Constraining Split Universal Extra Dimensions

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MUED: only parameter R

- Features: all fields in bulk, flat, KK parity
- Constrained: 700 GeV $\lesssim 1/R \lesssim 850$ GeV

SUED: Fermion Bulk Mass term

$$S_{\rm SUED} \ni -\int d^4x \int_{-L}^{L} d\, y M_\Psi(y) \overline{\Psi}\Psi\,,$$

Preserves 5D Lorentz symmetry, gauge symmetry.
$M_\Psi(y)$ Odd to preserve KK parity. Simplest: $M(y) \sim \theta(y)$

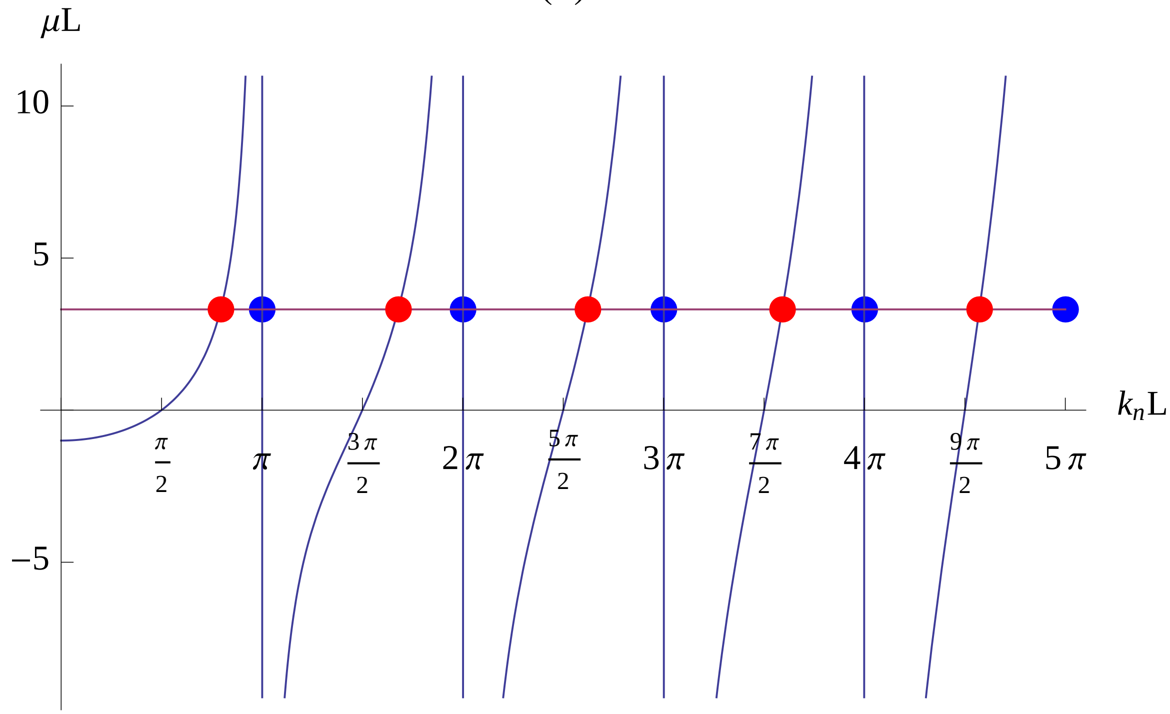
Flavor Bound: $\rightarrow \begin{cases} -M_Q = M_U = M_D = \mu_Q\, \theta(y) \\ -M_L = M_E = \mu_L\, \theta(y) \end{cases}$

Universal bulk mass limit: $\mu_L = \mu_Q \equiv \mu$

Split Spectrum: KK Fermion Masses

$$m^2_{\Psi(n)} = \begin{cases} \lambda^2_\Psi v^2 & \text{if } n = 0 \\ \mu^2 + k_n^2 + \lambda^2_\Psi v^2 & \text{if } n \geq 1 \end{cases}$$

$\mu = -k_n \cot(k_n L)$ for odd n, possible imaginary k_1



Recovering the MUED limit at $\mu = 0$

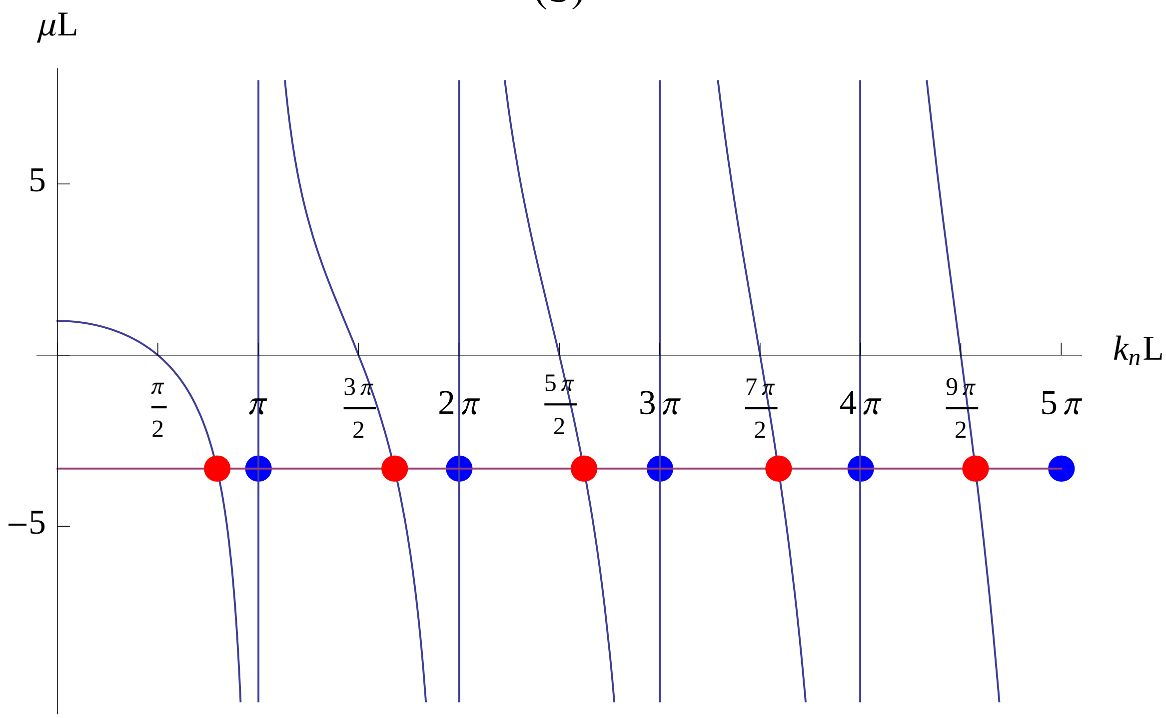
LKP $= \gamma_1$ for $\mu > 0$

Split Spectrum: KK Fermion Masses

$$m^2_{\Psi(n)} = \begin{cases} \lambda_\Psi^2 v^2 & \text{if } n = 0 \\ \mu^2 + k_n^2 + \lambda_\Psi^2 v^2 & \text{if } n \geq 1 \end{cases}$$

$\mu = +k_n \cot(k_n L)$ for odd n, possible imaginary k_1

(b)



Recovering the MUED limit at $\mu = 0$

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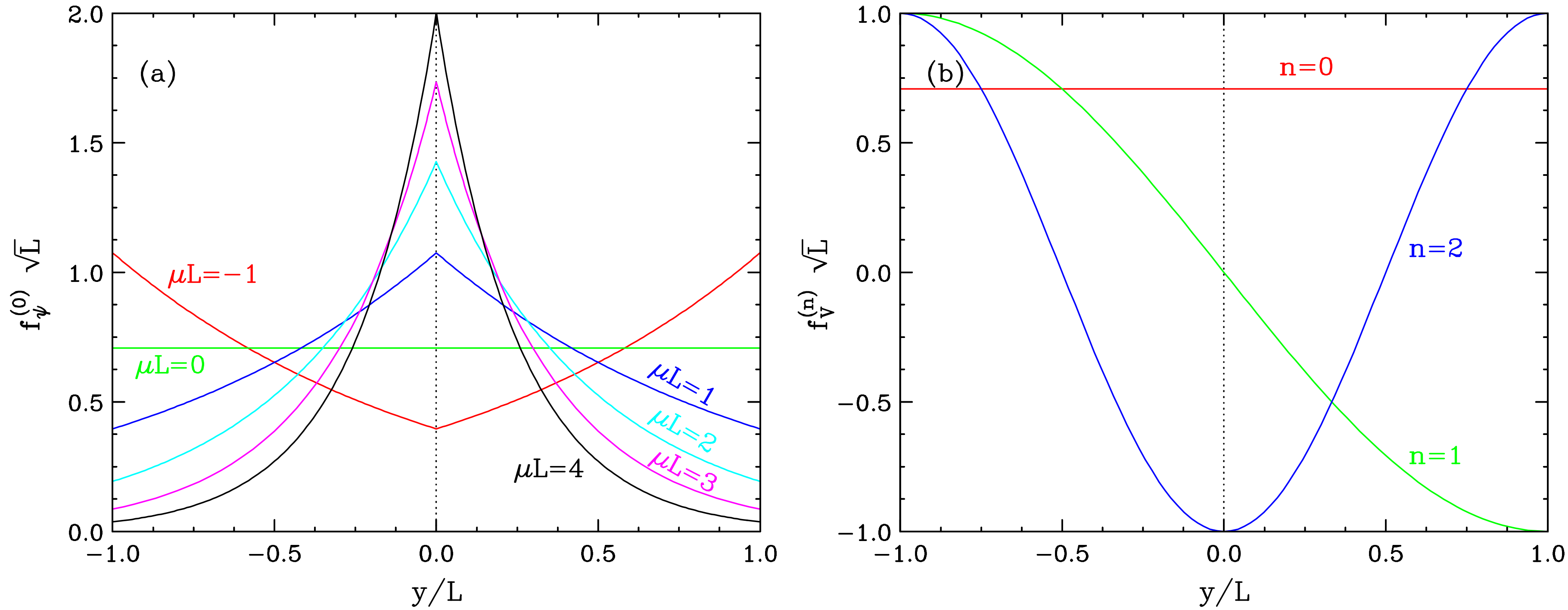
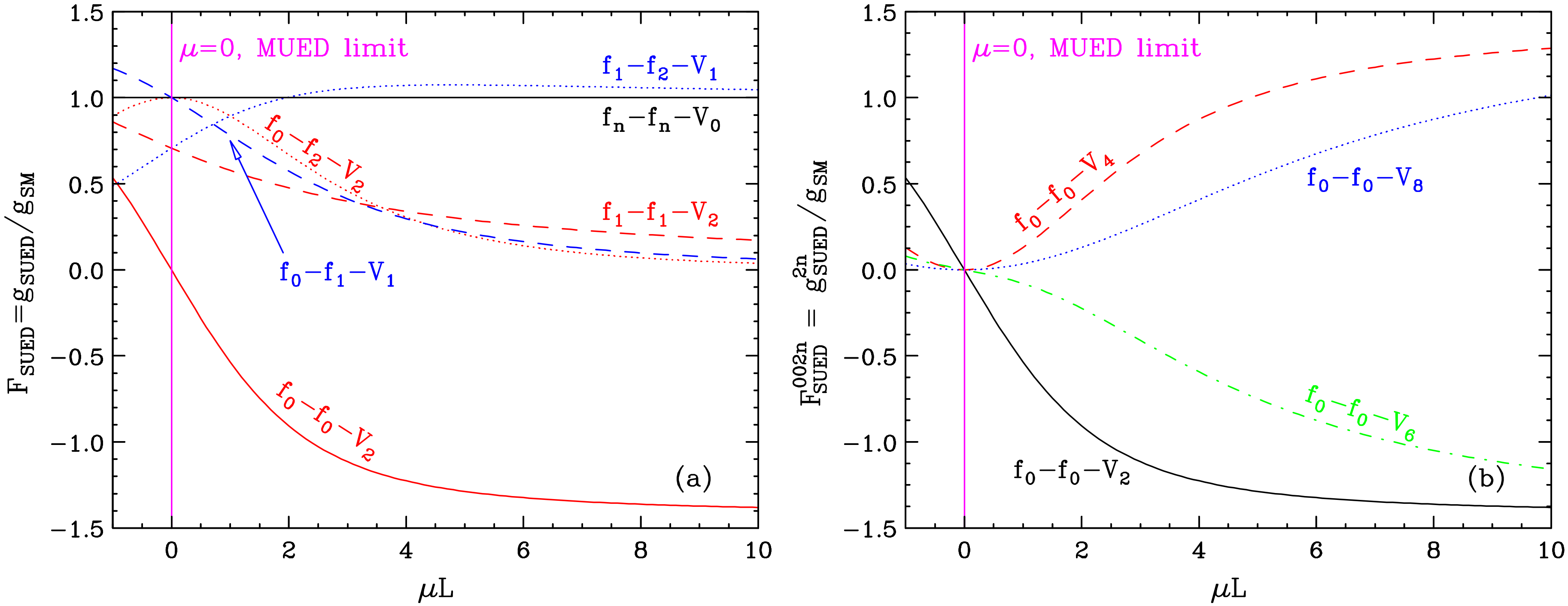
Fermion and Gauge Boson Bulk Profiles



KK couplings, from overlap integrals

$$g_{m\ell n} = \frac{g_5}{\sqrt{2L}} \int_{-L}^{L} dy\, \psi_m(y) \psi_\ell^*(y) f_V^n(y) \equiv g_{\rm SM} \mathcal{F}_{m\ell}^n(\mu_\Psi L)$$

$$\mathcal{F}_{00}^{2n} = \frac{x_\Psi^2 \left[1 - (-1)^n e^{2x_\Psi}\right] \left[1 - \coth(x_\Psi)\right]}{\sqrt{2(1+\delta_{0n})}\left[x_\Psi^2 + n^2\pi^2/4\right]}, \; x_\Psi = \mu_\Psi L$$



Large μ, asymptotic behavior

Constraining the parameter space

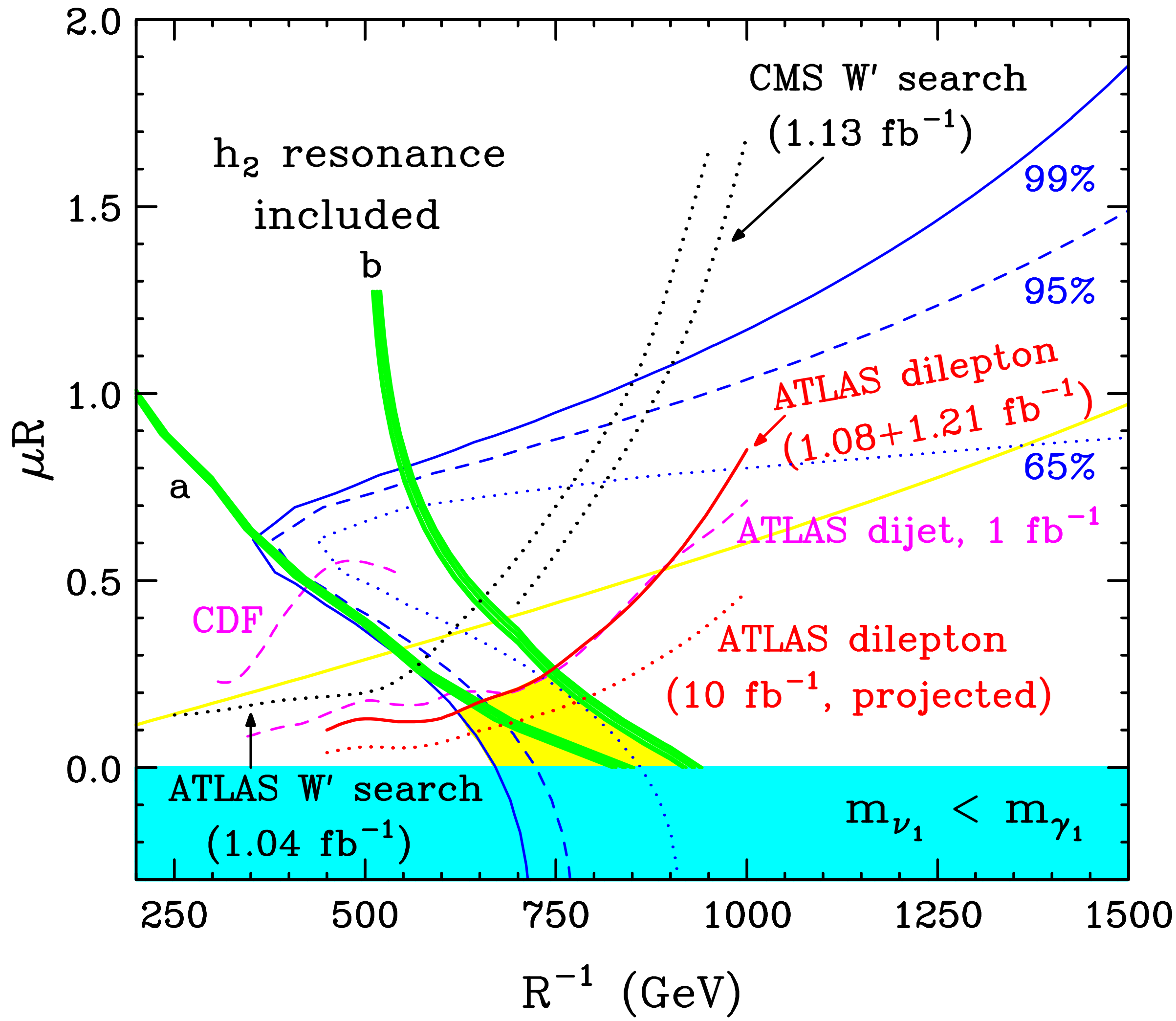
- Relic Density
- Collider
- Electroweak (Oblique, 4-Fermi, $g - 2$...)

Special Cases:

- Universal Bulk Mass (μ, R^{-1})
- Non-Universal Bulk Mass (μ_Q, μ_L, R^{-1})

The Universal Case: $\mu_L = \mu_Q$

Summary Plot of Constraints



Relic Density: $\Omega h^2 \propto n \cdot m_{DM} \sim 0.112,\ n \propto \frac{1}{<\sigma v>}$

Annihilation

via KK-1 fermions (t-, u-) and KK-2 bosons (s-channel)
$\rightarrow ff$, WW, hh final states
$m_{f1} = \sqrt{m_{f0}^2 + k_1^2 + \mu^2} > 1/R$ for $\mu > 0$, raised from MUED
Smaller cross-section, higher relic density, lower DM mass

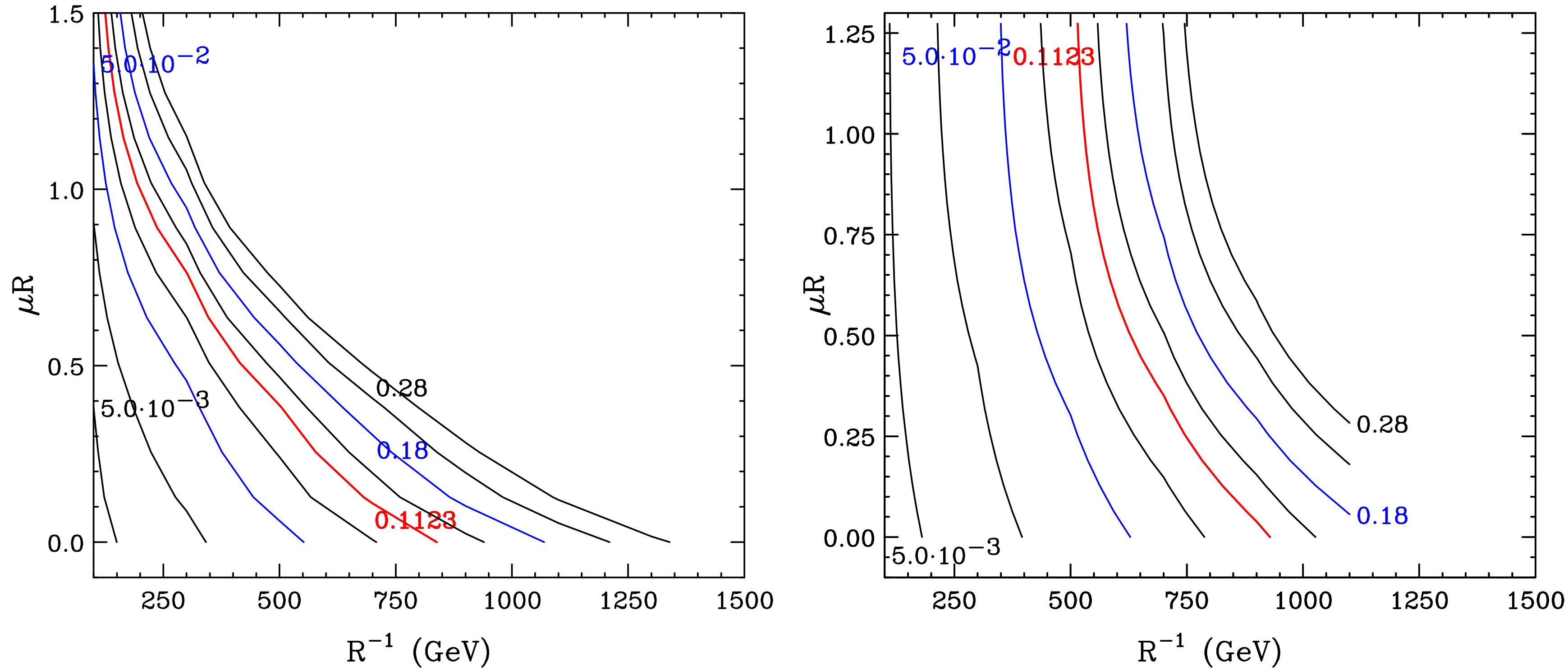
Resonance through h_2

Effect evident when mass difference within a few percent
Detailed one-loop calculation needed

Coannihilation with KK-1 particles

Need near degeneracy $\sim$ few $\%$
Broken by μ for $\mu R > 0.01$ and radiative correction

Relic density contours
Without and with h_2 coannihilation



Collider Searches of KK excitations

MUED

KK-1 particles can be pair-produced
(KK-parity, $\not{E}$ signature)
$1/R \gtrsim 700$ GeV from first year LHC data
KK-2 production loop suppressed.

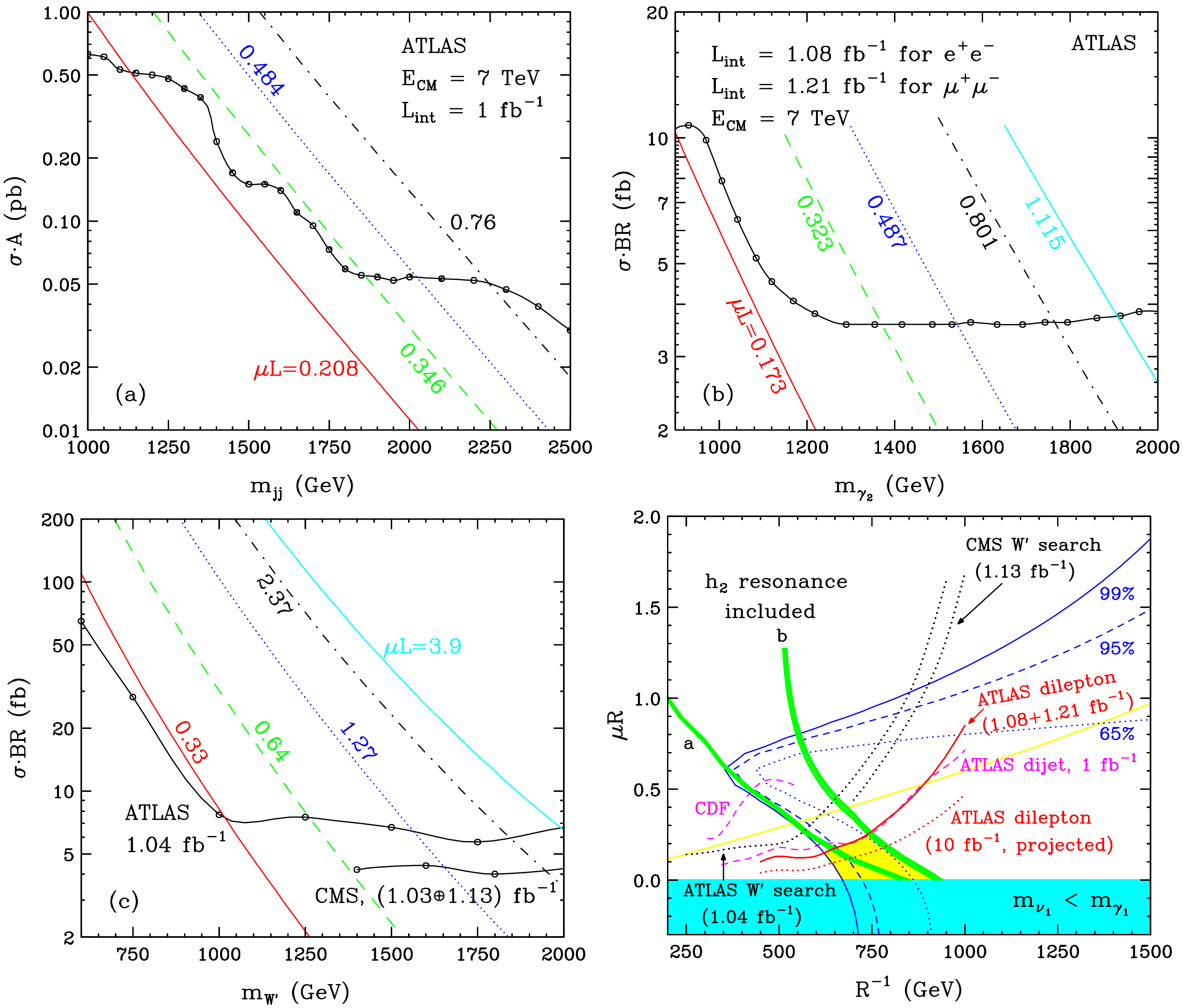
SUED

$\mathcal{F}^2_{00}$ at tree-level
Resonance/Single production of KK-2 bosons (LHC 2011)
$jj, \ell\ell, \ell\nu$ channels

Bounds on masses of KK resonances

jj channel: G_2 $(\gamma_2, Z_2\ W_2)$, $\delta m \sim 0.3 m_{\gamma_2}$

$\ell\ell$ channel: $\gamma_2 + Z_2$, $\delta m \sim 0.07 m_{\gamma_2}$



S, T, U in UED

$$S = \frac{4s_W^2}{\alpha}\left[\frac{3g^2}{4(4\pi)^2}\left(\frac{2}{9}\sum_n \frac{m_t^2}{(n/R)^2}\right) + \frac{g^2}{4(4\pi)^2}\left(\frac{1}{6}\frac{m_h^2}{1/R}\right)\zeta(2)\right]$$

$$T = \frac{1}{\alpha}\left[\frac{3g^2}{2(4\pi)^2}\frac{m_t^2}{m_W^2}\left(\frac{2}{3}\sum_n \frac{m_t^2}{(n/R)^2}\right) + \frac{g^2 s_W^2}{(4\pi)^2 c_W^2}\left(-\frac{5}{12}\frac{m_h^2}{1/R}\right)\zeta(2)\right]$$

$$U = -\frac{4s_W^2}{\alpha}\left[\frac{g^2 s_W^2}{(4\pi)^2}\frac{m_W^2}{(1/R)^2}\left(\frac{1}{6}\zeta(2) - \frac{1}{15}\frac{m_h^2}{(1/R)^2}\zeta(4)\right)\right]$$

Riemann zeta functions: $\zeta(m) = \sum_n \frac{1}{n^m}$
Contributions from top, guage and Higgs loops

S, T, U in SUED

- Corrections from Fermion Mass
- Corrections from KK W contributions to G_F

S, T, U in SUED

- Corrections from Fermion Mass

$$\sum_n \frac{m_t^2}{(n/R)^2} \to \sum_n \frac{m_t^2}{m_t^2 + \mu^2 + (n/R)^2}$$

- Corrections from KK W contributions to G_F

$$\begin{aligned} S_{SUED} &= S_{UED} \\ T_{SUED} &= T_{UED} - \frac{1}{\alpha}\frac{\delta G_F}{G_F} \\ U_{SUED} &= U_{UED} + \frac{4s_W^2}{\alpha}\frac{\delta G_F}{G_F} \end{aligned}$$

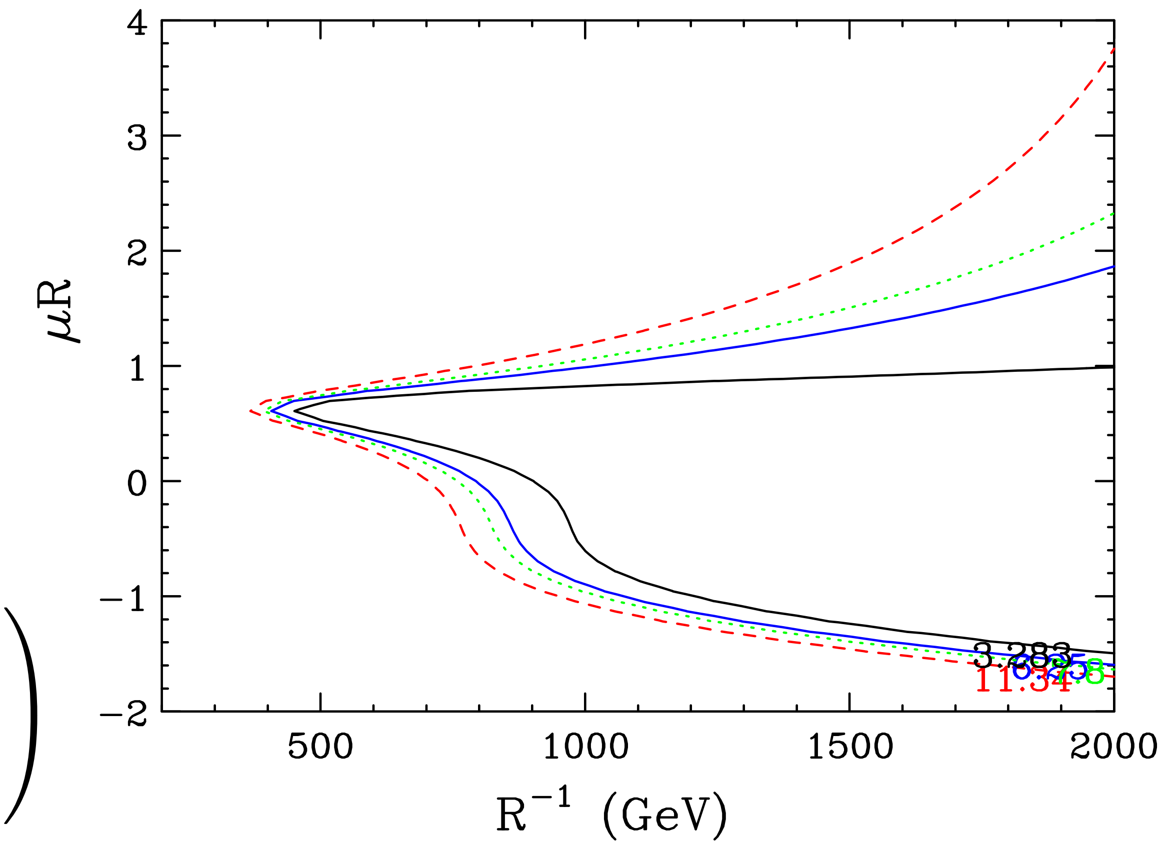
$$G_F = G_F^0 + \delta G_F = \frac{g^2}{\sqrt{32} m_W^2} + \frac{1}{\sqrt{32}} \sum_n \frac{g_{002n}^2}{m_W^2 + \left(\frac{2n}{R}\right)^2}$$

S, T, U fitting contours

from Gfitter

- fitted values
  $S_{NP} = 0.04 \pm 0.10,$
  $T_{NP} = 0.05 \pm 0.11,$
  $U_{NP} = 0.08 \pm 0.11,$
- reference point
  $m_h = 120$ GeV,
  $m_t = 173$ GeV
- correlation coeffs

$$\begin{pmatrix} 1 & 0.89 & -0.45 \\ 0.89 & 1 & -0.69 \\ -0.45 & -0.69 & 1 \end{pmatrix}$$



KK EW gauge boson contribute to 4-point interactions.
PDG bounds for quark lepton compositeness

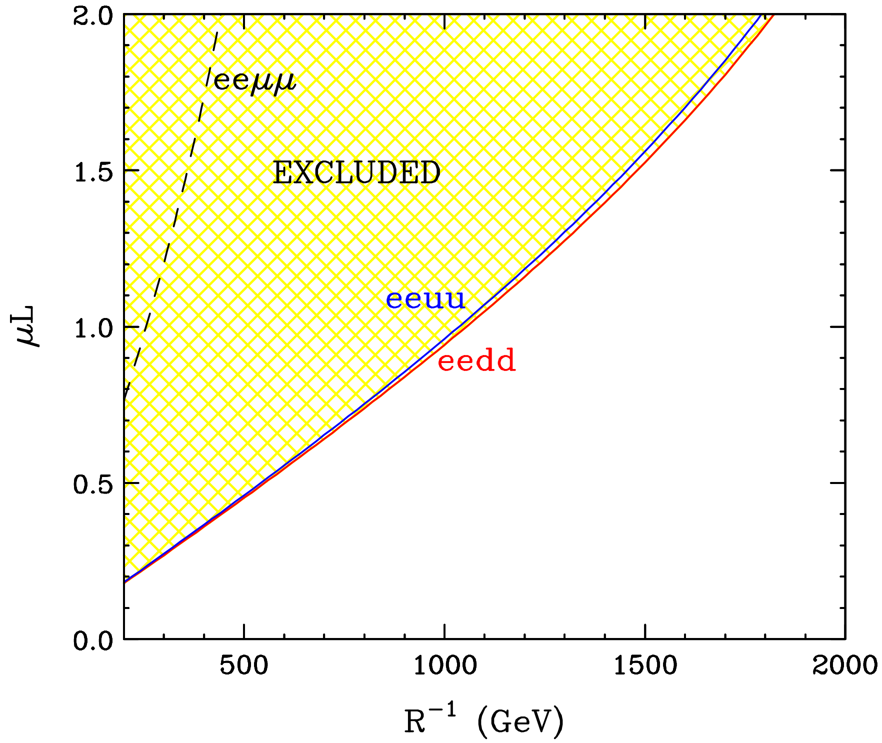
TeV	$eeee$	$ee\mu\mu$	$ee\tau\tau$	$\ell\ell\ell\ell$	$qqqq$	$eeuu$	$eedd$
Λ^+_{LL}	> 8.3	> 8.5	> 7.9	> 9.1	> 2.7	> 23.3	> 11.1
Λ^-_{LL}	> 10.3	> 9.5	> 7.2	> 10.3	2.4	> 12.5	> 26.4

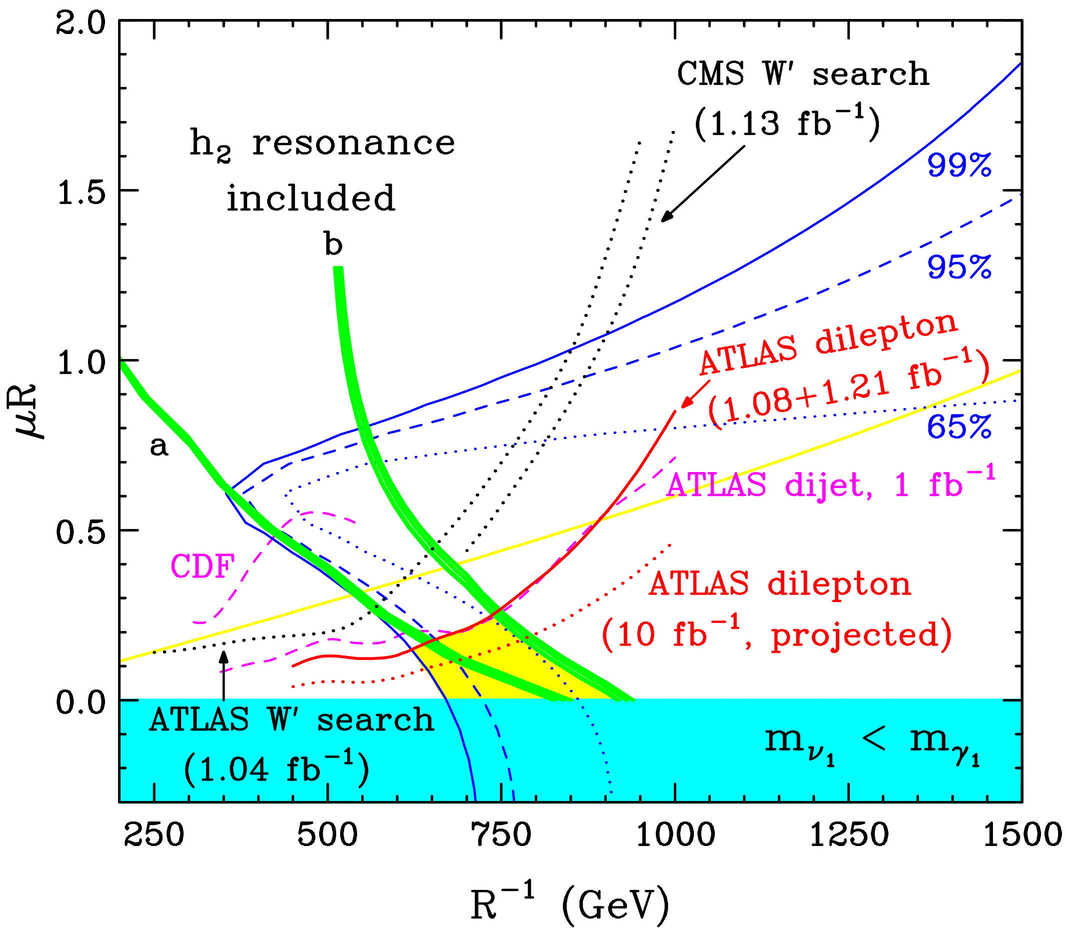
Most relevant operators:

$$\mathcal{L}^{eq}_{\text{eff}} \ni \sum_{q=u,d} \sum_{\{A,B\}=\{L,R\}} \frac{4\pi}{\Lambda^2_{q,AB}} \eta^q_{AB}\, \bar{e}_A \gamma^\mu e_A \bar{q}_B \gamma_\mu q_B$$

$$\begin{aligned} \frac{4\pi}{\Lambda^2_{q,AB}} \eta^q_{AB} &= 4\pi N_c \sum_{n=1}^{\infty} \left(\mathcal{F}^{2n}_{00}(\mu R)\right)^2 \times \left[\frac{3}{5} \frac{\alpha_1 Y_{e_A} Y_{q_B}}{Q^2 - M^2_{B_{2n}}} + \frac{\alpha_2 T^3_{e_A} T^3_{q_B}}{Q^2 - M^2_{W^3_{2n}}}\right] \\ &\approx -\pi N_c R^2 \left(\frac{3}{5}\alpha_1 Y_{e_A} Y_{q_B} + \alpha_2 T^3_{e_A} T^3_{q_B}\right) \times \sum_{n=1}^{\infty} \frac{\left(\mathcal{F}^{2n}_{00}(\mu R)\right)^2}{n^2} \end{aligned}$$

Four-Fermi constraints from $ee\mu\mu$, $eeuu$ and $eedd$





without h_2 resonance

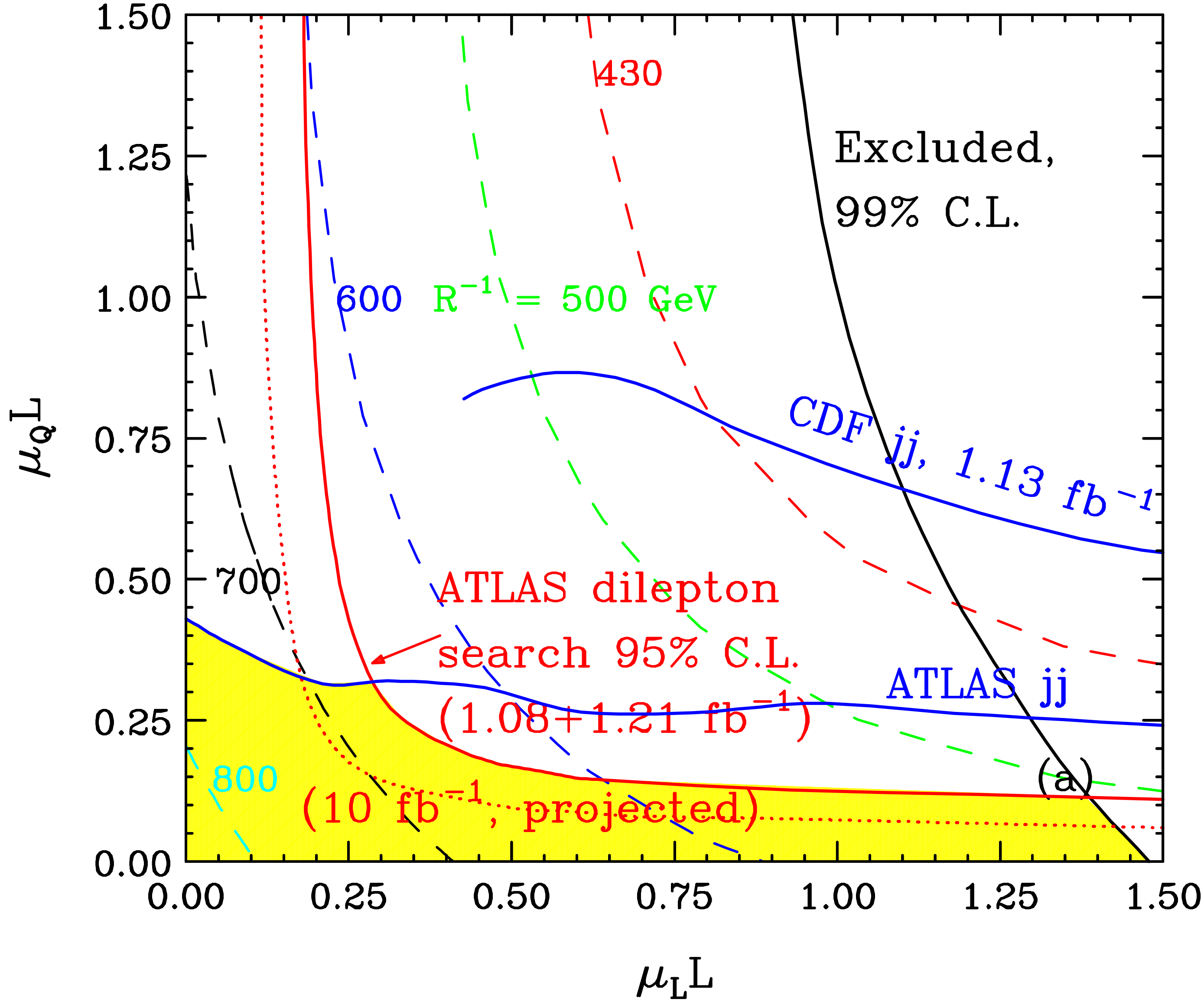
$650\text{GeV} \lesssim 1/\text{R} \lesssim 850\text{GeV}$ and $\mu R \lesssim 0.2$

with h_2 resonance

$750 \lesssim 1/R \lesssim 950\text{GeV}$ and $\mu R \lesssim 0.3$

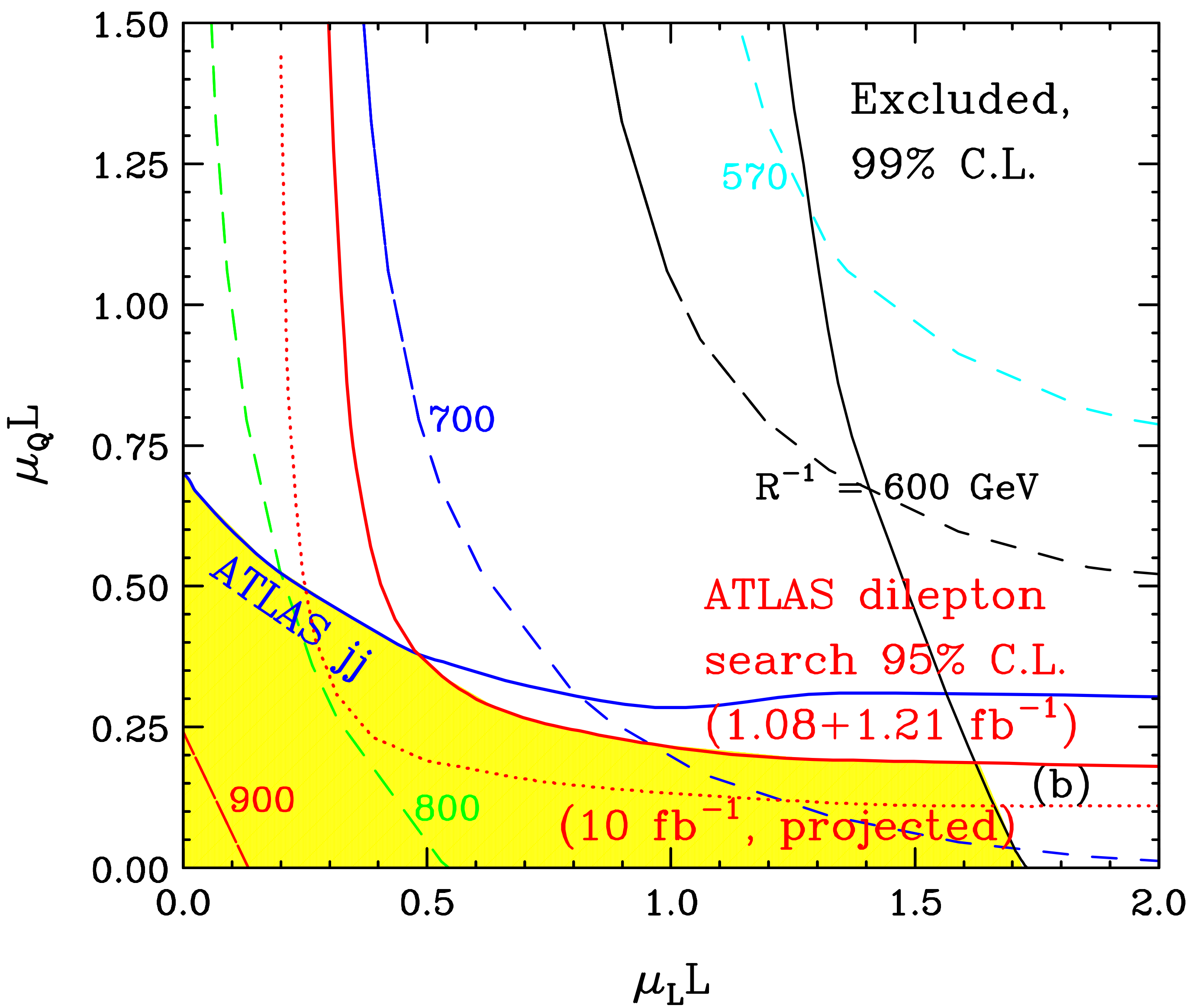
A Non-Universal Case: $\mu_L \neq \mu_Q$

Summary of Constraints (without h_2 resonance)

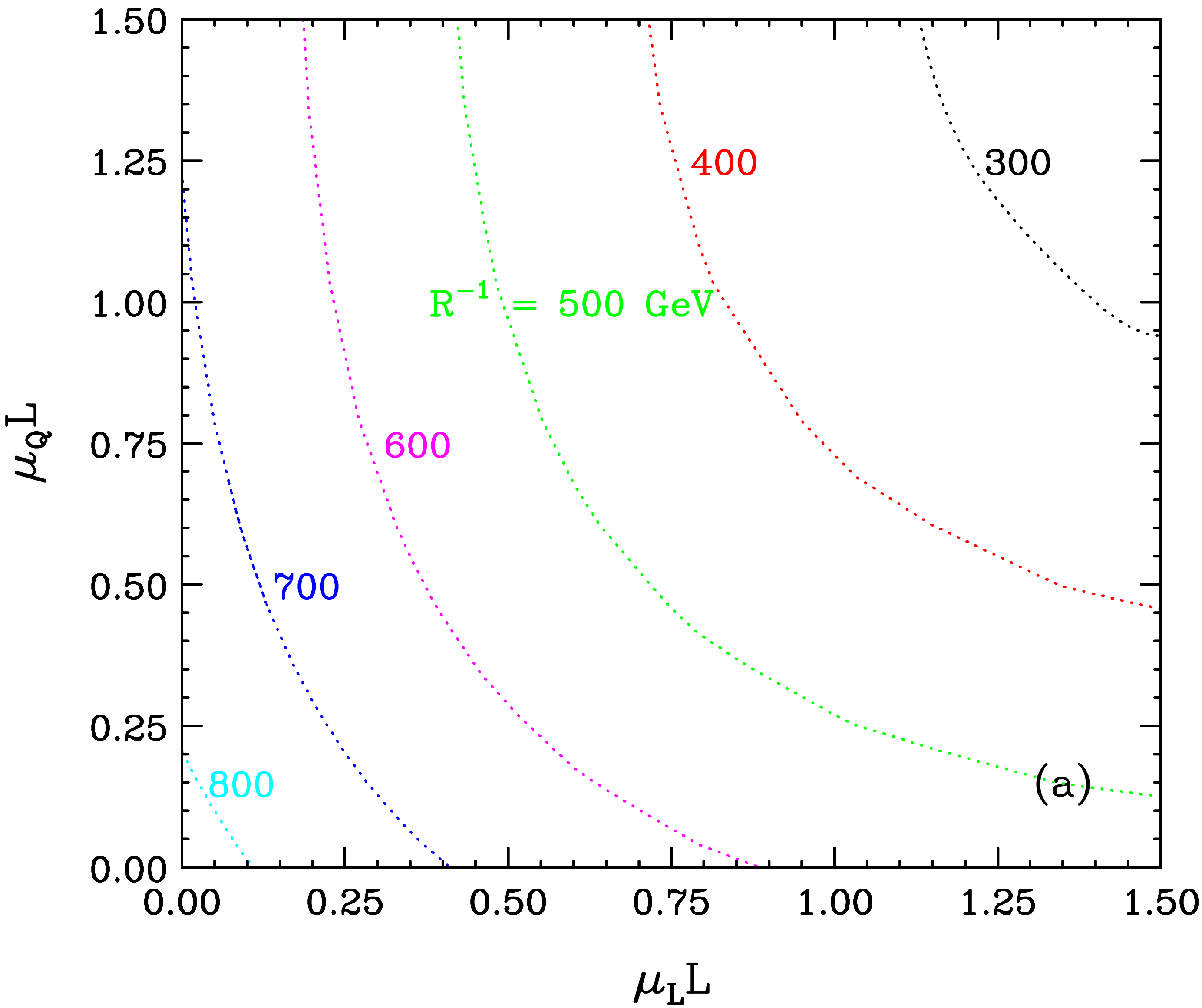


A Non-Universal Case: $\mu_L \neq \mu_Q$

Summary of Constraints (with h_2 resonance)

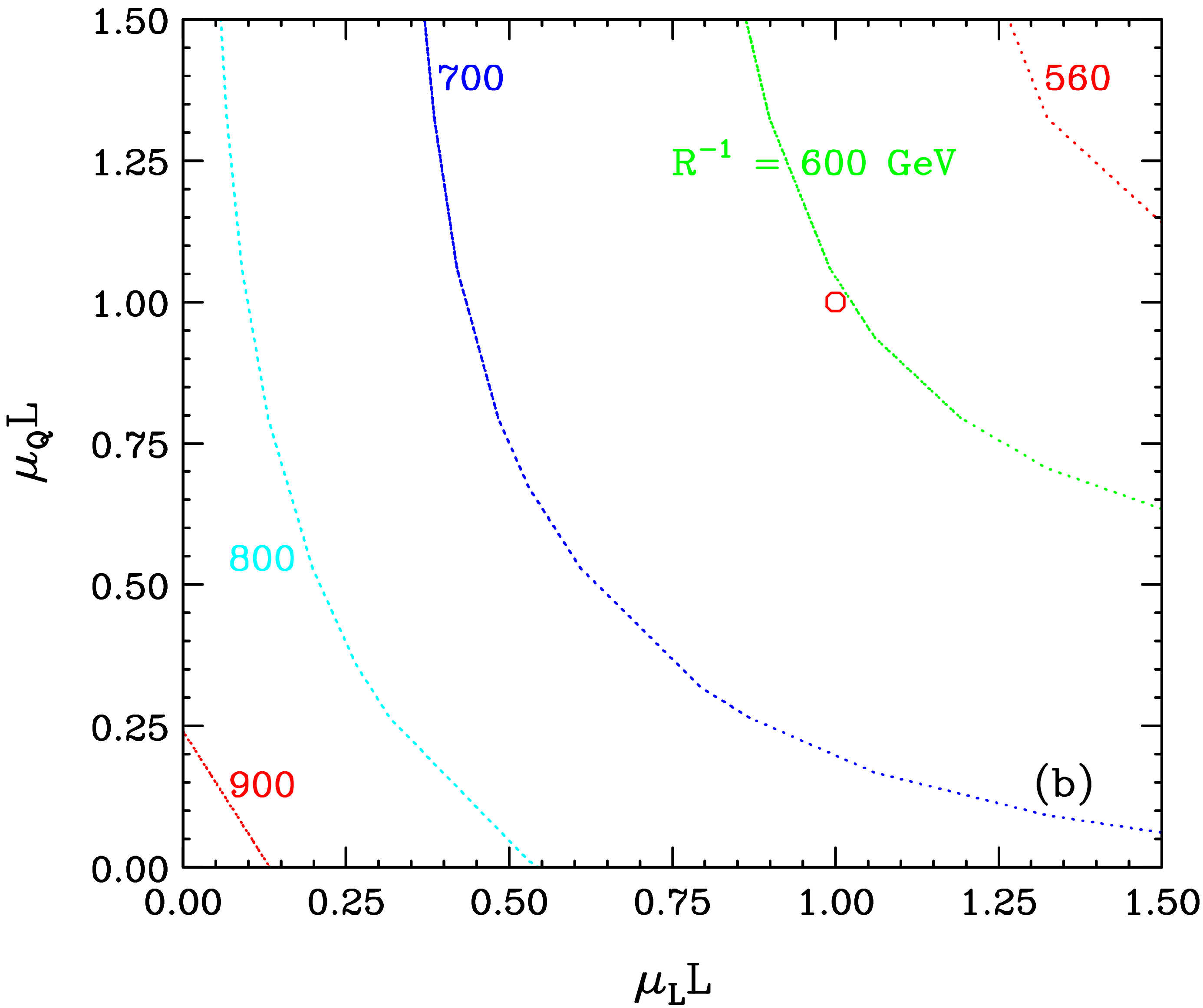


Relic abundance (without h_2 resonance)



μ_Q and μ_L factor in similarly with some difference
Contours 'roughly' symmetric about the diagonal

Relic abundance (with h_2 resonance)



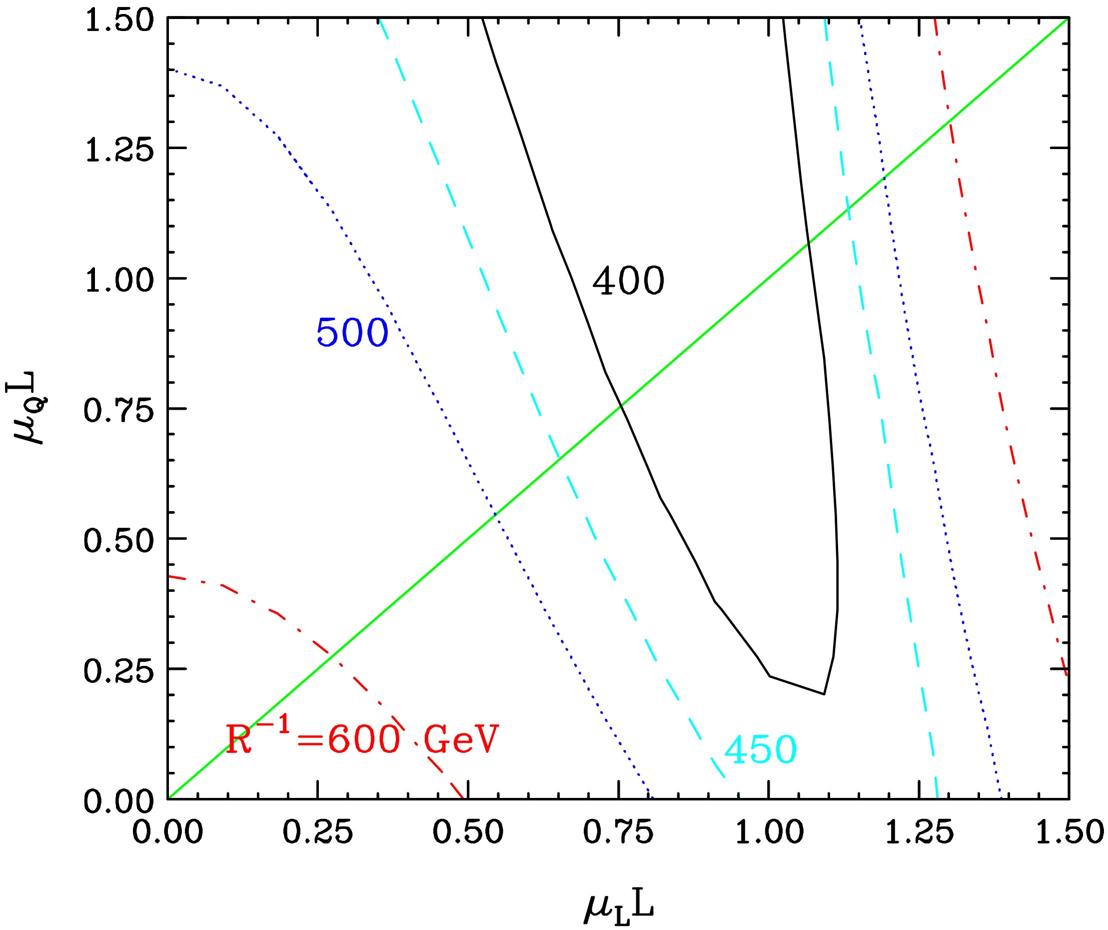
μ_Q and μ_L factor in similarly with some difference

Contours ‘roughly’ symmetric about the diagonal

Simple substitutions

$\mu \to \mu_Q$ in KK-top loops, $\mu \to \mu_L$ in δG_F

99% C.L. fit surfaces in (μ_Q, μ_L, R^{-1}) projected down to fit countours in (μ_Q, μ_L)

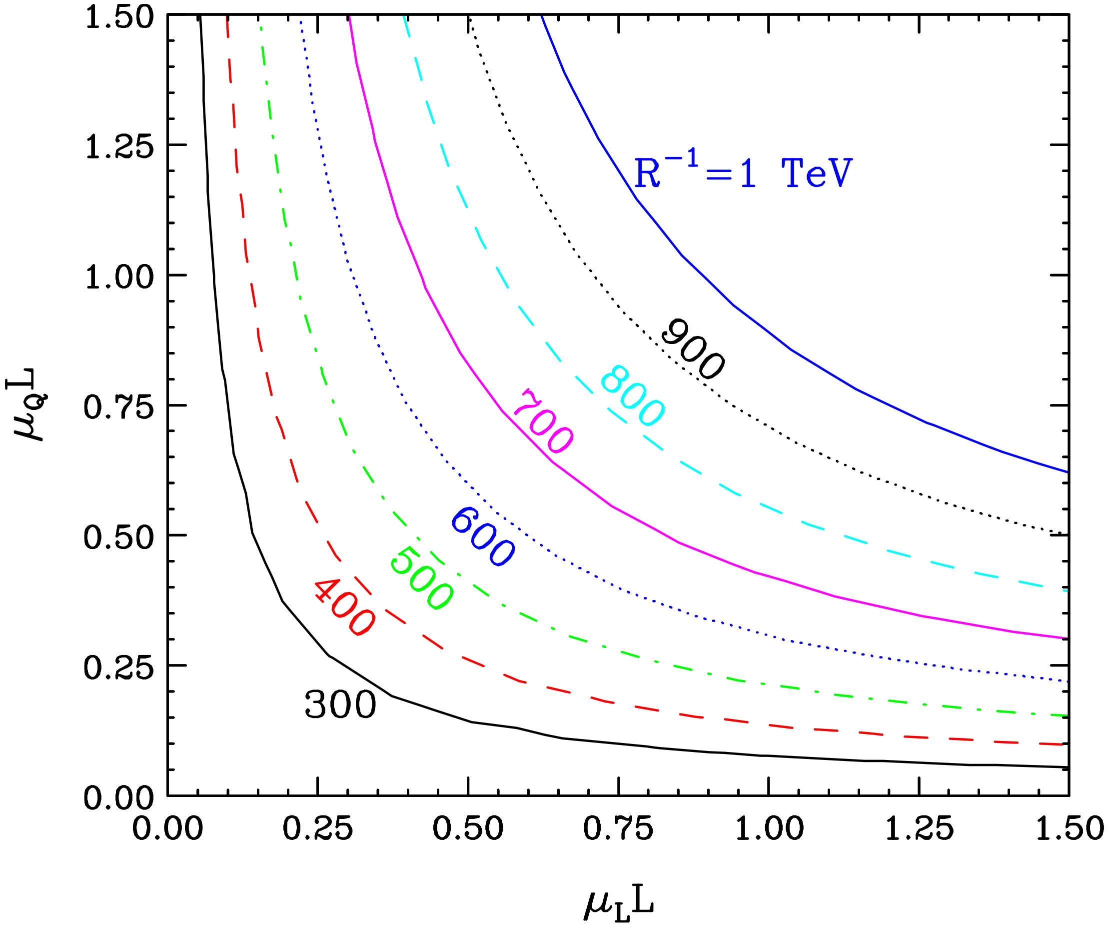


Leptons/Quarks treated differently, (S, T, U) may be insufficient

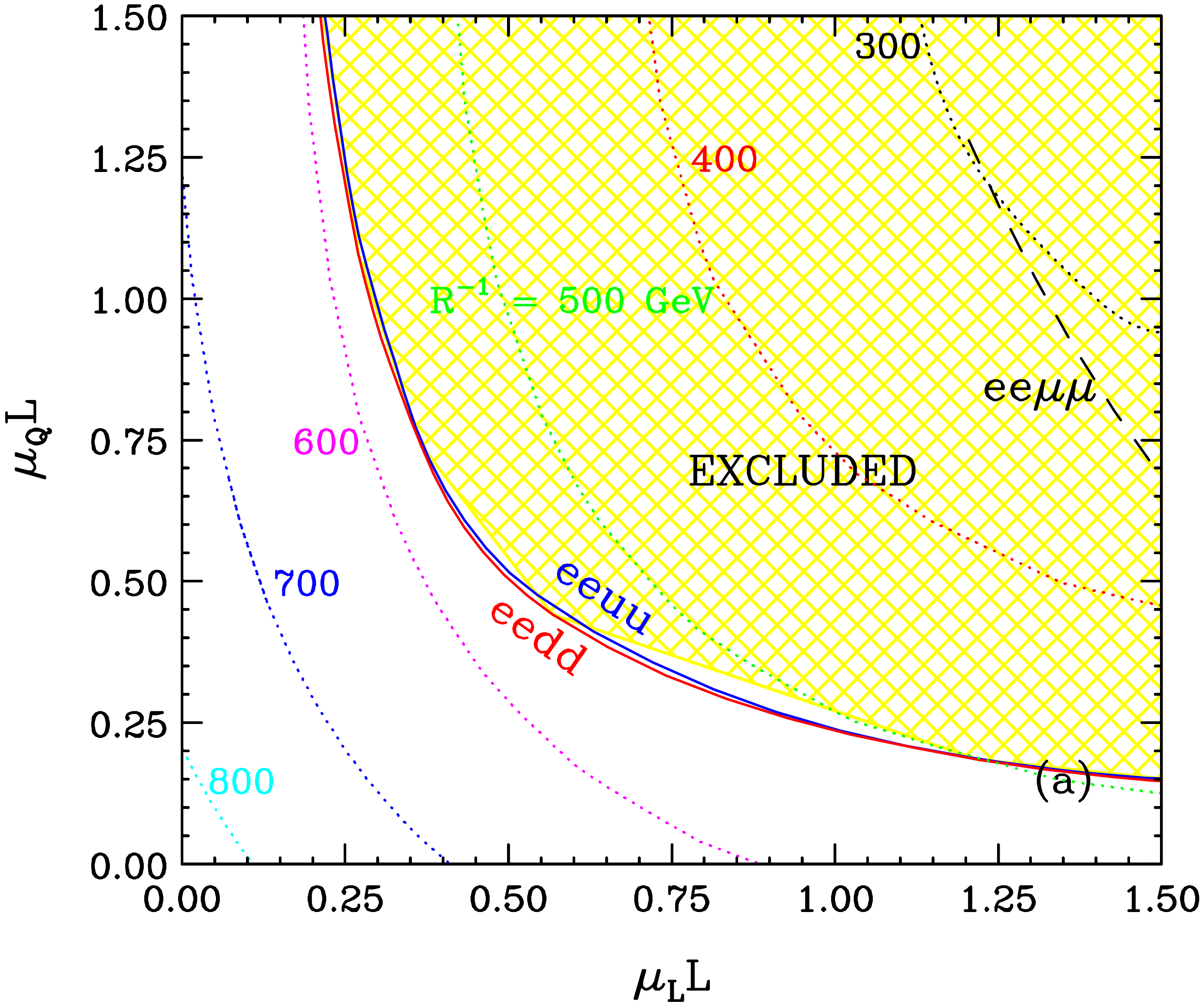
Different dependence on μ_Q, μ_L

$$\left(\mathcal{F}_{00}^{2n}(\mu R)\right)^2 \to \mathcal{F}_{00}^{2n}(\mu_Q R)\mathcal{F}_{00}^{2n}(\mu_L R)$$

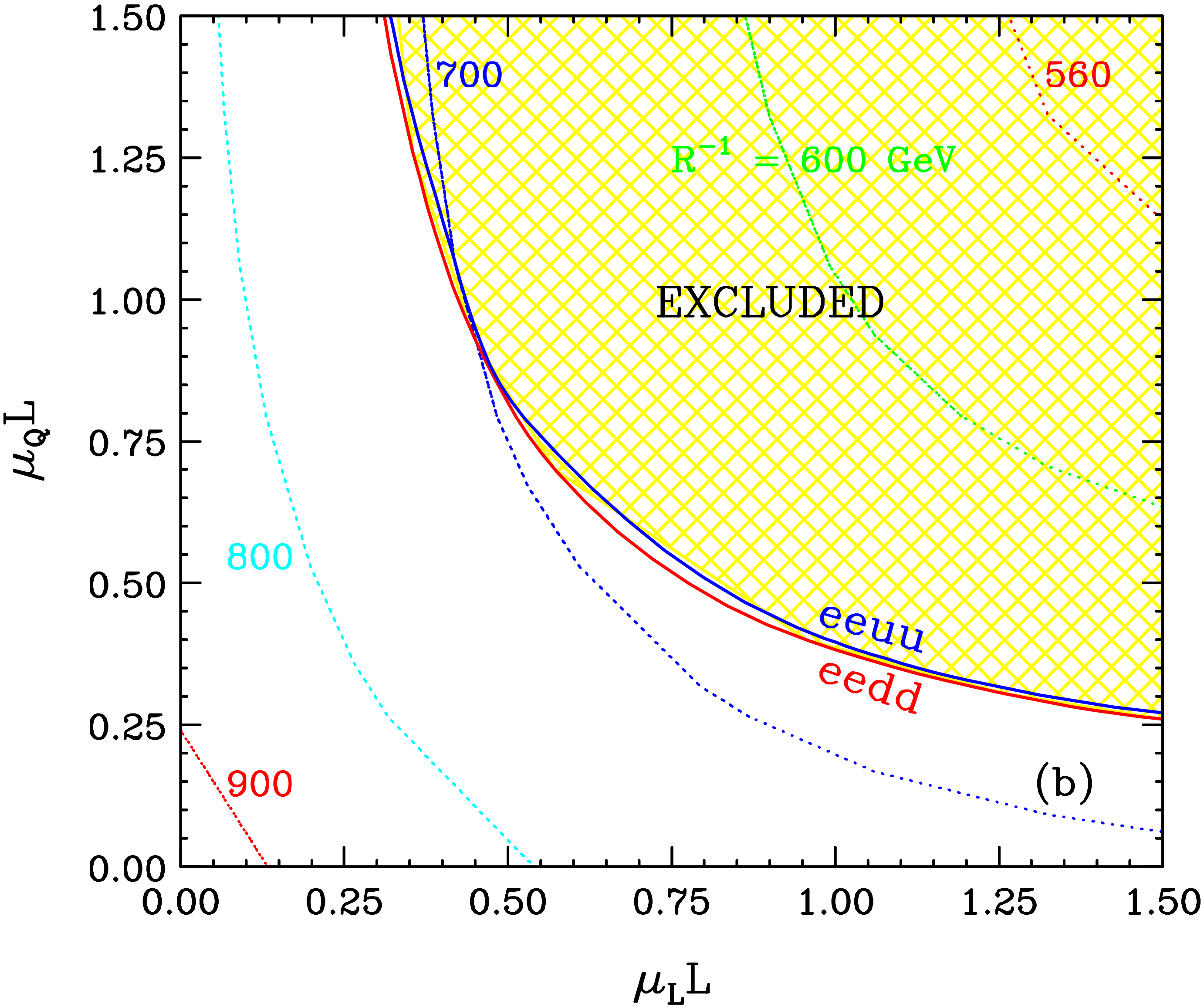
$eedd$ constraint surface projected down



Four-Fermi combined/intersected with relic abundance (without h_2 resonance)

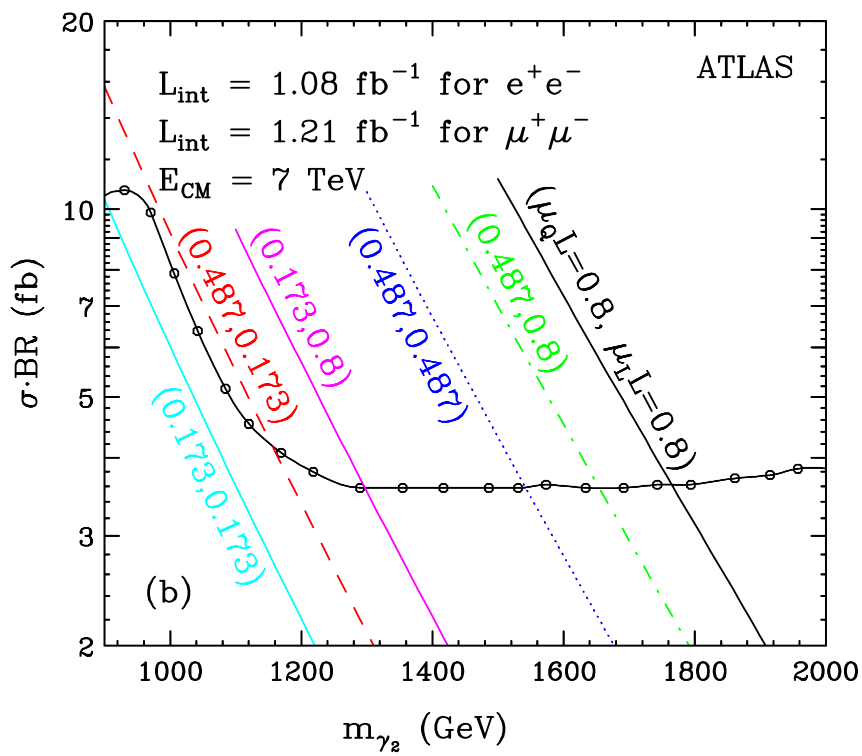


Four-Fermi combined/intersected with relic abundance (with h_2 resonance)



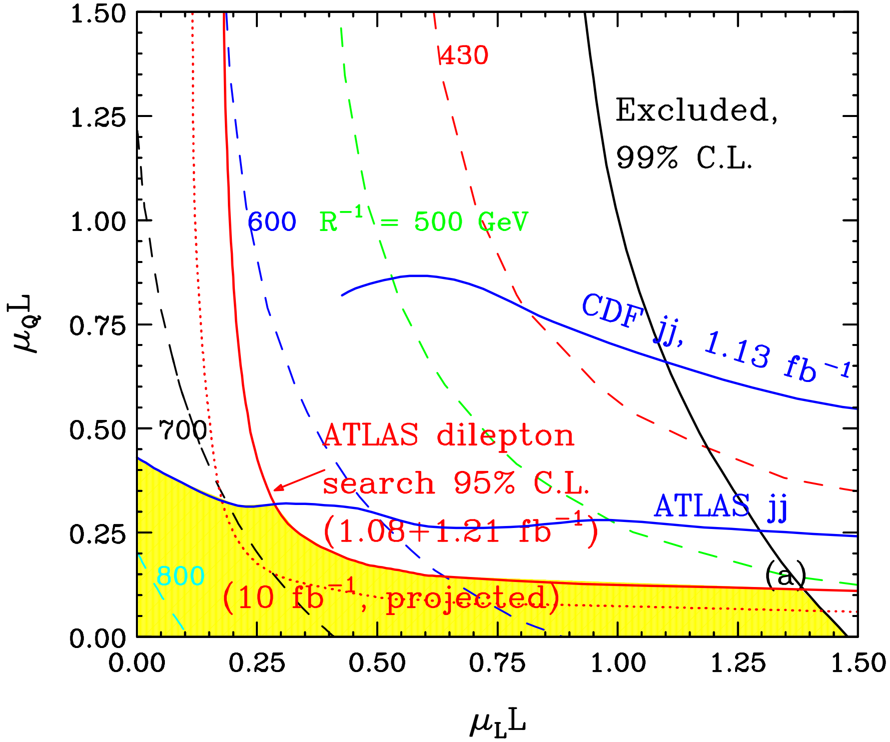
jj channel, only μ_Q relevant
$\ell\ell, \ell\nu$ channels, both μ_Q and μ_L

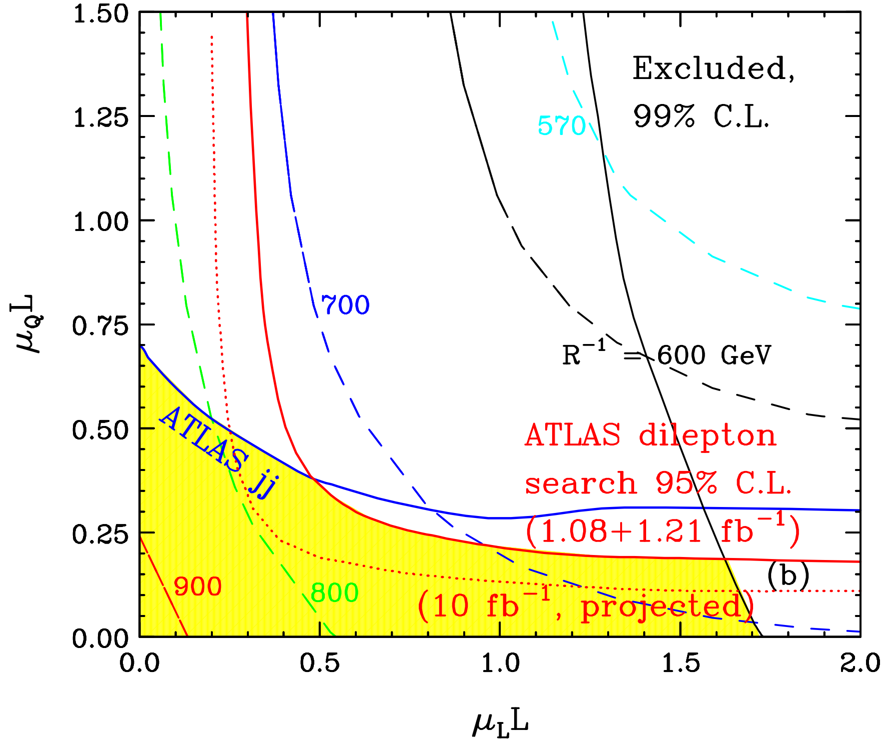
$\ell\ell$ channel search limit



jj channel search limit

Identical to the Universal case, with $\mu \to \mu_Q$





without h_2 resonance

$$500\text{GeV} \lesssim 1/\text{R} \lesssim 850\text{GeV},\ \mu_Q L \lesssim 0.4,\ \mu_L L \lesssim 1.5$$

with h_2 resonance

$$650\text{GeV} \lesssim 1/\text{R} \lesssim 950\text{GeV},\ \mu_Q L \lesssim 0.7,\ \mu_L L \lesssim 1.7$$

Lower bound on $1/R$ relaxed, μ_L less constained than μ_Q

SUED parameter space

- Tightly Constrained

R^{-1} within a couple hundred GeV range, below TeV
prefers small μ

- Slightly Relaxed

UED $\rightarrow$ SUED with μ $\rightarrow$ SUED with μ_Q, μ_L

- LHC

Key role in remaining parameter space
Used $\sim$ 1 fb^{-} at 7 TeV, has $>$ 5 fb^{-1}
15 fb^{-} at 8 TeV by 2012

- SUED S=?