Dark Matter from Lorentz invariance at the LHC

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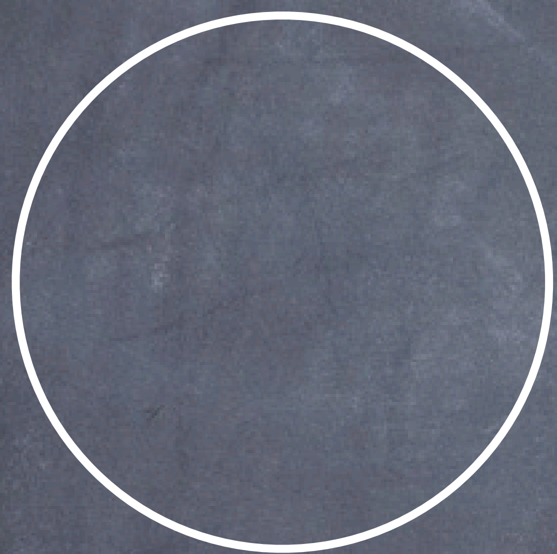
Extra dimensions are a versatile tool, they can address:

- Weak scale stability: Gauge-Higgs unification, warped space...
- Fermion mass hierarchy, neutrino masses
- Gauge symmetry breaking: Higgsless models, GUTs...
- strongly interacting conformal sector: composite Higgs, QCD, Higgsless/walking technicolor...
- Predicted by String Theories

Is it there a natural Dark Matter candidate?

No! The typical situation is:



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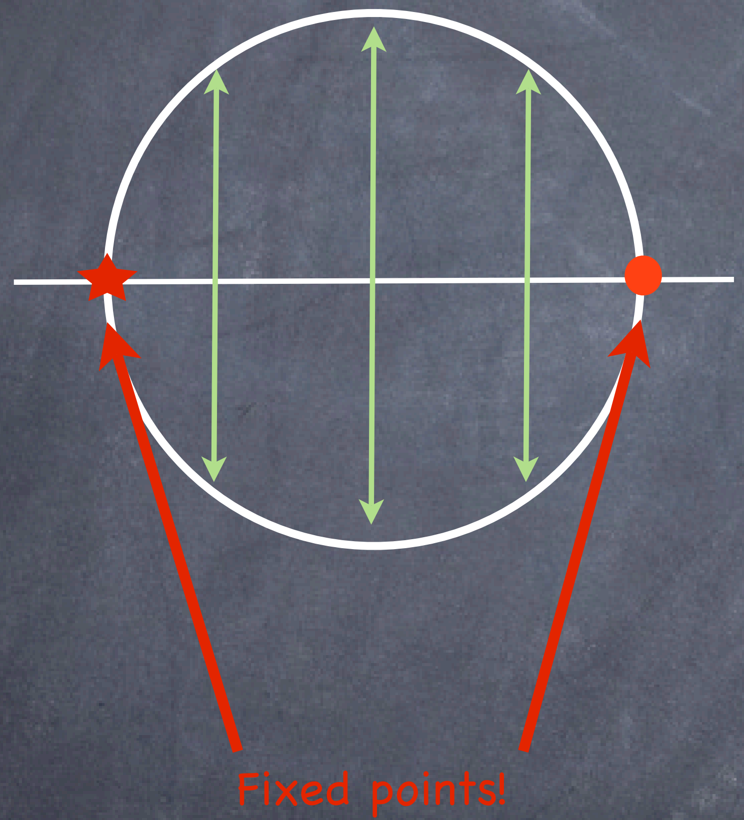

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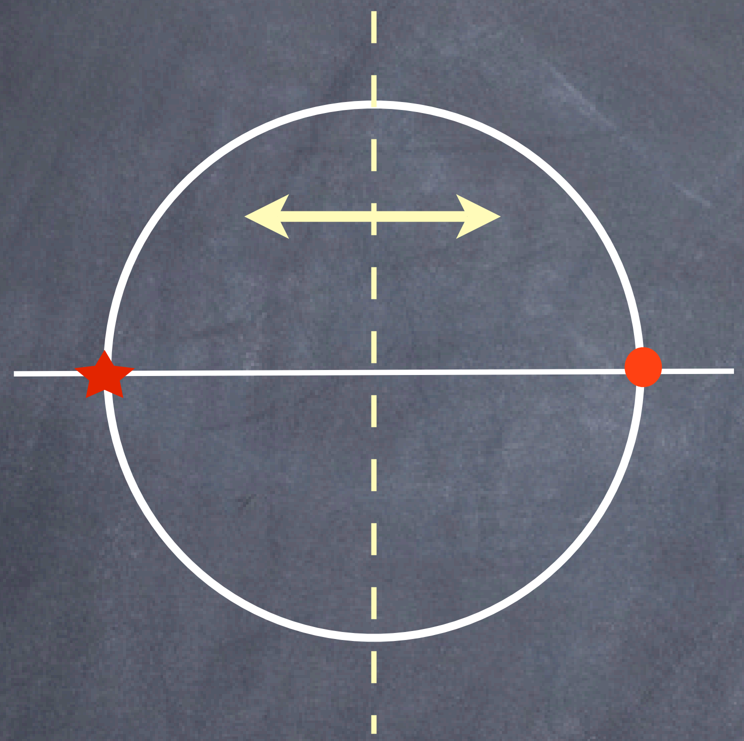

Fixed points!

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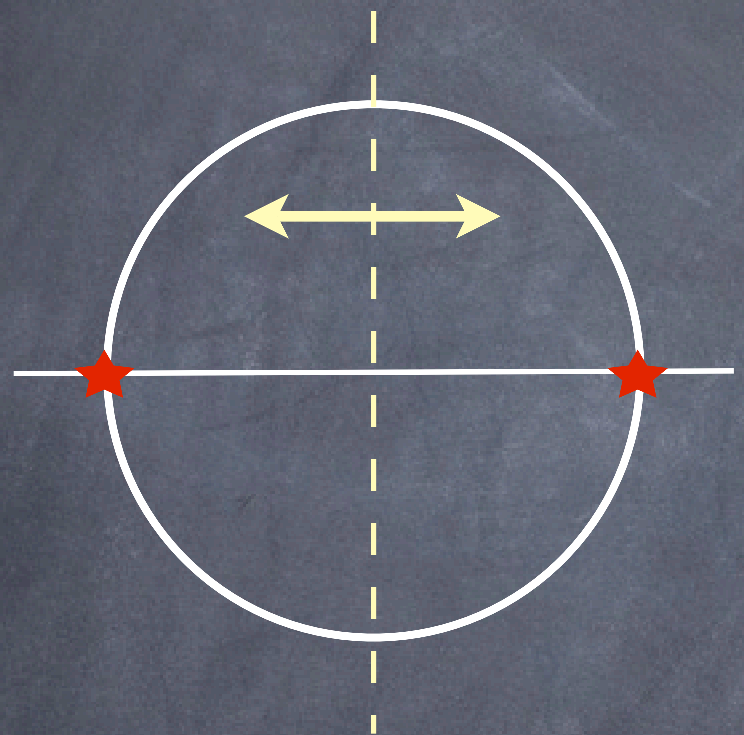

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The KK parity is added ad hoc,
it requires to identify two DIFFERENT
fixed points!

Orbifold without fixed points:

- In 2D there are 17 orbifolds (discrete symmetries of the plane)...
- of which 3 do not have fixed points/lines:

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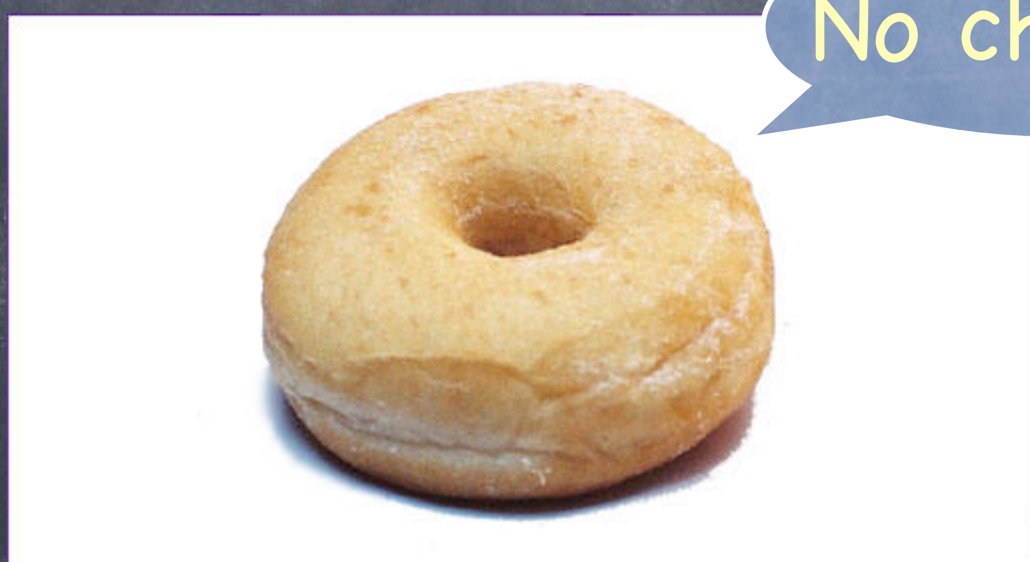
1: torus



No chirality!

2: Klein bottle

3: Real projective plane...

The real projective plane

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

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

Two singular points:

$$(0, \pi) \sim (\pi, 0)$$

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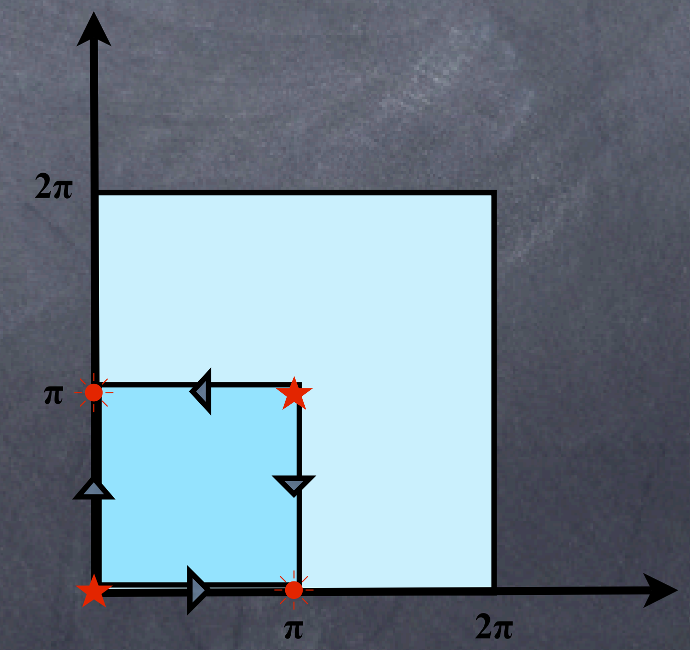

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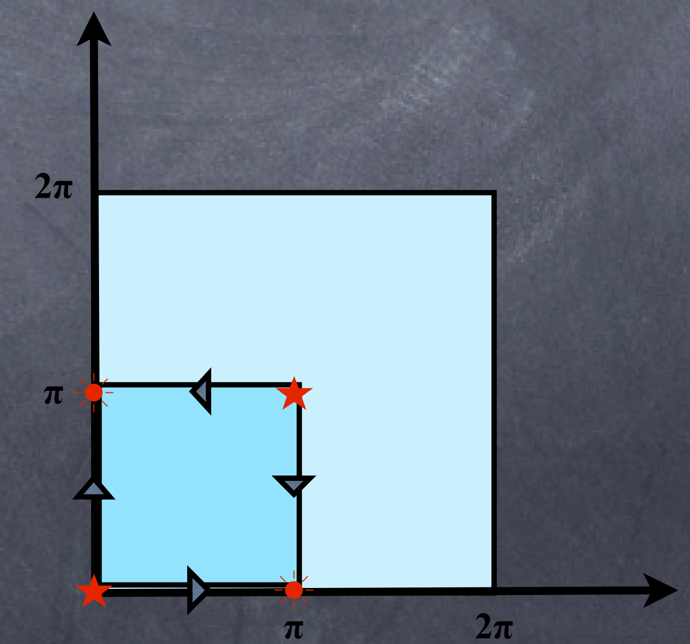
KK parity is an exact symmetry of the space!

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



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

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)

Splitting: loops and Higgs VEV

- Generic loop contributions can be written as:

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

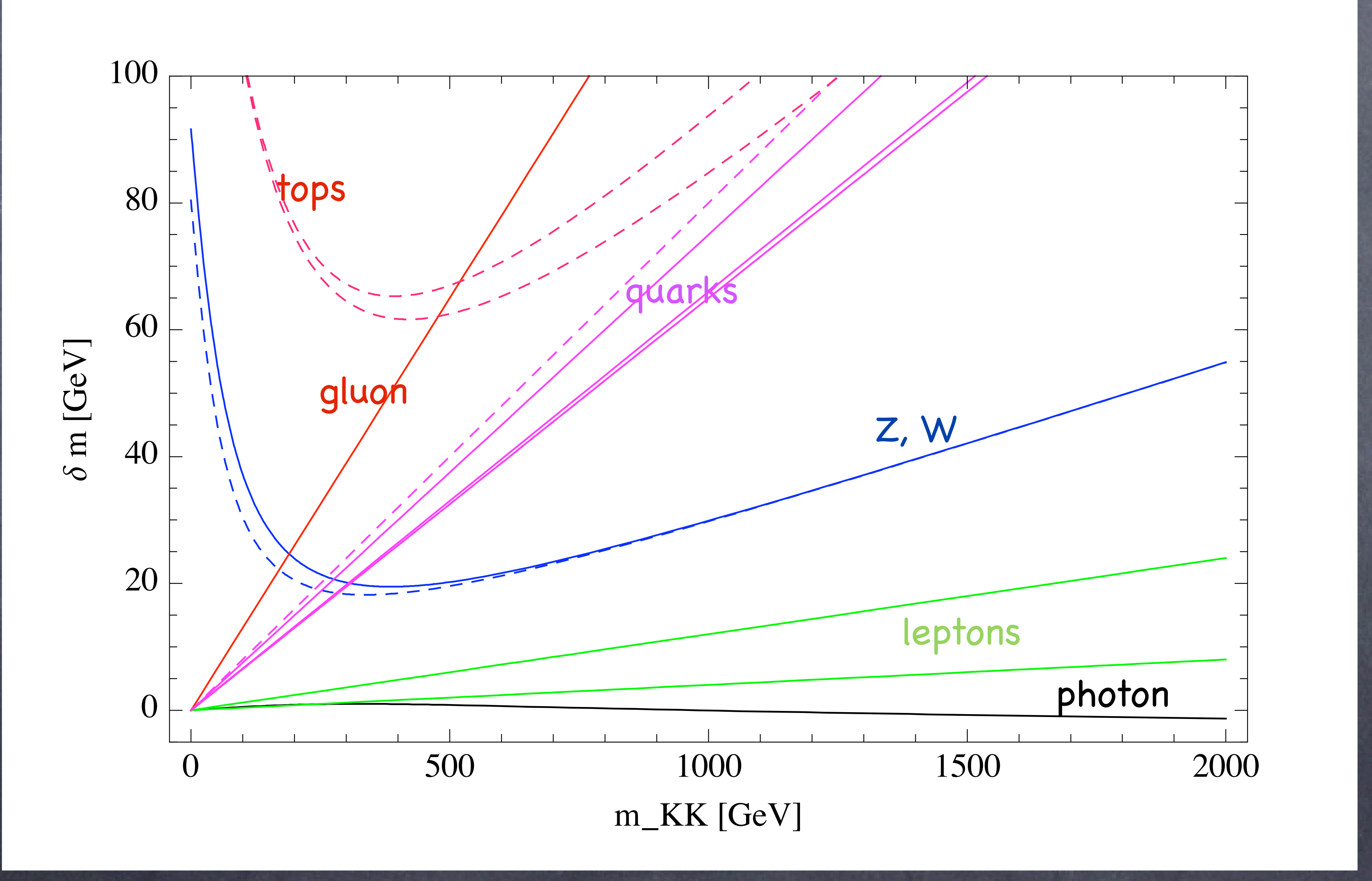
Log divergence!

- For gauge scalars:

$$\begin{aligned}
\delta m_B^2 &= \frac{{g'}^2}{64\pi^4 R^2}\left[-79 T_6 + 14\zeta(3) + \pi^2 n^2 L + \dots\right] , \\
\delta m_W^2 &= \frac{g^2}{64\pi^4 R^2}\left[-39 T_6 + 70\zeta(3) + 17\pi^2 n^2 L + \dots\right] , \\
\delta m_G^2 &= \frac{{g_s}^2}{64\pi^4 R^2}\left[-36 T_6 + 84\zeta(3) + 24\pi^2 n^2 L + \dots\right] .
\end{aligned}$$

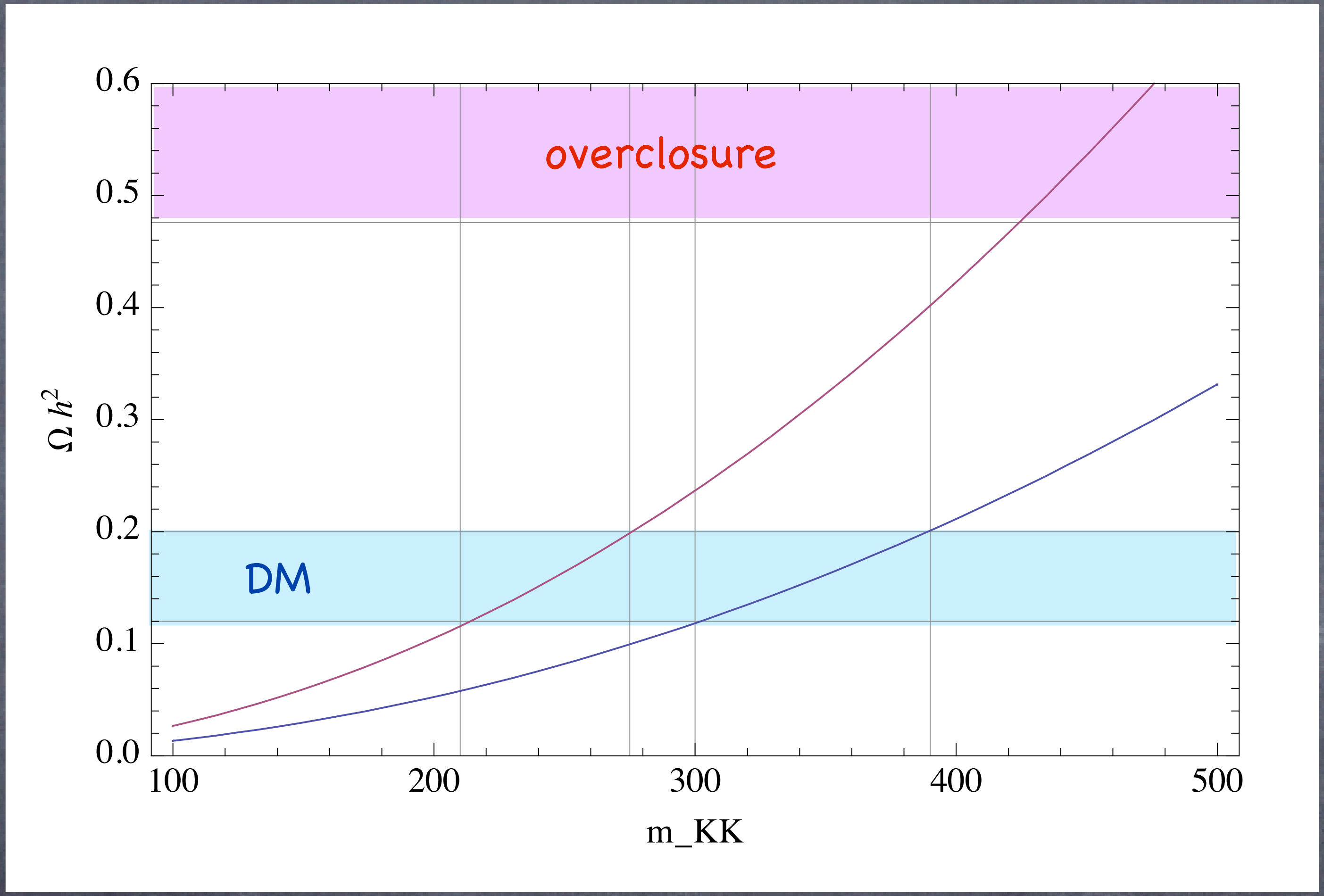
- Including the EWSB (Higgs VEV): neutral weak bosons

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



100
80
60
40
20
0
δ m [GeV]
0
500
1000
1500
2000
m_KK [GeV]
tops
quarks
gluon
Z, W
leptons
photon

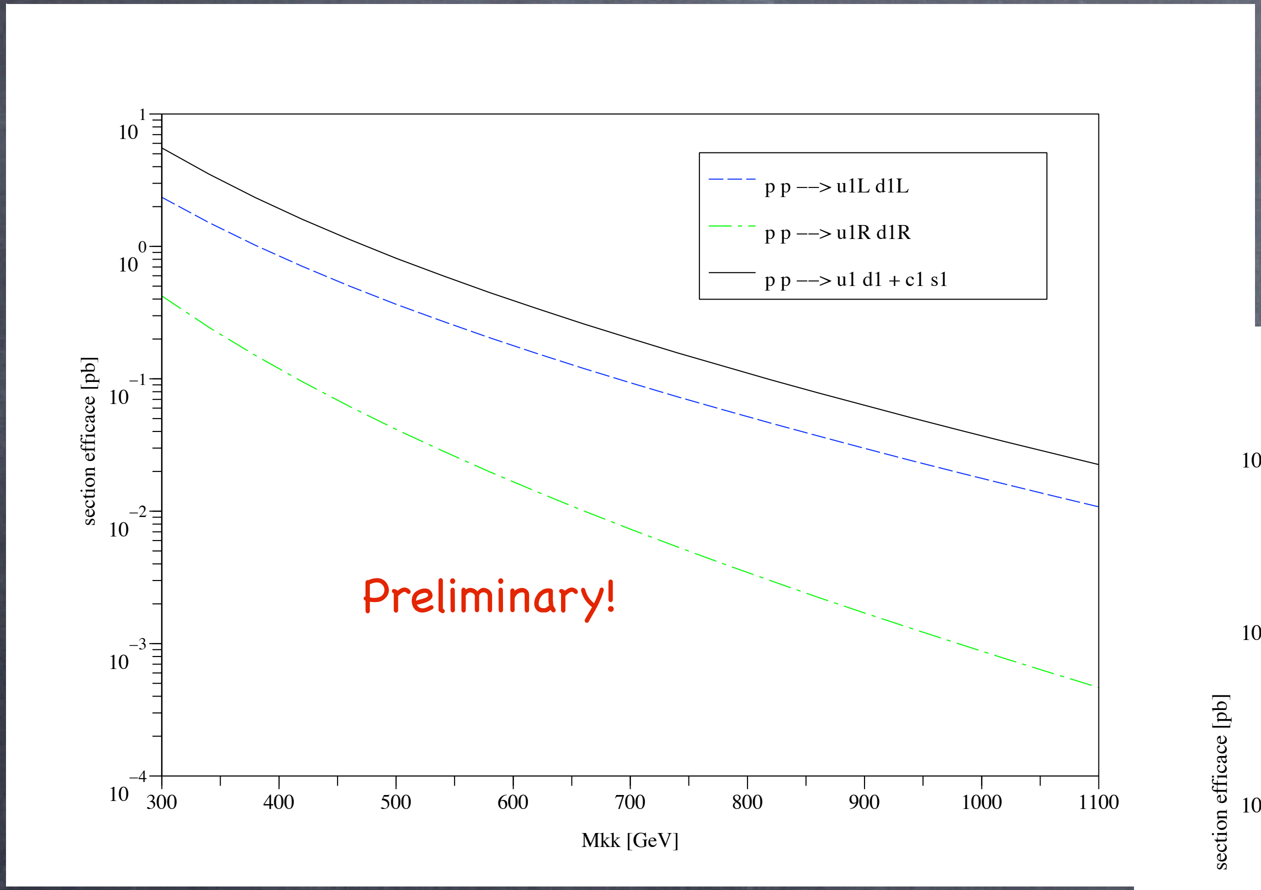
Relic abundance

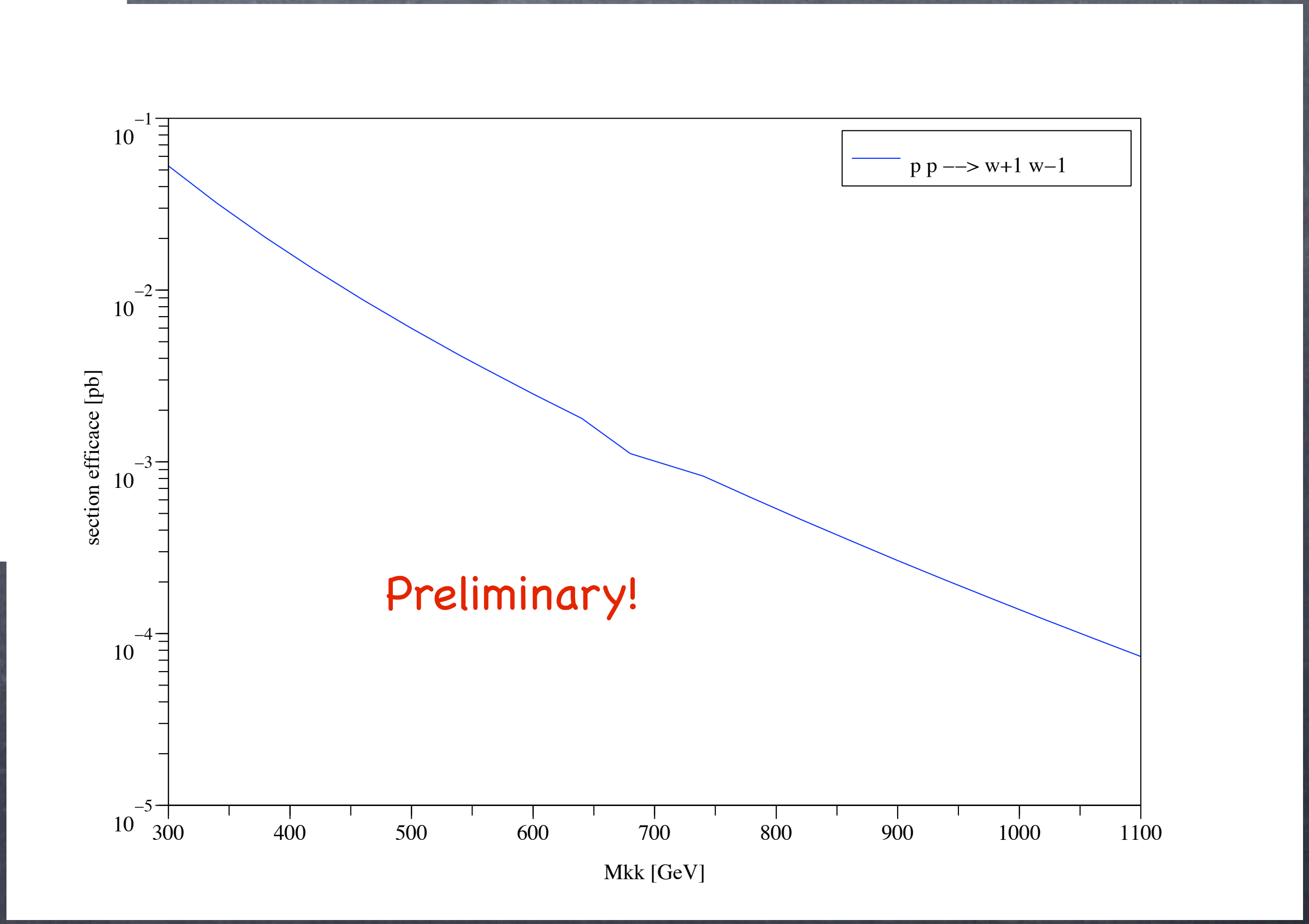


200 < mKK < 300 GeV

Phenomenology at the LHC

- Production rates are large:





Thanks to Bogna Kubik-Deriaz

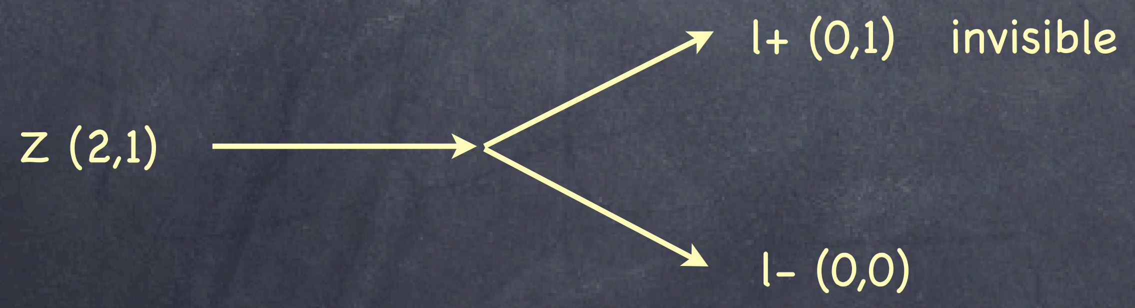
Phenomenology at the LHC

- 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	-	

Phenomenology at the LHC

- Small splittings make detection of lightest tier challenging.
- Tiers (1,1) and (2,0) decay to SM particles:
- nice resonances, but no MET!
- Tier (2,1) decays in (1,0) + (0,0): SM + MET!
- As (1,0) is invisible, app. charge non-conservation is possible!



``5D" limit

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Conclusions and outlook

- KK parity can be a natural (no ad-hoc) symmetry - relic of Lorentz invariance
- We studied the UNIQUE 6D geometry where this happens
- New Phenomenology from other models in the literature: light resonances, small splittings, 5D limit...
- We are implementing the model in FeynRules: easy interface with calcHep, Madgraph, FeynArt...
- We are computing precise relic abundance (with A.Arbey)
- The paper will be out soon!