Dark Matter from Extra Dimensions

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arXiv:0907.4993 and 1104.3800
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work in progress with
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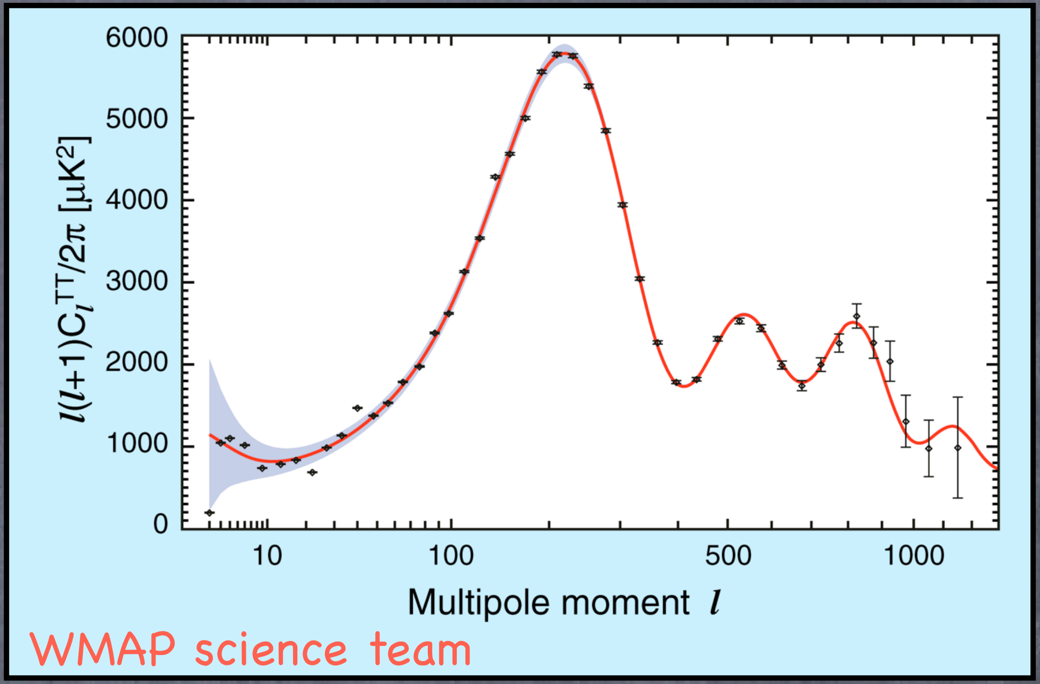
NeXT PhD workshop
Cosener's House (Abingdon)

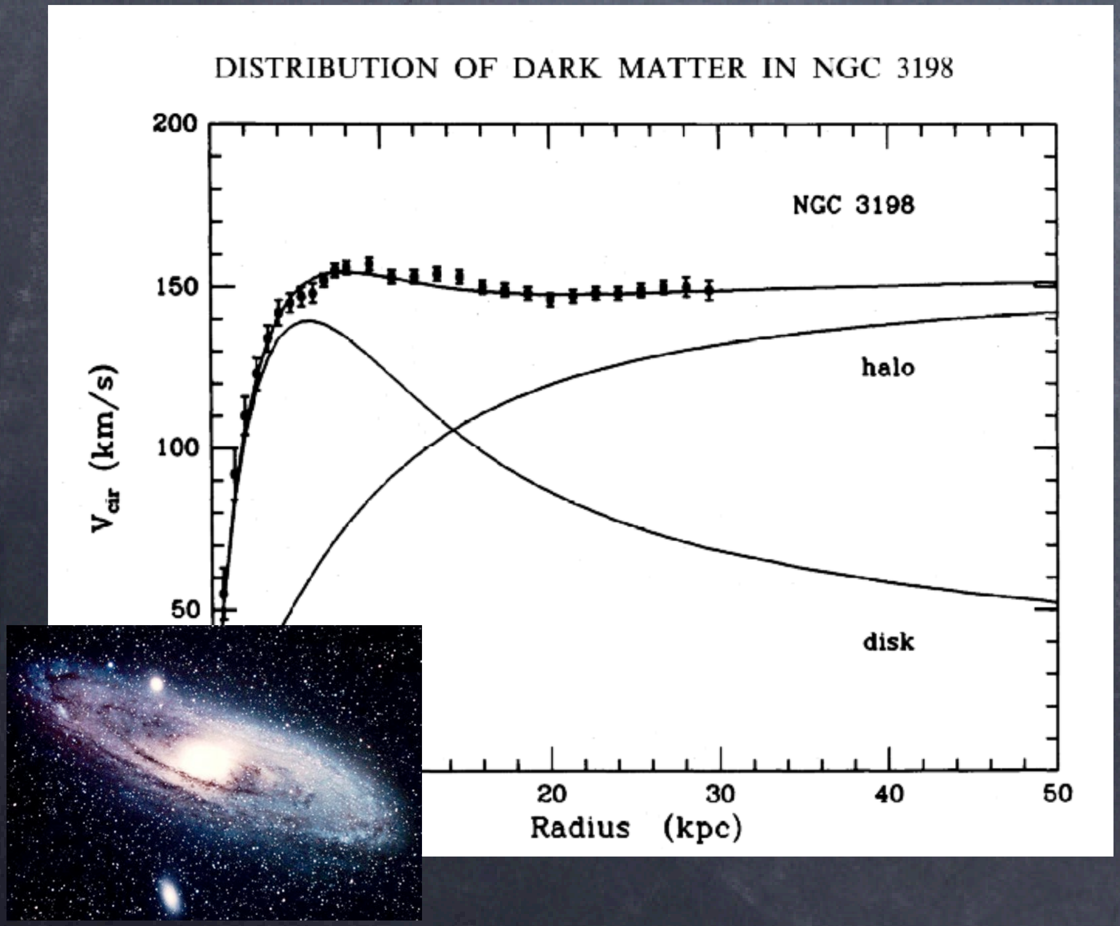
Why do we need Dark Matter?

Observations both in Astrophysics
and Cosmology suggest
the presence of "Dark" Matter,
not explained in the Standard Model!

Cosmic Microwave Background:



Astrophysical measurements:



- The Universe contains 4.6% of baryons, and 23.3% of unknown matter.
- The flat rotation curves of spiral galaxies can be explained by the presence of extra non-luminous matter.

Extra dimensions are a versatile tool for model building!

Gauge-Higgs unification, Higgsless models, GUTs, composite Higgs, technicolour, QCD...

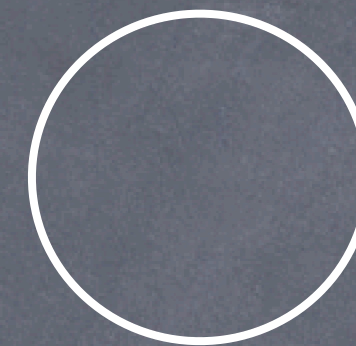
KK parity offers a new Dark Matter candidate: is it "natural"?
Is it generic in XD models?

Plan of the talk:

- I will convince you it's not generically the case: interesting models do not have it!
- we found a unique "natural" scenario in 6 dimensions.
- I will briefly discuss the LHC phenomenology of such scenario.

Intro to XD: a scalar field

Action for a massless scalar field:



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

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

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

4D field!

with:

$$f_{(k)} = \begin{cases} \cos(k x_5) \\ \sin(k x_5) \end{cases} \quad \Rightarrow \quad p^2 = k^2$$

Note that under x5 -> -x5, cos -> + cos while sin -> - sin !
Also, k=0 only allowed for cos!

Intro to XD: a scalar field

Action for a massless scalar fi

- masses and interactions determined by the wave functions!
- symmetries of the space turn into "parities" for the KK modes!

is solved by

$\phi_{(k)}(p)$

4D field!

with:

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Note that under x5 -> -x5, cos -> + cos while sin -> - sin !
Also, k=0 only allowed for cos!

DM and XD, a troubled couple?

The typical situation is:

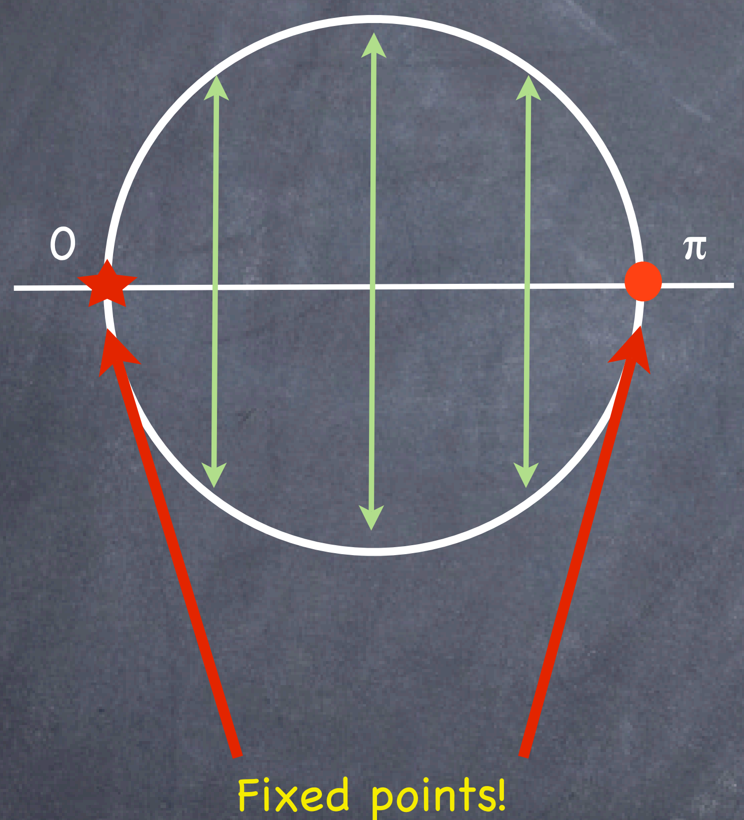
Let's consider the simplest case:
one compact extra dimension!

A circle.

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

DM and XD, a troubled couple?

The typical situation is:



We impose an "orbifold":
identify points related by a symmetry

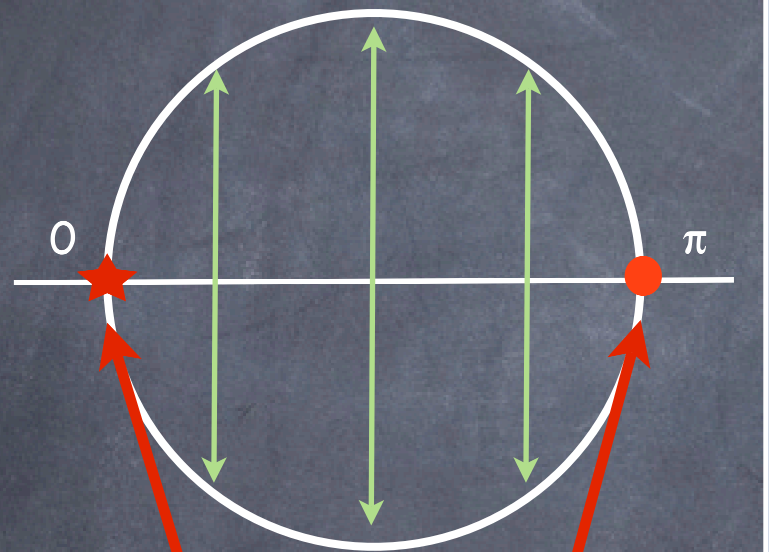
$$x_5 \to -x_5 = 2\pi - x_5$$

$$\phi(x_5) = \pm\phi(-x_5)$$

Required by chirality!!!

DM and XD, a troubled couple?

The typical situation is:



$$\Psi = \begin{pmatrix} \chi \\ \bar{\eta} \end{pmatrix}$$ chiral components

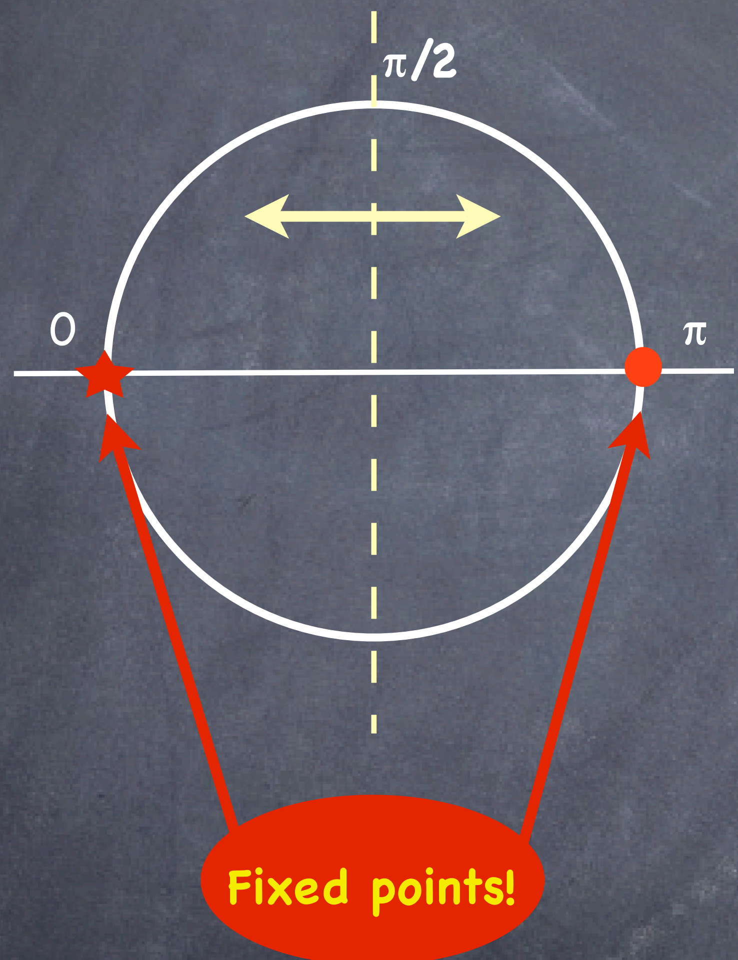
$$S = \int dx_5 \; i\bar{\chi}\bar{\sigma}^\mu \partial_\mu \chi + i\eta\sigma^\mu\partial_\mu\bar{\eta} - \eta\partial_5\chi + \bar{\chi}\partial_5\bar{\eta}$$

different parities for chiral components only under a symmetry that changes sign to all extra coordinate(s)

Required by chirality!!!

KK parity is not natural!

The typical situation is:



The half-circle is symmetric under:

$$x_5 \to \pi - x_5$$

Is it? NO!
The two fixed points are different!

We need to impose a symmetry on the fixed points to have a DM candidate!!!

In this example, the parity is added ad-hoc, it has nothing to do with the extraD!!

Do orbifolds exist without fixed points and with chiral fermions?

- There is none in 5D...
- In 6D there are 17 orbifolds (characterised by the discrete symmetry groups of the flat plane)...
- only ONE has chirality and no fixed points/lines! Unique candidate!

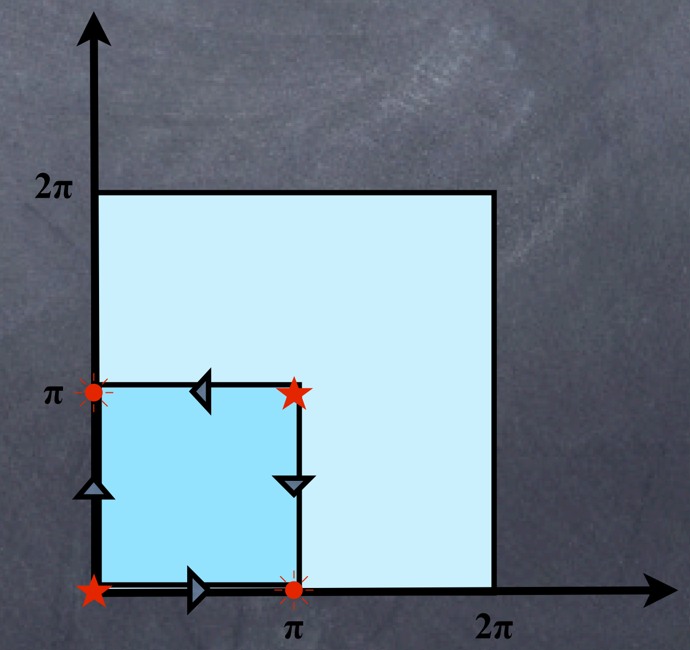
The real projective plane

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

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

Translations defined as:

$$\begin{aligned} t_5 &= g^2 \\ t_6 &= (gr)^2 \end{aligned}$$



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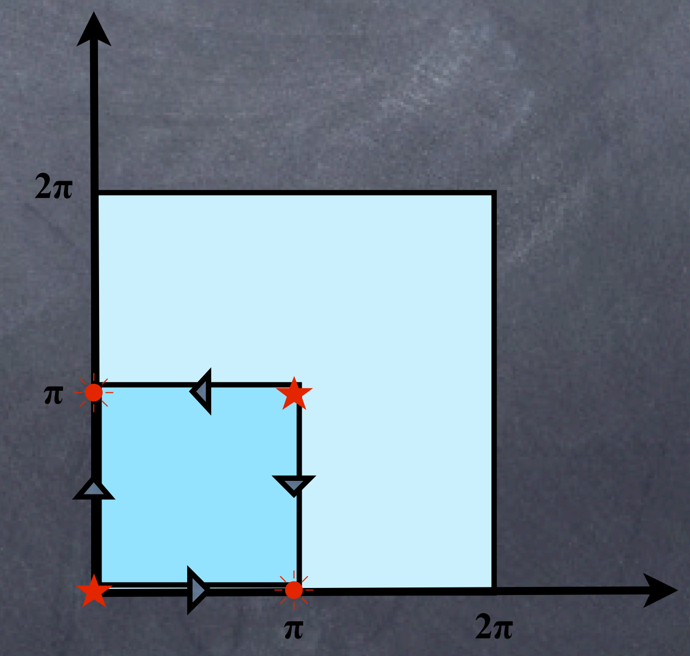
Two singular points:

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

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



The real projective plane

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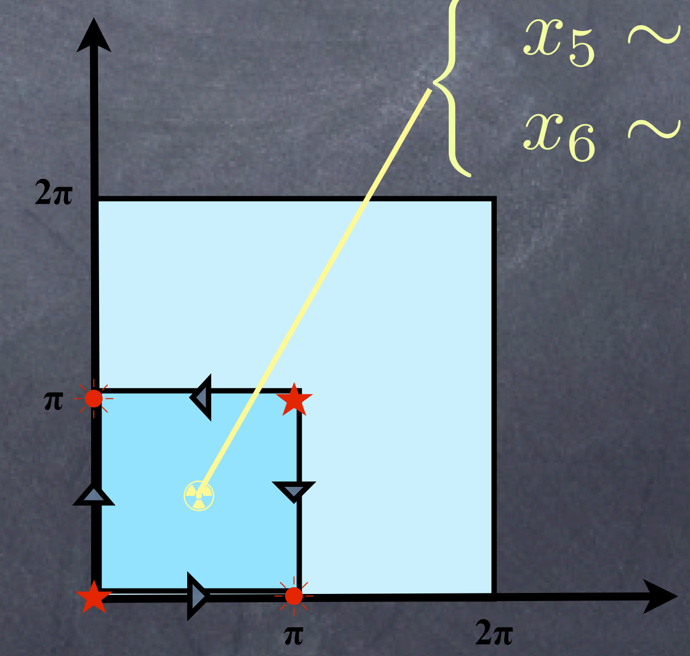
KK parity is an exact symmetry of the space!

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



$$\begin{cases} x_5 \sim -x_5 + \pi \\ x_6 \sim -x_6 + \pi \end{cases}$$

SM on the real projective plane

- To each SM field -> a 6D field
- For simplicity, from now on I'll set:

$$R_5 = R_6 = R = 1$$

- All masses in unit of:

$$m_{KK} = \frac{1}{R}$$

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

$$F_{5\mu} = \partial_5 A_\mu - \partial_\mu A_5 + g\,[A_5, A_\mu]$$

After solving the Equations of Motion,
and imposing orbifold parities [μ → (++), 5 → (−+), 6 → (−−)]
the spectrum is:

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

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

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)

DM candidate here!

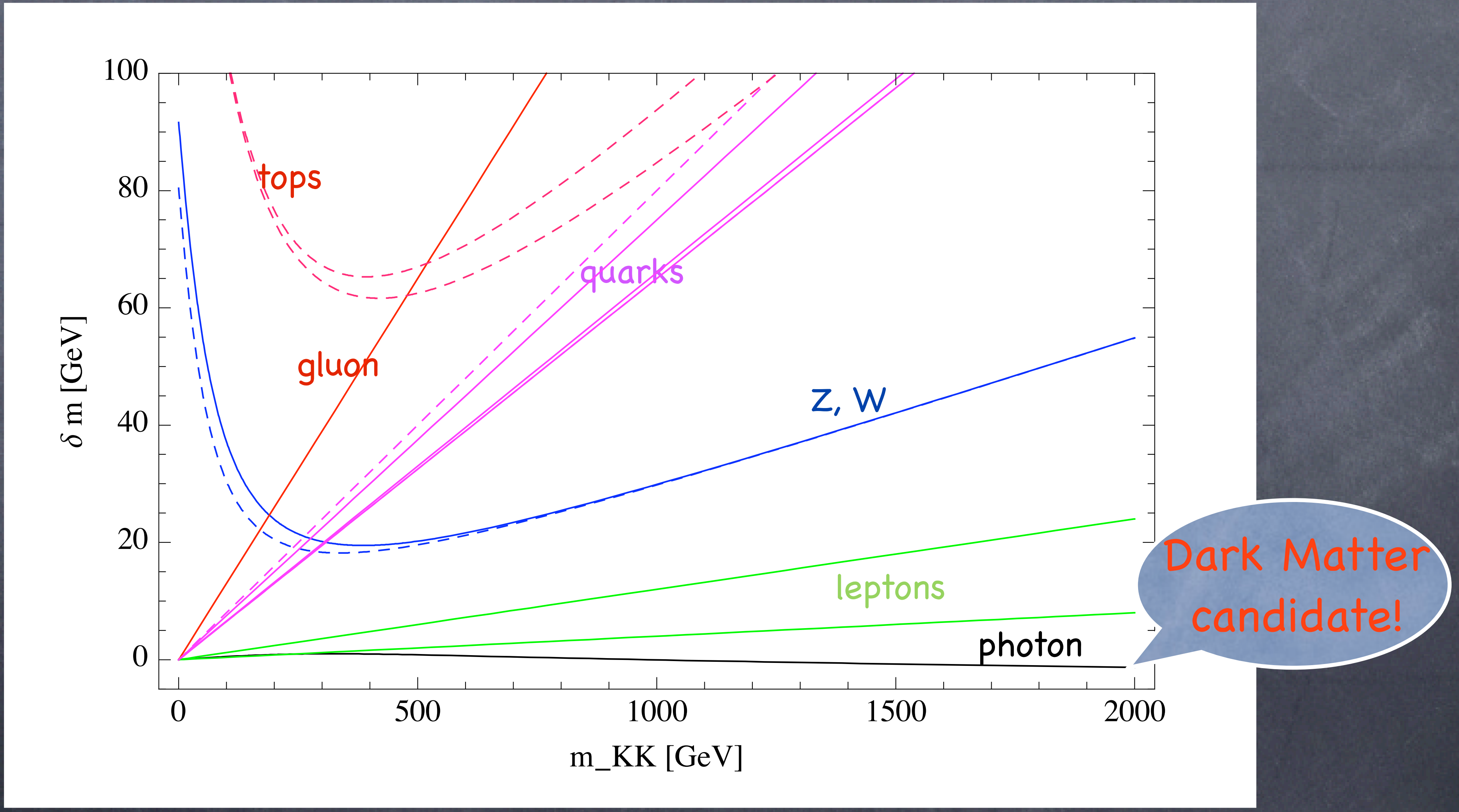
Dark Matter candidate:
lightest state in tier (1,0) and/or (0,1)

- Tier contain gauge scalars and fermions. Which one is the lightest?
- Degenerate at leading order, however masses are split by:
- -> loop corrections
- -> the Higgs VEV (electroweak symmetry breaking)
- -> localised operators

Higher order in
the effective theory:
neglect for now...

For the levels (1,0) and (0,1):

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

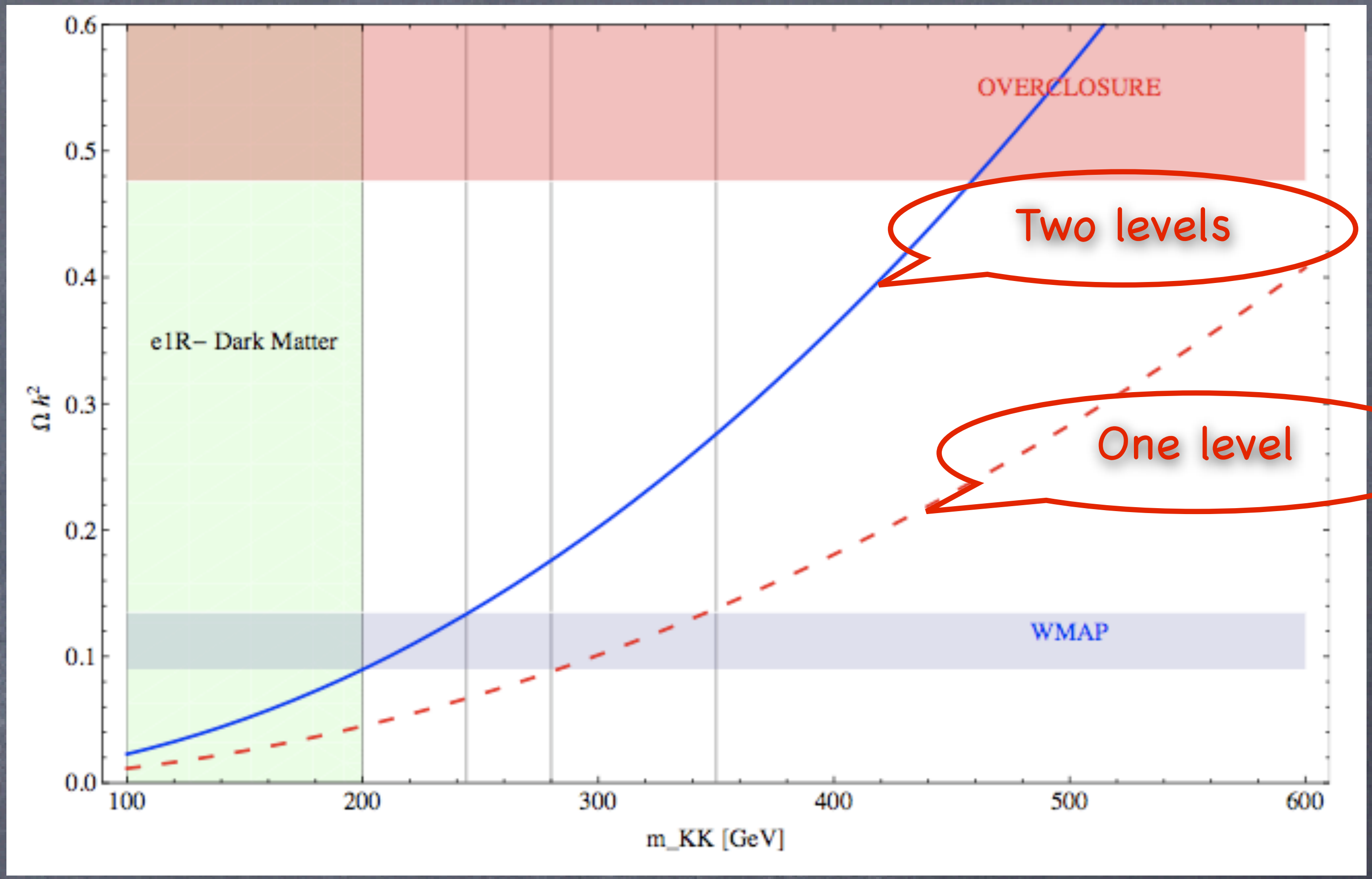


Relic abundance

Estimate takes into account annihilation and co-annihilation with leptons and W/Z.

Limit cases of degenerate and split (1,0) and (0,1) levels.

Note the UPPER BOUND on the mass scale!!!



J. Llodra-Perez' PhD Thesis

A more accurate estimate is in progress with B.Kubik!

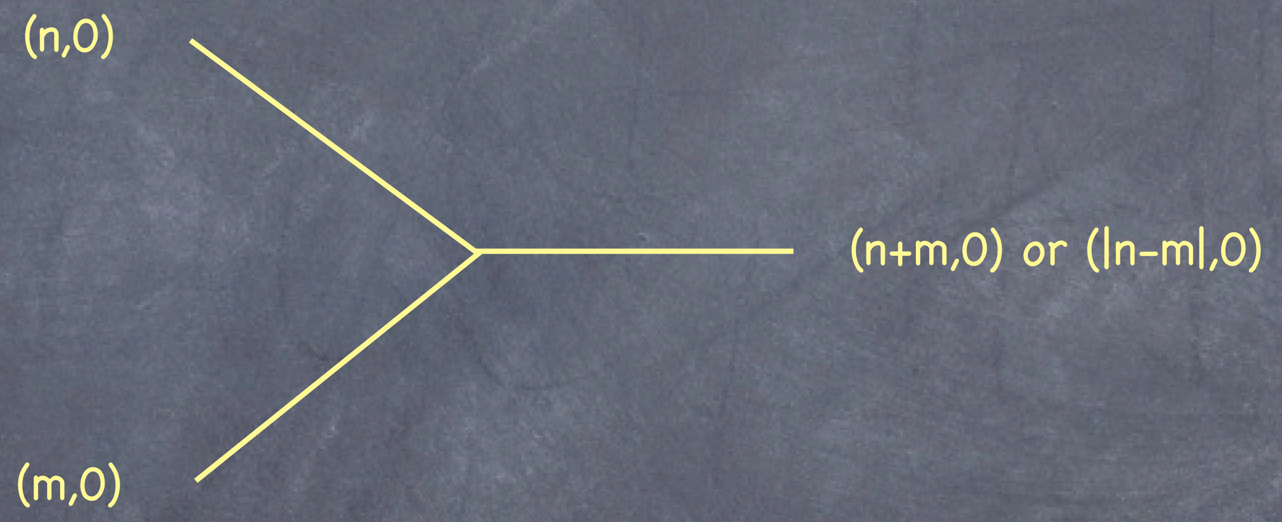
200 < mKK < 350 GeV

Phenomenology:

- The model predicts a rich zoology of new states below 1 TeV.
- Interactions and quantum numbers strictly related to the SM ones (in minimal extensions...)
- How do the new states interact? How do they decay?

Phenomenology: bulk interactions

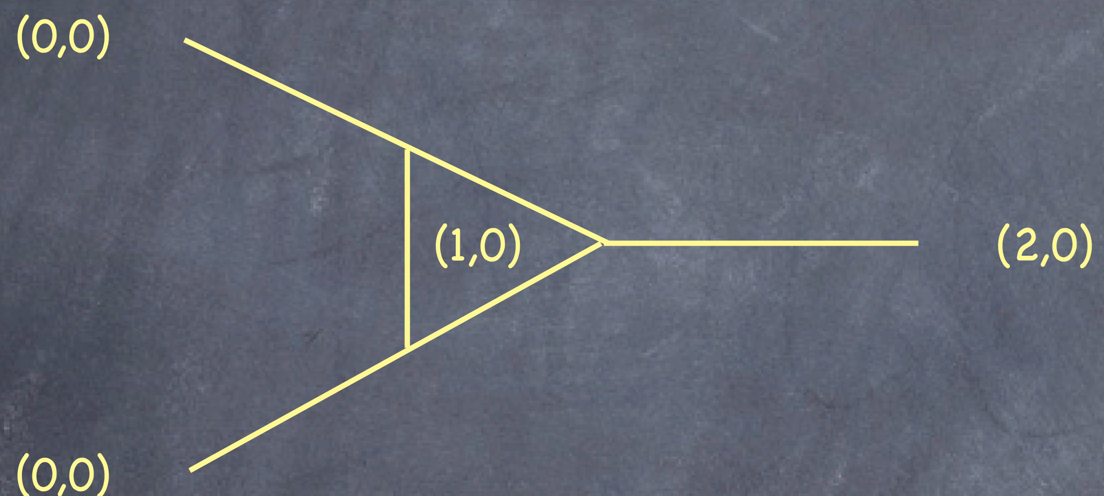
- Bulk interactions: conservation of XD momentum! (from integral of sin/cos → same strength as SM couplings)

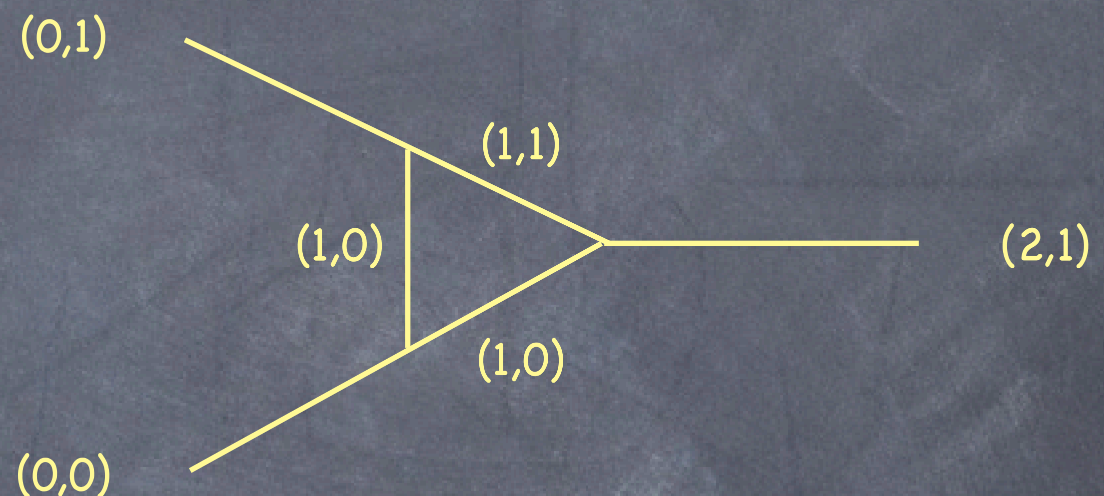


- Only pair production off SM states is allowed!
- Decays are "on-threshold": crucial the small mass splittings!

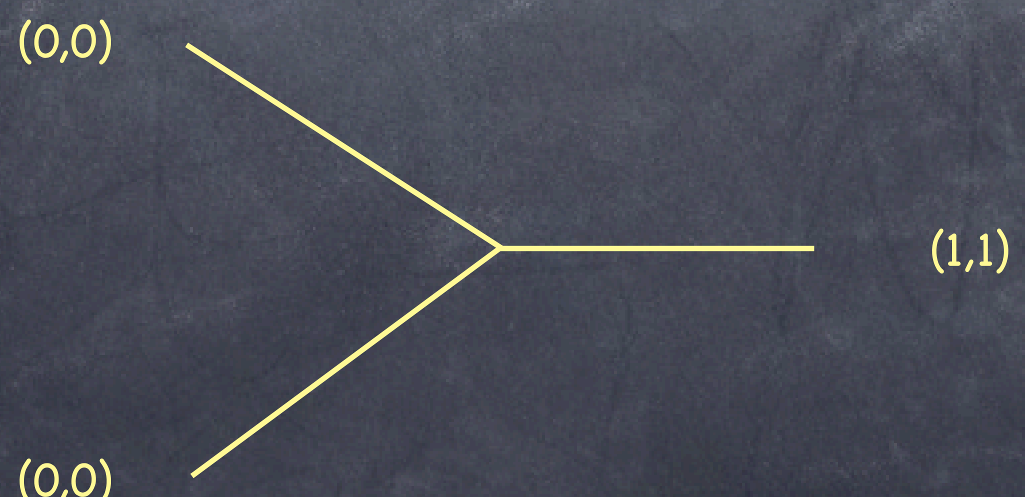
Phenomenology: loop interactions

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



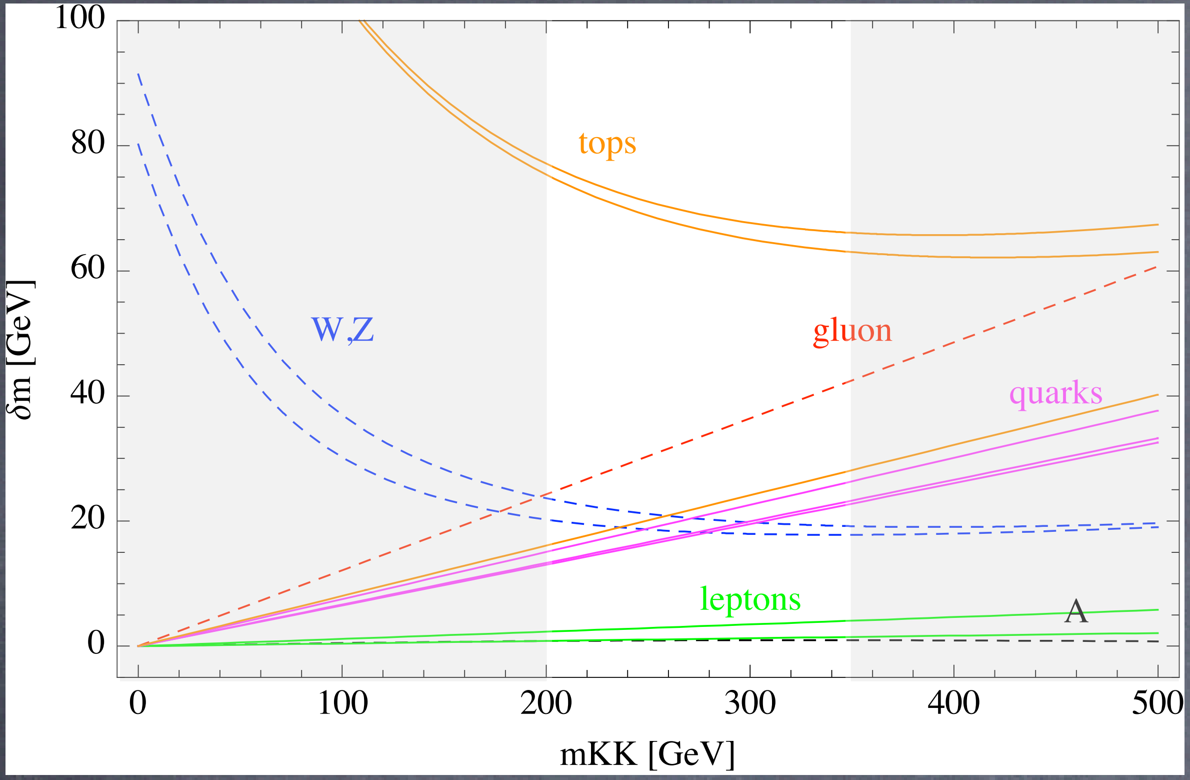


- Localised interactions: even less constrained, only preserve KK parity



Phenomenology at the LHC

Tiers (1,0) and (0,1)



$Z_{(1,0)} \to l_{(1,0)}\, l \to l\, l\, A_{(1,0)}$

100%

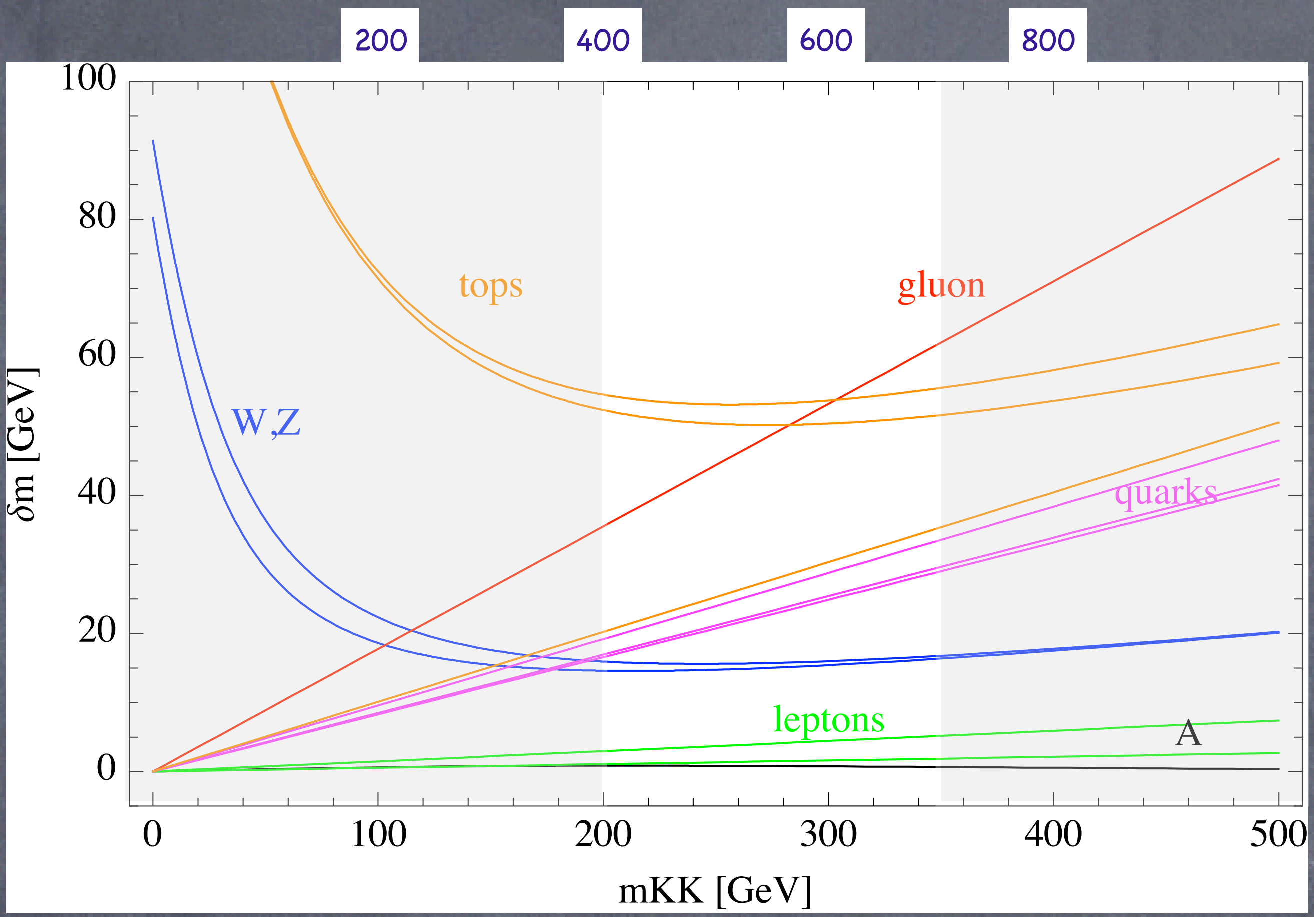
$Q_{(1,0)} \to q\, A_{(1,0)}$

100%

Detailed study in progress!

- Total QQbar cross section huge: 30 pb!
- Jets are typically soft: pT < 30 GeV, challenging to detect!
- High pT jets from ISR and/or boost at production.
- ATLAS and CMS published first bounds on Jet + MET events!

Tiers (2,0) and (0,2)

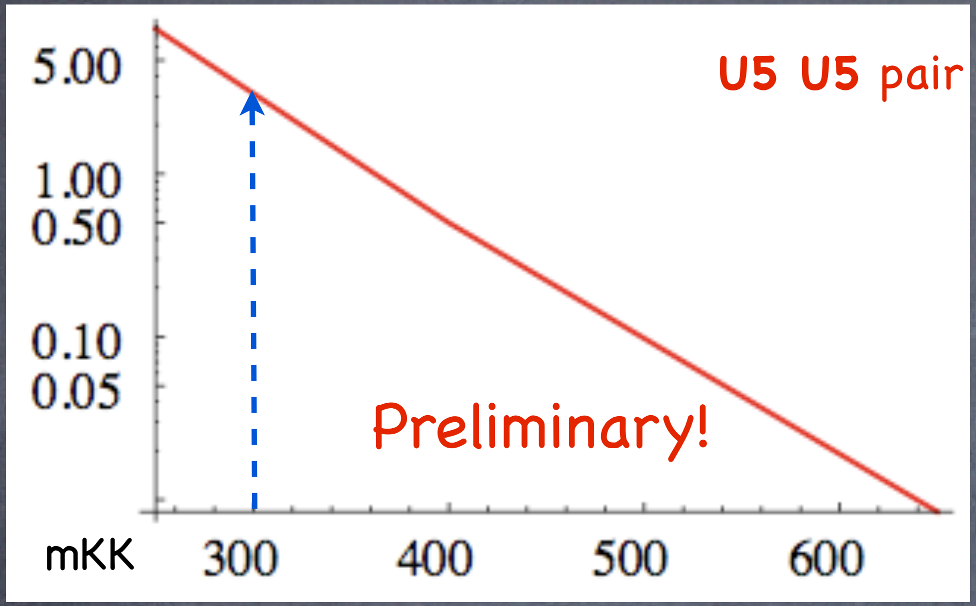


$G_{(2,0)}$ -> $q_{(2,0)}$ q -> ...

-> $q_{(1,0)}$ $q_{(1,0)}$ -> jets + $A_{(1,0)}$ $A_{(1,0)}$

-> di-jets, t t

Tiers (2,0) and (0,2): up quarks



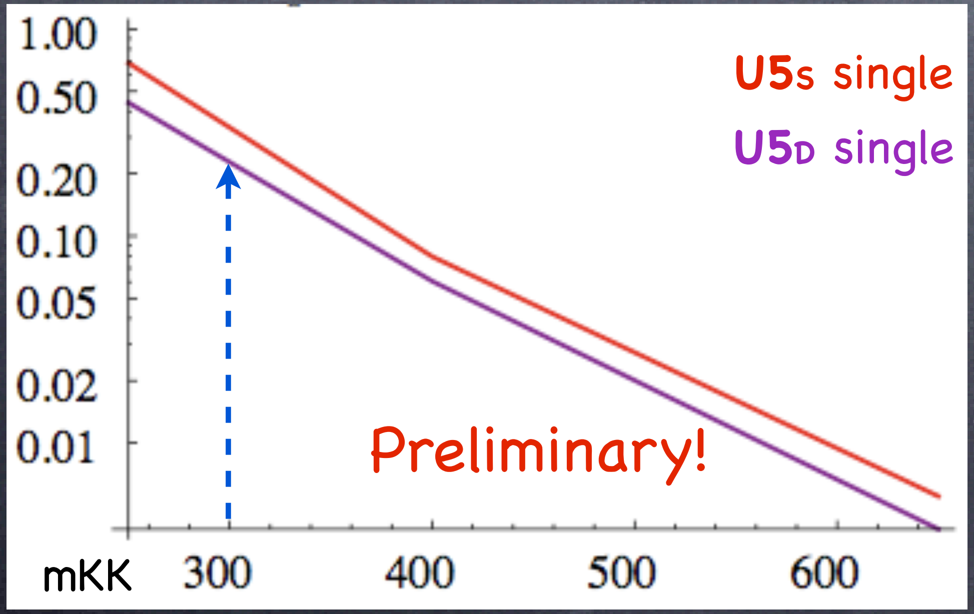
@ 7 TeV

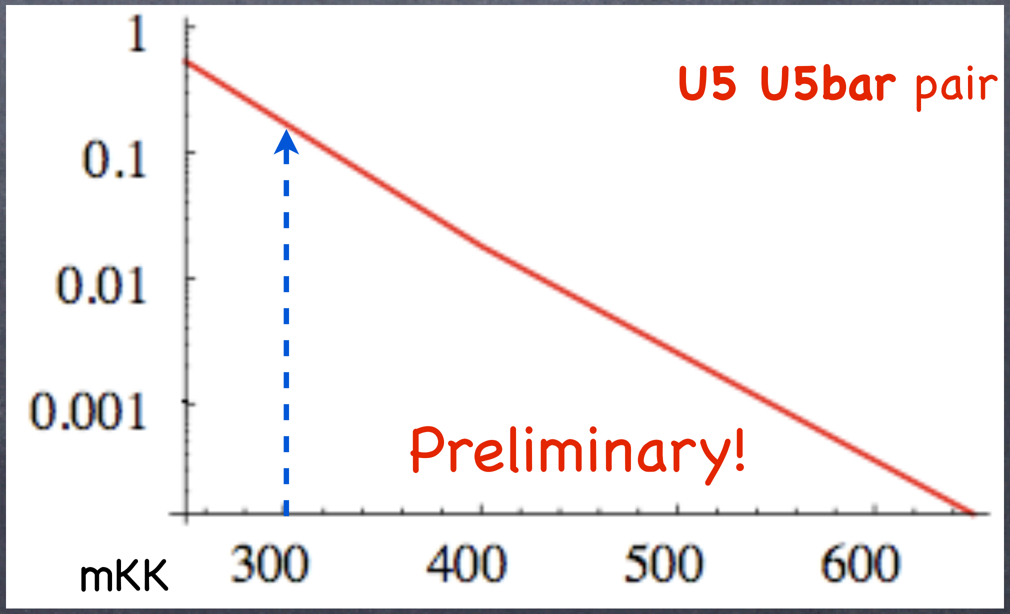
UU pair: 3 pb
Single: 600 fb
UUbar pair: 150 fb

Benchmark point: mKK = 300 GeV

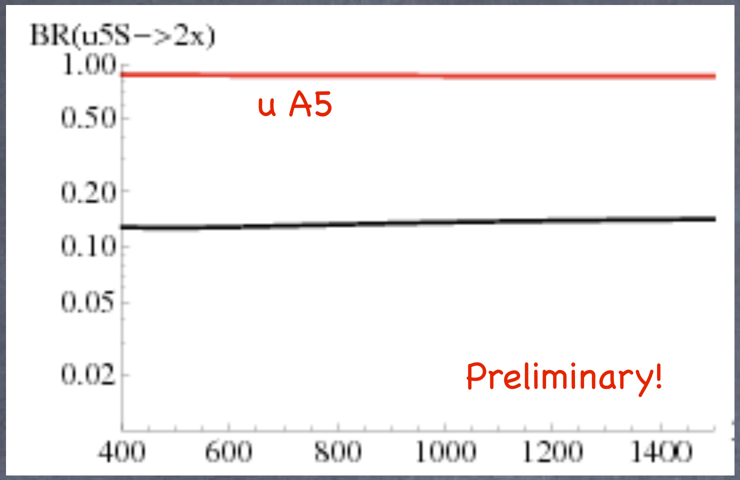
Plots from
J. Llodra-Perez' PhD Thesis

5 -> level (2,0)





Tiers (2,0) and (0,2): ups



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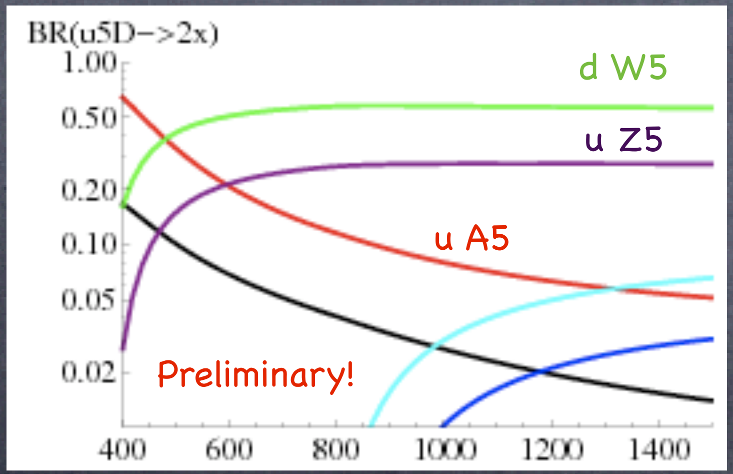


BR(A5 -> jj) = 80%
BR(A5 -> tt) = 20 %

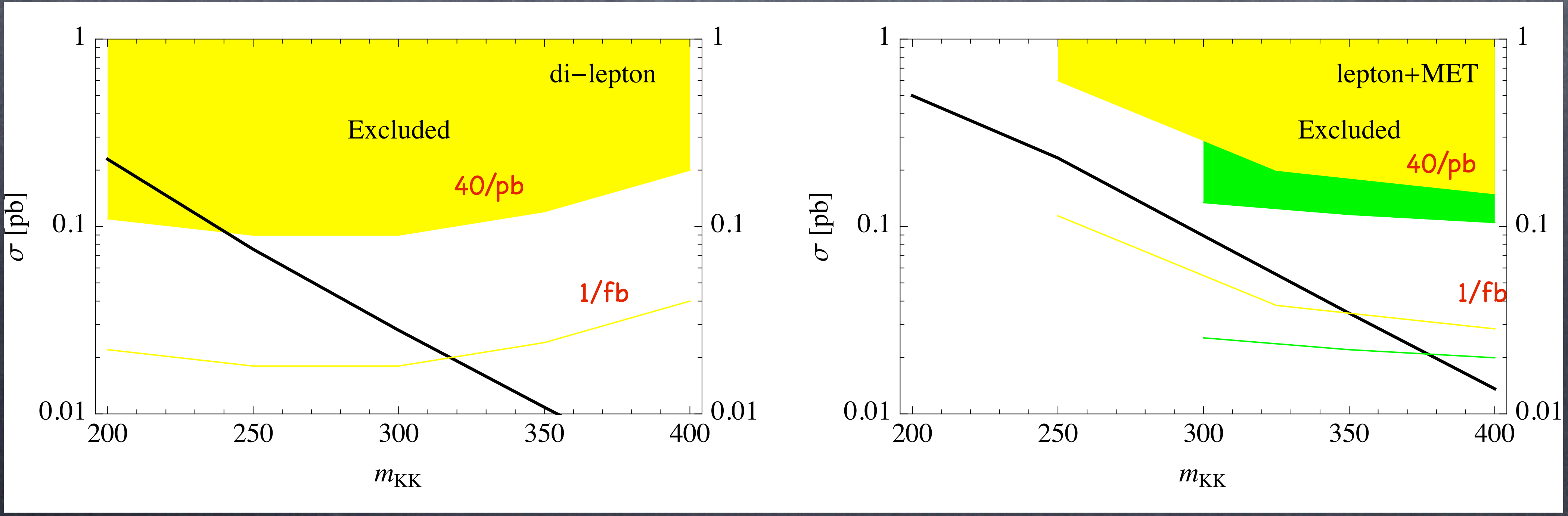
u5S:	625.4
u A5	86%
u1 A1	14%

u5D:	628.8
d W5	50%
u Z5	23%
u A5	22%
u1 A1	5%

Tiers (2,0) and (0,2): resonances

Effective cross sections (fb)
for mKK = 300 GeV

	total	l+l−	l + MET	ttbat	ttt
QQ	4142.7	15.5453	53.143	733.099	42.5807
GQ	4074.	11.0148	32.4113	654.41	30.33
GG	838.	1.3801	3.6089	111.592	4.31129
total	9054.7	27.9401	89.1632	1499.1	77.222



Conclusions and outlook:

XDim & DM can be a happy couple!

- KK parity can be a "natural" (not ad-hoc) symmetry - RPP in 6D
- Interesting models can be implemented: Gauge-Higgs unification, fermion masses, etc.
- We implemented the model in FeynRules (including one-loop corrections): easy interface with calcHep, Madgraph, FeynArt...
- Work in progress: study phenomenology in detail (early LHC), detailed calculation of DM relic abundance and bounds, Model Building (Gauge-Higgs unification, RPP on a sphere...)

Back-up

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

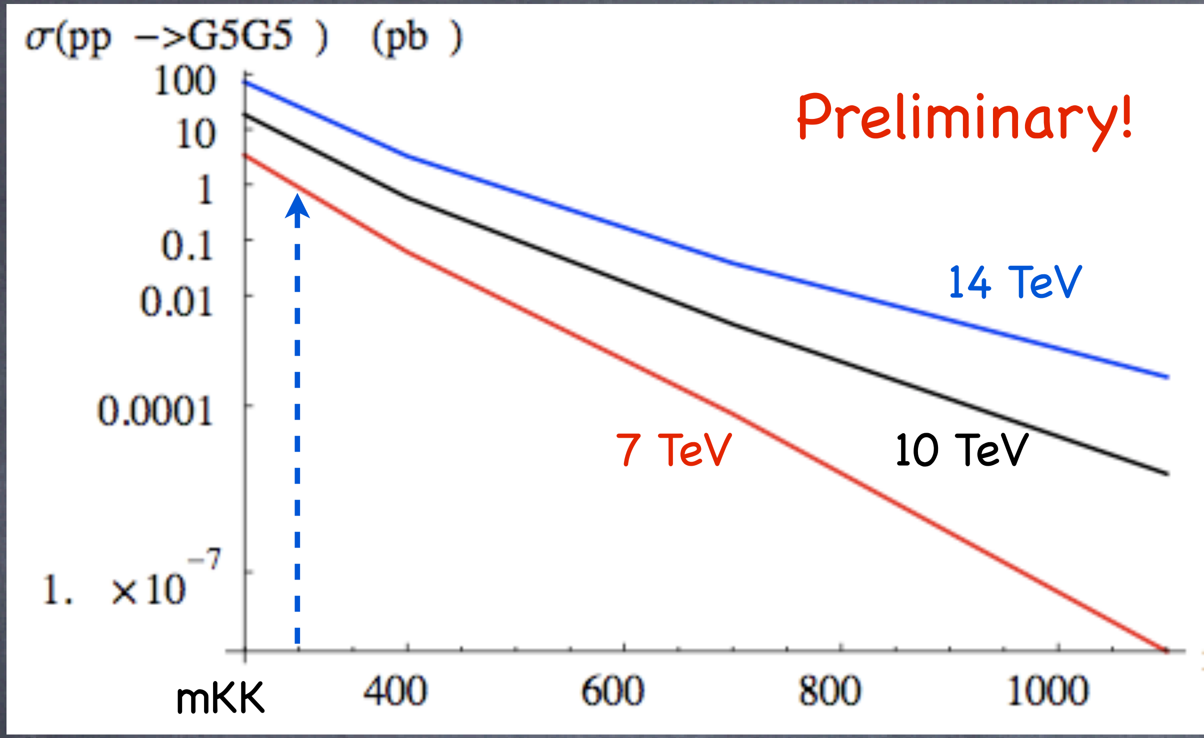
is solved by $$\phi(p, x_5, x_6) = \sum_{k,l} f_{(k,l)}(x_5, x_6) \phi_{(k,l)}(p)$$

4D field!

with:

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

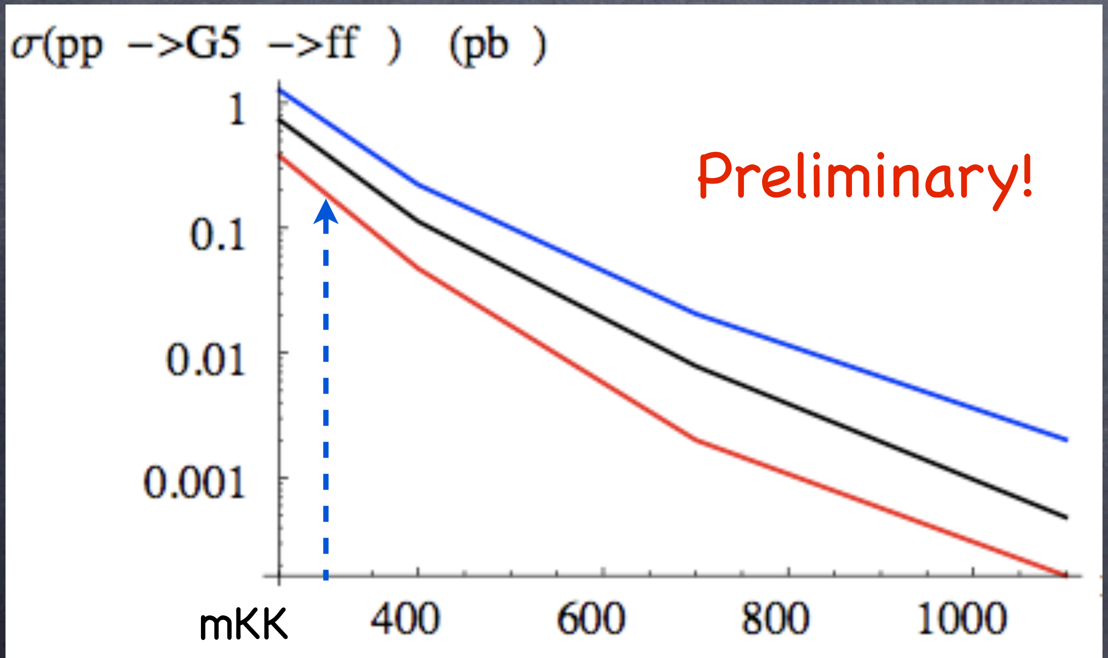
Tiers (2,0) and (0,2): gluon

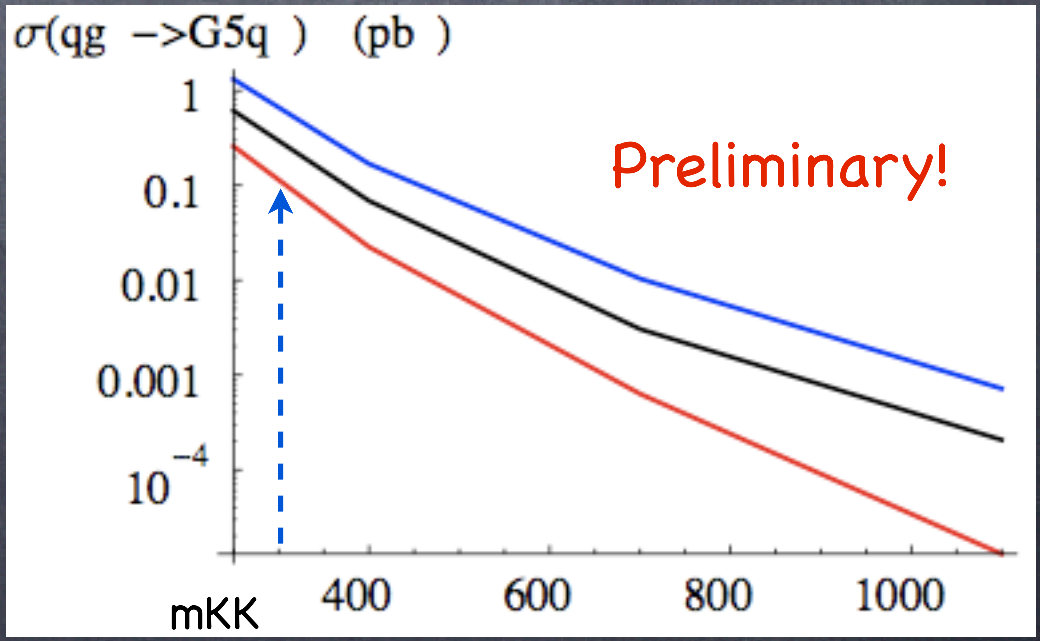


@ 7 TeV

Pair: 1 pb
Single: 200 fb
q+single: 100 fb

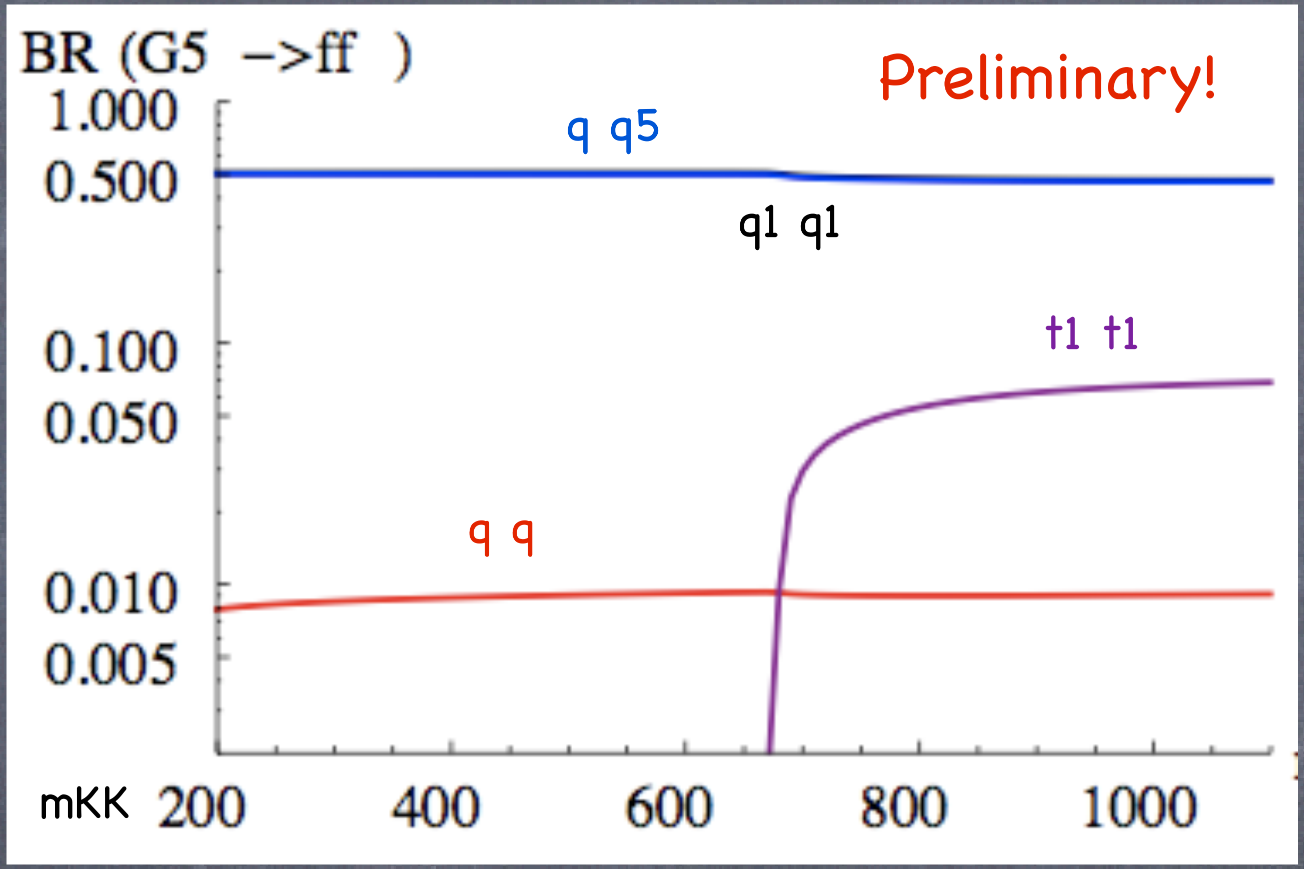
Plots from
J. Llodra-Perez' PhD Thesis





Tiers (2,0) and (0,2): gluon

5 -> level (2,0)
1 -> level (1,0)



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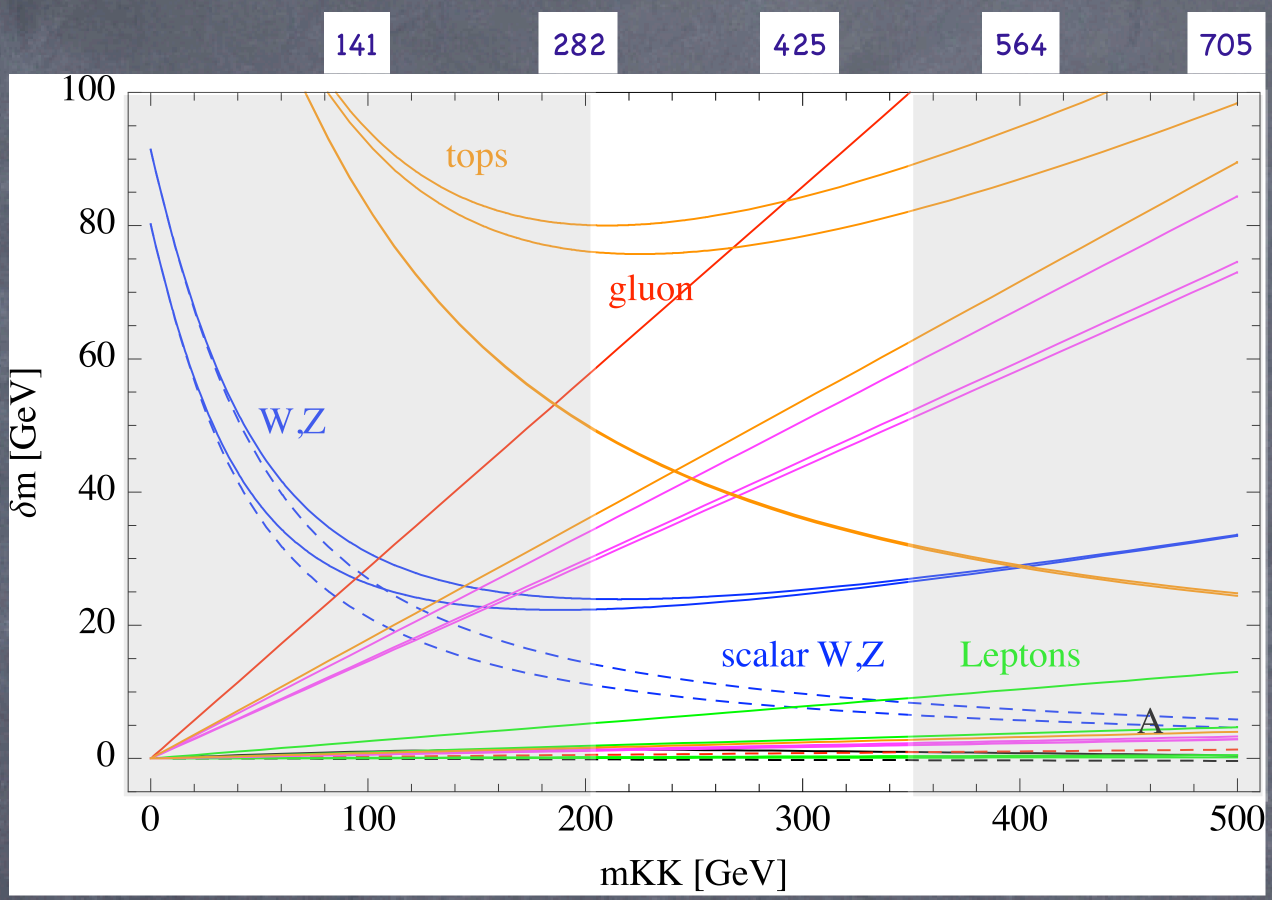
Circa 50% in q $q_{(2,0)}$ and 50% in $q_{(1,0)}$ $q_{(1,0)}$
1% in qq (jet jet)

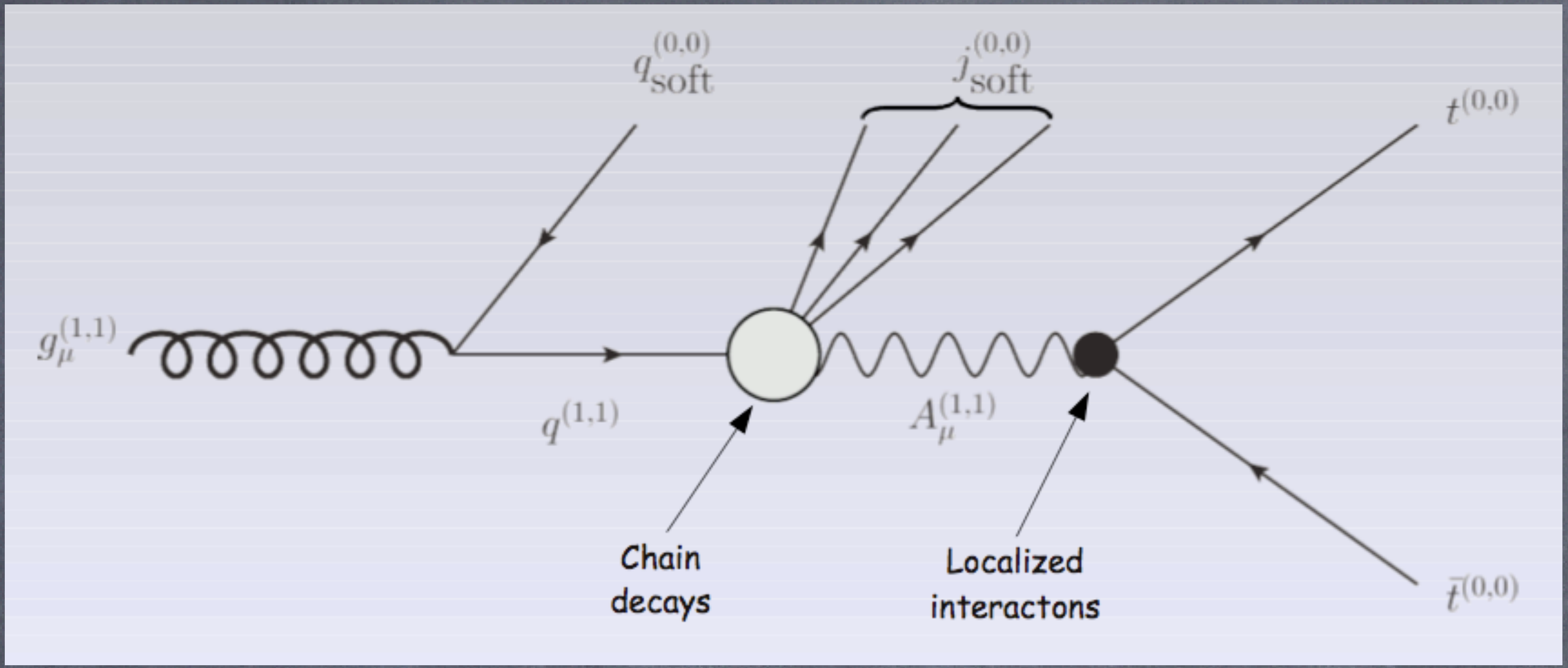
Note: $q_{(1,0)}$ $q_{(1,0)}$ is invisible!

Tier (1,1)



- mostly pair produced! Each state will decay within the level!
- decays of $A_{(1,1)}$ controlled by localised operators: may be stable or long lived, may decay preferably to heavy SM particles (tops?)
- interesting 4 tops signature!!

Tier (1,1)



Very large cross sections at 7 TeV!

Analysis in progress with CMS group in Lyon

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