Lectures on Beyond the Standard Model Physics III

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Extra Dimensions

Fields in Extra Dimensions

- Any extra Dimension should be compact.
- Let's denote by x^μ our ordinary dimensions.
- Extra dimensions: y^M
- Take the circular topology of extra dimensions and require that after a turn, the wave function comes back to its original value

$$\Phi(x, y_i + 2\pi R_i) = \Phi(x, y_i), \qquad \Phi(x, y) = \frac{1}{\sqrt{V_d}} \sum_n \tilde{\Phi}_n(x) \exp\left(in\frac{y}{R}\right) \tag{48}$$

Kaluza Klein Modes

- Simple case: $d = 1$,

$$S = \int d^4x dy (\partial_A \Phi)^* \partial_A \Phi = \sum_n \int d^4x \left[\partial_\mu \tilde{\Phi}_n^* \partial^\mu \tilde{\Phi}_n + \frac{n^2}{R^2} \tilde{\Phi}_n^* \tilde{\Phi}_n \right] \tag{49}$$

- From the pont of view of a four dimensional observer, we have a tower of massive excitations !
- These excitations is what are called Kaluza Klein modes.
- In many extra dimensions, one can generalize the argument and the masses of the KK modes are

$$(M_{KK}^{n_1,n_2,\ldots n_d})^2 = \sum_i \left(\frac{n_i}{R_i} \right)^2 \tag{50}$$

Lowering the Planck Scale

- Idea: We live in a four dimensional wall, but there are extra dimensions and only gravity can penetrate into them.
- Problem: If gravity can penetrate intro the extra dimensions, Newton law will be modified

$$\vec{F} = \frac{m_1 m_2 \hat{r}}{\left(M_{Pl}^{\rm fund}\right)^{2+d} r^{2+d}} \tag{51}$$

- $M_{Pl}^{\rm fund}$ = Fundamental Planck Scale. Behaviour valid for $r \ll R$. For $r \gg R$, instead

$$\vec{F} = \frac{m_1 m_2 \hat{r}}{\left(M_{Pl}^{\rm fund}\right)^{2+d} r^2 R^d} \tag{52}$$

- Hence,

$$M_{Pl}^2 = \left(M_{Pl}^{\rm fund}\right)^{2+d} R^d \tag{53}$$

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Size of flat Extra Dimensions

- Let's assume that the fundamental Planck scale is of the order of 1 TeV, to solve the hierarchy problem.

$$M_{Pl}^2 = (1\text{TeV})^{2+d} R^d \tag{58}$$

- Then, the value of R is given by

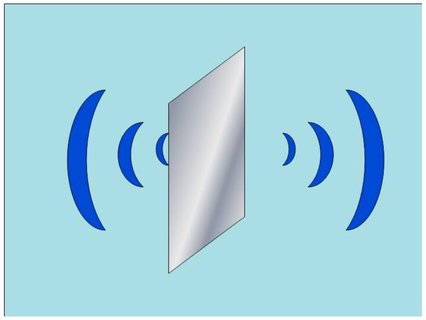
$$R = 10^{32/d} 10^{-17}\text{cm} \tag{59}$$

- For $d = 1$ we get $R = 10^{15}$ cm $\rightarrow$ Excluded
- For $d = 2$ we get $R \simeq 1$ mm $\rightarrow$ Allowed !
- For $d = 6$ we get $R \simeq 10^{-12}$ cm.
- The scenario is allowed for $d \geq 2$

Gravity in Extra Dimensions (ED)

Gravity in ED $\Longrightarrow$ fundamental scale, pushed down to electroweak scale by geometry

Metric: $ds^2 = e^{-2k|y|}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2$ $\Longrightarrow$Solution to 5d Einstein eqs.



k=0 (flat)

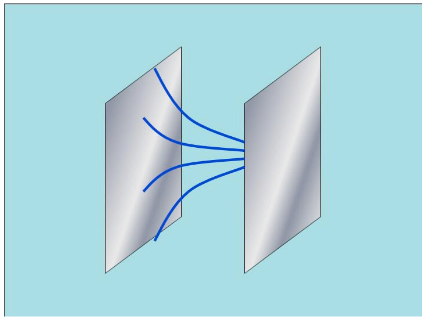
gravity flux in ED $\Longrightarrow$ Newton's law modified:

$$M_{Pl}^2 = (M_{Pl}^{\text{fund.}})^{2+d}\, R^d$$

this lowers the fundamental Planck scale,

$\Longrightarrow$ depending on the size & number of ED.

$M_{Pl}^{\text{fund.}} \simeq 1$ TeV $\Longrightarrow$ R= 1 mm, 10^{-12} cm if d = 2,6



k≠0 (warped ED)

$$M_{Pl}^2 = \frac{(M_{Pl}^{\text{fund.}})^3}{2k}(1 - e^{-2kL})$$

fundamental scales: $M_{Pl} \sim M_{Pl}^{\text{fund.}} \sim v \sim k$

$\Longrightarrow$ Physical Higgs v.e.v. suppressed by e^{-kL}

$\Longrightarrow$ $\tilde{v} = v\, e^{-kL} \simeq m_Z$ if $kL \approx 34$

How can we probe ED from our 4D wall (brane)?

Flat case ($k = 0$) : 4-D effective theory:

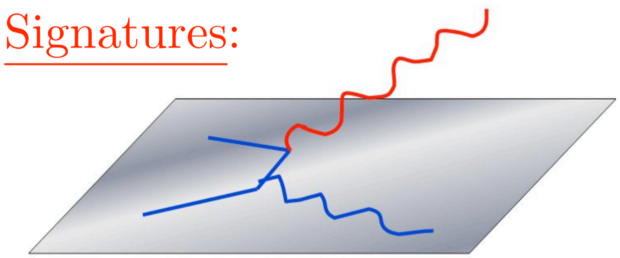
SM particles + gravitons + tower of new particles:

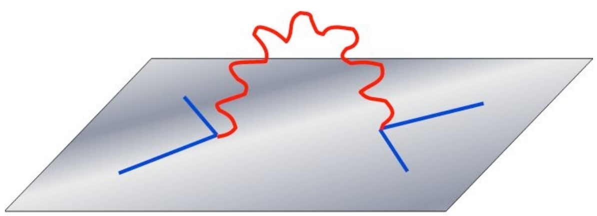
Kaluza Klein (KK) excited states with the same quantum numbers as the graviton and/or the SM particles

Mass of the KK modes $\Longrightarrow$ $E^2 - \vec{p}^2 = p_d^2 = \sum_{i=1,d} \frac{n_i^2}{R^2} = M_{G_{\vec{n}}}^2$

imbalance between measured energies and momentum in 4-D

Signatures:





- Coupling of gravitons to matter with $1/M_{Pl}$ strength
  $R^{-1} \simeq 10^{-2}$ GeV $(d = 6)$;
  $1/R \simeq 10^{-4}$ eV $(d = 2)$;

(a) Emission of KK graviton states: $G_n \Leftrightarrow \not{E}_T$
(gravitons appear as continuous mass distribution)

(b) Graviton exchange $2 \rightarrow 2$ scattering
deviations from SM cross sections

Effective Cross Sections

- Let us consider the emission of gravitons in the collision of electrons and positrons (protons and antiprotons).
- Final state will be γ + Missing energy (jets + Missing Energy)
- Each graviton extremely weakly coupled but cross section will be given by the sum of the individual KK graviton production cross section, scaling with $N_K K$.
- Again, the effective gravitational constant appears and we get

$$\sigma \simeq \frac{1}{M_{Pl}^2} (E^d R^d) \tag{60}$$

$$\sigma \simeq \frac{1}{s} \left(\frac{\sqrt{s}}{M_{Pl}^{\rm fund}} \right)^{2+d} \tag{61}$$

Warped Case

- Graviton KK modes have 1/TeV coupling strength to SM fields and masses starting with a few hundred GeV.
- KK graviton states produced as resonances.
- One can rewrite the warp factor and the massive graviton couplings in terms of mass parameters as:

$$\exp(-kL) = \frac{m_n}{kx_n}$$
$$\Lambda_\pi \simeq \frac{\bar{M}_{Pl} m_1}{kx_1} \tag{62}$$

with $x_1 \simeq 3.8$, $x_n \simeq x_1 + (n-1)\pi$.

- Calling $\eta = k/\bar{M}_{Pl}$, one gets that the graviton width is

$$\Gamma(G^n) \simeq m_1 \eta^2 \frac{x_n^3}{x_1} \tag{63}$$

Flat Extra Dimensions

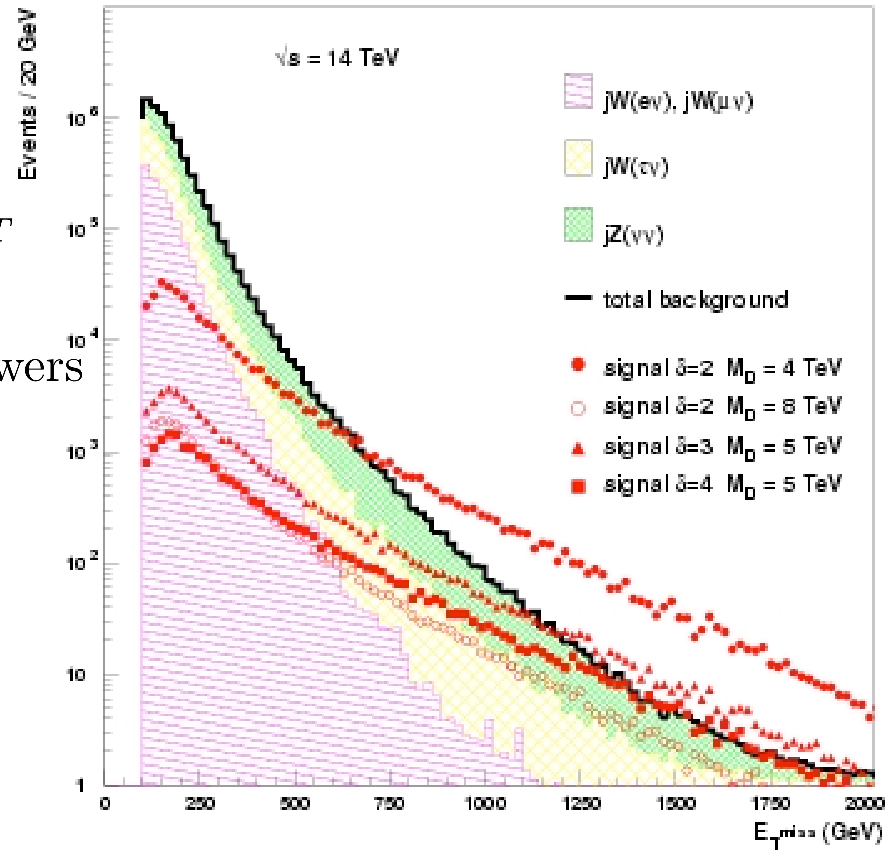
- Emission of KK graviton states

$$pp \to g\, G_N \;(G_N \to \not\!\!E_T) \longrightarrow \text{jet}+\not\!\!E_T$$

Cross section summed over full KK towers

$$\Longrightarrow \qquad \sigma/\sigma_{SM} \propto (\sqrt{s}/M_{\rm Pl}^{\rm fund})^{2+d}$$

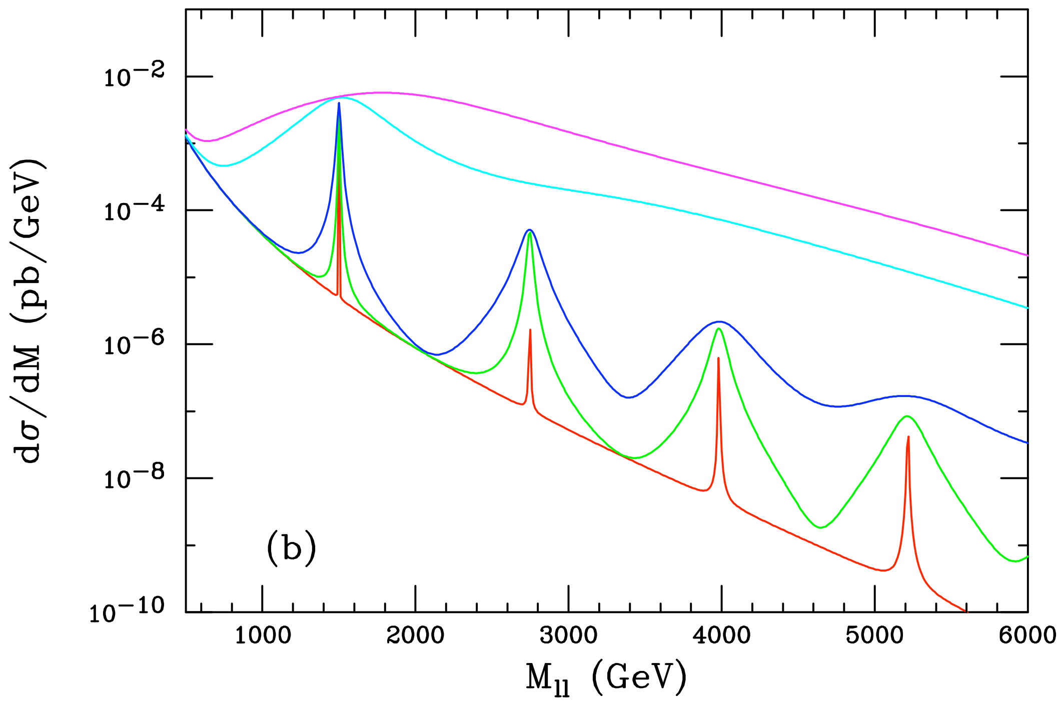
Emitted graviton appears as a continuous mass distribution.



Discovery reach for fundamental Planck scales on the order of 5–10 TeV (depending on d = 4,3,2)

• Warped Extra Dimensions

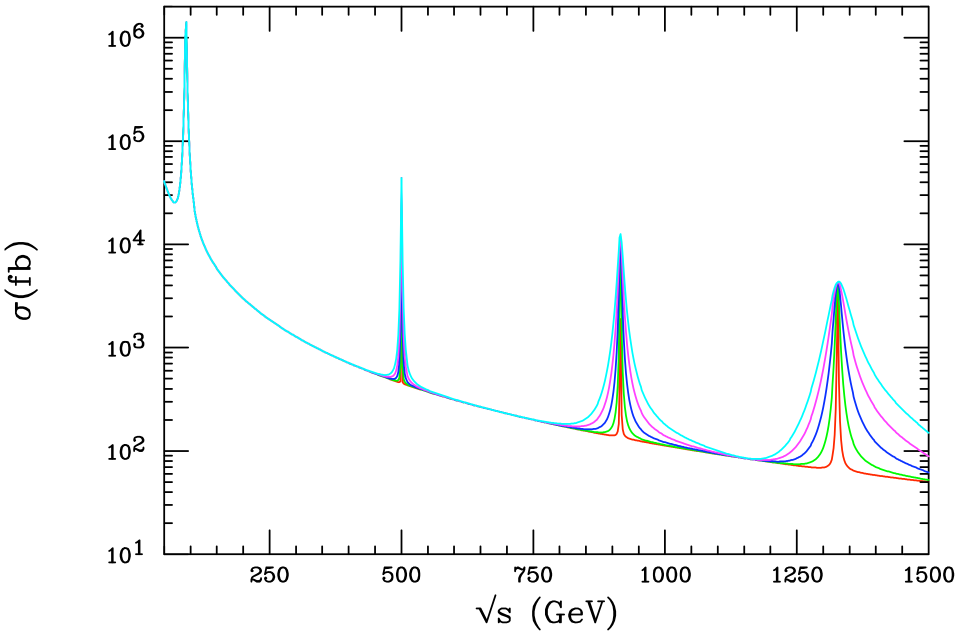
Narrow graviton resonances: $pp \to G_N \to e^+e^-$



From top to bottom: $k/M_{Pl} = 1, 0.5, 0.1, 0.05, 0.01$

Warped ED:

• Given sufficient center-of-mass energy, KK graviton states produced as resonances:



$\sigma(e^+e^- \to \mu^+\mu^-)$ as a function of $\sqrt{s}$, including KK graviton exchange,

$m_1 = 500$ GeV, $k/M_{Pl} = 0.01$–0.05 range.

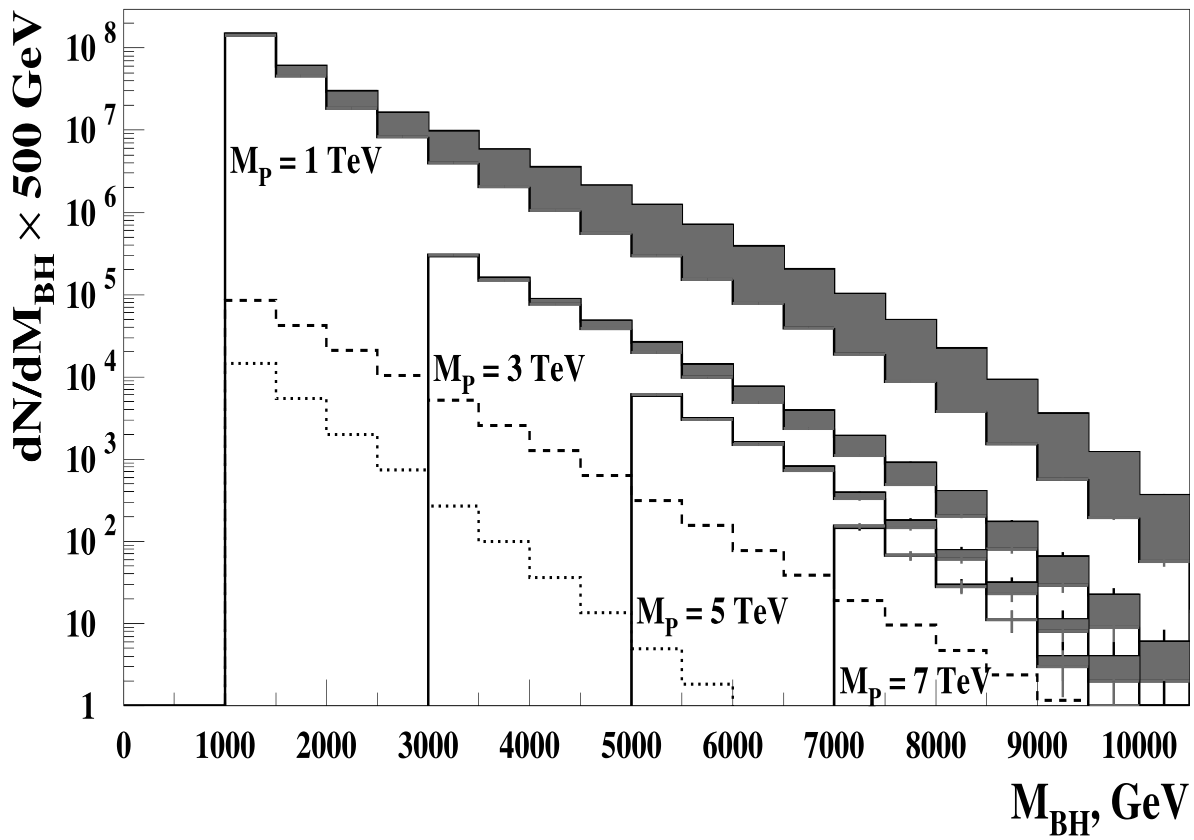
Black Hole Production ?

- Two partons with center of mass energy $\sqrt{s} = M_{BH}$, with $M_{BH} > M_{Pl}^{fund}$ collide with a impact parameter that may be smaller than the Schwarzschild radius.

  $$R_S \simeq \frac{1}{M_{Pl}^{fund}} \left(\frac{M_{BH}}{M_{Pl}^{fund}} \right)^{\frac{1}{d+1}}$$

- Under these conditions, a blackhole may form
- If $M_{Pl}^{fund} \simeq 1$ TeV $\rightarrow$ more than 10^7 BH per year at the LHC (assuming that a black hole will be formed whenever two partons have energies above $M_{Pl}^{\rm fund}$).
- Decay dictaded by blackhole radiation, with a temperature of order $1/R_S$. Signal is a spray of SM particles in equal abundances: hard leptons and photons.
- At LHC, limited space for trans-Planckian region and quantum gravity.

Black Hole production at the LHC



Dimopoulos and Lansberg; Thomas and Giddings '01

Sensitivity up to $M_{Pl}^{\rm fund} \simeq 5 - 10$ TeV for 100 fb^{-1}.

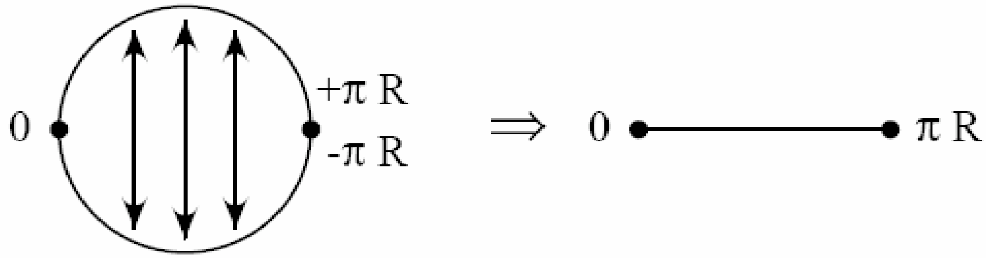
Universal Extra Dimensions

Most natural extension of four dimensional description:

- All particles live in all dimensions, including quarks, leptons, Higgs bosons, gauge bosons and gravitons.
- Universality implies a translational invariance along the extra dimension, and thus conservation of the component of momentum in the that direction.
- This implies that a KK state with $n \neq 0$, carrying non-zero momentum in the extra dimension, cannot decay into standard, zero modes.
- The lightest KK particle is stable, being a good dark matter candidate.
- Other intersting properties that arise in six dimensions are natural proton stability and an explanation of the number of generations

Orbifold

- Massless 5d spinors have 4 components, leading to mirror fermions at low energies.
- If extra dimension is compactified in a circle, no standard chiral theory may be obtained.
- Chiral theories may be obtained by invoking orbifold boundary conditions, projecting out unwanted degrees of freedom.
- Fold the extra dimension, identifying y with $-y$



- Boundary Conditions:
  $\Psi(-y) = \gamma_5 \Psi(y)$
  $V_\mu(-y) = V_\mu(y), V_5(-y) = -V_5(y)$

KK Decomposition

- We expand fields in KK modes:

$$\Phi(x^\mu, y) = \sum_n f^n(y)\Phi^n(x^\mu) \tag{6}$$

- Flat, universal extra dimension:
  - Even fields (A_μ, Ψ_L) have zero modes:

$$\Phi(x^\mu, y) = \sqrt{\frac{1}{\pi R}}\Phi^0(x^\mu) + \sum_{n\geq 1}\sqrt{\frac{2}{\pi R}}\cos\left(\frac{ny}{R}\right)\Phi^n(x^\mu) \tag{7}$$

  - Odd fields (A_5, Ψ_R) don't:

$$\Phi(x^\mu, y) = \sum_{n\geq 1}\sqrt{\frac{2}{\pi R}}\sin\left(\frac{ny}{R}\right)\Phi^n(x^\mu) \tag{8}$$

  - KK masses (before EWSB): n/R

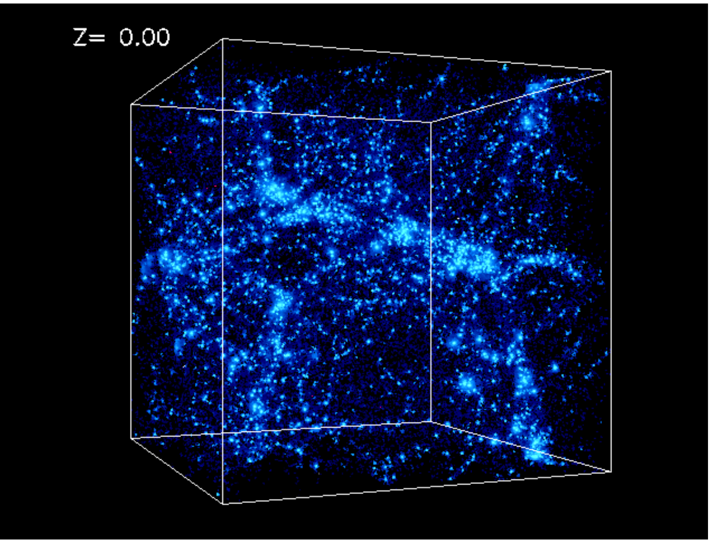
- KK fermions are Dirac, with vector-like interactions.
- In a chiral theory, the left- and right-handed zero modes each have a *separate* tower of KK modes.
- This is somewhat like SUSY, with each SM particle accompanied by partner fields.

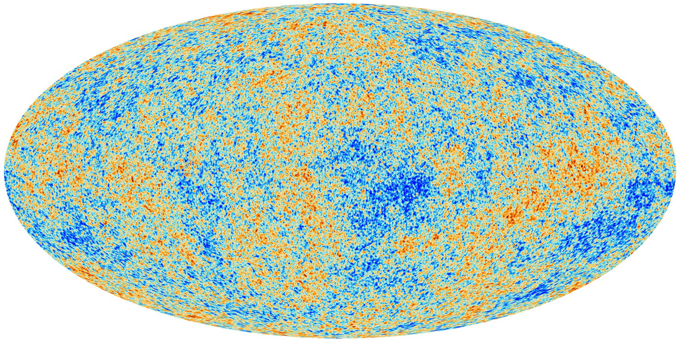
KK Parity

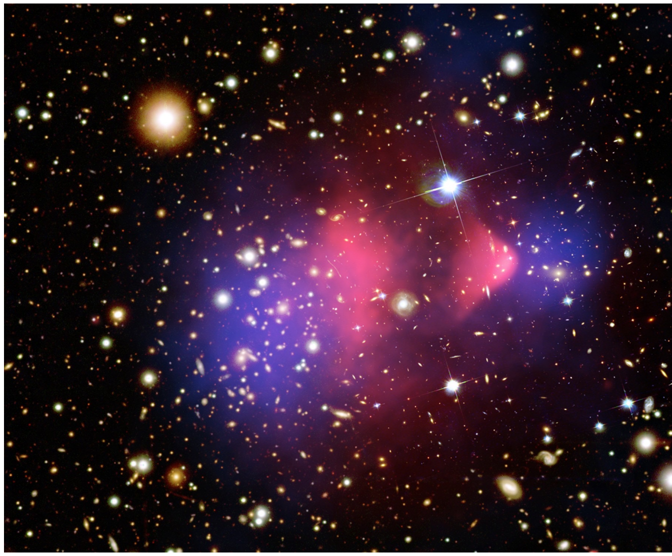
- Conservation of KK number is broken to conservation of KK parity: $(-1)^n$.
- KK-parity requires odd KK modes to couple in pairs:
- The lightest first-level KK mode is stable.
- First level KK modes must be pair-produced.
- The Lightest Kaluza-Klein Particle plays a crucial role in phenomenology, similar to the LSP of SUSY:
- All relic KK particles decay to LKPs.
- Any first level KK particle produced in a collider decays to zero modes and an LKP.
- KK parity is also present with boundary fields, provided the same fields live on both boundaries.

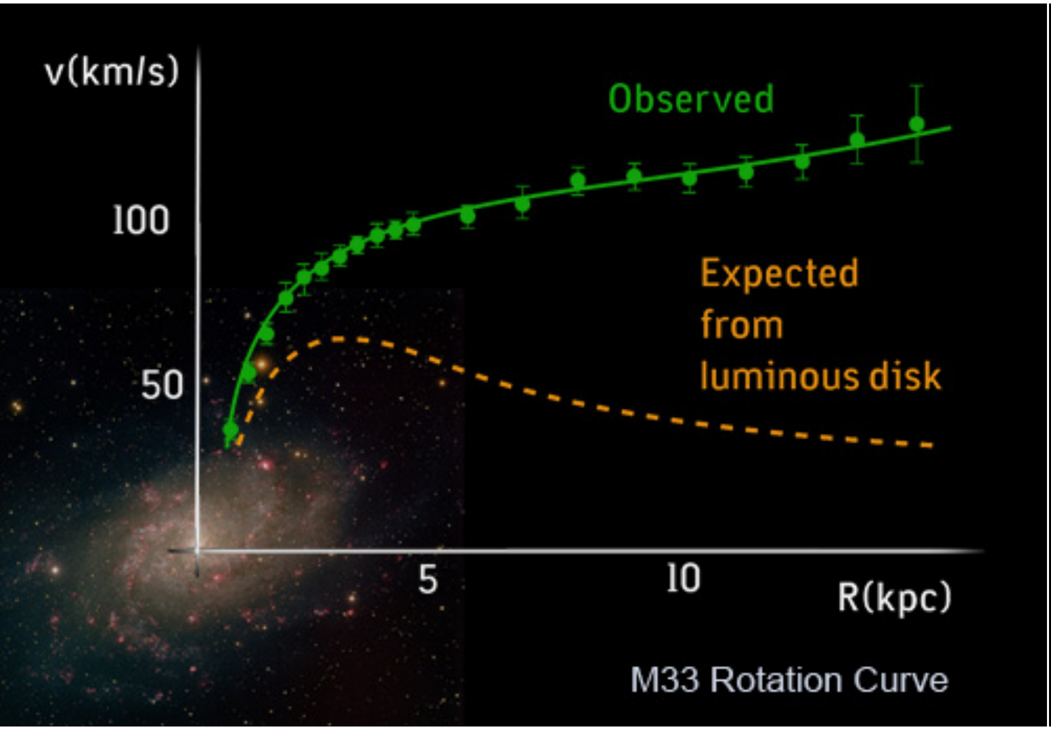
Dark Matter

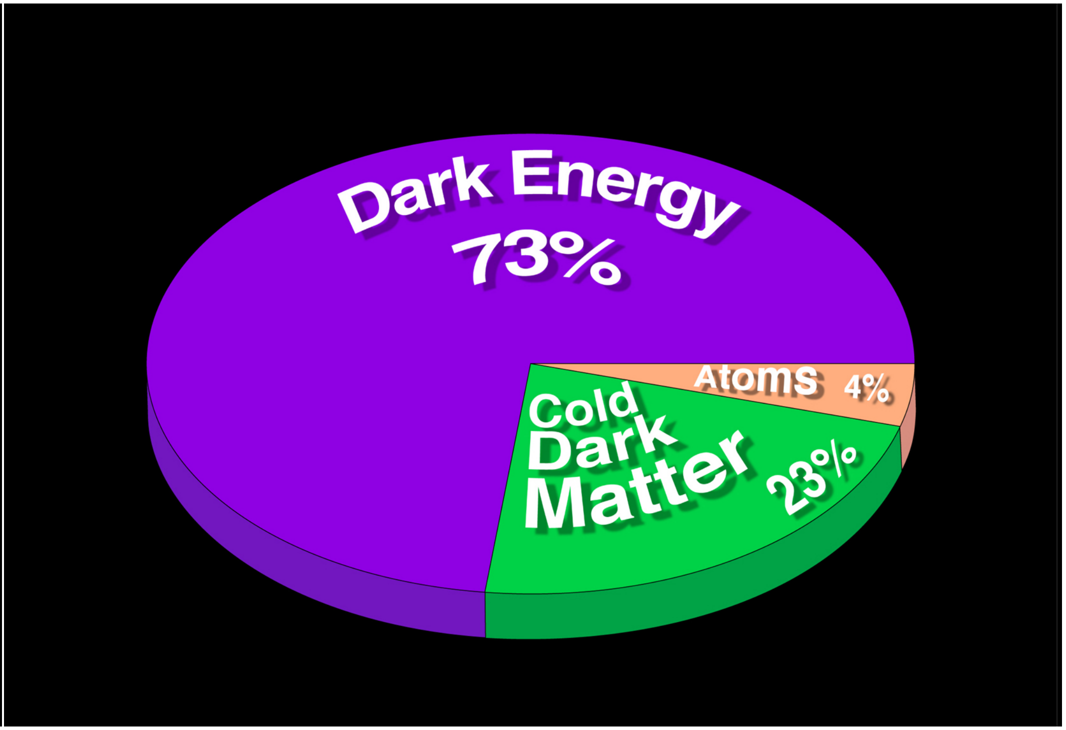
Existence of Dark Matter Supported by overwhelming indirect evidence





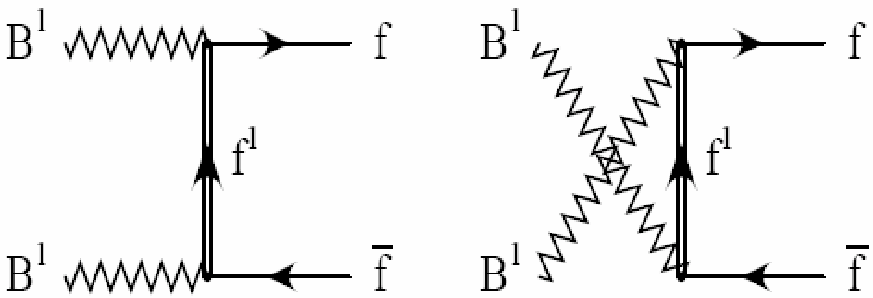






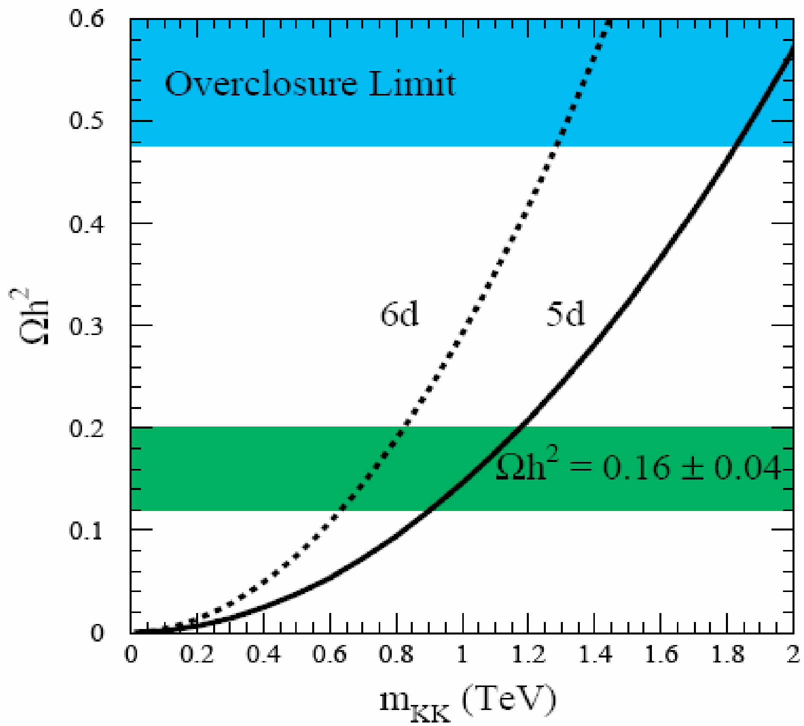
Dark Matter

- Relic Density depends strongly on annihilation cross section.
- In the case of universal extra dimensions, dominant annihilation diagram is given by interchange of first tower of KK particles.



- Whenever the KK mode of the right-handed leptons is close enough in mass to the LKP, coannihilation should be also taken into account

Relic Density: Results

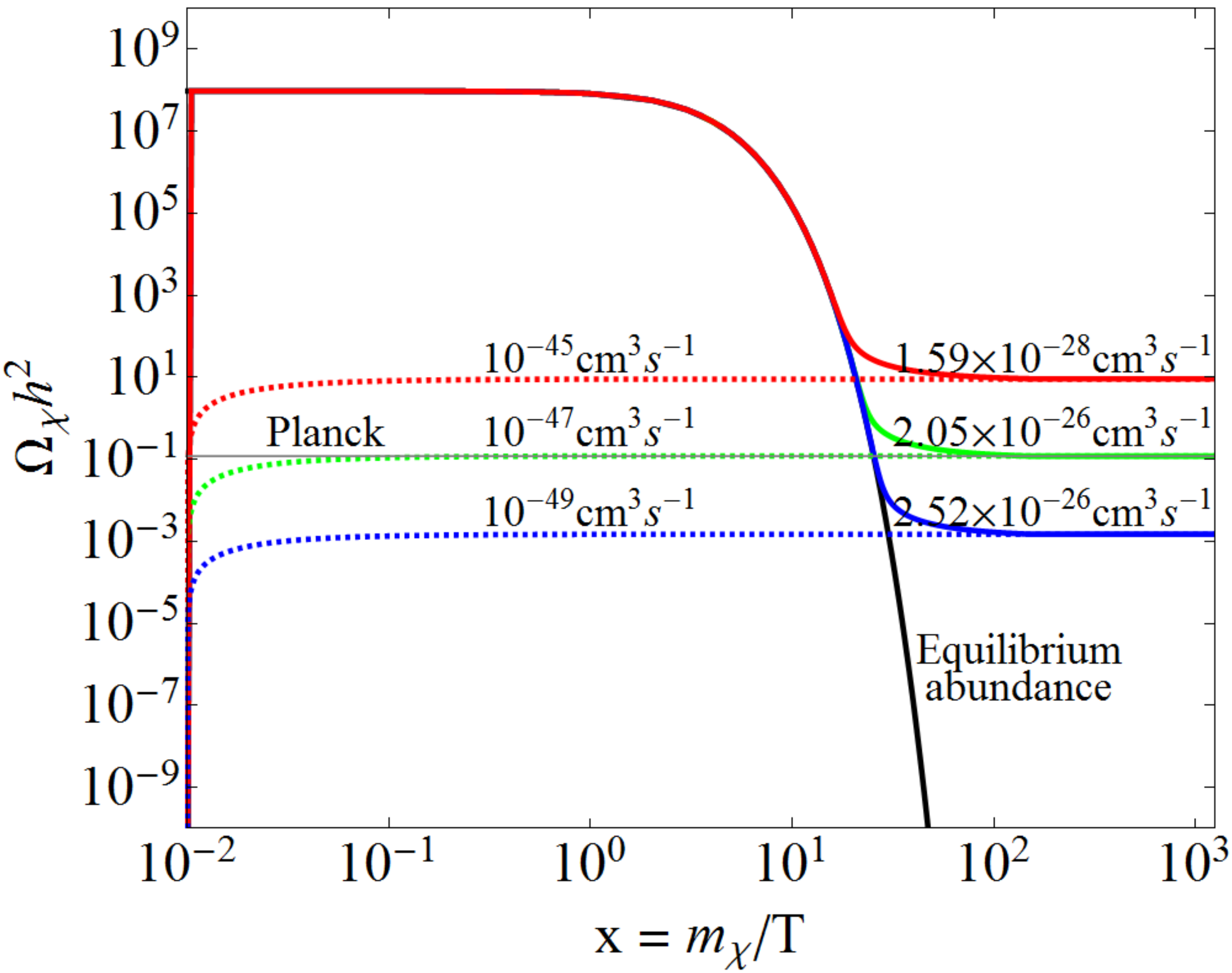


Universal extra dimensions of the order of 500 GeV–1 TeV preferred for the LKP to be a good dark matter candidate

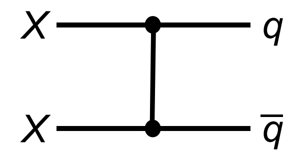
Coannihilation and Graviton effects may modify this picture

Matchev and Kong'06; Shah & Wagner'06

Dark Matter as a Big Bang Relic



$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$



m_X ~ 100 GeV, g_X ~ 0.6 → Ω_X ~ 0.1

Weak scale size masses and couplings roughly consistent with Ω

The Randall Sundrum Scenario (RS)

Universal Extra Dimensions in Warped Case

The RS scenario: generalities

Sensitivity to UV physics in Higgs sector $\longrightarrow$ new physics at weak scale

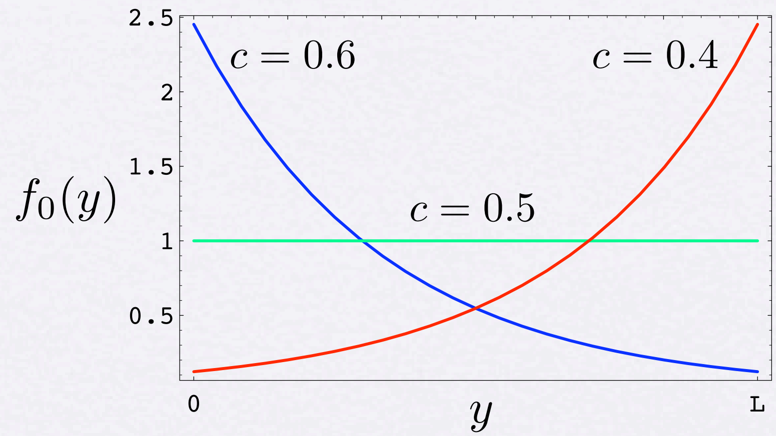
Randall-Sundrum proposal (1999)

Slice of AdS: $\quad ds^2 = e^{-2ky}\eta_{\mu\nu}dx^\mu dx^\nu - dy^2 \qquad y \in [0, L]$

UV brane IR brane

- If Higgs on IR brane: scales of order TeV
- Bulk fermions:
  - geom. mass hierarchies
  - Suppression of FCNC
- Breaking of symmetries by B.C.'s

  $\longrightarrow$ Light states are a common ocurrence

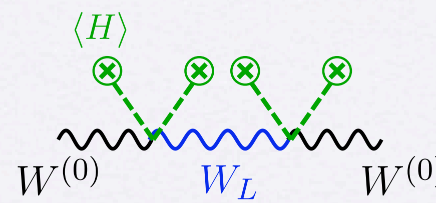


- 4-dimensional description through AdS/CFT
  (However, actual computation performed in 5D theory)
- Potentially exciting phenomenology at the TeV scale...

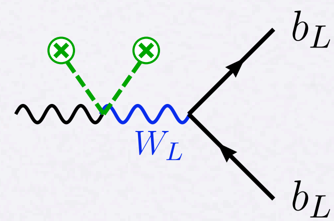
But how light the new physics?

Tree level corrections to SM observables $\longrightarrow$ stringent constraints

Large contributions to oblique parameters, e.g. T



Shifts in fermion-gauge boson couplings



Top quark , near IR brane $\longrightarrow$ b_L near IR brane

But if light generations near UV brane (motivated by flavor)

$\longrightarrow$ Large corrections to $Zb_L\bar{b}_L$ coupling

Expect third generation to play important role

These constraints easily lead to $M_{\mathrm{KK}} > 10\ \mathrm{TeV}$

But how light the new physics?

In this talk I will consider models that tame the large corrections by

- Imposing a custodial SU(2) symmetry **(Agashe,Delgado,May,Sundrum)**

The upshot will be that

- for gauge KK resonances: $M_{\rm KK} \sim 2 - 3\ {\rm TeV}$

Note that generically, loop corrections to Higgs mass parameter are cutoff well above $M_{\rm KK}$ $\longrightarrow$ "little" hierarchy problem

An attractive solution: embed Higgs into 5D gauge field

Realization of the pseudo Goldstone Boson scenario **(Contino, Nomura, Pomarol)**

Higgs Mass preferred to be in the range 100 GeV to 150 GeV (Medina, Shah, C.W. '07)

The R_D problem

$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)}, \quad \ell = \mu, e.$$

Ratio of decay of B mesons into D mesons and different leptons

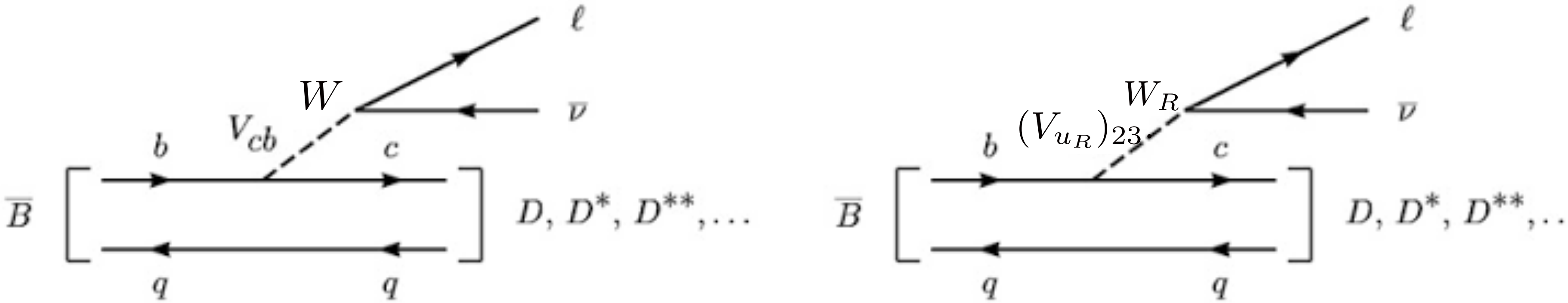
$$R_D^{\rm SM} = 0.300 \pm 0.011, \quad R_{D^*}^{\rm SM} = 0.254 \pm 0.004$$

Combination of BABAR, Belle and LHCb measurements

$$R(D) = 0.407 \pm 0.046\,, \qquad R(D^*) = 0.304 \pm 0.015\,,$$

Clear discrepancy with respect to the SM !

SM contribution is tree-level. Additional gauge bosons, coupled to left handed currents lead to tension with other flavor observables. Right-handed currents are a possible alternative.



Asadi, Buckley, Shih, arXiv:1804. 04135
Greljo, Robinson, Shakya, Zuppan, arXiv:1804.04642

$$\mathcal{L}_{eff} = -\frac{4G_F}{\sqrt{2}} V_{cb} C_\tau (\bar{c}_R \gamma^\mu b_R)(\bar{\tau}_R \gamma_\mu \nu_{\tau_R})$$

Carena, Megıas, Quiros and C.W, arXiv:1809.01107

Implementation in a warped $SU(2)_L \times SU(2)_R \times U(1)_Y$ Model

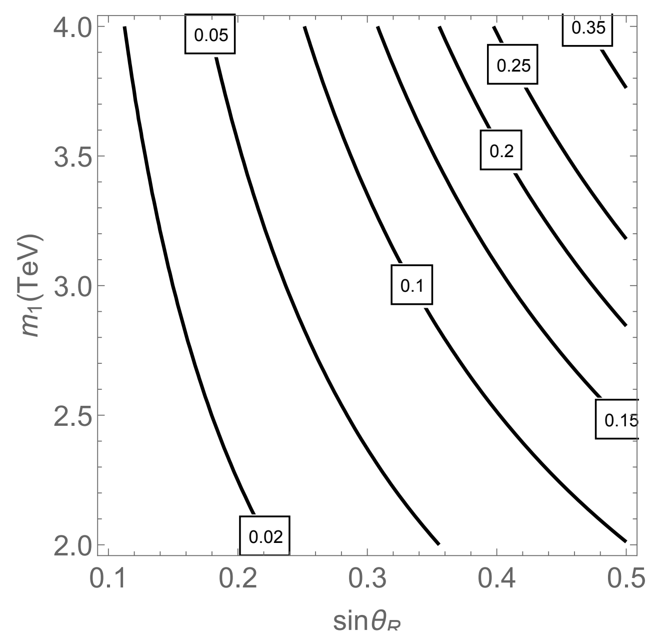
- Existing model to solve hierarchy problem, without tension with precision electroweak observables
- Coupling to leptons differ due to localization of lepton fields in warped extra dimension
- Well defined, predictive framework.
- Third generation quarks and right-handed leptons localized at infrared brane.
- Flavor violating mixing of leptons suppressed by lepton flavor symmetries.
- Strong couplings of KK modes are natural and essential to avoid experimental constraints from LHC.

$$\frac{R_{D^{(*)}}}{R^{SM}_{D^{(*)}}} = 1 + |C_\tau|^2 \qquad C_\tau \simeq 0.46$$

$$C_\tau = \sum_n \left(\frac{g_R}{2} G_3^n \frac{v}{m_n}\right)^2 \frac{(V^\dagger_{u_R})_{23}}{V_{cb}} \simeq 1.45 \left(\frac{g_R}{2} G_3 \frac{v}{m_1}\right)^2 \frac{(V^\dagger_{u_R})_{23}}{V_{cb}}$$

$$m_1 \simeq \frac{0.64}{\sin\theta_R} \left(\frac{\left(V^\dagger_{u_R}\right)_{23}}{V_{cb}}\right)^{1/2} \text{TeV} \qquad \sin\theta_R = \frac{g_Y}{g_R}$$

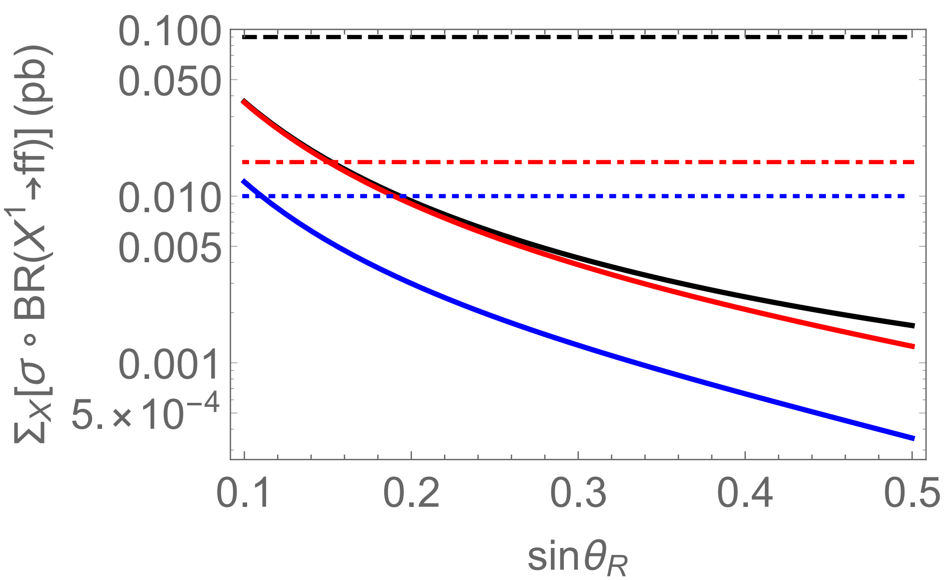
Countors of constant $(V_{u_R})_{23}$.



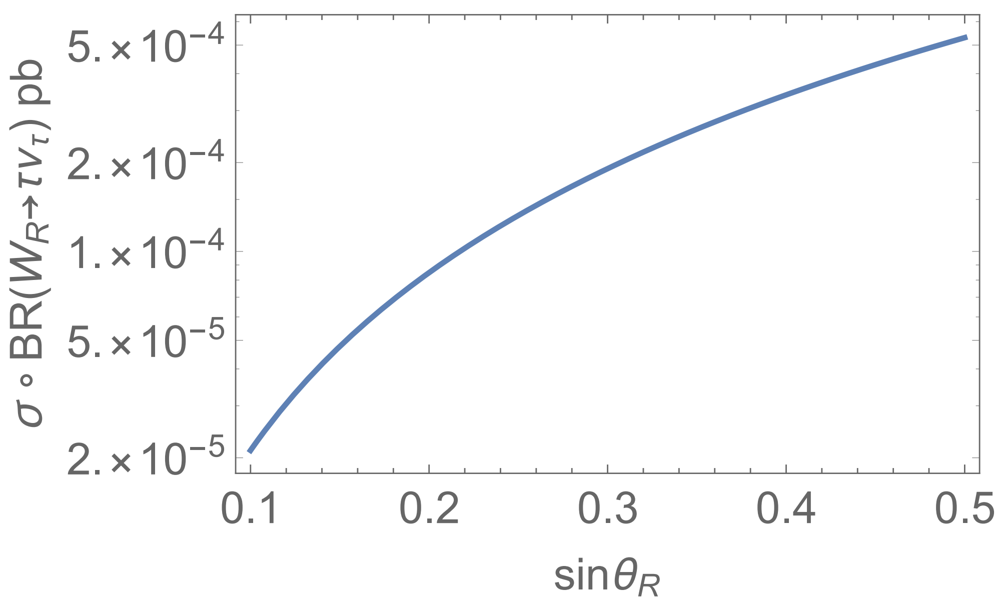
Carena, Megıas, Quiros and C.W, arXiv:1809.01107

Current LHC Bounds
Example of 3 TeV resonance

Model is in agreement with all constraints from flavor and collider physics.
It can be tested by the LHC,looking for the charged and neutral resonances, decaying to either third generation quarks and leptons.
Bounds below don't include width effects, which may be significant due to large couplings.
They increase the cross section at low energies, due to constructive interference contributions of different KK modes, but reduce the efficiency of the search due to the disappearance of narrow resonances.



Black Dashed : Bound on production of Bottom pairs
Red Dashed : Bound on production of Top pairs
Blue Dashed : Bound on production of Tau pairs

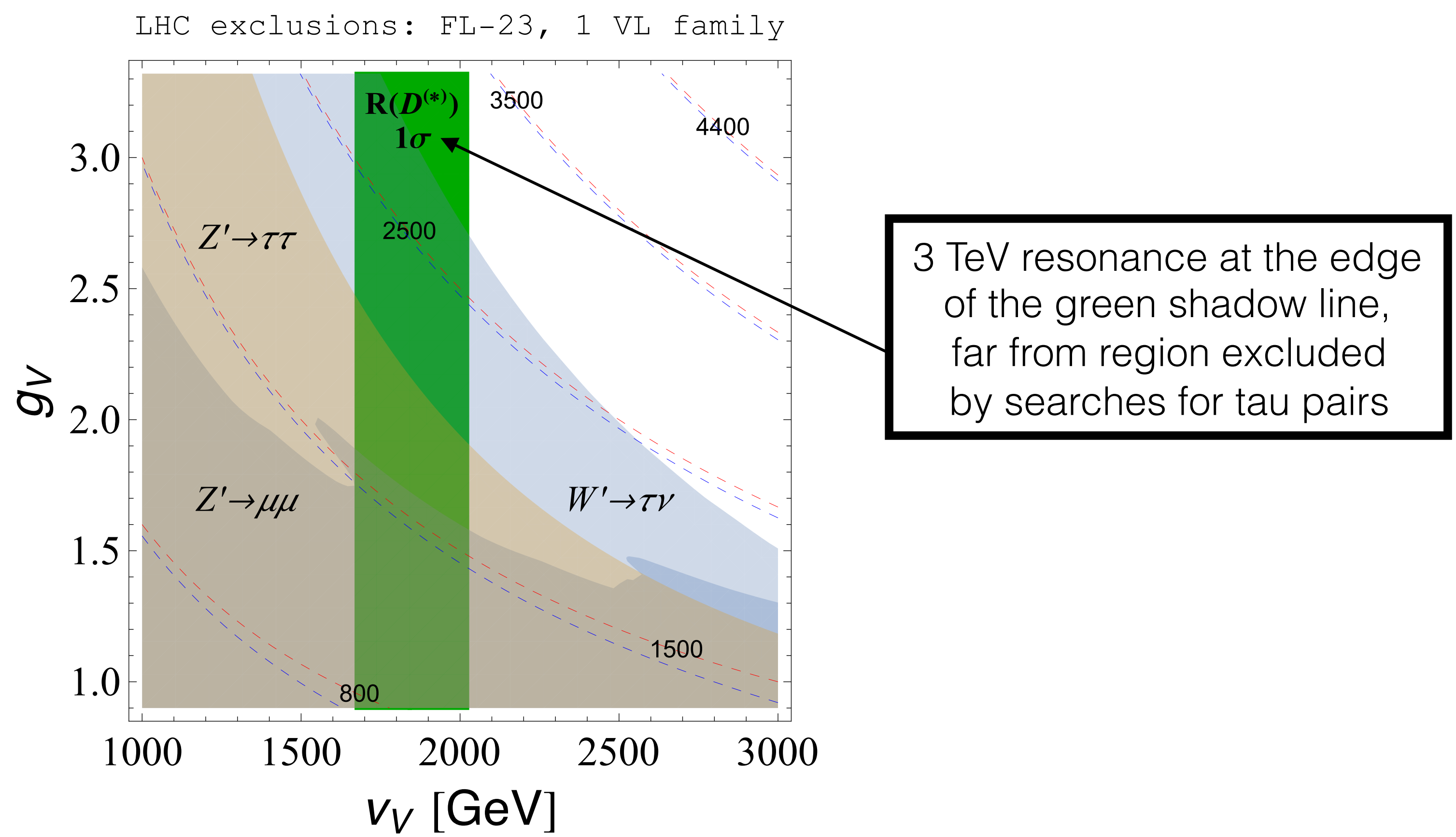


$\sigma(pp \to W_R^1) \times \mathcal{B}(W_R^1 \to \tau_R \nu_{\tau_R})_{exp} \lesssim 0.0035$ pb

Bounds including width effects

Greljo, Robinson, Shakya, Zuppan, arXiv:1804.04642

A resonance of mass 3 TeV is consistent with the collider bounds



These bounds were obtained considering $(V_{u_R})_{23} = 1$.
R_D scales like $g_R^4((V_{u_R})_{23})^2$. Cross section scales like $g_R^2((V_{u_R})_{23})^2$.
Hence, to keep consistency with flavor observables, if one assumes a mixing $(V_{u_R})_{23} = 0.2$, for a mass of order 3 TeV, the coupling must be increased by a factor of order 2, while the charged current cross section will be reduced by a factor of order 4.

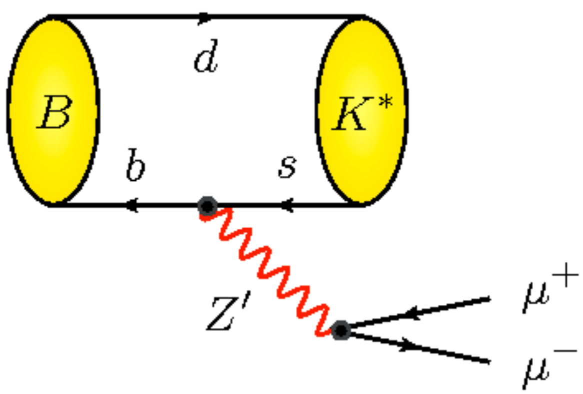
Related Flavor Anomaly

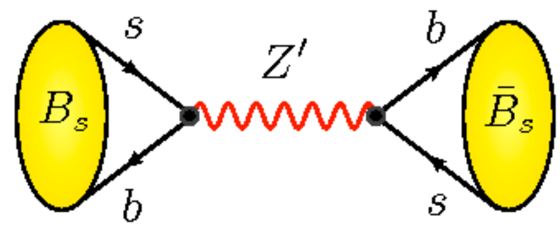
LHCb Results :

$$R(K) = \frac{B \to K\mu^+\mu^-}{B \to Ke^+e^-} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

$$R(K^*) = 0.660^{+0.110}_{-0.070} \pm 0.024$$

Altmannshofer, Gori, Pospelov, Yavin'14





Megias, Quiros'17

Carena, Megias, Quiros and C.W, arXiv:1809.01107

In the custodial warped XD scenario, fixed by LH currents

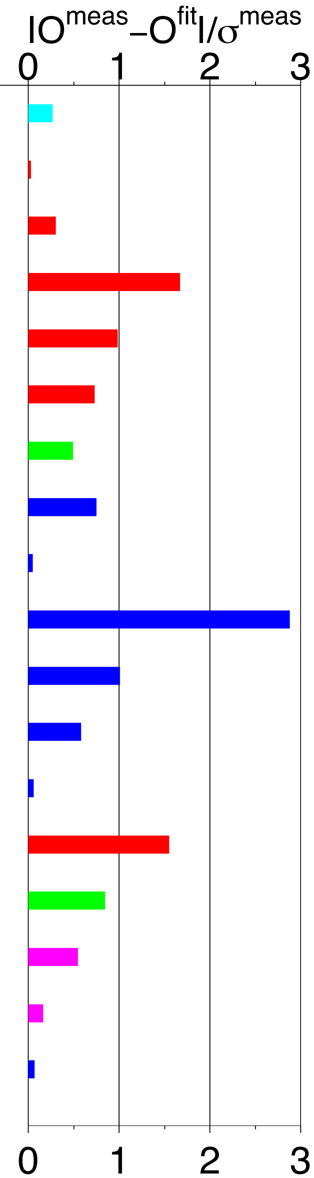
Additionally, in this scenario, due to the rho parameter cancellation, one can also fix the forward backward asymmetry problem !

Electroweak Precision Measurements

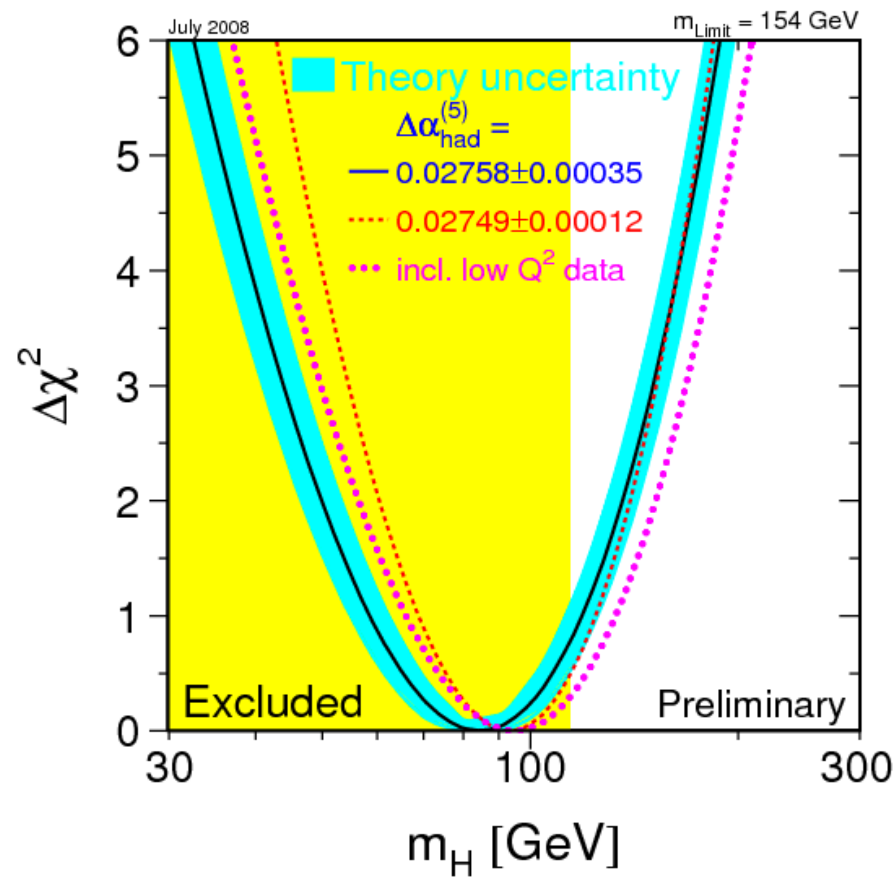
Electroweak Precision Measurements

LEPEWWG'12

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02750 ± 0.00033	0.02759
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^{0} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.385 ± 0.015	80.377
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.20 ± 0.90	173.26



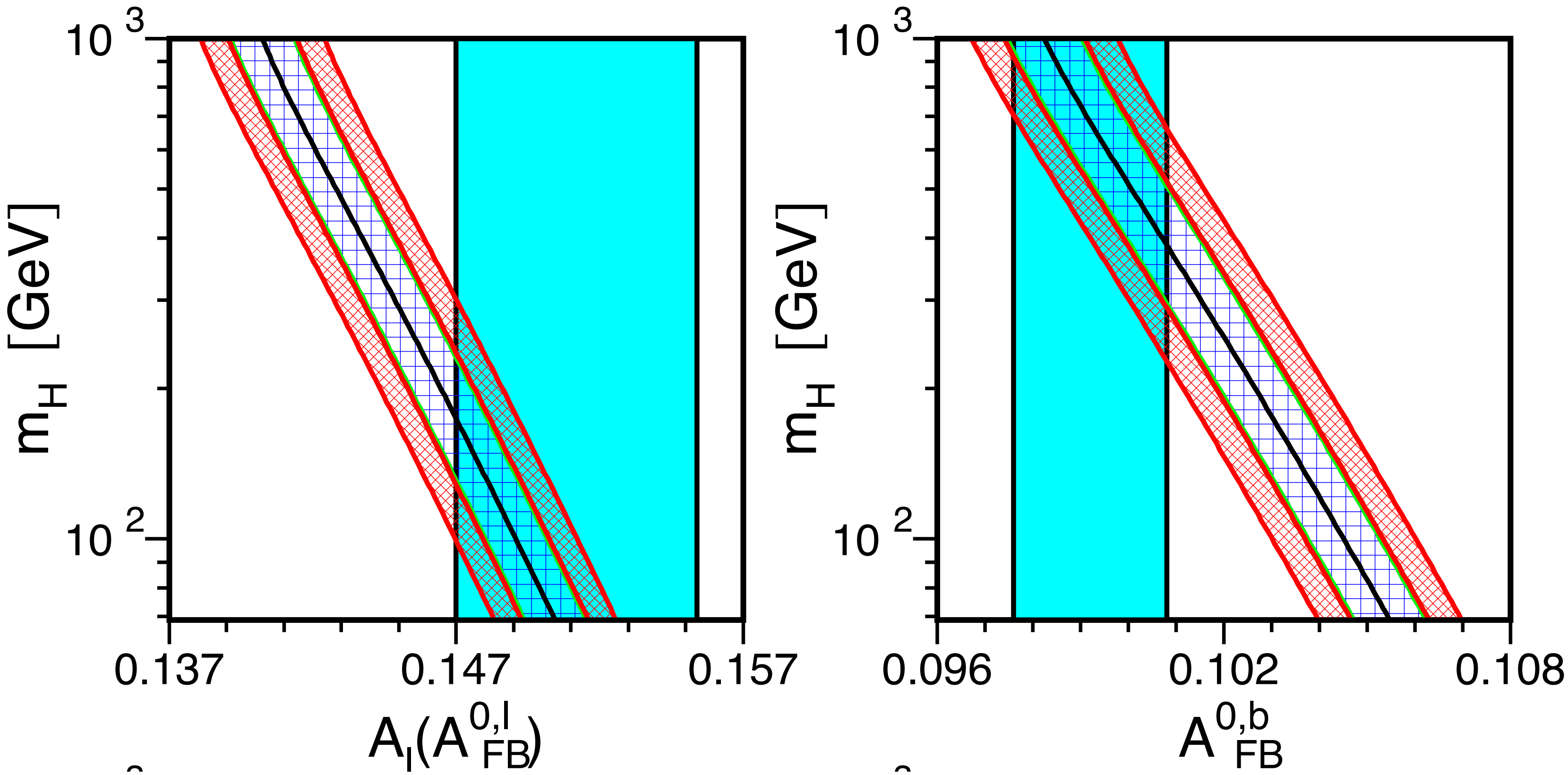
March 2012



Very good Agreement with SM expectations.
Bottom FB Asymmetry seems to be 3σ away.

The other fact, emphasized by Chanowitz is that it is this anomalous value of the FB asymmetry that allows consistency of the current data with the measured Higgs mass

M. Chanowitz, arXiv:hep-ph/0207123



LEP and SLD EWWG, arXiv:hep-ex/0509008

Formulation of the Problem

$$\mathcal{L}_{Zb\bar{b}} = \frac{-e}{s_W c_W} Z_\mu \bar{b} \gamma^\mu \left[\bar{g}_L^b P_L + \bar{g}_R^b P_R \right] b$$

The relevant b-sector quantities are defined as

$$R_b \equiv \frac{\Gamma(Z \to b\bar{b})}{\Gamma(Z \to \text{hadrons})} \simeq \frac{(\bar{g}_L^b)^2 + (\bar{g}_R^b)^2}{\sum_q [(\bar{g}_L^q)^2 + (\bar{g}_R^q)^2]}$$

$$A_{FB}^b|_{\sqrt{s} \simeq m_Z} = \frac{3}{4} A_\ell \, A_b$$

where

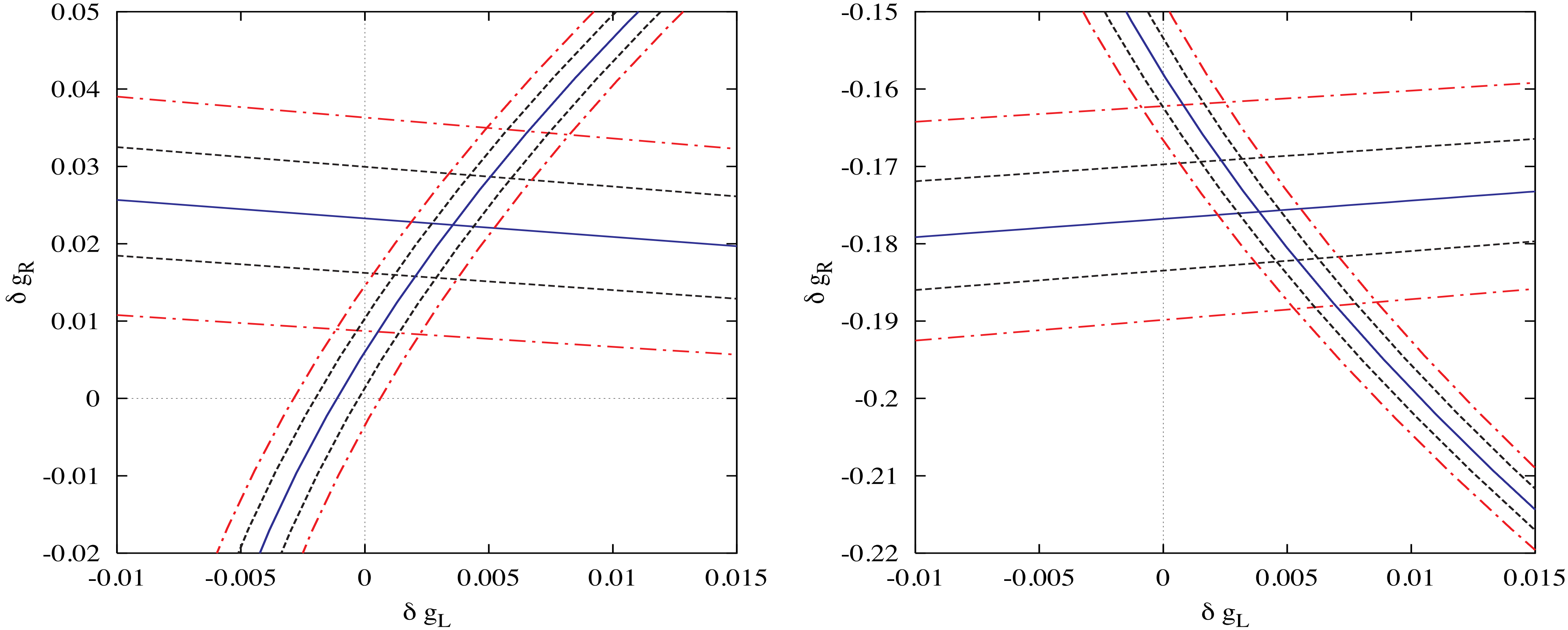
$$A_b \simeq \frac{(\bar{g}_L^b)^2 - (\bar{g}_R^b)^2}{(\bar{g}_L^b)^2 + (\bar{g}_R^b)^2}$$

$$A_\ell \simeq \frac{(g_L^\ell)^2 - (g_R^\ell)^2}{(g_L^\ell)^2 + (g_R^\ell)^2}.$$

To explain the observed values the right-handed coupling must differ in a significant way from the SM values :

$$(\bar{g}_L^b, \bar{g}_R^b) \approx (\pm 0.992 g_L^b(SM), \pm 1.26 g_R^b(SM))$$

Corrections of the left and right-handed couplings

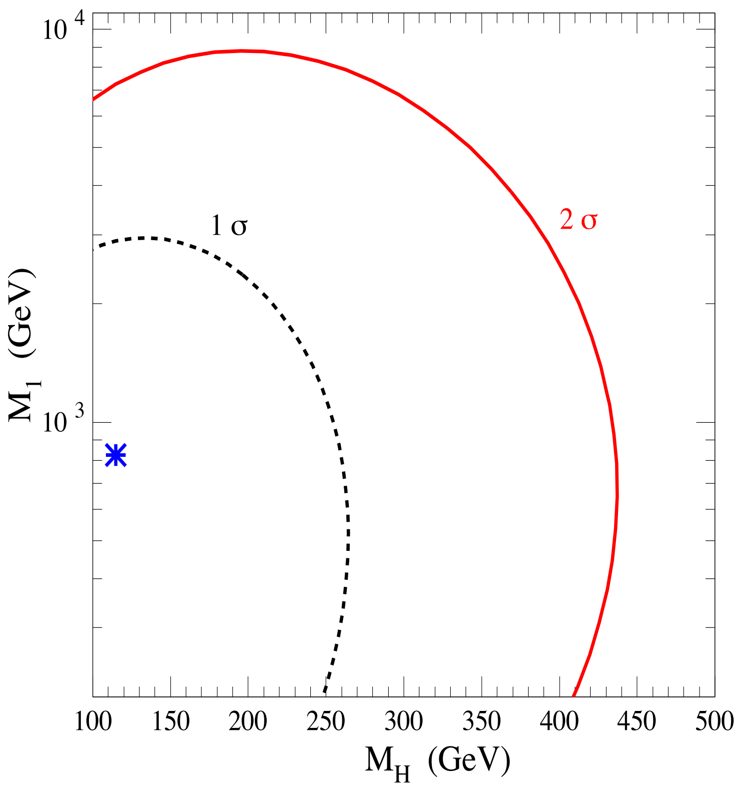


$$g_L^{\mathrm{SM}} = -\frac{1}{2} + \frac{\sin^2\theta_W}{3} \simeq -0.42 \qquad g_R^{\mathrm{SM}} = \frac{\sin^2\theta_W}{3} \simeq 0.08$$

D. Choudhury, T. Tait, C. Wagner, arXiv:hep-ph/0109097

Fit to the Data : Mixing with Exotic Fermions (4/3,1/3)

Although the mixing angles depend only on ratios of the masses and the off-diagonal Yukawas, there is a dependence on the overall scale via the corrections to other precision observables, most notably the T parameter, that for a fixed mixing angle increases with M_1.



Exotic Searches already constrain these masses to be allowed mean value

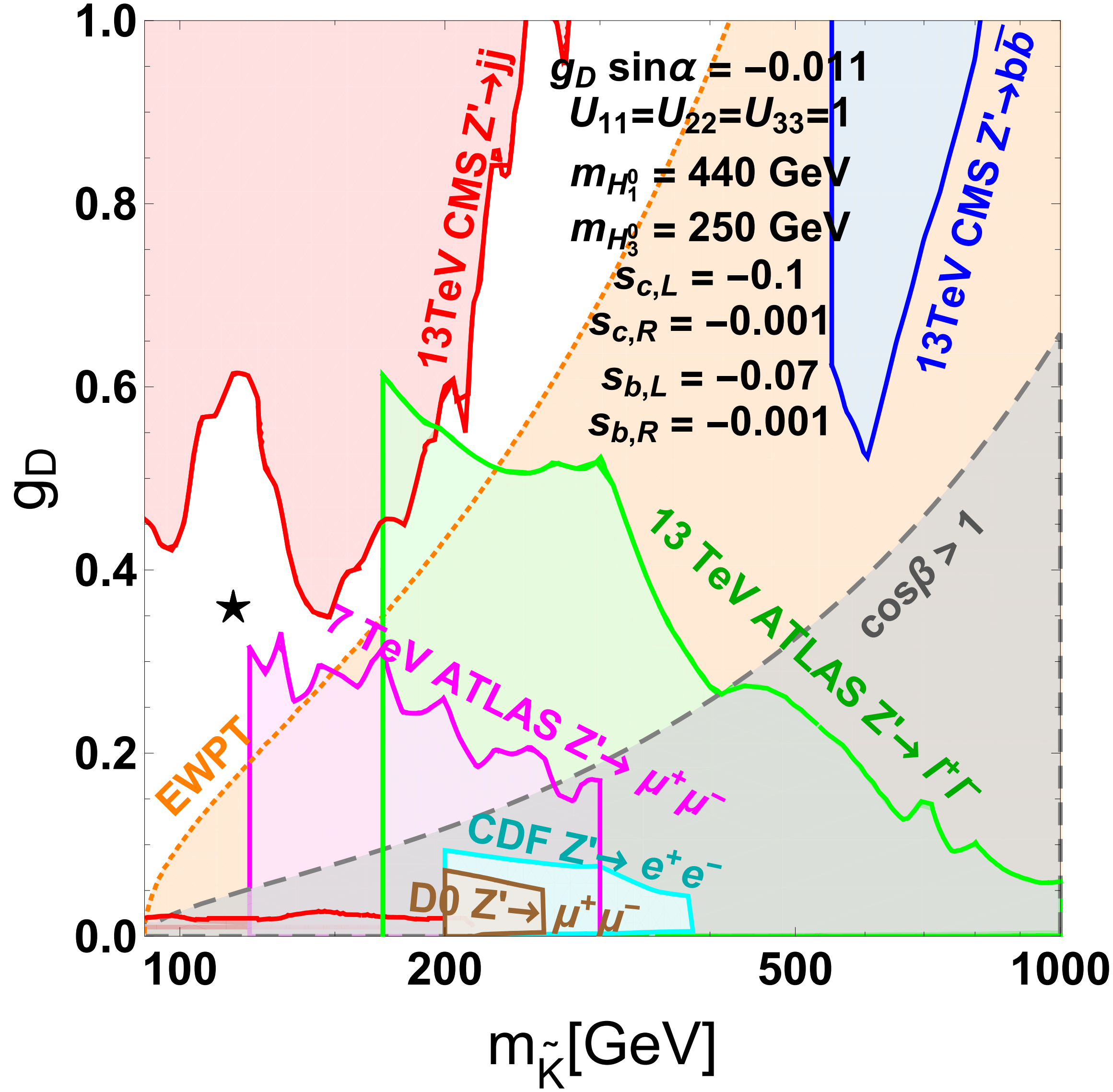
$$T' \to bW^+, \quad B' \to W^- t$$
$$B' \to (Z, H) b$$

This fit, performed before the Higgs Discovery, led to a preference for a light Higgs and vector like quarks with masses up to a few TeV. Observe that quarks of charge 1/3 and 4/3 would be predicted.

D. Liu, J. Liu, X. Wang, C. W., arXiv:1712.05082

Mixing of gauge bosons with the Z

Search for Z' has been carried out in many different channels.



Small decay branching ratio into leptons makes the constraints weaker.
It is interesting the “excess” in the boosted di-jet searches that is apparent in the Figure.

More on Dark Matter

WIMP must be neutral and stable

- Stability may be ensured by a discrete symmetry under which new particles are charged and SM is neutral
- Neutrality may be obtained when particle masses depend on the strength of their gauge interactions
- Typical example is SUSY. The symmetry is R-Parity

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

- Any weakly interacting theory fulfilling the above properties will have a natural DM candidate.

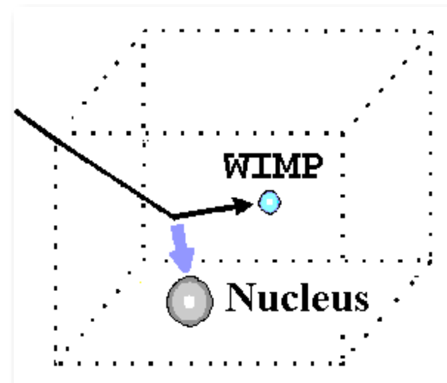
Direct Detection Dark Matter Experiments

- **Collider experiments can find evidence of DM through $\not{E}_T$ signature but no conclusive proof of the stability of a WIMP**

- Direct Detection Experiments can establish the existence of Dark Matter particles

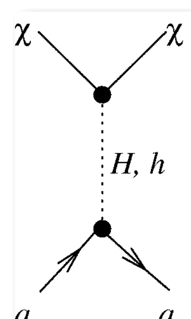
WIMPs elastically scatter off nuclei in targets, producing nuclear recoils

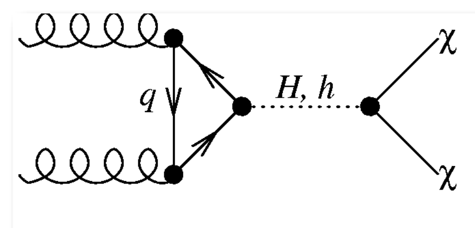
$$R = \sum_i N_i \, \eta_\chi \langle \sigma_{i\chi} \rangle$$



Direct DM experiments:
sensitive mainly to spin-independent elastic scattering cross section ($\sigma_{SI} \leq 10^{-8}\, pb$)

==> dominated by virtual exchange of H and h

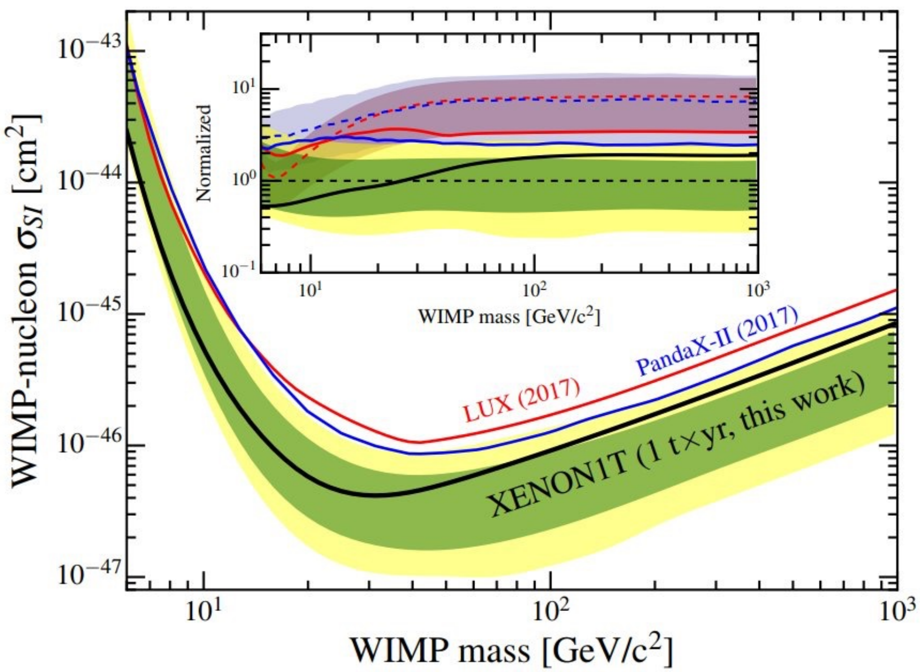


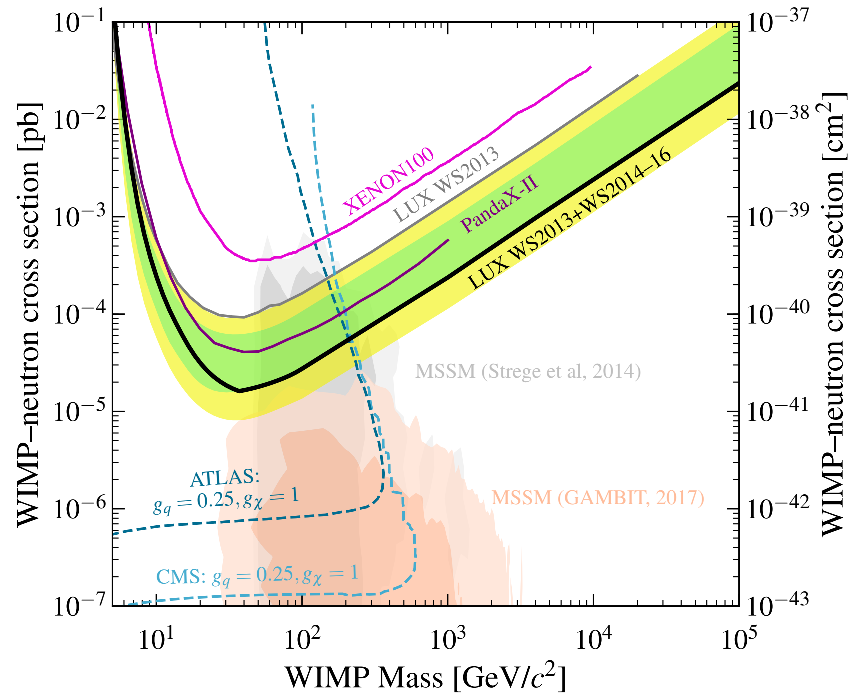


- $\tan\beta$ enhanced couplings of H to strange, and to gluons via bottom loops

$$\frac{\sigma_{SI}}{A^4} \approx \frac{0.1 g_1^2 g_2^2 N_{11}^2 N_{13}^2 m_p^4 \tan^2\beta}{4\pi m_W^2 M_A^4}$$

DM : Direct Detection Bounds





$$\sigma_p^{\rm SI} \propto \frac{m_Z^4}{\mu^4}\left[2(m_{\tilde\chi_1^0} + 2\mu/\tan\beta)\frac{1}{m_h^2} + \mu\tan\beta\frac{1}{m_H^2} + (m_{\tilde\chi_1^0} + \mu\tan\beta/2)\frac{1}{m_{\tilde Q}^2}\right]^2$$

Blind Spot :

$$2\left(m_{\tilde\chi_1^0} + 2\frac{\mu}{\tan\beta}\right)\frac{1}{m_h^2} \simeq -\mu\tan\beta\left(\frac{1}{m_H^2} + \frac{1}{2m_{\tilde Q}^2}\right)$$

$$\mu \times m_{\tilde\chi^0} < 0$$
$$m_{\tilde\chi^0} \simeq M_1$$

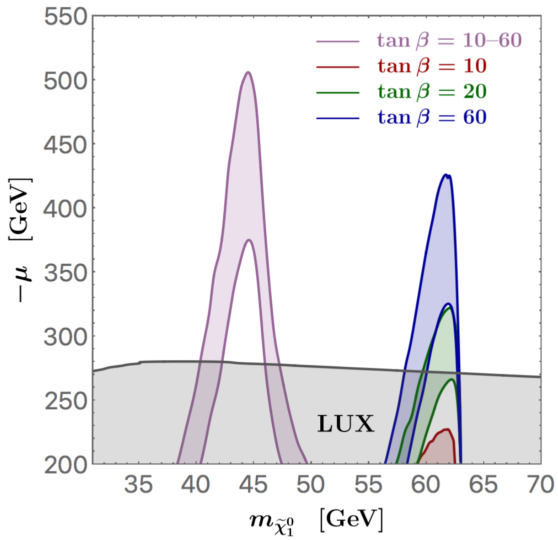
Cheung, Hall, Pinner, Ruderman’12, Huang, C.W.’14, Cheung, Papucci, Shah, Stanford,Zurek'14

$$\sigma^{\rm SD} \propto \frac{m_Z^4}{\mu^4}\cos^2(2\beta)$$

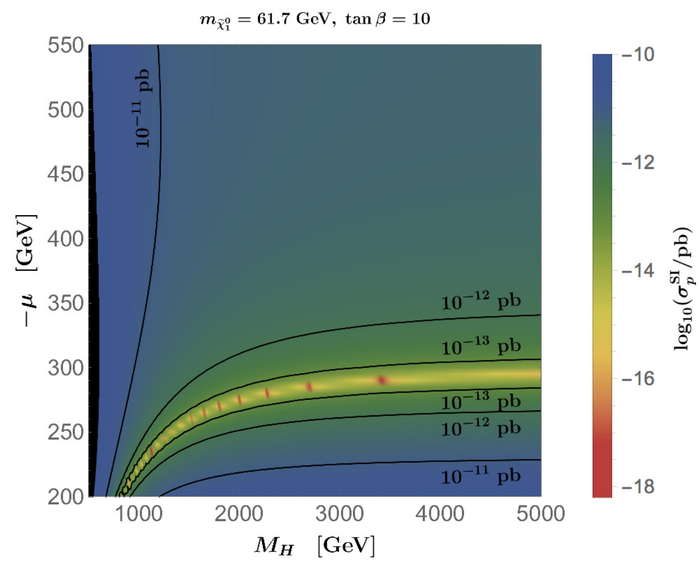
Carena, Osborne, Shah, C.W. ‘18

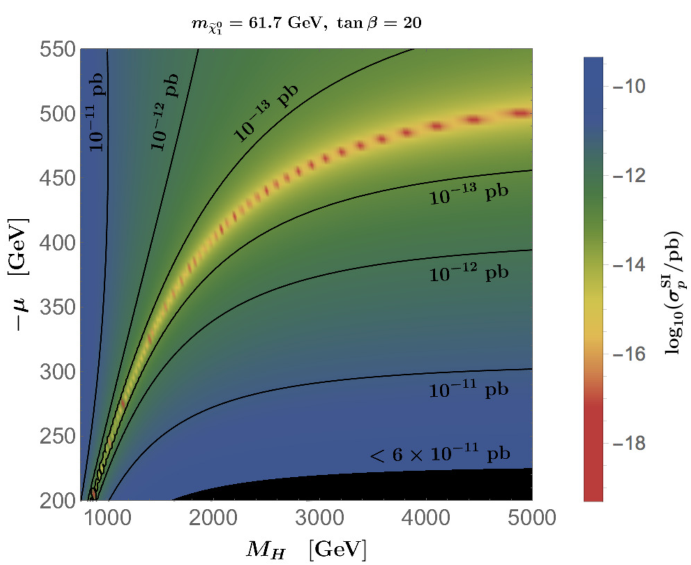
ATLAS Excess : Dark Matter Phenomenology

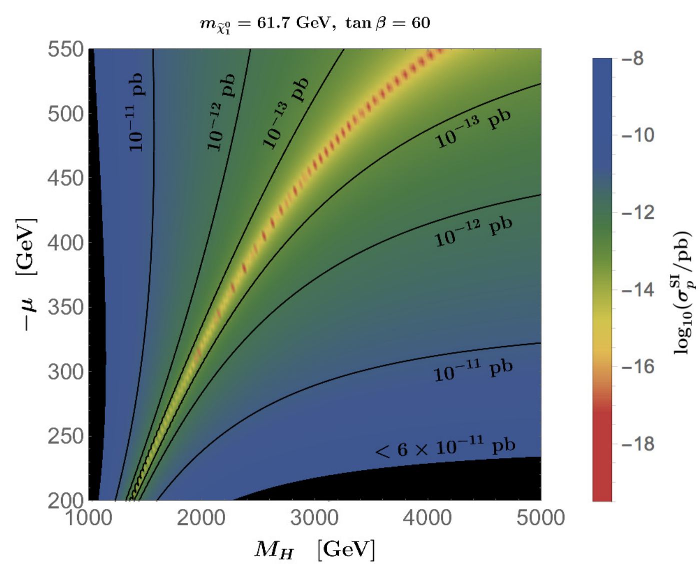
Higgs and Z Resonant Annihilation Regions
SD Cross Section Bounds satisfied
provided $|\mu| > 270$ GeV



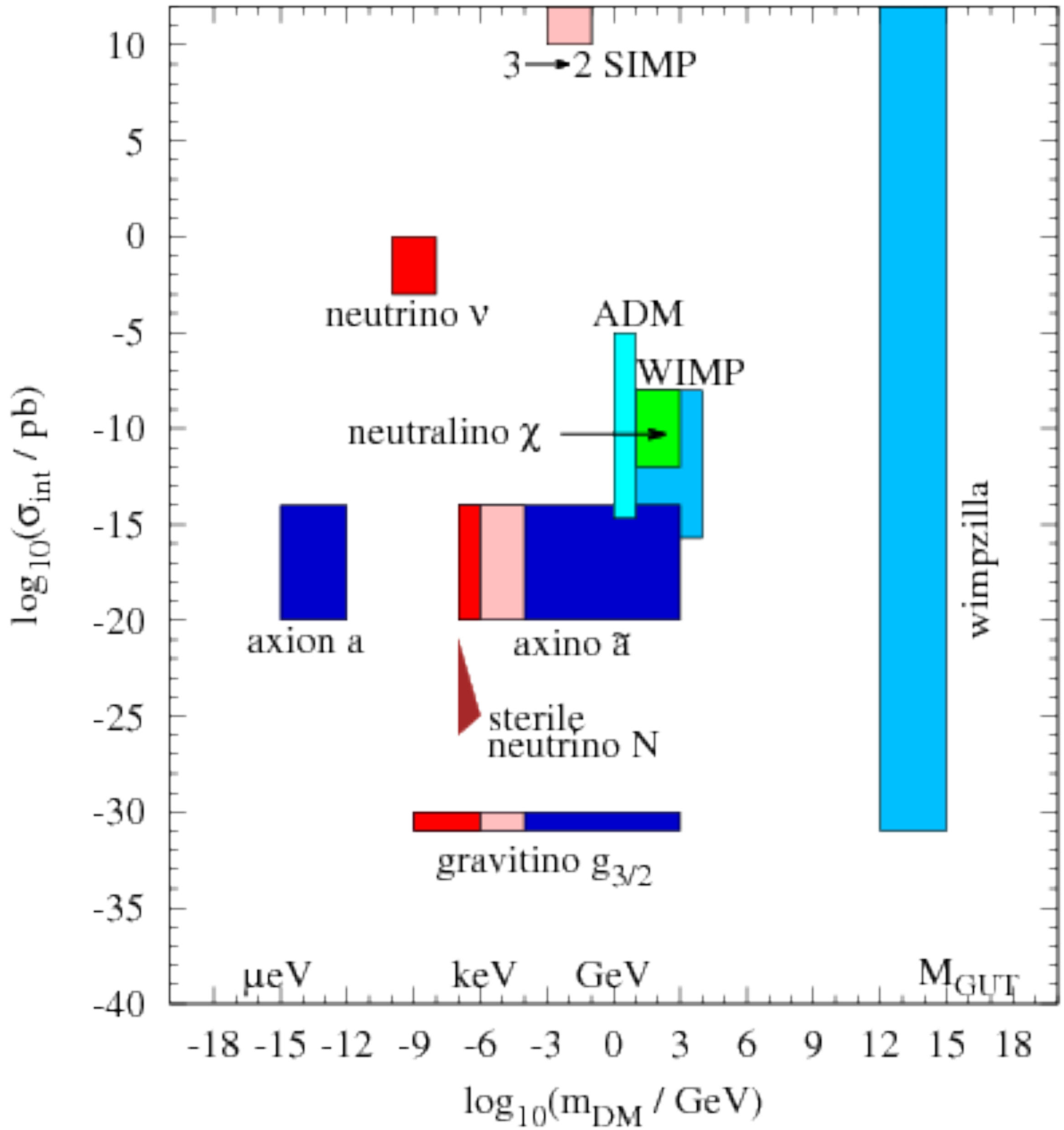
Existence of Blind Spot Regions Suppresses the SI cross section below the current limits in most of the parameter space.







Beyond the WIMP Dark Matter



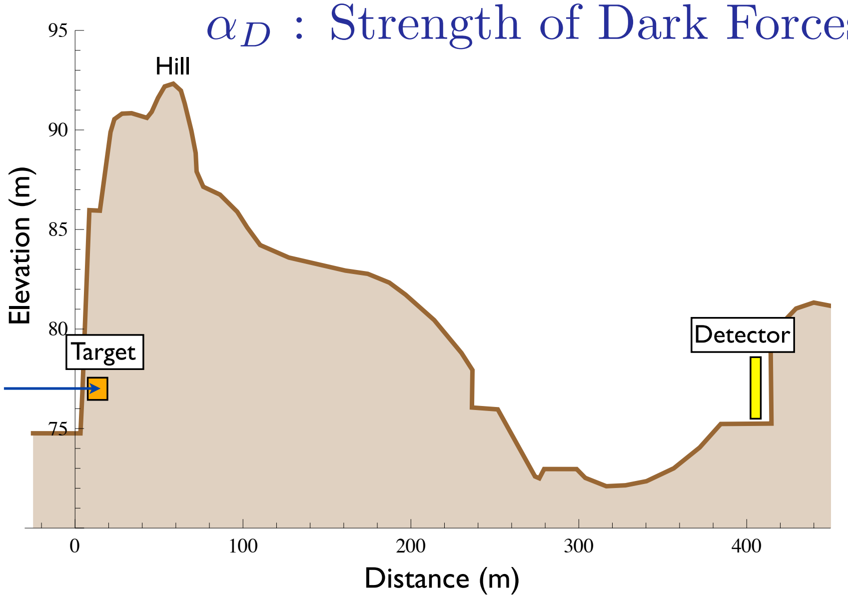
Dark Matter from a Dark Sector

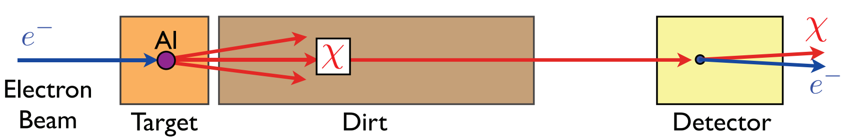
Sub-GeV Dark Sectors from SLAC Beam Dump E137

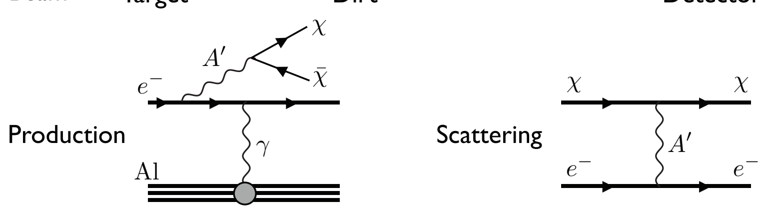
Batell, Essig, Surujon'14

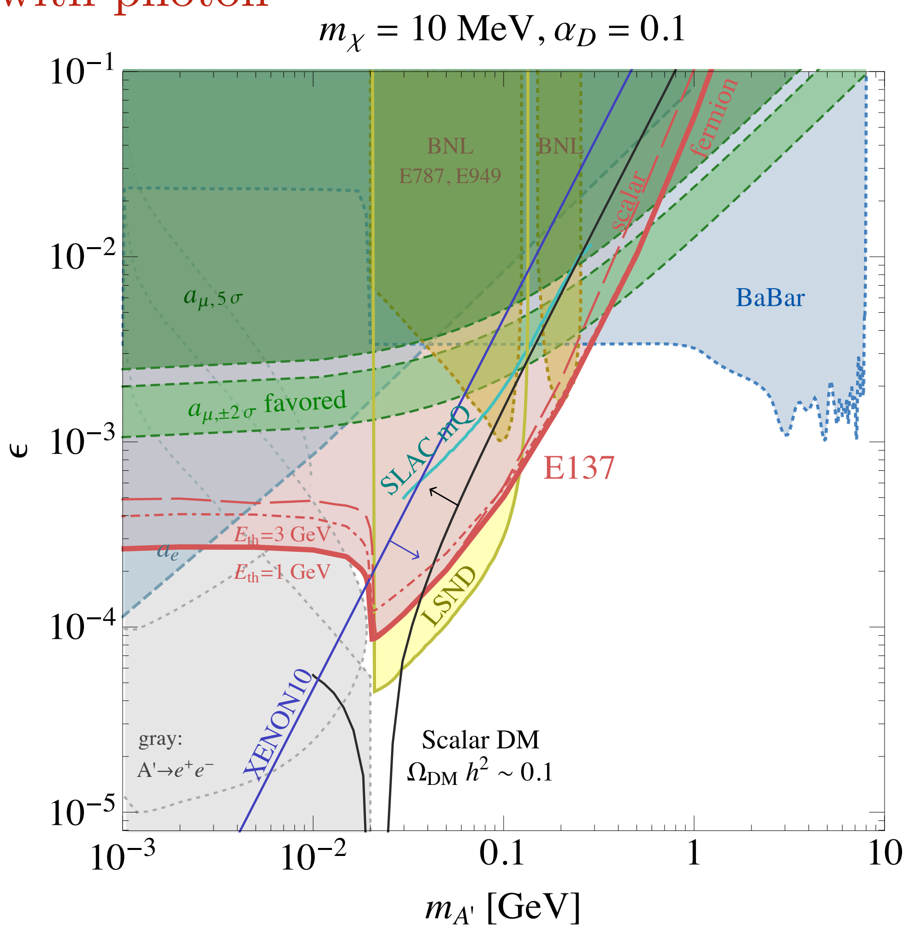
ϵ : Mixing of new Gauge Boson with photon

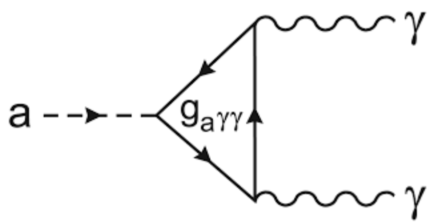
α_D : Strength of Dark Forces





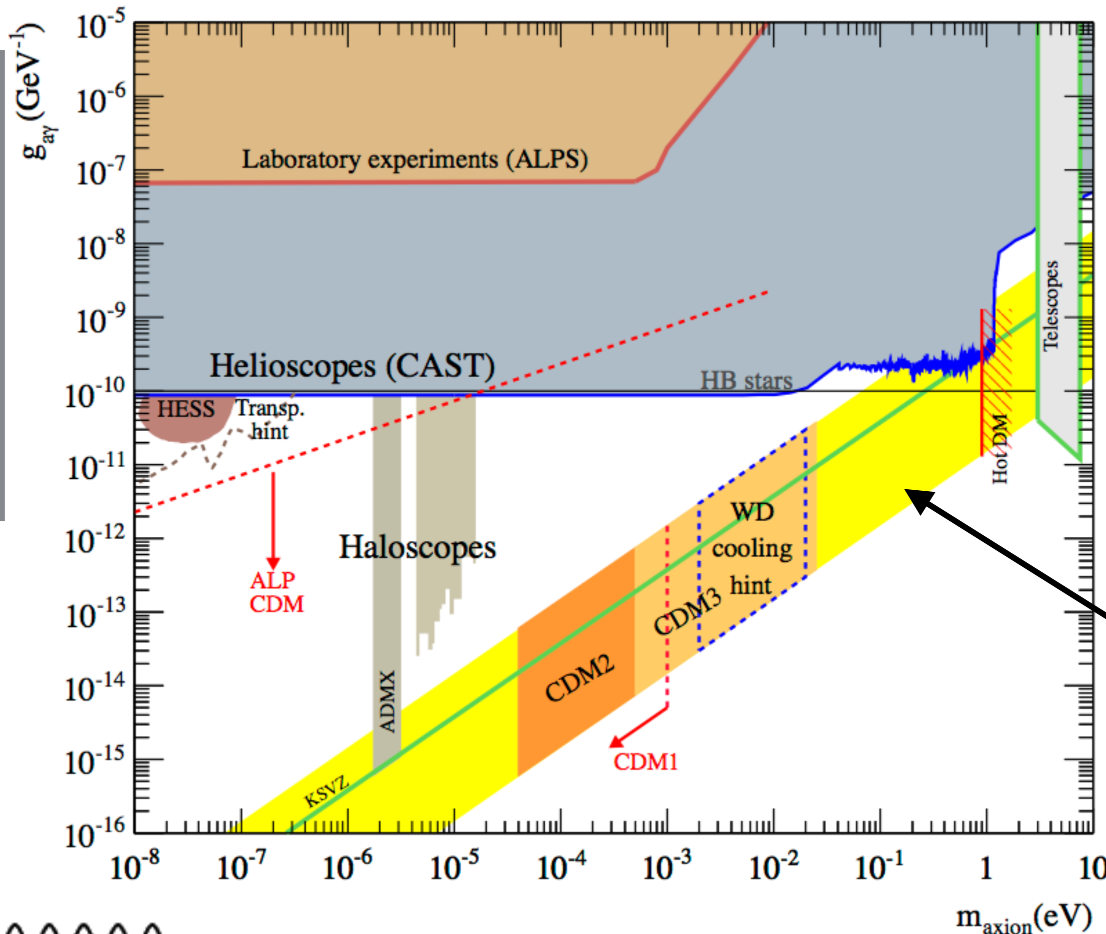




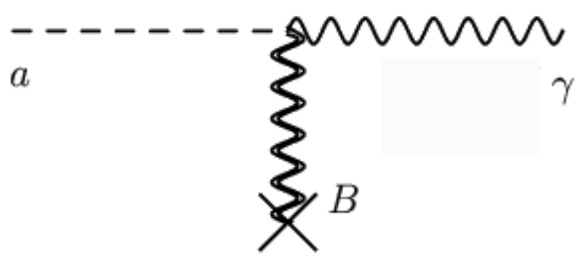


Axions : Solve the strong CP Problem They are also a good CDM candidate

Axions produced in solar core (conversion to X Rays) :



QCD Axion



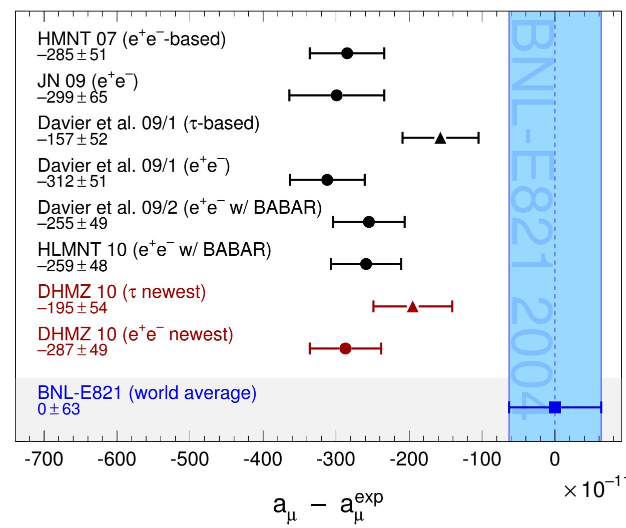
Halo Axions : Resonant Magnetic Cavity Searches

Muon Anomalous Magnetic Moment

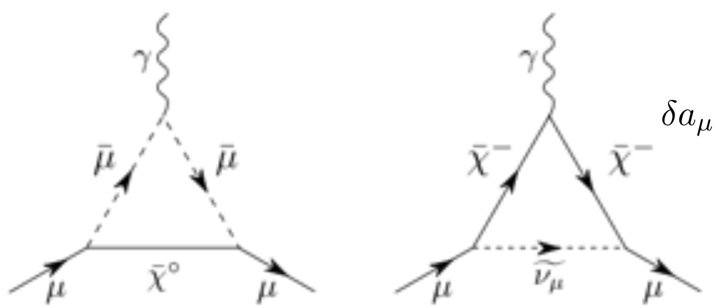
Present status: Discrepancy between Theory and Experiment at more than three Standard Deviation level

$$\delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm theory} = 268(63)(43) \times 10^{-11}$$

3.6σ Discrepancy



New Physics at the Weak scale can fix this discrepancy. Relevant example : Supersymmetry



$$\delta a_\mu \simeq \frac{\alpha}{8\pi s_W^2}\frac{m_\mu^2}{\widetilde{m}^2}{\rm Sgn}(\mu M_2)\tan\beta \simeq 130\times 10^{-11}\left(\frac{100\ {\rm GeV}}{\widetilde{m}}\right)^2 {\rm Sgn}(\mu M_2)\tan\beta$$

Grifols, Mendez'85, T. Moroi'95,
Giudice, Carena, C.W.'95, Martin and Wells'00 ....

Here $\tilde{m}$ represents the weakly interacting supersymmetric particle masses.

For $\tan\beta \simeq 10$ (50), values of $\tilde{m} \simeq 230$ (510) GeV would be preferred.

Masses of the order of the weak scale lead to a natural explanation of the observed anomaly !

Carena, Osborne, Shah, C.W. '18

ATLAS Excess : Anomalous Magnetic Moment $(g-2)_\mu$

As expected, s-leptons with masses of the order of 400 GeV lead to an explanation of g-2 for the benchmark point.

Dependence on tan(beta) follows the expected behavior