Dark Matter from Lorentz Invariance in 6D: a LHC Friendly Scenario with a Natural LKP

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IPNL, Lyon, 13th Décember 2010

G.Cacciapaglia, A.Deandrea, JLP, Arxiv : 0907.4993
G.C, A.D, JLP, Arxiv : 1102.XXXX
Work in progress with G.Cacciapaglia, A.Deandrea,B.Kubik, L.Pannizzi.

WHY EXTRA-DIMENSIONS ?

- Many puzzles in the Standard Model:
  - Hierarchy problem, EWSB mechanism, DM existence, ...
- XD are a usefull tool for model building, lots of new perspectives to explore Standard Model puzzles
  - Gauge Higgs Unification, warping, GUTs, ...
- XD inspirated by string theory.

But DM comes from KK parity imposed by hand, like in Susy (R-parity) or in Little Higgs (T-parity)

Outline

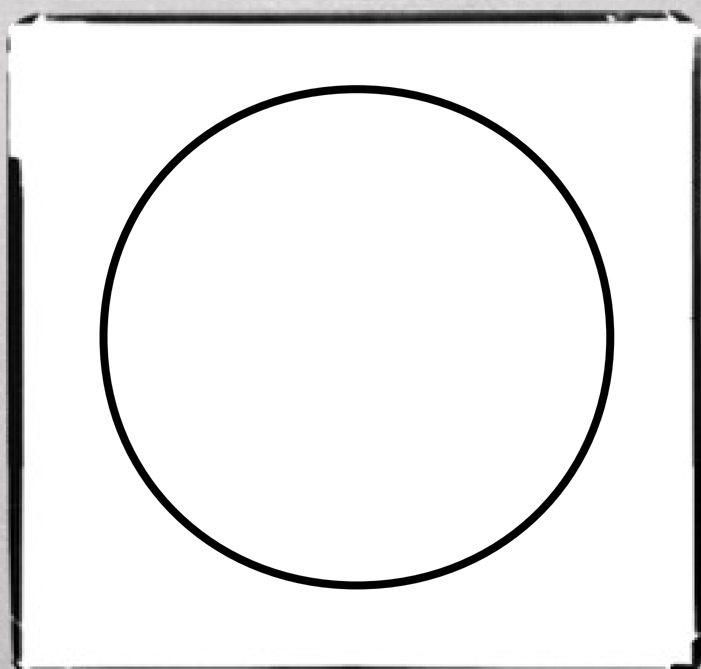
Is it possible to obtain an extra dimensional model with a "natural" dark matter candidate?

↓

- 6D Universal Extra Dimension on a real projective plane: UNIQUE 6D orbifold with an exact KK parity.
- Dark matter "constraints" for the extra dimensional radii.
- Preliminary results and discussions for the rich phenomenology at LHC.

5D Model and KK-Parity

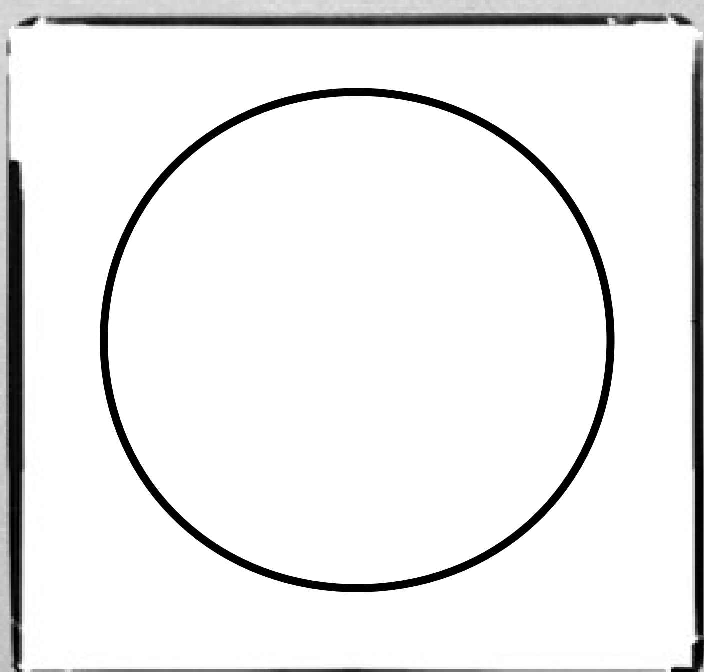
Extra dimension: S_1



$$x_5 \leftrightarrow x_5 + 2\pi$$

5D Model and KK-Parity

Extra dimension: S_1



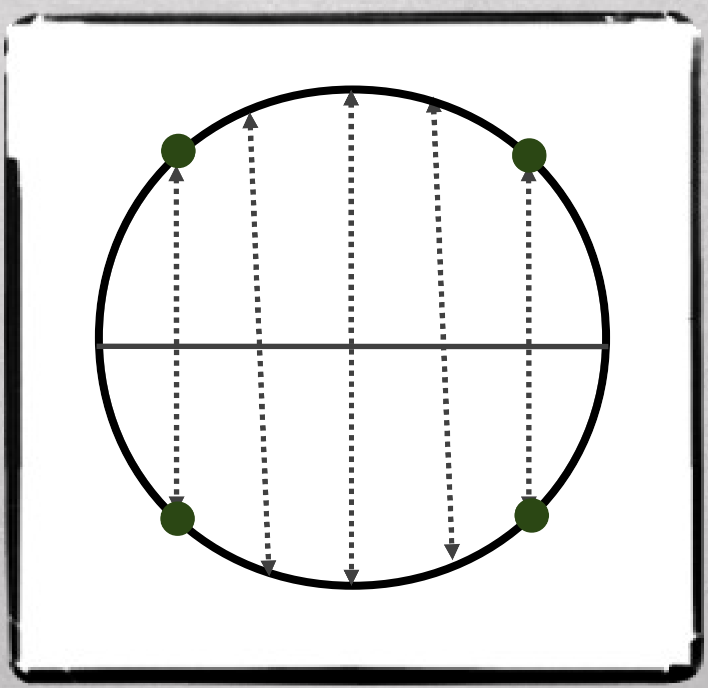
No KK-Parity

No Chiral Fermions

$x_5 \leftrightarrow x_5 + 2\pi$

5D Model and KK-Parity

Extra dimension: S_1/Z_2



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Chiral

Fermions

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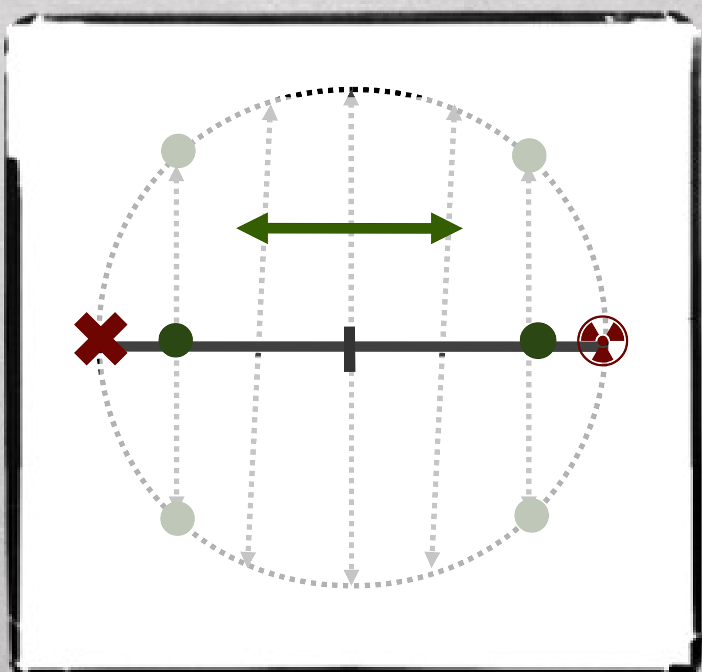
$$x_5 \to -x_5 = -x_5 + 2\pi$$

5D Model and KK-Parity

Extra dimension: S_1/Z_2



KK-Parity
only in the bulk

Chiral
Fermions

$x_5 \to \pi - x_5$

Localized interactions on fixed points
⟶ Extra symmetry to identify them

Orbifold Without Fixed Points: 6D Model

- In 6D, 17 possible ways to compactify the extra $\boldsymbol{R}^2$
- Only 3 without fixed points

1-Torus

☢ ☢ ☢ ☢ ☢ ☢

No Chiral Fermions

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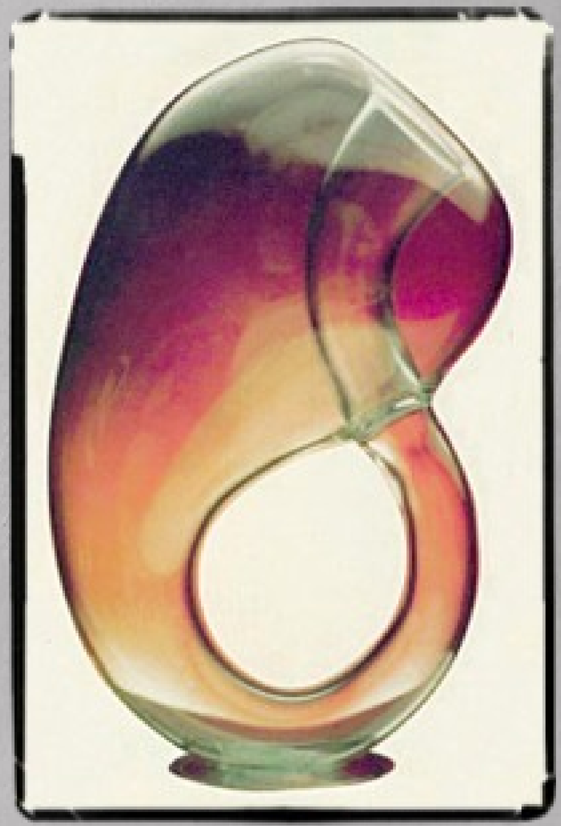
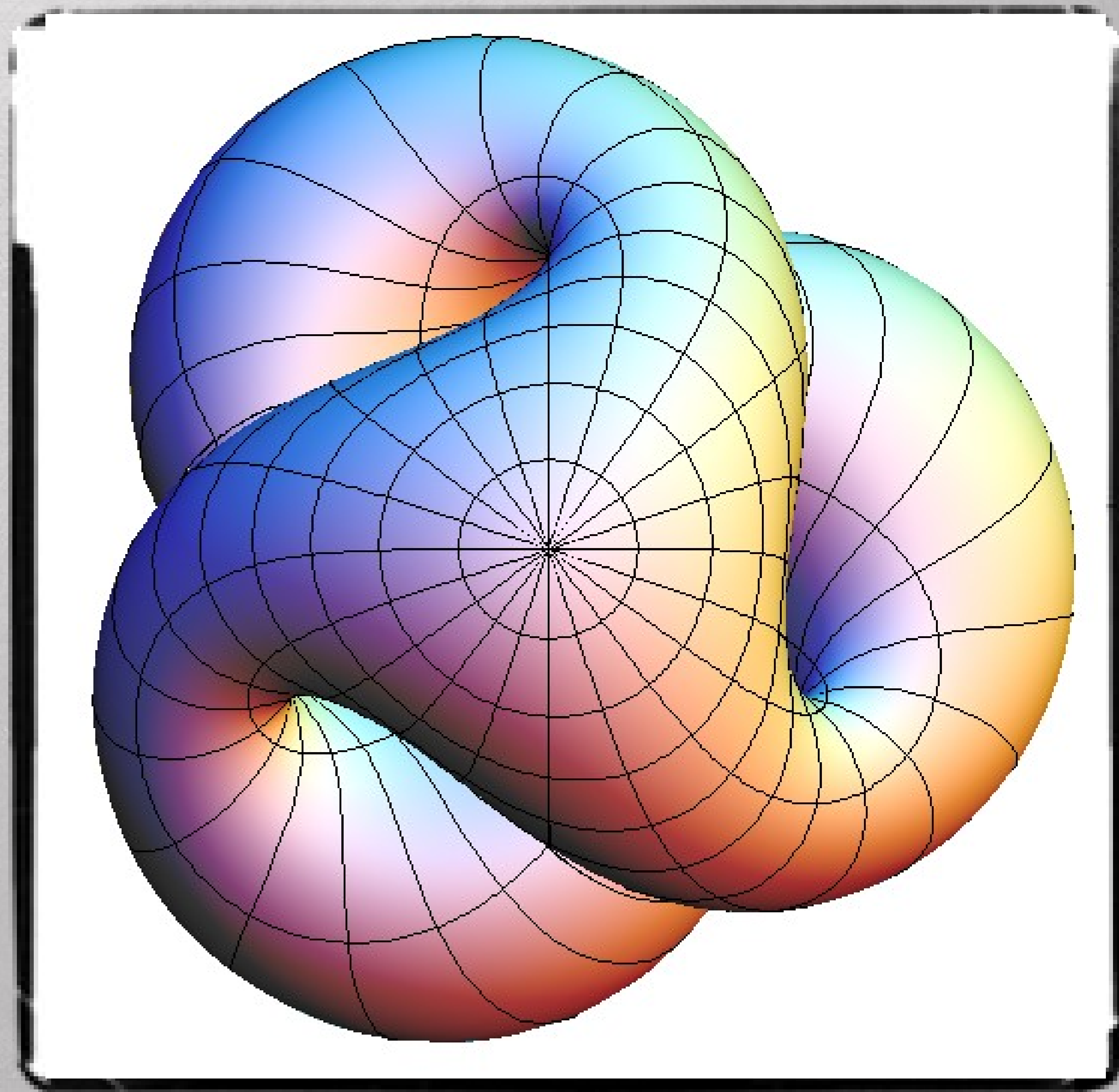


2-Klein Bottle

Last Possibility: The Real Projective Plane



Last Possibility: The Real Projective Plane

- Definition: $R^2/\mathbf{pgg}$ where **pgg** $=\{r,g\,|\,r^2=(g^2r)^2=\mathbf{1}\}$

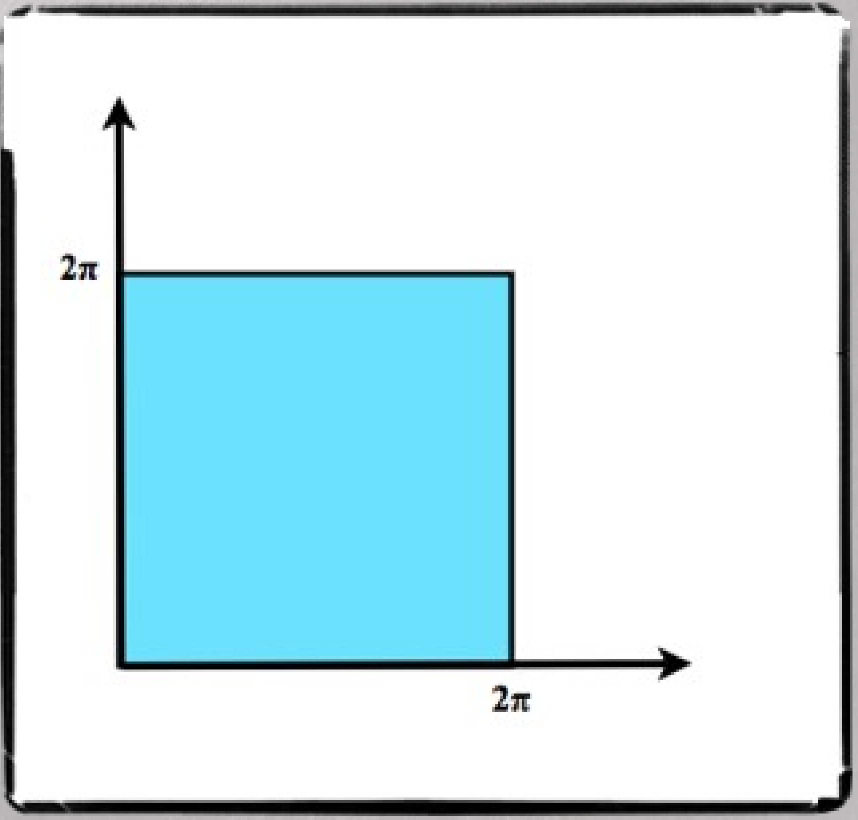
$$r \quad : \quad \begin{cases} x_5 \sim -x_5 \\ x_6 \sim -x_6 \end{cases},$$

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

$$\Downarrow$$

$$t_5 = g^2 \quad : \quad \begin{cases} x_5 \sim x_5 + 2\pi R_5 \\ x_6 \sim x_6 \end{cases},$$

$$t_6 = (rg)^2 \quad : \quad \begin{cases} x_5 \sim x_5 \\ x_6 \sim -x_6 + 2\pi R_6 \end{cases}.$$



Fondamental domain
Step 1: The torus

Last Possibility: The Real Projective Plane

- Definition: $R^2/\mathbf{pgg}$ where **pgg** $=\{r,g \mid r^2=(g^2r)^2=\mathbf{1}\}$

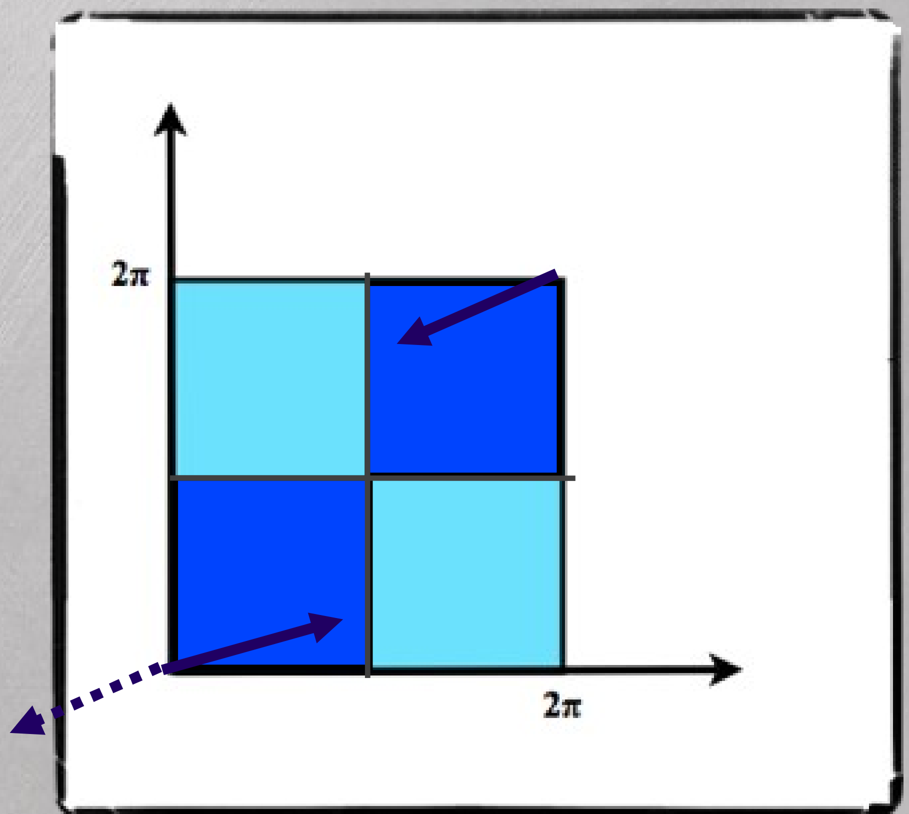
$$\boxed{r \quad : \quad \begin{cases} x_5 \sim -x_5 \\ x_6 \sim -x_6 \end{cases} ,}$$

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

$$\Updownarrow$$

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

$$g' = gr \quad : \quad \begin{cases} x_5 \sim -x_5 + \pi R_5 \\ x_6 \sim x_6 + \pi R_6 \end{cases} .$$



Fundamental domain
Step 2: The rotation

Last Possibility: The Real Projective Plane

- Definition: $R^2/\mathbf{pgg}$ where $\mathbf{pgg} = \{r, g \mid r^2 = (g^2 r)^2 = \mathbf{1}\}$

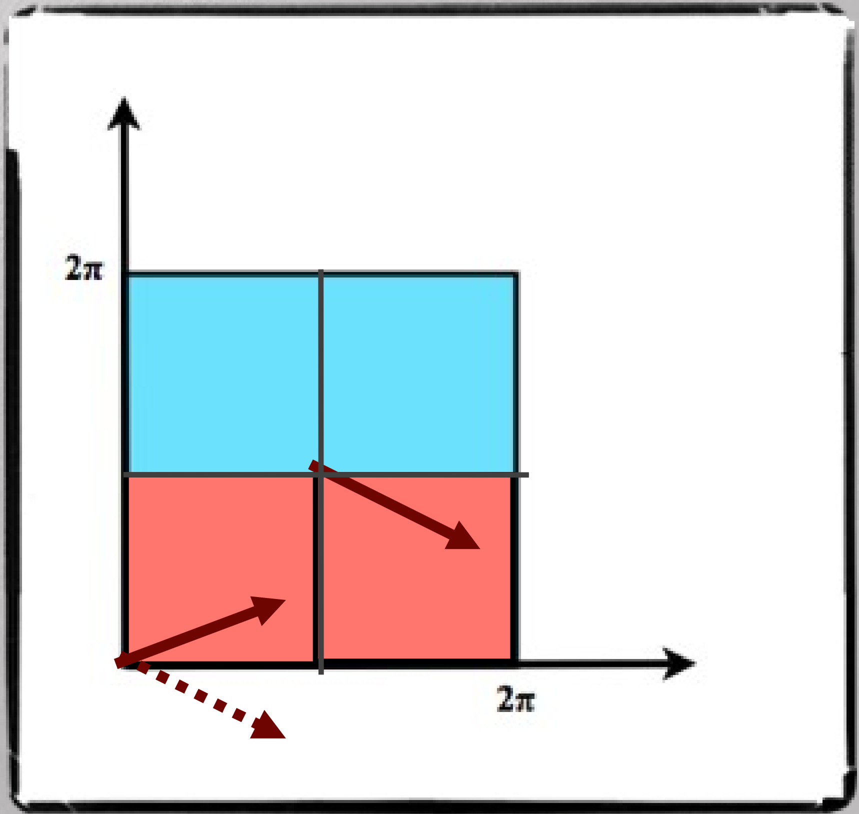
$$r \quad : \quad \begin{cases} x_5 \sim -x_5 \\ x_6 \sim -x_6 \end{cases} ,$$

$$\boxed{g \quad : \quad \begin{cases} x_5 \sim x_5 + \pi R_5 \\ x_6 \sim -x_6 + \pi R_6 \end{cases}} .$$

$$\Updownarrow$$

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

$$g' = gr \quad : \quad \begin{cases} x_5 \sim -x_5 + \pi R_5 \\ x_6 \sim x_6 + \pi R_6 \end{cases} .$$



Fundamental domain
Step 3: The glide

Last Possibility:
The Real Projective Plane

- Definition: $R^2/\mathbf{pgg}$ where $\mathbf{pgg}=\{r,g\,|\,r^2=(g^2r)^2=\mathbf{1}\}$

$$r \quad : \quad \begin{cases} x_5 \sim -x_5 \\ x_6 \sim -x_6 \end{cases} ,$$

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

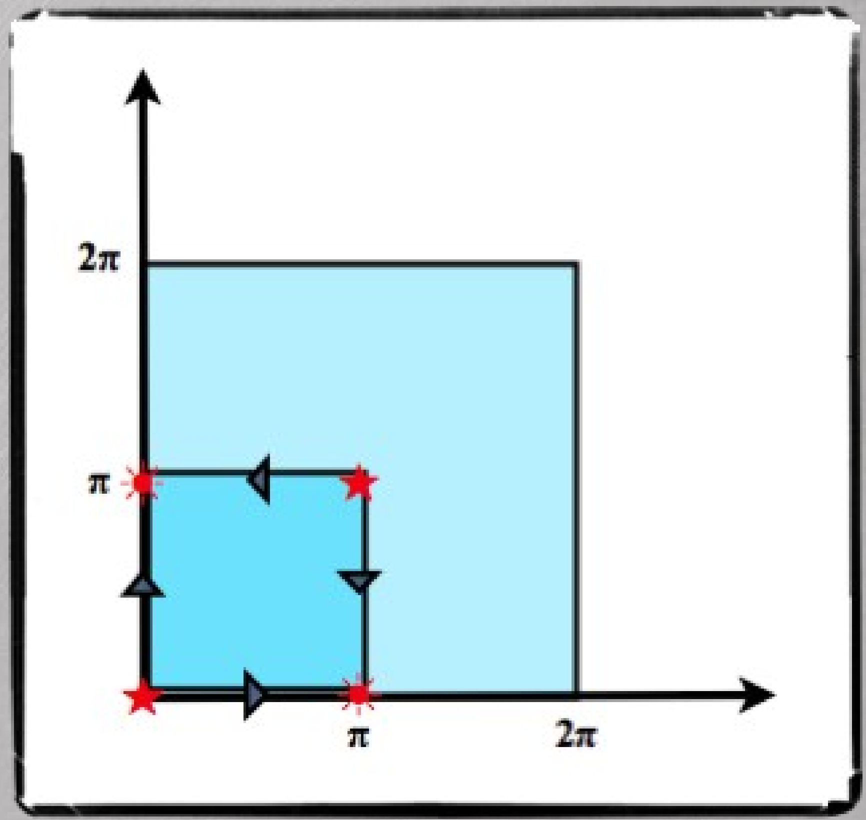
$$\Updownarrow$$

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

$$g' = gr \quad : \quad \begin{cases} x_5 \sim -x_5 + \pi R_5 \\ x_6 \sim x_6 + \pi R_6 \end{cases} .$$

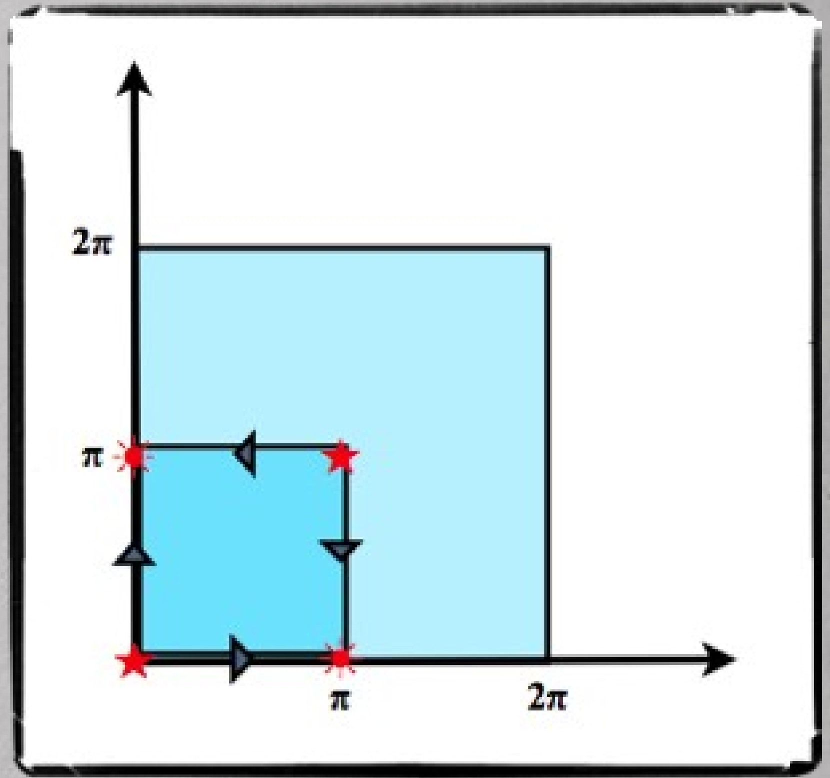
$\Longrightarrow$

Fundamental domain



Unbroken KK-Parity: "Natural" DM Candidate

- In the bulk, two discrete parities.
- No "fixed" point but conical singularities (0, π) ~ (π, 0) & (π,π) ~ (0,0)
  → Localized interactions



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Chiral Fermions
&
KK-Parity
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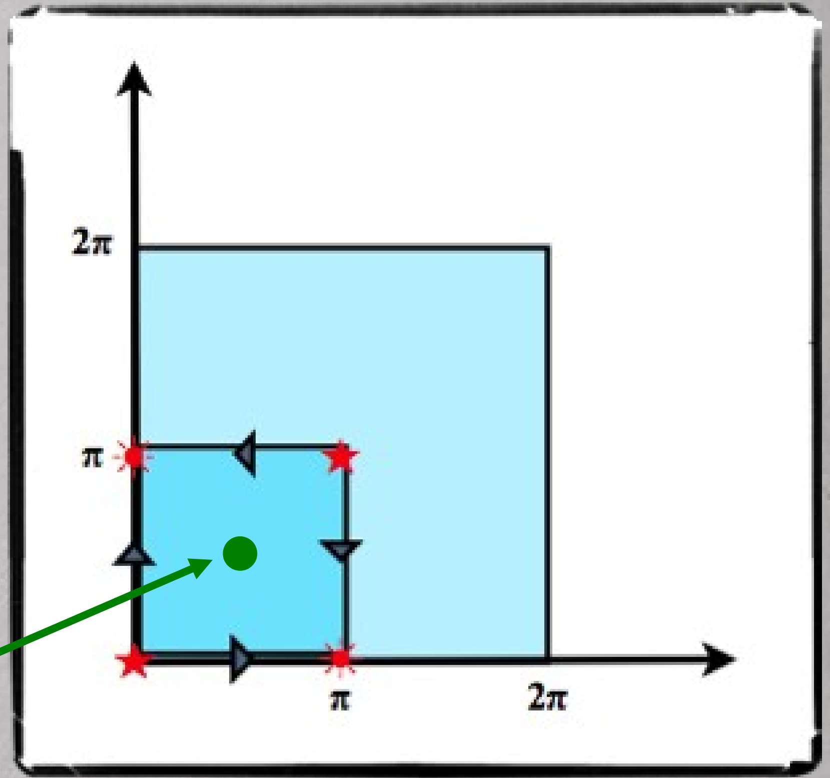
Unbroken KK-Parity: "Natural" DM Candidate

- In the bulk, two discrete parities.

- No "fixed" point but conical singularities
(0, π) ~ (π, 0) & (π,π) ~ (0,0)
⟶ Localized interactions

- **One discrete parity** remains **unbroken** even by localized terms



$$P_{KK} \quad : \quad \begin{cases} x_5 \sim x_5 + \pi R_5 \\ x_6 \sim x_6 + \pi R_6 \end{cases}$$

⟶ **Relic of 6D Lorentz invariance**

- Phase for generic KK modes with momenta (k,l) ⟶ $(-1)^{k+l}$

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Chiral Fermions
&
KK-Parity
✪ ✪ ✪

Scalar fields in this Framework

$$S_{\text{scalar}} = \iint_0^{2\pi} dx_5\, dx_6 \left\{ \partial_\mu \Phi^\dagger \partial^\mu \Phi - \partial_5 \Phi^\dagger \partial^5 \Phi - \partial_6 \Phi^\dagger \partial^6 \Phi - M^2 \Phi^\dagger \Phi \right\},$$

4D Field

$$\Phi = \sum_{(k,l)} f_{(k,l)}(x_5, x_6)\, \Phi_{(k,l)}$$

Wave function

- Eq. of motion: $(p^2 + \partial_5^2 + \partial_6^2) f_{(k,l)} = 0$ and $m_{KK}^{(k,l)} = \sqrt{\frac{k^2}{R_5^2} + \frac{l^2}{R_6^2}}$
- 4 possibles $f_{(k,l)}$ with differents parity under **r** and **g** (p_r,p_g):

$f_{(k,l)}$	p_r	p_g	p_{KK}
$\cos kx_5\ \cos lx_6$	$+$	$(-1)^{k+l}$	$(-1)^{k+l}$
$\sin kx_5\ \sin lx_6$	$+$	$(-1)^{k+l+1}$	$(-1)^{k+l}$
$\sin kx_5\ \cos lx_6$	$-$	$(-1)^{k+l}$	$(-1)^{k+l}$
$\cos kx_5\ \sin lx_6$	$-$	$(-1)^{k+l+1}$	$(-1)^{k+l}$

$\boxed{\text{Zero mode}}$

Gauge Bosons

$$S_{\text{gauge}} = \int_0^{2\pi} dx_5\, dx_6 \left\{ -\frac{1}{4} F_{\alpha\beta} F^{\alpha\beta} - \frac{1}{2\xi}\left(\partial_\mu A^\mu - \xi \underbrace{(\partial_5 A_5 + \partial_6 A_6)}_{=0 \text{ if } \xi \to \infty} \right)^2 \right\},$$

$$\begin{cases} A_5 = \sum \phi_5(x_5, x_6) A_{(k,l)} \\ A_6 = \sum \phi_6(x_5, x_6) A_{(k,l)} \end{cases} \quad \text{with} \quad \partial_5 \phi_5 + \partial_6 \phi_6 = 0$$

- Eq. of motion: $(p^2 + \partial_5^2 + \partial_6^2)\phi_{5/6} = 0$ and $m_{KK}^{(\mathrm{k,l})} = \sqrt{\frac{k^2}{R_5^2} + \frac{l^2}{R_6^2}}$
- After we impose parity under **r** and **g:** (p_r, p_g)

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

Tree Level Spectrum
6D Extension of SM

- First and easy approach:

  → *Universal Extra-Dimension on the RPP.*

- SM fields live in the bulk of a 6D flat space.

- Gauge fields:

  SM gauge group SU(3)xSU(2)xU(1)

  → 6 components: 1 vector A_μ and 2 extra scalars A_5&A_6

- Fermions are now general Dirac fermions:

  a 6D fermion for each chiral SM fermion.

  → Doublets Q&L, Singlet U, D, E, (N)

- EWSB is generated by Higgs mechanism in the bulk.

Tree Level Spectrum Standard Model

Levels	Mass	$P_{KK}=(-1)^{k+1}$	Gauge Vectors (A^μ, Z^μ, W^μ, G^μ)	Gauge Scalars (A^5, A^6,...)	Fermions	Higgs
(0,0)	0	+	YES	**NO**	YES (Chiral)	YES
(1,0) &(0,1)	1/R	**-**	**NO**	YES	YES (Dirac)	**NO**
(1,1)	$\sqrt{2}/R$	+	YES	YES	YES (Dirac) x 2	YES
(2,0) &(0,2)	2/R	+	YES	**NO**	YES (Dirac)	YES
(2,1) &(1,2)	$\sqrt{5}/R$	-	YES	YES	YES (Dirac) x 2	YES

Choice of degenerate case: $R_5=R_6=R$

Tree Level Spectrum: LKP Level

Levels	Mass	$P_{KK}=(-1)^{k+1}$	Gauge Vectors (A^μ, Z^μ, W^μ, G^μ)	Gauge Scalars (A^5, A^6,...)	Fermions	Higgs
(0,0)	0	+	YES	**NO**	YES (Chiral)	YES
(1,0) &(0,1)	1/R	-	**NO**	YES	YES (Dirac)	**NO**
(1,1)	$\sqrt{2}/R$	+	YES	YES	YES (Dirac) x 2	YES
(2,0) &(0,2)	2/R	+	YES	**NO**	YES (Dirac)	YES
(2,1) &(1,2)	$\sqrt{5}/R$	-	YES	YES	YES (Dirac) x 2	YES

Choice of degenerate case: $R_5=R_6=R$

One 6D-Loop Corrections : mixed propagator

- 6D mixed propagator on a torus

5D propagator

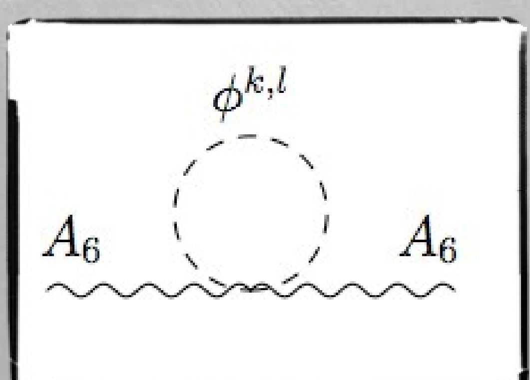
$$G_S^{6D}(k, \overrightarrow{y} - \overrightarrow{y}') = \sum_{l=-\infty}^{\infty} \boxed{\frac{i\cos\chi_m(\pi - |x_5 - x_5'|)}{2\,\chi_m\ \sin\chi_m\pi}}\, f_l^*(x_6) f_l(x'_6)$$

$$\text{with} \quad f_l(x_6) = \frac{1}{\sqrt{2\pi}} e^{ilx_6} \quad \text{and} \quad \chi_l = \sqrt{p^2 - l^2}$$

- Propagator on the orbifold

Da Rold, ArXiv hep-th/0311063,

$$G_S^{orb}(p, \overrightarrow{y}, \overrightarrow{y}') = \frac{1}{4}\Big[G_S^{6D}(p, \overrightarrow{y} - \overrightarrow{y}') + p_g\, G_S^{6D}(p, \overrightarrow{y} - g(\overrightarrow{y}'))$$
$$+ p_r\, G_S^{6D}(p, \overrightarrow{y} - r(\overrightarrow{y}')) + p_r\, p_g\, G_S^{6D}(p, \overrightarrow{y} - r * g(\overrightarrow{y}'))\Big]$$



$$\longrightarrow \Pi^{66} = \underbrace{\Pi_T}_{\propto T_6 = \frac{1}{\pi}\sum_{(k,l)\neq(0,0)} \frac{1}{(k^2+l^2)^2} \simeq 1.92} + \underbrace{p_g\, \Pi_G + p_g p_r\, \Pi_{G'}}_{\text{finite}} + \underbrace{p_r\, \Pi_R}_{\propto \mathrm{Log}\frac{\Lambda^2 R^2 + n^2}{n^2} = L}$$

Mass Splitting: Radiative Corrections

- Calculation for LLP level
- 6D loop calculations: Mixed propagator method
  Ex: Gauge boson field (0,n) with odd n.

Divergences on the singularities, proportional to n^2

$$\delta m_B^2 = \frac{g'^2}{64\pi^4 R^2}\left[-79T_6 + 14\zeta(3) + \underbrace{\pi^2 n^2 L} + B_1 - 4B_2\right] ,$$

$$\delta m_W^2 = \frac{g^2}{64\pi^4 R^2}\left[-39T_6 + 70\zeta(3) + \underbrace{17\pi^2 n^2 L} + 7B_1 - 32B_2 - 2B_3\right] ,$$

$$\delta m_G^2 = \frac{{g_s}^2}{64\pi^4 R^2}\left[-36T_6 + 84\zeta(3) + \underbrace{24\pi^2 n^2 L} + 9B_1 - 42B_2 - 3B_3\right] .$$

Proportional to KK mass scale

Higher levels computation: Work done by L. Panizzi, B. Kubik & G.Cacciapaglia

For (0,n) with even n similary results are obtained.

Mass Splitting: Higgs Mechanism

- Universal Extra-dimension : Higgs in the $\underbrace{\text{Bulk of flat space}}$

Constant vev

No mixing between levels

$$S_{higgs} = \iint_0^{2\pi} dx_5\, dx_6 \left\{ D_\alpha H^\dagger D^\alpha H - V(H^\dagger H) \right\}$$

$$\Longrightarrow \iint_0^{2\pi} dx_5\, dx_6 \left\{ m_W^2 W_\mu^a W^{a\,\mu} + m_B^2 B_\mu B^\mu \right\}$$

- Standard mixing between W^3/B
- At one loop for the (n,0) with odd n:

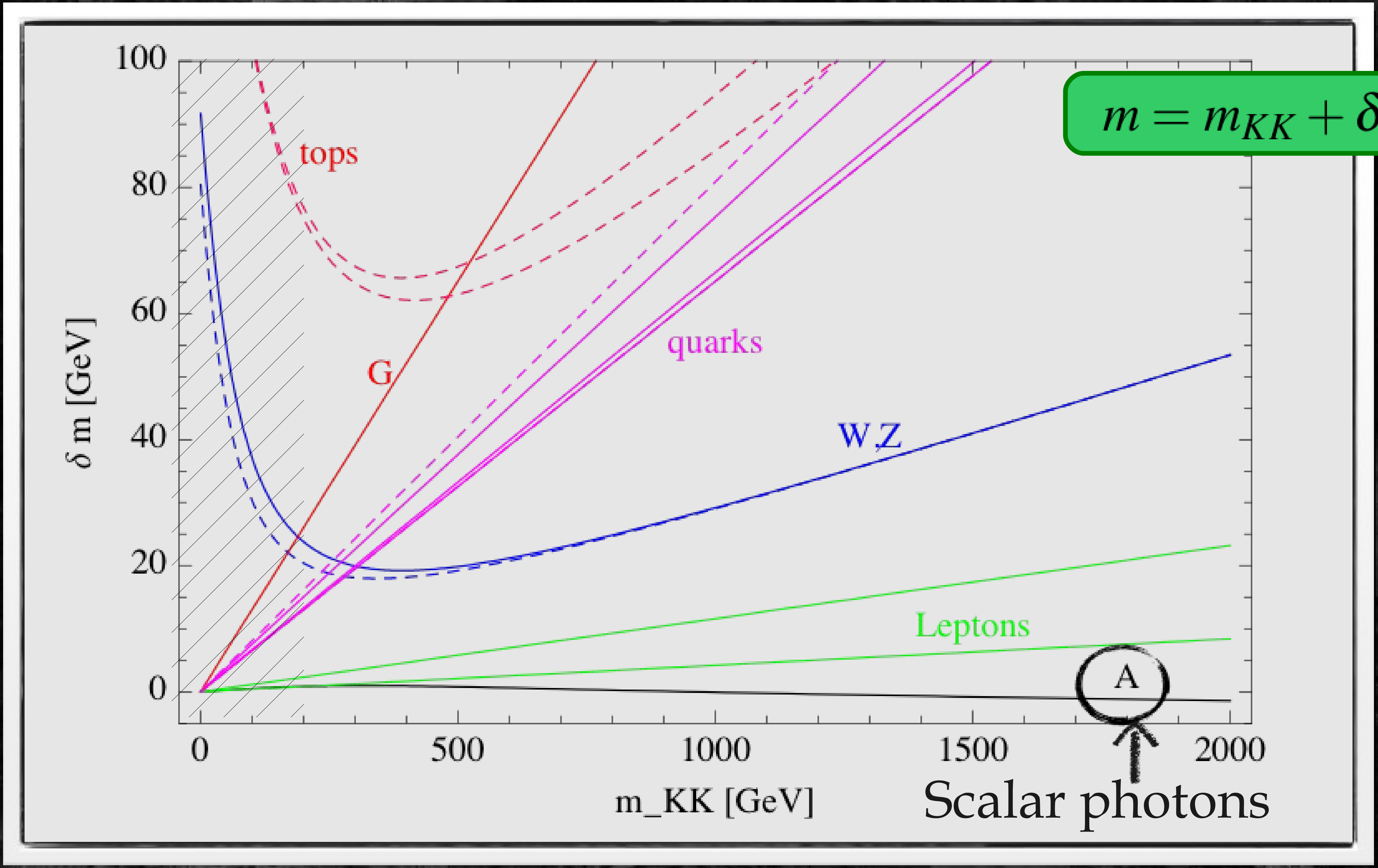
$$\begin{pmatrix} W_{n,0}^3 & B_{n,0} \end{pmatrix} \cdot \begin{pmatrix} \delta m_W^2 + m_W^2 & -\tan\theta_W^n m_W^2 \\ -\tan\theta_W^n m_W^2 & \delta m_B^2 + \tan^2\theta_W^n m_W^2 \end{pmatrix} \cdot \begin{pmatrix} W_{n,0}^3 \\ B_{n,0} \end{pmatrix}$$

$$= \begin{pmatrix} Z_{n,0} & A_{n,0} \end{pmatrix} \cdot \begin{pmatrix} m_{Zn}^2 & 0 \\ 0 & m_{An}^2 \end{pmatrix} \cdot \begin{pmatrix} Z_{n,0} \\ A_{n,0} \end{pmatrix}.$$

$\theta_W^n(M_{KK}^2) < \theta_W^{SM}$

$\theta_W^n(M_{KK}^2) \xrightarrow{M_{KK}\to\infty} 0$

Dark Matter Candidate: Heavy Scalar Photon



$$m = m_{KK} + \delta m$$

5D Limit Of This Model

$R_6 \longrightarrow 0$

Levels	Mass	$P_{KK}=(-1)^{k+1}$	Gauge Vectors (A^μ, Z^μ, W^μ, G^μ)	Gauge Scalars (A^5, A^6,...)	Fermions	Higgs
(0,0)	0	+	YES	**NO**	YES (Chiral)	YES
(1,0) &~~(0,1)~~	1/R	-	**NO**	YES	YES (Dirac)	**NO**
~~(1,1)~~	~~$\sqrt{2}$/R~~	~~+~~	~~YES~~	~~YES~~	~~YES (Dirac) x 2~~	~~YES~~
(2,0) &~~(0,2)~~	2/R	+	YES	**NO**	YES (Dirac)	YES
~~(2,1) &(1,2)~~	~~$\sqrt{5}$/R~~	~~-~~	~~YES~~	~~YES~~	~~YES (Dirac) x 2~~	~~YES~~

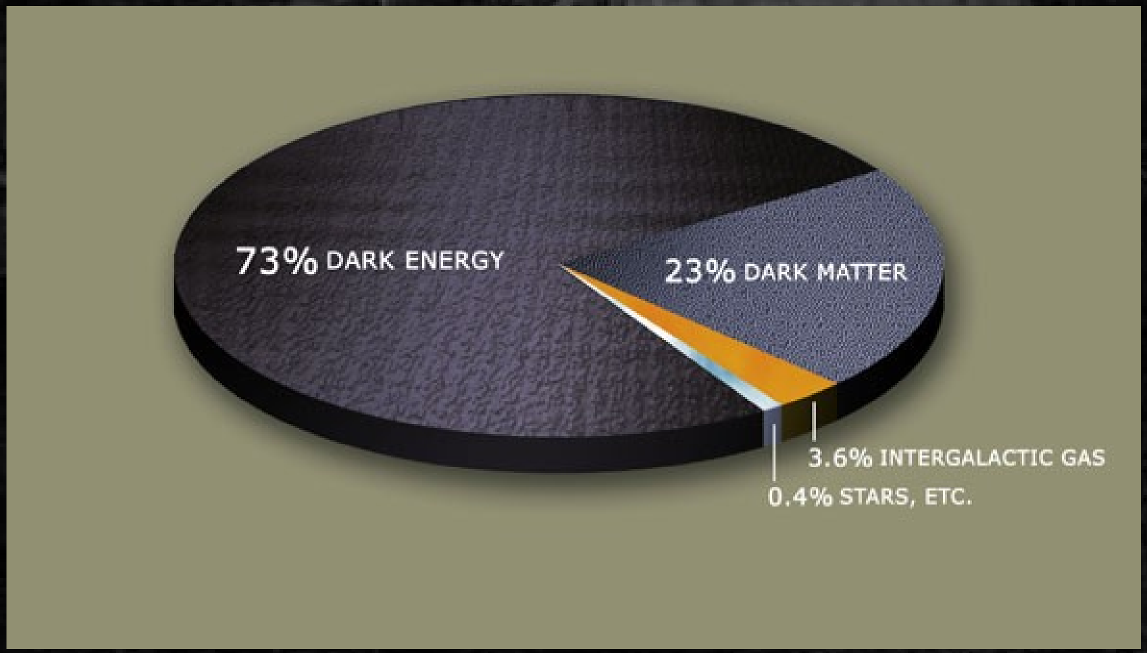
5D Limit Of This Model
$R_6 \longrightarrow 0$

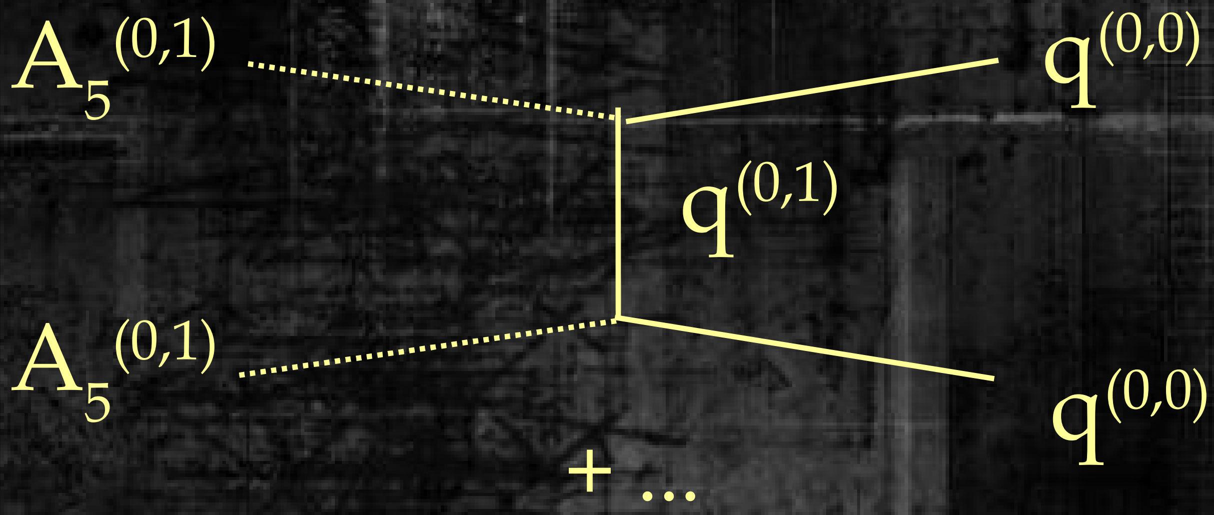
Levels	Mass	$P_{KK}=(-1)^{k+1}$	Gauge Vectors (A^μ, Z^μ, W^μ, G^μ)	Gauge Scalars (A^5, A^6,...)	Fermions	Higgs
(0,0)	0	+	YES	**NO**	YES (Chiral)	YES
(1,0)	1/R	-	**NO**	**YES (Only A^6, Z^6,...)**	YES (Dirac)	**NO**
(2,0)	2/R	+	YES	**NO**	YES (Dirac)	YES

Not a usual 5D UED Model limit

$\longrightarrow$ Topological Consequences

General Relic Density Calculation in XD





$\longrightarrow \langle\sigma_{\text{annihilation}}\, v\rangle$ falls as $1/M_{KK}^2$ ie R^2

Bolzmann equations

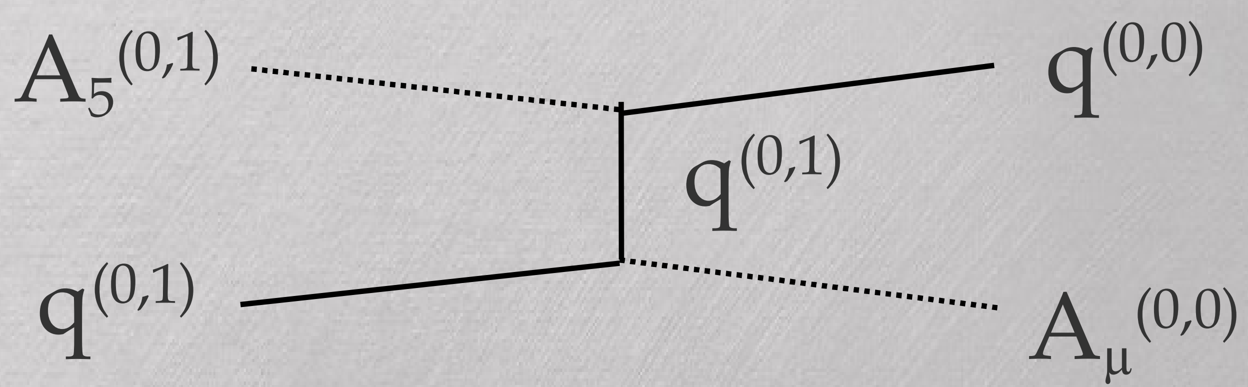
$T_{\text{Freeze out}}$, relic density are function of R

Relic density constraint $\longrightarrow$ Mass range for size of XD

G. Servant, T. Tait, ArXiv hep-th/0206071v2

First calculation of relic density

- Included effects:
  - Large co-annihilation because of small mass splittings
  - Ex:



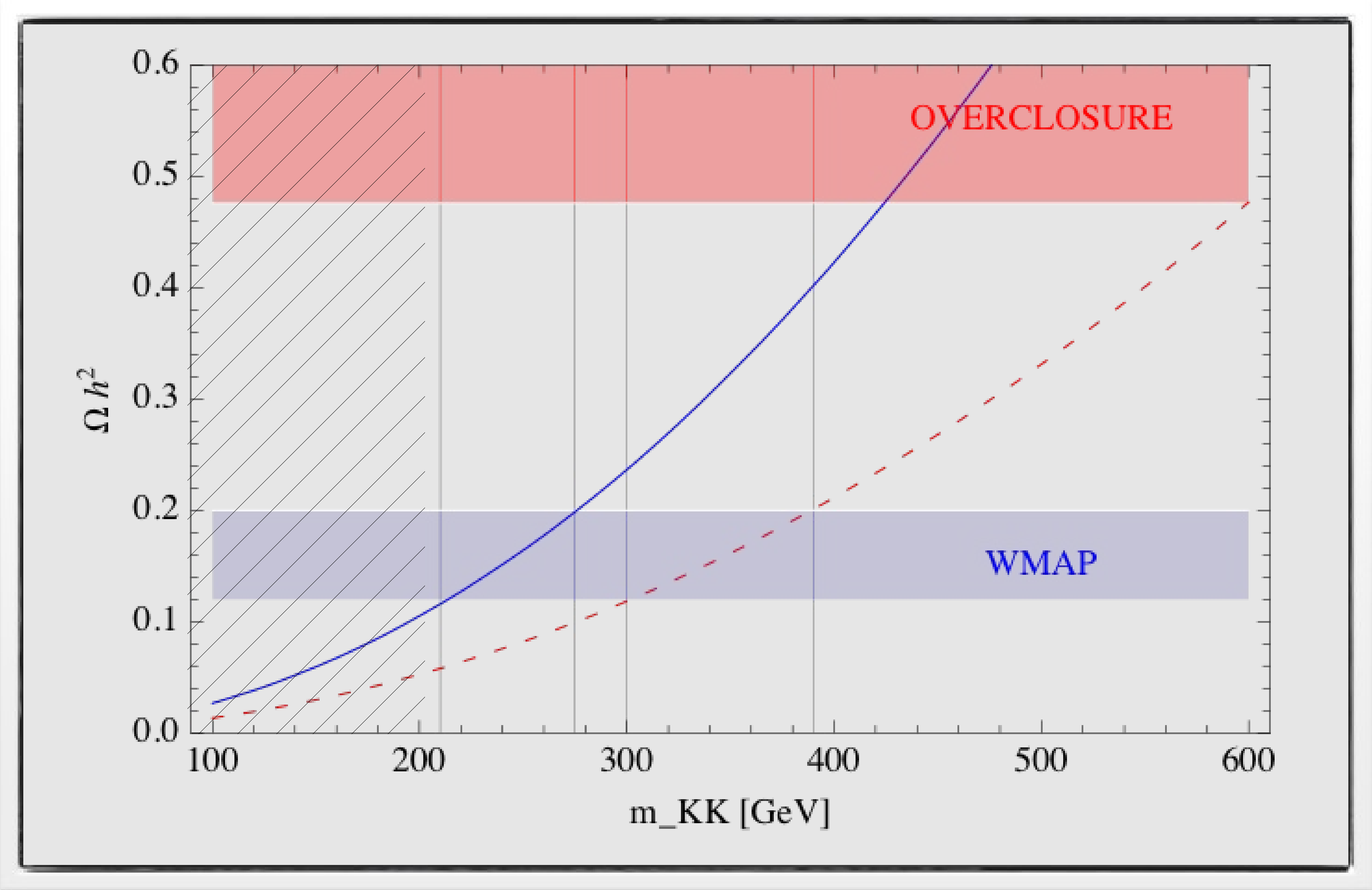
$\Delta m \sim T_{\text{Freeze-out}}$

- First approximation:
  - EWSB neglected for SM fields.
  - No resonant annihilation via Higgs or (0,2)-(2,0) tiers
  - Localized kinetic terms neglected

↓

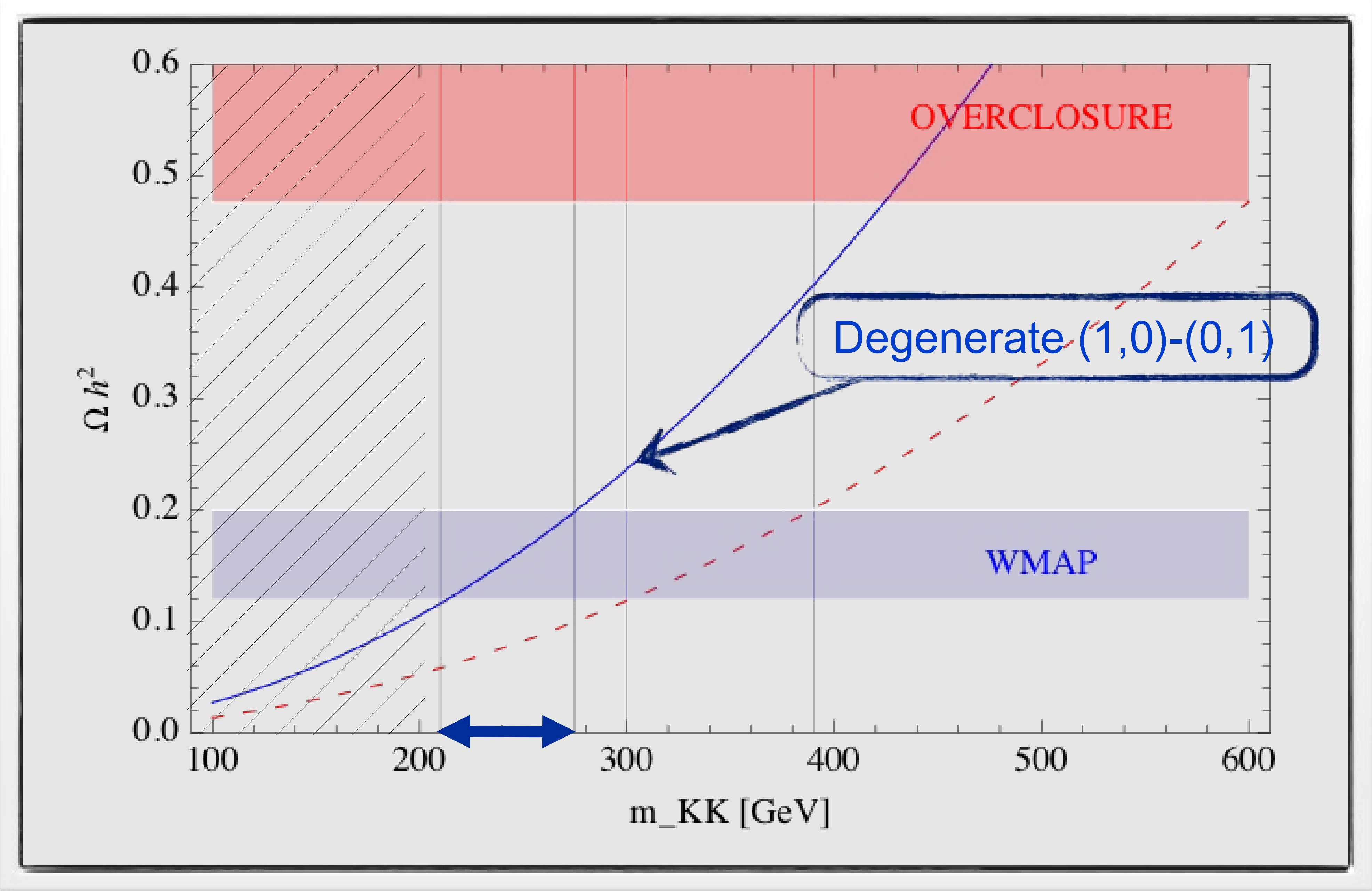
Model implemented in FeynRules & more precise calculations *(B.Kubik)*

Relic Density And Radii "First Estimation"



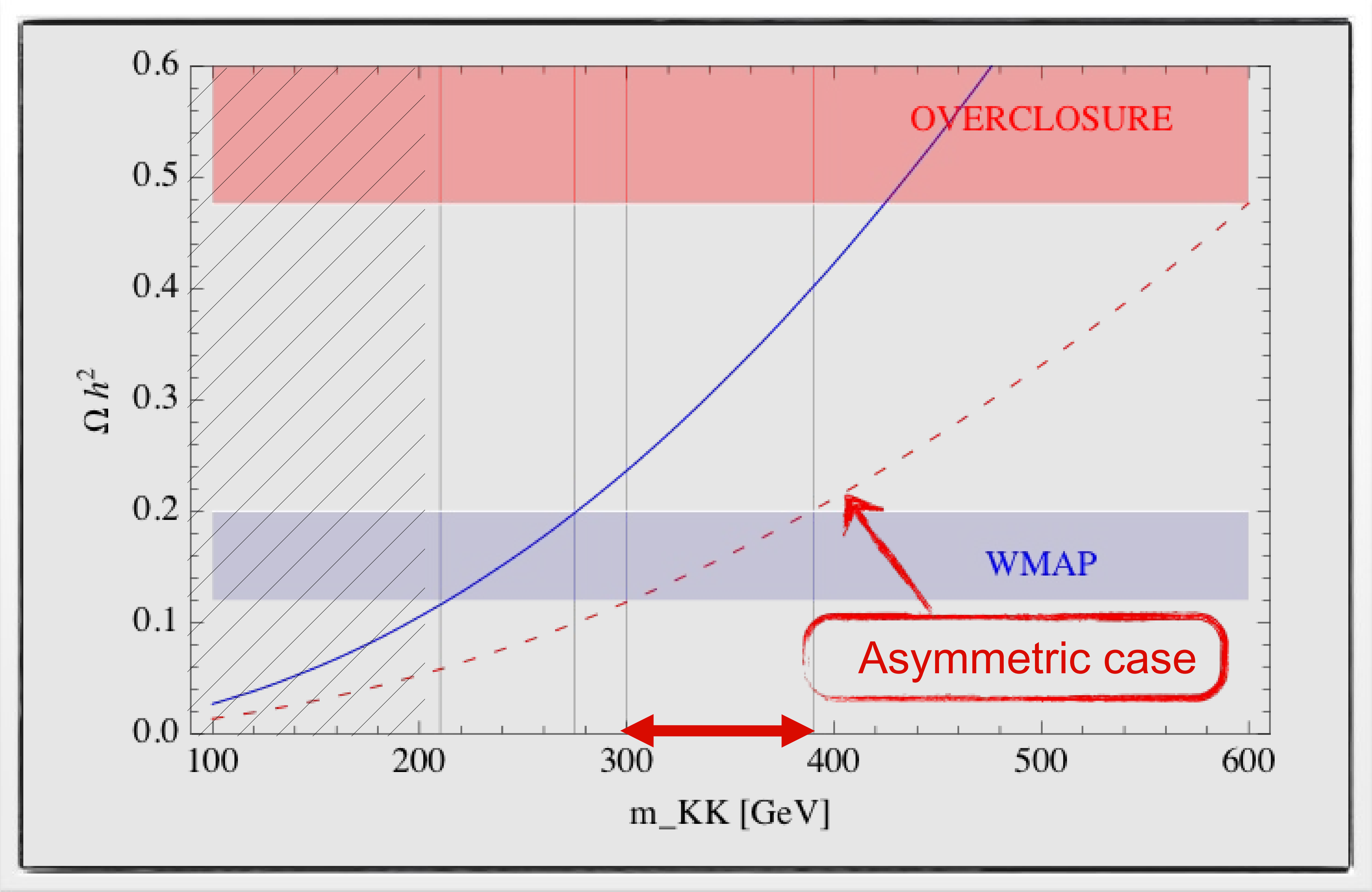
Relic Density And Radii "First Estimation"

200 GeV<1/R<300 GeV

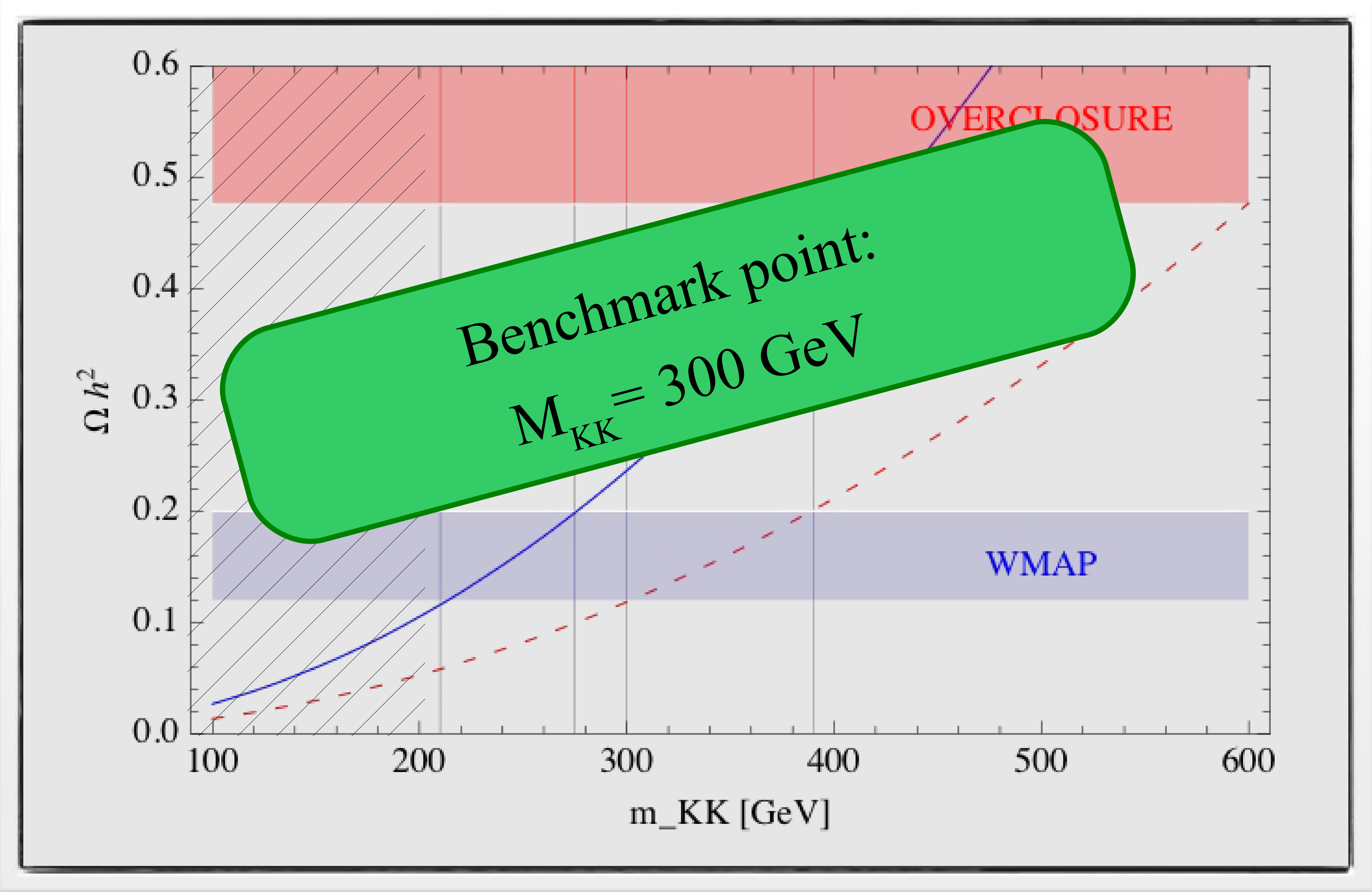


Relic Density And Radii "First Estimation"

300 GeV<1/R<400 GeV



Relic Density And Radii "First Estimation"

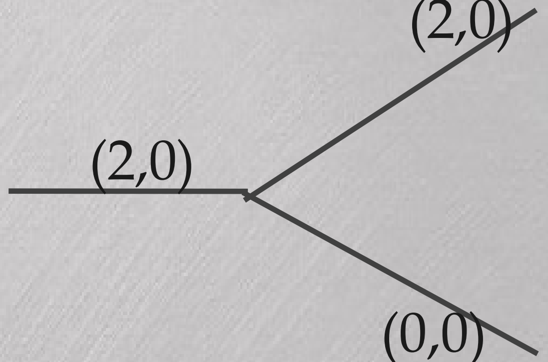


Phenomenology @ LHC
A Friendly scenario

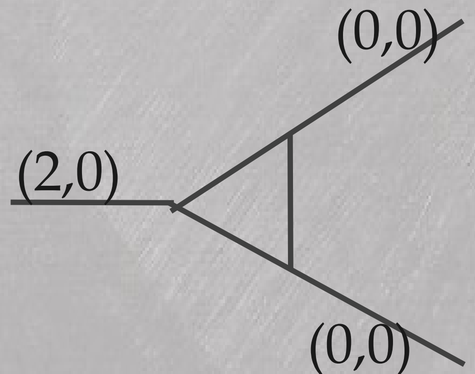
- Light upper bound
  → Lot of new heavy states below 1 TeV
- Quantum number related to SM ones
- What can we expect?
  → First preliminary results

Phenomenology @ LHC : Interactions in this framework

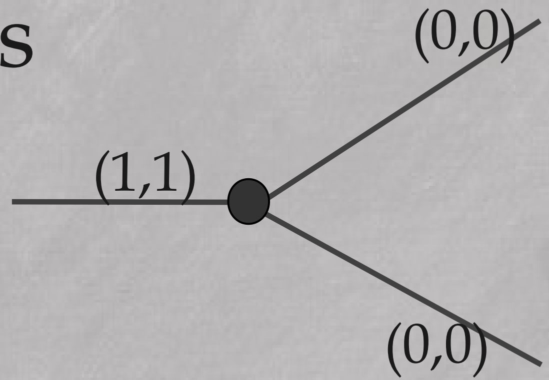
- Bulk interactions
  ⟶ Conservation of all parities and of XD momenta
  ⟶ Pair producting



- Loops induced processes
  ⟶ Less constraint, discrete parities conserved
  ⟶ Single production



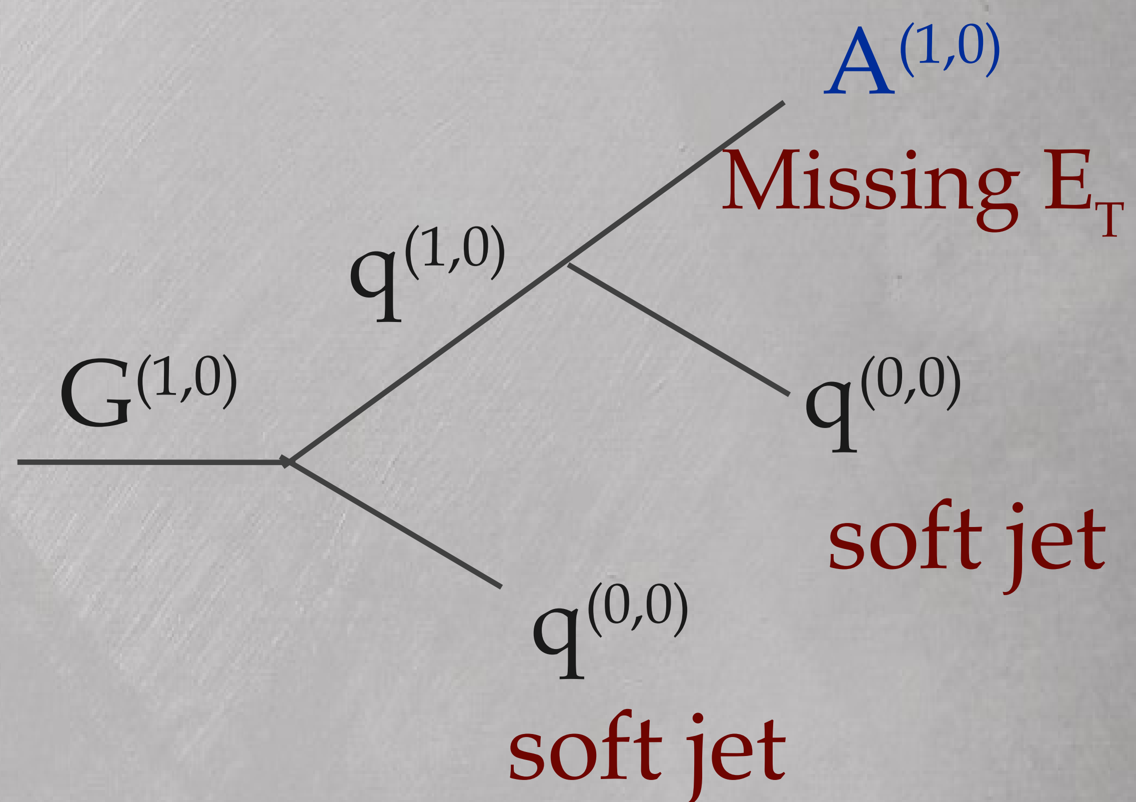
- Counter-term generated processes
  ⟶ Only KK-parity preserved



Phenomenology @ LHC : Decays of lightest tier

- Only Pair Production:
  for 1/R ~ 300÷400 GeV: 10 fb < σ_{prod} < 1 pb
- Small splittings $\longrightarrow$ Detection of the lightest tier will not be easy

	$m_X - m_{LLP}$ 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	-	



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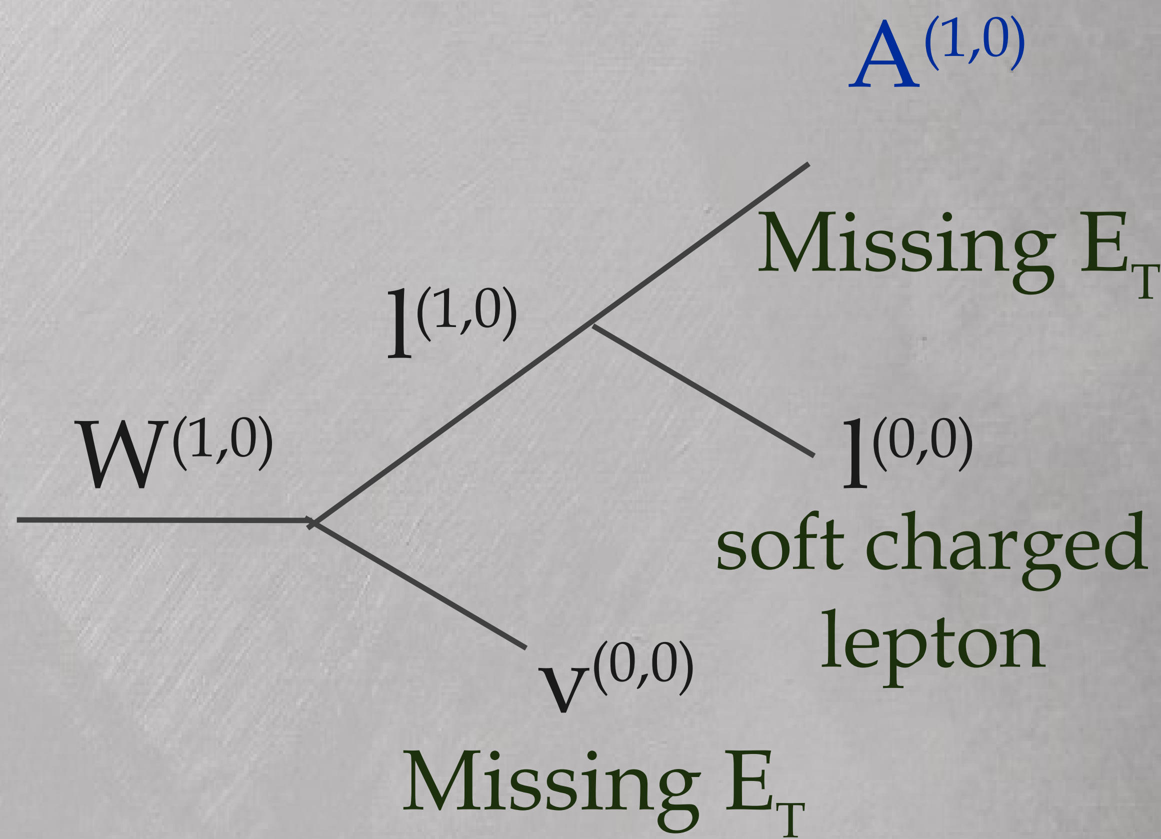
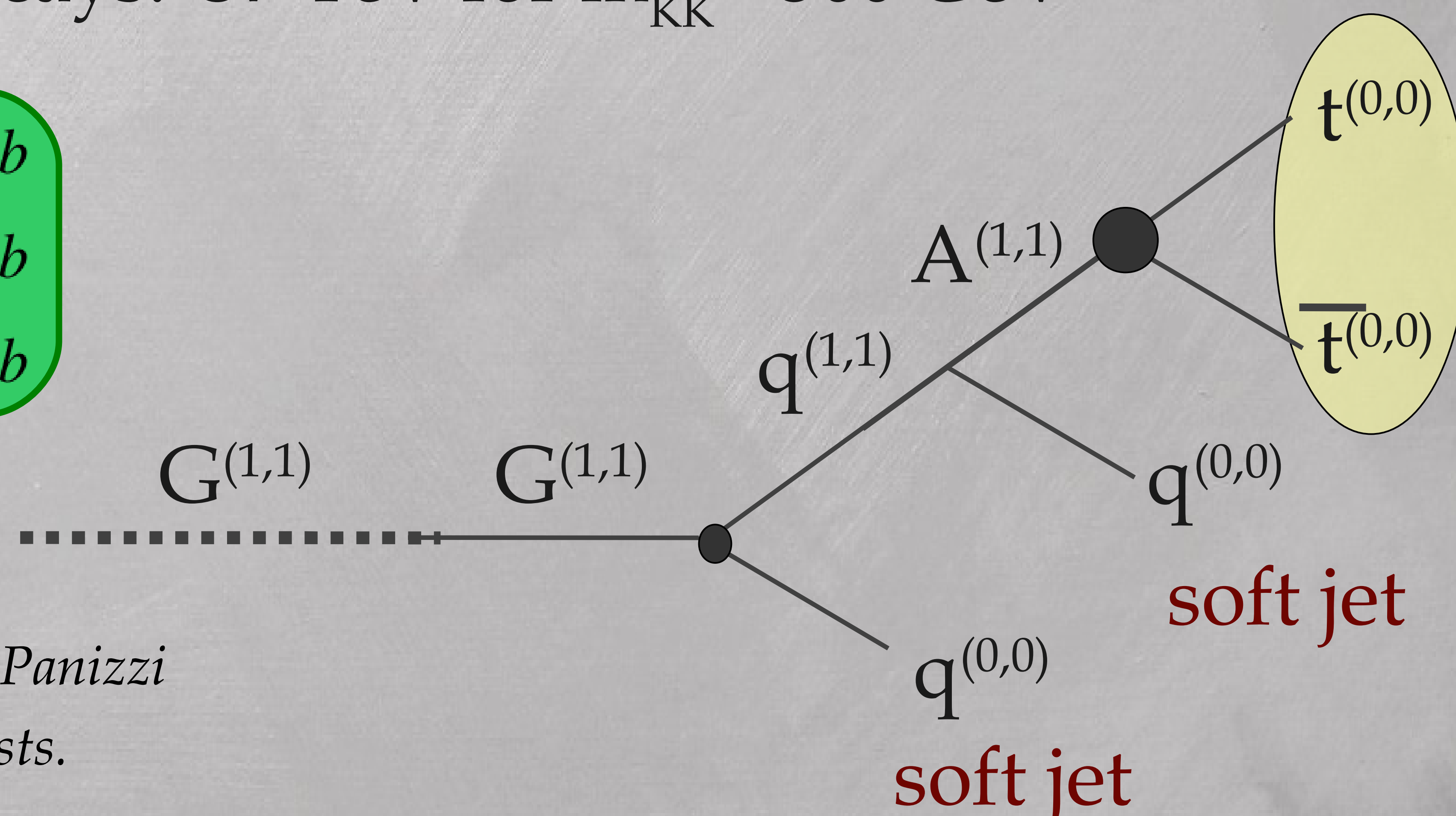
$A^{(1,0)}$	0	-	



Phenomenology @ LHC : Decays of (1-1) tier @ √2/R

- Localized interactions
  → long lived? stable? prefer decay into tops?
- Mainly resonant decays into SM particles & no Missing E_T
- Ex: 4-tops decays: @7 TeV for m_{KK}= 300 GeV

$$\sigma(Q_{(1,1)}Q_{(1,1)}) = 7.3pb$$
$$\sigma(Q_{(1,1)}G_{(1,1)}) = 5.6pb$$
$$\sigma(G_{(1,1)}G_{(1,1)}) = 0.7pb$$

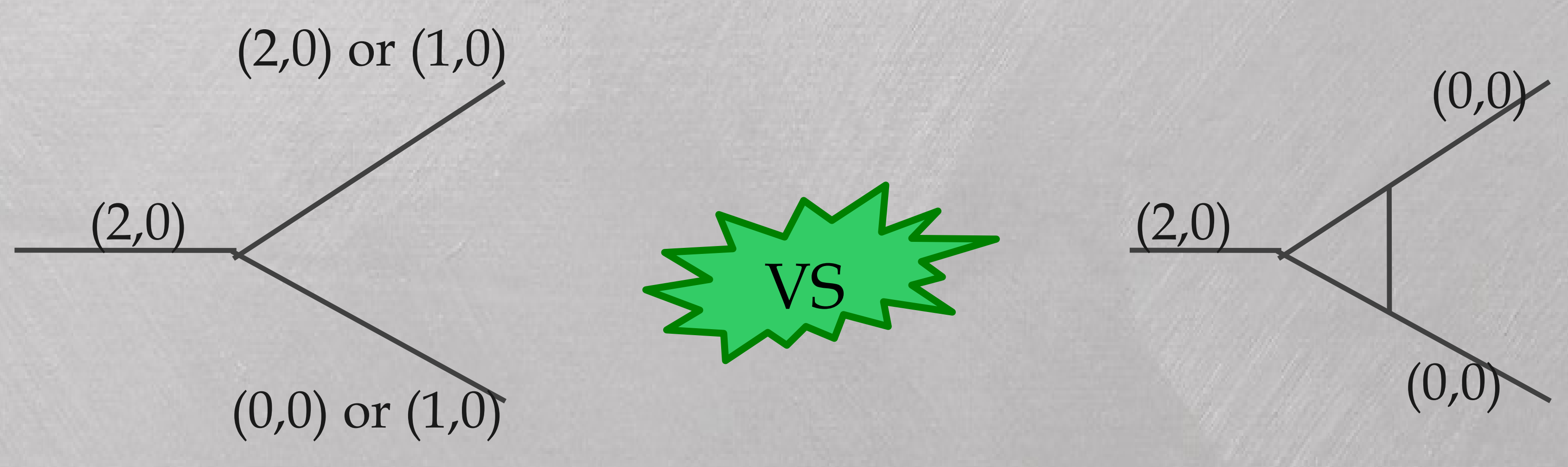


Work in progress by G.C, L. Panizzi
& CMS Lyon experimentalists.

Phenomenology @ LHC : Decay of (2,0)-(0,2) tiers @2/R

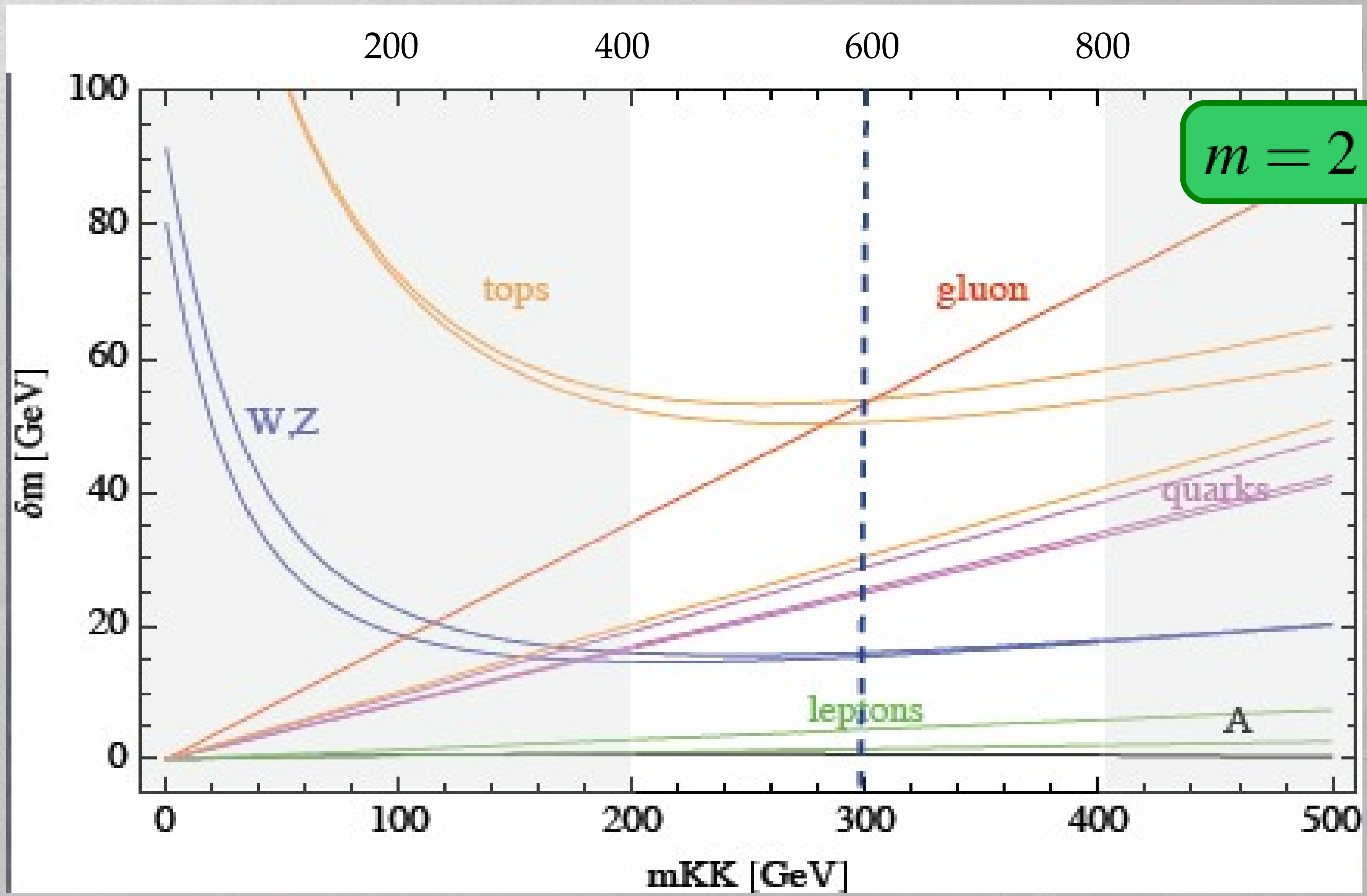
R6=0
Asymmetric case

- Tree level decay to (1,0) often suppressed:
  Small mass splitting also loop induced
  → No or small phase space
- Loop induced: loop factor suppression



- Main challenge → Compute the spectrum and the dominant loop induced couplings to estimate the branchings

Spectrum of (2,0) tiers

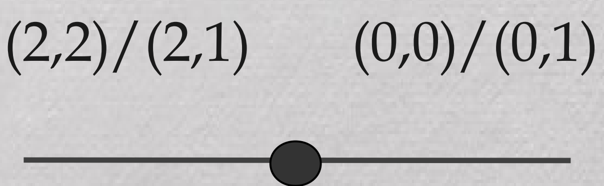


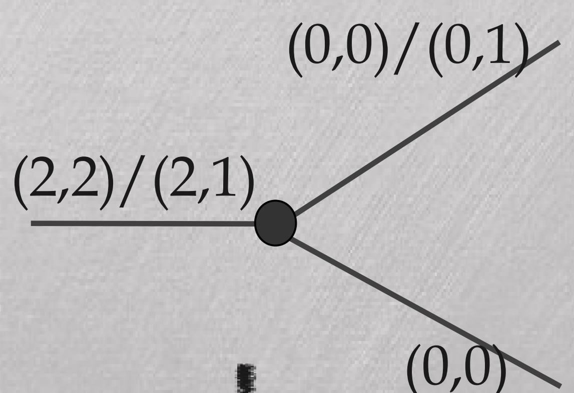
$m = 2\, m_{KK} + \delta m$

(n,0) with even n spectrum computed by B.Kubik, G.Cacciapaglia

Coupling calculation : 4D-Loops tricks

- Divergent contribution of loop induced couplings is dominant.
- Divergences come from singularities generated by the rotation.
- How to compute them? Tricks with 4D loops



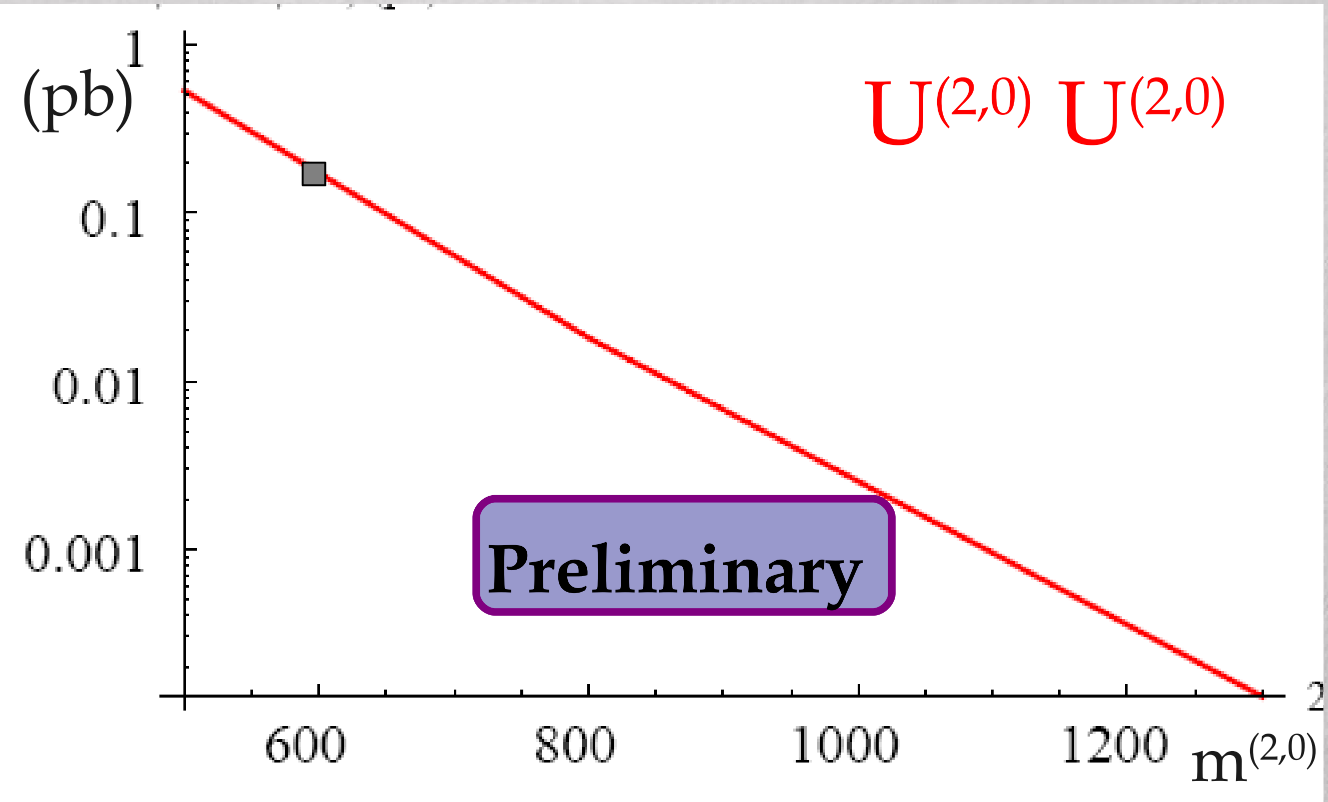


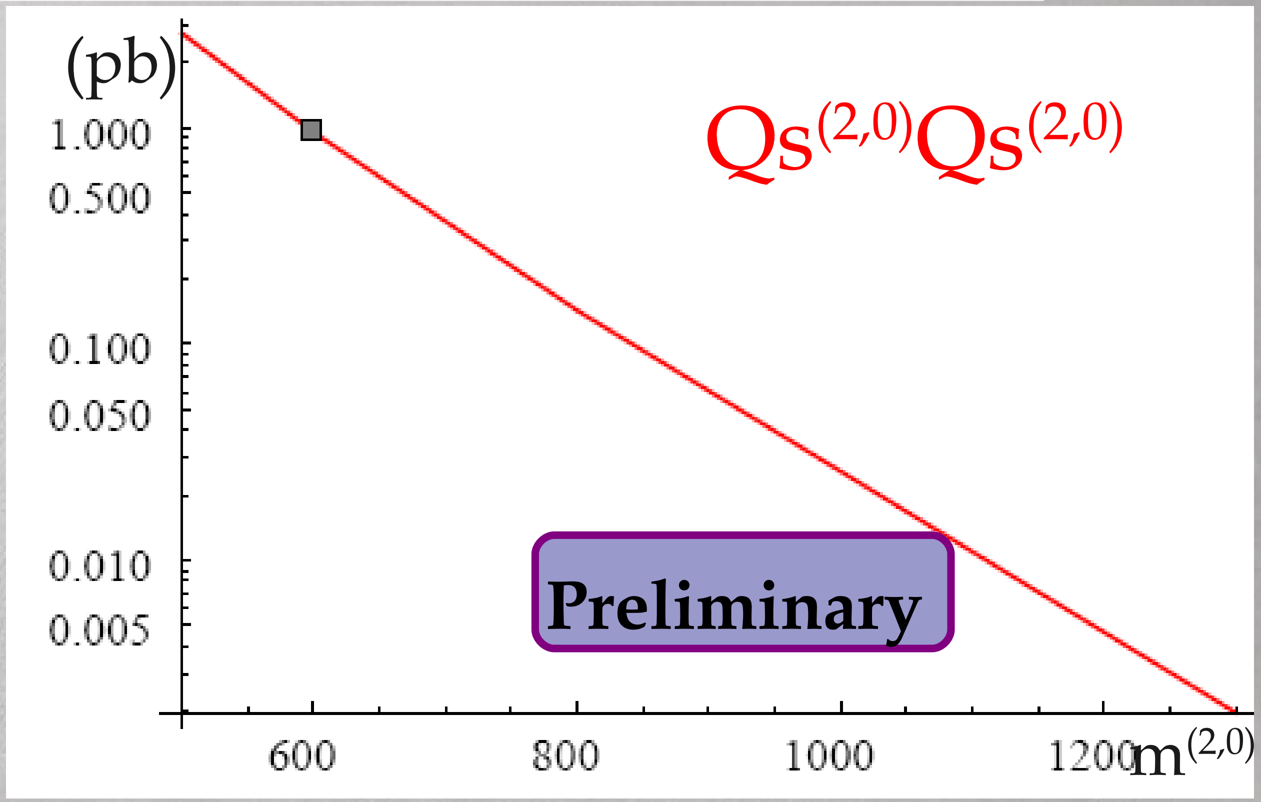
Only divergent contribution for "few" 4D-loops

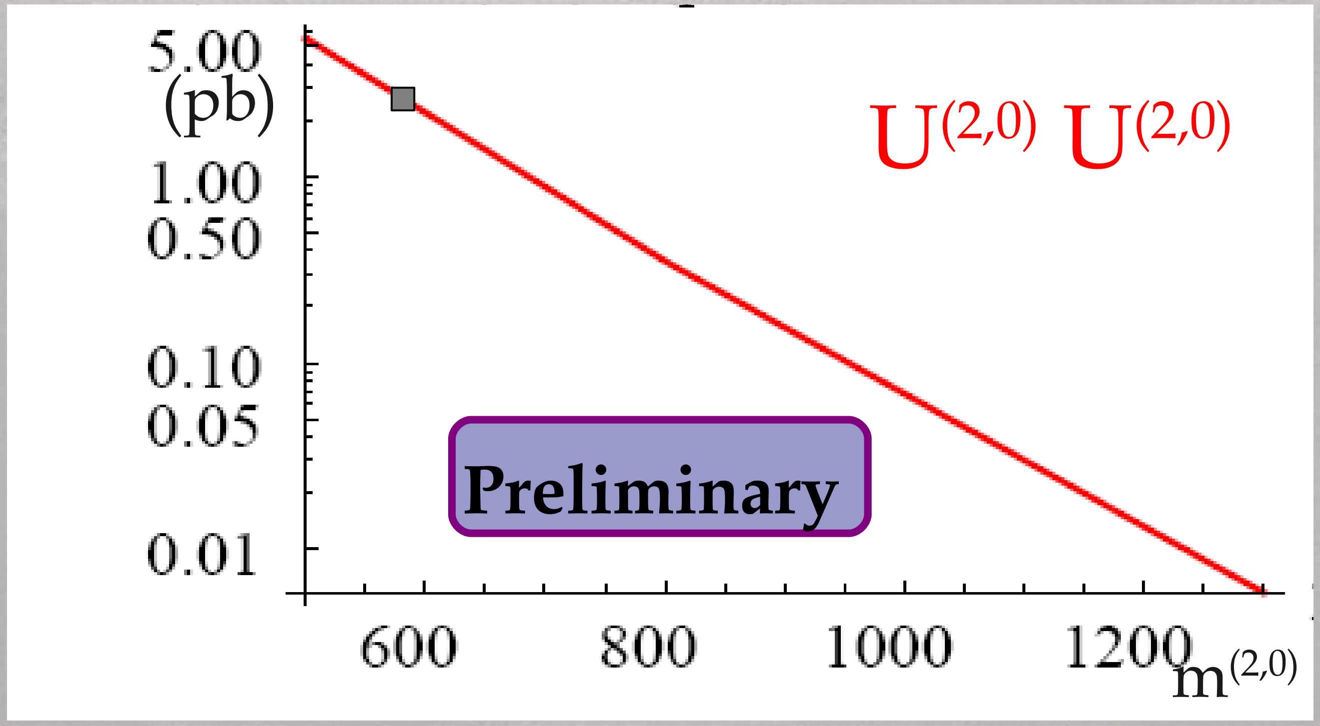
$$\mathcal{L}_{c.t.}(\xi=-3)=\iint_0^{2\pi} dxdy\delta_i\Big(-\frac{1}{4}\delta Z_3(F^a_{\alpha\beta})^2-\frac{1}{2\xi}\left(\partial_\mu A^{a,\mu}\right)^2+\bar{\Psi}(i\delta Z_2\partial^\mu\gamma_\mu-\delta_m)\Psi$$
$$+\delta Z_\phi(D^\mu\phi)^\dagger(D_\mu\phi)+\delta m^2_\phi\;\phi^\dagger\phi+\ldots\Big)$$

- Compensate divergences from singularities
- Gauge invariant in "Magic gauge" ξ=-3
- Used to compute contributions for all modes, for instance with (2,0)

Phenomenology @ LHC : Production of quarks (2,0)







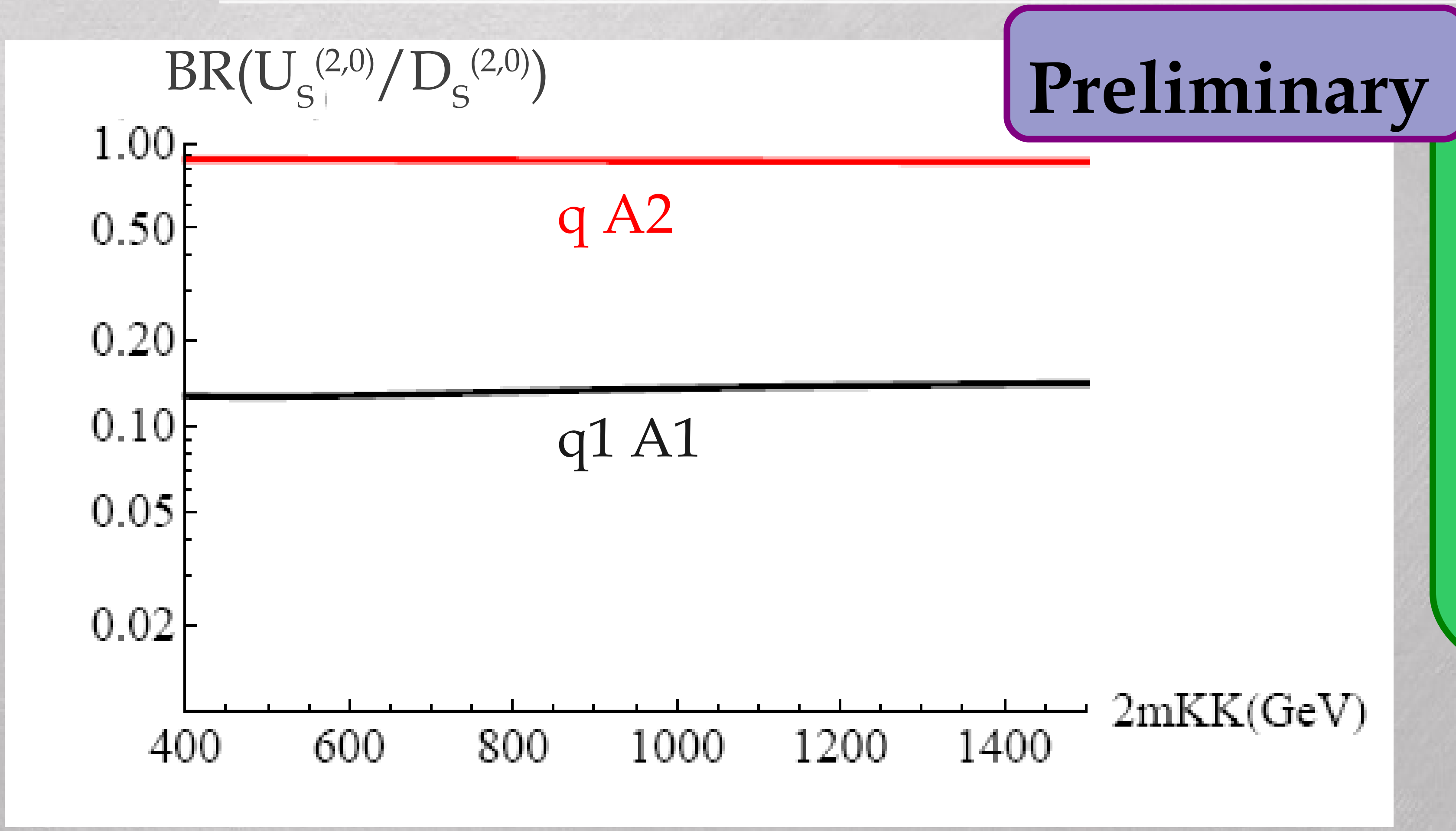
Xsection: M_{KK}= 300 GeV & @ 7 TeV

$U^{(2,0)}\ U^{(2,0)}$: 3 pb

$U^{(2,0)}\ U^{(2,0)}$: 150 fb

$Q_S^{(2,0)}\ Q_S^{(2,0)}/Q_S^{(2,0)}$: 950 fb

Phenomenology @ LHC : BR of quark singlet (2,0)



$U_S^{(2,0)}$ @ 625.4 GeV

$D_S^{(2,0)}$ @ 624.9 GeV

BR (q=u/d)	
$q\,A_\mu^{2,0}$	86%
$q_s^{1,0}\,A_6^{1,0}$	14%

$A_\mu^{(2,0)}$ @ 600.7 GeV

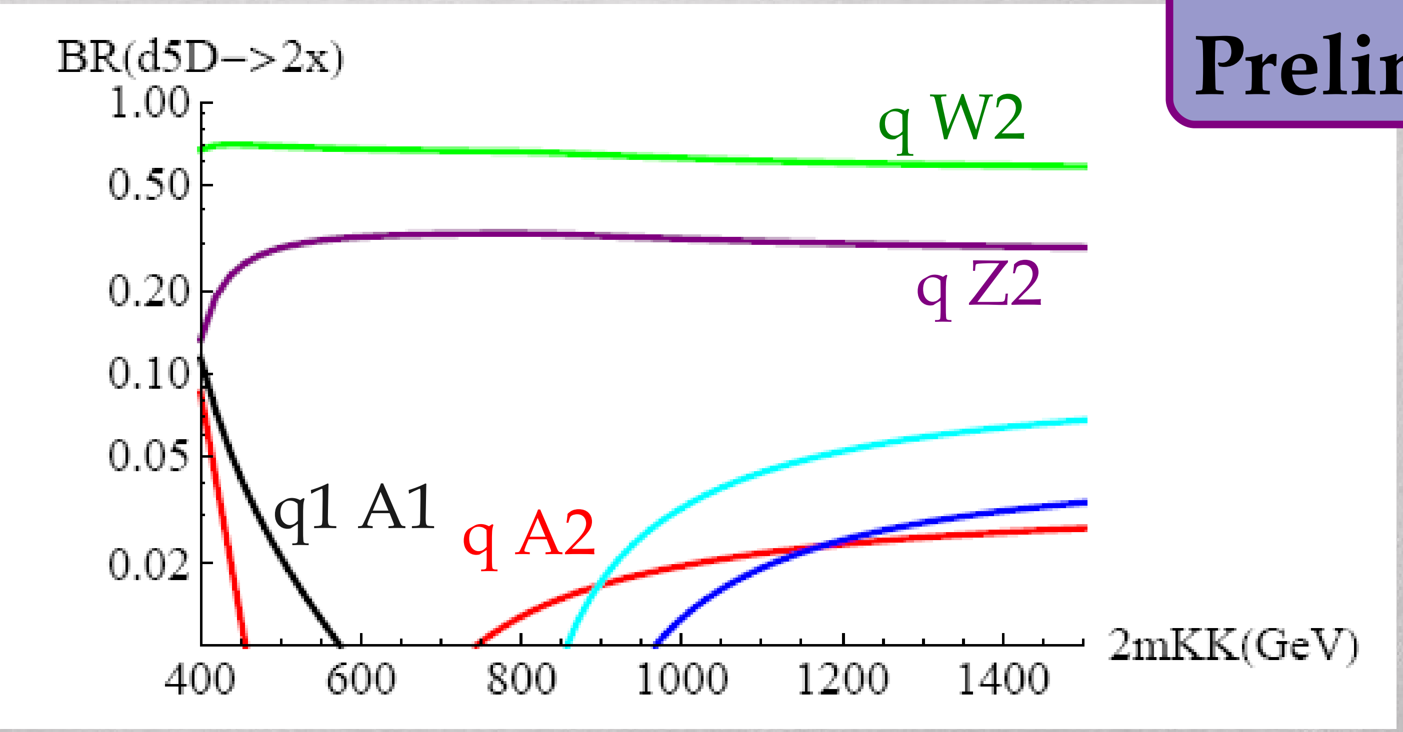
BR ($A_\mu^{2,0}$)	
jj	76%
$t\bar{t}$	18%
$Z_o\,h$	4%

→

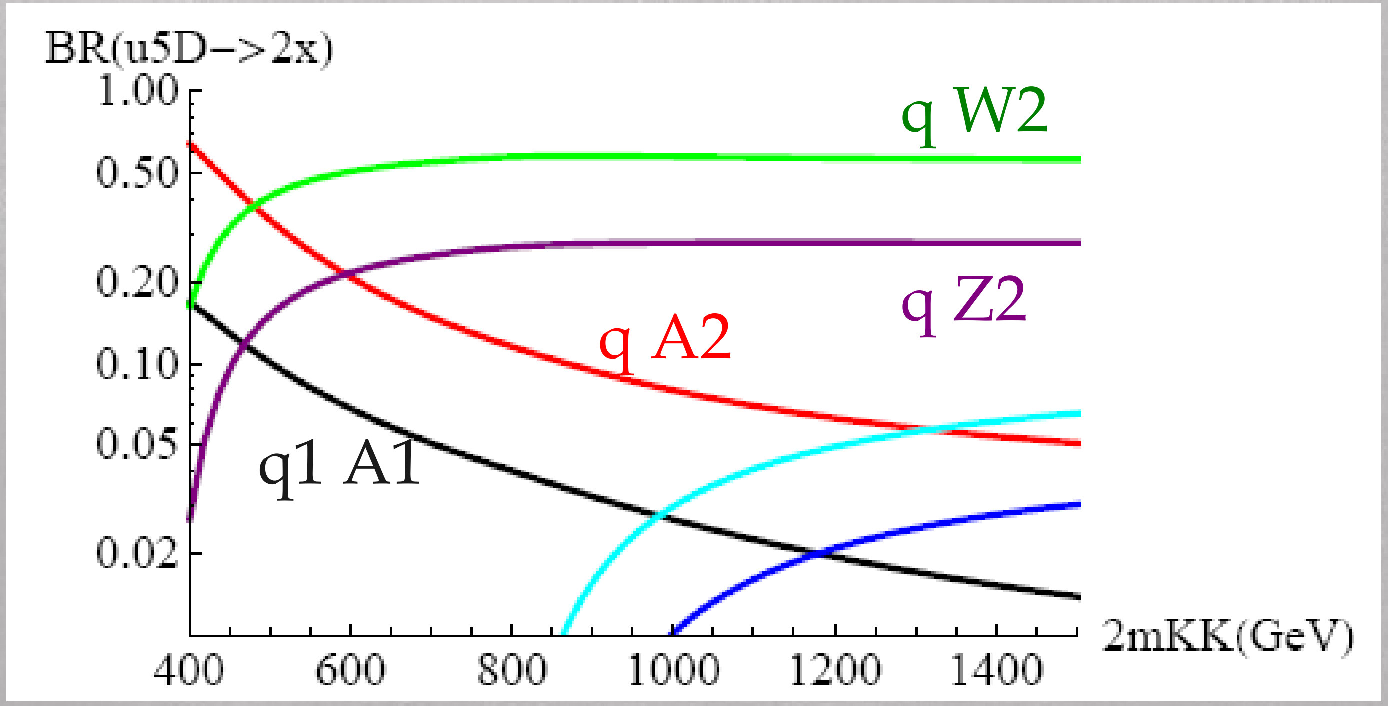
@ 7 TeV

$\sigma(pp \to t\bar{t}t\bar{t}) \sim 20 fb$

Phenomenology @ LHC : BR of quark doublet (2,0)



Preliminary



$U_D^{(2,0)}$ @ 628.8 GeV

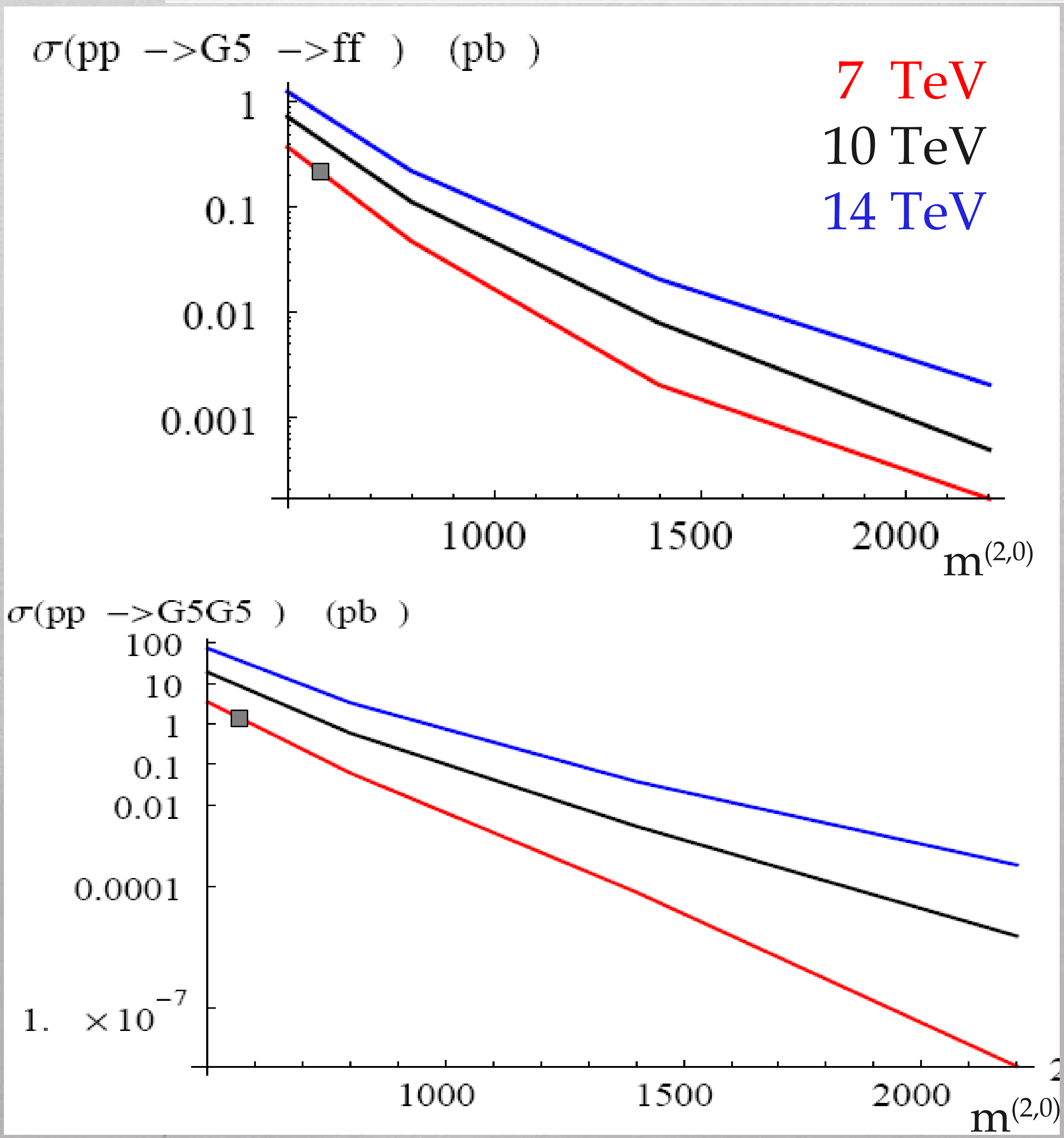
$D_D^{(2,0)}$ @ 628.8 GeV

BR (q=u/d)	
$q\, W_\mu^{2,0}$	50/60%
$q\, Z_\mu^{2,0}$	20/30%
$q\, A_\mu^{2,0}$	6/0.1%

$Z_\mu^{(2,0)}$ @ 616 GeV

BR ($Z_\mu^{2,0}$)	
invisible	70%
$l^{2,0} l$	20%
$j\, j$	5%

Phenomenology @ LHC : Production of gluons (2,0)



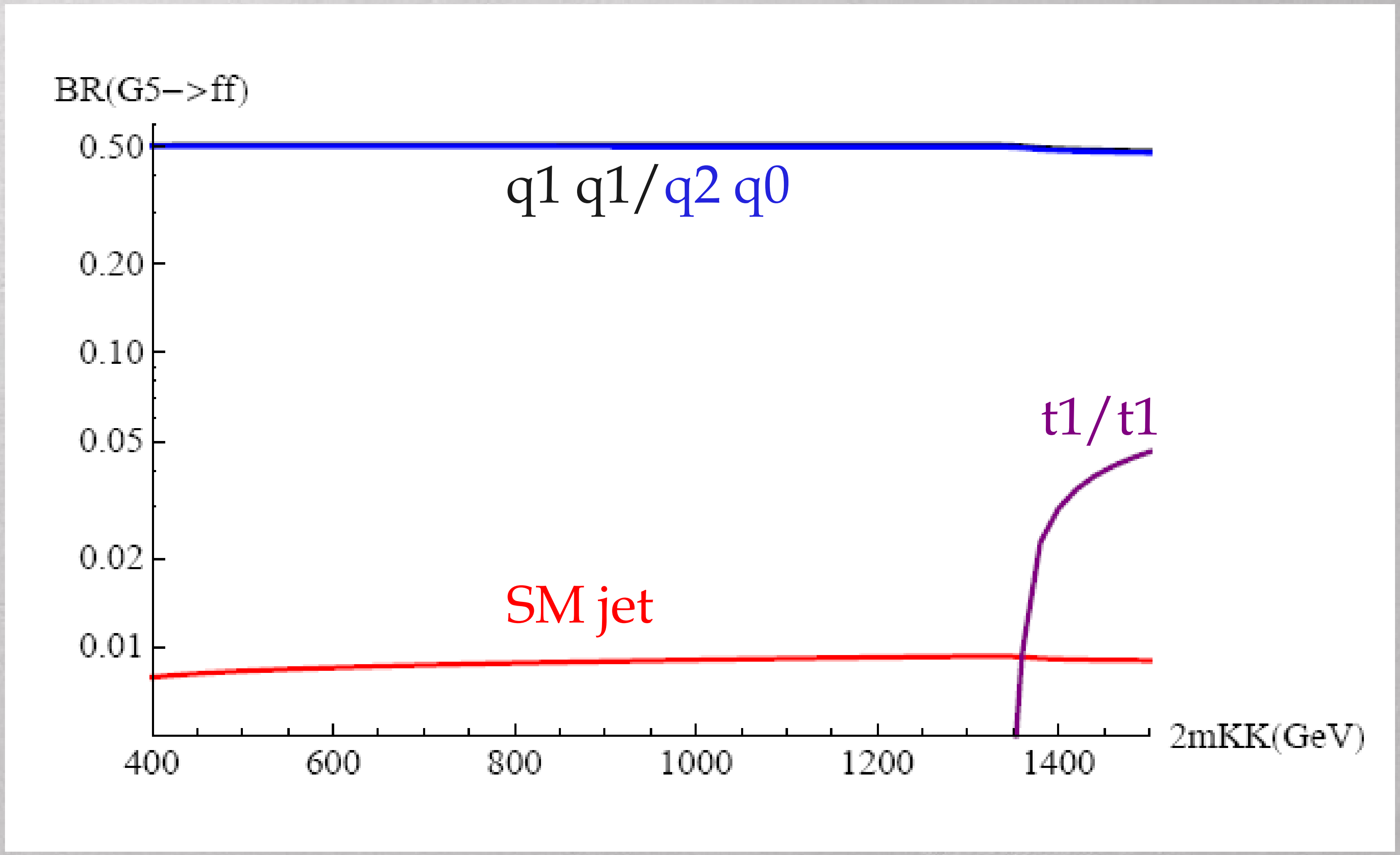
Preliminary

Xsection: M_{KK}= 300 GeV
& @ 7 TeV

$G^{(2,0)}$ single prod : 200 fb

$G^{(2,0)}$ $G^{(2,0)}$: 1 pb

Phenomenology @ LHC : BR for gluons (2,0)



- Decay : 50% into $q^{(2,0)}$+soft jet (to be added to previous Xsection)
  & 50% into $q^{(1,0)}q^{(1,0)}$ (invisible)
  & less than 1% into SM jets

Summary:
Decays of heavier tiers

- Tiers (1,1) @ 1.4/R & Tiers (2,0)-(0,2) @ 2/R

via localized kinetic terms

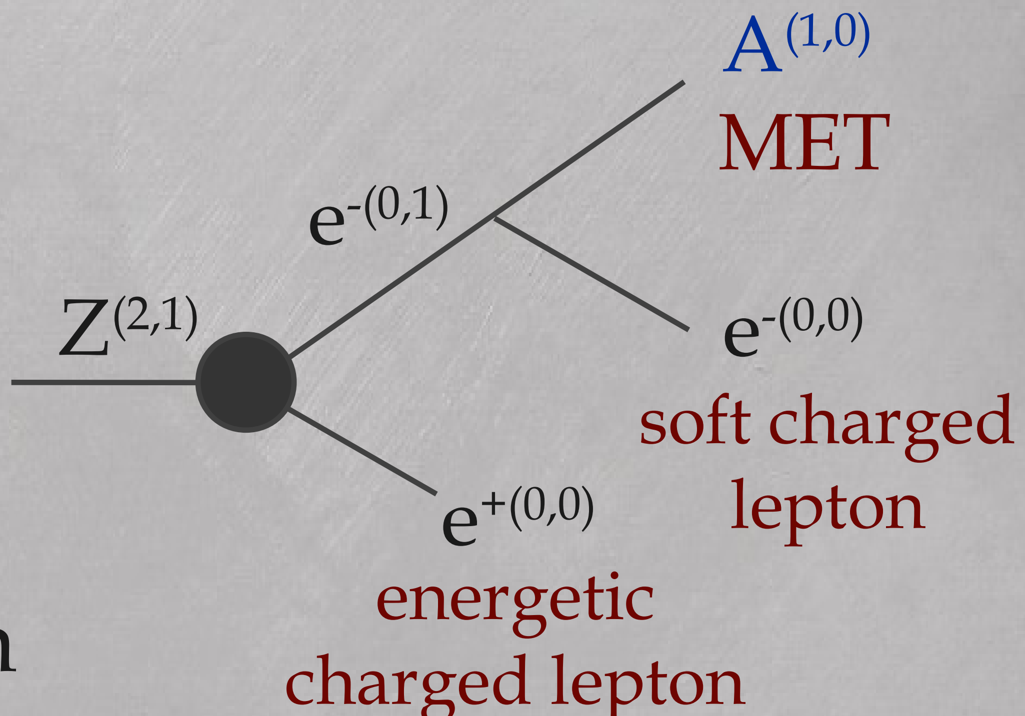
via loops (& kinetic terms)

Mainly resonant decays into SM particles & with/without MET

- Tiers (2,1) @ 2.2/R

via loops (& kinetic terms)

➠ Can decay into SM particles & MET
➠ Rare but clear signature like singled charged lepton



Conclusion

- ✓ KK-Parity is build-in in this 6D space:
  - from topology and Lorentz invariance
  - without imposing new extra-parity
- ✓ Good predictability : not so many localized interactions
- ✓ Low mass range for KK-states : explored or excluded with few fb^{-1} luminosity at LHC.
- ✓ Possible extensions: Gauge-Higgs Unification, warped space,...
- ✓ Implemened in Feynrules: interface for Calchep, Madgraph,...

- ❖ Early LHC phenomenology, calculation for higher luminosity
- ❖ Relic density including EWSB effects, resonant effects,...
  (B. Kubik in collaboration with A. Arbey)
- ❖ Model buiding and study of possible extensions.

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  - from topology and Lorentz invariance
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THE END

BR for A(2,0)/Z(2,0)

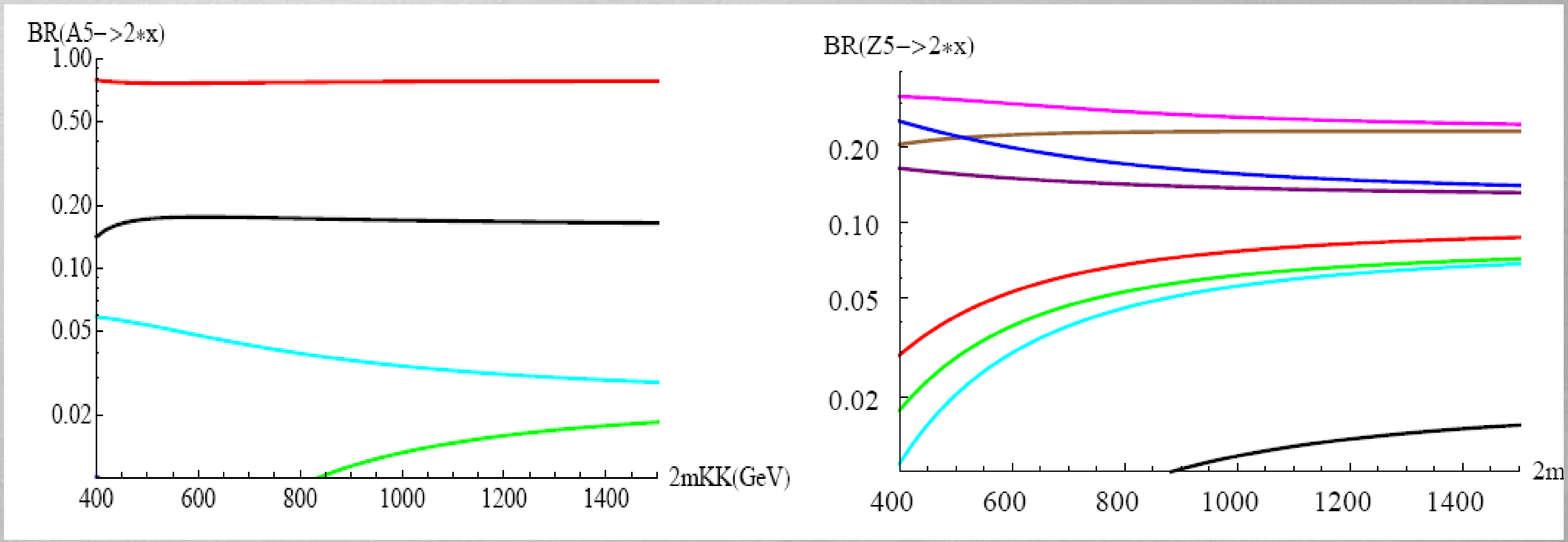


Figure 11: Branching ratios of the heavy $Z^{2,0}$ as a function of m_{KK}: N1N1,L1 L1, N2 ν, L2 SMlep,SMjet, SM tops,W_L W_L, Z_o h

UED on the Real Projective plane and EWPT

- EW observable expected to be cut-off dependent
  Log-divergences expected due to density of states in 6D in UED (Appelquiest, Cheng, Dobrescu, Arxiv:hep-ph/0012100)

- Highly model dependent (compactification, EWSB,...) !!!

- Gauge higgs unification, warping, ... can be implemented as well and totally change the allowed range

Fermions in this Framework

$$
\begin{aligned}
S_{\pm} &= \int dx_5 \int dx_6 \, \frac{i}{2}\Big\{ \bar{\Psi}_{\pm}\Gamma^{\alpha}\partial_{\alpha}\Psi_{\pm} - \left(\partial_{\alpha}\bar{\Psi}_{\pm}\right)\Gamma^{\alpha}\Psi_{\pm} \Big\} = \\
&= \int dx_5 \int dx_6 \, \Big\{ \; i\bar{\psi}_{L\pm}\gamma^{\mu}\partial_{\mu}\psi_{L\pm} + i\bar{\psi}_{R\pm}\gamma^{\mu}\partial_{\mu}\psi_{R\pm} + \\
&\quad + \frac{1}{2}\left[\bar{\psi}_{L\pm}\gamma_5(\partial_5 \mp i\partial_6)\psi_{R\pm} + \bar{\psi}_{R\pm}\gamma_5(\partial_5 \pm i\partial_6)\psi_{L\pm} + h.c. \right] \Big\} \; ;
\end{aligned}
$$

For a left-handed fermion, case $(+\pm)$, the KK modes are given by:

(k,l)	χ_+	χ_-	$\bar{\eta}_+$	$\bar{\eta}_-$
$(0,0)$	$\frac{1}{2\sqrt{2}\pi}$	$\pm\frac{1}{2\sqrt{2}\pi}$	0	0
$(0,l)$	$\frac{1}{2\pi}\cos lx_6$	$\pm(-1)^l\frac{1}{2\pi}\cos lx_6$	$-\frac{i}{2\pi}\sin lx_6$	$\pm(-1)^l\frac{i}{2\pi}\sin lx_6$
$(k,0)$	$\frac{1}{2\pi}\cos kx_5$	$\pm(-1)^k\frac{1}{2\pi}\cos kx_5$	$-\frac{1}{2\pi}\sin kx_5$	$\mp(-1)^k\frac{1}{2\pi}\sin kx_5$

while for both $k, l \neq 0$, there are 2 degenerate solutions for each level which can be parameterized as

$$
\Psi^{(+\pm)} = \begin{pmatrix} (a\cos kx_5\, \cos lx_6 + b\sin kx_5\, \sin lx_6)\, f_l \\ \pm(-1)^{k+l}\,(c\sin kx_5\, \cos lx_6 - d\cos kx_5\, \sin lx_6)\, \bar{f}_r \\ \pm(-1)^{k+l}\,(a\cos kx_5\, \cos lx_6 - b\sin kx_5\, \sin lx_6)\, f_l \\ (c\sin kx_5\, \cos lx_6 + d\cos kx_5\, \sin lx_6)\, \bar{f}_r \end{pmatrix}, \tag{3.16}
$$

where we can use the EOMs and normalization condition to fix the coefficients

$$
\begin{aligned}
a &= \tfrac{\cos\alpha}{\sqrt{2}\pi} & \qquad c &= -\tfrac{k\cos\alpha - il\sin\alpha}{\sqrt{2}\pi\sqrt{k^2+l^2}} \\
b &= \tfrac{\sin\alpha}{\sqrt{2}\pi} & \qquad d &= \tfrac{k\sin\alpha - il\cos\alpha}{\sqrt{2}\pi\sqrt{k^2+l^2}}
\end{aligned} \tag{3.17}
$$

Mass Splitting: Localized Counter-terms

- Localized counters-terms on the singularities
  - ▸Compensation of the Log-divergences from rotation
    - ⟶ Terms at order of 1-loop
  - ▸Respect 4D residual invariance
  - ▸Mixing between mode (l,k) & remove degeneracies

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

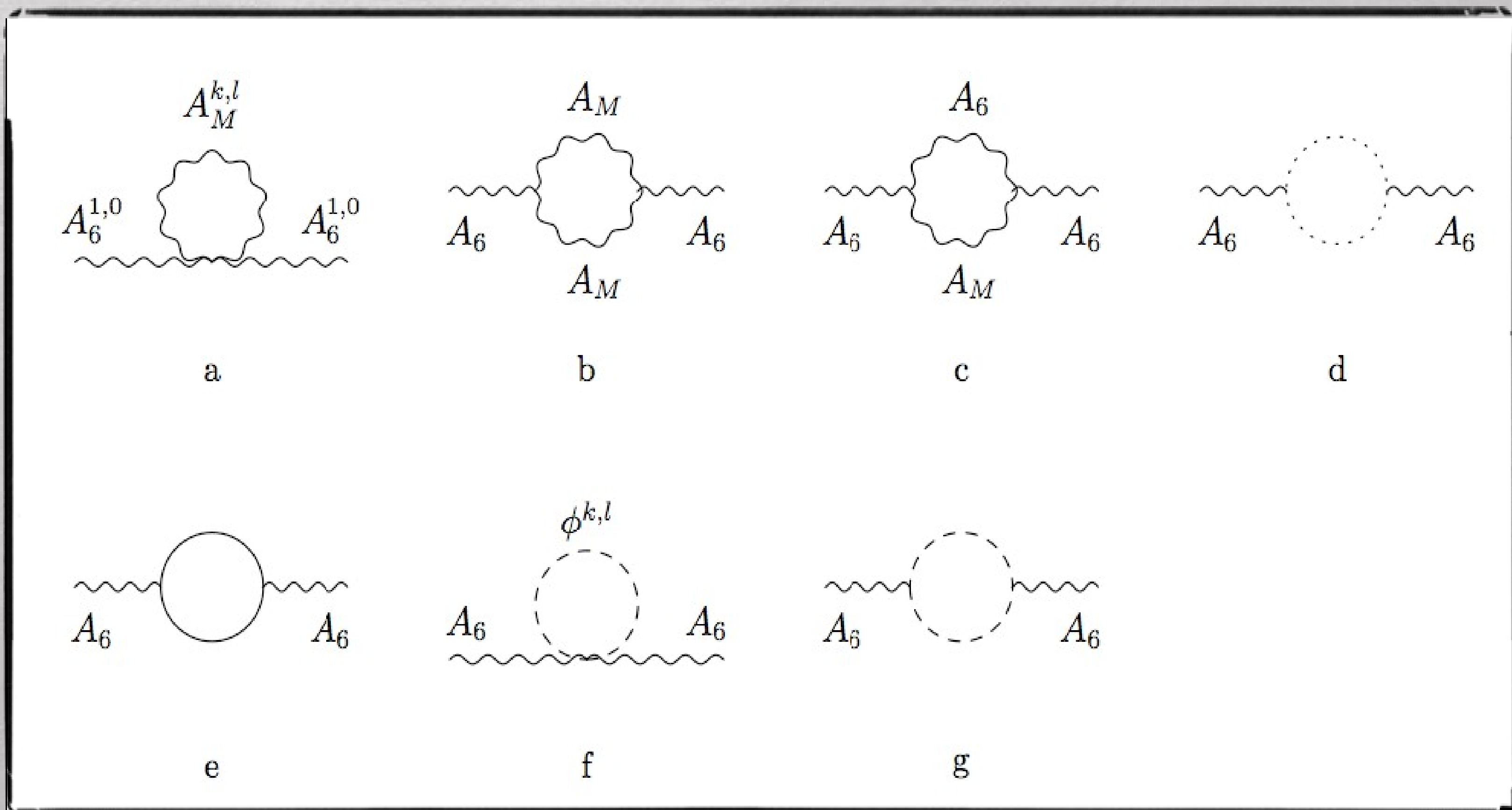
$$\mathscr{L}_i = \frac{\delta_i}{\Lambda^2}\left(-\frac{r_{1i}}{4}F_{\mu\nu}^2 - \frac{r_{2i}}{2}F_{56}^2 + \frac{r_{5i}}{2}F_{5\mu}^2 + \frac{r_{6i}}{2}F_{6\mu}^2 + \frac{r_{56i}}{2}F_{5\mu}F_6^\mu\right);$$

Vector Kinetic Term corrections

Mass term corrections For Gauge & Scalars part

$$(k,l)_\pm = \frac{(k,l)\pm(l,k)}{\sqrt{2}}, \quad \text{with } l > k$$

Splittings : One 6D-Loop And EWSB Corrections



$$T_6 = \frac{1}{\pi} \sum_{(k,l)\neq(0,0)} \frac{1}{(k^2+l^2)^2} \sim 1.92$$

$$L = \log\left(\frac{\Lambda^2+n^2}{n^2}\right)$$

$$\frac{1}{4}\frac{g^2 C(r)}{16\pi^4 R^2} \times$$

δm^2 gauge scalars		$\times p_g$	$\times p_g p_r$	$\times p_r$
a	$5T_6$	$5\cdot 7\zeta(3)$	$3\cdot(7\zeta(3)+B_1(n))$	$3n^2\pi^2 L$
b	0	0	$-12B_2(n)$	0
c	$-T_6$	$-3\cdot 7\zeta(3)$	$-(7\zeta(3)+B_3(n))$	$5n^2\pi^2 L$
d	0	0	$-2B_2(n)$	0
e	$-8T_6$	0	0	0
f	T_6	$7\zeta(3)$	$(7\zeta(3)+B_1(n))$	$n^2\pi^2 L$
g	0	0	$-4B_2(n)$	0

Splittings : One 6D-Loop And EWSB Corrections

- Calculation for LLP level
- 6D loop calculations: Mixed propagator method

$$\delta m_B^2 = \frac{{g'}^2}{64\pi^4 R^2}\left[-79T_6 + 14\zeta(3) + \pi^2 n^2 L + B_1 - 4B_2\right] ,$$
$$\delta m_W^2 = \frac{g^2}{64\pi^4 R^2}\left[-39T_6 + 70\zeta(3) + 17\pi^2 n^2 L + 7B_1 - 32B_2 - 2B_3\right] ,$$
$$\delta m_G^2 = \frac{{g_s}^2}{64\pi^4 R^2}\left[-36T_6 + 84\zeta(3) + 24\pi^2 n^2 L + 9B_1 - 42B_2 - 3B_3\right] .$$

- EWSB: Higgs VEV

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

$$\longrightarrow \boxed{\begin{aligned} m_{A_n,Z_n}^2 &= \frac{n^2}{R^2} + \frac{1}{2}\Big(m_Z^2 + \delta m_B^2 + \delta m_W^2 \\ &\mp \sqrt{(m_Z^2 + \delta m_B^2 - \delta m_W^2)^2 - 4m_W^2(\delta m_B^2 - \delta m_W^2)}\Big) \\ m_{W^+}^2 &= \frac{n^2}{R^2} + \delta m_W^2 + m_W^2 ; \end{aligned}}$$

Splittings : Heavy Top mass Corrections

- 6D loop calculations: Mixed propagator method

$$\begin{aligned} S_{\text{Yukawa}} &= -\int dx_5 dx_6\, Y_6\, \bar{\Psi}_Q H \Psi_U + h.c. = \\ &= -\int dx_5 dx_6\, Y_6\, [\eta_{Q+} H \chi_{U-} + \eta_{Q-} H \chi_{U+} + \bar{\chi}_{Q+} H \bar{\eta}_{U-} + \bar{\chi}_{Q-} H \bar{\eta}_{U+}] + h.c. \end{aligned}$$

$$\mathcal{L}_{\text{Yukawa(k,l)}} = -(-1)^{k+l} m_{\text{top}} \left(\bar{q}_l^{(k,l)} u_r^{(k,l)} - \bar{q}_r^{(k,l)} u_l^{(k,l)} \right) + h.c.\,.$$

- EWSB: Higgs VEV

$$\mathcal{L}_{\text{mass}} = -\begin{pmatrix} \bar{q}_l & \bar{u}_l \end{pmatrix} \cdot \begin{pmatrix} \frac{1}{R} + \delta m_Q & -m_{\text{top}} \\ m_{\text{top}} & \frac{1}{R} + \delta m_U \end{pmatrix} \cdot \begin{pmatrix} q_r \\ u_r \end{pmatrix} + h.c.\,.$$

$$m_{t1/2}^2 = \frac{1}{R^2} + m_{\text{top}}^2 + \delta m_Q \left(\frac{1}{R} + \frac{1}{2}\delta m_Q \pm B \right) + \delta m_U \left(\frac{1}{R} + \frac{1}{2}\delta m_U \mp B \right),$$

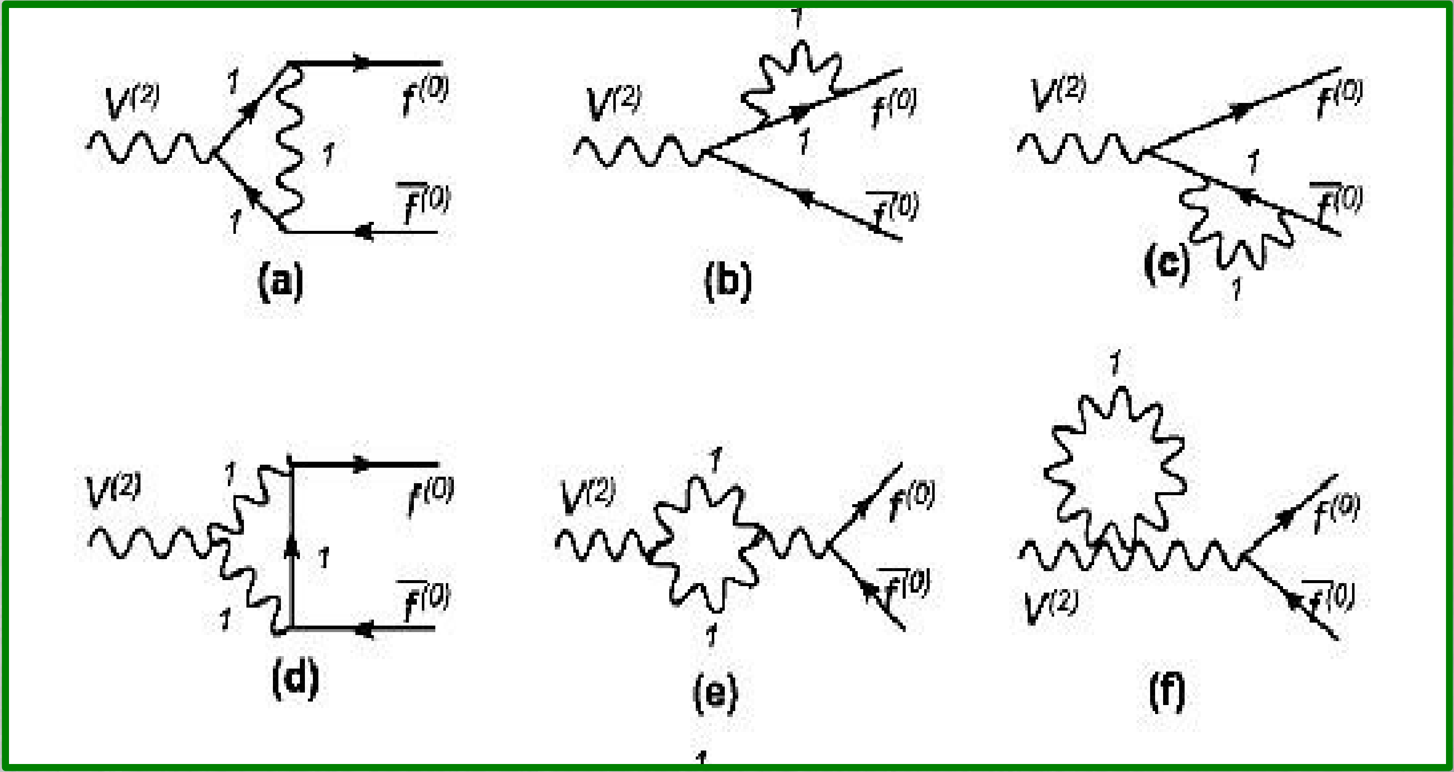
with

$$B = \sqrt{\left(\frac{1}{R} + \frac{\delta m_Q + \delta m_U}{2} \right)^2 + m_{\text{top}}^2}\,.$$

Decay of (2,0)-(0,2) tiers: 1-loop vertex corrections

Preliminary

$$V^{\mu} = i\,\frac{1}{4}\,\frac{g^3}{16\pi^4 R^3}\,\frac{1}{2\sqrt{2}n^2}\,\alpha\, t^a \gamma^{\mu} P_{L(R)}$$



α	$\times p_g$		$\times p_g p_r$	$\times p_r$
a	0	0	$(-1)^n(\Phi_1(n)+\Phi_3(n)+\Phi_2(n)-\Phi_4(n))$	0
b	0	0	$(-1)^n(-6\Phi_2(n))$	$4n^2\pi^2 L$
c	0	0	$(-1)^n(-6\Phi_2(n))$	$4n^2\pi^2 L$
d	0	0	$(-1)^{n+1}\ (5\Phi_1(n)+5\Phi_3(n)+8\Phi_4(n))$	$8n^2\pi^2 L$
e+f	0	0	$(-1)^{n+1}\,(-2\Phi_1(n)+12\Phi_2(n)-\Phi_3(n))$	$12n^2\pi^2 L$