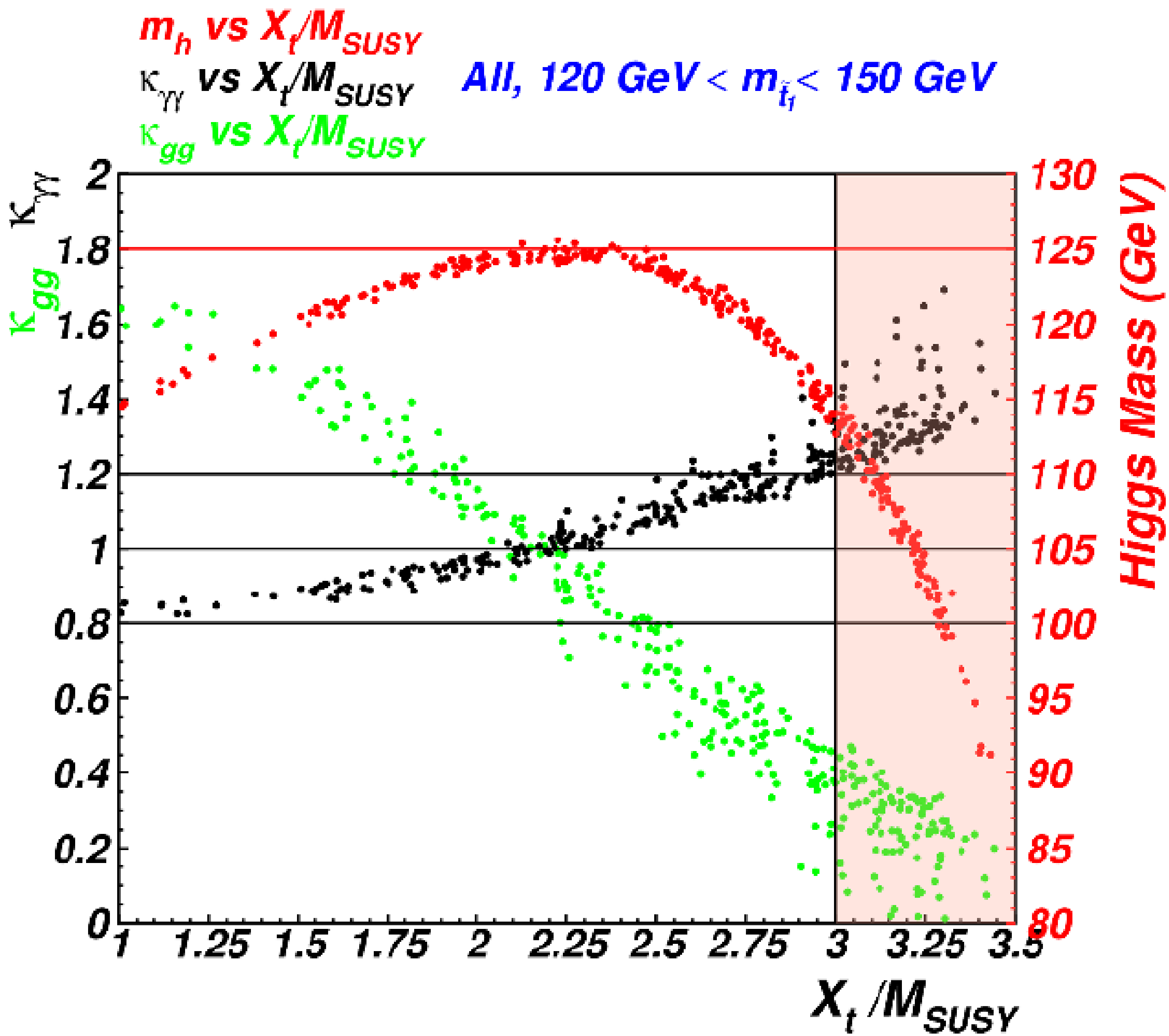
For moderate to large values of tan beta and large non-standard Scalar boson masses

$$\boxed{m_h^2 \cong M_Z^2 \cos^2 2\beta + \frac{3}{4\pi^2}\frac{m_t^4}{v^2}\left[\frac{1}{2}\tilde{X}_t + t + \frac{1}{16\pi^2}\left(\frac{3}{2}\frac{m_t^2}{v^2} - 32\pi\alpha_3\right)\left(\tilde{X}_t t + t^2\right)\right]}$$

$$t = \log(M_{SUSY}^2 / m_t^2) \qquad \tilde{X}_t = \frac{2X_t^2}{M_{SUSY}^2}\left(1 - \frac{X_t^2}{12 M_{SUSY}^2}\right) \qquad X_t = A_t - \mu/\tan\beta \rightarrow \text{LR stop mixing}$$

$$\boxed{m_h \leq 130 \text{ GeV}}$$ (for sparticles of ~ 1 TeV)

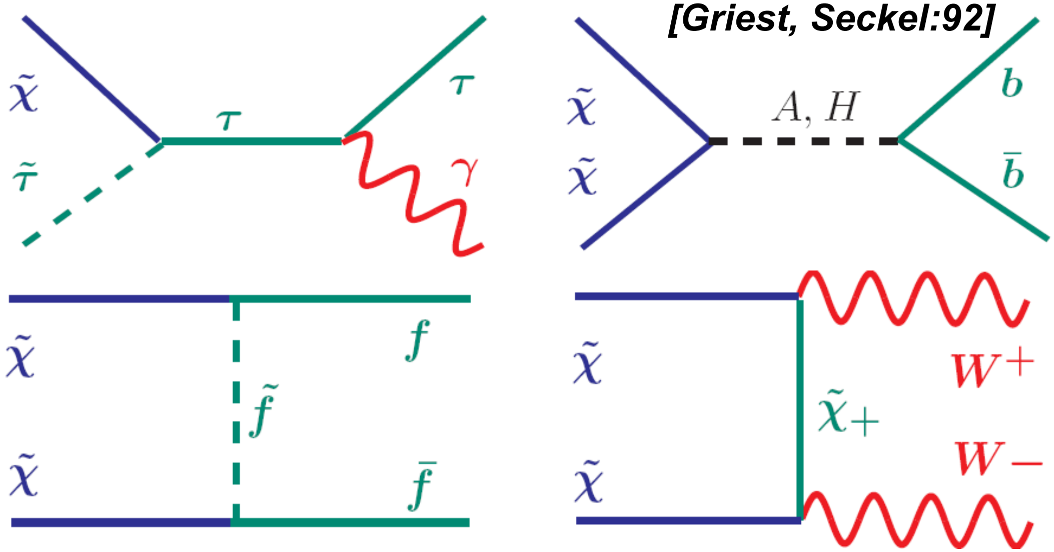
Effects from the light Stops



Evolution of neutralino relic density

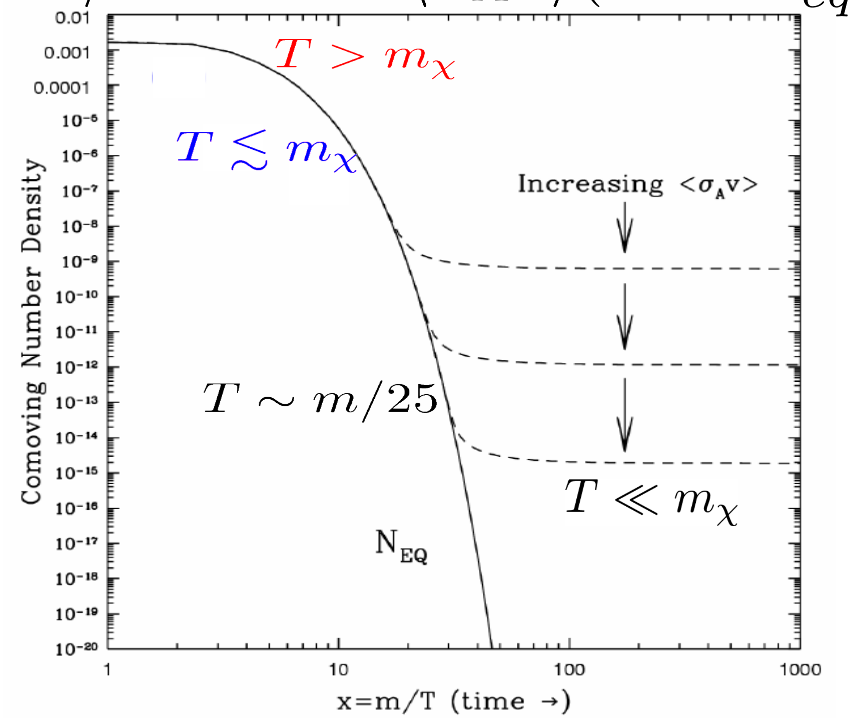
Challenge is to evaluate thousands annihilation/co-annihilation diagrams

[Griest, Seckel:92]



time evolution of number density is given by Boltzmann equation

$$\mathrm{dn/dt}{=}\text{-}3\mathrm{Hn}\text{-}\langle\sigma_A v\rangle(n^2 - n_{eq}^2)$$



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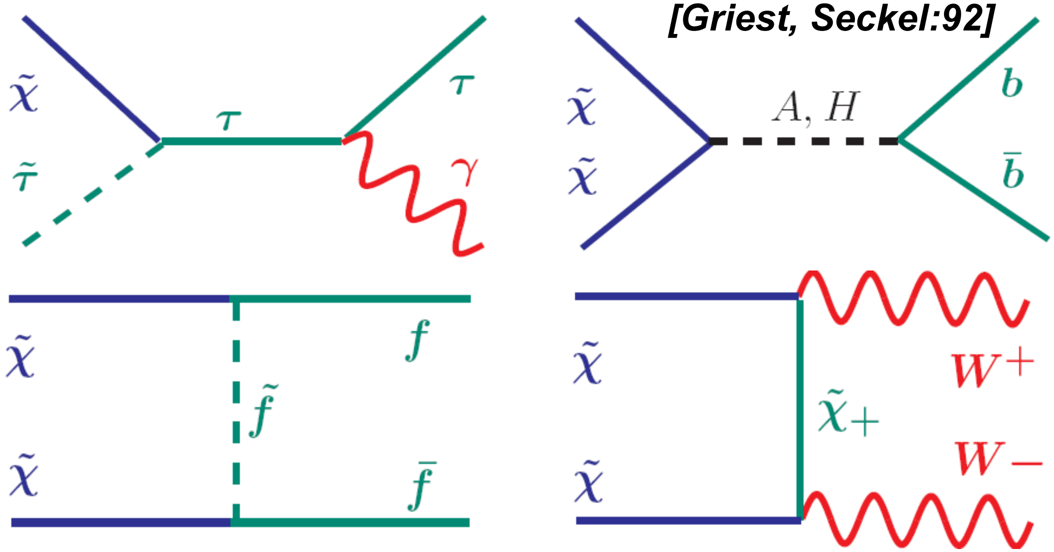
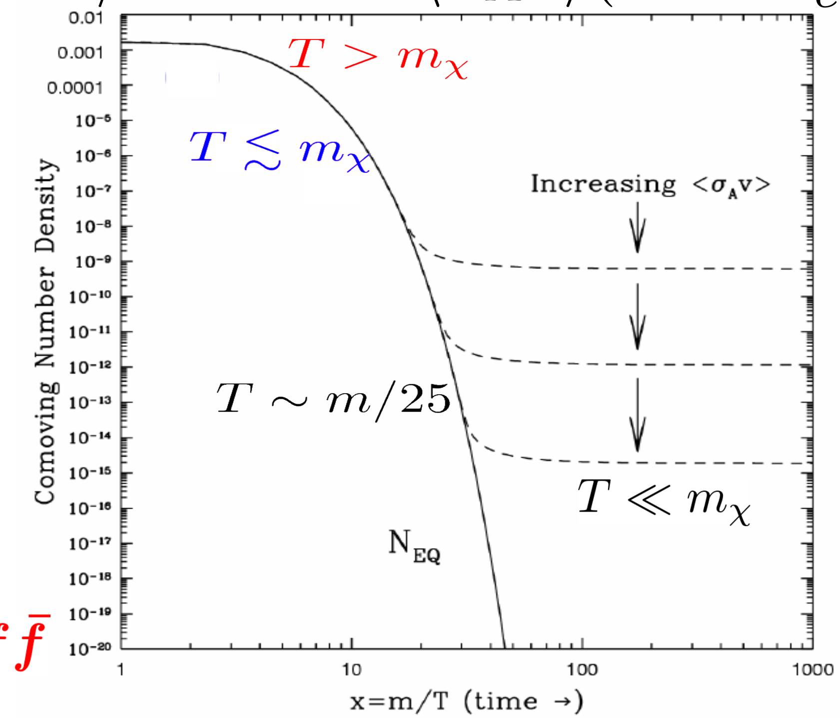


$\langle\sigma_A v\rangle$

relic density depends crucially on thermal equilibrium stage: $T > m_\chi, \;\; \chi\chi \leftrightarrow f\bar{f}$

time evolution of number density is given by Boltzmann equation

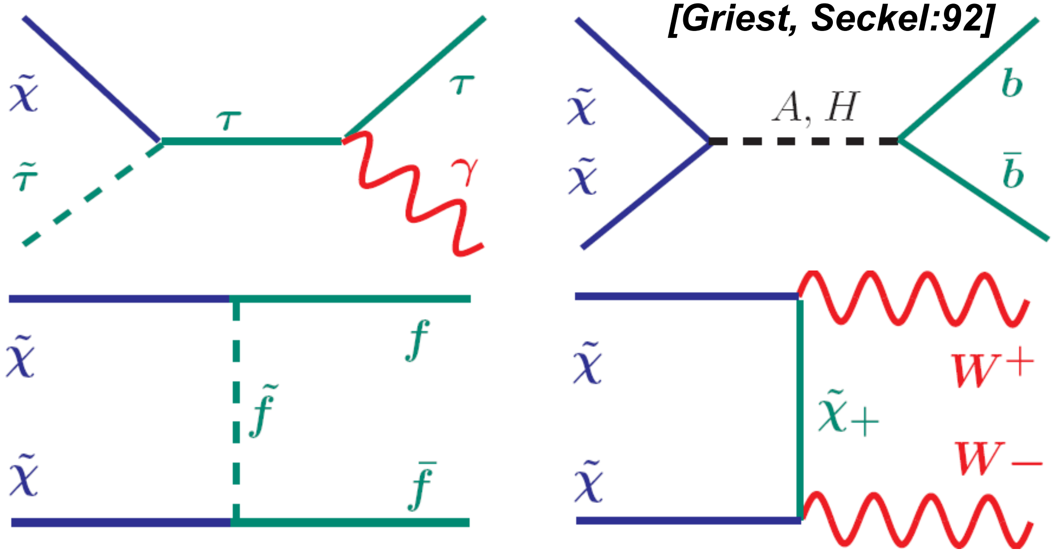
$$\mathrm{dn/dt}{=}\text{-}3\mathrm{Hn}\text{-}\langle\sigma_A v\rangle(n^2 - n_{eq}^2)$$



Evolution of neutralino relic density

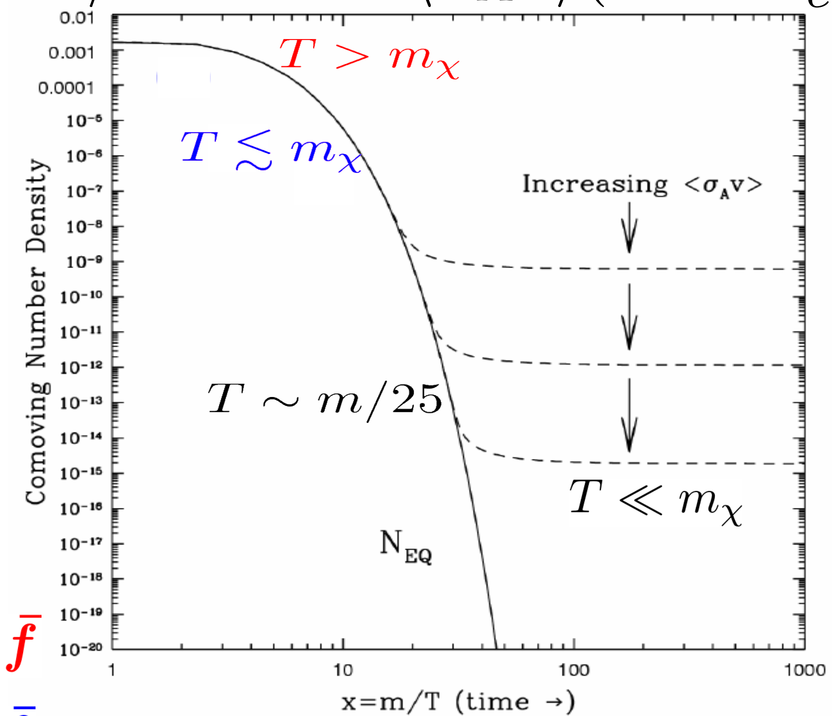
Challenge is to evaluate thousands annihilation/co-annihilation diagrams

[Griest, Seckel:92]



time evolution of number density is given by Boltzmann equation

$$dn/dt = -3Hn - \langle \sigma_A v \rangle (n^2 - n_{eq}^2)$$



relic density depends crucially on $\langle \sigma_A v \rangle$

thermal equilibrium stage: $T > m_\chi, \quad \chi\chi \leftrightarrow f\bar{f}$

universe cools: $T \lesssim m_\chi, \quad \chi\chi \not\leftrightarrow f\bar{f}$

$n = n_{eq} \sim e^{-m/T}$

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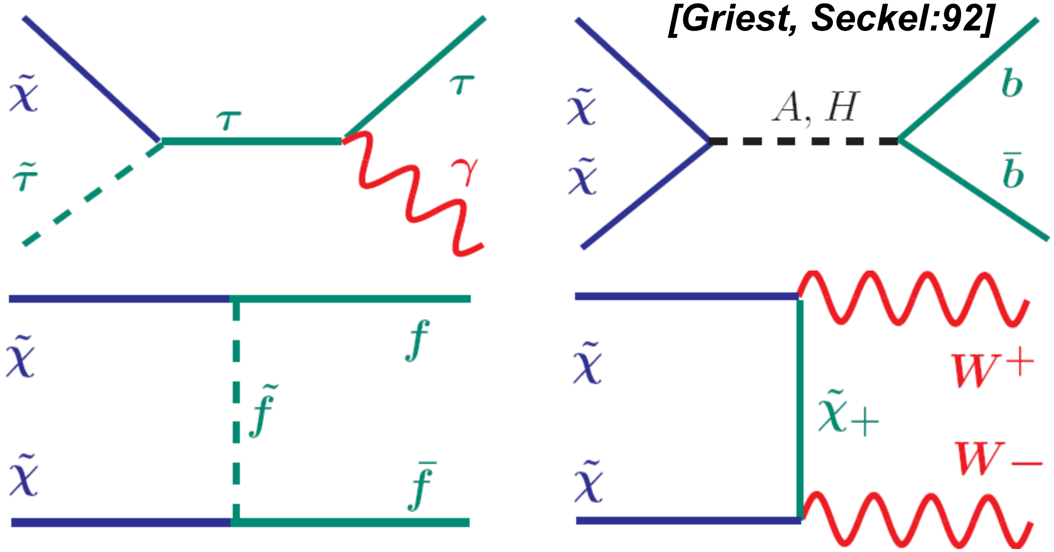

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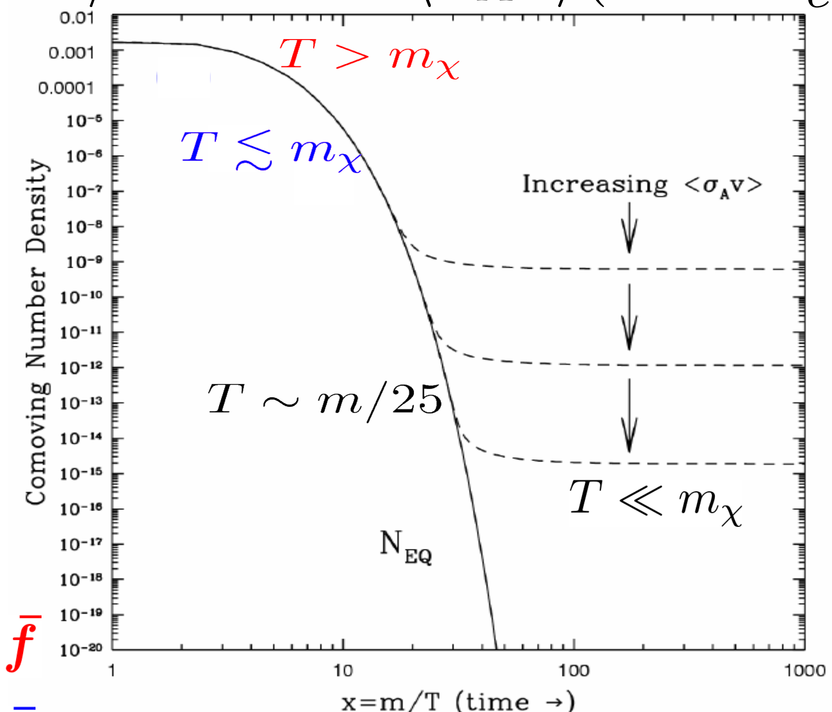

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Packages:
MicrOMEGAs (Pukhov et al), DarkSusy, ISARED

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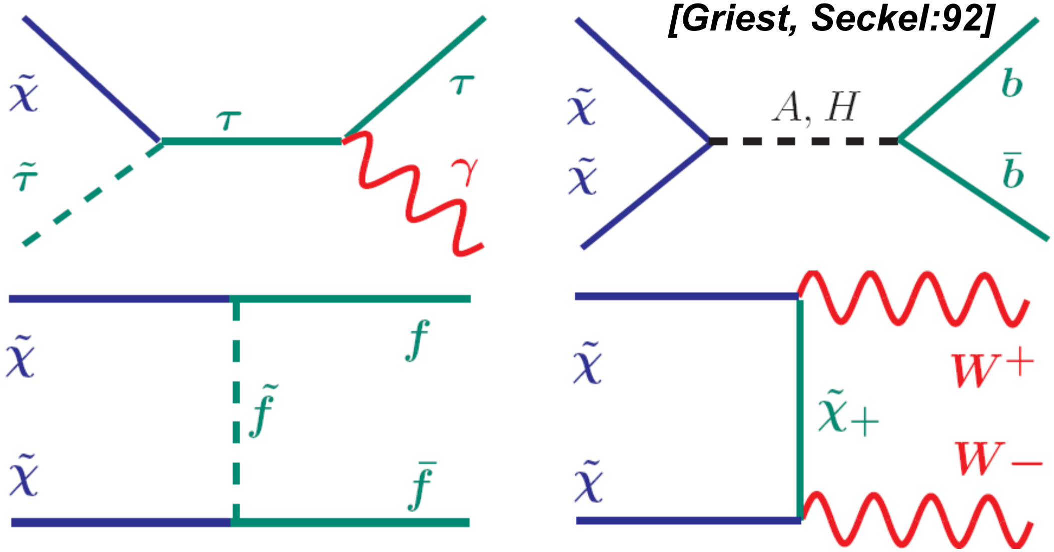

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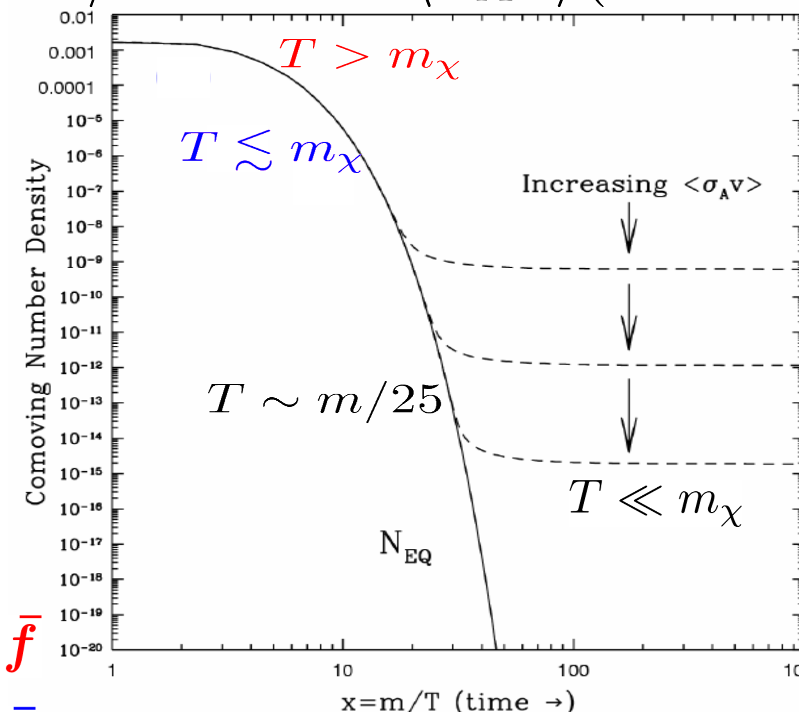

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$$\Omega_\chi = \frac{10^{-10}\text{GeV}^{-2}}{\langle \sigma_A v \rangle}$$

$$\Omega_\chi = 0.112 \longrightarrow \langle \sigma_A v \rangle = 1\text{pb}$$

$$\langle \sigma_A v \rangle = \frac{\pi \alpha^2}{8 m^2}$$

$$m = 100\text{GeV}$$

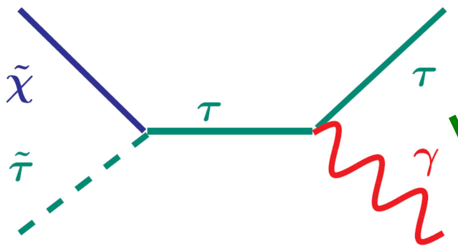
mass of the mediator

Packages:
MicrOMEGAs (Pukhov et al), DarkSusy, ISARED

Neutralino relic density in mSUGRA

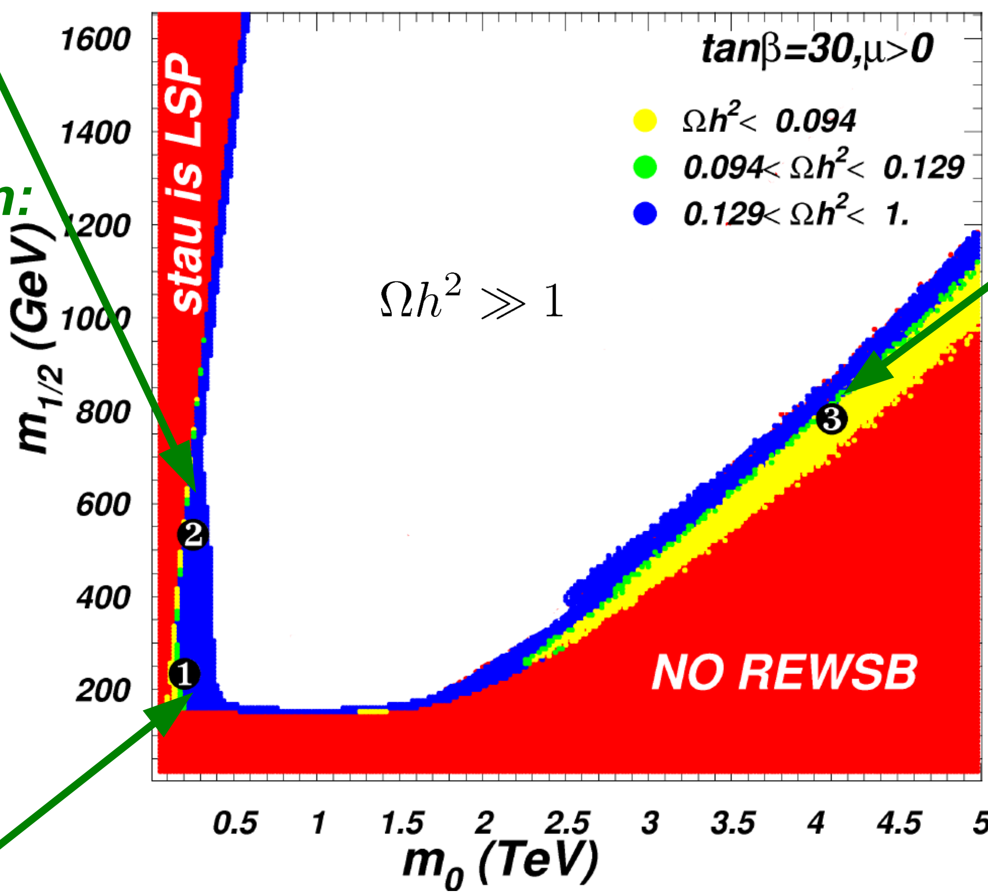
most of the parameter space is ruled out! $\Omega h^2 \gg 1$

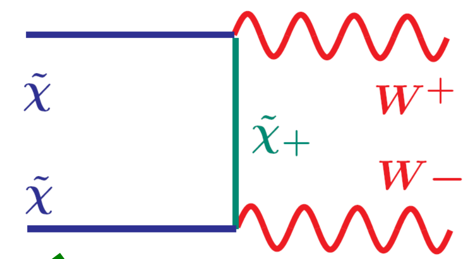
special regions with high σ_A are required to get $0.094 < \Omega h^2 < 0.129$



2. stau coannihilation:
degenerate χ and stau

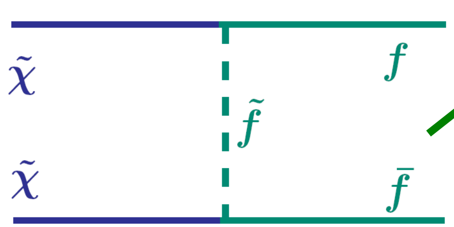
Baer, A.B., Balazs '02





3. focus point:
mixed neutralino, low μ, importance of higgsino-wino component

$$\mu^2 + M_Z^2/2 \approx -\varepsilon m_0^2 + 2m_{1/2}^2$$



1. bulk region: ***light sfermions***

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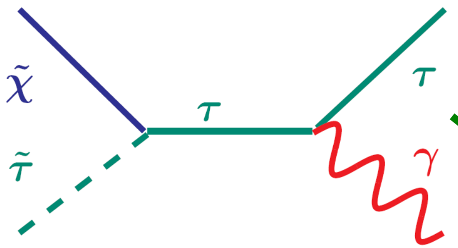

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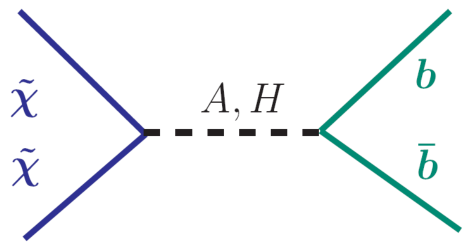
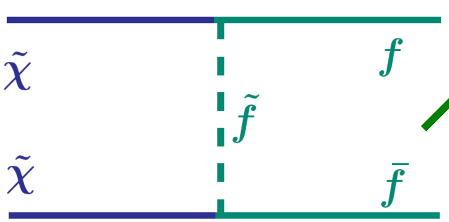


4. funnel: (large tanβ) annihilation via A, H



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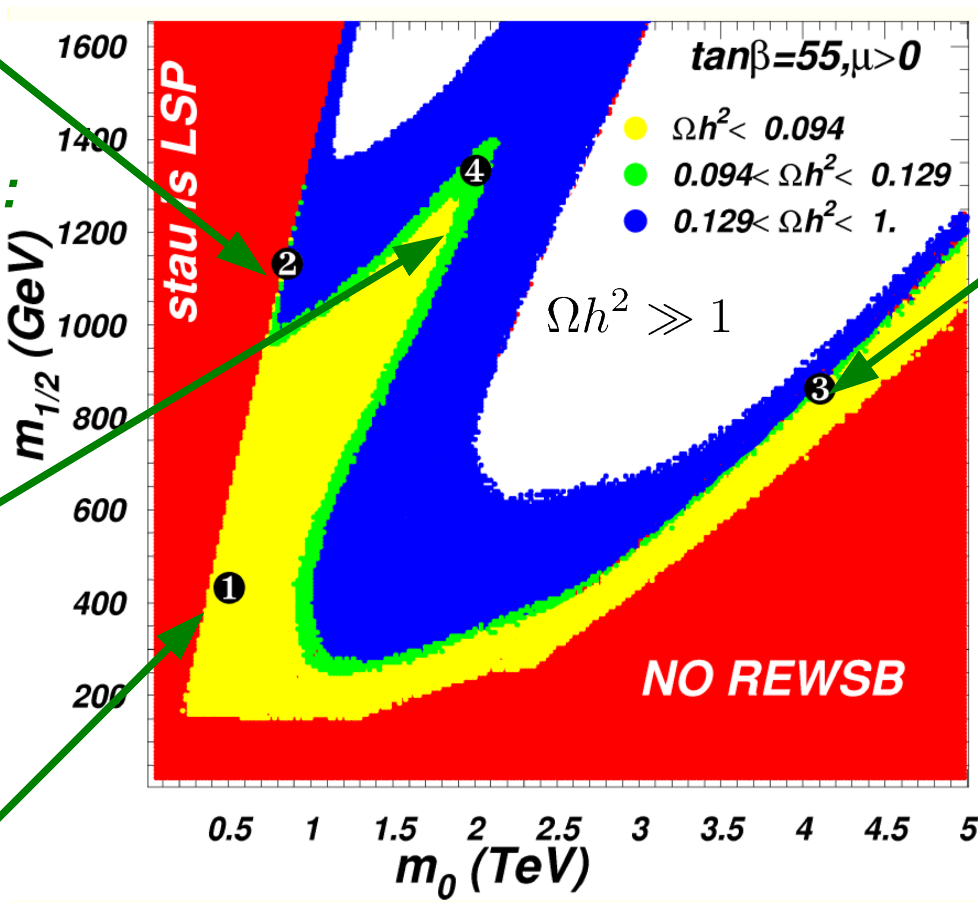

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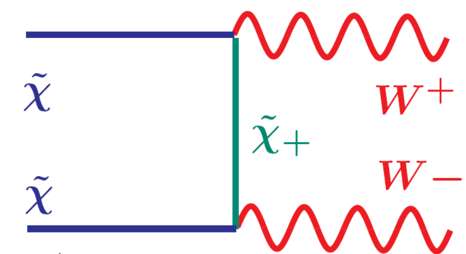


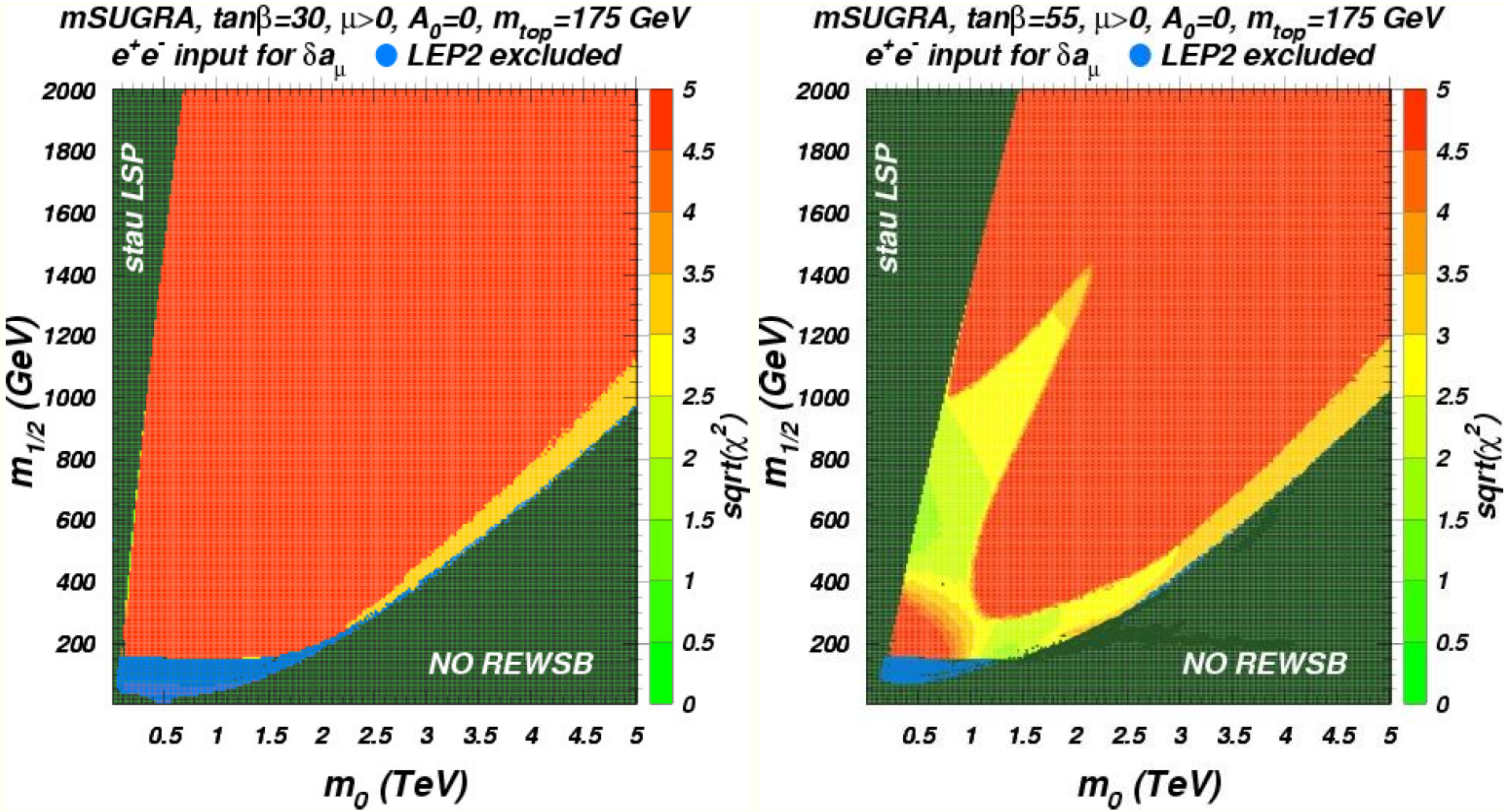
3. focus point:
mixed neutralino, low μ, importance of higgsino-wino component

$$\mu^2 + M_Z^2/2 \approx -\varepsilon m_0^2 + 2m_{1/2}^2$$

additional regions:
Z/h annihilation
stop coannihilation

Pre LHC mSUGRA $\chi^2 = \chi^2_{\delta a_\mu} + \chi^2_{\Omega h^2} + \chi^2_{b\to s\gamma}$ analysis

- Δa_μ favors light second generation sleptons, while $BF(b \to s\gamma)$ prefers heavy third generation: hard to realize in mSUGRA model.

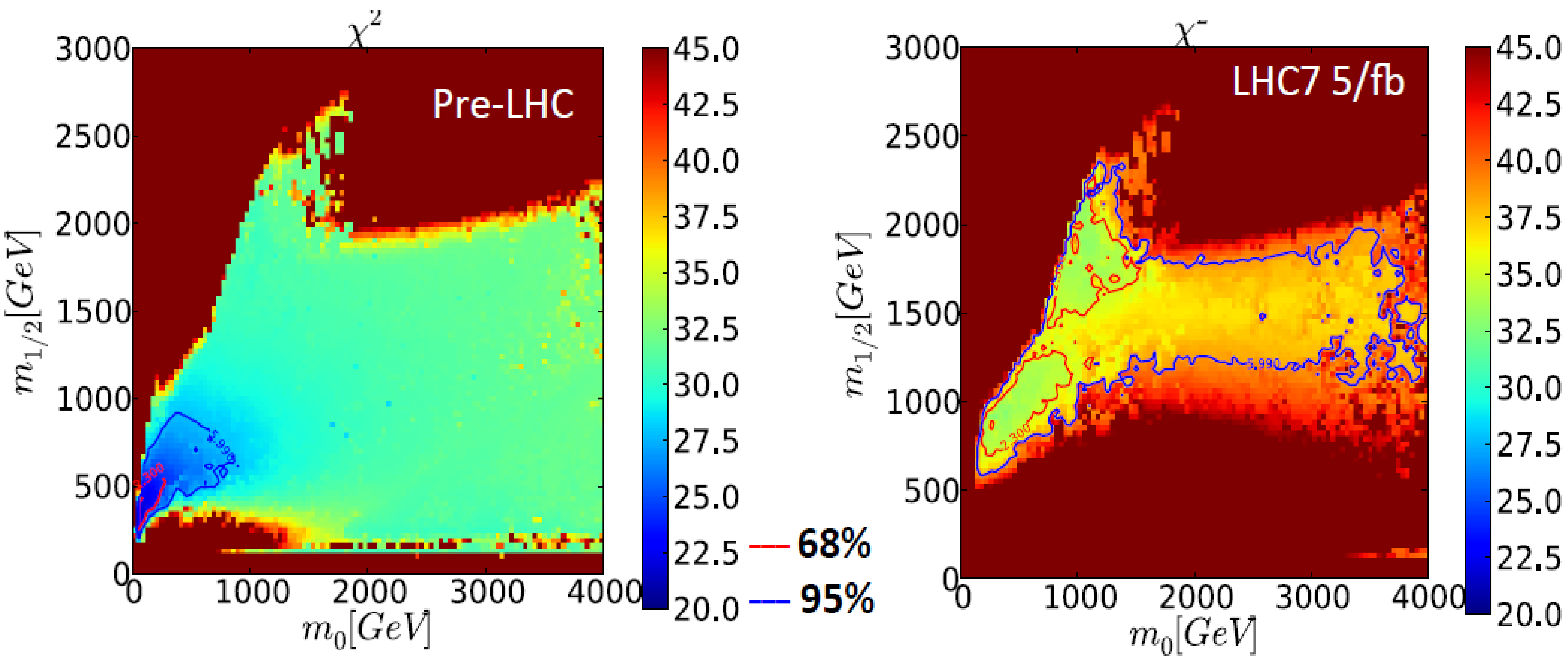


Baer, A.B., Krupovnickas, Mustafayev hep-ph/0403214

Implications of LHC search for SUSY fits

Buchmueller, Cavanaugh, De Roeck, Dolan, Ellis, Flaecher, Heinemeyer, Isidori, Marrouche, Martınez, Santos, Olive, Rogerson, Ronga, de Vries, Weiglein,

Global frequentist fits to the CMSSM using the MasterCode framework



The EW measure of Fine Tuning

$$\mathcal{L}_{\text{MSSM}} = \mu \tilde{H}_u \tilde{H}_d + \text{h.c.} + (m^2_{H_u} + |\mu|^2)\ |H_u|^2 + (m^2_{H_d} + |\mu|^2)\ |H_d|^2 + \ldots$$

The EW measure requires that there be no large/unnatural cancellations in deriving m_Z from the weak scale scalar potential:

$$\frac{m_Z^2}{2} = \frac{(m^2_{H_d} + \Sigma^d_d) - (m^2_{H_u} + \Sigma^u_u)\tan^2\beta}{(\tan^2\beta - 1)} - \mu^2 \simeq -m^2_{H_u} - \mu^2$$

using fine-tuning definition which became standard

Ellis, Enqvist, Nanopoulos, Zwirner '86; Barbieri, Giudice '88

$$\Delta_{FT} = max[c_i], \qquad c_i = \left|\frac{\partial \ln m_Z^2}{\partial \ln p_i}\right| = \left|\frac{p_i}{m_Z^2}\frac{\partial m_Z^2}{\partial p_i}\right|$$

one finds $\Delta_{FT} \simeq \Delta_{EW}$ **which requires as well as**

$$\boxed{\begin{array}{l} |\mu^2| \simeq M_Z^2 \\ |m^2_{H_u}| \simeq M_Z^2 \end{array}}$$

The last one is GUT model-dependent, so we consider the value $|\mu^2|$ as a measure of the minimal fine-tuning

"Compressed Higgsino" Scenario (CHS)

chargino-neutralino mass matrices

in $(\tilde{W}^-, \tilde{H}^-)$ basis

$$\begin{pmatrix} M_2 & \sqrt{2} m_W c_\beta \\ \sqrt{2} m_W s_\beta & \mu \end{pmatrix}$$

charginos

in $(\tilde{B}^0, \tilde{W}^0, \tilde{H}^0_1, \tilde{H}^0_2)$ basis

$$\begin{pmatrix} M_1 & 0 & -m_Z c_\beta s_w & m_Z s_\beta s_w \\ 0 & M_2 & m_Z c_\beta c_w & -m_Z s_\beta c_w \\ -m_Z c_\beta s_w & m_Z c_\beta c_w & 0 & -\mu \\ m_Z s_\beta s_w & -m_Z s_\beta c_w & -\mu & 0 \end{pmatrix}$$

neutralinos

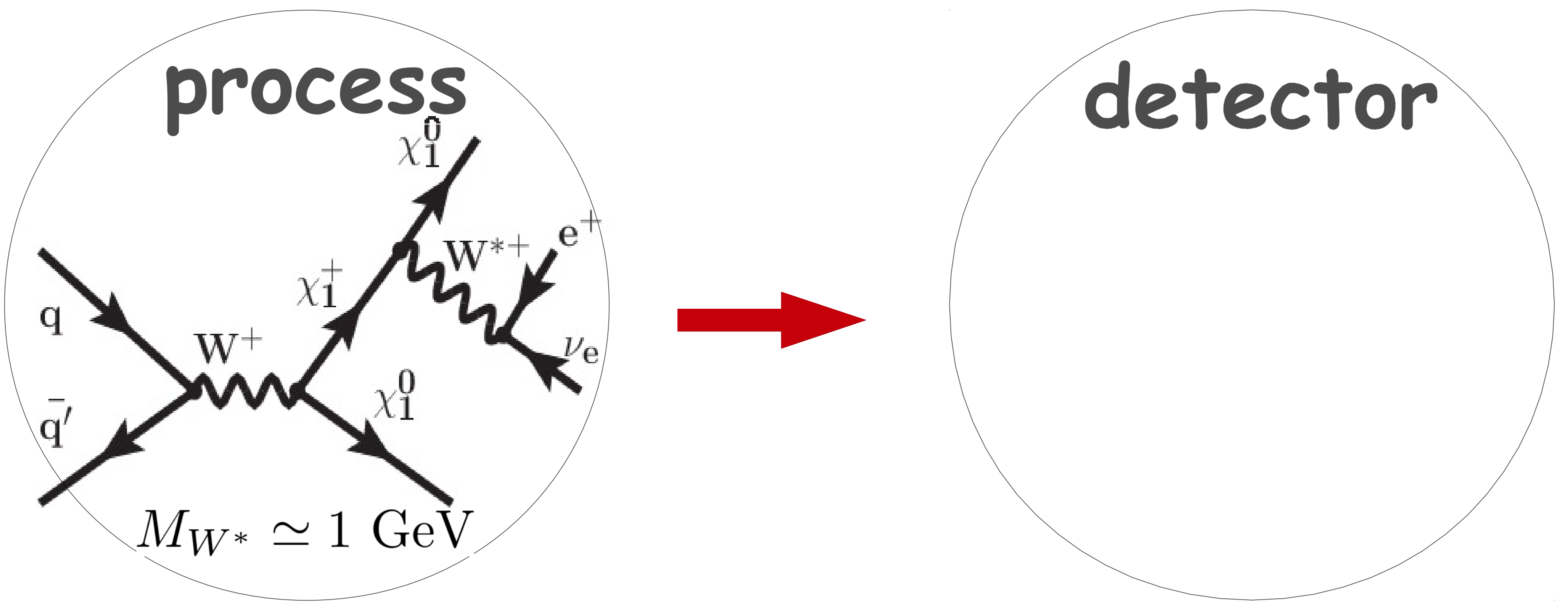
$$M_2 \text{ real}, \qquad M_1 = |M_1| e^{-\Phi_1}, \qquad \mu = |\mu| e^{i\Phi_\mu}$$

- Case of μ << M1, M2: $\chi^0_{1,2}$ and $\chi^\pm$ become quasi-degenerate and acquire large higgsino component. This provides a naturally low DM relic density via gaugino annihilation and co-annihilation processes into SM V's and H
- This is the case of relatively light higgsinos-electroweakinos compared to the other SUSY particles.
- This scenario is not just motivated by its simplicity, but also by the lack of evidence for SUSY to date

CHS Mass Spectrum and Challenge for the LHC

- The most challenging case takes place when only $\chi^0_{1,2}$ and $\chi^\pm$ are accessible at the LHC, and the mass gap between them is not enough for any leptonic signature

- The only way to probe CHS is a mono-jet signature
  ["Where the Sidewalk Ends? ..." Alves, Izaguirre,Wacker '11] ,
  which has been used in studies on compressed SUSY spectra, *e.g.*
  Dreiner,Kramer,Tattersall '12; Han,Kobakhidze,Liu,Saavedra,Wu'13; Han,Kribs,Martin,Menon '14



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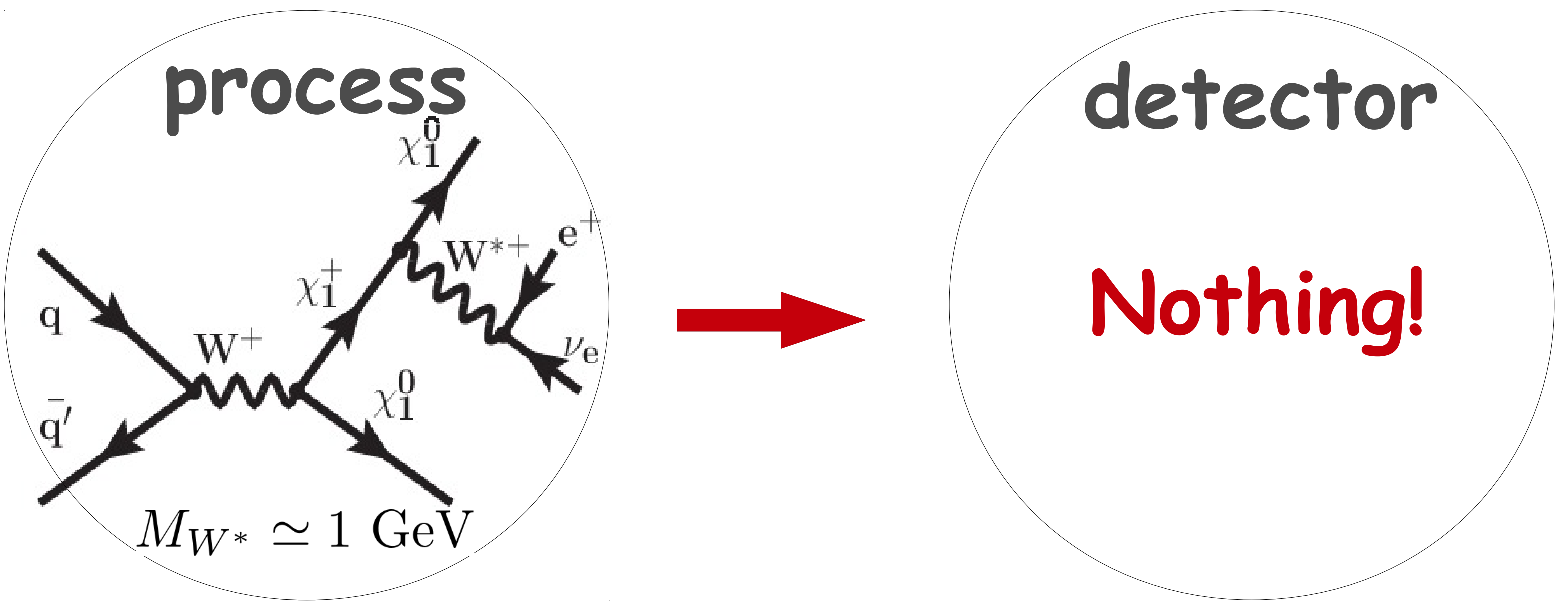

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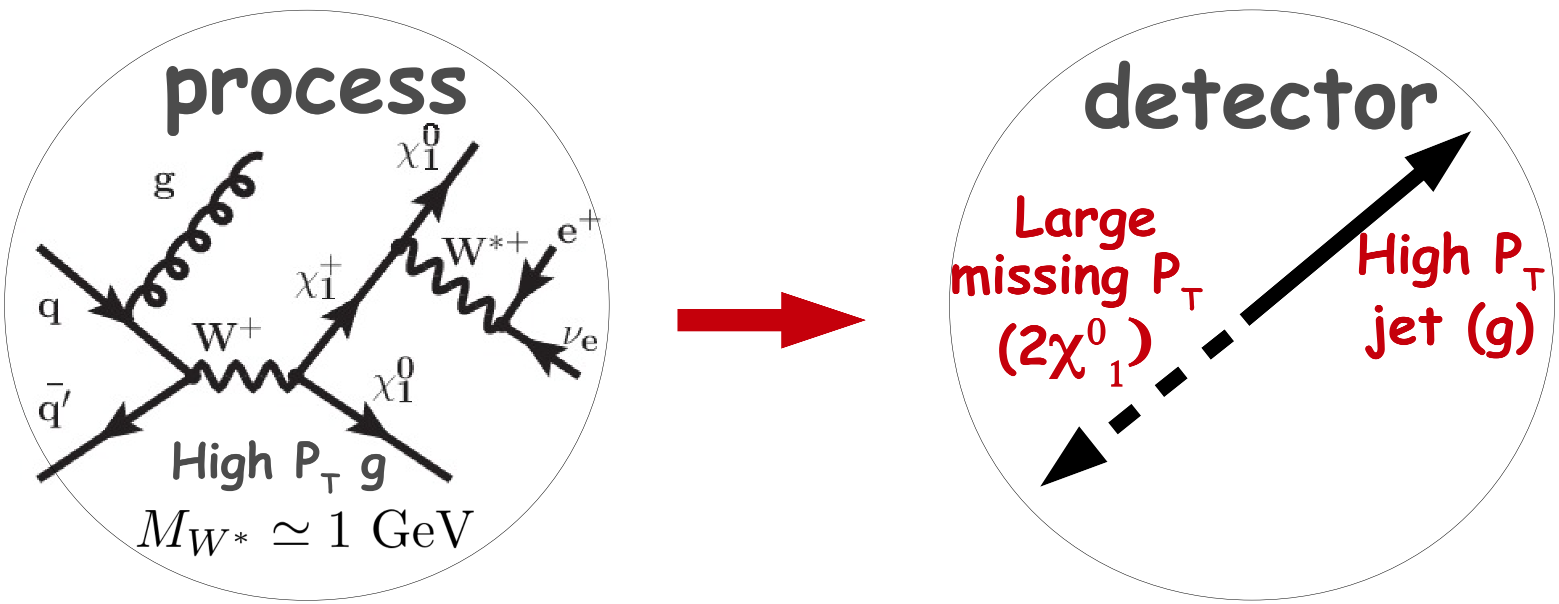

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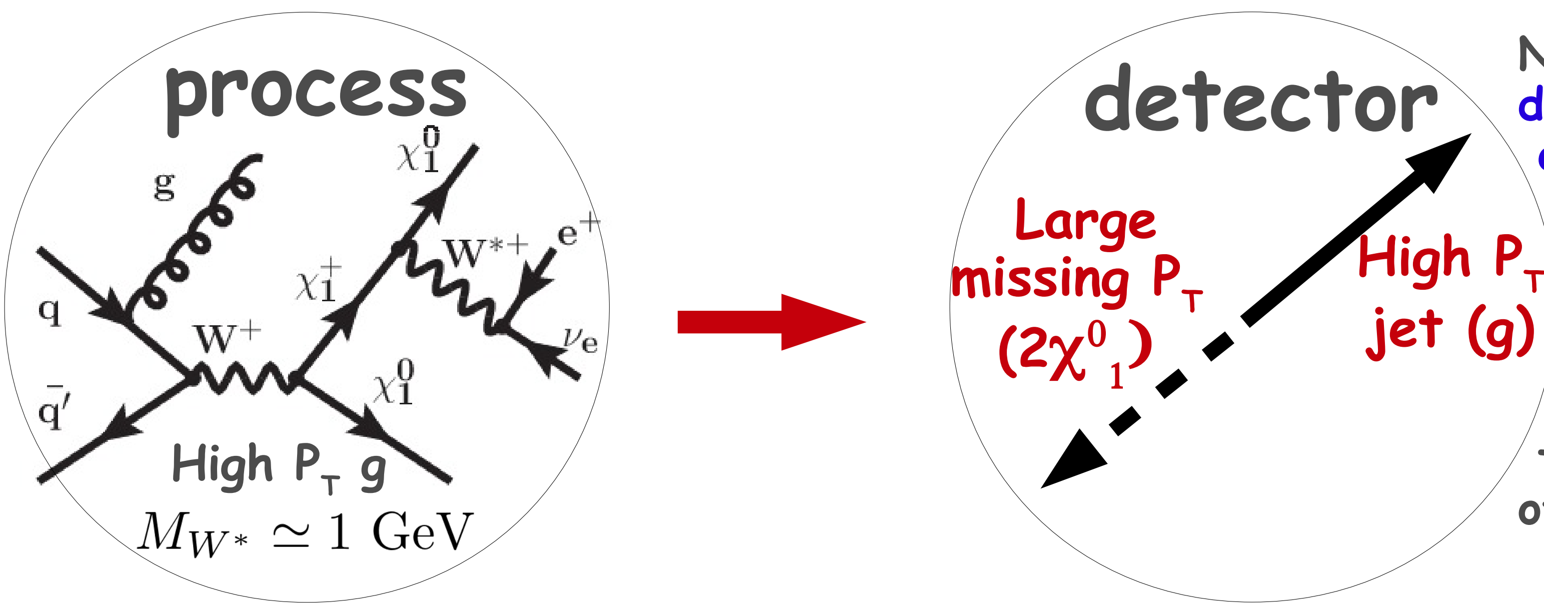
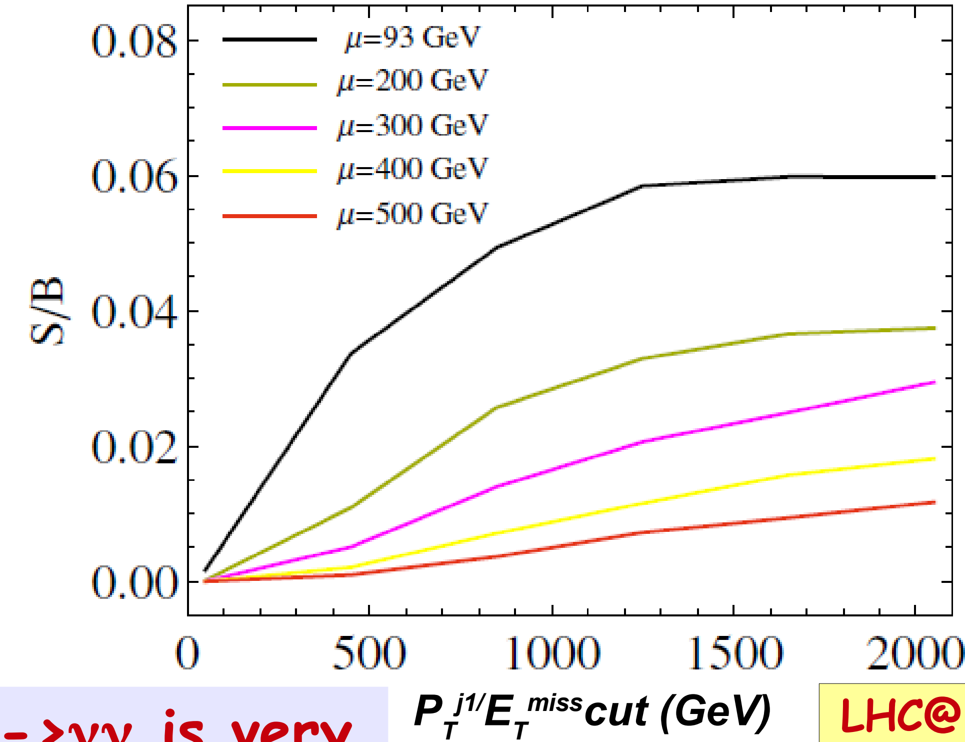
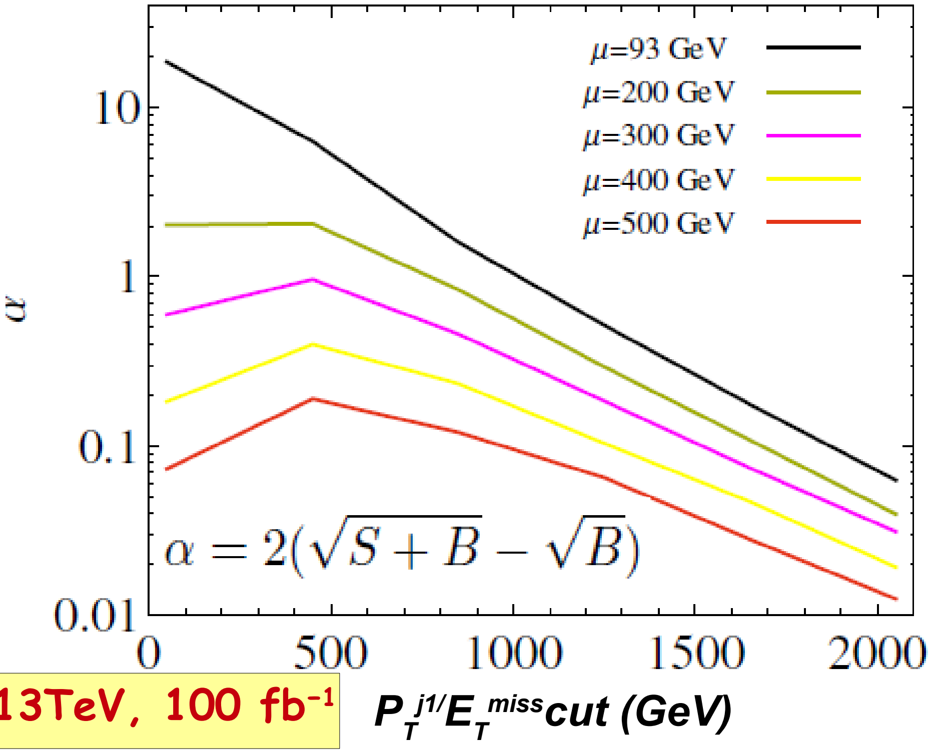


Note that **W* decay products do not get large boost** – it is proportional to the mass of W* which is much smaller than the mass of the LSP

S/B vs Signal significance





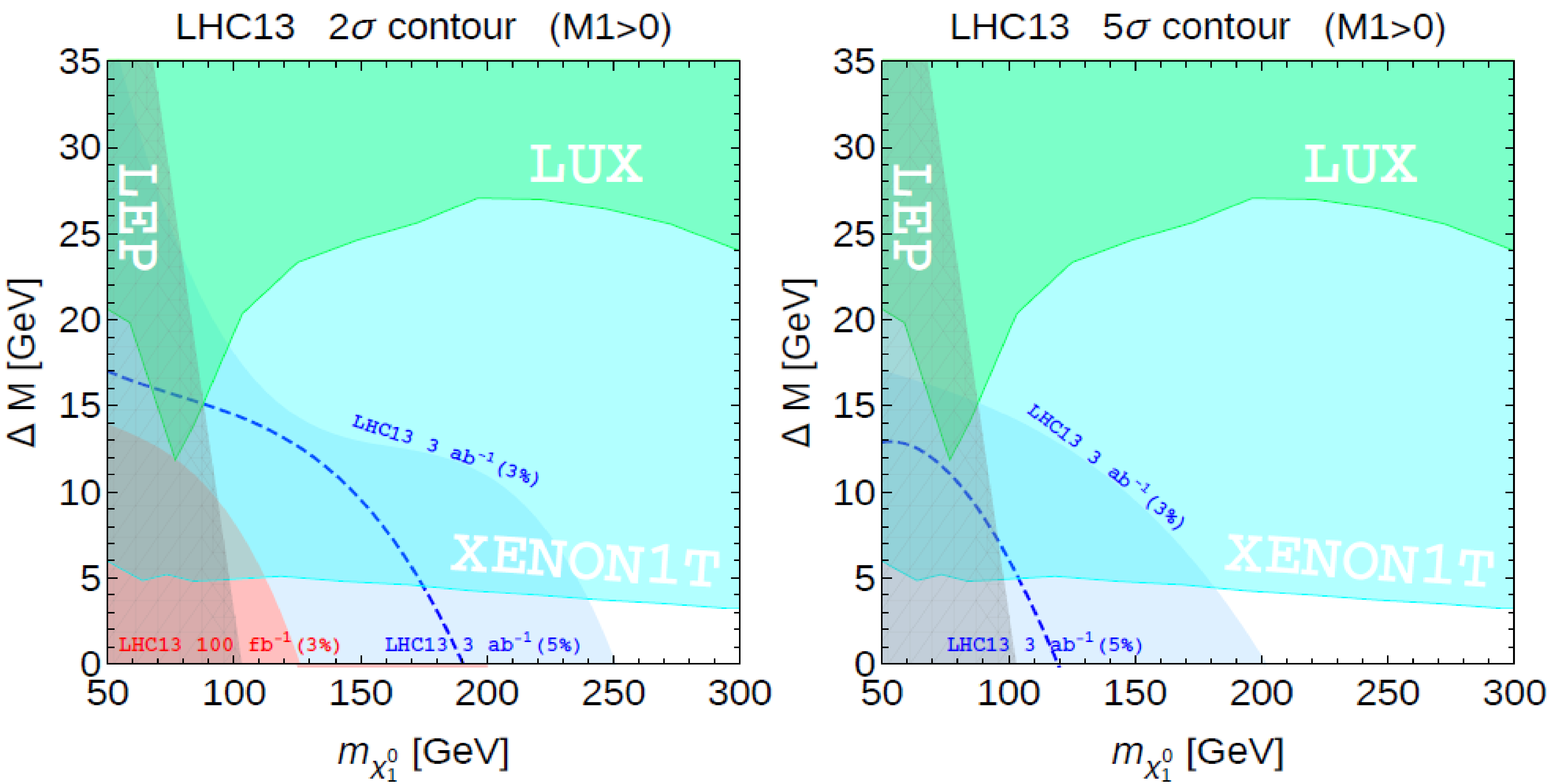
LHC@13TeV, 100 fb^{-1}

Z->νν is very problematic background!

	$Z(\nu\bar{\nu})j$	$W(\ell\nu)j$	$\mu = 93$ GeV	$\mu = 500$ GeV
$p^T_{jet} > 50$ GeV, $\lvert\eta_{jet}\rvert < 5$	6.4 E+7	2.9 E+8	2.6 E+5	948
Veto $p^T_{e^\pm,\mu^\pm/\tau^\pm}$ >10/20 GeV	6.2 E+7	1.2 E+8	2.5 E+5	921
p^T_j >500 GeV	2.5 E+4	2.0 E+4	1051	32
$p^T_j = \not{E}_T$ >500 GeV	1.5 E+4	4.1 E+3	747	27
$p^T_j = \not{E}_T$ >1000 GeV	315 (375)	65 (32)	21 (31)	2 (2)
$p^T_j = \not{E}_T$ >1500 GeV	18 (20)	2 (1)	1 (2)	0 (0)
$p^T_j = \not{E}_T$ >2000 GeV	1 (1)	0 (0)	0 (1)	0 (0)

- There is an important tension between S/B and signal significance
- S/B pushes E_t^{miss} cut up towards an acceptable systematic
- significance requires comparatively low (below 500 GeV) E_t^{miss} cut

LHC/DM direct detection sensitivity to CHS



"Uncovering Natural Supersymmetry via the interplay between the LHC and Direct Dark Matter Detection", Barducci,AB,Bharucha,Porod,Sanz, arXiv:1504.02472 (JHEP)

- **SUSY, at least DM, can be around the corner (100 GeV), it is just very hard to detect it!**

Question:
“Can experimentally rule out SUSY in general and e.g. cMSSM in particular?”

Question:

"Can experimentally rule out SUSY in general and e.g. cMSSM in particular?"

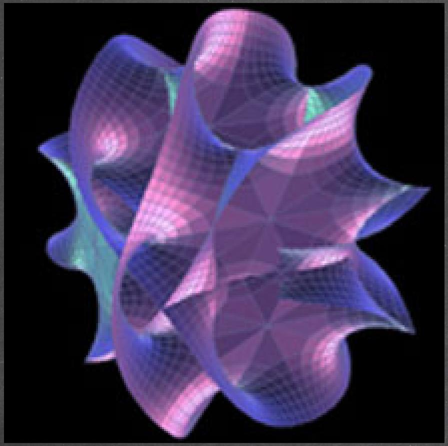
Answer:

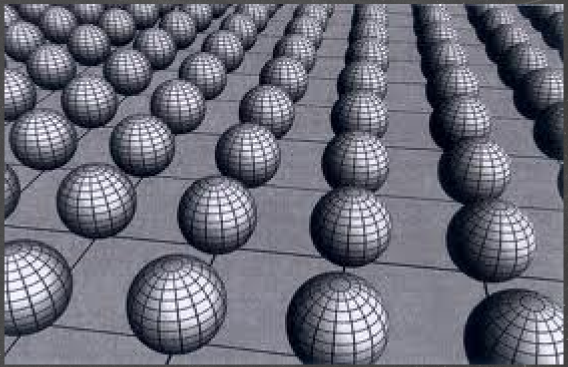
NO!

SUSY can be either discovered or abandoned!

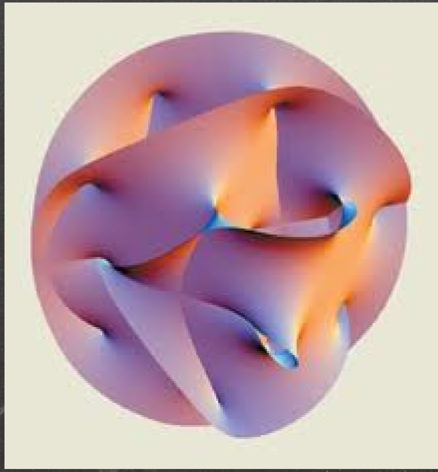
Original statement from Leszek Roszkowski: "Low energy SUSY cannot be experimentally ruled out. It can only be discovered. Or else abandoned."

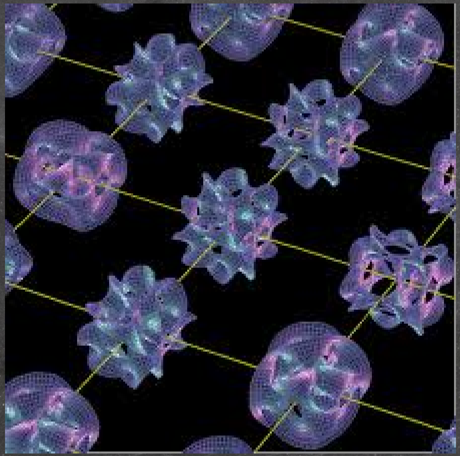
Lecture III: Extra-Dimensional and Technicolor/Composite Higgs models





eXtra Dimensions (XD)





Motivations for XD

- String theory, the best candidate to unify gravity & gauge interactions,
  is only consistent in 10 D space-time

- Extending symmetries:
  Internal symmetries - GUTs, technicolour...; Fermionic spacetime- SUSY
  Bosonic spacetime - Extra dimensions

- The presence of XD could have an impact on scales << M_{planck} (started with ADD)
  The question is what is the size and the shape of XD ?!

New perspectives of XD

- The nature of electroweak symmetry breaking
- The origin of fermion mass hierarchies
- The supersymmetry breaking mechanism
- The description of strongly interacting sectors (provide a way to model them)
- ....

Brief History

- 1914: Nordstrom tried to unify gravity and electromagnetism in 5D
  (A_μ -> A_M, where M = 0,1,2,3,4)

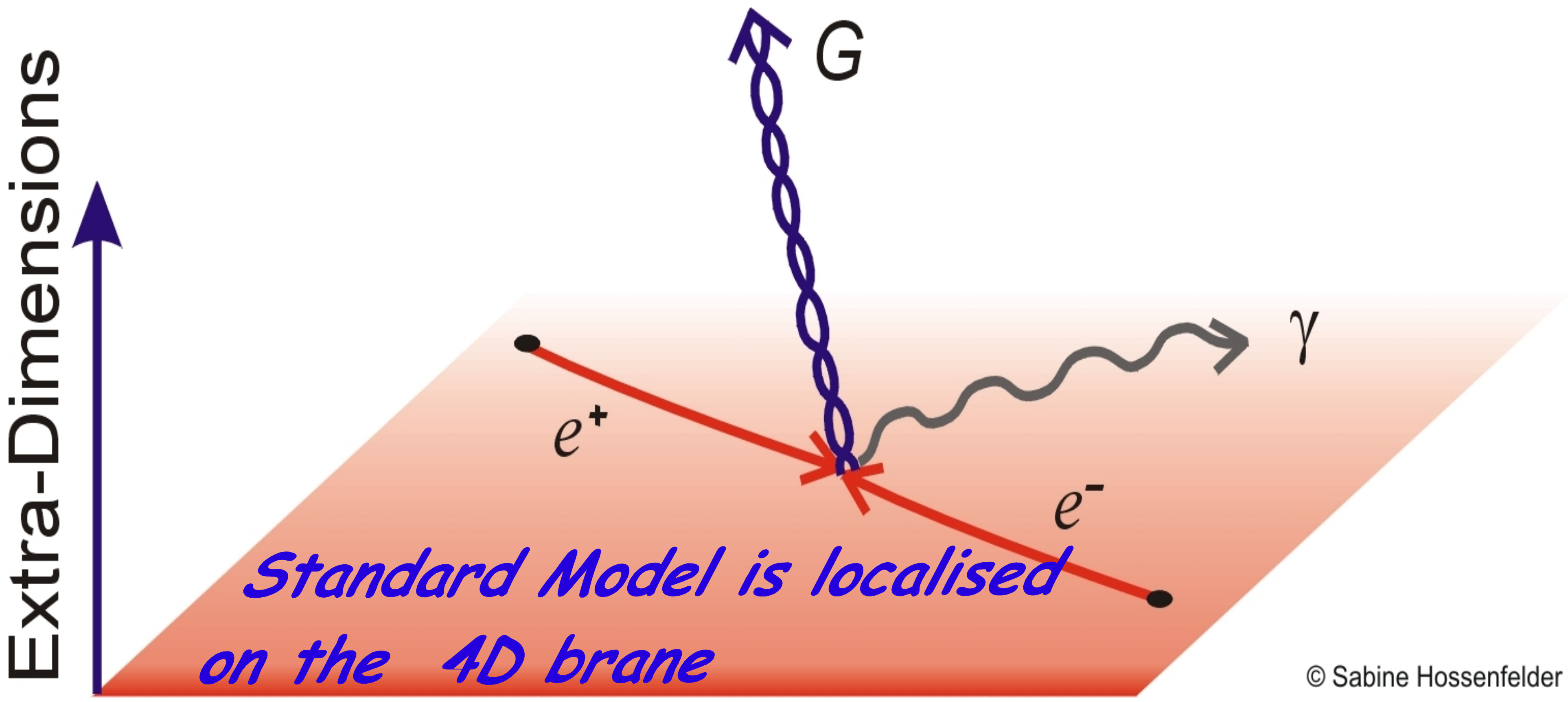
- 1920's: Kaluza and Klein tried using Einstein's equations in 5D ($g^{\mu\nu}$ -> g^{MN} ~ $g^{\mu\nu}$, $g^{\mu 4}$, g^{44})

- 1970's: Development of superstring theory and supergravity required extra dimensions

- 1998: Arkani-Hamed, Dimopoulos, and Dvali propose Large Extra Dimensions (ADD) as a solution to the Hierarchy /Fine tuning problem of the Standard Model

The idea of ADD

- The Standard Model has been tested to r ~ 10^{-16} mm,
  Gravity has been tested to r ~ 1 mm only



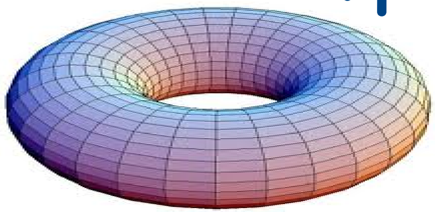
The idea of ADD

- The Standard Model has been tested to r ~ 10^{-16} mm,
  Gravity has been tested to r ~ 1 mm only
- 4D –> (4 + n)D
  The effective D = 4 action is

$$\frac{M_{\rm f}^{2+n}}{2}\int d^4x \int_0^{2\pi R} d^n Z\,\sqrt{G}\,R_{4+n} \longrightarrow \frac{1}{2}M_{\rm f}^{2+n}\,V_n \int d^4x\,\sqrt{g}\,R$$

In case of toroidal compactification of equal radii, R

$$V_n = (2\pi R)^n$$



$$M_P^2 = M_f^{2+n} V_n$$

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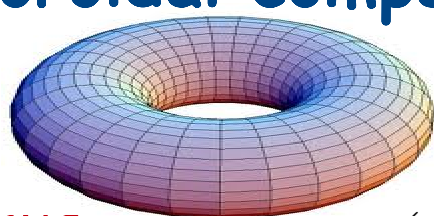

$$M_P^2 = M_f^{2+n} V_n$$

r>>R ⇒ the torus effectively disappear

$$V(r) = -G_N\frac{m_1 m_2}{r} = -\frac{m_1 m_2}{M_P^2 r}$$

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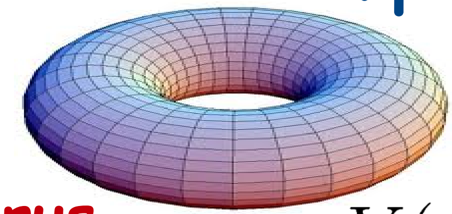

$$M_P^2=M_f^{2+n}V_n$$

r>>R ⇒ the torus effectively disappear

$$V(r)=-G_N\frac{m_1m_2}{r}=-\frac{m_1m_2}{M_P^2 r}$$

r<<R ⇒ observer is able to feel the bulk

$$V(r)=-G_*\frac{m_1m_2}{r}=-\frac{m_1m_2}{M_f^{2+n}r^{1+n}}$$

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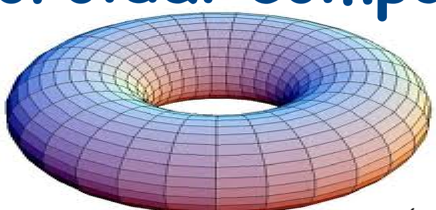
In case of toroidal compactification of equal radii, R

$$V_n = (2\pi R)^n$$



$$M_P^2 = M_f^{2+n} V_n$$

r>>R ⇒ the torus effectively disappear

$$V(r) = -G_N\frac{m_1 m_2}{r} = -\frac{m_1 m_2}{M_P^2 r}$$

r<<R ⇒ observer is able to feel the bulk

$$V(r) = -G_*\frac{m_1 m_2}{r} = -\frac{m_1 m_2}{M_f^{2+n} r^{1+n}}$$

Fundamental quantum gravity scale

The current status of ADD

So, $M_P^2 = M_f^{n+2}(2\pi R)^n$ and respectively,

$$R = \frac{1}{2\pi}\frac{1}{M_f}\left(\frac{M_P}{M_f}\right)^{\frac{2}{n}} [\mathrm{GeV}^{-1}] \times 0.197[\ \mathrm{GeV\ m}]$$

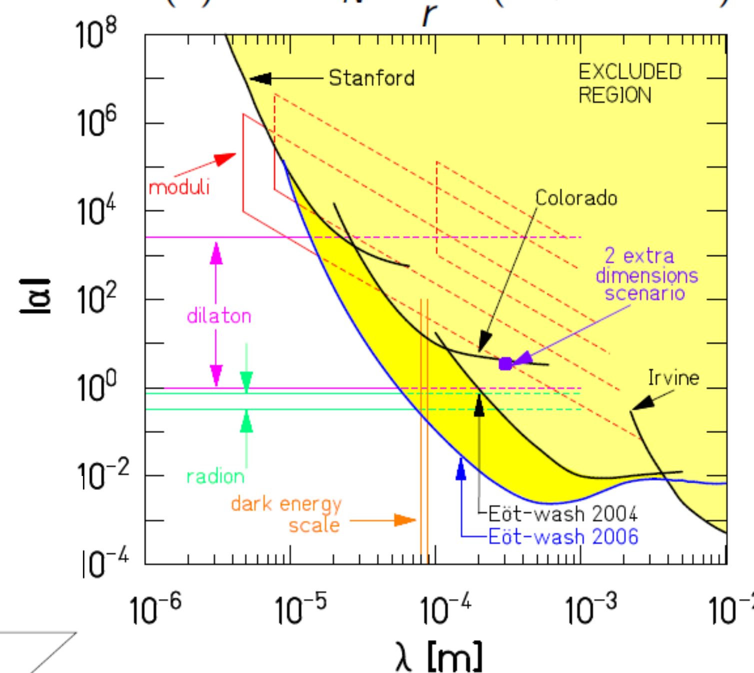
How big are these dimensions are?

Let us assume $M_f \sim 1$ TeV, then

$$R \sim \begin{cases} 10^{15}\ \mathrm{mm} & n=1 \\ 1\ \mathrm{mm} & n=2 \\ 10^{-6}\ \mathrm{mm} & n=3 \\ \vdots & \end{cases}$$

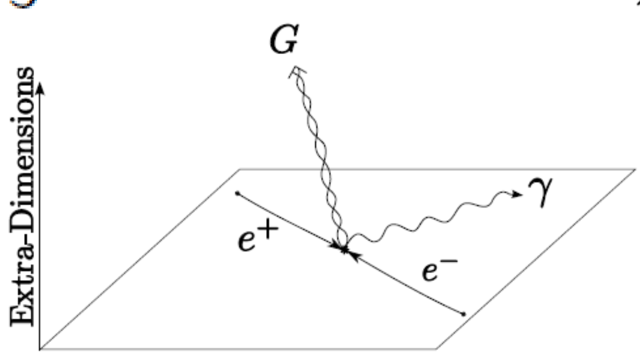
✕ Already
✕ ruled out

$$V(r) = -G_N \frac{m_1 m_2}{r}(1 + \alpha e^{-r/\lambda})$$



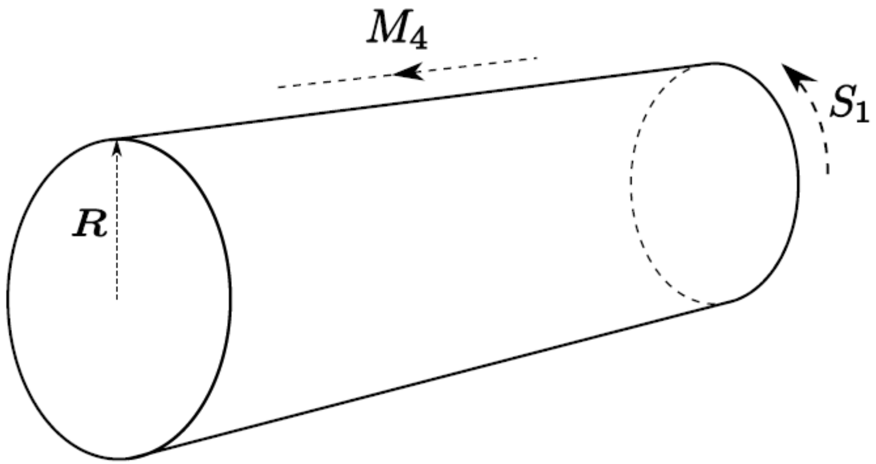
Collider signature:

$$pp \to jet + \not{E}_T$$



The current bound is $R < 37\ \mu\mathrm{m}$
For $n = 2$ this means that
$M > 1.4\ \mathrm{TeV}$

KK-towers from XD

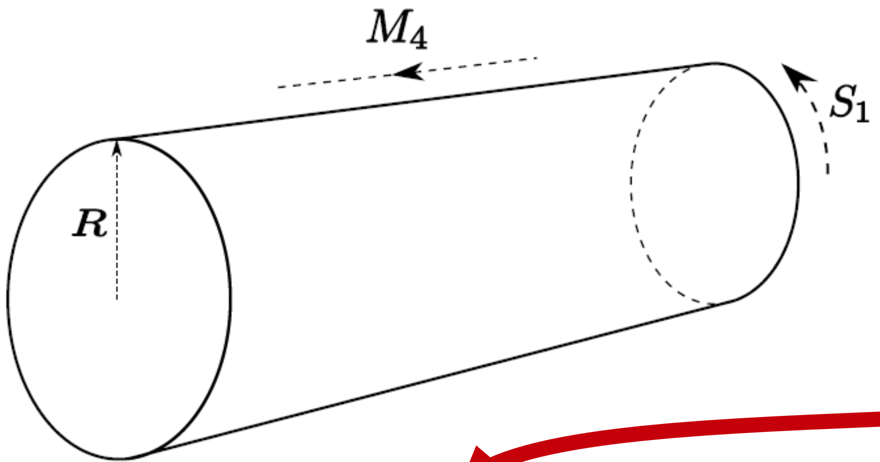


$$\Phi(x_\mu,\ Z) = \Phi(x_\mu,\ Z + 2\pi R)$$

$$\mu = 0, 1, 2, 3$$

Periodicity in Z

KK-towers from XD



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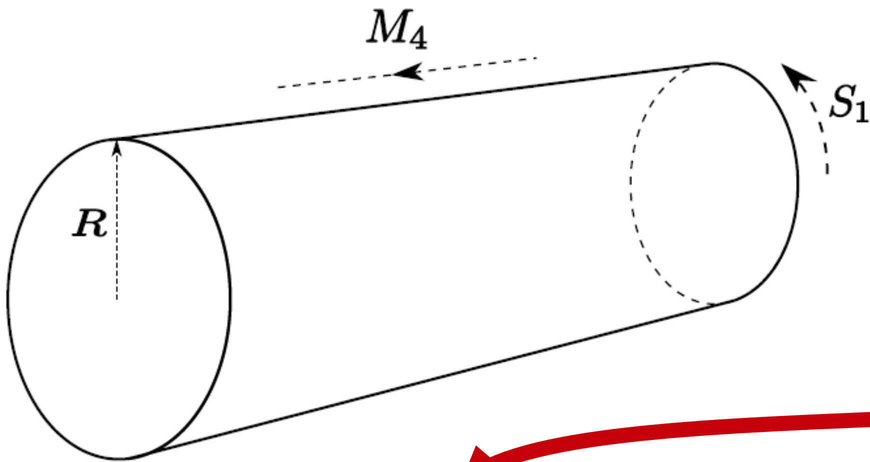
Periodicity in Z

Fourier series

$$\Phi(x_\mu,\ Z) = \sum_{k=0,\pm 1,\ldots} \phi_k(x_\mu) e^{ikZ/R}$$

KK-towers from XD



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Periodicity in Z

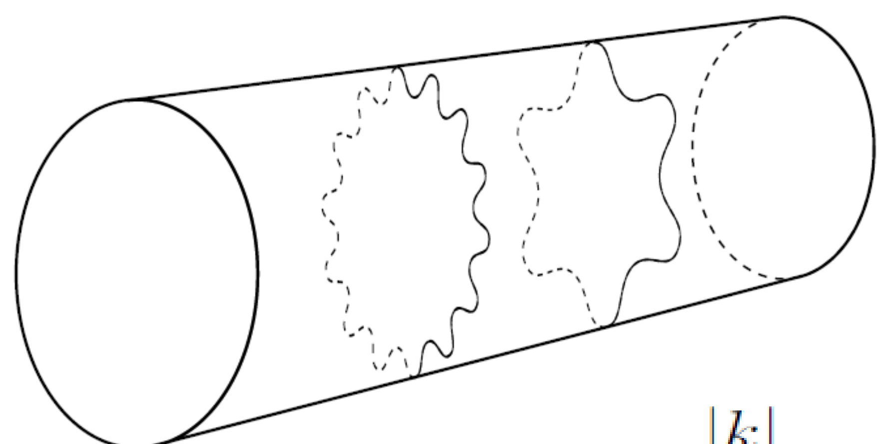
Fourier series

$$\Phi(x_\mu,\ Z) = \sum_{k=0,\pm 1,\ldots} \phi_k(x_\mu) e^{ikZ/R}$$

The non-zero modes in the KK decomposition

$$\Box_5\, \Phi(x_\mu,\ Z) \equiv \left(\partial_\mu^2 - \frac{\partial^2}{\partial Z^2}\right) \Phi(x_\mu,\ Z) = 0$$

$$\left(\Box_4 + \frac{k^2}{R^2}\right) \phi_k(x_\mu) \equiv \left(\partial_\mu^2 + \frac{k^2}{R^2}\right) \phi_k(x_\mu) = 0$$



$$m_k = \frac{|k|}{R}$$

From Brane – to Bulk: Universal Extra Dimensions (UED)

[Appelquist, Cheng, Dobrescu '01]

- all fields propagate in the extra dimensions, so $1/R > 1$ TeV to obey experimental data
- for D=5 (minimal UED = MUED) we immediately find that $M_f = 10^{15}$ GeV for $1/R = 1$TeV
- hierarchy problem is not addressed

  but MUED has interesting features ...

Minimal Universal Extra Dimensions

compactifying on the circle

$$\phi(x,y) = \frac{1}{\sqrt{2\pi R}}\phi_0(x) + \sqrt{\frac{\pi}{R}}\sum_{n=1}^{\infty}\left[\phi_n^+(x)\cos\frac{ny}{R} + \phi_n^-(x)\sin\frac{ny}{R}\right]$$

$$S = \int d^4x \overbrace{\int_0^{2\pi R} dy\, \underbrace{\frac{1}{2}\left[\partial_M\phi\partial^M\phi - m^2\phi(x,y)^2\right]}_{\mathcal{L}_5}}^{\mathcal{L}_4}$$

$$\mathcal{L}_4 = \frac{1}{2}\left[\partial_\mu\phi_0\partial^\mu\phi_0 - m^2\phi_0^2\right] + \sum_{n=1}^{\infty}\frac{1}{2}\left[\partial_\mu\phi_n^\pm\partial^\mu\phi_n^\pm - \overbrace{\left(m^2 + \frac{n^2}{R^2}\right)}^{m_n^2}\phi_n^{\pm\,2}\right]$$

- **all fields propagate in the bulk – 5D momentum conservation**

Minimal Universal Extra Dimensions

compactifying on the circle

$$\phi(x,y) = \frac{1}{\sqrt{2\pi R}}\phi_0(x) + \sqrt{\frac{\pi}{R}}\sum_{n=1}^{\infty}\left[\phi_n^+(x)\cos\frac{ny}{R} + \phi_n^-(x)\sin\frac{ny}{R}\right]$$

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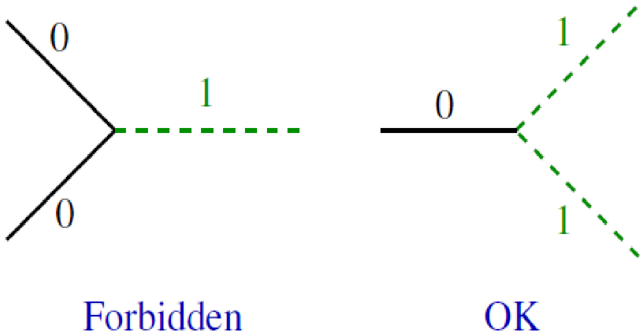
- all fields propagate in the bulk - 5D momentum conservation
- This leads to the KK-number conservation at this point: $\pm n_1 \pm n_2 = \pm n_3$

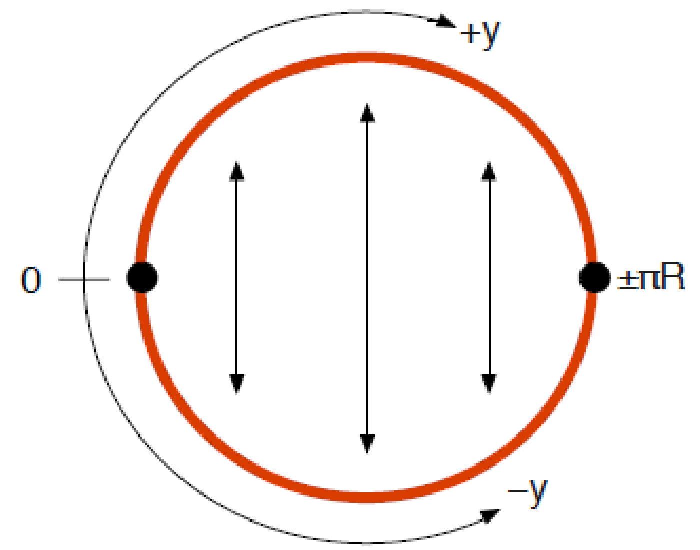


Universal Extra Dimensions (UED)

compactifying on the orbifold

- Choose action of Z_2 symmetry on Dirac Fermions to project out ½ of them and arranges chirality:

$$\psi_\pm(y) \mapsto \psi'_\pm(-y) = \pm\gamma^5\psi_\pm(y)$$



If we identify $y \sim -y$ then we require $\psi'_\pm(y) = \psi_\pm(y)$, so

$$\psi_\pm(y) = \psi_0^{R,L} + \sum_n \left(\psi_n^{R,L}\cos_n + \psi_n^{L,R}\sin_n\right)$$

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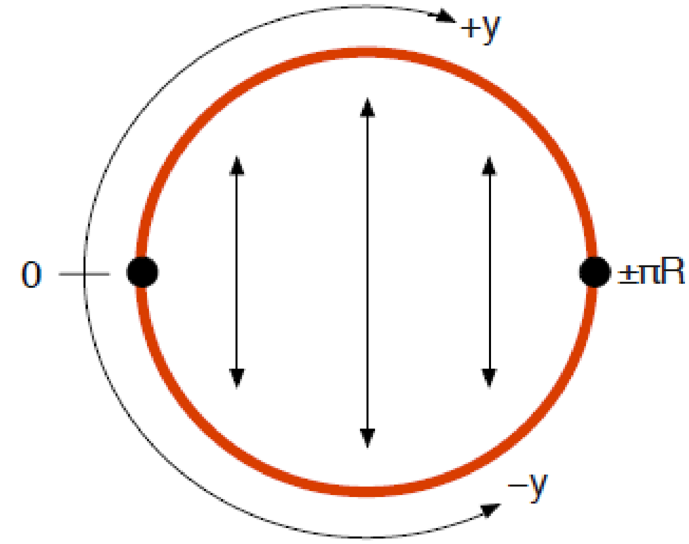

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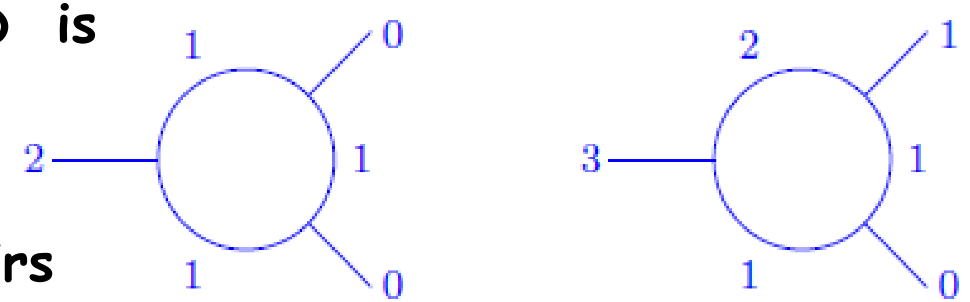
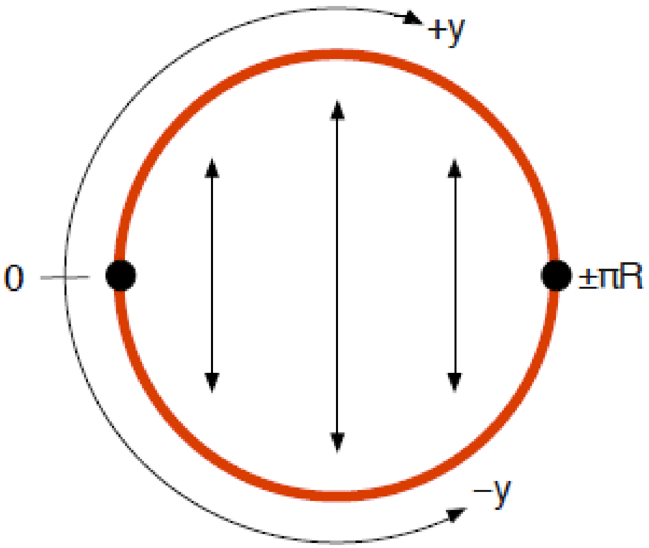
- Translational invariance along the 5th D is broken, but KK parity is preserved!
- KK number n broken down to the KK parity, $(-1)^n$: KK excitations must be produced in pairs



These vertices are allowed and can be generated at loop-level

- LKP is stable DM candidate!

Minimal Universal Extra Dimensions

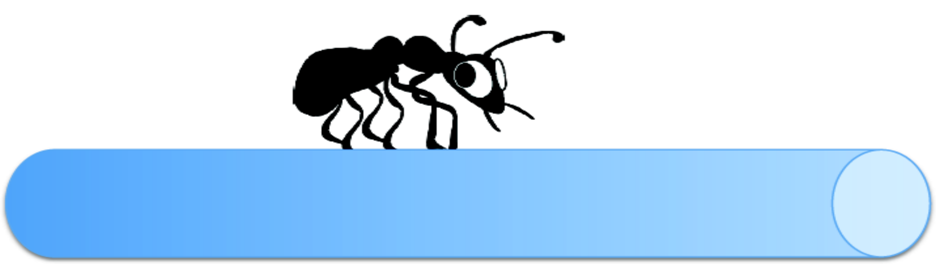


$$\boxed{SU(3) \times SU(2) \times U(1)}$$

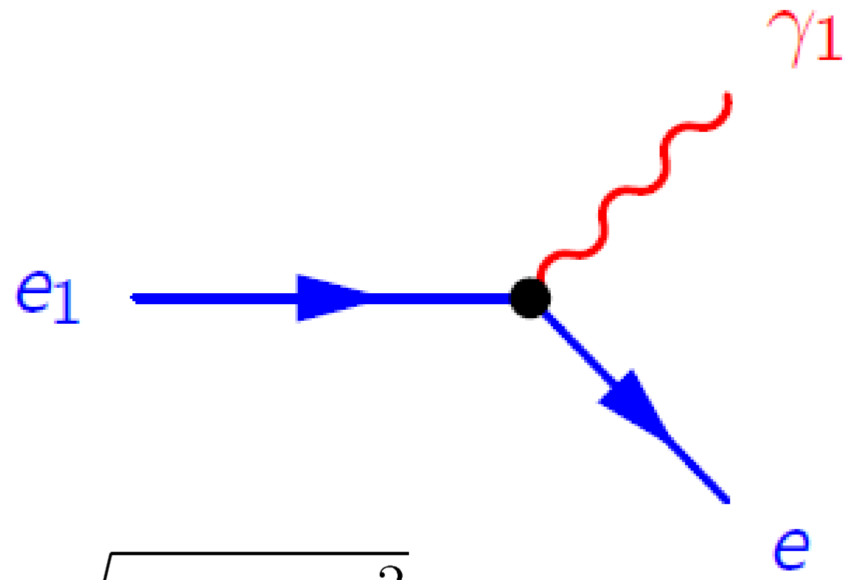
$$\psi^{R,L}(x) \to \psi^{\pm}(x,y)$$
$$A_\mu(x) \to A_M(x,y)$$
$$\phi(x) \to \phi(x,y)$$

$S^1/\mathcal{Z}_2$ orbifold — SM Gauge group — SM field content

brane localised terms are zero at the cutoff scale



The role of radiative corrections



$$\sqrt{m_e^2 + \frac{1}{R}^{2}} < m_e + \frac{1}{R} (!!!)$$

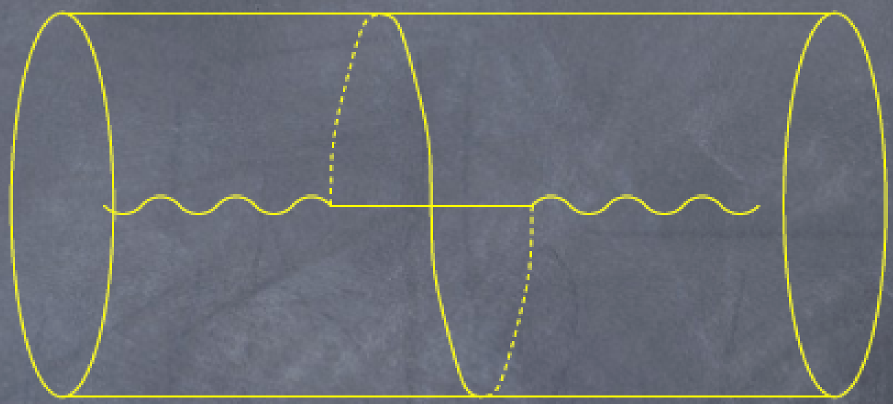
e.g. the 1st KK excitation of the electron is stable at tree-level!

Dark Matter would be charged – which is not acceptable

MUED at one loop

Cheng, Matchev, Schmaltz
2002

Loop corrections come from 5D Lorentz violating processes. They appear as tree-level mass corrections in 4D.



- Bulk corrections :

the gauge bosons receive an extra mass which is KK-independent

$$\delta m_n^2 = \alpha_i \frac{1}{R^2}$$

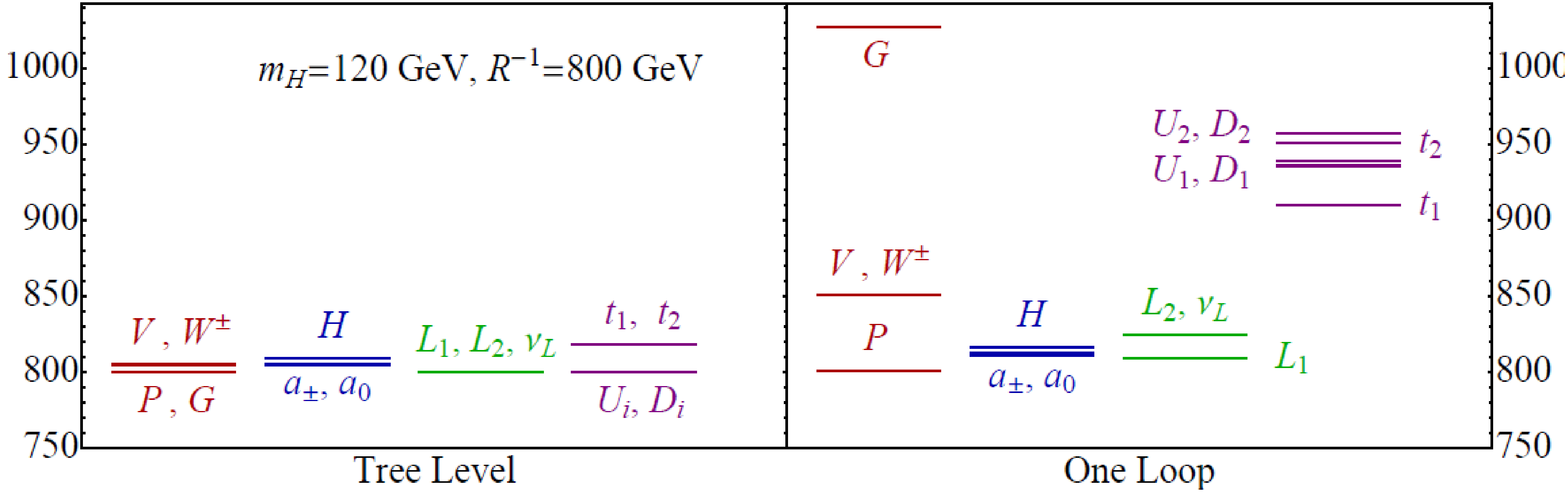
- Brane corrections : p_5 is not conserved, all particles receive a mass correction

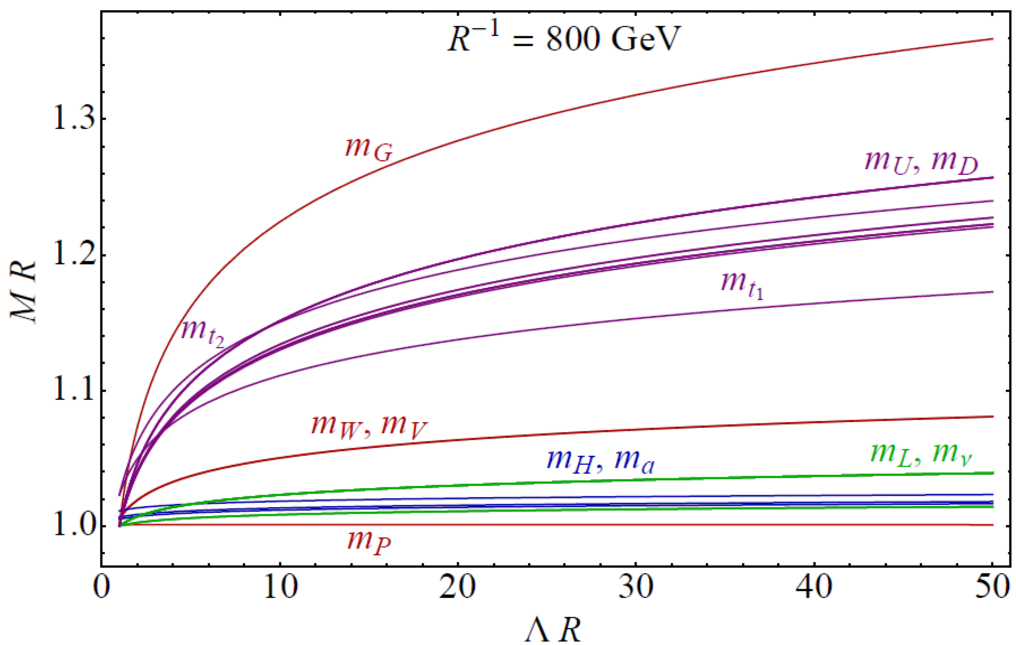
$$\delta m_n = \beta_i \frac{n}{R} \ln \frac{\Lambda^2}{\mu^2} \qquad \text{for fermions}$$

$$\delta m_n^2 = \beta_i \frac{n^2}{R^2} \ln \frac{\Lambda^2}{\mu^2} \qquad \text{for bosons}$$

Problem : Electroweak symmetry breaking was not included

MUED spectrum at 1loop vs tree-level





Model implementation

- MUED is implemented in Feynman and unitary gauges in LanHEP (generates the Feynman rules out of a Lagrangian) [AB,Brown,Moreno,Papineau arXiv:1212.4858] (BBMP)

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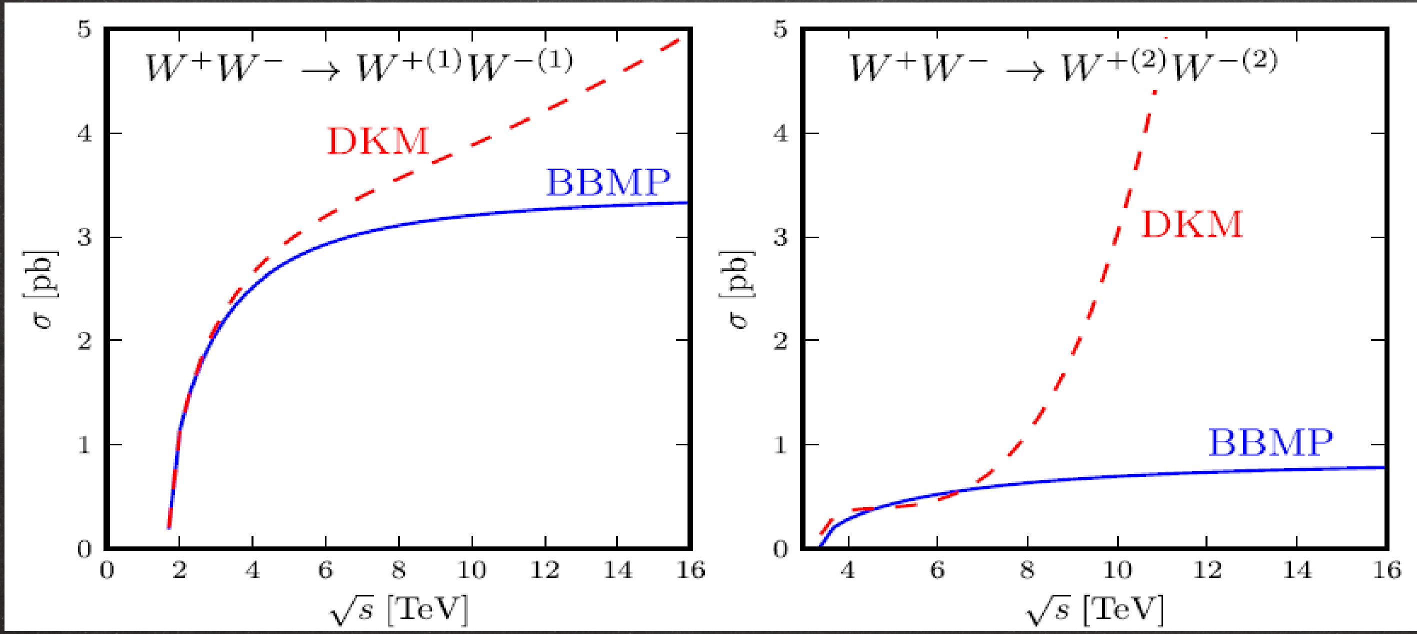
- Compared and Validated against existing implementation by Datta,Kong,Matchev, arXiv:1002.4624 (DKM) and private implementation form Belanger, Semenov, Pukhov,Kakizaki.



If the sum of KK numbers of the external particles is 5 or less [<2*(n+1) in general] gauge invariance is ensured

Proper implementation of the Higgs sector lead to the correct High Energy asymptotic which respects Unitarity

EW precision constraints

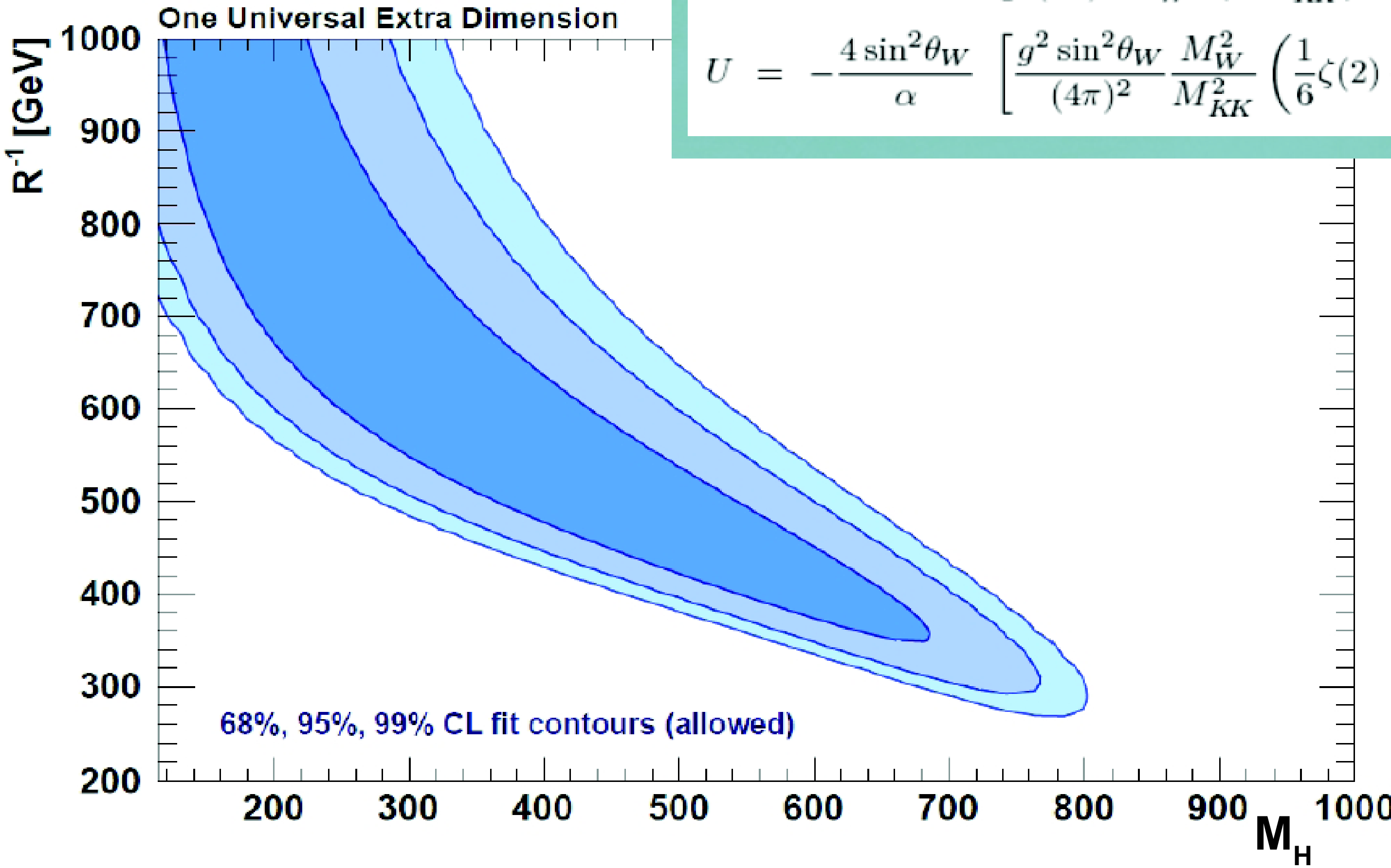
The tower of KK particles modify the gauge bosons self-energies, contributing to the S,T, and U electroweak parameters:

T. Appelquist H.-U. Yee 2001
I. Gogoladze and C. Macesanu, 2006

$$S = \frac{4\sin^2\theta_W}{\alpha}\left[\frac{3g^2}{4(4\pi)^2}\left(\frac{2}{9}\frac{m_t^2}{M_{KK}^2}\right)\zeta(2) + \frac{g^2}{4(4\pi)^2}\left(\frac{1}{6}\frac{M_H^2}{M_{KK}^2}\right)\zeta(2)\right],$$

$$T = \frac{1}{\alpha}\left[\frac{3g^2}{2(4\pi)^2}\frac{m_t^2}{M_W^2}\left(\frac{2}{3}\frac{m_t^2}{M_{KK}^2}\right)\zeta(2) + \frac{g^2\sin^2\theta_W}{(4\pi)^2\cos^2\theta_W}\left(-\frac{5}{12}\frac{M_H^2}{M_{KK}^2}\right)\zeta(2)\right],$$

$$U = -\frac{4\sin^2\theta_W}{\alpha}\left[\frac{g^2\sin^2\theta_W}{(4\pi)^2}\frac{M_W^2}{M_{KK}^2}\left(\frac{1}{6}\zeta(2) - \frac{1}{15}\frac{M_H^2}{M_{KK}^2}\zeta(4)\right)\right],$$



Gfitter

arXiv: 1107.0975

FCNC and DM constraints

FCNC

K. Agashe, N.G. Deshpande, G.-H. Wu
L. A. J. Buras, A. Poschenrieder, M. Spranger, A. Weiler

KK modes will give contributions to FCNC processes . From $b \to s\gamma$

$$1/R > 600 \text{ GeV}$$

Cosmology (DM)

Belanger, Kakizaki, Pukhov

The evaluation of the LKP relic abundance depends on the spectrum details and on the number of KK levels included in the calculation (eg level 2 resonances, level 2 particles in the final state, etc) Electroweak symmetry breaking effects are also important.

Matsumoto, Senami '05; Kong, Matchev '05
Brunel, Kribs '05; Belanger, Kakizaki, Pukhov '10
....

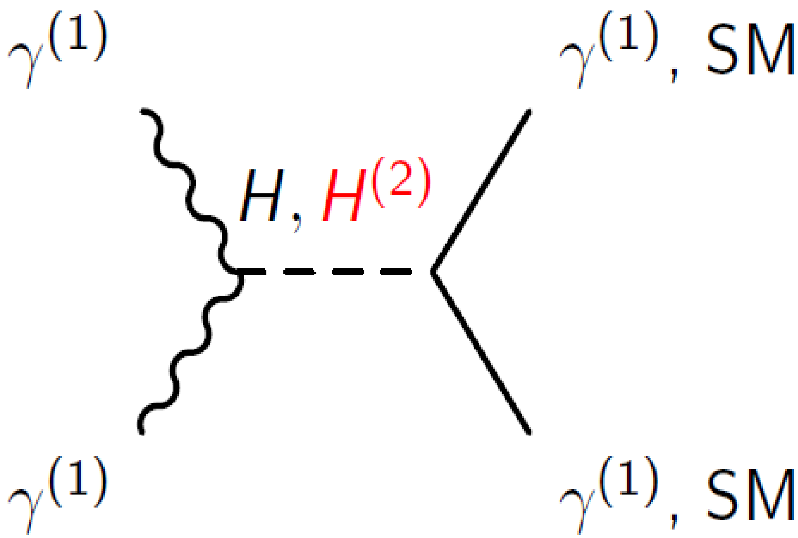
Plank/WMAP set bound from above to DM scale: if DM were heavier it would lead to the Universe having a measurable positive curvature

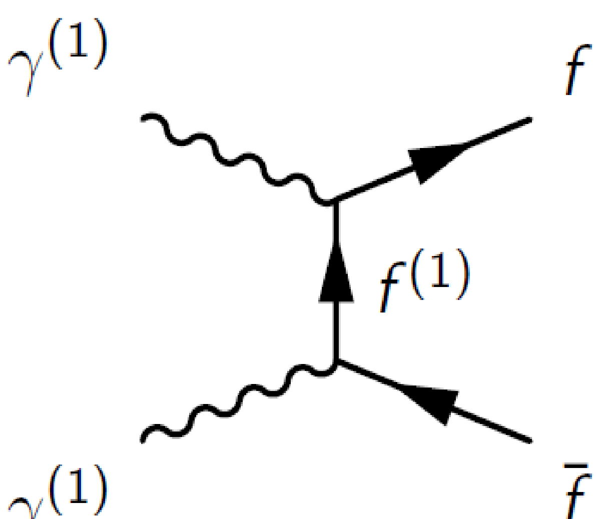
$$1/R < 1.6 \text{ TeV}$$

The role of the 2nd level of KK excitation

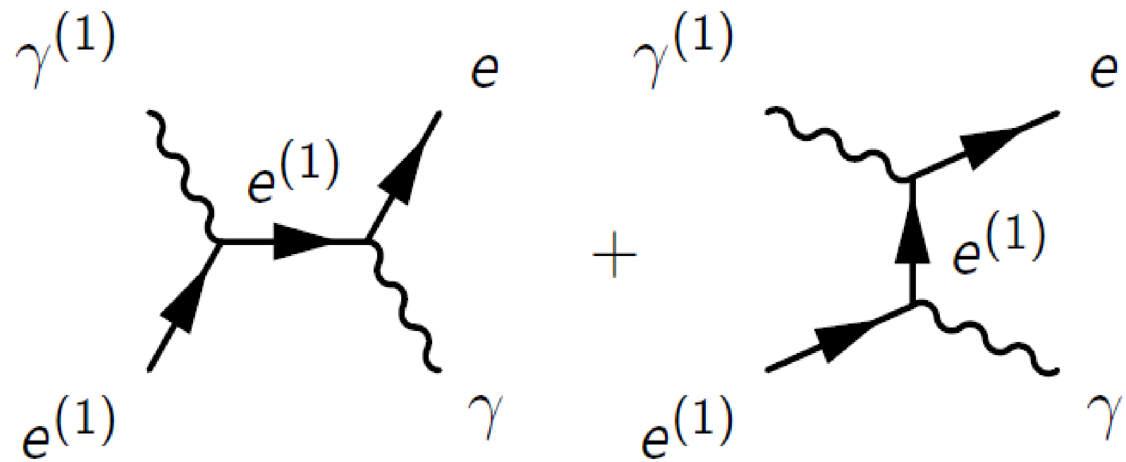
Processes important for calculating DM relic abundance. . .

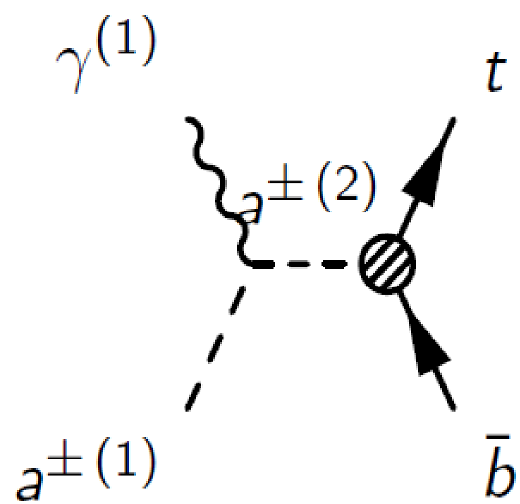
Self-annihilation

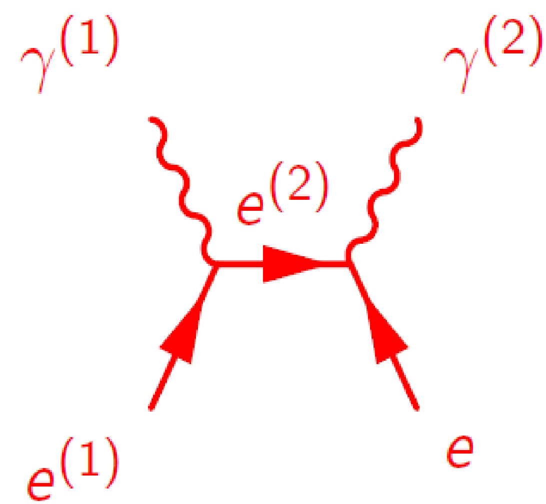




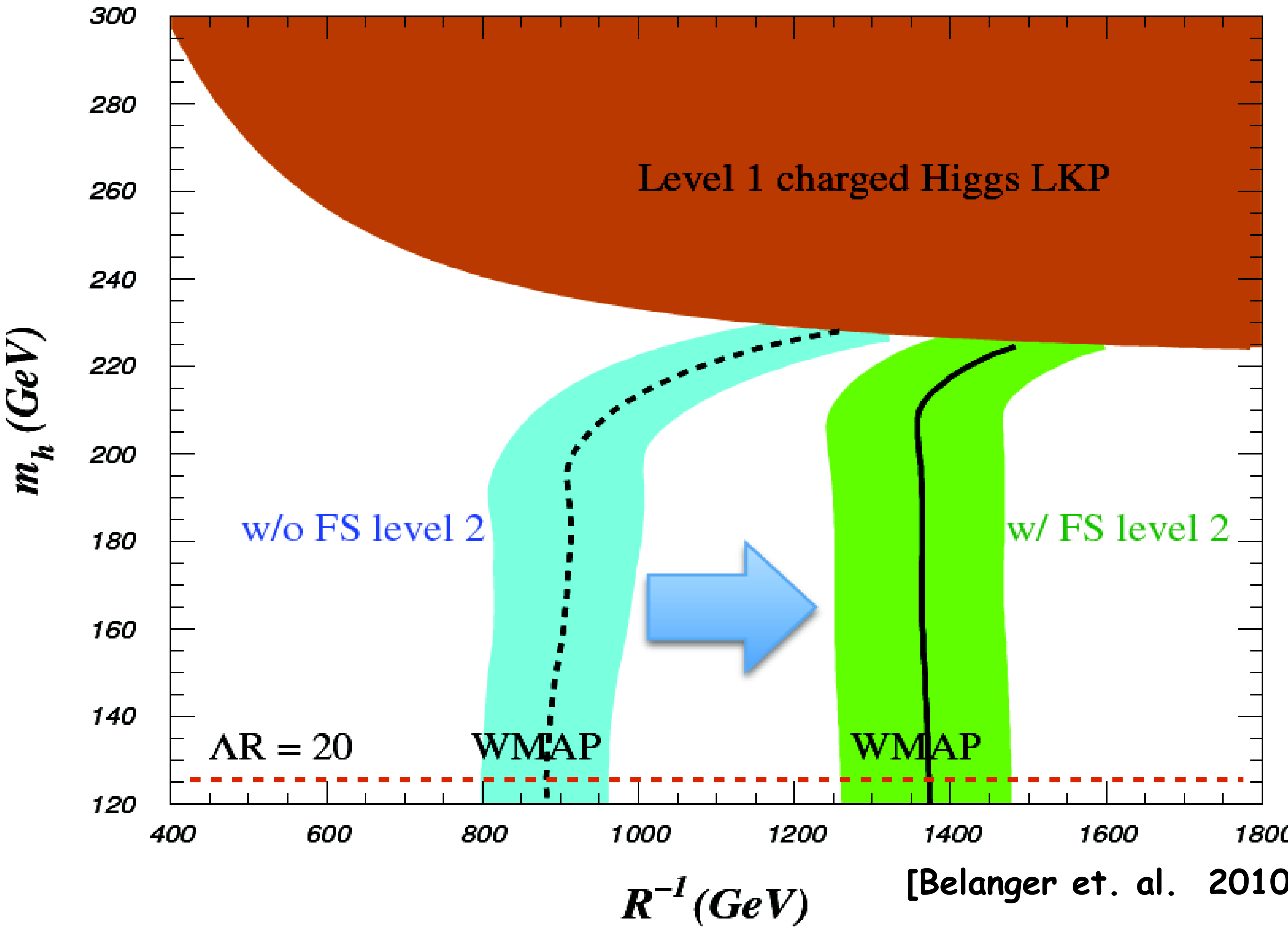
Co-annihilation





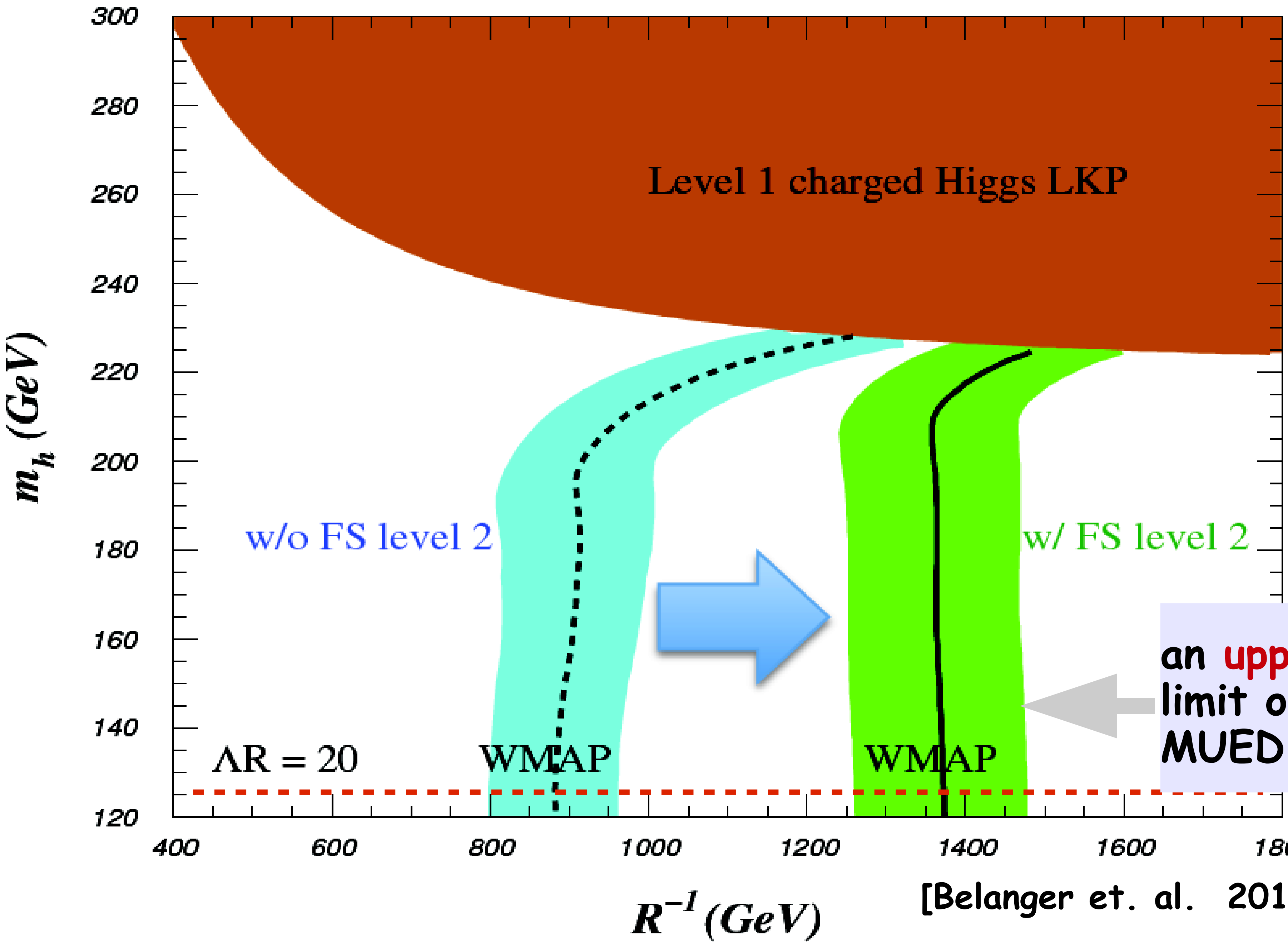


The role of the 2nd level of KK excitation



[Belanger et. al. 2010]

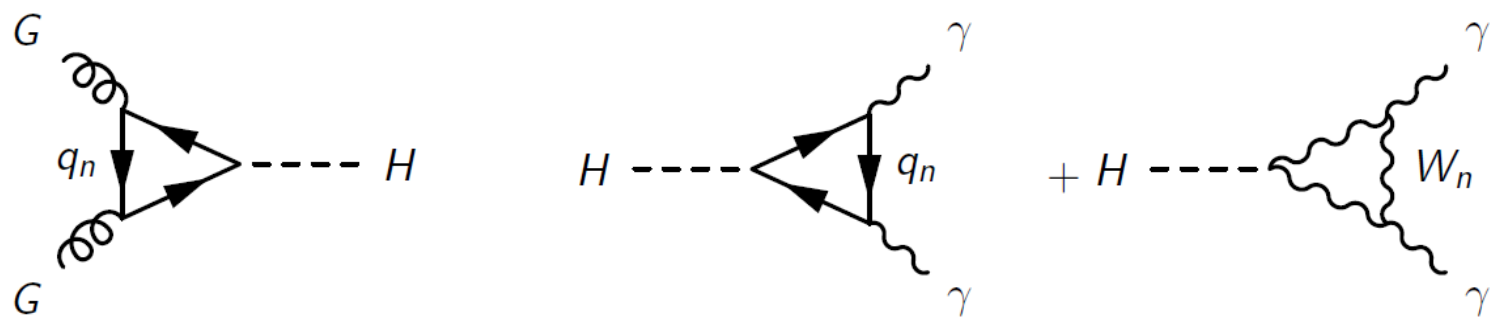
The role of the 2nd level of KK excitation

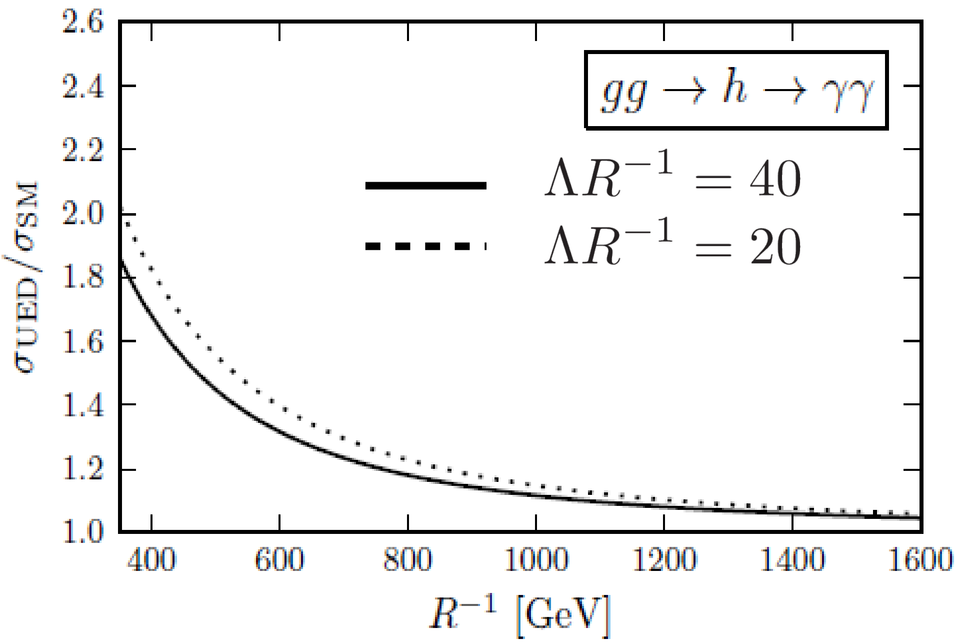


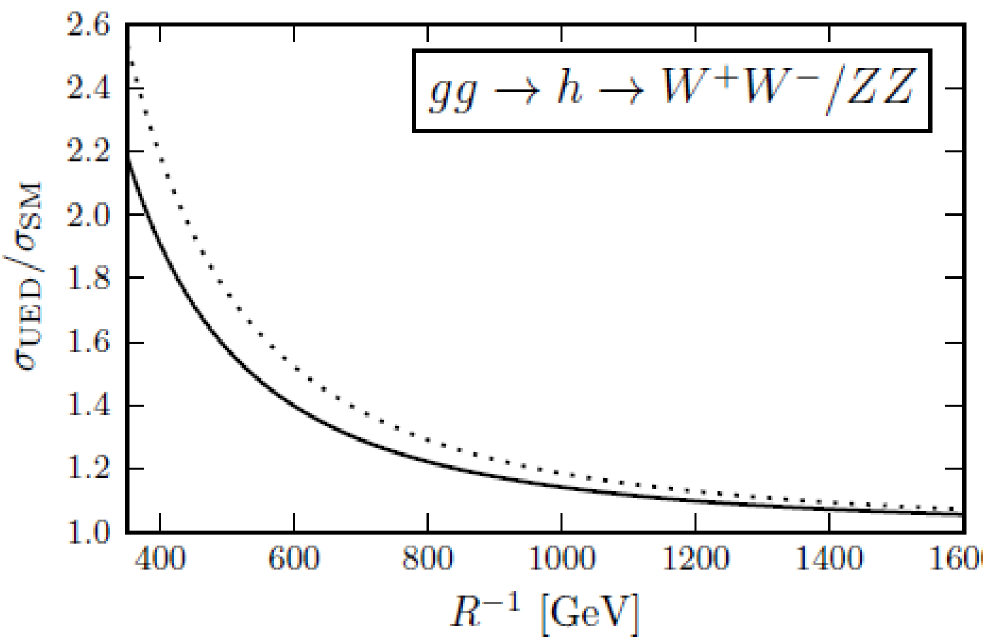
an upper limit on the MUED scale!

[Belanger et. al. 2010]

Constraints from the Higgs data



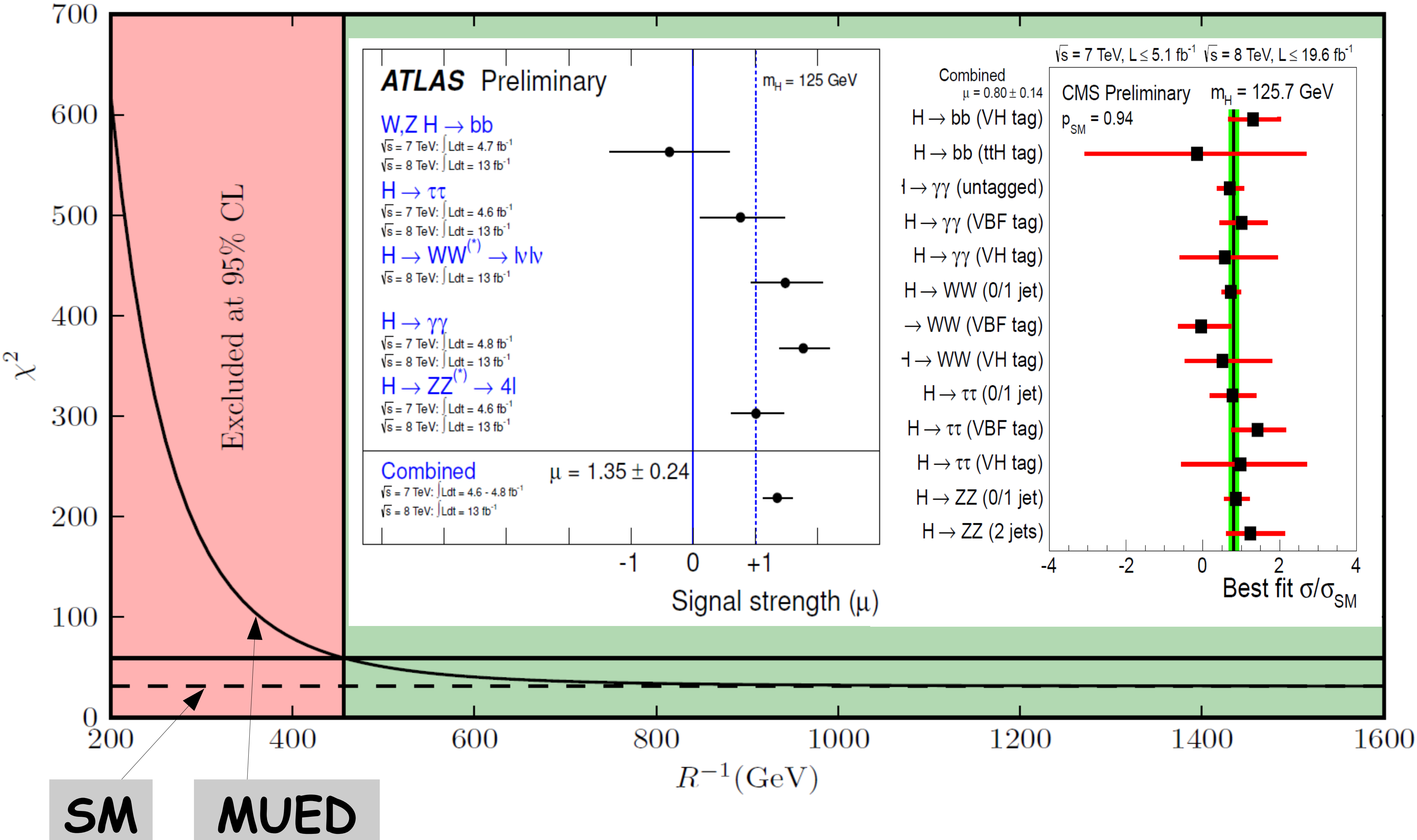




- **Production is enhanced**
- **Decay is slightly suppressed**
- **Overall, the GG->H->γγ is enhanced**

AB, Belanger, Brown, Kakizaki, Pukhov '12

Data Fit with MUED vs SM



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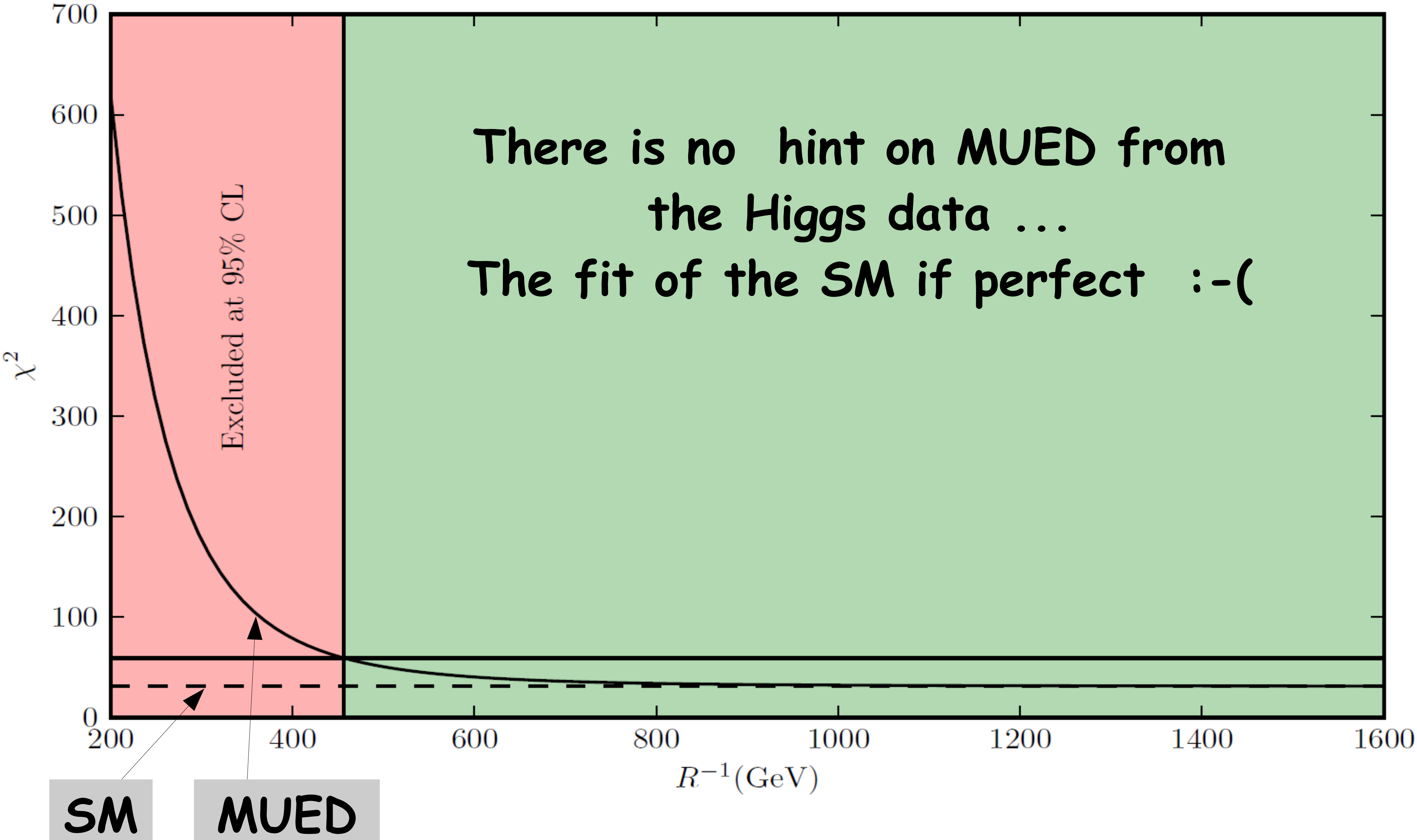

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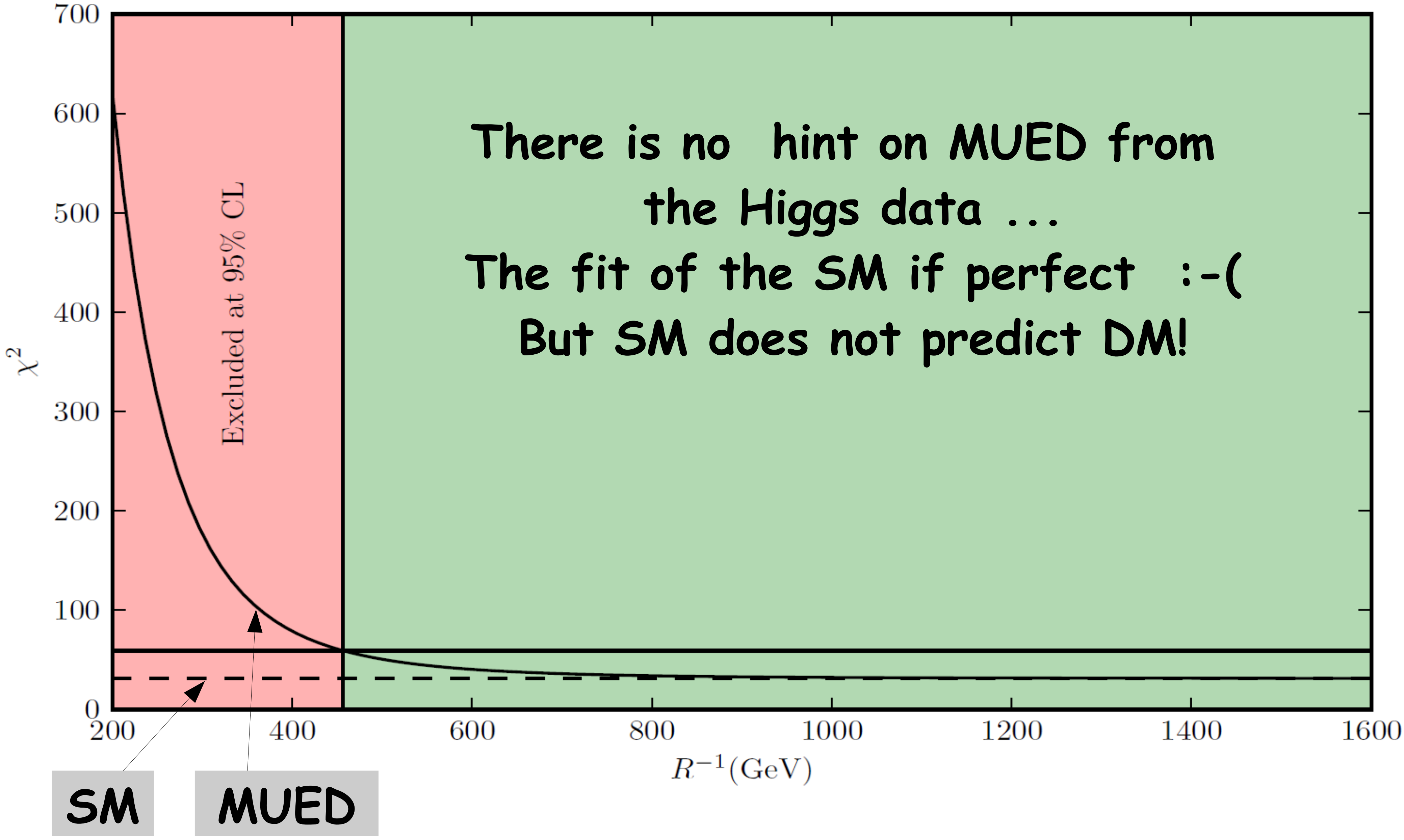
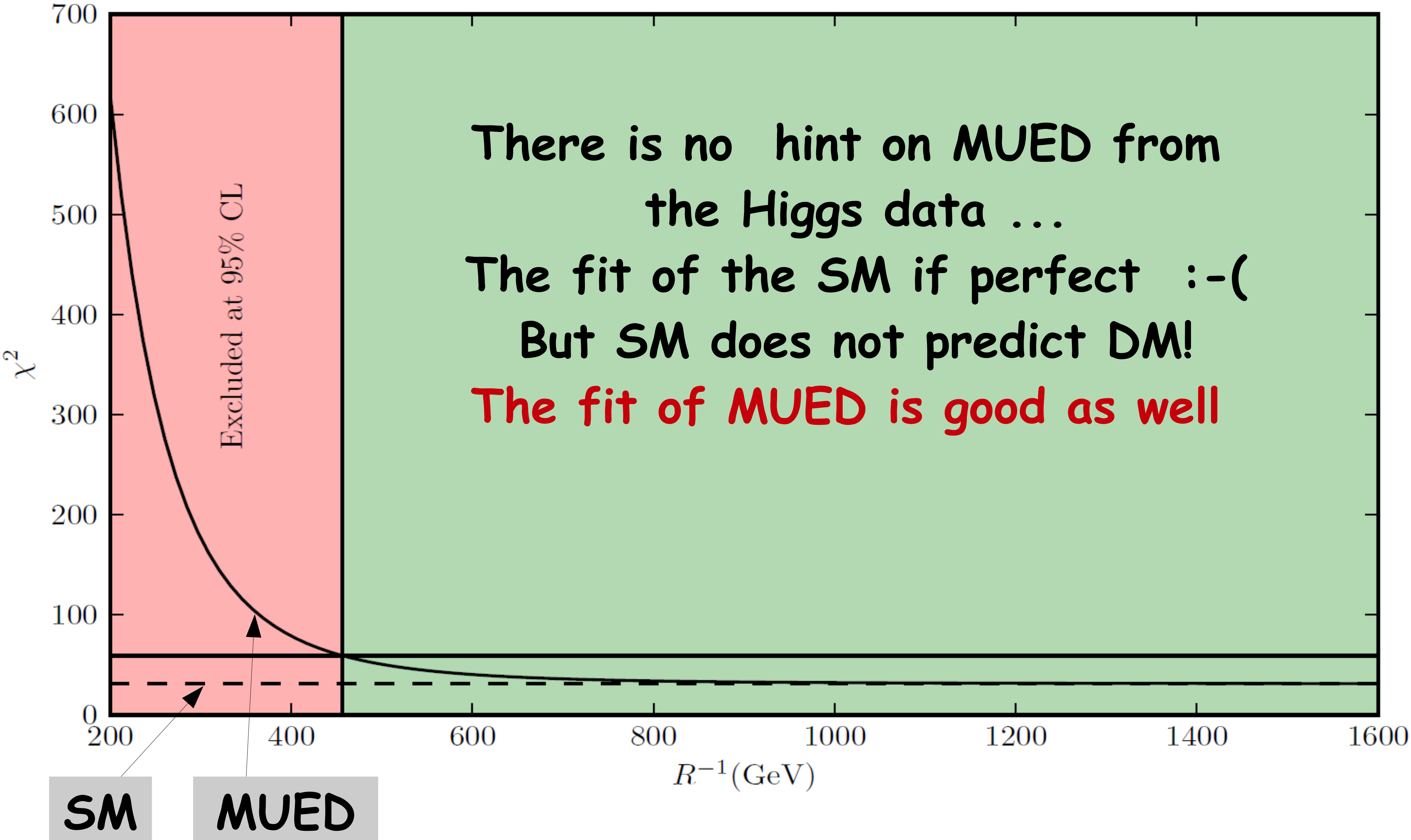
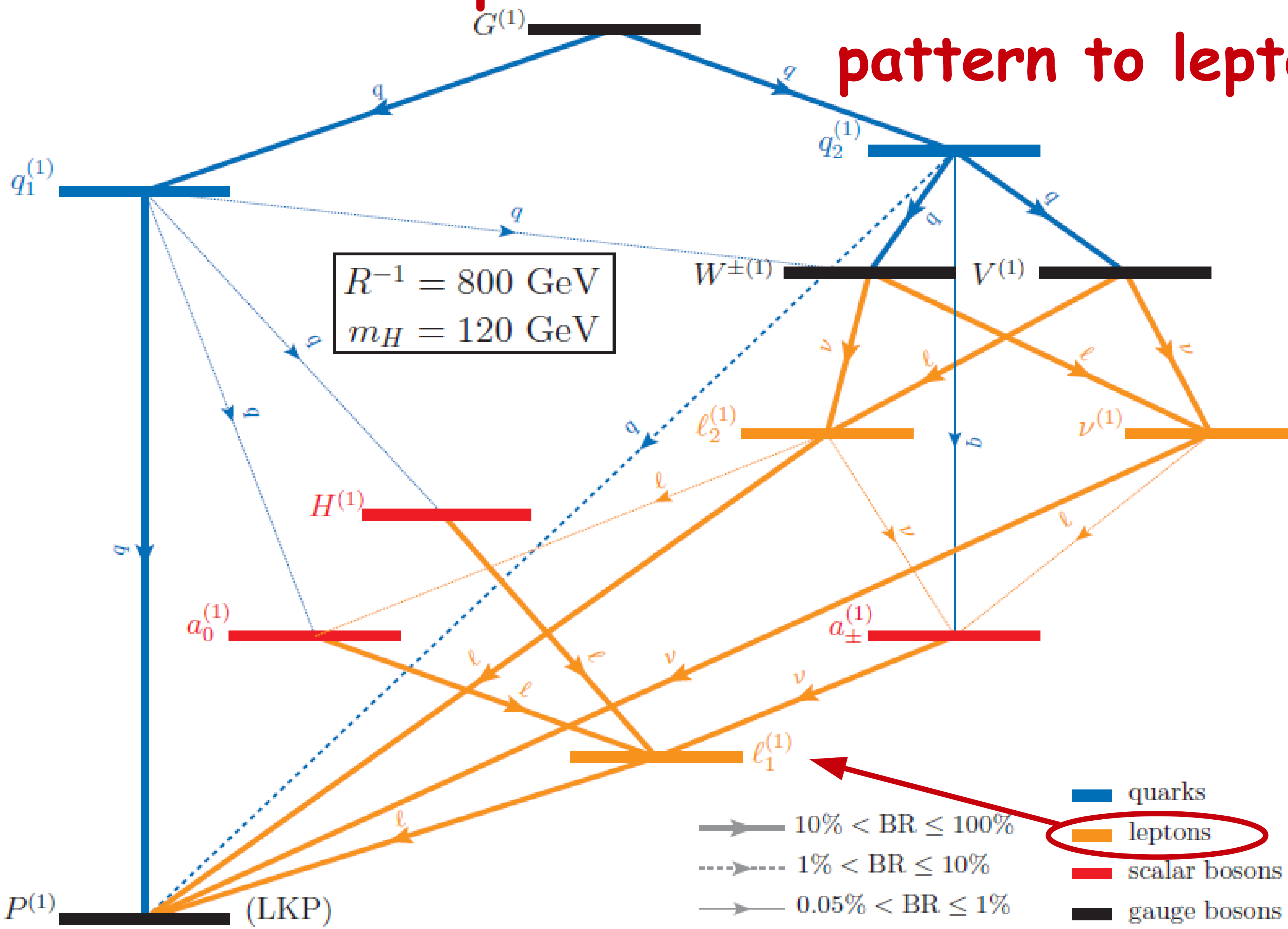


There is no hint on MUED from the Higgs data ...
The fit of the SM if perfect :-(
But SM does not predict DM!

Data Fit with MUED vs SM



mUED: the mass spectrum defines dominant decay pattern to leptons!!!



$$M_{G^{(1)}} > M_{q^{(1)}} > M_{W^{(1)}}, M_{Z^{(1)}} > M_{l^{(1)}} > M_{\gamma^{(1)}}$$

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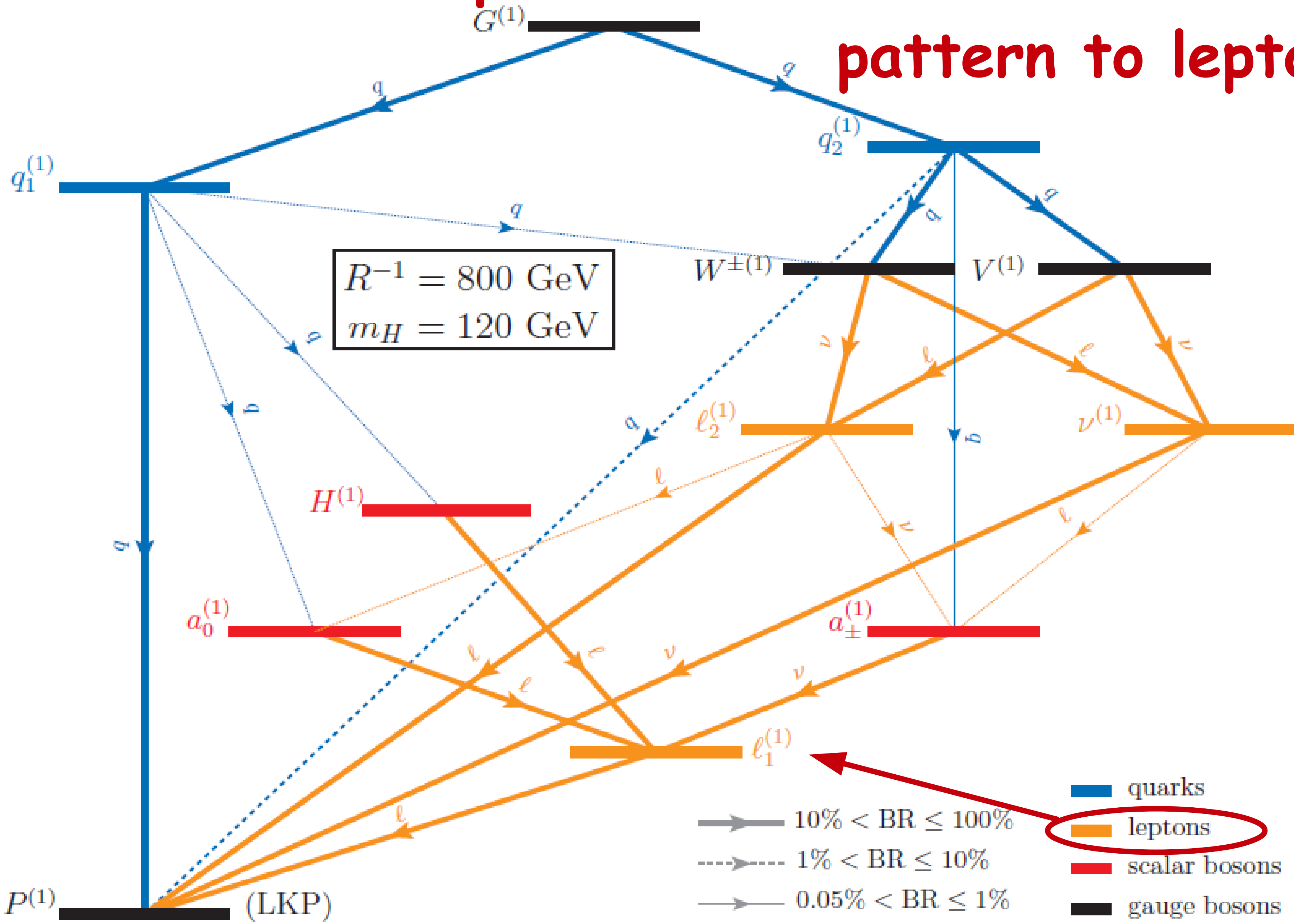
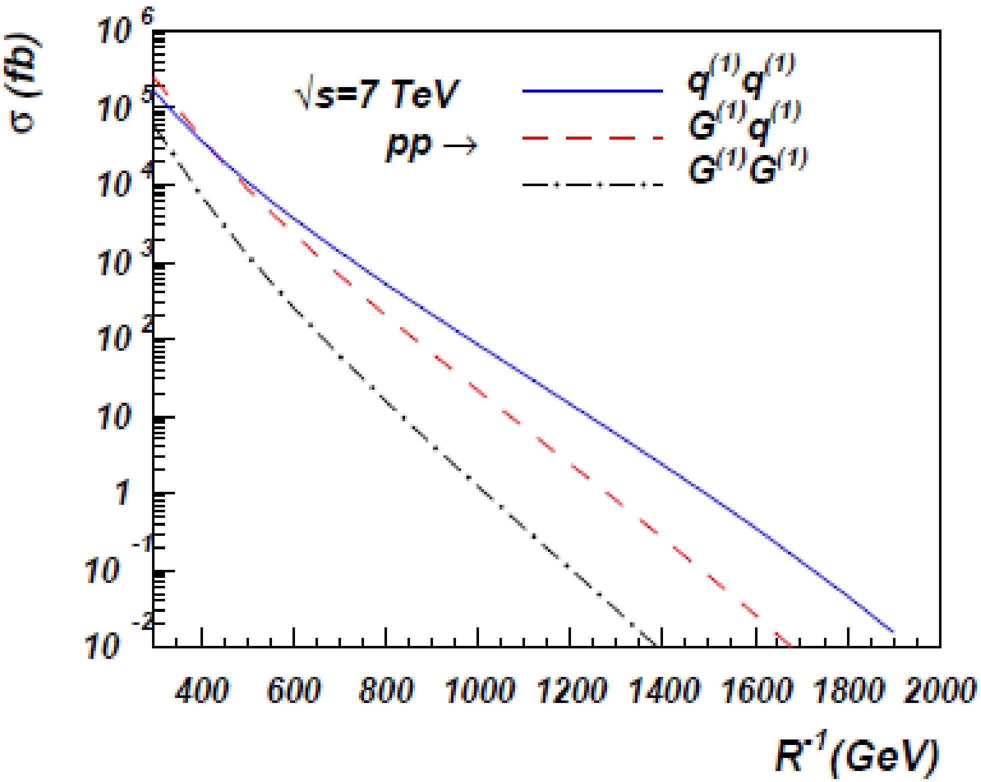


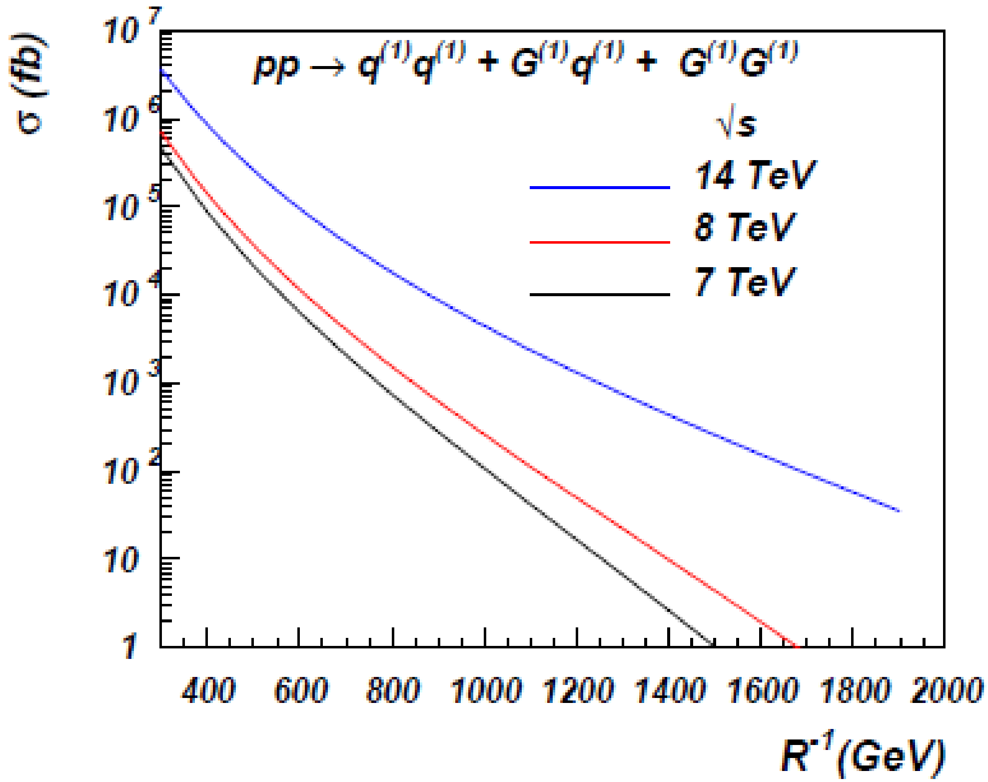
$$M_{G^{(1)}} > M_{q^{(1)}} > M_{W^{(1)}}, M_{Z^{(1)}} > M_{l^{(1)}} > M_{\gamma^{(1)}}$$

Can SUSY have this pattern?!

mUED collider phenomenology with leptons

AB, Brown, Moreno, Papineau'12





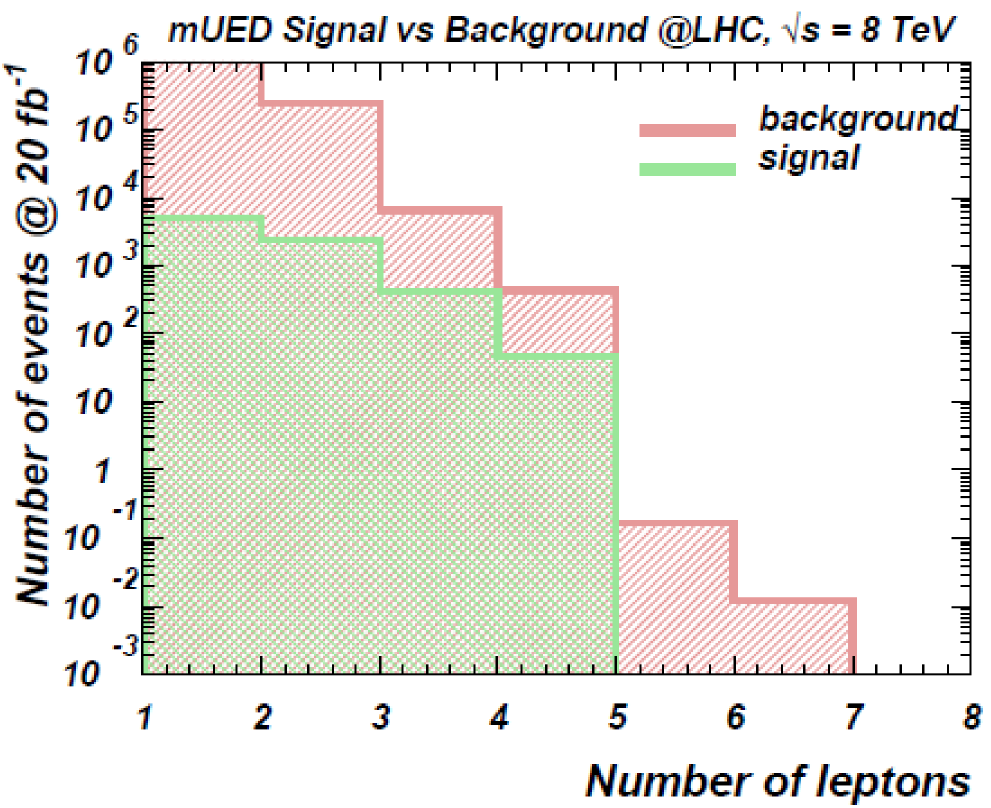
Q^1 Q^1 production rate is the highest

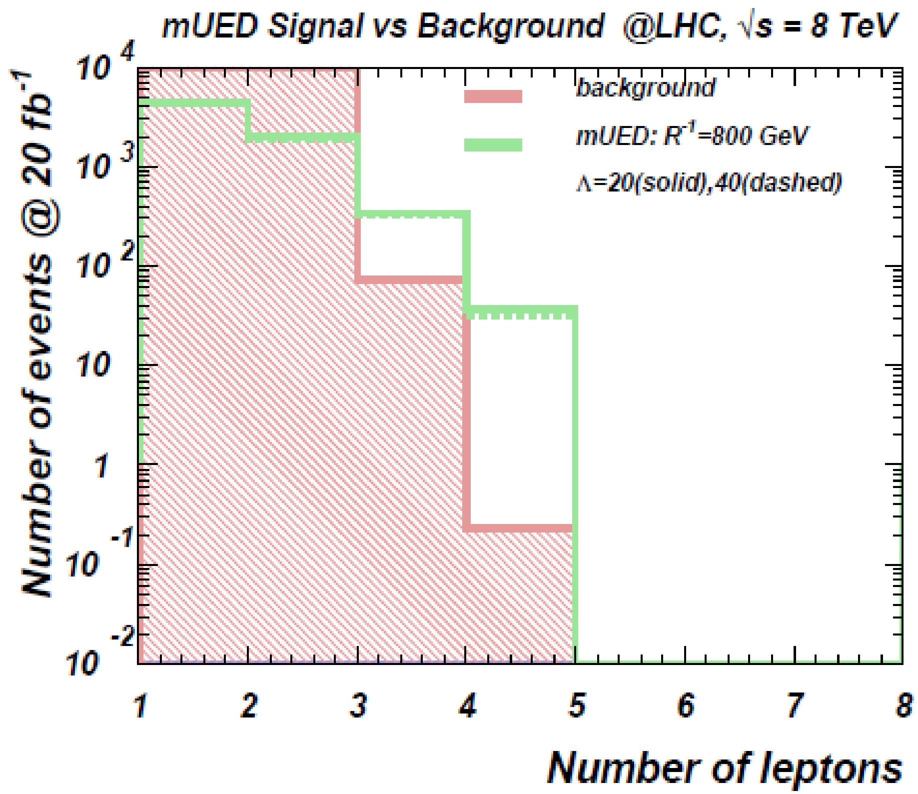
mUED collider phenomenology with leptons

Lepton multiplicity:

AB, Brown, Moreno, Papineau'12

Signal vs BG before (left) and after(right) selection cuts





$P_T^{\ell_1} > 20$ GeV, $P_T^{\ell}(\text{all}) > 10$ GeV, $|\eta_\ell| < 2.5$, $\Delta R_{\ell j} = \sqrt{\Delta\phi_{\ell j}^2 + \Delta\eta_{\ell j}^2} > 0.5$

$|m_Z - M_{\ell\bar{\ell}}| > 10\,\text{GeV}$

$\not{P}_T > 50\,\text{GeV}$

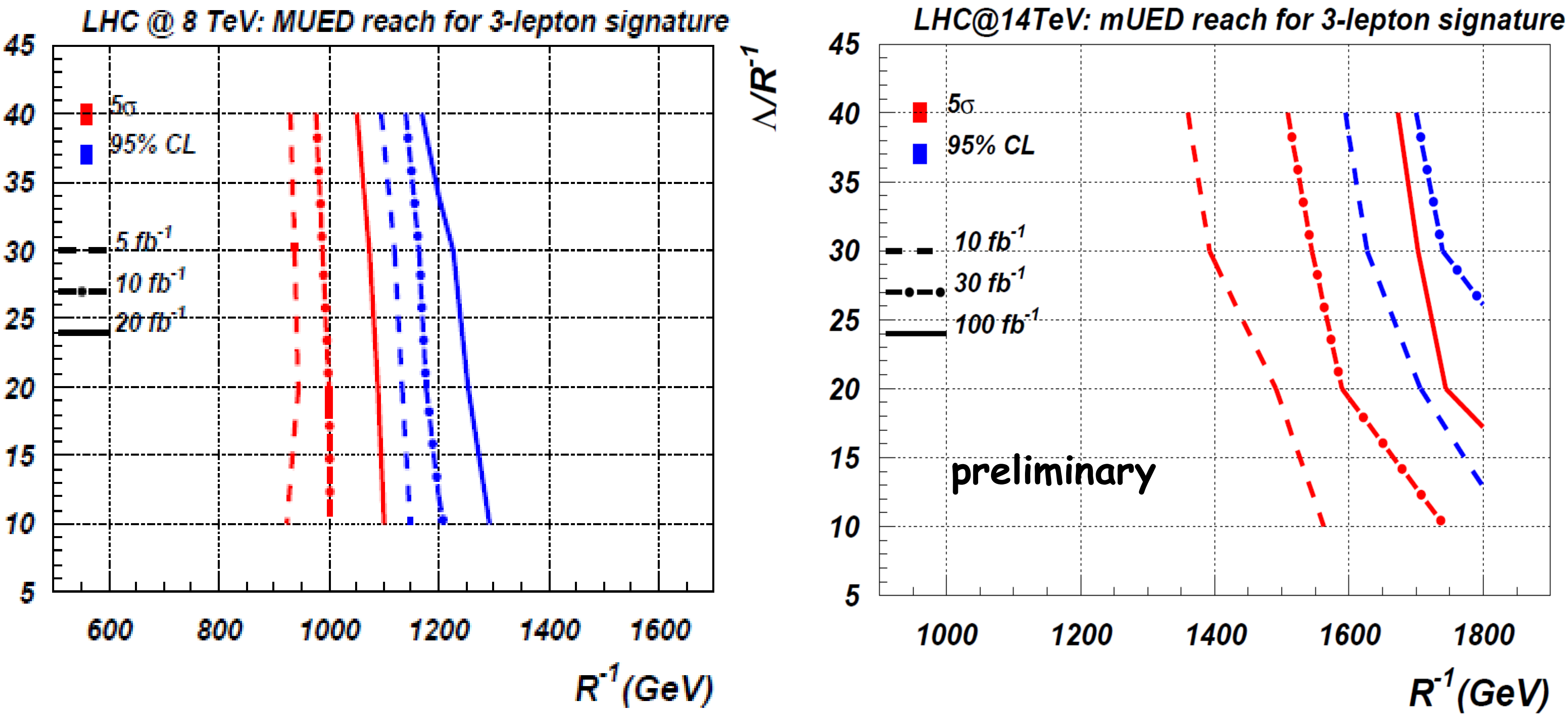
$P_T^{\ell_1} < 100\,\text{GeV}$; $P_T^{\ell_2} < 70\,\text{GeV}$; $P_T^{\ell_3} < 50\,\text{GeV}$

$M_{\text{eff}} > R^{-1}/5$ $\quad M_{\text{eff}} = \not{P}_T + \sum_{\ell,j} P_T$

Selection/Analysis cuts

mUED collider phenomenology with leptons

AB, Brown, Moreno, Papineau'12

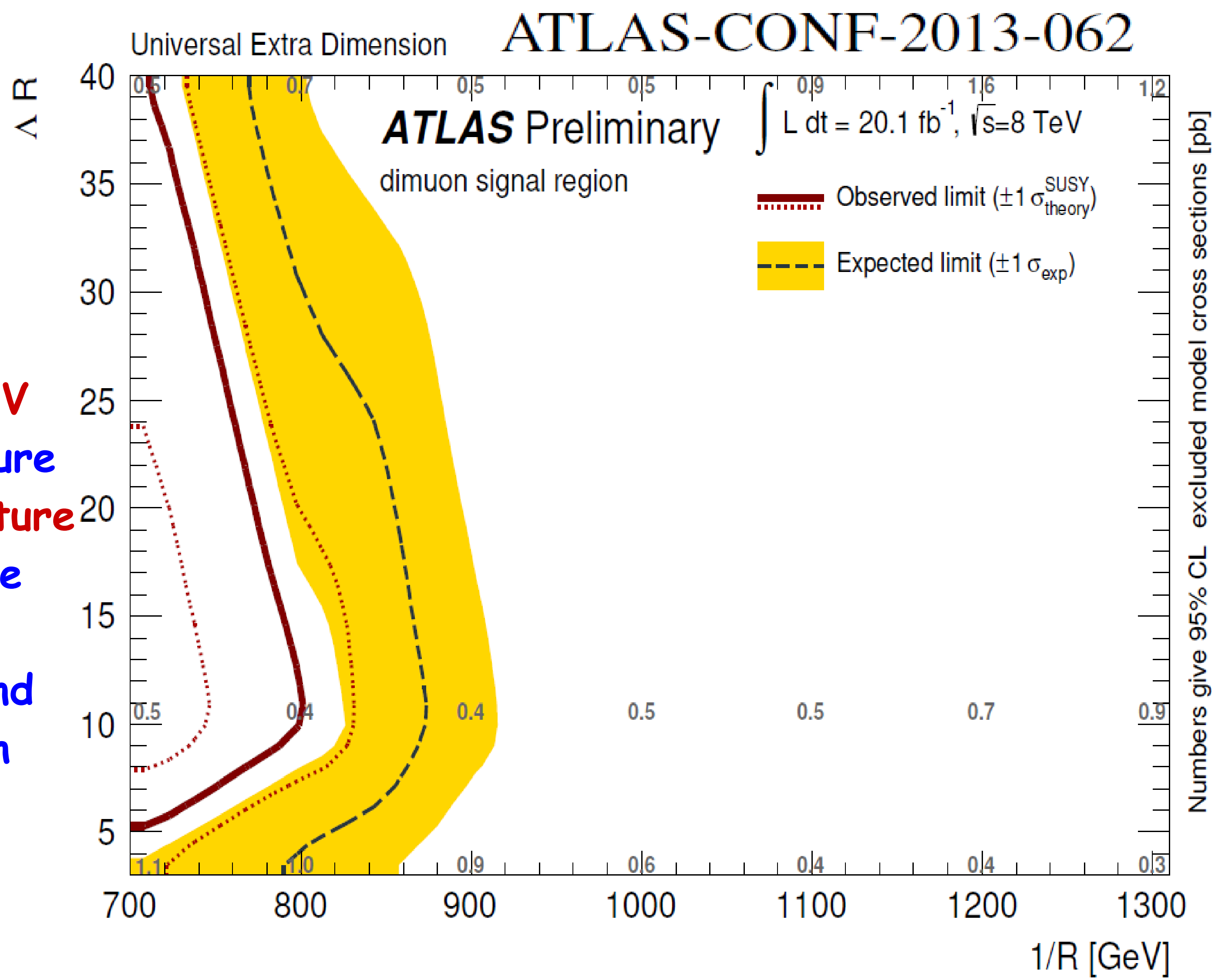


- Small mass gap (as compared to MSSM) – much lower missing PT
- Quite a few PHENO papers, but there is only one (ATLAS) dedicated study the projected limit from this study: R^{-1} > 1.2—1.3 TeV
- 3-lepton signature – is very promising: LHC@13/14 will eventually discover or close MUED!

First Results from Atlas!

- Di-muon channel
- Herwig++ for signal

- Limits are stronger than from loop-induced processes: 800-900 GeV vs 600 GeV based on dilepton signature
- But from trilepton signature we expect the limit to be ~1.2 TeV
- Because the reducible and irreducible BGs are much higher for 2-lepton signature, while signal difference is small



UED summary

- UED are limited from above by DM relic abundance and from below by the LHC searches
  LHC and DM search experiments provide an important test: LHC@13 TeV will discover or exclude the complete parameter space for 5 & 6D UED

- There is only one (ATLAS) limit on MUED from di-muon signature only!
  3-lepton signal is very promising for MUED at the LHC.

- Consistent MUED with EWSB and loop-corrections is implemented into LanHEP and publicly available at HEPMDB [CalcHEP and UFO(Madgraph5) formats are available].
  It is ready to be used by experimentalists and theorists!

Rundal Sundrum ("warp scenario")[1999]

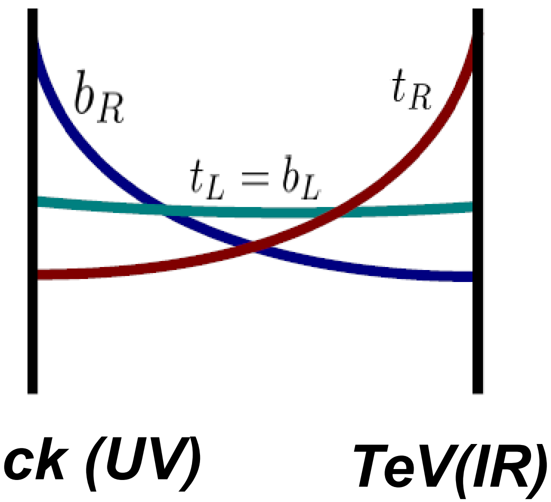
- a warped geometry is described by a metric of the form

$$ds^2 = e^{2A(y)} dx_4^2 + g_{mn}(y) dy^m dy^n$$

- where $dx_4^2 = \eta_{\mu\nu} dx^\mu dx^\nu$ is the 4D Minkowski line element

  y^n parameterise the XD of space-time, with metric g_{mn}
- The function e^A is the warp factor, defining 4D massscales
- gravity propagates in the compact & non-compact directions
- The 4D Newton's constant is related to the the D dimensional one by

$$G_N^{-1} = G_D^{-1} \int d^{D-4} y \sqrt{g}\, e^{2A}$$



- 4D Planck scale M_D exponentially suppressed by the warp factor

$$M_D = M_{PL} exp(-\pi k R)$$

where *k,R* are related to A(y)

Technicolor

EWSB from Technicolor: (Weinberg 78, Susskind 78)

1. In the SM without a Higgs, QCD breaks the EW symmetry:

(Farhi & Susskind 81)

$$\langle \bar{u}_L u_R + \bar{d}_L d_R \rangle \neq 0 \quad \to \quad M_W = \frac{g f_\pi}{2} \,.$$

2. Consider a new strongly interacting gauge theory with $F_\Pi = v_{EW} = 246 GeV$.
3. Let the electroweak gauge group be a subgroup of the chiral symmetry group.

Left-handed technifermions in weak doublets,
right-handed in weak singlets

$$Q^a_L = \begin{pmatrix} U^a \\ D^a \end{pmatrix}_L, \; Q^a_R = (U^a_R, D^a_R),$$
$$a = 1, \ldots d(\mathcal{R}_{TC})$$

At the weak scale, the technifermions condense and break the weak symmetries correctly to EM:

$$\langle \bar{U}_L U_R + \bar{D}_L D_R \rangle \neq 0$$

Technicolor

In QCD at a scale Λ_{QCD} the interaction becomes strong and the quarks form a bound state with non-zero vev:

$$\langle 0|\, \bar{u}_L u_R + \bar{d}_L d_R \,|0\rangle \neq 0\,,\ T_L^3 + Y_L = Y_R = Q \ \Rightarrow\ SU(2)_L \times U(1)_Y \to U(1)_{EM}$$

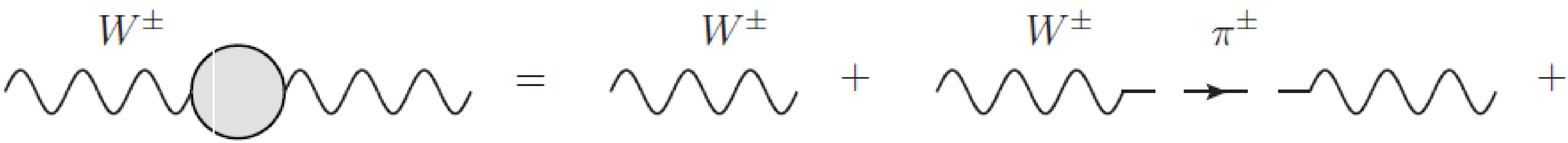
Redefine fields in terms of composite colorless states, like pions:

$$q = (u, d)\,,\ j^\mu_{5a} = \bar{q}\gamma^\mu\gamma^5\frac{\tau_a}{2}q = f_\pi \partial^\mu \pi_a$$

and plug in $\mathcal{L}_{k-f}$

$$\mathcal{L}_{k-f} \supset \frac{g}{2} f_{\pi^+} W^+_\mu \partial^\mu \pi^+ + \frac{g}{2} f_{\pi^-} W^-_\mu \partial^\mu \pi^- + \frac{g}{2} f_{\pi^0} W^0_\mu \partial^\mu \pi^0 + \frac{g'}{2} f_{\pi^0} B^+_\mu \partial^\mu \pi^0$$

Technicolor



$$= \frac{1}{p^2} + \frac{1}{p^2}(g f_{\pi^\pm}/2)^2 \frac{1}{p^2} + \ldots = \frac{1}{p^2 - (g f_{\pi^\pm}/2)^2}$$

The EW bosons have acquired mass:

$$M_W^{QCD} = g f_{\pi^\pm}/2, \;\; \rho = \frac{M_W^{QCD}}{\cos\theta_w M_Z^{QCD}} = 1,$$

Given the experimental value for the pion decay constant

$$f_\pi = 93\,\mathrm{MeV} \quad \Rightarrow \quad M_W^{QCD} = 29\,\mathrm{MeV}!$$

Technicolor

The effective Lagrangian expansion breaks down at

$$\Lambda_{QCD} \simeq 4\pi f_\pi = 1.2\,\mathrm{GeV} \Rightarrow \Lambda_{TC} \simeq 4\pi v = 3\,\mathrm{TeV}, \;\; v = 246\ \mathrm{GeV}\,.$$

A Technicolor (TC) model able to give the right masses to the EW gauge bosons is simply "scaled up" QCD:

$$SU(N)_{TC} \times SU(3)_C \times SU(2)_L \times U(1)_Y\,.$$

No fundamental scalar $\Rightarrow$ no fine-tuning!

The mass spectrum can be estimated by multiplying the mass of QCD composite states by v/f_π.

New Strong Sector

1. The SM gauge group is augmented:

$$G_{SM} \to SU(3)_{\mathrm{c}} \times SU(2)_{\mathrm{W}} \times U(1)_{\mathrm{Y}} \times G_{\mathrm{SD}} \;.$$

(SD=Strong Dynamics/Technicolor)

2. The Higgs sector of the SM is replaced:

$$\mathcal{L}_{Higgs} \to -\frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} + i\bar{Q}_{\mathrm{L}}\gamma_\mu D^\mu Q_{\mathrm{L}} + i\bar{Q}_{\mathrm{R}}\gamma_\mu D^\mu Q_{\mathrm{R}} + \ldots$$

$$\langle \bar{U}_L U_R + \bar{D}_L D_R \rangle \sim F^3_\Pi \to M_W = \frac{gF_\pi}{2}$$

Minimal chiral symmetries: 3 GB's + Custodial + DM.

$$SU_L(2) \times SU_R(2) \times U_{TB}(1) \to SU_V(2) \times U_{TB}(1) \;.$$

Minimal fermion content:
2 Dirac techni-fermions in a weak doublet,
TC charge but no QCD charges:

$$Q^a_{\mathrm{L}} = \begin{pmatrix} U^a \\ D^a \end{pmatrix}_{\mathrm{L}}, \quad Q^a_R = (U^a_{\mathrm{R}}, D^a_{\mathrm{R}}),$$
$$a = 1, \ldots d(\mathcal{R}_{\mathrm{TC}})$$

Higgs boson mass

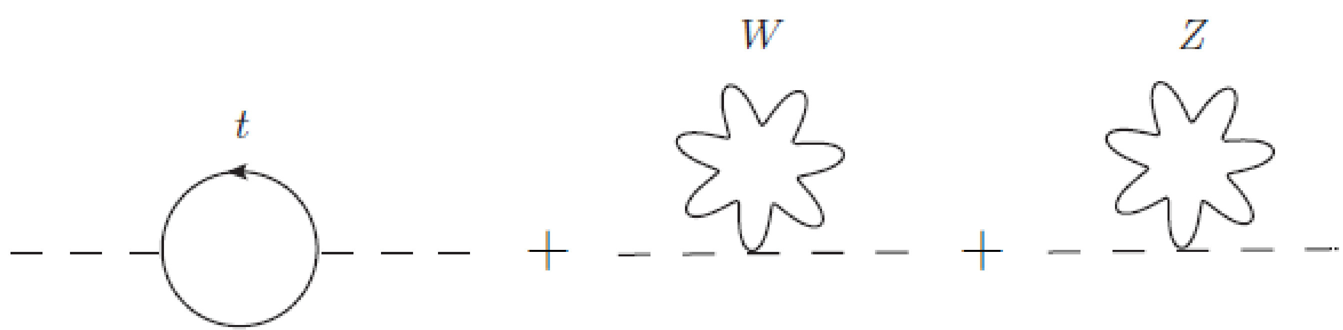
In QCD the composite scalar is σ (or $f_0(500)$ in PDG):

$$M_\sigma = 400 - 550 \text{ MeV} \quad \Rightarrow \quad M_H^{TC} \simeq M_\sigma v/f_\pi = 1 - 1.4 \text{ TeV}$$

To this estimate one must add also the (Higgsless) SM loop corrections:

$$M_H^2 \simeq (M_H^{TC})^2 + \frac{3 f_\Pi^2}{v^2}\left[-4 r_t^2 m_t^2 + 2 s_\pi \left(m_W^2 + \frac{m_Z^2}{2}\right)\right], \quad r_t, s_\pi = O(1)\,.$$

$\Delta M_H^2 =$



For "scaled up" QCD: $f_\Pi = v \quad \Rightarrow \quad M_H = 125$ GeV for $r_t = 1.7 - 2.4$!

To generate the SM fermion masses an Extended Technicolor (ETC) interaction is necessary.

Foadi et al. '12

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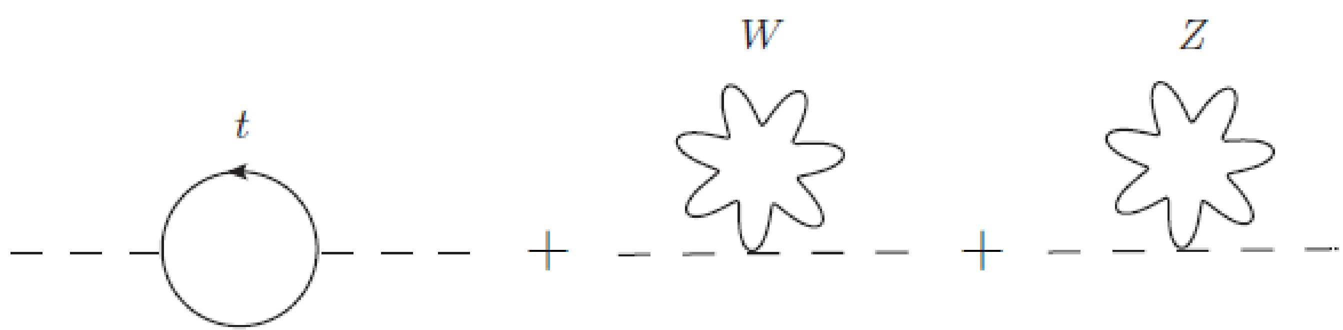
$\Delta M_H^2 =$ 

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Foadi et al. '12

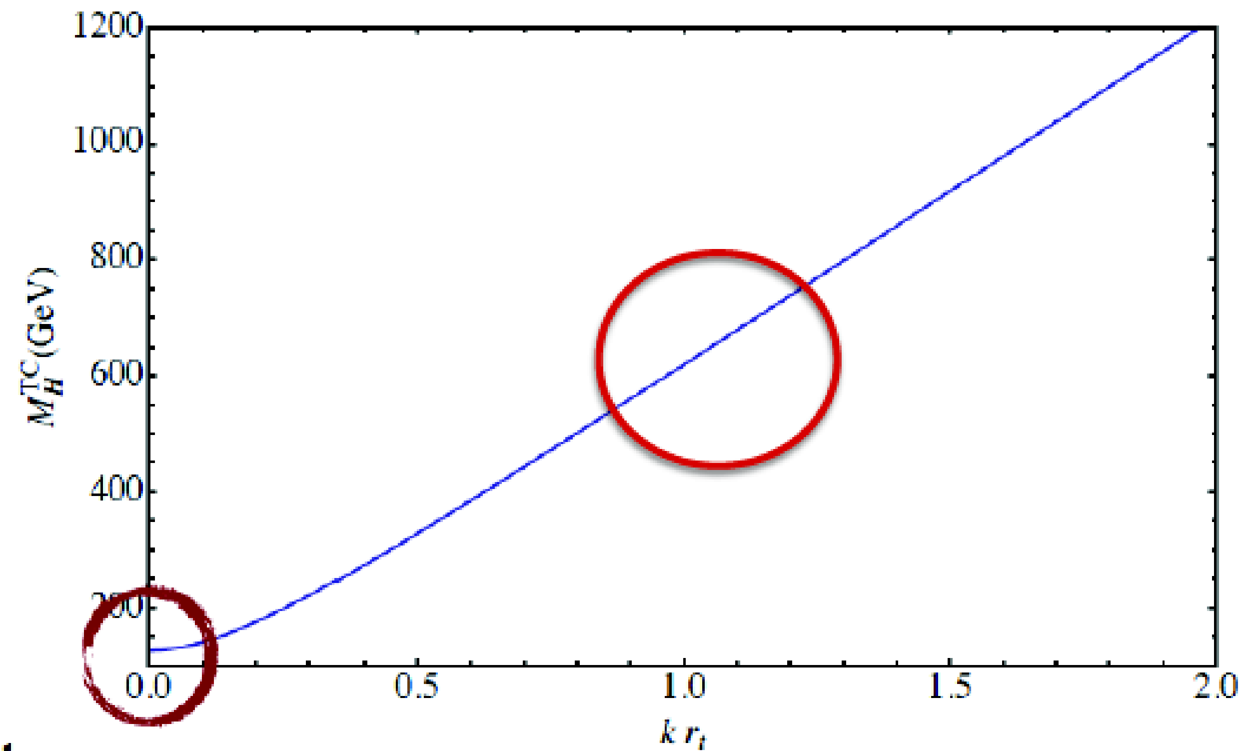
Higgs boson mass

Light TC-Higgs from radiative corrections

$$(M_H^{\rm TC})^2 \simeq M_H^2 + 12\,\kappa^2 r_t^2 m_t^2$$

$k\ r_t$ ~ TC x ETC

$$F_\Pi = v$$



Not too light!

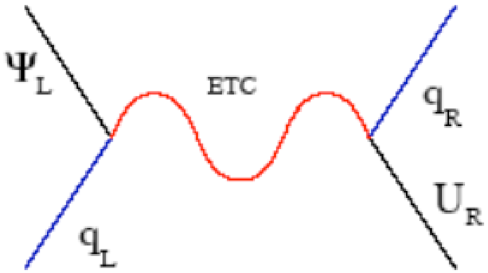
(Foadi, MTF & Sannino '12)

Effect correlated with the next TC resonance mass via κ and ETC via r_t

Extended Technicolor

- SU(N_{TC}) break the chiral symmetry of techniquarks
- their condensate breaks EW Symmetry

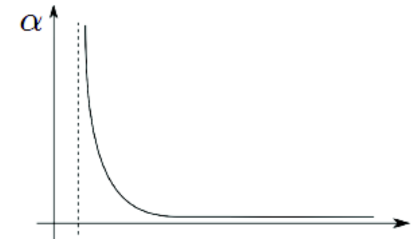
- Important componet of the theory-
  Extended Technicolor Sector – describes how SM fermions interact with the technifermion condensate to acquire mass



$$\Rightarrow \frac{g_{ETC}^2}{M_{ETC}^2}(\overline{\Psi}_L U_R)(\overline{q}_R q_L)$$

$$m_q \approx \frac{g_{ETC}^2}{M_{ETC}^2}\langle \overline{U}U \rangle_{ETC}$$

Extended Technicolor



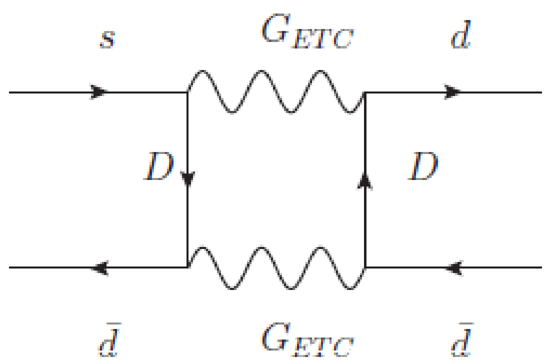
$$\langle \overline{U}U \rangle_{ETC} = \langle \overline{U}U \rangle_{TC} \exp\left(\int_{\Lambda_{TC}}^{M_{ETC}} \frac{d\mu}{\mu} \gamma_m(\mu) \right)$$

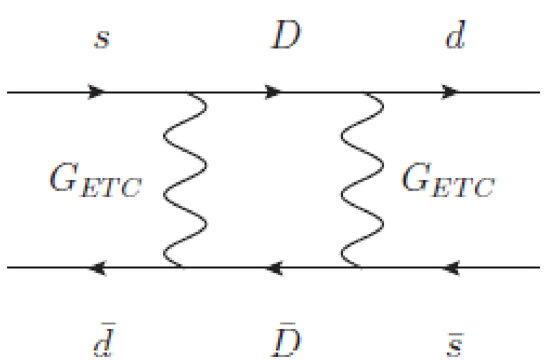
- **For QCD - like running TC**
  γ_m is small over this range, so:

$$< \bar{Q}Q >_{ETC} \sim \ln\left(\frac{\Lambda_{ETC}}{\Lambda_{TC}}\right)^{\gamma} < \bar{Q}Q >_{TC}$$

$$\langle \overline{U}U \rangle_{ETC} \approx \langle \overline{U}U \rangle_{TC} \approx 4\pi F_{TC}^3$$

$$\frac{M_{ETC}}{g_{ETC}} \approx 40\,\mathrm{TeV} \left(\frac{F_{TC}}{250\,\mathrm{GeV}} \right)^{\frac{3}{2}} \left(\frac{100\,\mathrm{MeV}}{m_q} \right)^{\frac{1}{2}}$$



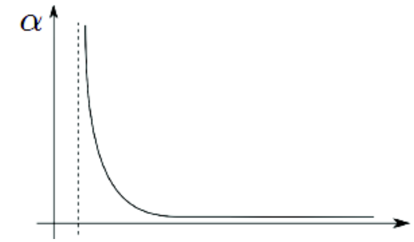


The second terms generate masses for the SM fermions, while the third terms are responsible for Flavor Changing Neutral Currents (FCNC):

$$\mathcal{L}_{\Delta S=2} = \gamma_{sd} \frac{(\bar{s}\gamma^5 d)(\bar{s}\gamma^5 d)}{\Lambda_{ETC}^2} + hc,\ \gamma_{sd} \sim \sin^2\theta_c \simeq 10^{-2}.$$

Extended Technicolor

$$\langle \overline{U}U \rangle_{ETC} = \langle \overline{U}U \rangle_{TC} \exp\left(\int_{\Lambda_{TC}}^{M_{ETC}} \frac{d\mu}{\mu} \gamma_m(\mu) \right)$$



- For QCD – like running TC $\qquad < \bar{Q}Q >_{ETC} \sim \ln(\frac{\Lambda_{ETC}}{\Lambda_{TC}})^{\gamma} < \bar{Q}Q >_{TC}$

  γ_m is small over this range, so:

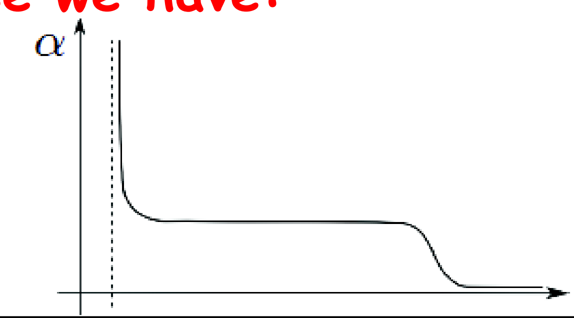
$$\langle \overline{U}U \rangle_{ETC} \approx \langle \overline{U}U \rangle_{TC} \approx 4\pi F_{TC}^3 \qquad \frac{M_{ETC}}{g_{ETC}} \approx 40\,\text{TeV} \left(\frac{F_{TC}}{250\,\text{GeV}} \right)^{\frac{3}{2}} \left(\frac{100\,\text{MeV}}{m_q} \right)^{\frac{1}{2}}$$

Measured value of the neutral kaon mass splitting determines tight bound on ETC scale:

$$\frac{\Delta m^2}{m_K^2} \simeq \gamma_{sd} \frac{f_K^2 m_K^2}{\Lambda_{ETC}^2} \lesssim 10^{-14} \Rightarrow \Lambda_{ETC} \gtrsim 10^3 \text{ TeV}\,.$$

- Difficult to get masses even for s- and c-quarks: TC dynamics should be NOT like QCD. Theory should "walk" and in this case we have:

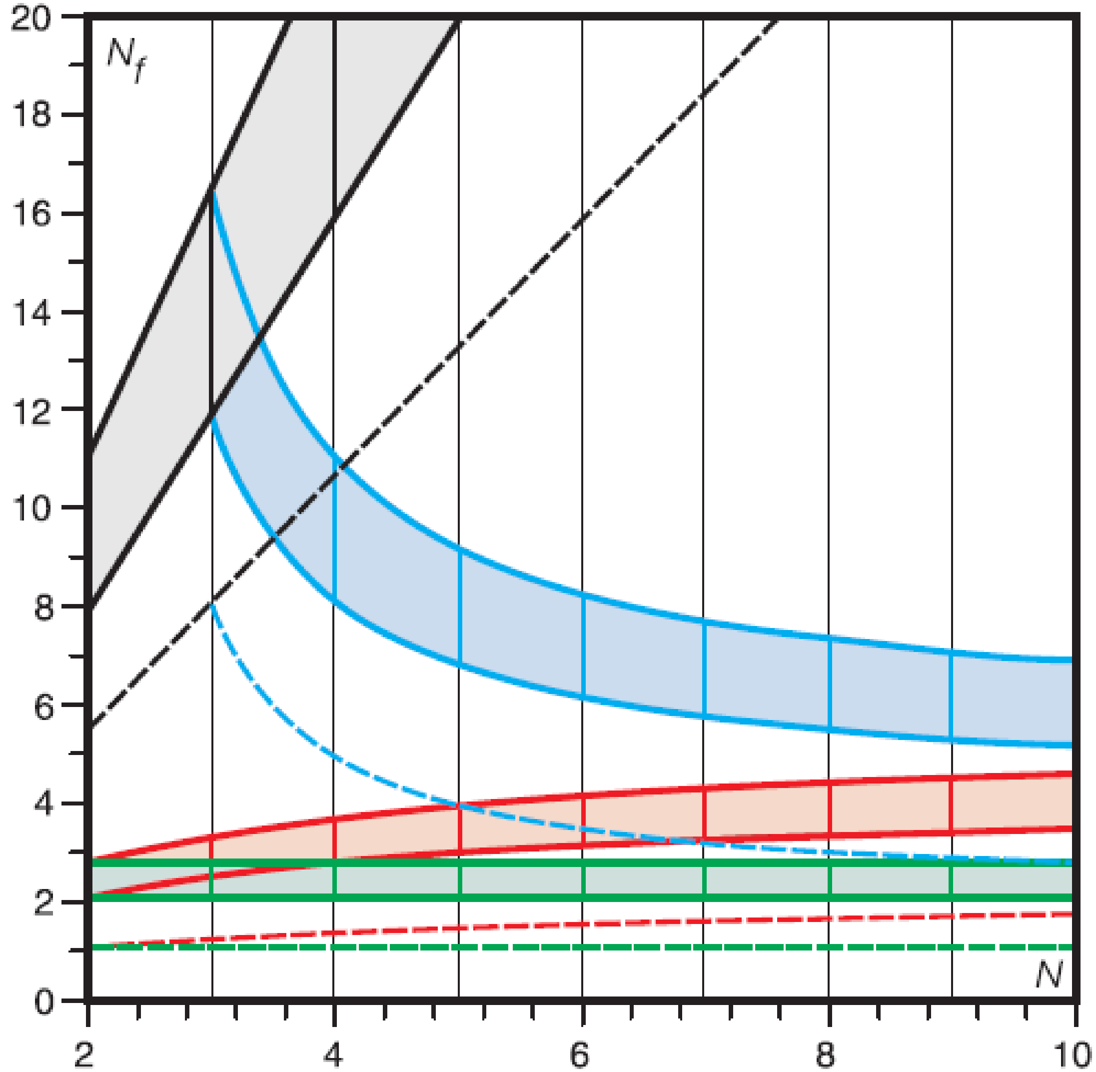
$$< \bar{Q}Q >_{ETC} \sim (\frac{\Lambda_{ETC}}{\Lambda_{TC}})^{\gamma(\alpha^*)} < \bar{Q}Q >_{TC}$$



Holdom 81; Appelquist, Wijewardhana 86

Enhanced SM fermion masses and suppressed FCNC

"Near conformal" regions for SU(N)



Dietrich, Tuominen, Sannino '05; Dietrich, Sannino '06

Phase diagram for theories with fermions in the:

- fundamental representation (grey)
- two-index antisymmetric (blue)
- two-index symmetric (red)
- adjoint representation (green)

The S parameter for a TC model is estimated by:

$$S_{th} \approx \frac{1}{6\pi}\frac{N_f}{2}d(\mathrm{R}),$$

$$12\pi\, S_{exp} \leq 6 \text{ @ } 95\%$$

SM Higgs vs Technicolor

- simple and economical
- GIM mechanism, no FCNC problems, EW precision data are OK for preferably light Higgs
- SM is established, perfectly describes data

- fine-tuning and naturalness problem; triviality problem
- there is no example of fundamental scalar

- Scalar potential parameters and yukawa couplings are inputs

- complicated at the eff theory level
- FCNC constraints requires walking, potential tension with EW precision data
- no viable ETC model suggested yet, work in progress

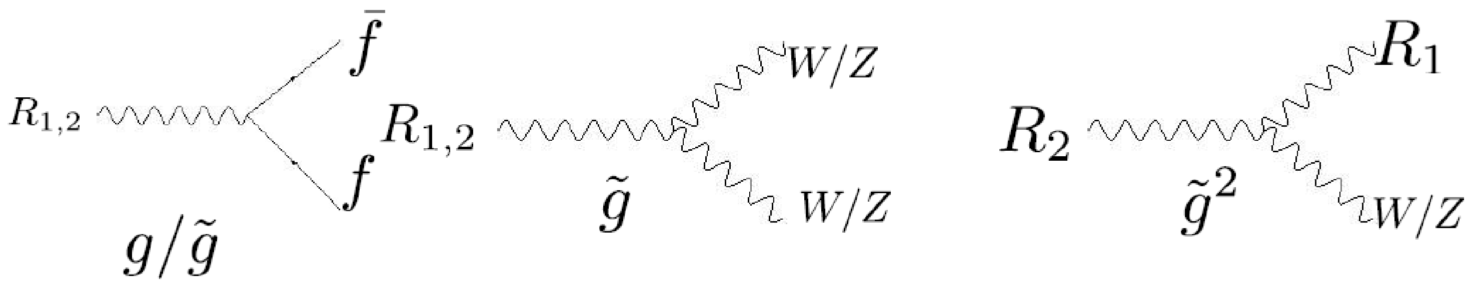
- no fine-tuning, the scale is dynamically generated
- Superconductivity and QCD are examples of dynamical symmetry breaking
- parameters of low-energy effective theory are derived once underlying ETC is constructed

Walking TC @the LHC

EFT for strong dynamics @ LHC

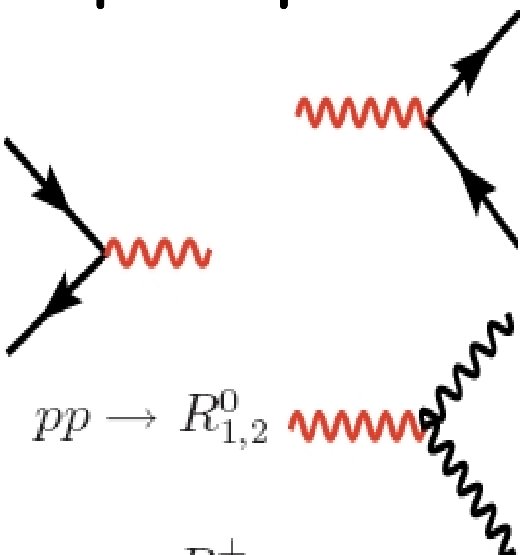
$SU_L(2) \times SU_R(2) \times U_{TB}(1) \rightarrow SU_V(2) \times U_{TB}(1)$

Coupling structure to SM fields :



Model implementation: AB,Foadi, Frandsen,Jarvinen,Sannino,Pukhov 2009

http://hepmdb.soton.ac.uk/hepmdb:1012.0102



$pp \rightarrow R^0_{1,2}$

$pp \rightarrow R^\pm_{1,2}$

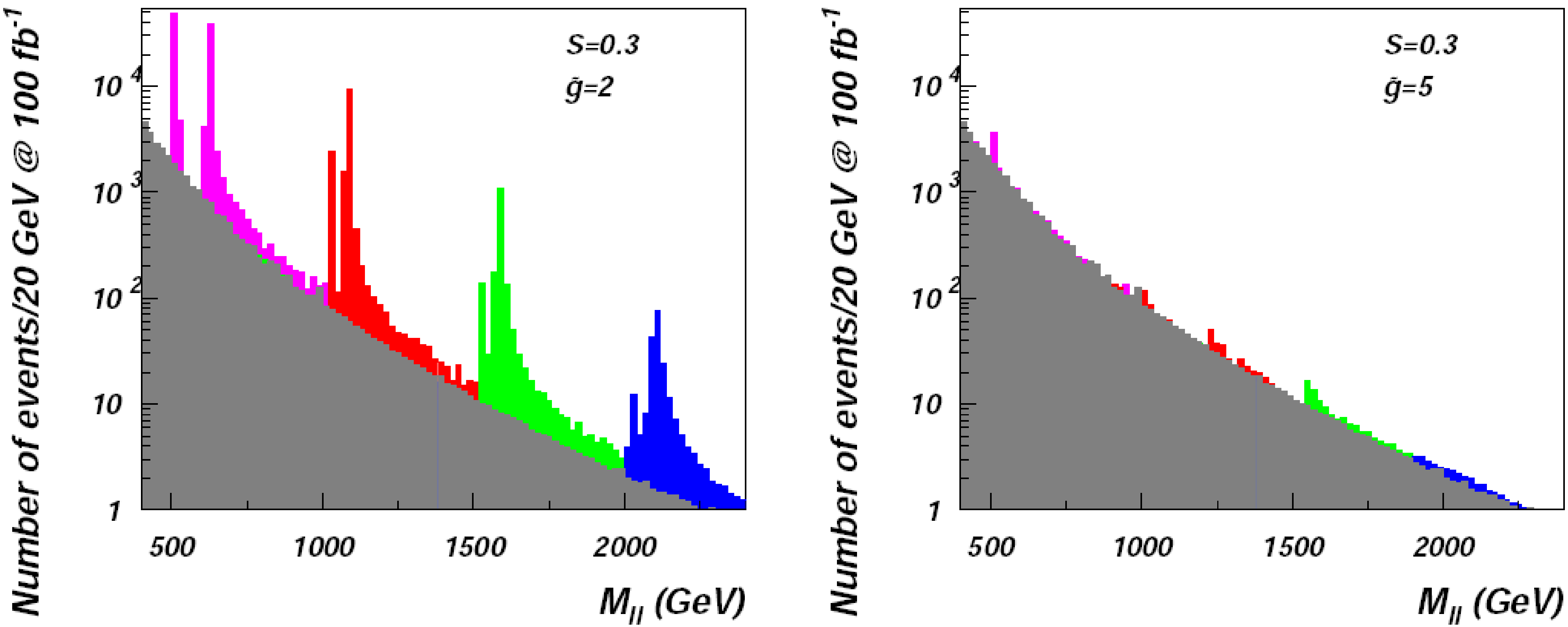
(1) $\ell^+\ell^-$ signature from the process $pp \rightarrow R^0_{1,2} \rightarrow \ell^+\ell^-$

(2) $\ell + \not{E}_T$ signature from the process $pp \rightarrow R^\pm_{1,2} \rightarrow \ell^\pm\nu$

(3) $3\ell + \not{E}_T$ signature from the process $pp \rightarrow R^\pm_{1,2} \rightarrow ZW^\pm \rightarrow 3\ell\nu$

Walking TC @the LHC

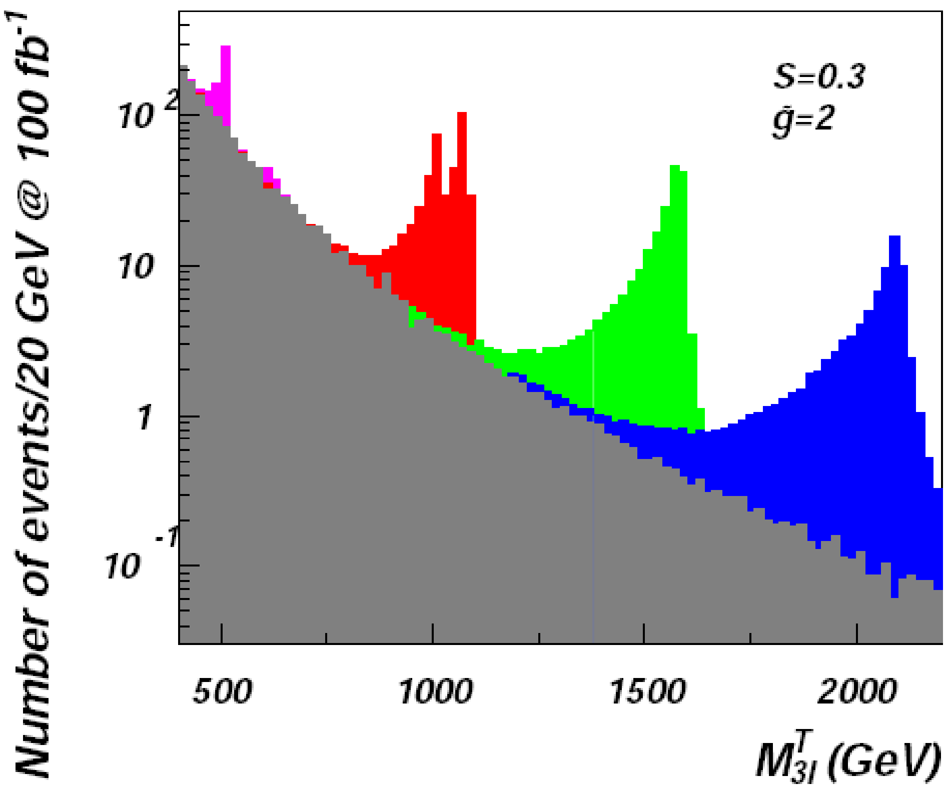
(1) $\ell^+\ell^-$ signature from the process $pp \to R^0_{1,2} \to \ell^+\ell^-$

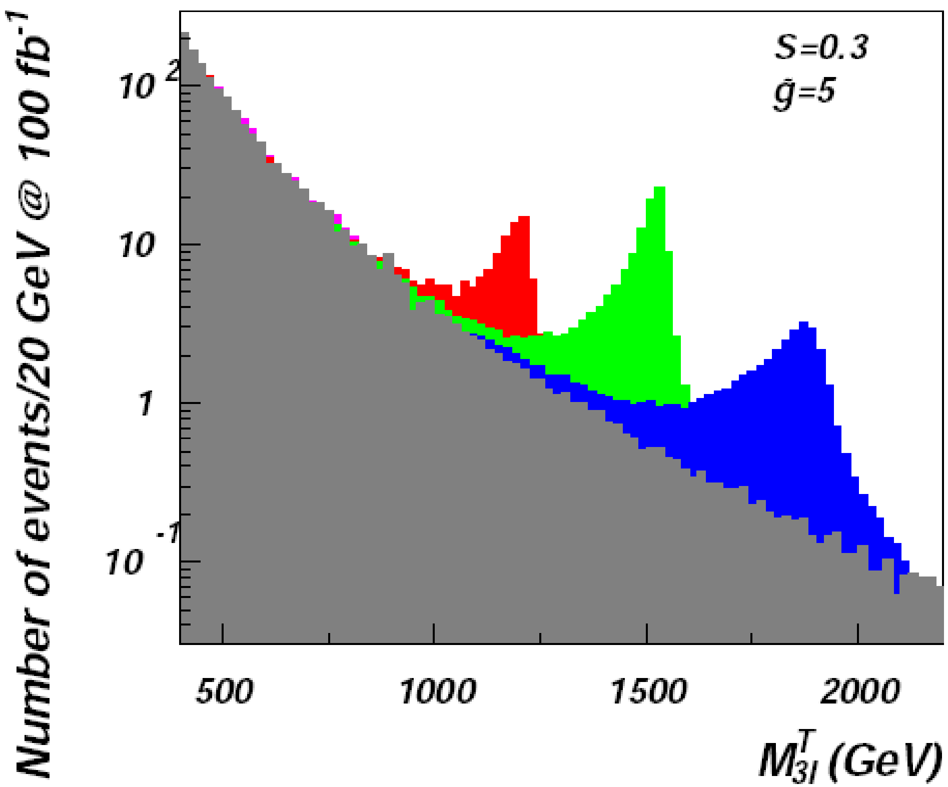


Walking TC @the LHC

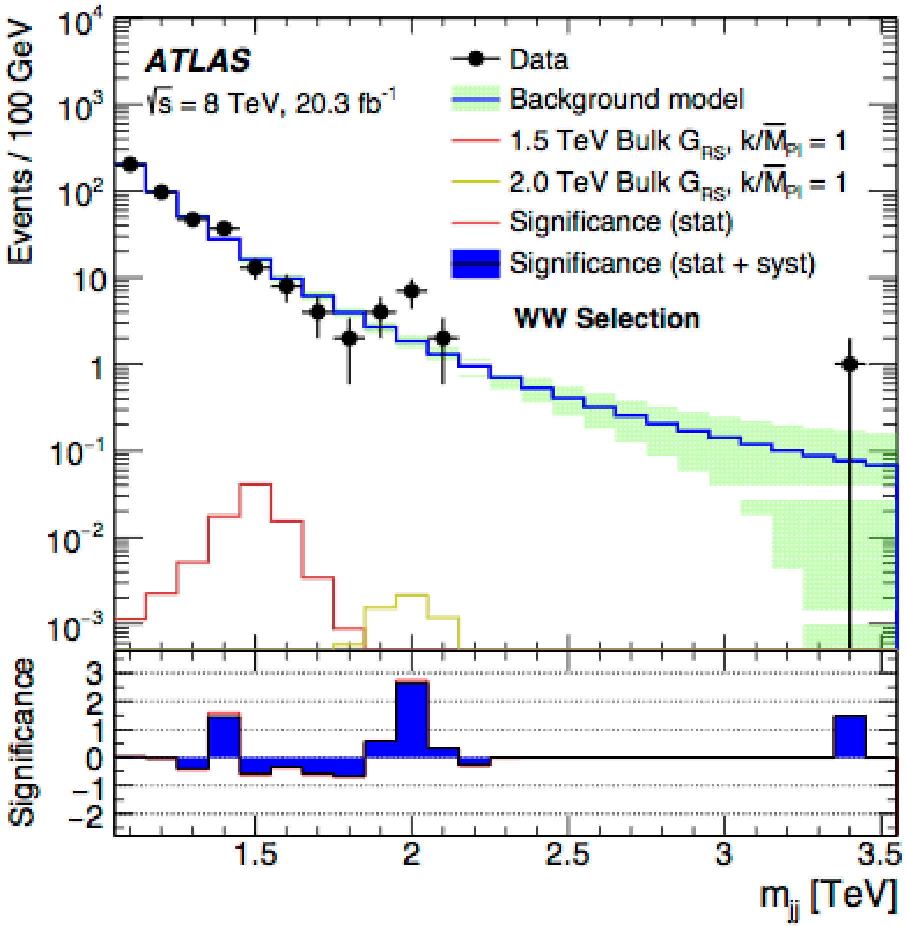
complementary di-boson signature

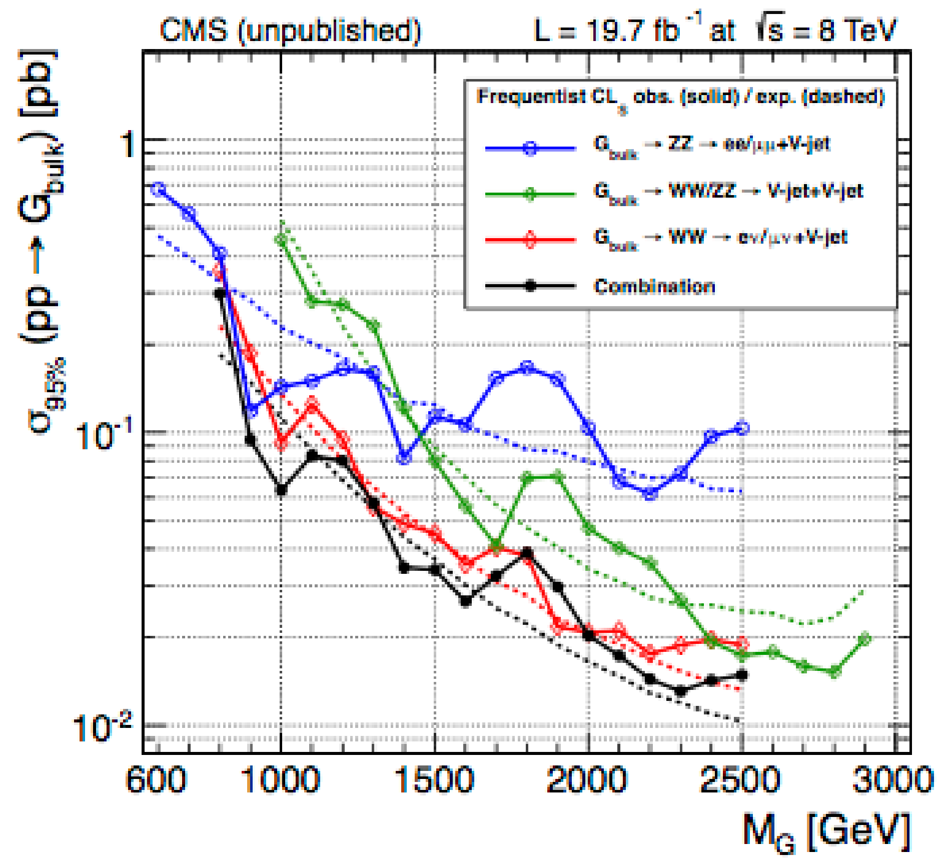
(3) $3\ell + \not{E}_T$ signature from the process $pp \to R^{\pm}_{1,2} \to ZW^{\pm} \to 3\ell\nu$





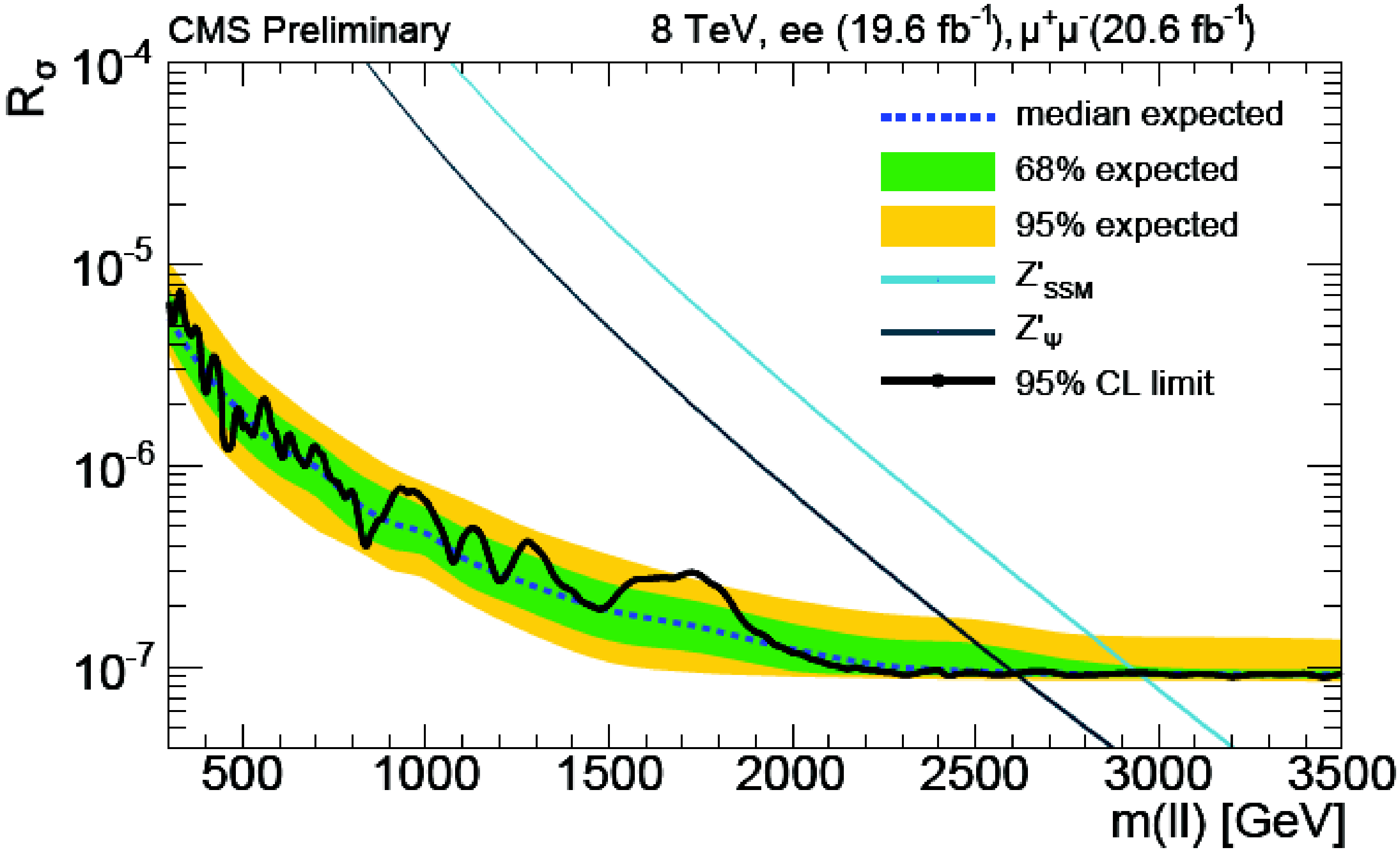
Lets take a look at di-boson invariant mass in the current data around 2 TeV ...



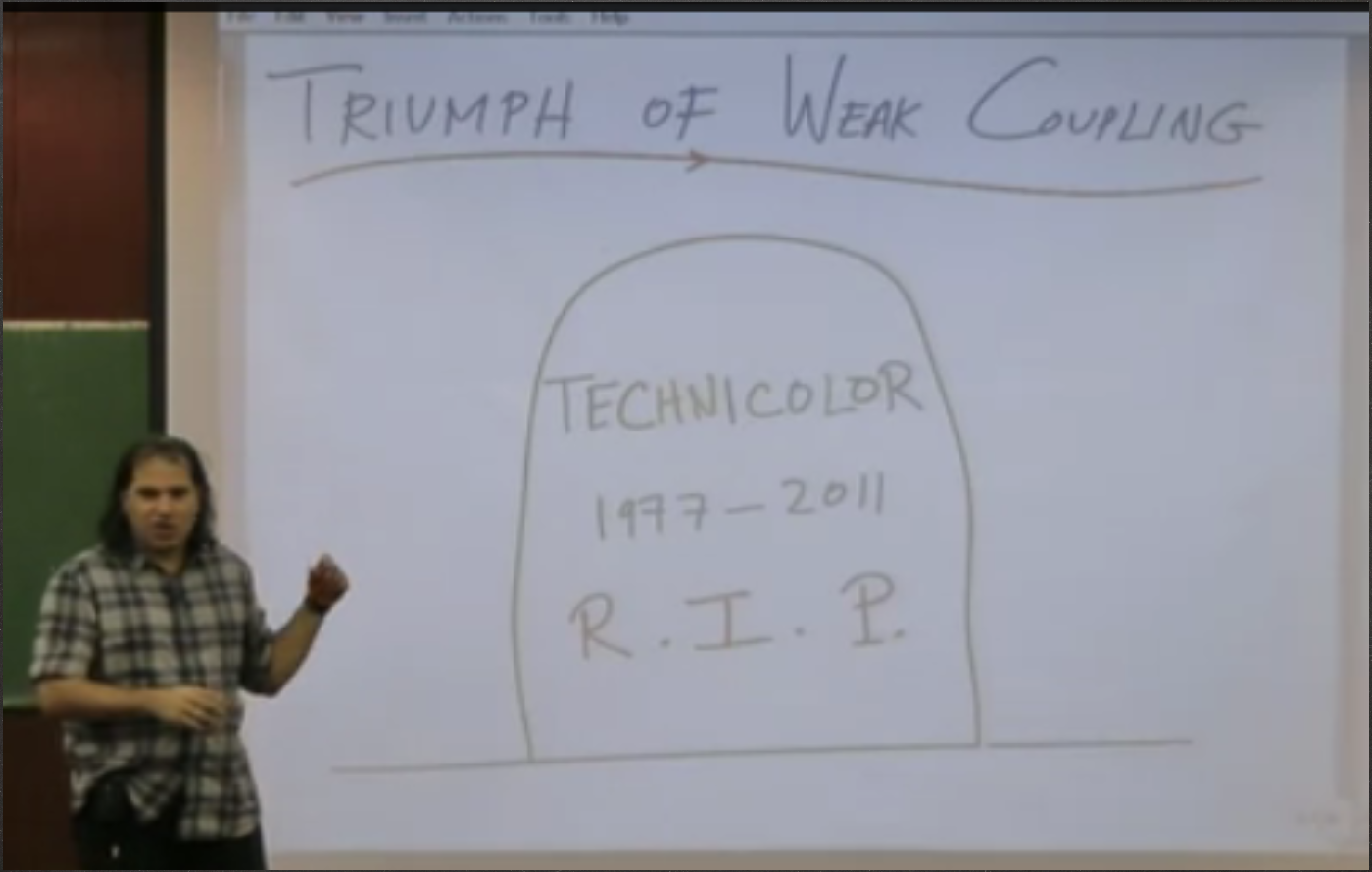


Sounds quite interesting ...

It is also intriguing to look at the correlation in di-lepton channel ...



Do we think that TC is really dead?



Do we think that TC is really dead?

If title contains question, then the answer is ...

Do we think that TC is really dead?

If title contains question, then the answer is ...

NO!

Composite Higgs
Unified approach

Two time-honoured extensions

- **New Strong Dynamics**
  - Expect new states at $4\pi\, f_{Strong}$?
  - Atleast one state needs to be quite a bit lighter…*known since LEP!*
  - Finding a light scalar did not change established picture *that* much…

m_h^{NSD}

m_h^{obs}

- **Supersymmetry**
  - Expect new states below v_{EW}?
  - Nature likes SUSY heavy (and fine-tuned?) since LEP

m_h^{SUSY}

New Strong Dynamics

m_σ^{TC}

- **The Technicolor Composite Higgs**
  - 'Higgs' is the lightest scalar isospin-0 resonance of strong dynamics
  - Compare with the $f_0(500)$ in QCD

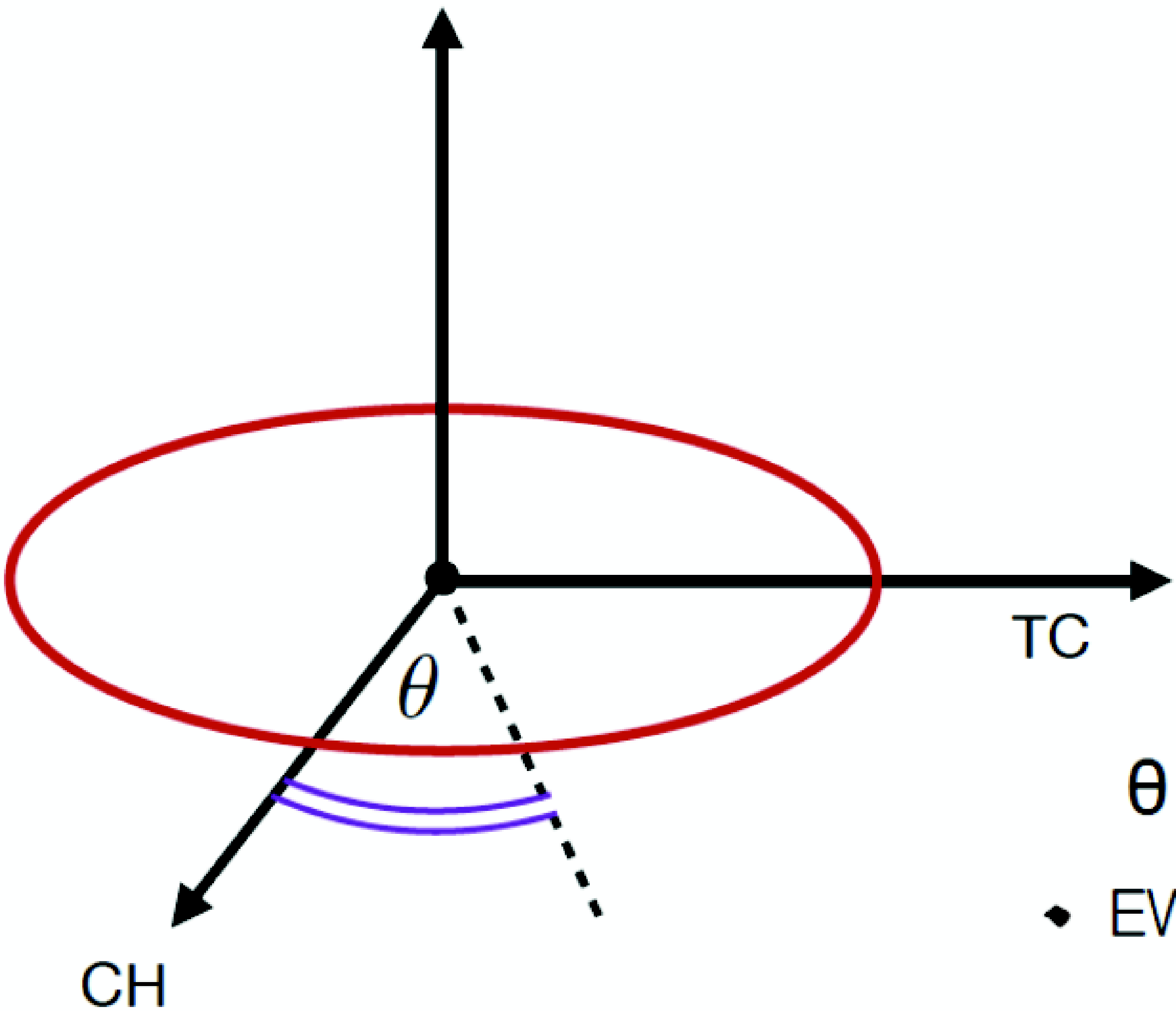
m_h^{obs}

- **The *Composite Higgs* Composite Higgs**
  - The Higgs doublet arises as goldstone bosons of global symmetry breaking
  - Electroweak symmetry breaks through vacuum misalignment

m_h^{CH}

Technicolor vs Composite Higgs

(Galloway, Evans, Tacchi & Luty '10
G. Cacciapaglia & F. Sannino '14)



$\theta = 0$

- EW does not break
- Higgs is exact GB

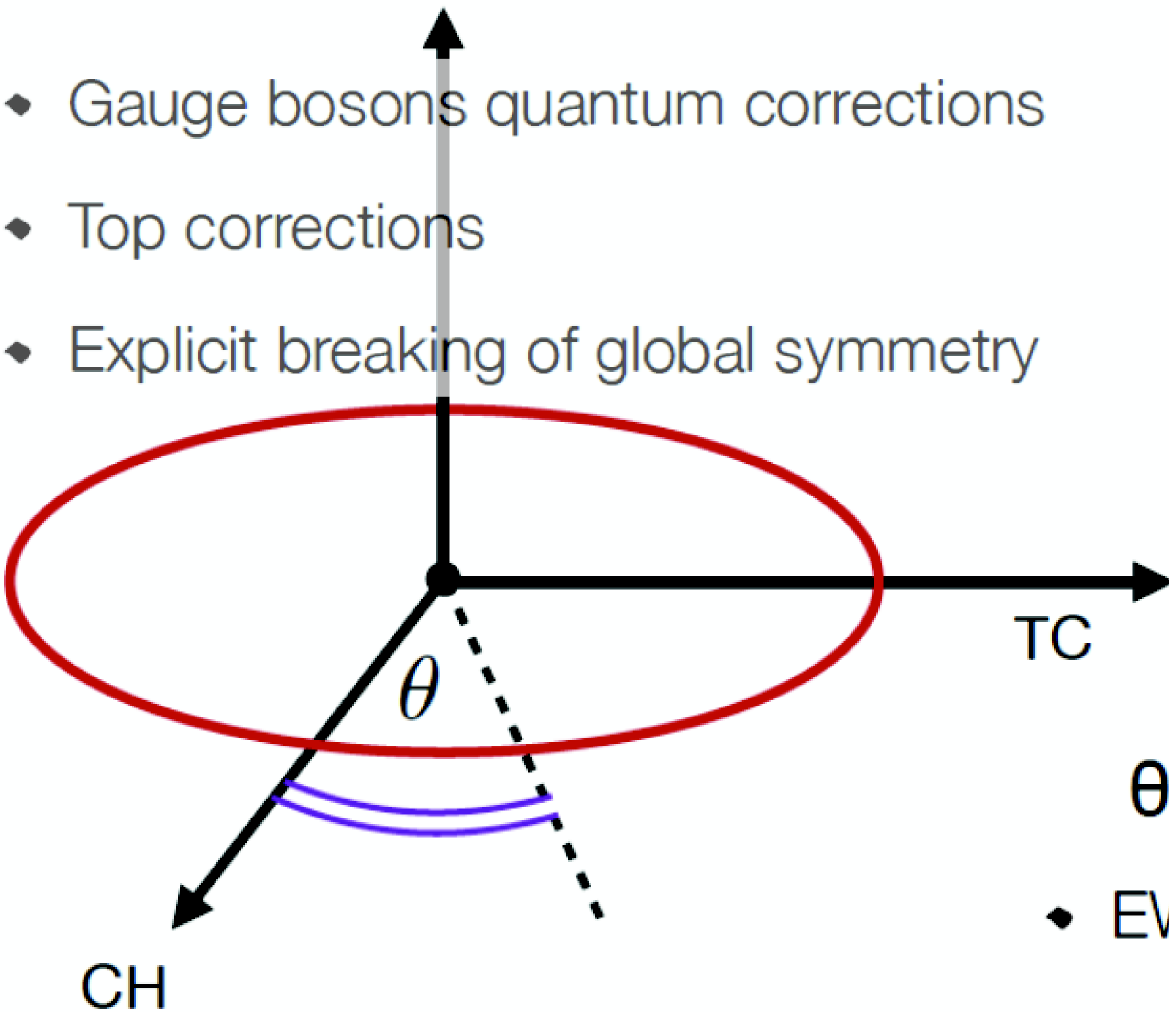
$\theta = \pi/2$

- EW breaks
- Higgs is massive excitation

Technicolor vs Composite Higgs

(Galloway, Evans, Tacchi & Luty '10
G. Cacciapaglia & F. Sannino '14)

- Gauge bosons quantum corrections
- Top corrections
- Explicit breaking of global symmetry



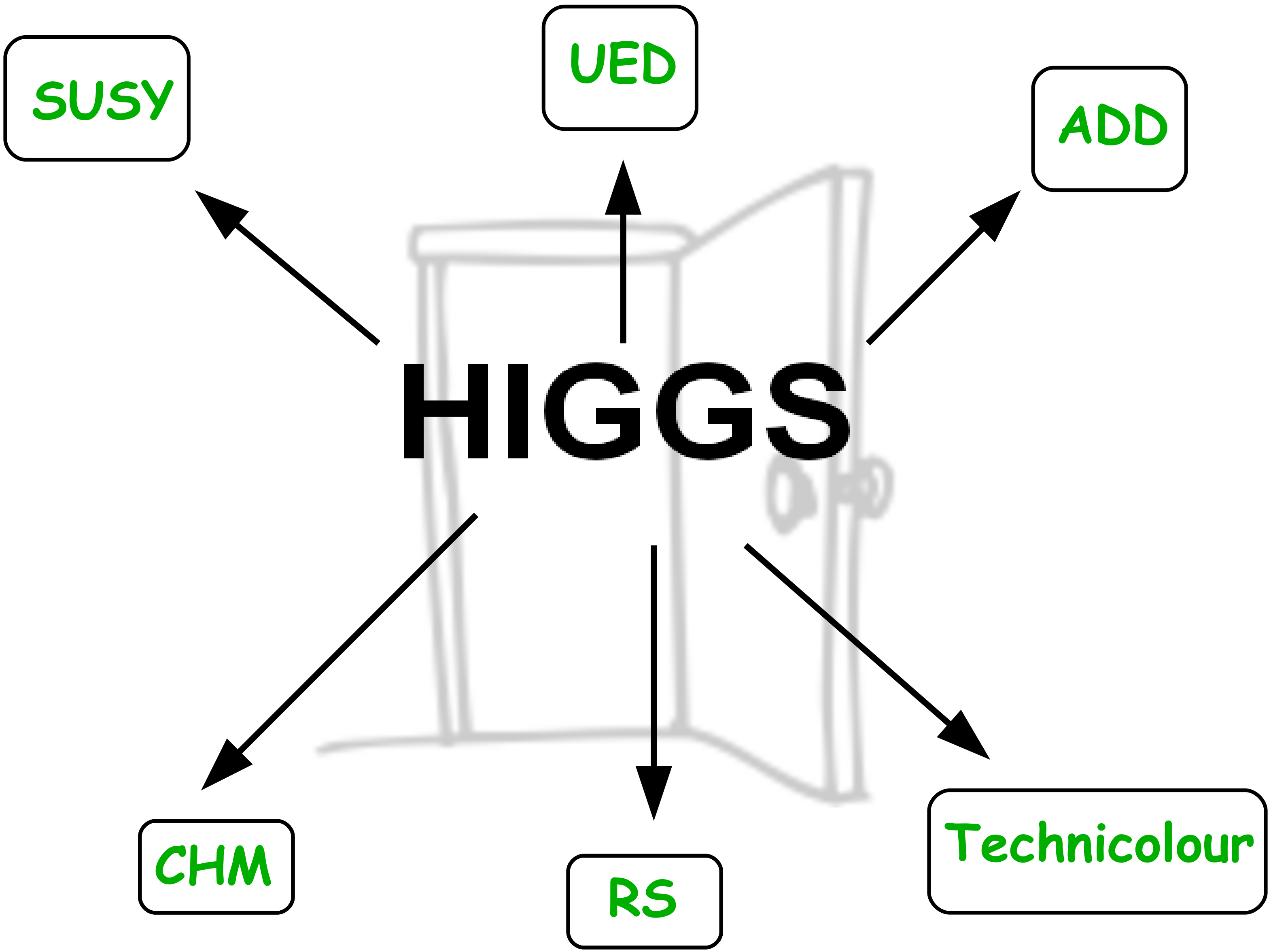
$\theta = 0$

- EW does not break
- Higgs is exact GB

$\theta = \pi/2$

- EW breaks
- Higgs is massive excitation

Higgs boson properties are consistent with all promising BSM models encouraging us to keep searching for underlying theory of Nature!



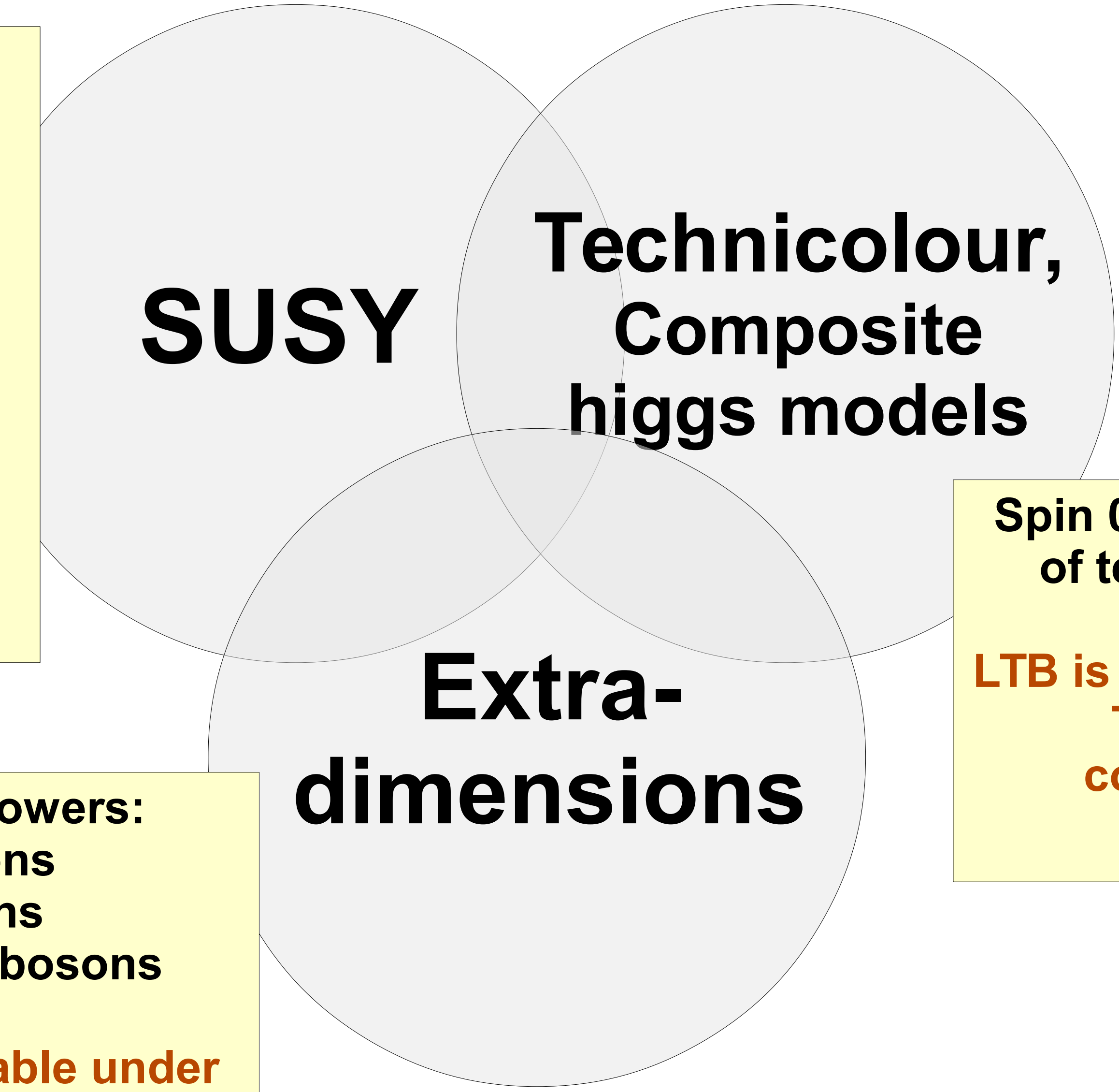
Theories and new particles

SUSY partners

New gauge bosons (USSM, E6SSM)

Exotics – diquarks, LQ (E6SSM)

LSP is stable under the R-parity



Spin 0,1 bound states of techni-quarks:

LTB is stable under the TB number conservation

KK – towers:
KK-gravitons
KK-fermions
KK-gauge bosons

LKP is stable under the KK-parity (UED)

Theories and new signatures

0,1,2,3,... leptons+
jets +
Missing PT

Di-lepton resonances

Same-sign leptons

SUSY

Technicolour,
Composite
higgs models

0,1,2,3,... leptons+ jets +
Missing PT

Di-lepton resonances

Lepton-neutrino
resonances

Extra-
dimensions

0,1,2,3,... leptons+
jets +
Missing PT

Di-lepton resonances

Same-sign leptons

Signatures can be really similar!

The main problem is to decode an underlying theory from the complicated set of signatures: down->top

SUSY | UED | ADD | Little Higgs | Technicolour | CHM | RS

top->down
Easy

Tons of Signatures

The main problem is to decode an underlying theory from the complicated set of signatures: down->top

SUSY | UED | ADD | Little Higgs | Technicolour | CHM | RS

top->down
Easy

down->top
Very difficult

Tons of Signatures

The main problem is to decode an underlying theory from the complicated set of signatures: down->top

SUSY | UED | ADD | Little Higgs | Technicolour | CHM | RS

top->down
Easy

down->top
Very difficult

Tons of Signatures

HEPMDB
High Energy Physics Model Data Base

https://hepmdb.soton.ac.uk/

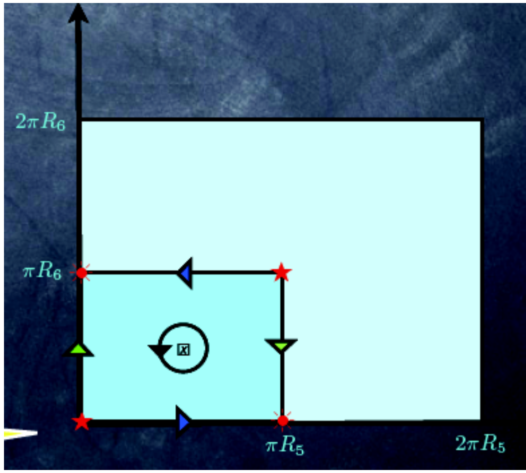
THANK YOU!

- Thanks to all organizers for fantastic School/Workshop/time in and the weather!
- Thanks to all for inspiring talks, questions and discussions!
- Thanks to everybody!

Additional Slides

6D UED
(Dark Matter in a twisted bottle)

Arbey,Cacciapaglia,Deandrea,Kubik'12



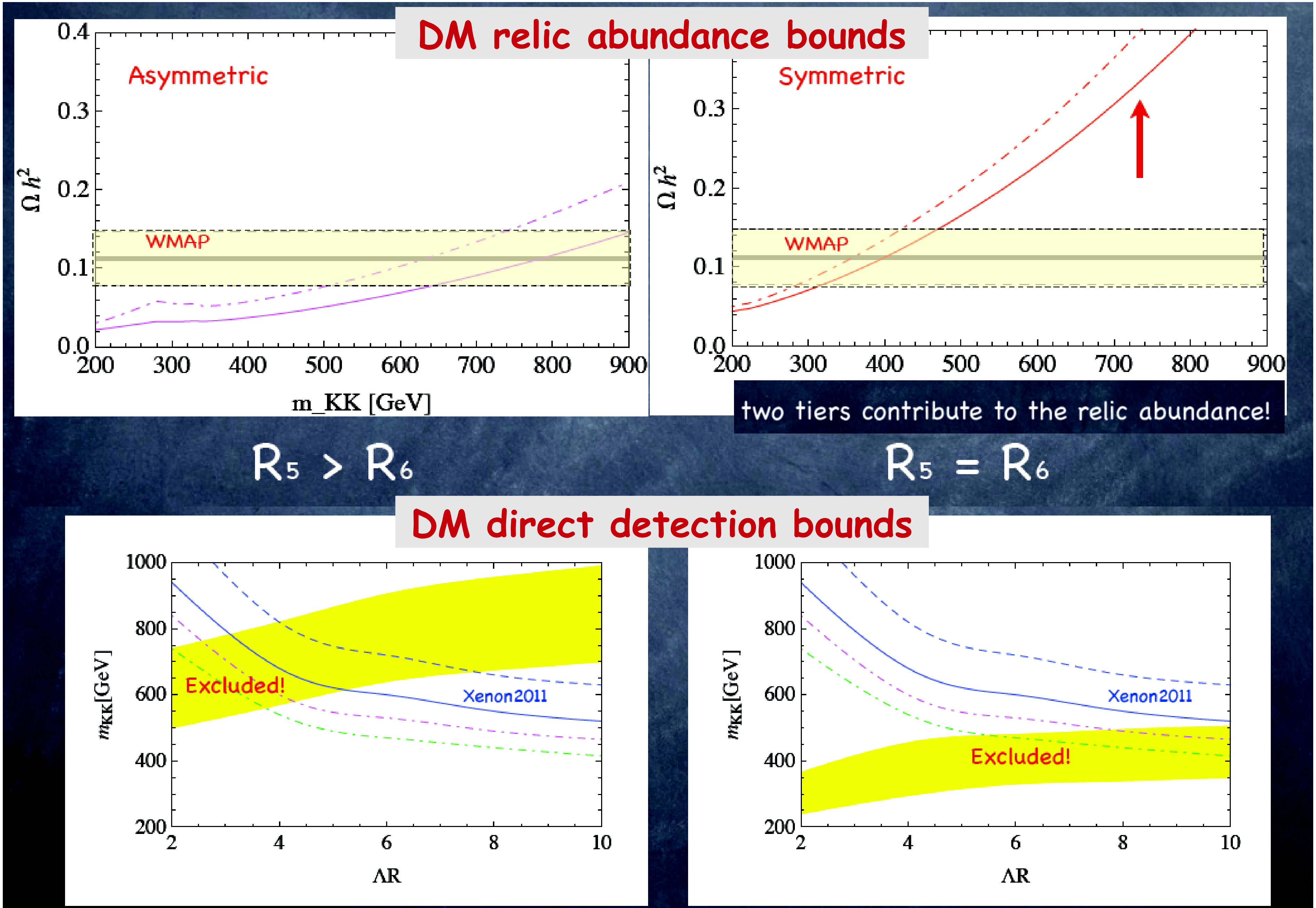
Spectrum of the SM

	+	−	+	+	−
$p_{KK} = (-1)^{k+l}$	(0,0) m = 0	(1,0) & (0,1) m = 1	(1,1) m = 1.41	(2,0) & (0,2) m = 2	(2,1) & (1,2) m = 2.24
Gauge bosons G, A, Z, W	✓		✓	✓	✓
Gauge scalars G, A, Z, W		✓	✓		✓
Higgs boson(s)	✓		✓	✓	✓
Fermions	✓	✓	✓ (x2)	✓	✓ (x2)

DM candidate here!

6D UED DM bounds

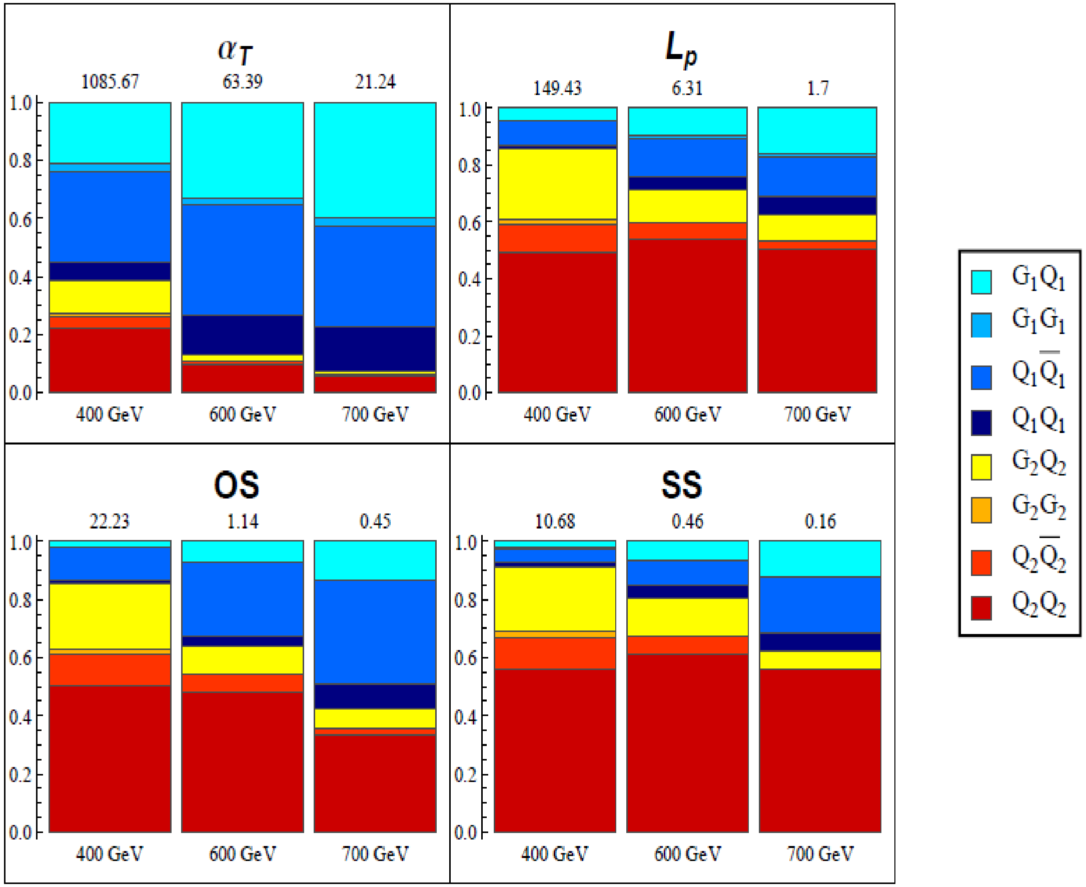
Arbey,Cacciapaglia,Deandrea,Kubik'12



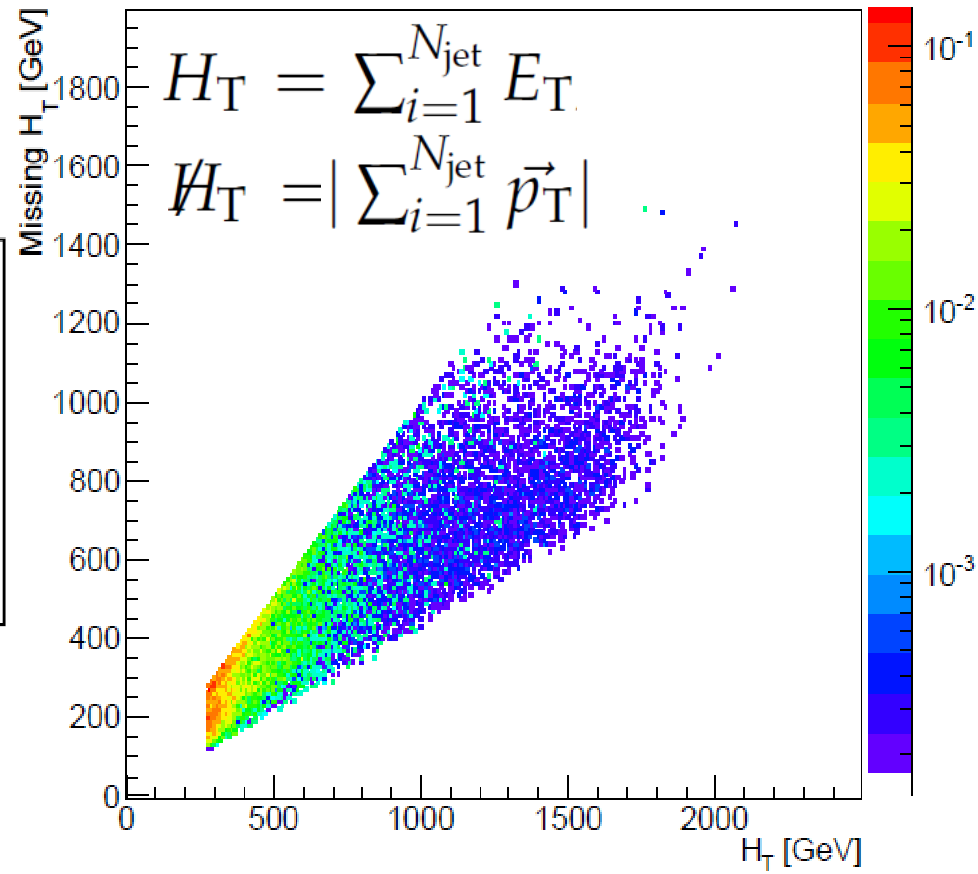
6D UED LHC bounds

Cacciapaglia, Deandrea, Ellis, Marrouche, Panizzi '13

"composition " of signal signatures



MHT-HT analysis plane



$$\alpha_T = \frac{p_T(j_2)}{M_{jj}} = \frac{p_T(j_2)}{\sqrt{H_T^2 - MH_T^2}}$$

Exclusion limit: M_{KK}>600-700 GeV
Almost all parameter space is excluded

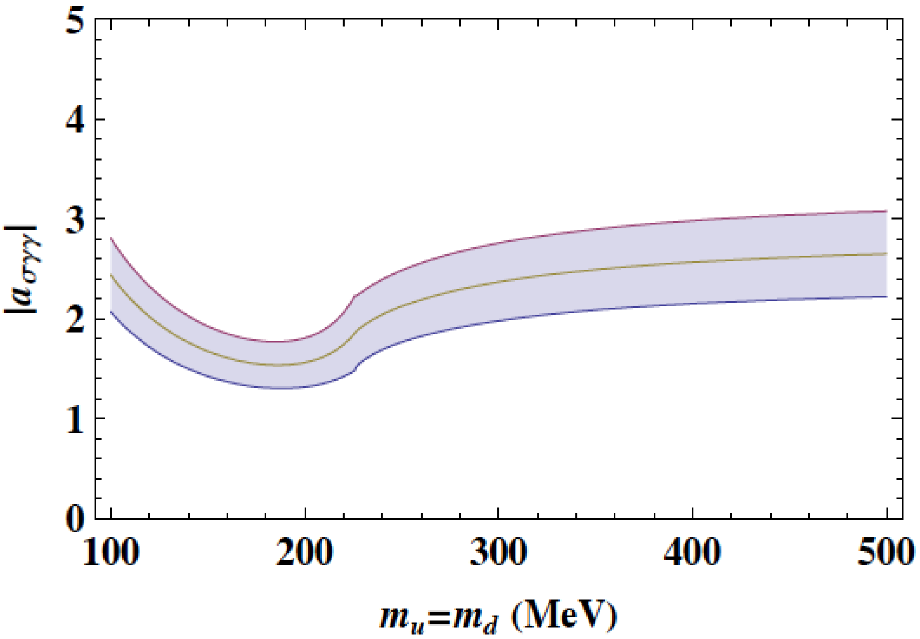
The lightest scalar in QCD

QCD σ-photon model Lagrangian, $a_{\sigma\gamma\gamma}$ composite fudge-factor

$$\Gamma_{\sigma\to\gamma\gamma} = \frac{\alpha^2\,(\mathrm{Re}\,m_\sigma)^3\,a_{\sigma\gamma\gamma}^2}{256\pi^3 f_\pi^2}\left|3\left(\frac{2}{3}\right)^2 F_{1/2}\left(\frac{4m_u^2}{(\mathrm{Re}\,m_\sigma)^2}\right)+3\left(-\frac{1}{3}\right)^2 F_{1/2}\left(\frac{4m_d^2}{(\mathrm{Re}\,m_\sigma)^2}\right)\right|^2$$

Compare with QCD data:

(Belyaev, Brown, Foadi, MTF & Sannino ’13)



The Techni-Higgs scalar in QCD

Scaled up QCD-like Techni-Higgs would have (diboson) Higgs-like couplings

Coefficient c_{π}~ 1 is independent of number of colors or size of representation

Techni-Higgs photon model Lagrangian

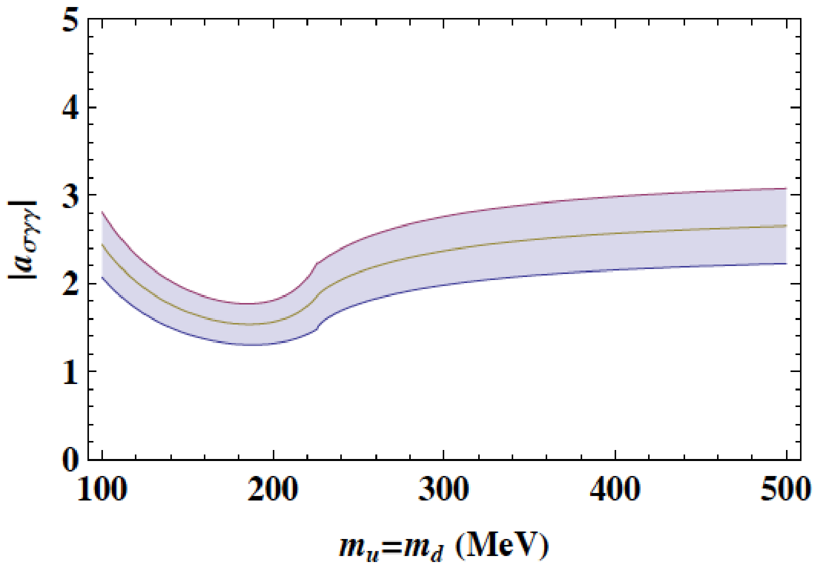
$$g_{H\gamma\gamma}^{\mathrm{TC}} = \frac{\alpha}{8\pi}\left| c_{\Pi}\,[F_1(\tau_W) - 2] + \sum_f c_f\, N_c^f\, Q_f^2\, F_{1/2}(\tau_f) + a_{H\gamma\gamma}\, d(R_{\mathrm{TC}}) \sum_F N_c^F\, Q_F^2\, F_{1/2}(\tau_F) \right|$$

The Techni-Higgs scalar in QCD

Example fit to LHC Data

$$g^{TC}_{H\gamma\gamma} = \frac{\alpha}{8\pi}\left| c_\Pi\,[F_1(\tau_W) - 2] + \sum_f c_f\, N_c^f\, Q_f^2\, F_{1/2}(\tau_f) + a_{H\gamma\gamma}\, d(R_{TC}) \sum_F N_c^F\, Q_F^2\, F_{1/2}(\tau_F) \right|$$

Fit to QCD data



Fit to LHC data