Extra Dimensions, Dark Matter and the LHC

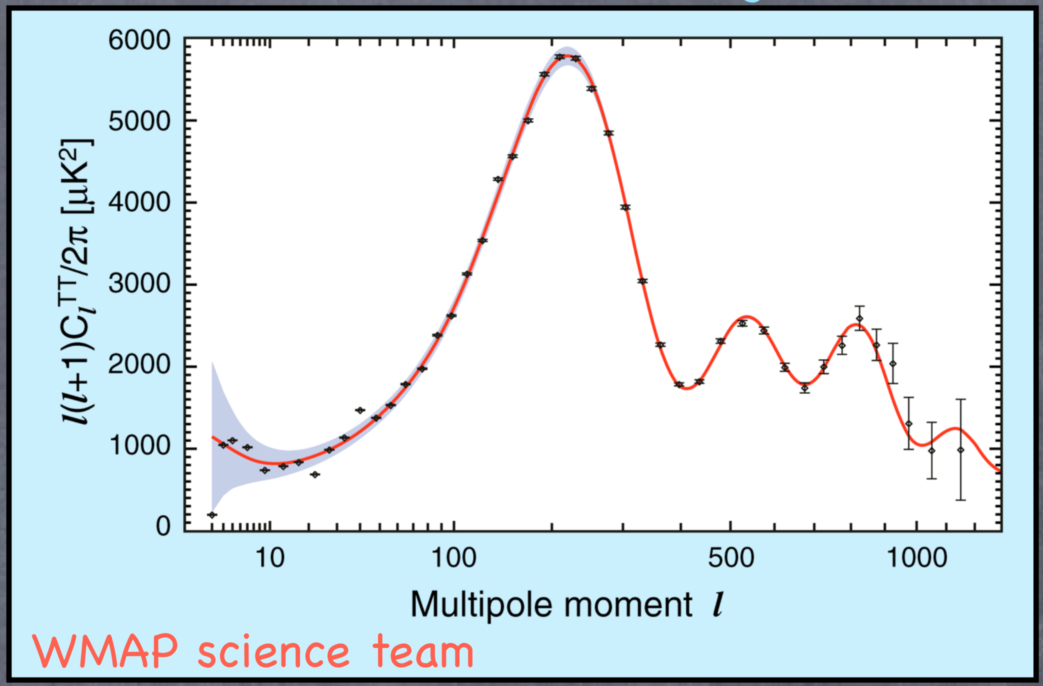
Giacomo Cacciapaglia
IPN Lyon (France)

Quy Nhon, 19 July 2012
Rencontres du Vietnam

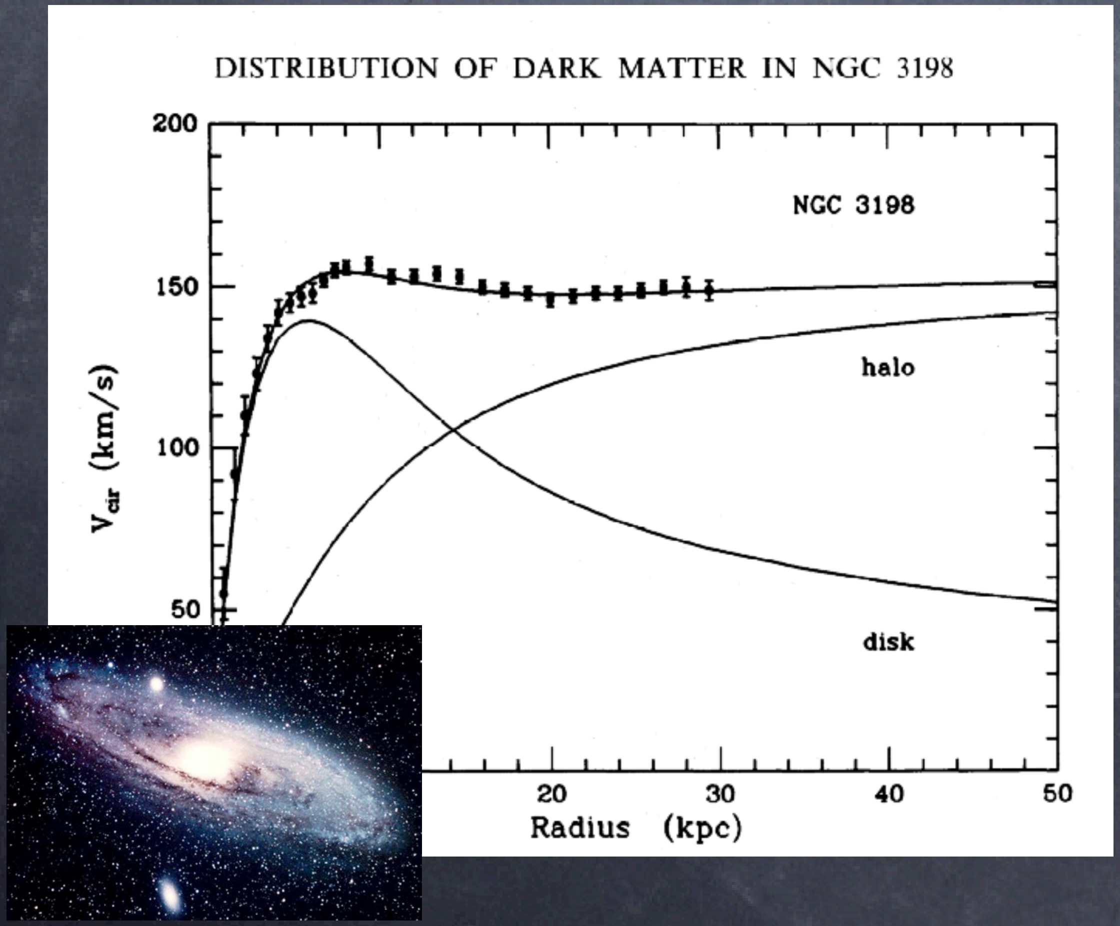
Why do we need Dark Matter?

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

Cosmic Microwave Background:



Astrophysical measurements:

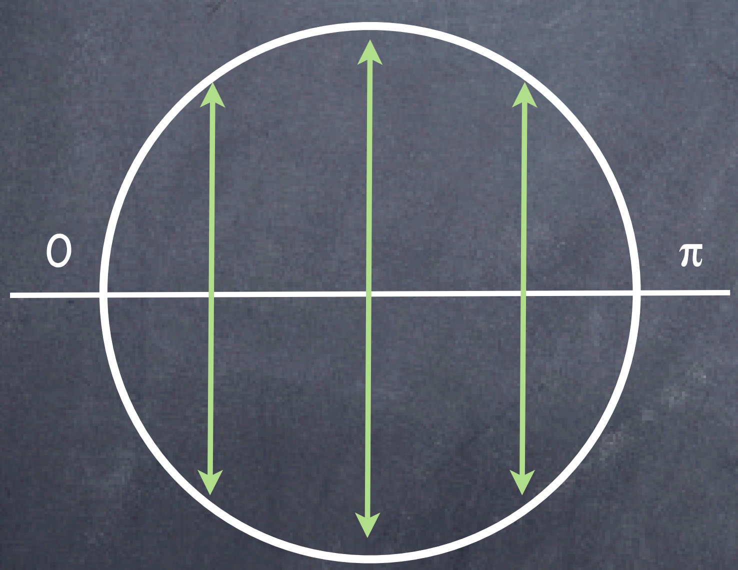


- The Universe contains 4.6% of baryons, and 23.3% of unknown matter.
- The flat rotation curves of spiral galaxies can be explained by the presence of extra non-luminous matter.

Extra dimensions are a versatile tool:

Can a parity arise ``naturally'' from extra dimensions?

- Symmetries of the compact space ARE parities for the Kaluza-Klein modes!
- The physics is in the wave functions: for instance



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

$$\begin{cases} \cos(kx_5) \to \cos k(2\pi - x_5) = \cos(kx_5) \\ \sin(kx_5) \to \sin k(2\pi - x_5) = -\sin(kx_5) \end{cases}$$

Is this enough?

DM and XD, a troubled couple?

The typical situation is:

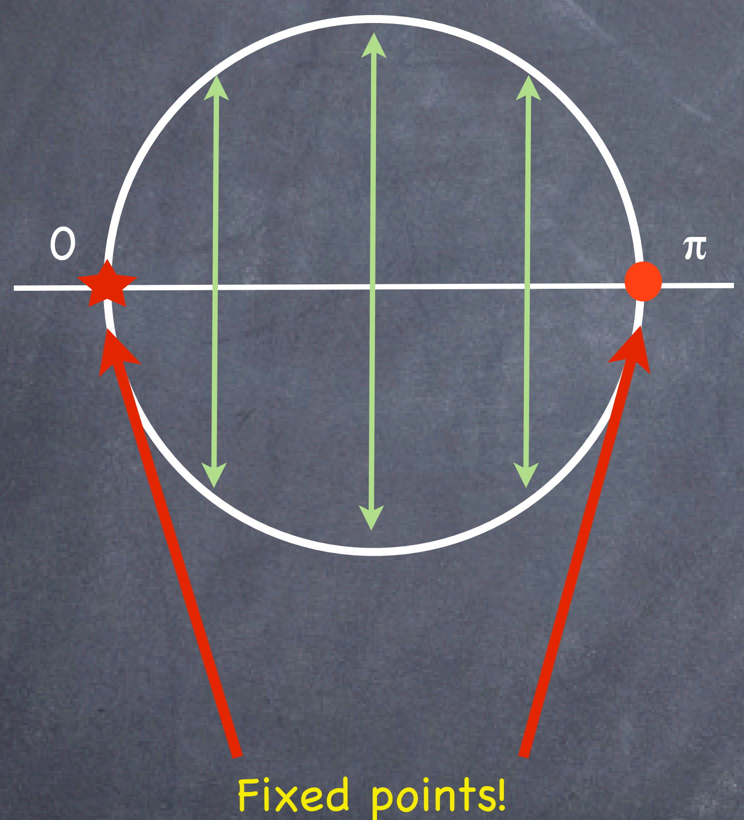
Let's consider the simplest case: one compact extra dimension!

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

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

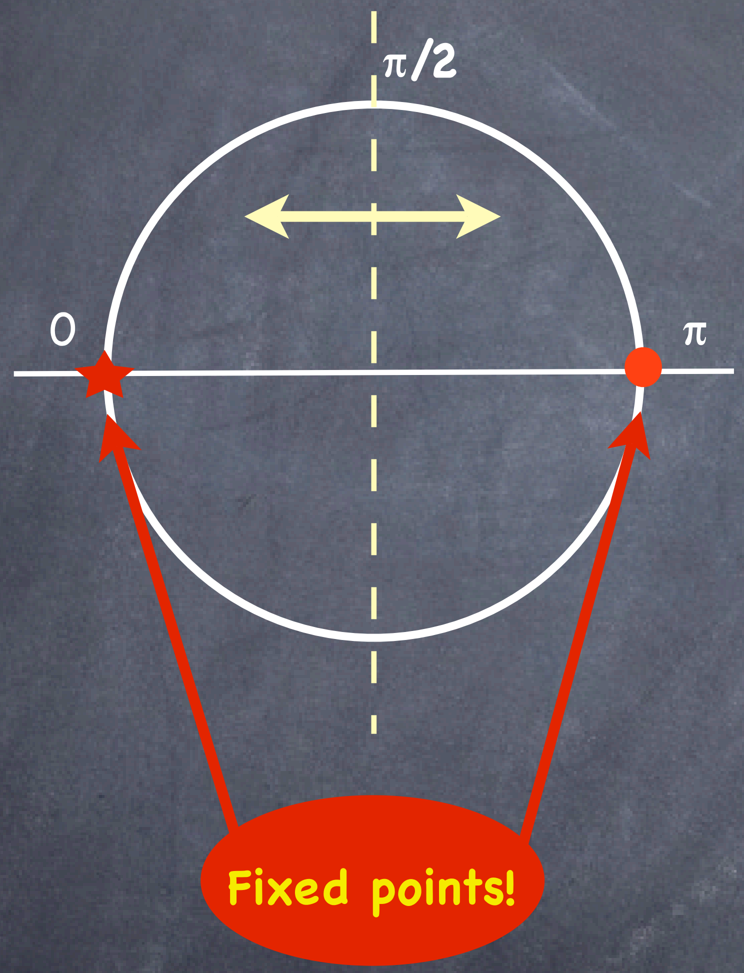
Each field has a fixed parity, and
KK modes of different parity are removed!

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

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!

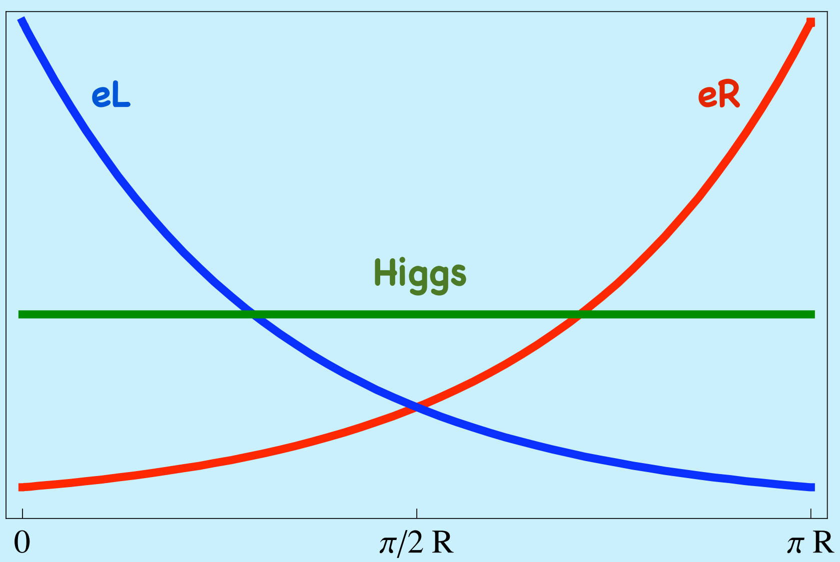
We need to impose a symmetry on the fixed points to have a DM candidate!!!

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

KK parity is not natural!

The typical situation is:

In Gauge-Higgs models (Hosotani mechanism)
fermion localisation is essential!



Bulk fermion masses break
the KK parity!

Already pointed out by
Barbieri, Contino, Creminelli, Rattazzi, Scrucca
hep-th/0203039

it has nothing to do with the extraD!!

Do orbifolds exist without fixed points and with chiral fermions?

G.C., A.Deandrea, J.Llodra-Perez 0907.4993

- 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!

Requiring an exact parity
and chirality is rather restrictive!

The flat real projective plane

$$\mathbf{pgg} = \langle r, g | r^2 = (g^2 r)^2 = \mathbf{1} \rangle$$ G.C., A.Deandrea, J.Llodra-Perez 0907.4993

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

Translations defined as:

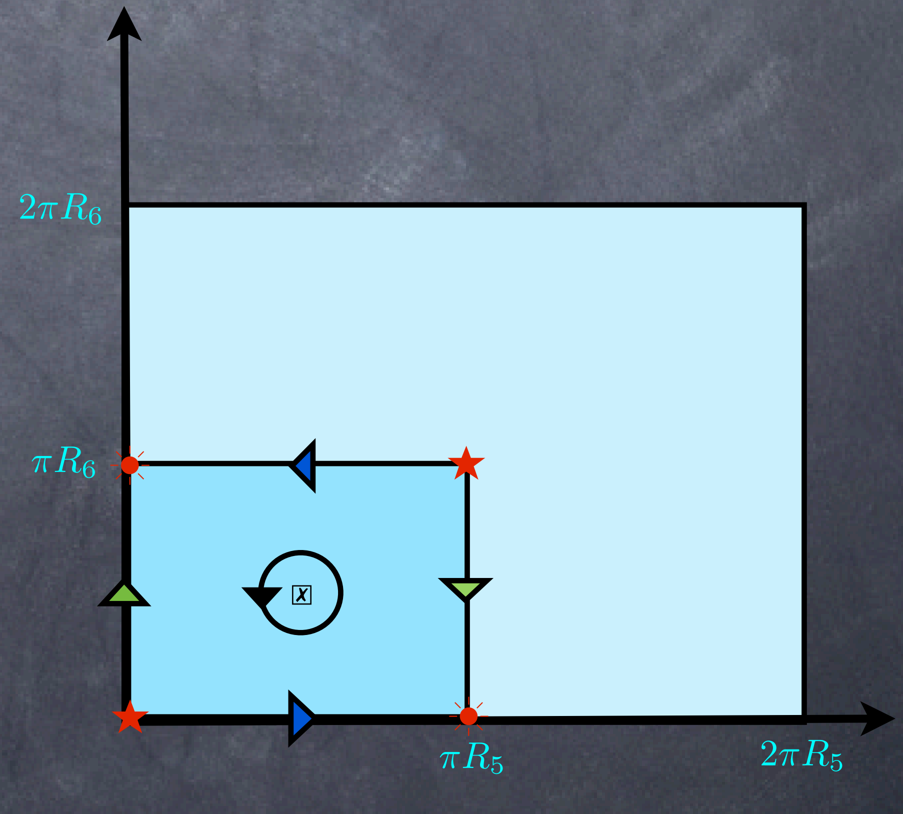
$$\begin{aligned} t_5 &= g^2 \\ t_6 &= (gr)^2 \end{aligned}$$

Two singular points:

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

KK parity is an exact symmetry of the space!

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



The flat real projective plane

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

G.C., A.Deandrea, J.Llodra-Perez 0907.4993

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

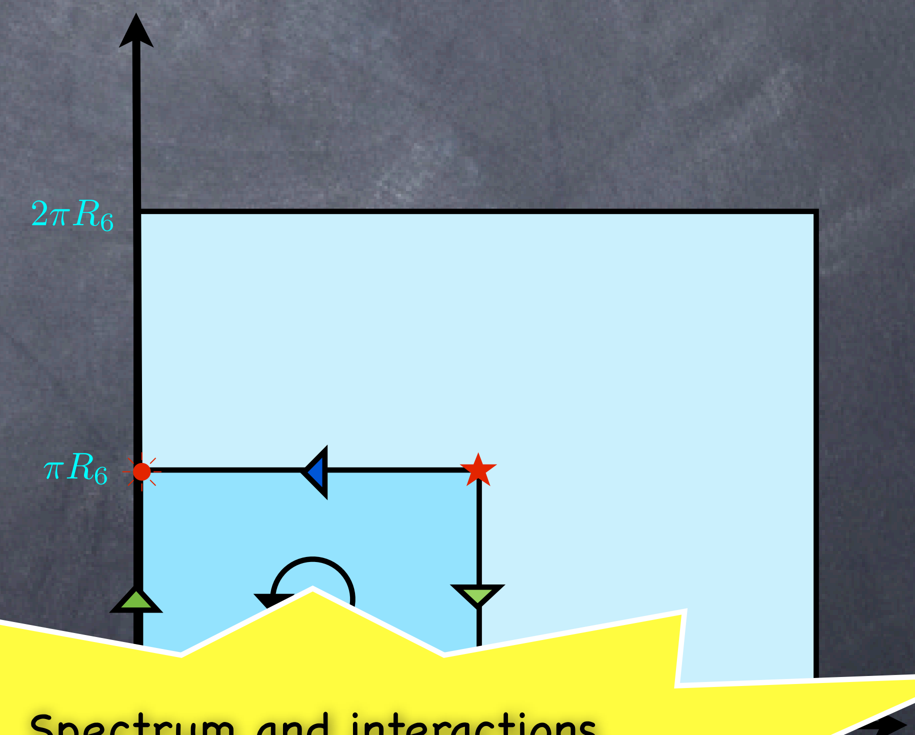
Translations defined as:

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

Two singular points:

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

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



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 and interactions determined by these symmetries!

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!

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)

One-loop corrections are crucial to determine spectrum and decays!

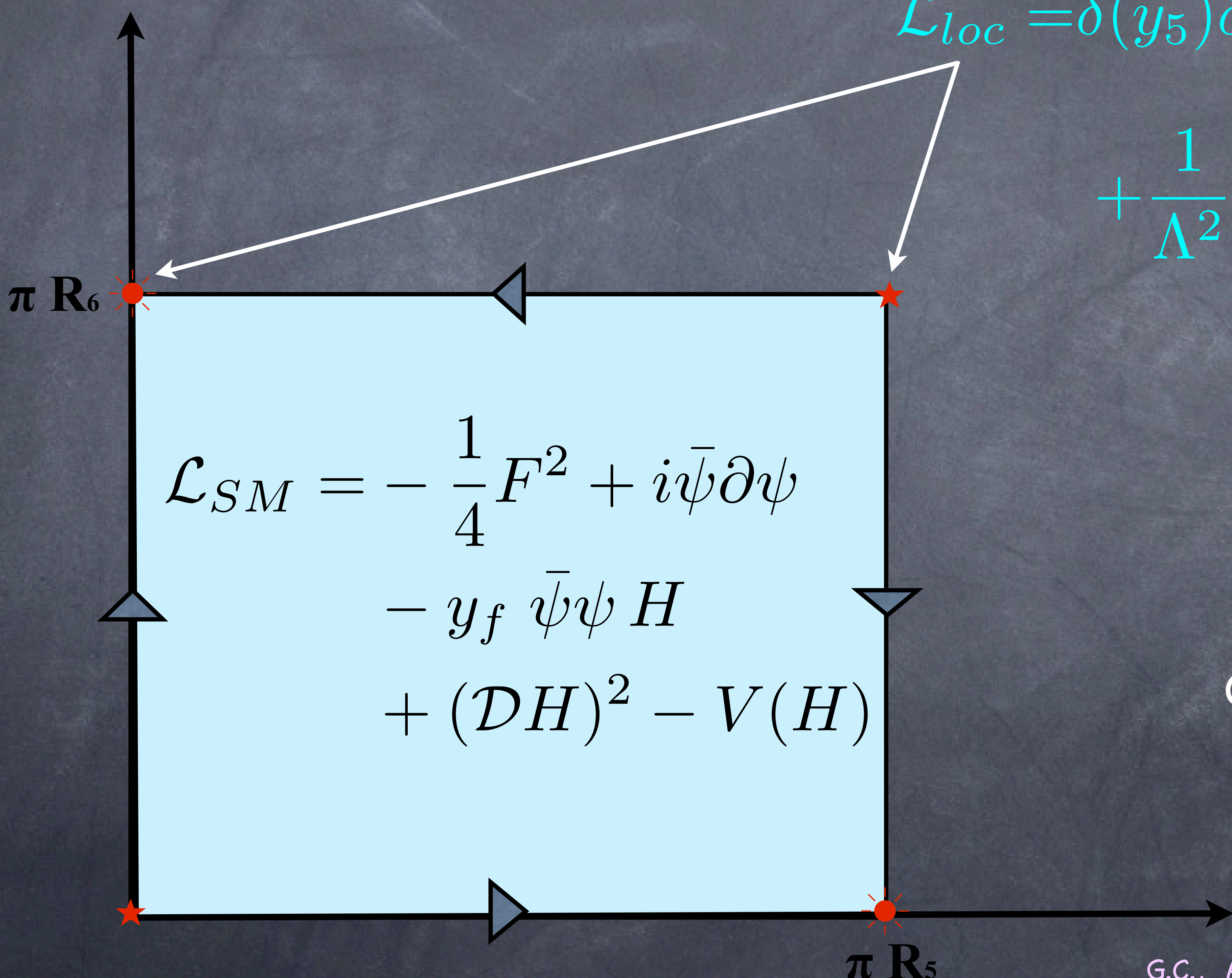
G.C., A.Deandrea, J.Llodra-Perez 1104.3800

Spectrum of the SM

Localised: KK number violating!

Bulk: KK number conserving!

$$\mathcal{L}_{loc} = \delta(y_5)\delta(y_6)\left\{ -m_{loc}^2 H^2 + + \frac{1}{\Lambda^2}\left(-\frac{1}{4}F^2 + \ldots \right) \right\}$$



Higher order operators!

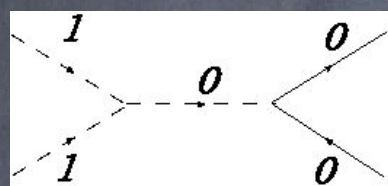
Counter-terms for 1-loop log divergences!

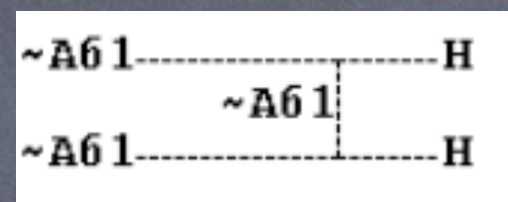
G.C., A.Deandrea, J.Llodra-Perez 1104.3800

WMAP bounds!

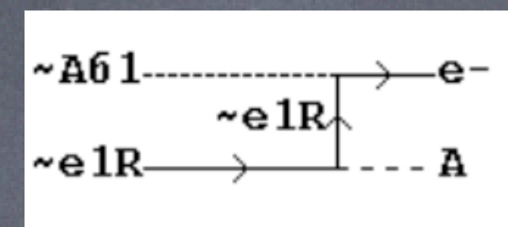
A.Arbey, G.C., A.Deandrea, B.Kubik 1207.????

There are several equally relevant contributions:

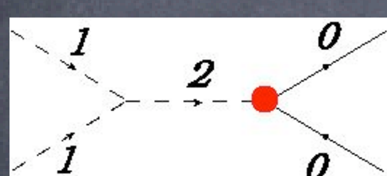


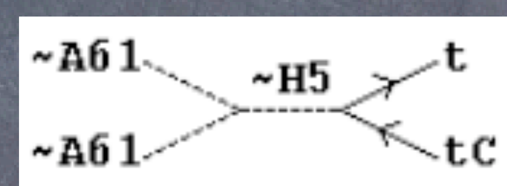


Annihilation

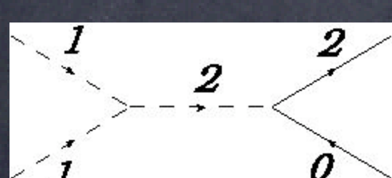


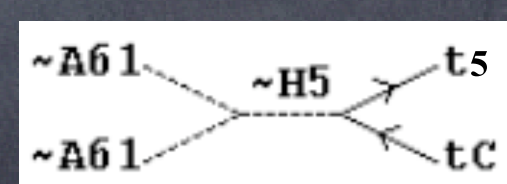
Co-annihilation
(small mass splitting)





Resonant annihilation
(s-channel level 2 states!)

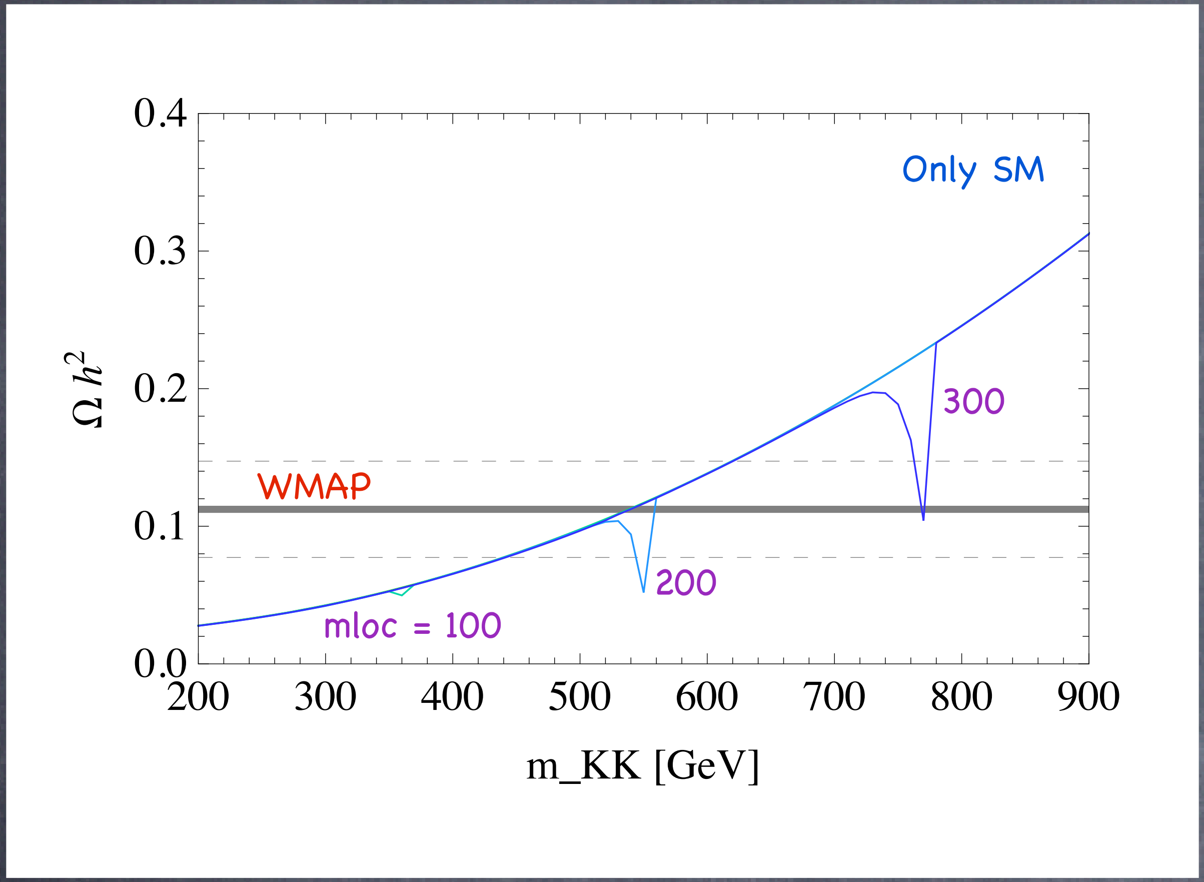


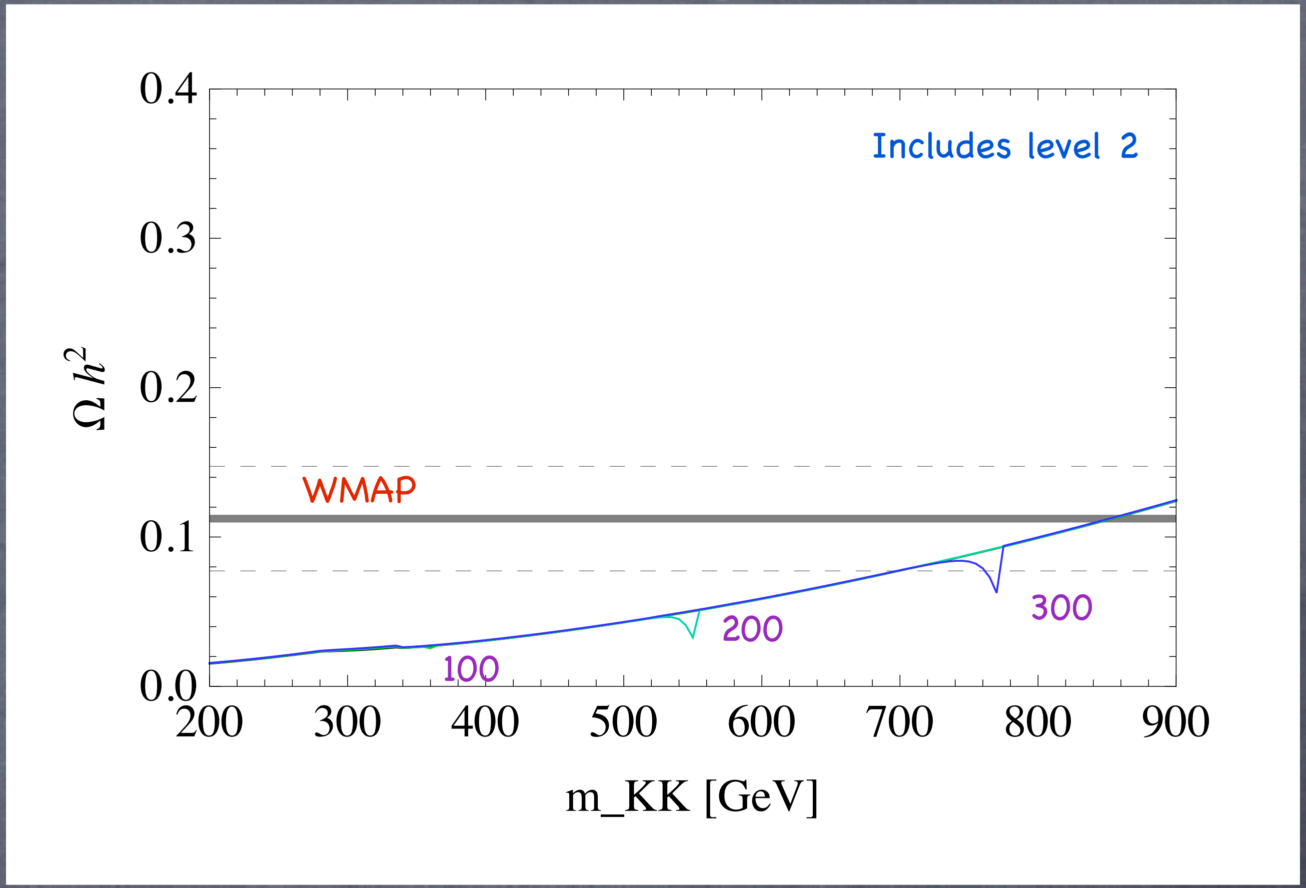


G.Belanger, M.Kakizaki, A.Phukov 1012.2577

Level 2 annihilation
(level 2 decaying into SM pair!)

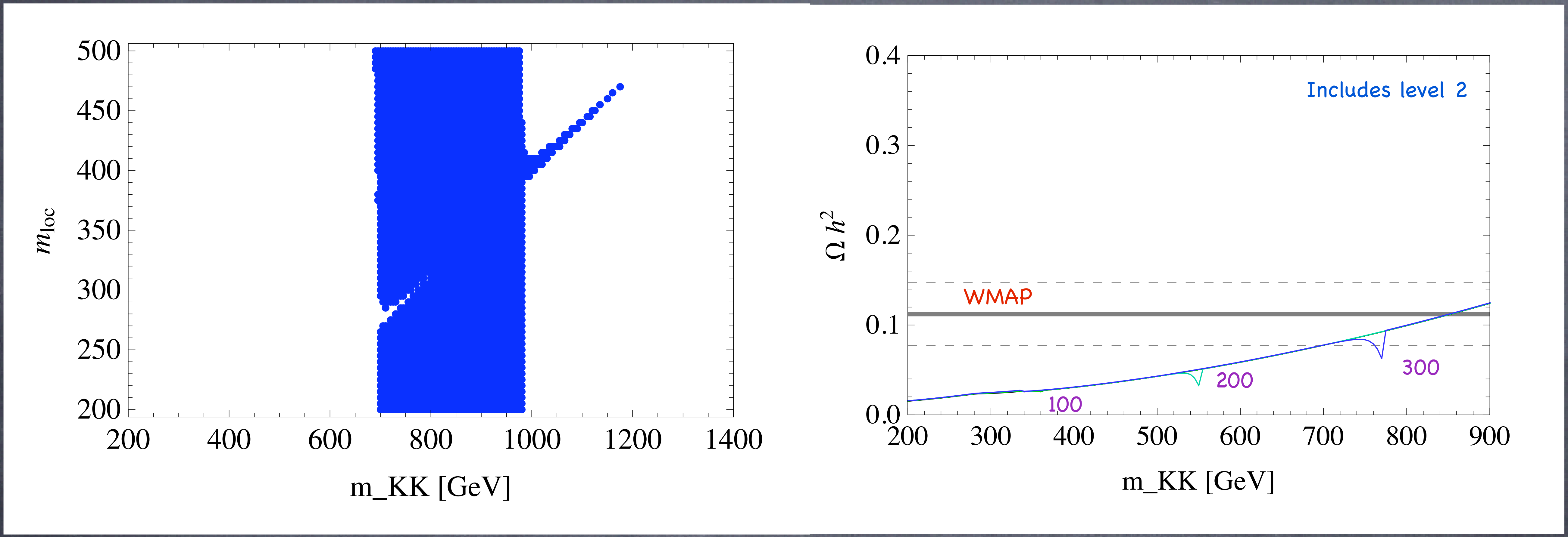
WMAP bounds!





- Annihilation into level-2 ⇒ increased cross-sections ⇒ higher mKK
- mloc controls $H_{(2,0)}$ resonance!
- $H_{(2,0)}$ opens resonant funnel!

WMAP bounds!



- Annihilation into level-2 ⇒ increased cross-sections ⇒ higher mKK
- mloc controls $H_{(2,0)}$ resonance!
- $H_{(2,0)}$ opens resonant funnel!

WMAP preferred range:

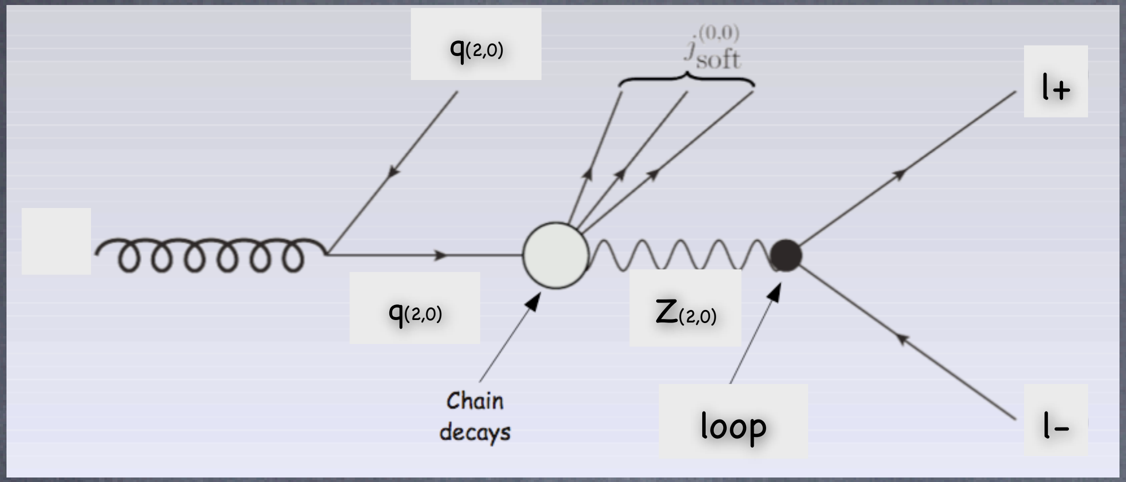
700 < mKK < 1000

LHC: signatures without MET:

tiers (2,0) and (0,2)

G.C., B.Kubik: w.i.p.

- Cleanest channels are di-lepton (Z') and single lepton + MET (W'):

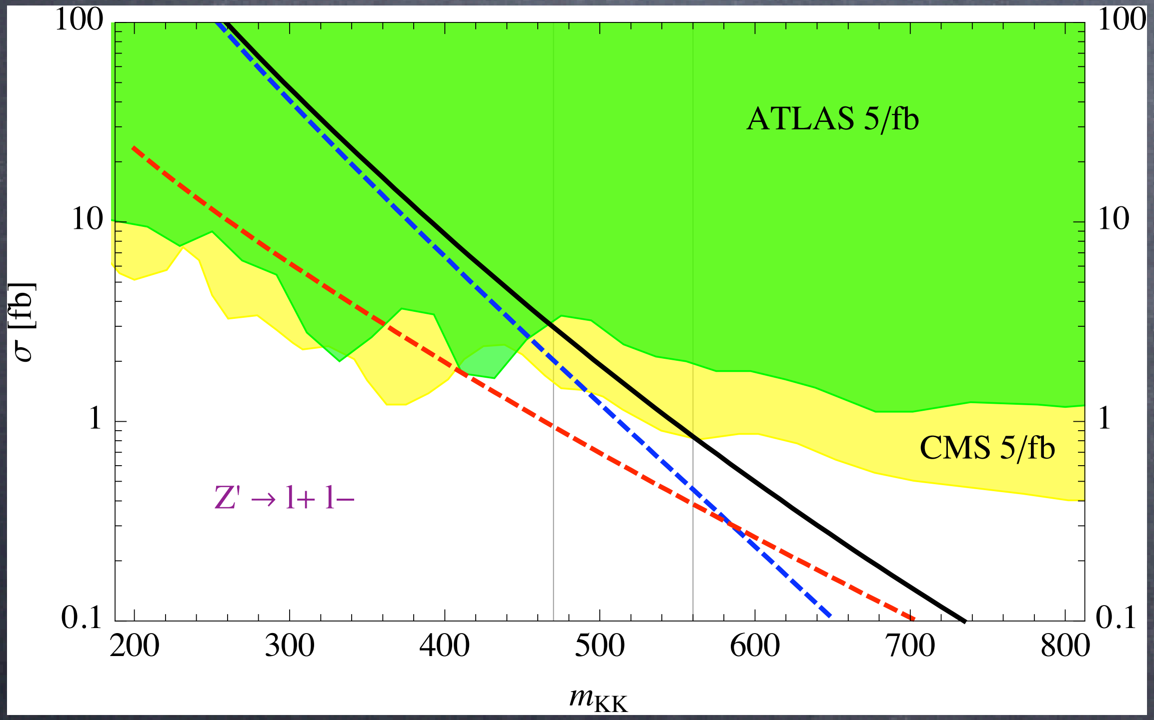


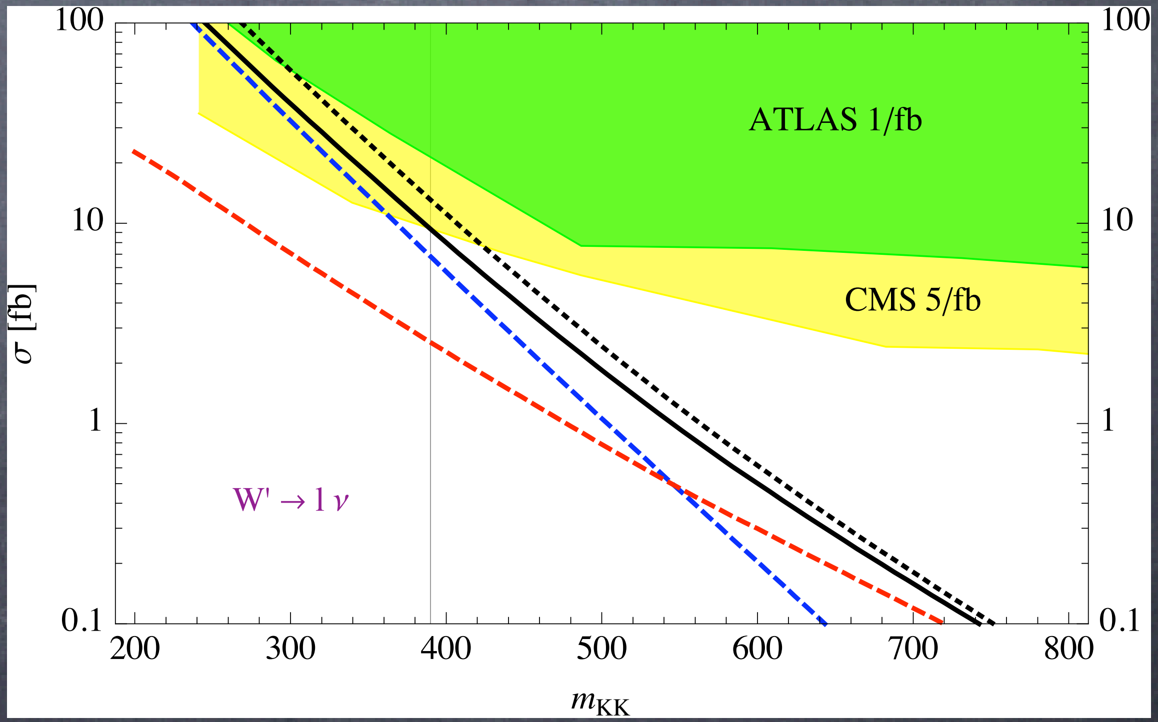
$Z_{(2,0)}$, $A_{(2,0)}$ -> l l

BR: 0.2% !!

$W_{(2,0)}$ -> l ν

2011 Data only!





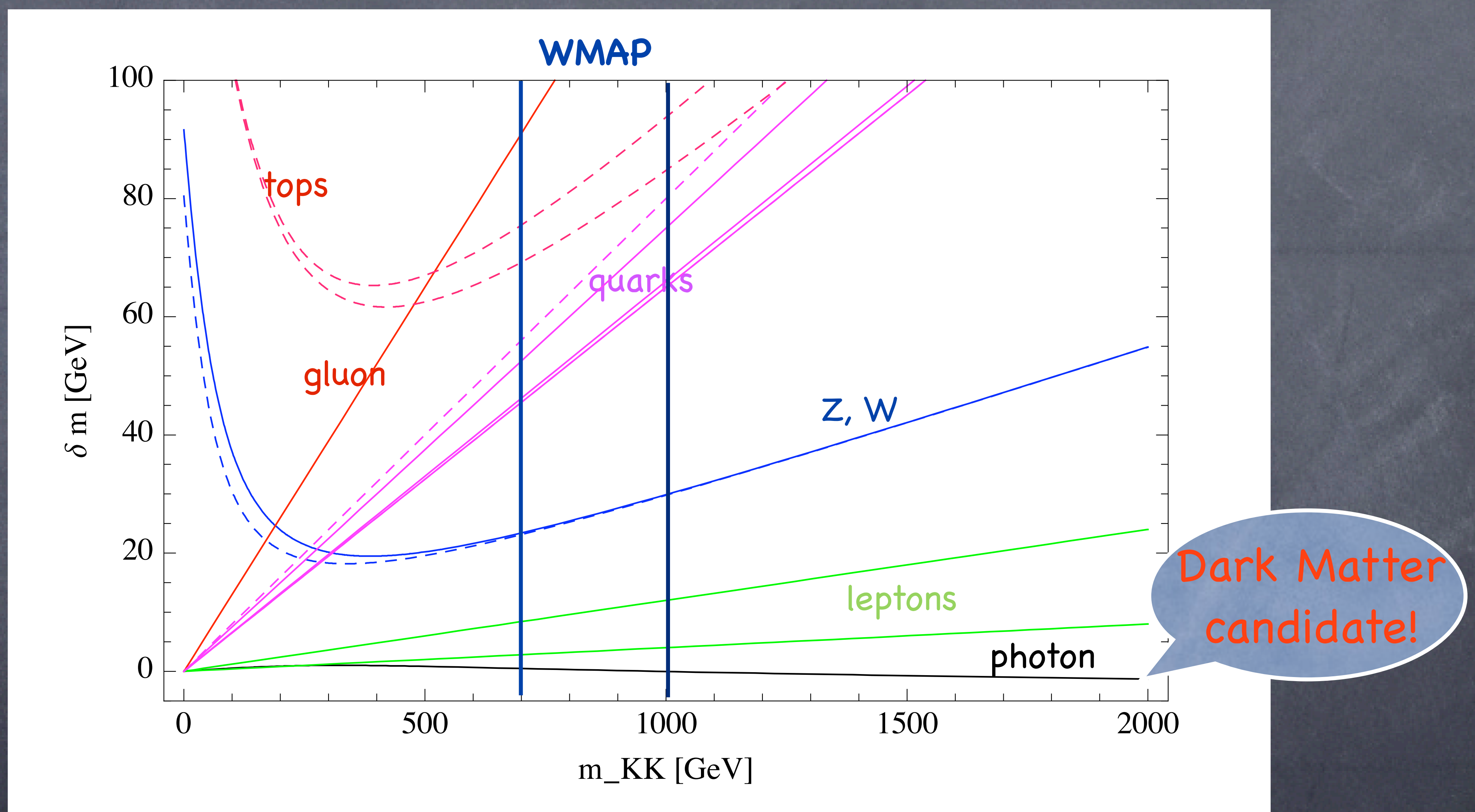
$R_5 > R_6$

Conclusions and outlook

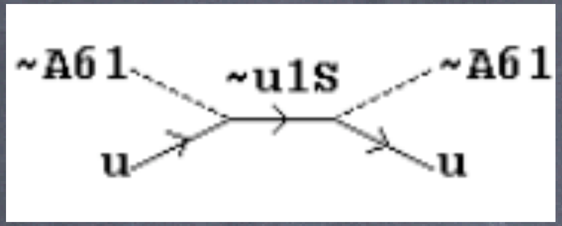
- KK parity can be a “natural” (not ad-hoc) symmetry
- Very selective requirement on XDs: RPP in 6D!
- Interesting models can be implemented: Gauge-Higgs unification, fermion mass hierarchies, etc.
- It is a selection rule for ``interesting” XDim scenarios!
- SM on the RPP: rich but challenging pheno (small splitting!)

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

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



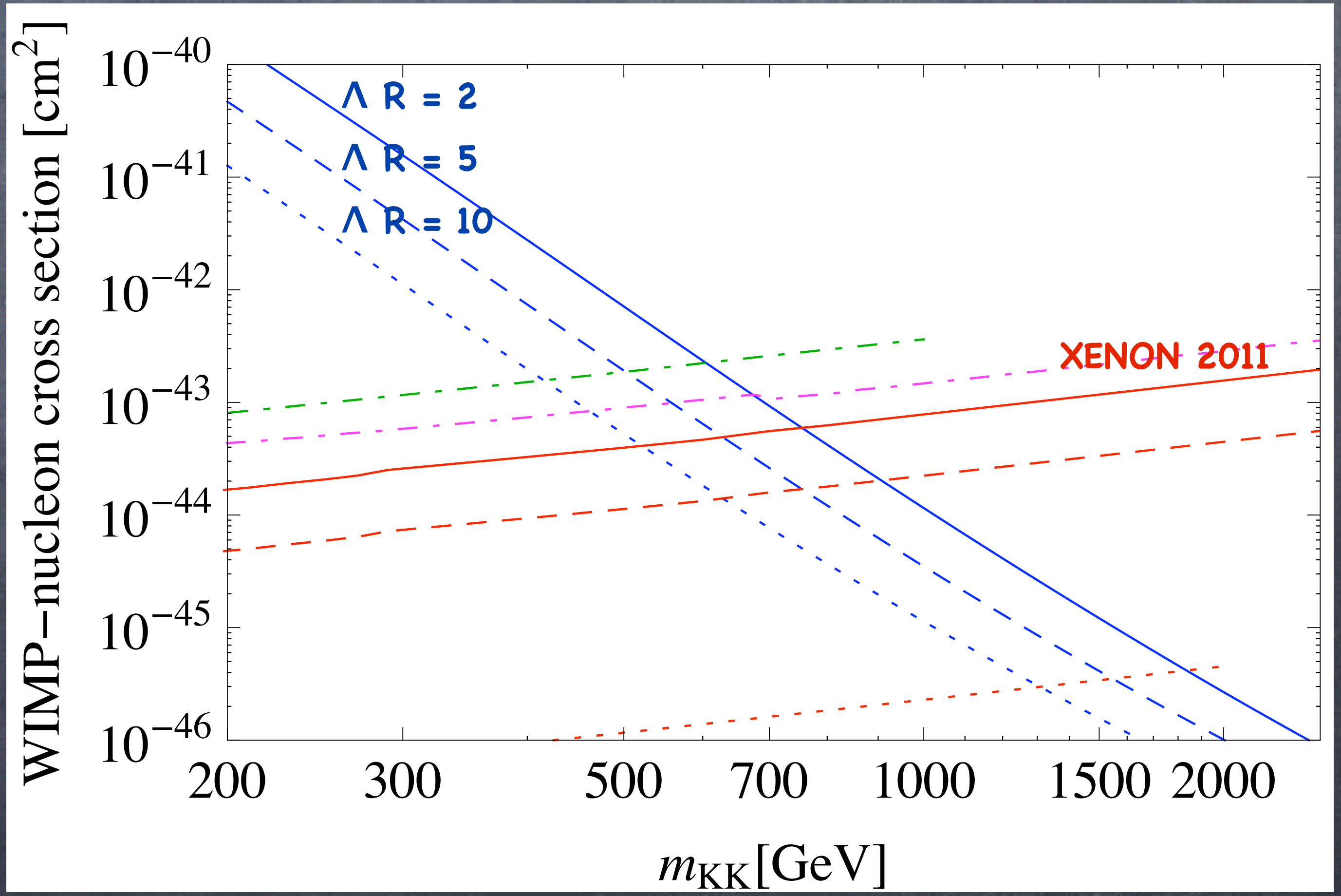
Direct detection bounds



Relevant processes:
crucial the loop corrections
to level-1 masses!

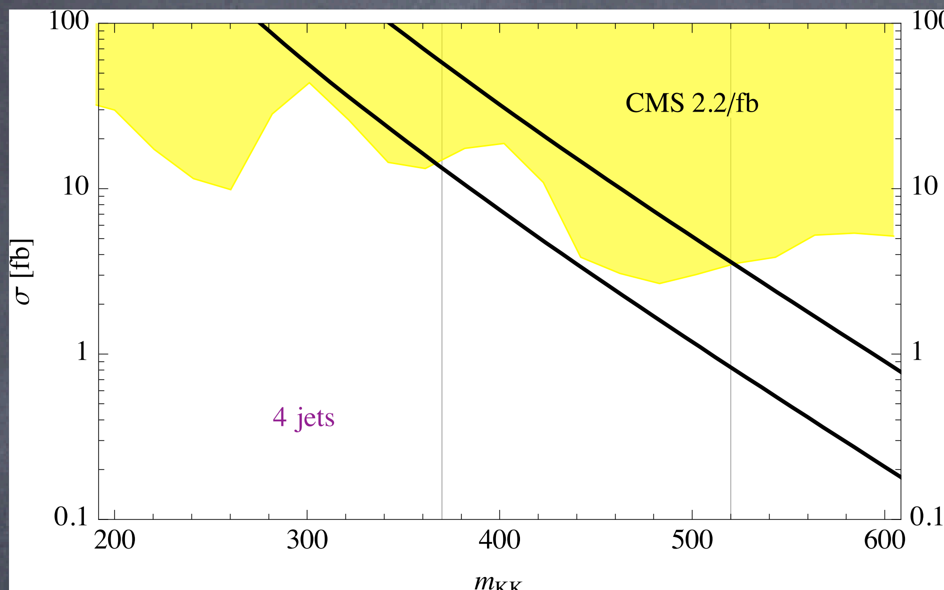
- The Spin-Independent cross section is enhanced by the small splittings!

Bound sensitive to
cut-off Λ
via log-div. loops!

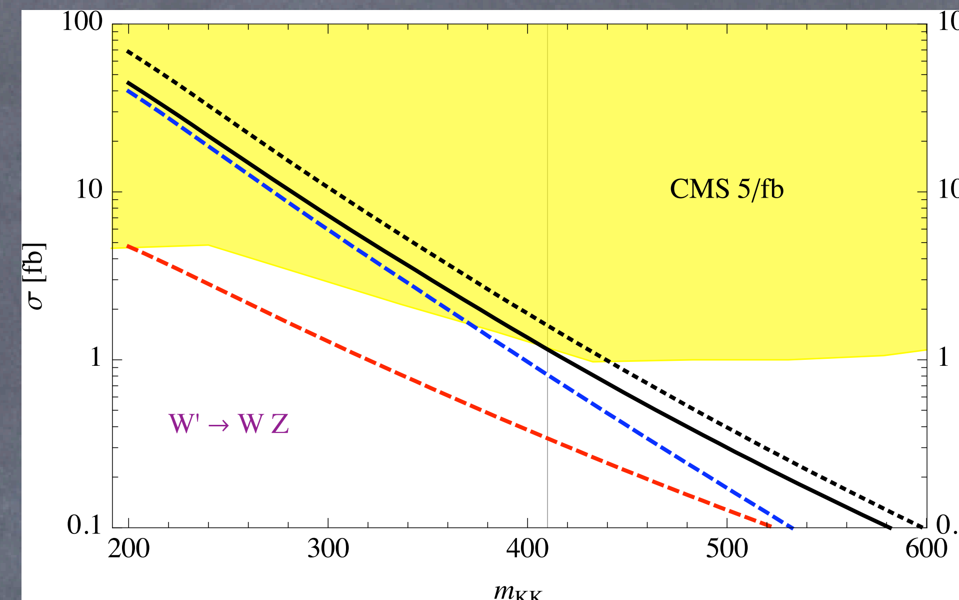


Other LHC bounds

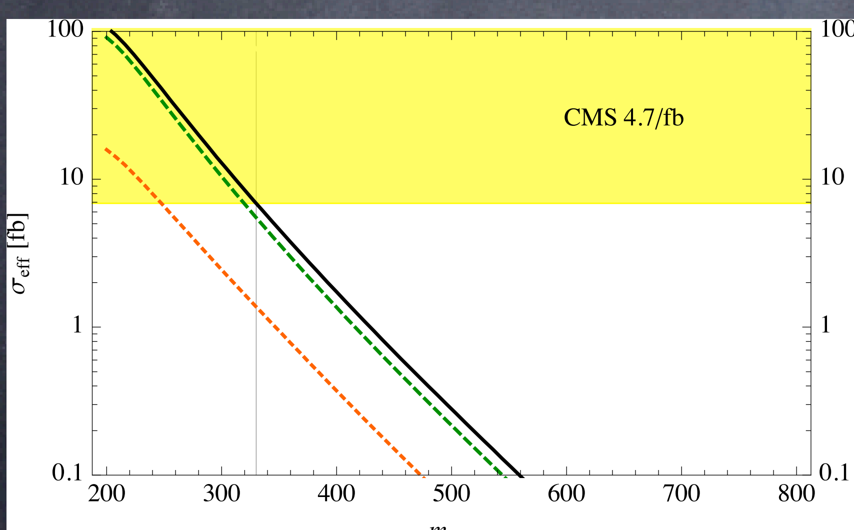
Pair of di-jet resonances



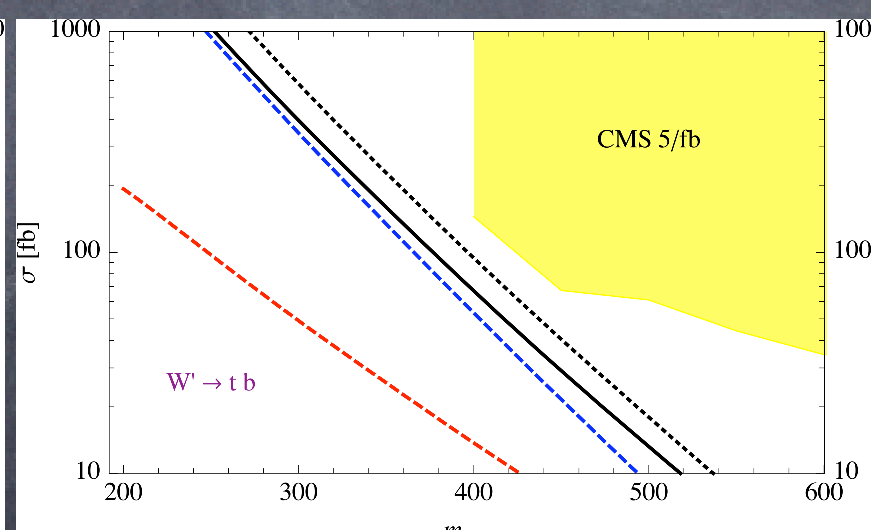
W' -> W Z



ss dilepton from 4tops



W' -> t b



Z' -> t t