Phenomenology at the LHC: a 6D scenario of Dark Matter

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3rd FCPPL Workshop

Lyon

New proposal:
"New Physics at the LHC"

Tsinghua University:

Wang Qing, Kuang YuPing, Zhang Bin + 3 students

IPN Lyon:

G.Cacciapaglia, A.Deandrea, L.Panizzi + 2 students

The complementarity between the two groups will allow us to study:

- signals of New Physics at the LHC (model dependent and independent);
- new physics using the chiral lagrangian technique: Higgsless models, extra dimensions...

Example: a new scenario of Dark Matter in 6 dimensions.

XDimensions are a versatile tool, many models have been proposed:
Gauge-Higgs unification, Higgsless models,
GUTs, composite Higgs, technicolour, QCD...

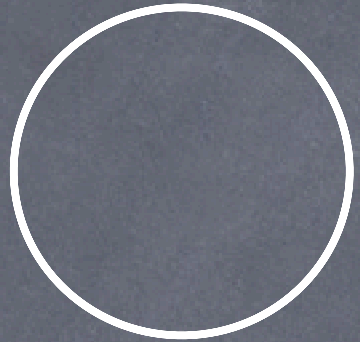
New DM candidate: KK parity makes lightest resonance stable.
Is it "natural" or ad-hoc? Is it generic in XD models?

- It's not generically the case: interesting models do not have it!
- we found a unique "natural" scenario in 6 dimensions where the symmetry is a direct consequence of the compactification!

arXiv:0907.4993
G.C., A.Deandrea, J.Llodra-Perez
work in progress with
J.Llodra-Perez, B.Kubik, L.Panizzi

Intro to XD: a scalar field

Action for a massless scalar:



$$S = \int_0^{2\pi} dx_5\, \partial_\mu \phi^\dagger \partial^\mu \phi - \partial_5 \phi^\dagger \partial_5 \phi$$

The equation of motion $$[p^2 + \partial_5^2]\, \phi(p, x_5) = 0$$

is solved by $$\phi(p, x_5) = \sum_k f_{(k)}(x_5)\, \phi_{(k)}(p)$$

4D field!

with:

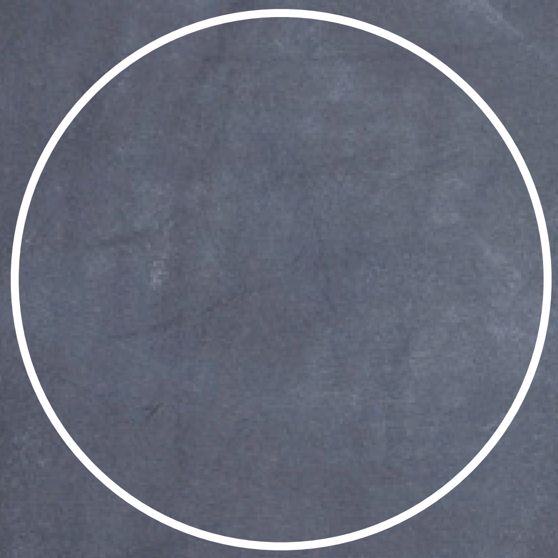
$$f_{(k)} = \begin{cases} \cos(kx_5) \\ \sin(kx_5) \end{cases} \Rightarrow\ p^2 = k^2$$

Note that under x5 -> -x5, cos -> + cos while sin -> -sin!

Also, k=0 only allowed for cos!

KK parity is not natural!

The typical situation is:



- We start from, say, 1 compact XD...

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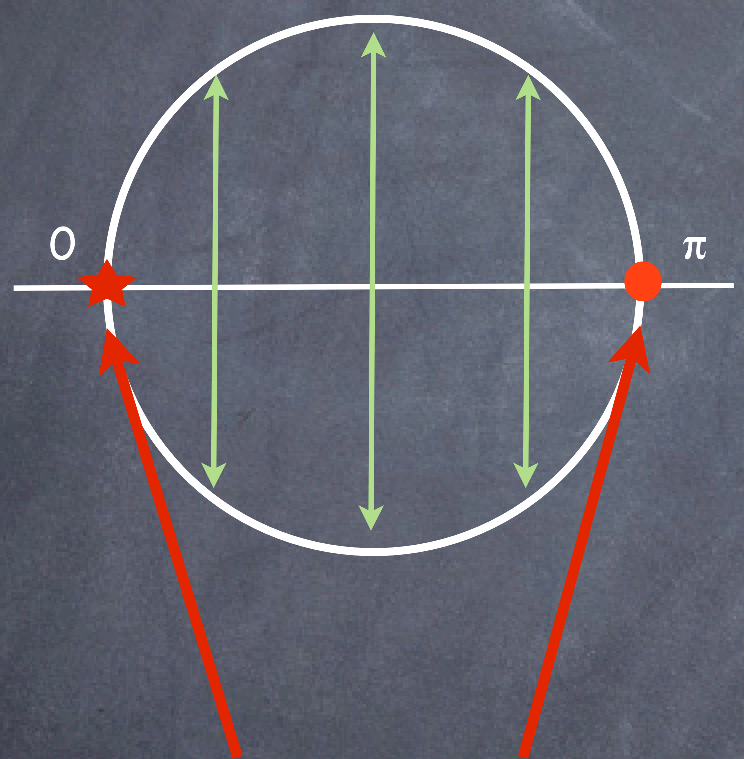

- We start from, say, 1 compact XD...
- We orbifold to obtain chiral fermions...

$x_5 \to -x_5$

KK parity is not natural!

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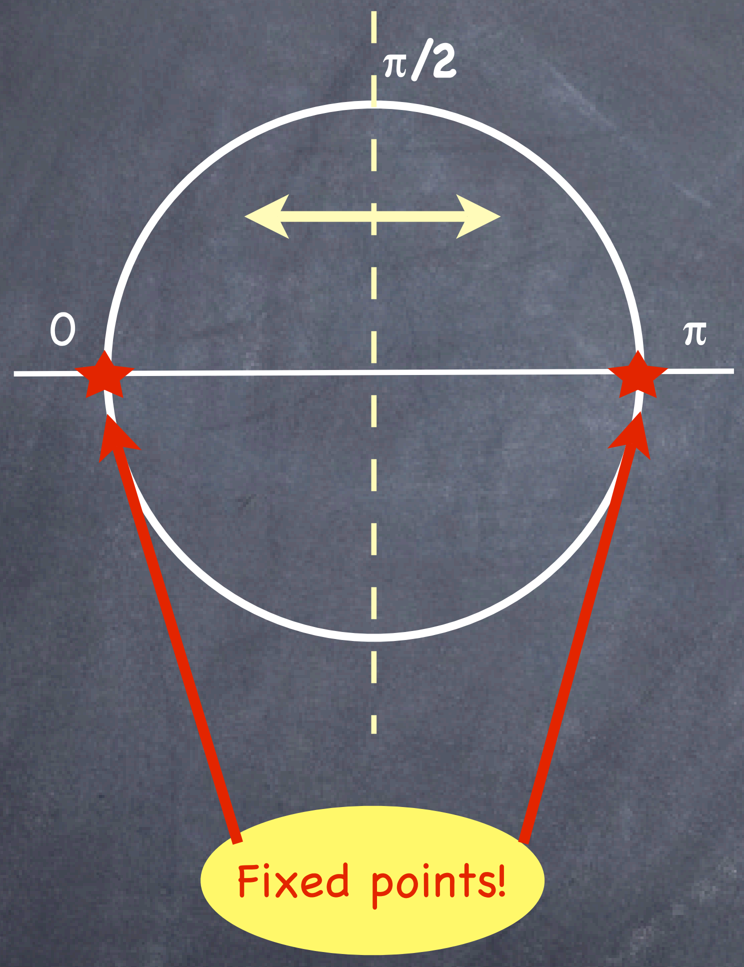


- We start from, say, 1 compact XD...
- We orbifold to obtain chiral fermions...
- We impose a discrete parity: Kaluza-Klein parity!

The KK parity is added ad hoc,
it requires to identify two DIFFERENT fixed points!

Orbifold without fixed points:

- In 2D there are 17 orbifolds (discrete symmetries of the plane)...
- of which only 1 does not have fixed points/lines and is chiral:

Real projective plane

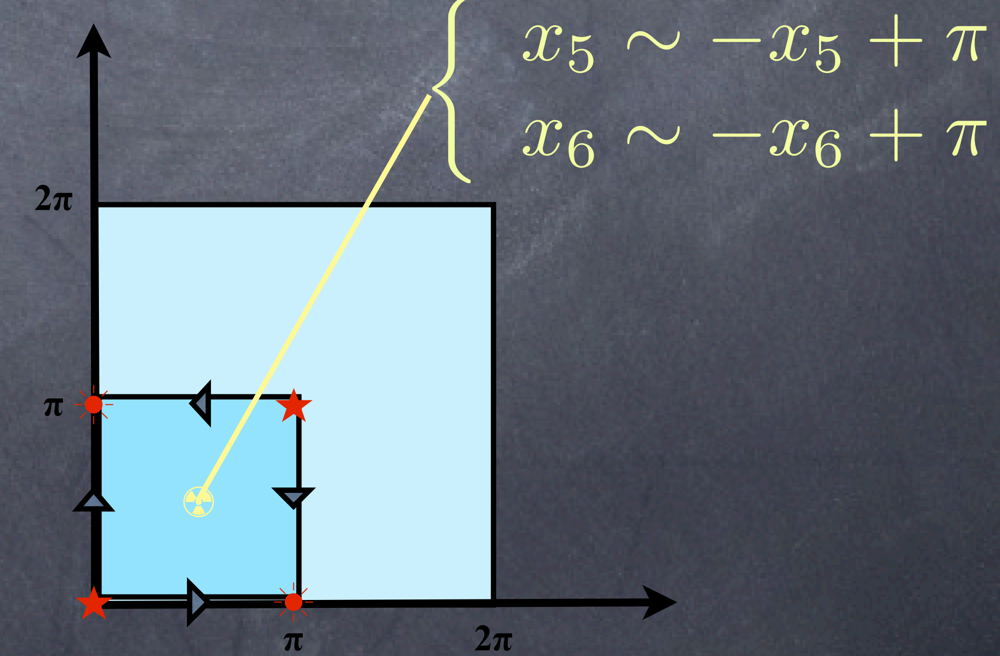
The real projective plane

$$\mathbf{pgg} = \langle r, g | r^2 = (g^2 r)^2 = \mathbf{1} \rangle$$

$$r : \begin{cases} x_5 \sim -x_5 \\ x_6 \sim -x_6 \end{cases} \qquad g : \begin{cases} x_5 \sim x_5 + \pi R_5 \\ x_6 \sim -x_6 + \pi R_6 \end{cases}$$

KK parity is an exact symmetry of the space!

$$p_{KK} : \begin{cases} x_5 \sim x_5 + \pi \\ x_6 \sim x_6 + \pi \end{cases}$$



Spectrum of the SM on the RPP

	+	−	+	+	−
$p_{KK} = (-1)^{k+l}$	(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)

Splittings I: loops

- Generic loop contributions can be written as:

$$\Pi = \Pi_T + p_g \, \Pi_G + p_r \, \Pi_R + p_g p_r \, \Pi_{G'}$$

- For gauge scalars, tier (1,0):

Log divergence!

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

$$\delta m_W^2 = \frac{g^2}{64\pi^4 R^2} \left[-39 T_6 + 70\zeta(3) + 17\pi^2 n^2 L + \ldots \right] ,$$

$$\delta m_G^2 = \frac{g_s{}^2}{64\pi^4 R^2} \left[-36 T_6 + 84\zeta(3) + 24\pi^2 n^2 L + \ldots \right] .$$

- Divergence localized on singular points and proportional to the tier mass!

- Proportional to the KK mass scale!

Calculation in progress by
J.Llodra-Perez, B.Kubik and L.Panizzi

Splittings II: Higgs VEV

- The Higgs VEV does not mix tiers (v is constant!)
- At level (0,0), we obtain the Standard Model!
- For massive tiers:

$$m^2_{(k,l)} = (k^2 + l^2) m^2_{KK} + m_0^2$$

- Mixing angle in the neutral gauge boson sector (A-Z): smaller than the Weinberg mixing angle!

$$W_n^3 \quad B_n \;\Big) \cdot \begin{pmatrix} \delta m_W^2 + m_W^2 & -\tan\theta_W m_W^2 \\ -\tan\theta_W m_W^2 & \delta m_B^2 + \tan^2\theta_W m_W^2 \end{pmatrix} \cdot \begin{pmatrix} W_n^3 \\ B_n \end{pmatrix} .$$

Splittings II: Higgs VEV

- The Higgs VEV does r
- At level (0,0), we ob
- For massive tiers:

$$\int_0^{2\pi} dx_5 dx_6 \ |\mathcal{D}H|^2 \Rightarrow \int_0^{2\pi} dx_5 dx_6 \ m_W^2 W^2$$

$$\Rightarrow \sum_{k,l} m_W^2 W_{k,l}^2$$

$$m^2_{(k,l)} = (k^2 + l^2) m^2_{KK} + m_0^2$$

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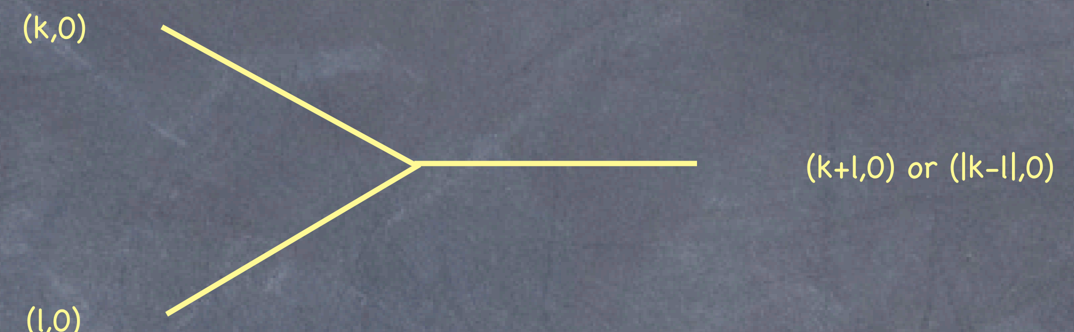
Phenomenology: interactions I

- Bulk interactions: same as SM couplings, conservation of XD momentum!



- Only pair production off SM states is allowed!

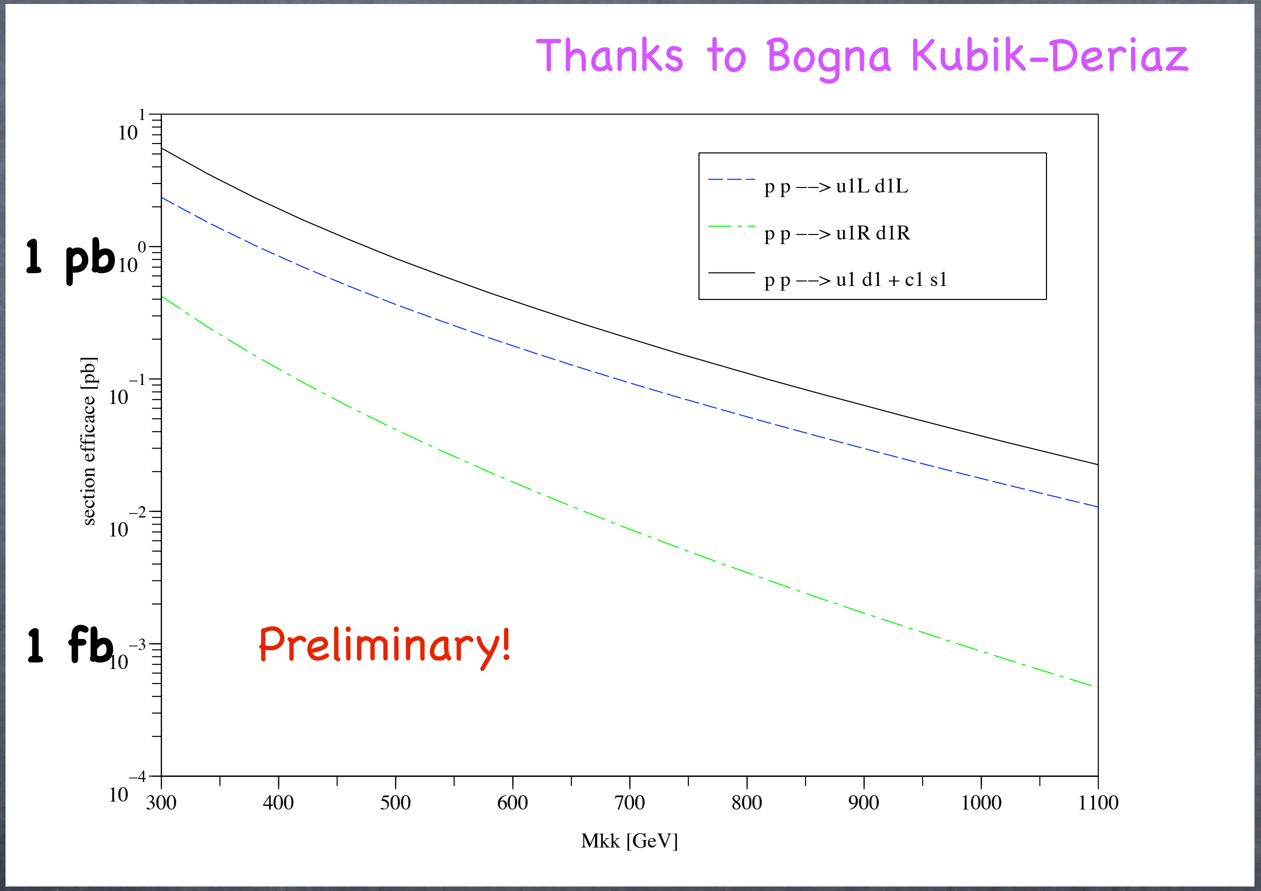
$$\text{i.e.} \quad (0,0) \Rightarrow (2,0) + (2,0)$$

- Phase-space suppressed decays:

$$\text{i.e.} \quad (2,0) \Rightarrow (1,0) + (1,0)$$
$$(2,0) \Rightarrow (2,0) + (0,0)$$

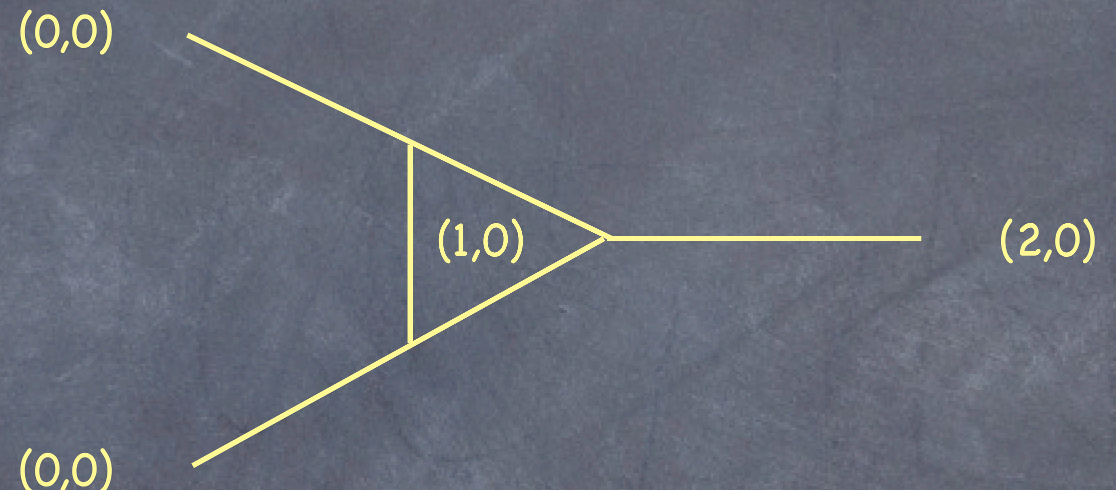
Phenomenology: interactions I

- Pair production rates are large:



Phenomenology: interactions II

- Loop interactions: suppressed, but less constrained.
- Single production and decays



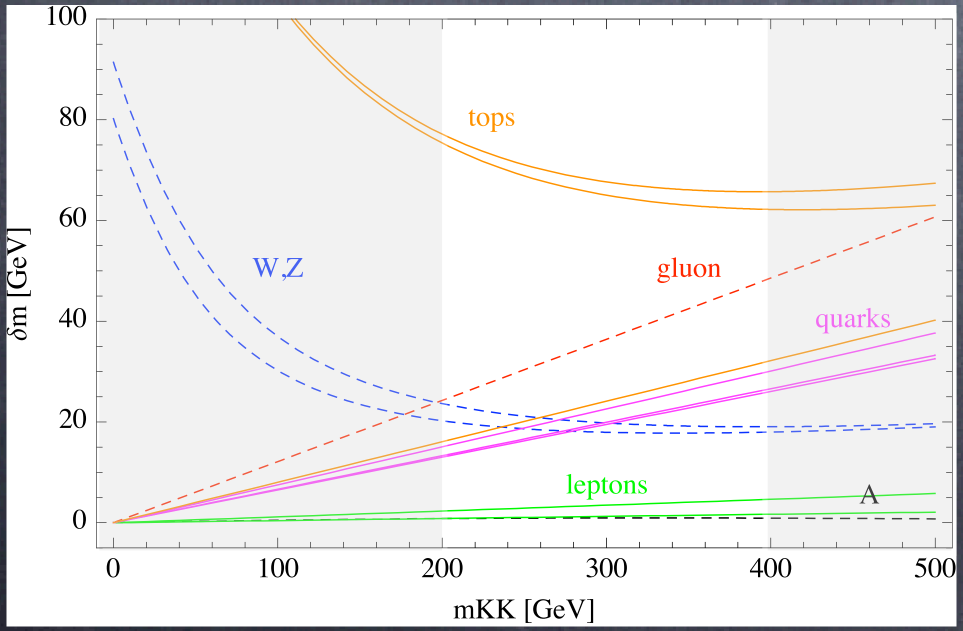
i.e. $(2,0) \Rightarrow (0,0) + (0,0)$

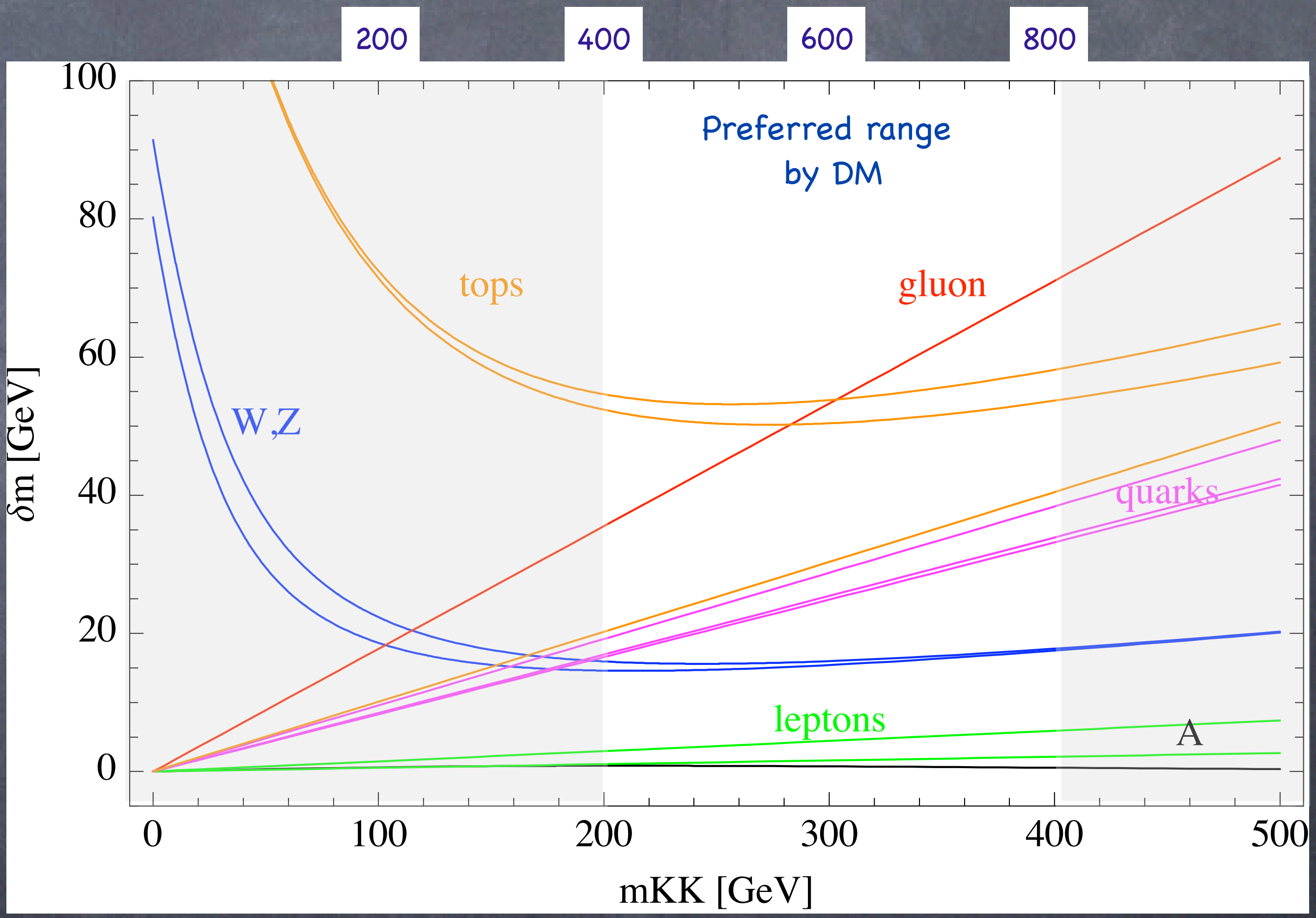
Calculation in progress by J.Llodra-Perez

Phenomenology at the LHC: tiers (2,0) and (0,2)

- Decay in pair of SM particles (via vertices at 1-loop)
- Small splittings: suppressed or forbidden decays in pair of (1,0)

$W_{(2,0)}, Z_{(2,0)} \to l_{(1,0)}\ l_{(1,0)}$
$top_{(2,0)} \to W_{(1,0)}\ b_{(1,0)}$
$g_{(2,0)} \to q_{(1,0)}\ q_{(1,0)}$
...





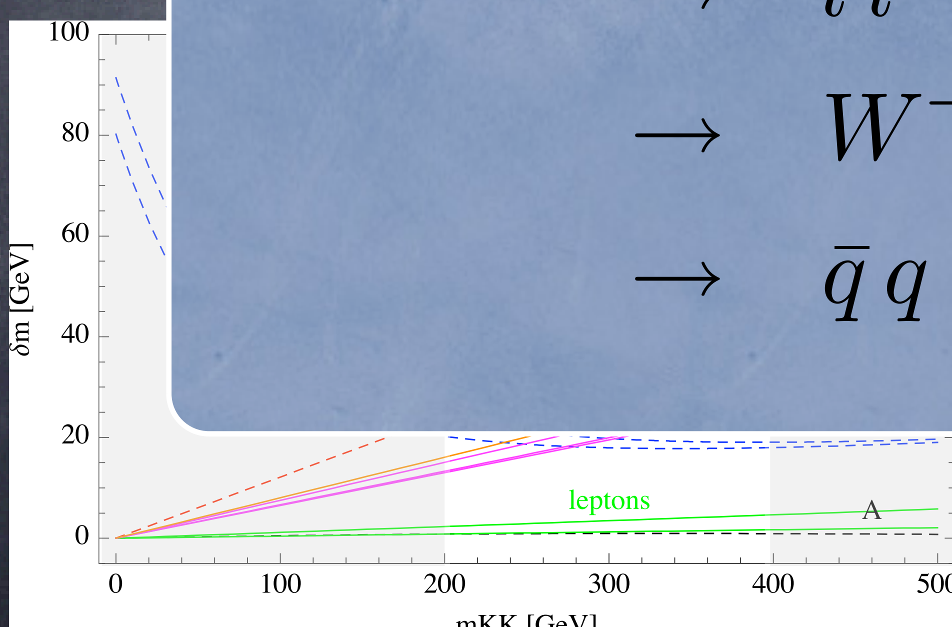
Phenomenology at the LHC: tiers (2,0) and (0,2)

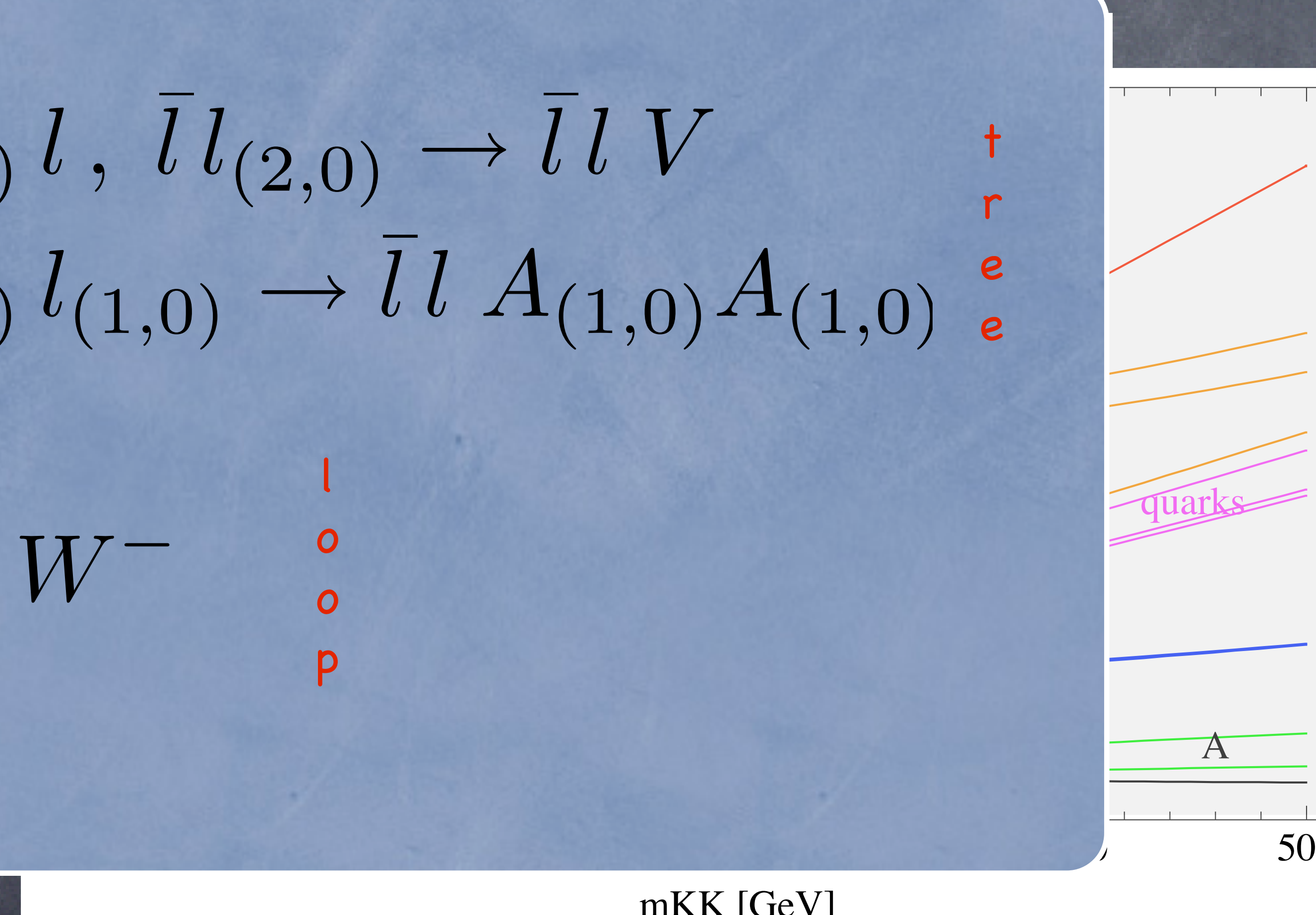
- Decay in pair of SM particles (via vertices at 1-loop)
- Small splittings: suppressed or forbidden decays in pair of (1,0)

$$
\begin{aligned}
Z_{(2,0)} \quad &\rightarrow \quad \bar{l}_{(2,0)}\, l\,,\ \bar{l}\, l_{(2,0)} \rightarrow \bar{l}\, l\, V \\
&\rightarrow \quad \bar{l}_{(1,0)}\, l_{(1,0)} \rightarrow \bar{l}\, l\, A_{(1,0)} A_{(1,0)} \\
&\rightarrow \quad \bar{l}\, l \\
&\rightarrow \quad W^{+} W^{-} \\
&\rightarrow \quad \bar{q}\, q
\end{aligned}
$$

tree

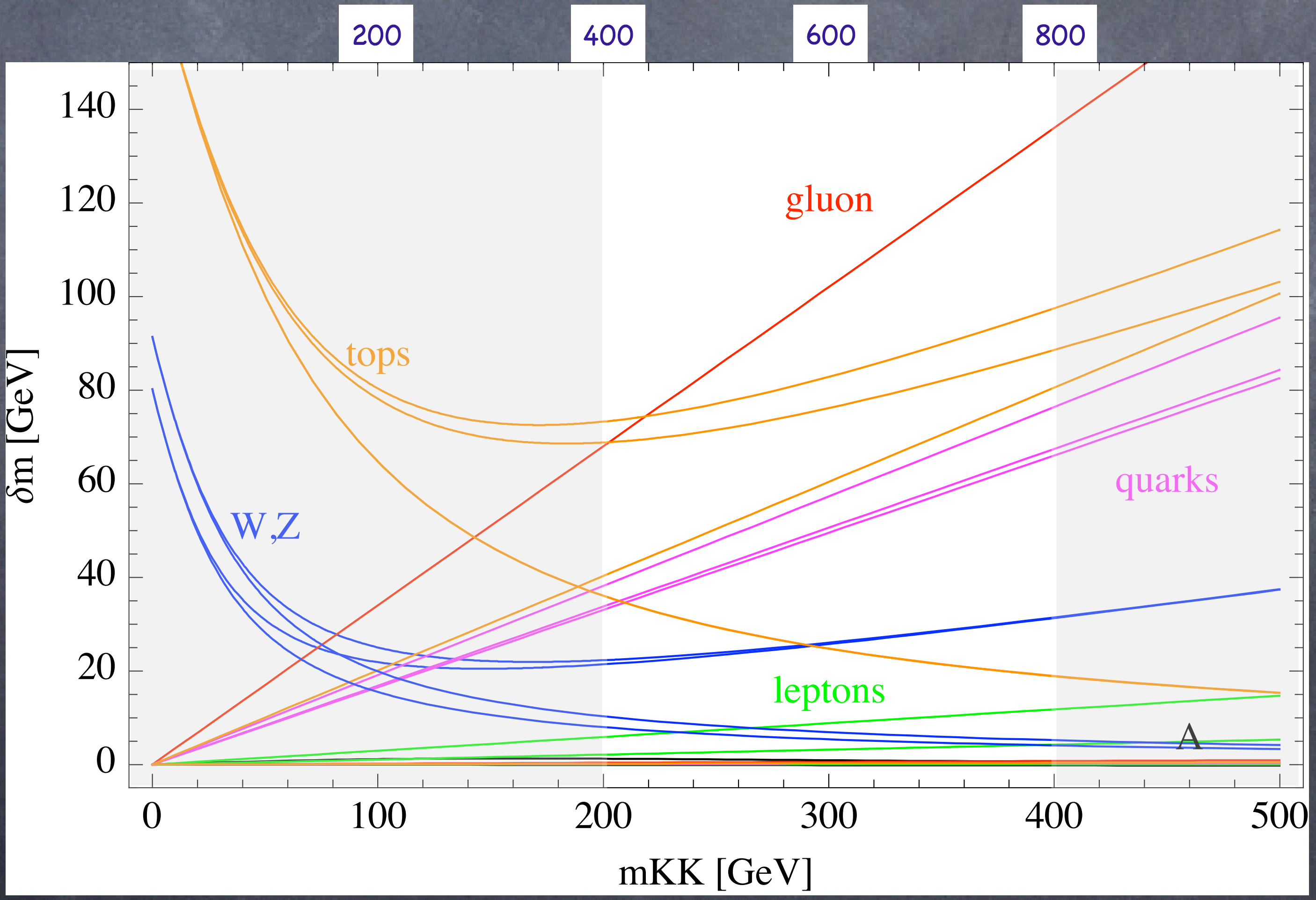
loop





Phenomenology at the LHC: (2,0)-(0,2) degenerate case

- loop induced mixing cannot be neglected: one heavier state, and a lighter (cut-off independent) one
- More (1,0)-(1,0) channels are open



Conclusions and outlook

- There is a unique 6D scenario with “natural” KK Dark Matter: interesting phenomenology!
- Small splittings make detection of lightest tier challenging: need boost to see!
- Tiers (1,1) and (2,0) decay to SM particles: nice resonances, but no MET! Interesting degenerate case.
- Tier (2,1) decays in (1,0) + (0,0): SM + MET!
- We implemented the model in FeynRules: easy interface with calcHep, Madgraph, FeynArt...

Bonus tracks

Example: a scalar field

Action for a massless scalar:

$$S = \int_0^{2\pi} dx_5 dx_6 \, \partial_\mu \phi^\dagger \partial^\mu \phi - \partial_5 \phi^\dagger \partial_5 \phi - \partial_6 \phi^\dagger \partial_6 \phi$$

The equation of motion $$[p^2 + \partial_5^2 + \partial_6^2]\phi(p, x_5, x_6) = 0$$

is solved by $$\phi(p, x_5, x_6) = \sum_{k,l} f_{(k,l)}(x_5, x_6) \, \phi_{(k,l)}(p)$$

4D field!

with:

$$f_{(k,l)}(x_5, x_6) = \begin{cases} \cos(kx_5)\cos(lx_6) \\ \cos(kx_5)\sin(lx_6) \\ \sin(kx_5)\cos(lx_6) \\ \sin(kx_5)\sin(lx_6) \end{cases} \Rightarrow \; p^2 = k^2 + l^2$$

Example: a scalar field

The parity of the field selects the solutions!

$$f_{(k,l)}(x_5, x_6) = \begin{cases} \cos(kx_5)\ \cos(lx_6) \\ \cos(kx_5)\ \sin(lx_6) \\ \sin(kx_5)\ \cos(lx_6) \\ \sin(kx_5)\ \sin(lx_6) \end{cases}$$

Rot.	Glide	KK
+	$p_{k,l}$	$p_{k,l}$
-	$-p_{k,l}$	$p_{k,l}$
-	$p_{k,l}$	$p_{k,l}$
+	$-p_{k,l}$	$p_{k,l}$

$$p_{k,l} = (-1)^{k+l}$$

$$\text{Rotation:} \begin{cases} x_5 \to -x_5 \\ x_6 \to -x_6 \end{cases}$$

$$\text{KK parity:} \begin{cases} x_5 \to x_5 + \pi \\ x_6 \to x_6 + \pi \end{cases}$$

$$\text{Glide:} \begin{cases} x_5 \to x_5 + \pi \\ x_6 \to -x_6 + \pi \end{cases}$$

Gauge bosons

$$S_{\text{gauge}} = \int_0^{2\pi} dx_5\, dx_6\, \left\{ -\frac{1}{4} F_{\alpha\beta}F^{\alpha\beta} - \frac{1}{2\xi}\left(\partial_\mu A^\mu - \xi(\partial_5 A_5 + \partial_6 A_6)\right)^2 \right\}$$

gauge fixing term

After solving the Equations of Motion,
and imposing orbifold parities [$\mu \to (++)$, $5 \to (-+)$, $6 \to (--)$]
the spectrum is:

$$p_{KK} = (-1)^{k+l} \qquad m_{(k,l)} = \sqrt{k^2 + l^2}$$

(k,l)	p_{KK}	$A_\mu^{(++)}$	$A_5^{(-+)}$	$A_6^{(--)}$
$(0,0)$	$+$	$\frac{1}{2\pi}$		
$(0,2l)$	$+$	$\frac{1}{\sqrt{2}\pi}\cos 2lx_6$		
$(0,2l-1)$	$-$		$\frac{1}{\sqrt{2}\pi}\sin(2l-1)x_6$	
$(2k,0)$	$+$	$\frac{1}{\sqrt{2}\pi}\cos 2kx_5$		
$(2k-1,0)$	$-$			$\frac{1}{\sqrt{2}\pi}\sin(2k-1)x_5$
$(k,l)_{\text{k+l even}}$	$+$	$\frac{1}{\pi}\cos kx_5 \cos lx_6$	$\frac{l}{\pi\sqrt{k^2+l^2}}\sin kx_5 \cos lx_6$	$-\frac{k}{\pi\sqrt{k^2+l^2}}\cos kx_5 \sin lx_6$
$(k,l)_{\text{k+l odd}}$	$-$	$\frac{1}{\pi}\sin kx_5 \sin lx_6$	$\frac{l}{\pi\sqrt{k^2+l^2}}\cos kx_5 \sin lx_6$	$-\frac{k}{\pi\sqrt{k^2+l^2}}\sin kx_5 \cos lx_6$

Splittings III: localized operators

- Can add kinetic terms on the two singular points:

$$\delta_0 = \frac{1}{2}\left(\delta(x_5)\delta(x_6) + \delta(x_5 - \pi)\delta(x_6 - \pi)\right)$$
$$\delta_\pi = \frac{1}{2}\left(\delta(x_5)\delta(x_6 - \pi) + \delta(x_5 - \pi)\delta(x_6)\right)$$

$$\mathcal{L}_i = \frac{\delta_i}{\Lambda^2}\left(-\frac{r_{1i}}{4}F^2_{\mu\nu} - \frac{r_{2i}}{2}(\partial_5 A_6 - \partial_6 A_5)^2\right)$$

Vectors:

$$m^2_{(k,l)} = \sqrt{k^2 + l^2}\left(1 - \frac{z_{(k,l)}}{4\pi^2\Lambda^2} + \dots\right)$$

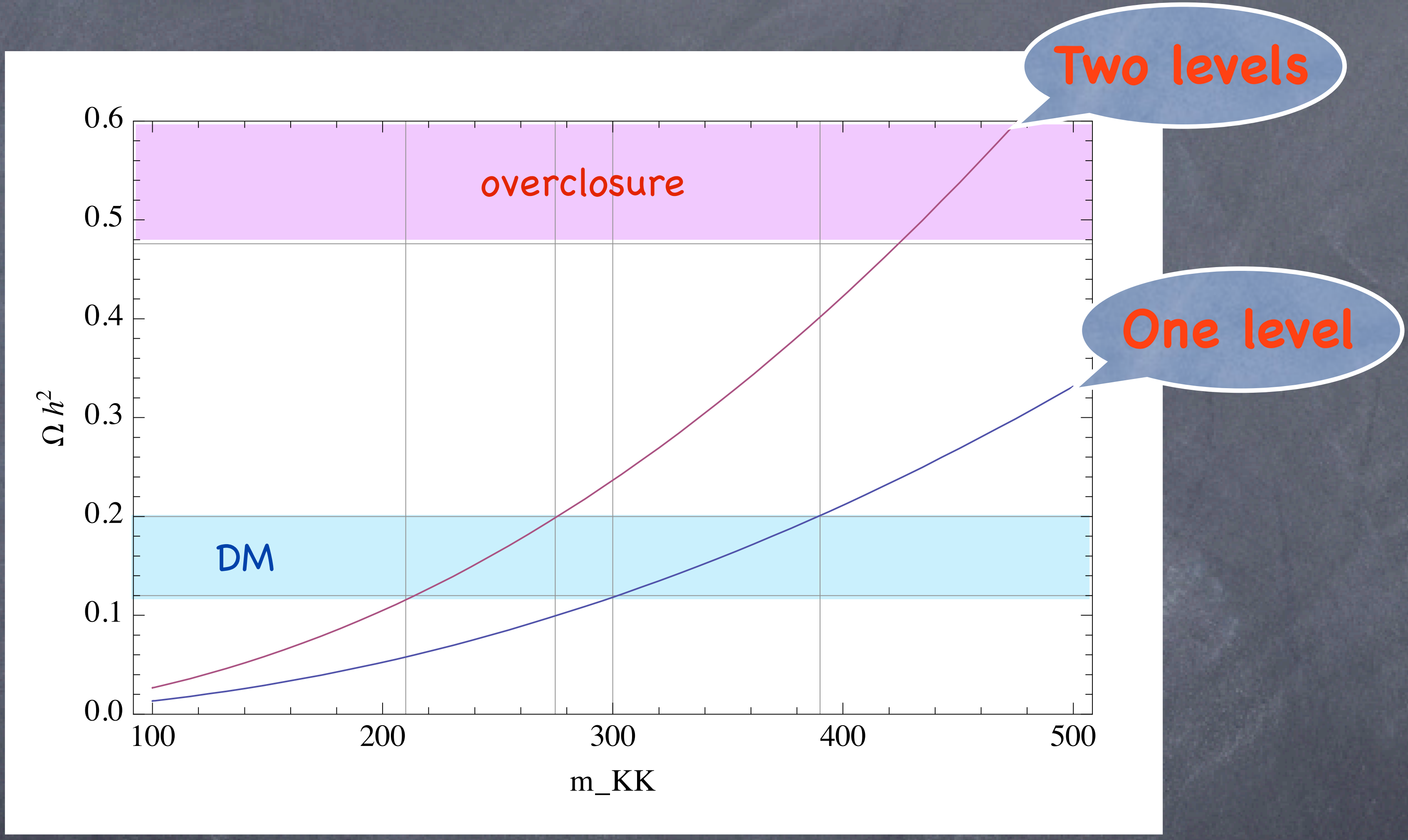
Scalars::

$$\delta m^2_{i,j} = m_i m_j \frac{\delta_{ij}}{4\pi^2\Lambda^2}$$

Note: remove degeneracy between (k,l) and (l,k)!

Small and arbitrary corrections: neglect for now!

Relic abundance



200 < mKK < 400 GeV

Phenomenology at the LHC: tiers (1,0) and (0,1)

- Small splittings make detection of lightest tier challenging:

	$m_X - m_{LLP}$ in GeV	decay mode	final state + MET
$t^{(1,0)}$	70	$bW^{(1,0)}$	bjj $bl\nu$
$G^{(1,0)}$	40-70	$qq^{(1,0)}$	jj
$q^{(1,0)}$	20-40	$qA^{(1,0)}$	j
$W^{(1,0)}$	20	$l\nu^{(1,0)}$, $\nu l^{(1,0)}$	$l\nu$
$Z^{(1,0)}$	20	$ll^{(1,0)}$	ll
$l^{(1,0)}$	< 5	$lA^{(1,0)}$	l
$A^{(1,0)}$	0	-