

THE RESCUE TO THE KALUZA KLEIN MODEL FORM THE (20) STATES CONTRIBUTIONS TO THE RELIC ABUNDANCE OF THE DARK MATTER

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Outline

① Motivations and General features

② Geometry

③ Dark Matter

- Analytical results of coannihilations
- Numerical results
 - Coannihilations into $(2,0)+(0,0)$ modes
 - Higgs resonance and Direct Detection

④ Summary and outlook



MOTIVATIONS OF MODELS WITH EXTRA DIMENSIONS

NEW PERSPECTIVES IN BEYOND STANDARD MODEL RESEARCH

- Hierarchy problem
- Number of fermion generations
- Neutrino masses
- Proton stability
- Predicted by string theories

EXTRA DIMENSIONS \Rightarrow DM CANDIDATE

- Most of matter in the Universe is a dark matter
- DM candidates: axion, LSP, LTP, **LKP**...
stable due to KK-parity



UED on the Real Projective Plane

Compatification

$$\mathcal{M}^4 \times \mathbb{R}P^2 \quad \text{where} \quad \begin{cases} \mathbb{R}P^2 = \mathbb{R}^2 / \Gamma & \Gamma = \langle r, g \mid r^2 = [g^2 r^2] = \mathbb{I} \rangle \\ g^{MN} = \text{diag}(1, -1, -1, -1, -1, -1) \end{cases}$$

KK symmetry - rotation of π about $(\frac{\pi}{2}, \frac{\pi}{2})$

Defining symmetries

$$\begin{cases} r & : z \sim -z \\ g & : z \sim z^* + i\pi + \pi \end{cases}$$

$$p_{KK} : z \sim z + \pi + i\pi$$

Generated symmetries

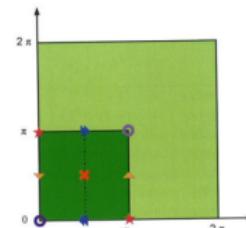
p_{KK} ensures the stability of the LKP :
 $(1, 0) \rightarrow (0, 0) + (0, 0)$

$$\begin{cases} t_1 = g^2 & : z \sim z + 2\pi \\ t_2 = [gr]^2 & : z \sim z^* + 2\pi i \end{cases}$$

No singular points

$$(0, 0) \xrightarrow{r} (0, 0) \xrightarrow{g} (\pi, \pi)$$

$$(0, \pi) \xrightarrow{[r, t_1]} (0, \pi) \xrightarrow{[g, -t_1]} (\pi, 0)$$





Real Projective Plane

Physics

- ★ The physics must be invariant under symmetry transformations $\theta \in \{r, g\}$

$$\mathcal{L}(\Omega(\theta[z])) = \mathcal{L}(\mathcal{P}_\theta \Omega(z)) = \mathcal{L}(\Omega(z))$$

- ★ Fields transformations on the real projective plane

$$\Omega(r[z]) = \mathcal{P}_R \Omega(-z)$$

$$\Omega(g[z]) = \mathcal{P}_G \Omega(z)$$

$$\Omega(p_{KK}[z]) = (-)^{k+l} \Omega(z)$$

- ★ The localized operators must preserve the p_{KK} symmetry

$$\mathcal{O}_{(0,0)} \equiv \mathcal{O}_{(\frac{1}{2}, \frac{i}{2})} \quad \mathcal{O}_{(0, \frac{i}{2})} \equiv \mathcal{O}_{(\frac{1}{2}, 0)}$$



Quantum fields on the RPP

Scalar field

$$S = \int_0^{2\pi} dx_4 \int_0^{2\pi} dx_5 \left(\partial_\alpha \Phi^\dagger \partial^\alpha \Phi - M^2 \Phi^\dagger \Phi \right)$$

$$\Phi(x^\nu, x_4, x_5) = \sum_{k,l=0}^{\infty} f^{(kl)}(x_4, x_5) \phi^{(kl)}(x^\nu)$$

$$\begin{cases} \left(\partial_\mu \partial^\mu + (M_{kl}^2 + M^2) \right) \phi^{(kl)} = 0 \\ \left(\partial_4^2 + \partial_5^2 + M_{kl}^2 \right) f^{(kl)} = 0 \end{cases}$$

THE PROPAGATION IN EXTRA DIMENSIONS
IS THE SOURCE OF MESSES FOR KK MODES

Chiral fermions

$$\Psi(z) = \begin{pmatrix} \chi_+ \\ \eta_- \\ \chi_- \\ \eta_+ \end{pmatrix}$$

$$\begin{cases} \Psi(g[z]) = p_g \Gamma_g \Psi(z) \\ \Psi(r[z]) = p_r \Gamma_r \Psi(z) \end{cases}$$

$$\begin{cases} \chi_\pm \rightarrow p_g \chi_\mp, \quad \eta_\pm \rightarrow p_g \eta_\mp \\ \chi_\pm \rightarrow p_r \chi_\pm, \quad \eta_\pm \rightarrow -p_r \eta_\mp \end{cases}$$

$$\Psi_{+r}^0 = \begin{pmatrix} \chi_+^0 \\ 0 \\ \chi_-^0 \\ 0 \end{pmatrix} \quad \Psi_{-r}^0 = \begin{pmatrix} 0 \\ \bar{\eta}_-^0 \\ 0 \\ \bar{\eta}_+^0 \end{pmatrix}$$



Particle content

	(0,0)	(1,0)	(2,0)
mass	m_{SM}	m_{KK}	$2m_{KK}$
$A_\mu(y)$	★		★
$A_{4/5}(y)$		★	★
$\Phi(y)$	★		★
$\Psi(y)$	★	★	★

Loop corrections will determine

- LHC phenomenology
- Dark Matter phenomenology

$$\begin{aligned}
 \Gamma(e^2) &= 1.619 * 10^{-4} \text{ GeV} \\
 \Gamma(e^2 \rightarrow eA^2) &= 1.101 * 10^{-4} \text{ GeV} \\
 \Gamma(e^2 \rightarrow eZ) &= 3.167 * 10^{-5} \text{ GeV} \\
 \Gamma(e^2 \rightarrow e^1 Z^1) &= 0 \text{ GeV} \\
 \Gamma(e^2 \rightarrow e^1 A^1) &= 1.737 * 10^{-5} \text{ GeV} \\
 \Gamma(e^2 \rightarrow eA) &= 2.716 * 10^{-6} \text{ GeV}
 \end{aligned}$$



Loop corrections

- Scalar field propagator on the orbifold

$$G_{\Phi}^{6D \text{ orb}}(p, \vec{y}_1 - \vec{y}_2) = \frac{1}{4} [\underbrace{p_g G_{\Phi}^{6D}(p, \vec{y}_1 - g(\vec{y}_2)) + p_{gr} G_{\Phi}^{6D}(p, \vec{y}_1 - (r * g)(\vec{y}_2))}_{\text{glide}} + \underbrace{G_{\Phi}^{6D}(p, \vec{y}_1 - \vec{y}_2)}_{\text{torus}} + \underbrace{p_r G_{\Phi}^{6D}(p, \vec{y}_1 - r(\vec{y}_2))}_{\text{rotation}}]$$

- mixed propagator method (*Da Rold ArXiv:hep-ph/0311163*)

$$G_{\Phi}^{6D}(k, \vec{y}_1 - \vec{y}_2) = \sum_{l=-\infty}^{\infty} \underbrace{i \frac{\cos \chi_l (\pi - |y_1 - y_2|)}{2 \chi_l \sin \chi_l \pi}}_{\text{5D propagator}} f_l^*(z_1) f_l(z_2) \quad \text{ou} \quad f_l(z) = \frac{1}{\sqrt{2\pi}} e^{ilz} \quad \chi_l(k) = \sqrt{k^2 - l^2}$$

- generic loop contributions

$$\Pi = \underbrace{\Pi_T}_{\sim \frac{1}{\pi} \sum_{(k,l)} \frac{1}{(k^2+l^2)^2} \approx 1.92} + \underbrace{\frac{p_g \Pi_G}{\sim \zeta(3)} + \frac{p_g p_r \Pi_{G'}}{\sim \ln \frac{\Lambda^2 R^2 + n^2}{n^2}}}_{+} + \underbrace{\frac{p_r \Pi_R}{+}}$$

$$\delta m_B^2 = \frac{g'^2}{64\pi^4 R^2} \left[-79 \text{ } T_6 + 14 \zeta(3) + \pi^2 n^2 L + \dots \right]$$

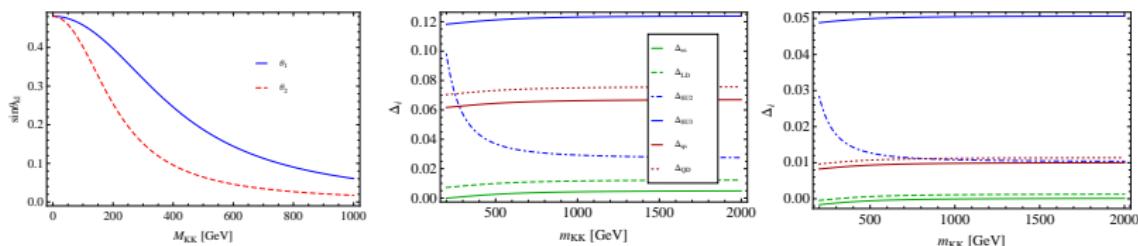


EWSB mixing and full spectrum

$$\begin{pmatrix} W_n^3 & B_n \end{pmatrix} \begin{pmatrix} m_{kl} + m_W^2 + \delta m_W^2 \\ -\text{tg}\theta_W m_W^2 \end{pmatrix} \begin{pmatrix} -\text{tg}\theta_W m_W^2 \\ m_{kl} + \text{tg}^2\theta_W m_W^2 + \delta m_B^2 \end{pmatrix} \begin{pmatrix} W_n^3 \\ B_n \end{pmatrix}$$

Different mixing angle at each (k, l) level

$$\begin{pmatrix} Z_\alpha^{(k,l)} \\ A_\alpha^{(k,l)} \end{pmatrix} = \begin{pmatrix} \cos \theta_{kl} & -\sin \theta_{kl} \\ \sin \theta_{kl} & \cos \theta_{kl} \end{pmatrix} \begin{pmatrix} W_\alpha^{3(k,l)} \\ B_\alpha^{(k,l)} \end{pmatrix}$$



The LKP is A_6^1 - the scalar photon

Mass splittings $\Delta_i = \left(\frac{m_i}{m_{LKP}} - 1 \right) \sim 0.01$ for $(1,0)$ level



Relic abundance

$$\Omega_{LKP} h^2 \approx \frac{1.04 \times 10^9}{M_{PL}} \frac{x_F}{\sqrt{g_*}} \frac{1}{I_a + 3I_b/x_F}$$

$$\langle \sigma_{eff} v \rangle = \sum_{ij} \sigma_{ij} \frac{g_i g_j}{g_{eff}^2} (1 + \Delta_i)^{\frac{3}{2}} (1 + \Delta_j)^{\frac{3}{2}} e^{-x(\Delta_i + \Delta_j)}$$

$$\Delta_i = \left(\frac{m_i}{m_{LKP}} - 1 \right)$$

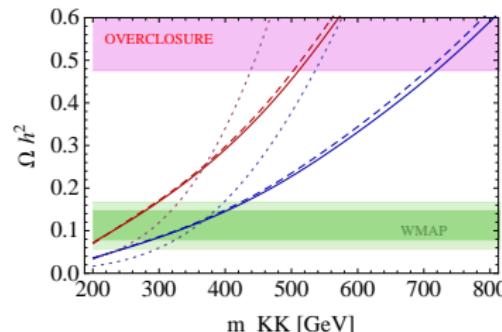
- ❶ $\Delta_i \sim 0.01 \Rightarrow$ we need to take into account the coannihilations
- ❷ we add the loop induced couplings $(2, 0) \rightarrow (0, 0) + (0, 0)$
- ❸ $M^{(2,0)} \approx 2M^{(1,0)} \Rightarrow$ we include the $(2,0)$ states into intermediate and final states
- ❹ study of two cases
 - ❶ $(1, 0) + (1, 0) \rightarrow (0, 0) + (0, 0)$ via $(k, 0)$ states, whith $k \in \{0, 1, 2\}$
 - ❷ $(1, 0) + (1, 0) \rightarrow (0, 0) + (0/2, 0)$ via $(k, 0)$ states, whith $k \in \{0, 1, 2\}$



Analytical results - influence of coannihilations

$(1, 0) + (1, 0) \rightarrow (0, 0) + (0, 0)$ via $(k, 0)$ with $k \in \{0, 1\}$

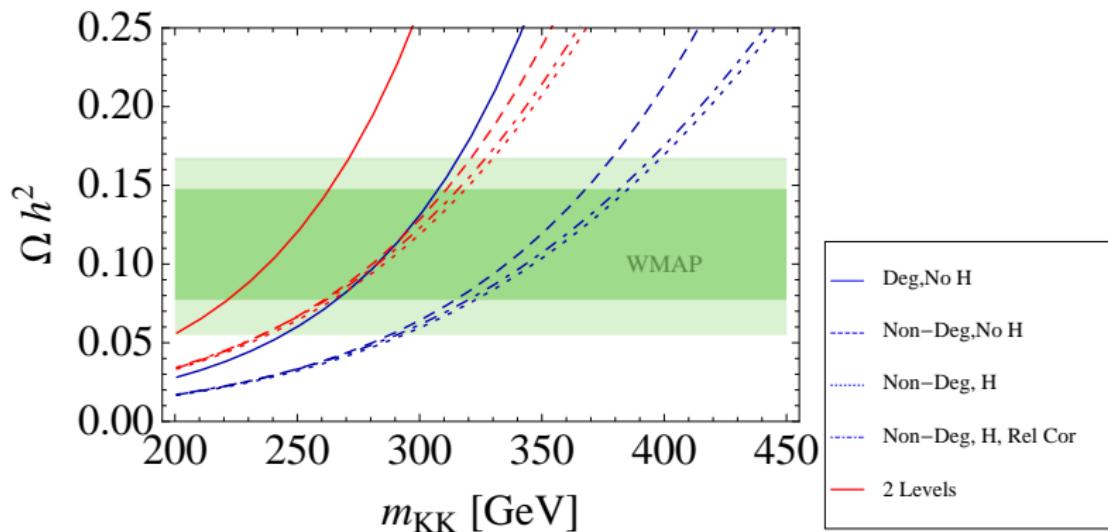
- if $R_5 \gg R_6$ then $m_{A_5} \ll m_{A_6}$, A_6 decouple and we have only one LKP (blue line)
- if $R_5 = R_6$ then $m_{A_5} = m_{A_6}$ and we have two LPKs (red line)



LKP mass range [GeV]	
$\gamma^1 \gamma^1$	$320 < m_{kk} < 380$
$\gamma^1 e_R^1$	$410 < m_{kk} < 550$
$\gamma^1 l_R^1$	$290 < m_{kk} < 400$
$\gamma^1, Z^1, W^{\pm 1}_R$	$670 < m_{kk} < 990$
all	$300 < m_{kk} < 390$



Relic abundance annihilations - Higgs effect





Relic abundance annihilations - Results

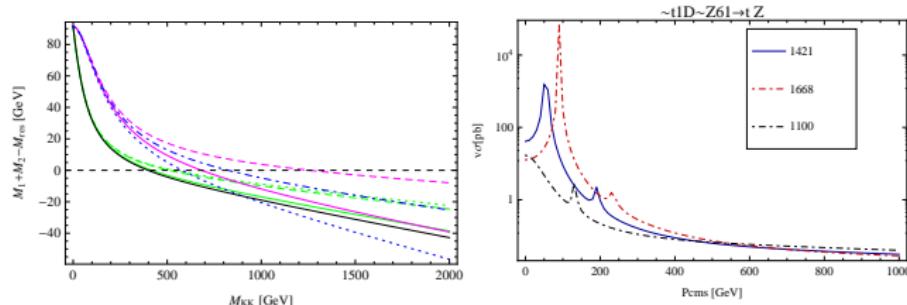
- The non degeneracy of 1st level masses $m^{(01)}$ changes a lot the cross section and hence the relic abundance
- for fermionic final states
 - A lot of states
 - helicity suppressed
 - $\sigma_{nonged} \sim \frac{1}{m_{LKP}^2 + m_{q10}^2} < \frac{1}{(2m_{lkp})^2} \sim \sigma_{deg} \Rightarrow m_{LKPnonged} < m_{LKPdeg}$
- opposite effect for bosonic final states
 $\sigma_{nonged} > \sigma_{deg} \Rightarrow m_{LKPnonged} > m_{LKPdeg}$
- since the fermionic final states are helicity suppressed the relevant corrections come from bosons ($A1A1 \rightarrow WW$) and the net result is the increase of the expected range of LKP
- adding Higgs \rightarrow new channels \rightarrow increase of m_{LKP}
- relativistic corrections \rightarrow light change



Numerical results - preliminary

$(1,0) + (1,0) \rightarrow (0,0) + (0/2,0)$ via $(k,0)$ with $k \in \{0,1\}$

- in both cases we expect new processes to contribute to the σ_{eff}
 - $t^5 \rightarrow t^1 Z^1$ for $m_{KK} > 600\text{GeV}$
 - $u^5 \rightarrow u^1 Z^1$ for $m_{KK} > 500\text{GeV}$
- we need to have $m_{1b} + m_{1a} \approx m_5$ otherwise a strong Boltzmann suppression
- in the case $(1,0) + (1,0) \rightarrow (0,0) + (0,0)$ the kinematics is not constraining but the $(2,0)$ particles goes only via loop induced couplings.
- in the case $(1,0) + (1,0) \rightarrow (0,0) + (0/2,0)$ states the kinematics is more constraining $m_{in} \approx m_{out}$ but we have a lot of new processes and the $(2,0)$ intermediate states can decay via tree couplings

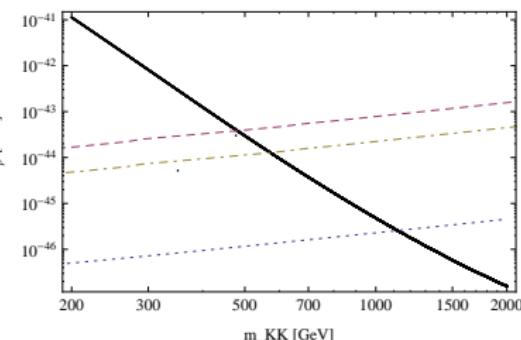
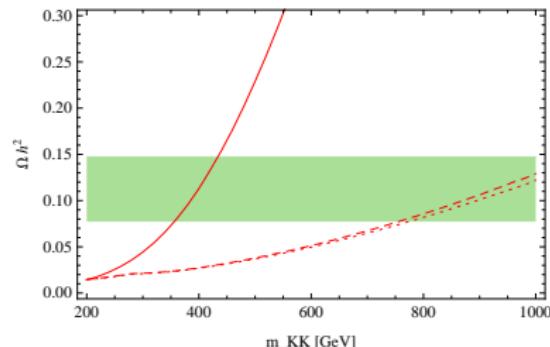




Numerical results - preliminary

$$(1,0) + (1,0) \rightarrow (0,0) + (0/2,0) \text{ via } (k,0) \text{ with } k \in \{0,1\}$$

- The inclusion of (2,0) modes in final states apparently pushes strongly the allowed m_{KK} to high values
 $m_{KK} > 755 \text{ GeV without loop couplings}$
 $m_{KK} > 760 \text{ GeV with loop couplings}$
- direc detection bounds, Xenon (2011) $m_{KK} > 450 \text{ GeV}$,
(2012) $m_{KK} > 550 \text{ GeV}$, (2017) $m_{KK} > 1150 \text{ GeV}$





Summary and outlook

- ① The RPP is an orbifold with natural DM candidate
 - ② $\Delta_i \approx 0.01$ ensures a very interesting DM phenomenology
 - ③ if $A_5 = A_6$ we have two DM particles not interacting with each other $\Rightarrow \Omega h^2 \rightarrow 2\Omega h^2$
 - ④ The relic abundance Ωh^2 and direct detection bounds set the scale of $m_{KK} \sim 300 - 400 \text{ GeV}$
 - ⑤ the inclusion of (2,0) final states and the m_{KK} values are pushed up to $m_{KK} > 700 \text{ GeV}$
- model $m_{KK} [\text{GeV}]$

Outlook

- ① m_H is a parameter of the model

$$m_{H^1}^2 = m_H^2 + m_{KK}^2 \quad m_{H^5}^2 = m_H^2 + 4m_{KK}^2$$

- ② we can expect resonances from H^5 in s-channels for $m_{H^5} < 2m_{KK}$
- ③ include the case $R_5 \neq R_6$ to observe the mixings effects