All Other Scenarios

Giacomo Cacciapaglia

IPN Lyon

UK HEP FORUM "Higgs and BSM"

Corsener's House, 22-23 November 2012

All Other Scenarios

The veritable BSM*

* Beyond Sypersymmetry Models

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Supersymmetry has been carefully studied, however...

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BSM has a rich zoology of models!

Composite Higgs, tops

Little Higgs

Gauge-Higgs Unification

Technicolour

Low scale gravity

Minimal Dark Matter

Dark Matter in Extra dimensions (UED)

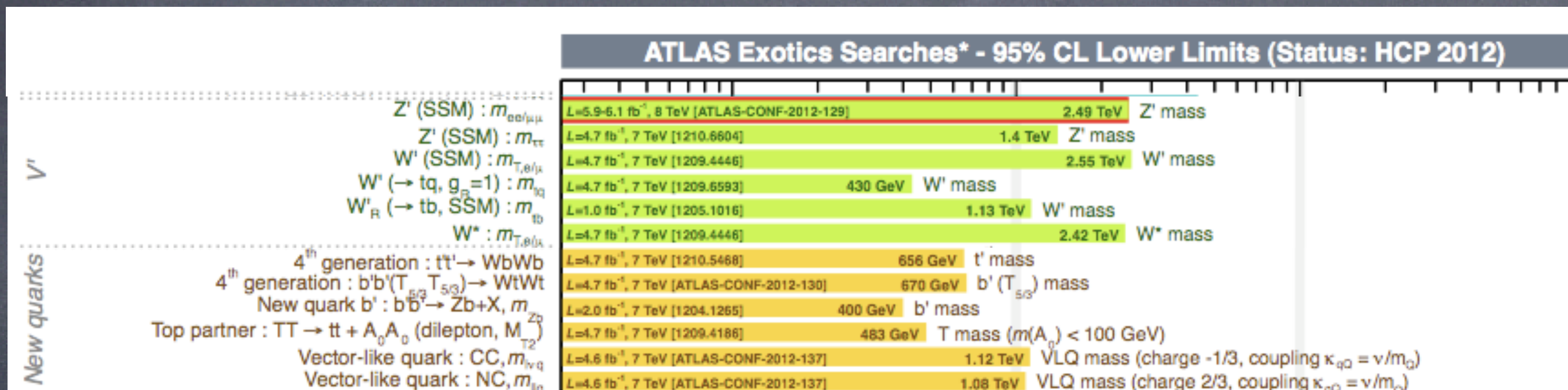
Low scale see-saw

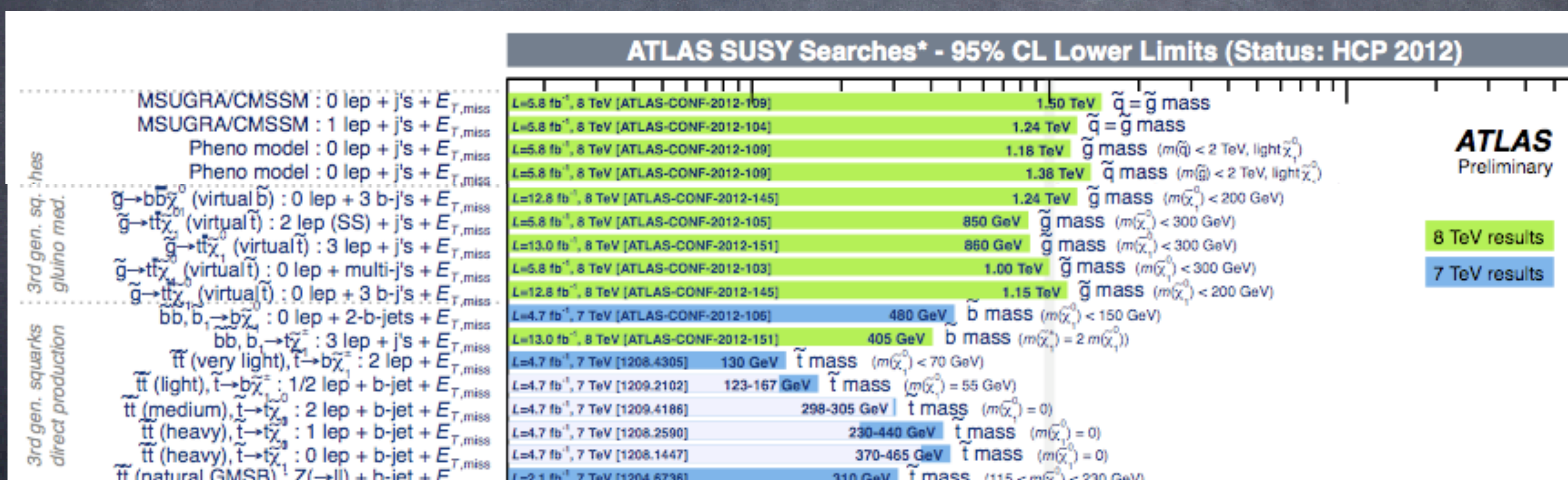
Naturalness!

Dark Matter!

LHC results:

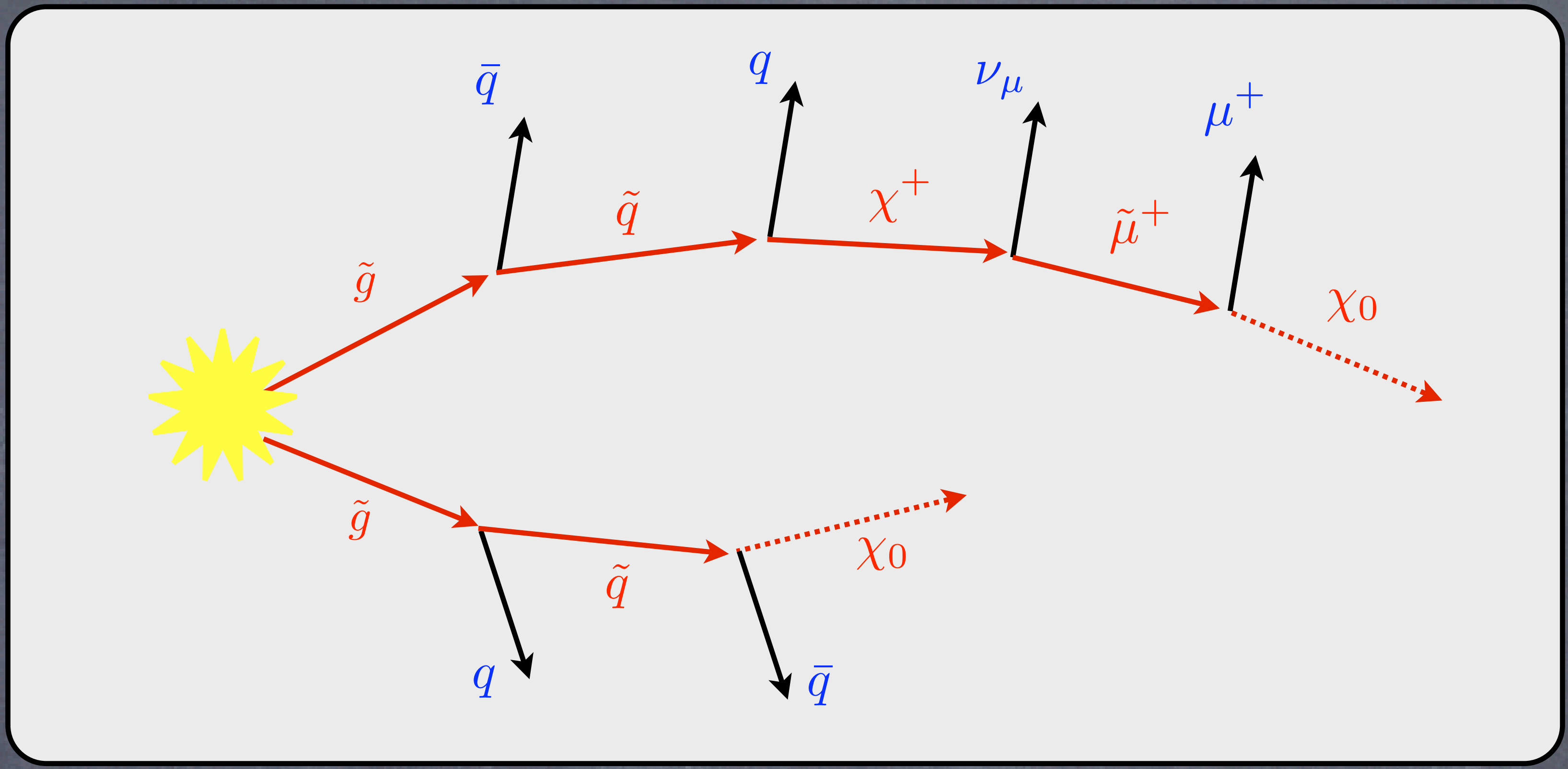
So far, it failed to discover signs of New Physics.





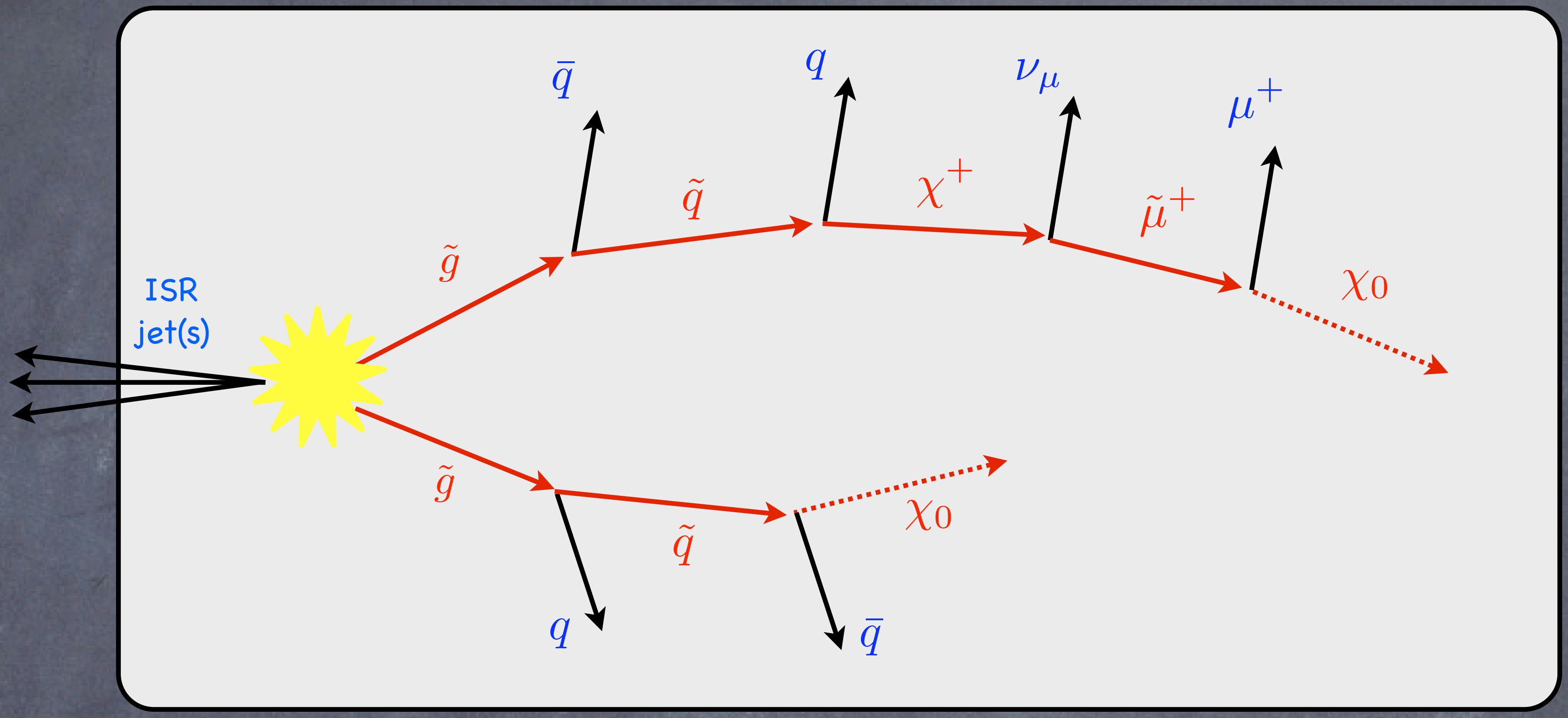
We went after the “easy catch”… what about tougher guys?

Search for Supersymmetry:



- Susy searches mostly based on energetic jets + MET (missing transverse momentum.
- Classic spectra have enough splitting! (from running or couplings) $\Rightarrow$ strong bounds!!!
- What if the spectra are compressed?

Search for Supersymmetry:

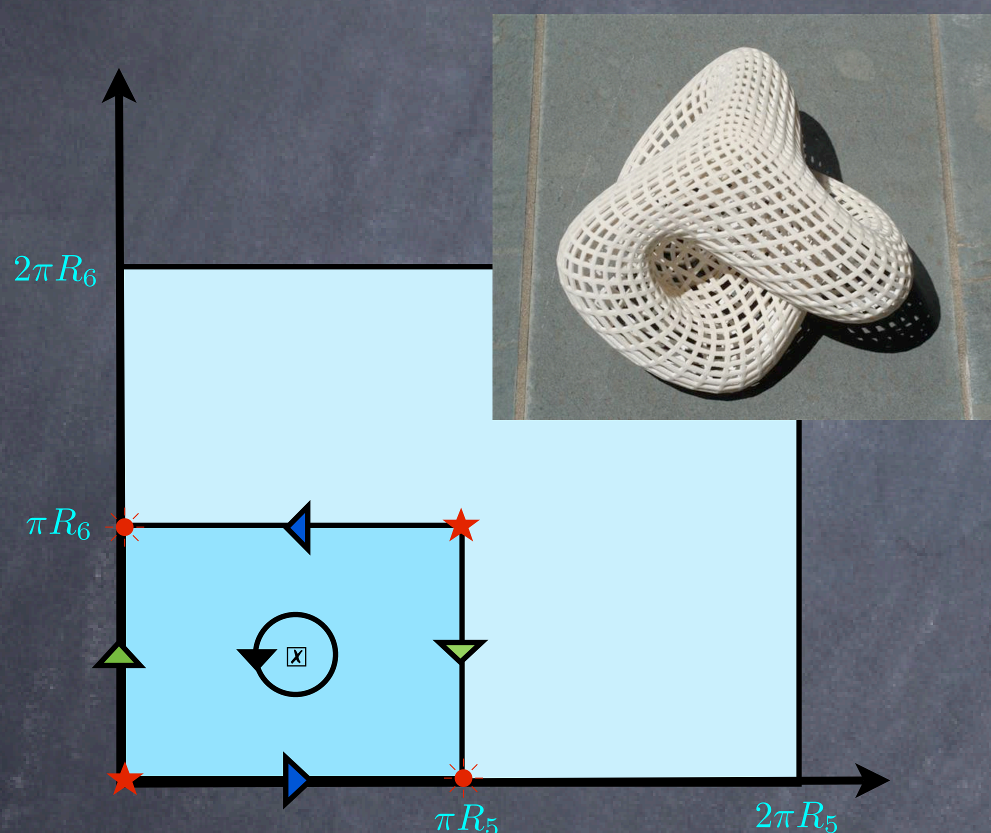


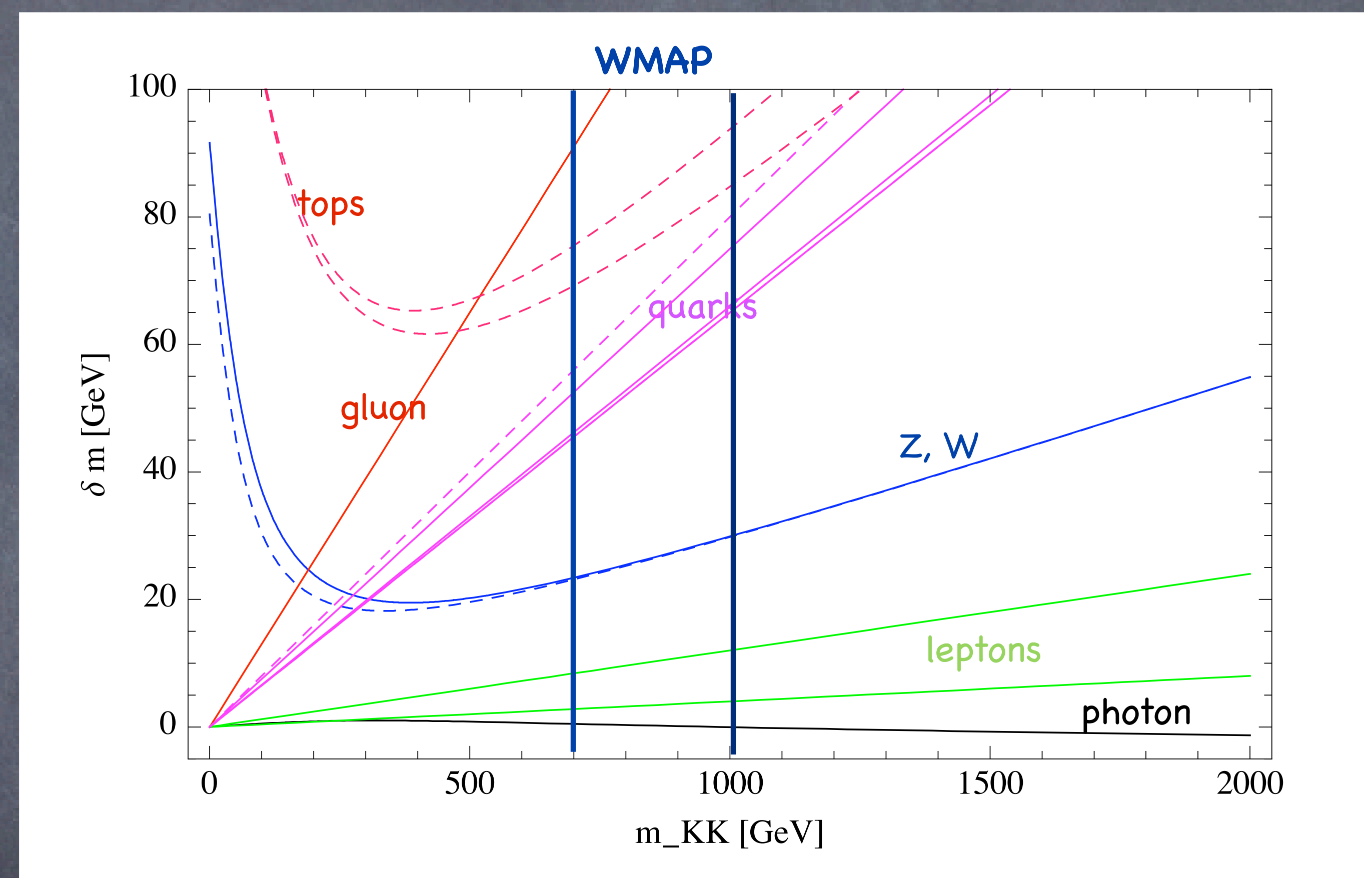
- What if the spectra are compressed?
- We need to rely on Initial State Radiation to boost the event!
- The cuts on pT become much more pricey on the signal!

Dark Matter in extra Dimensions:

- Compressed spectra arise naturally in extra dimensions!

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



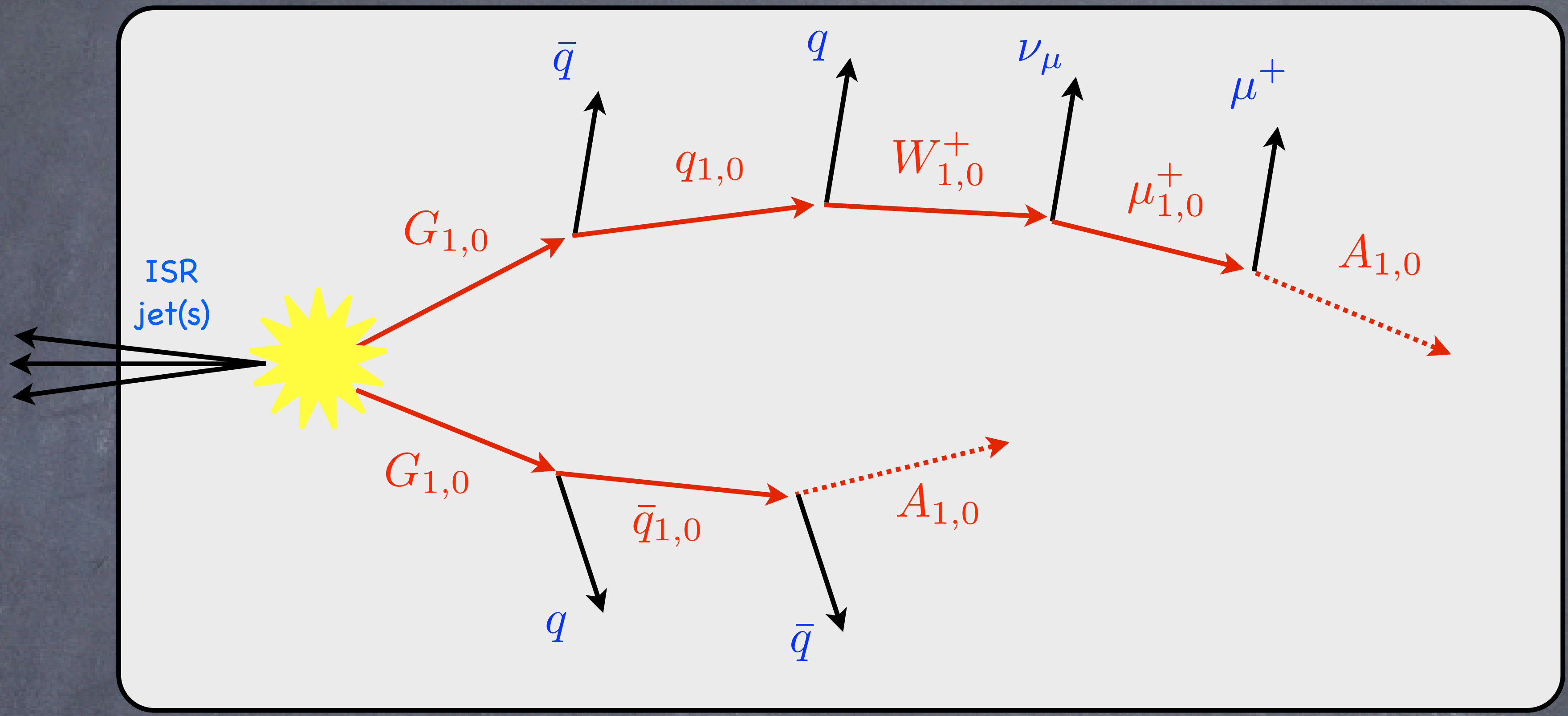


symmetry of the space ⇔ parity

bulk field ⇔ same-spin recurrences

Loop induced splittings are smaller than typical SUSY, and smaller than other UED models (5D, T2/Z2...)

Dark Matter in extra Dimensions:



- Same topology as Susy, different spins!
- Small splitting! Searches based on ISR!
- Distinctive signatures from even tiers...

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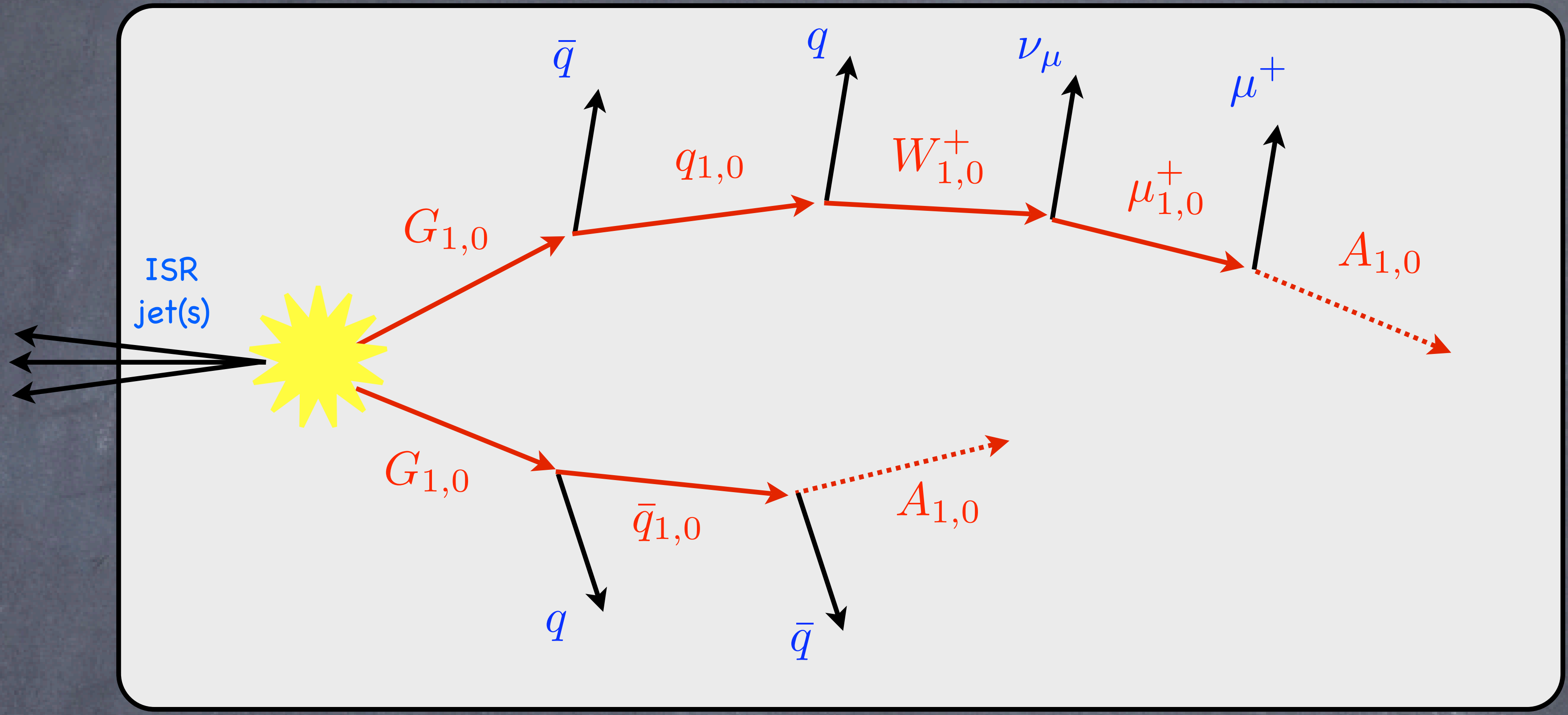

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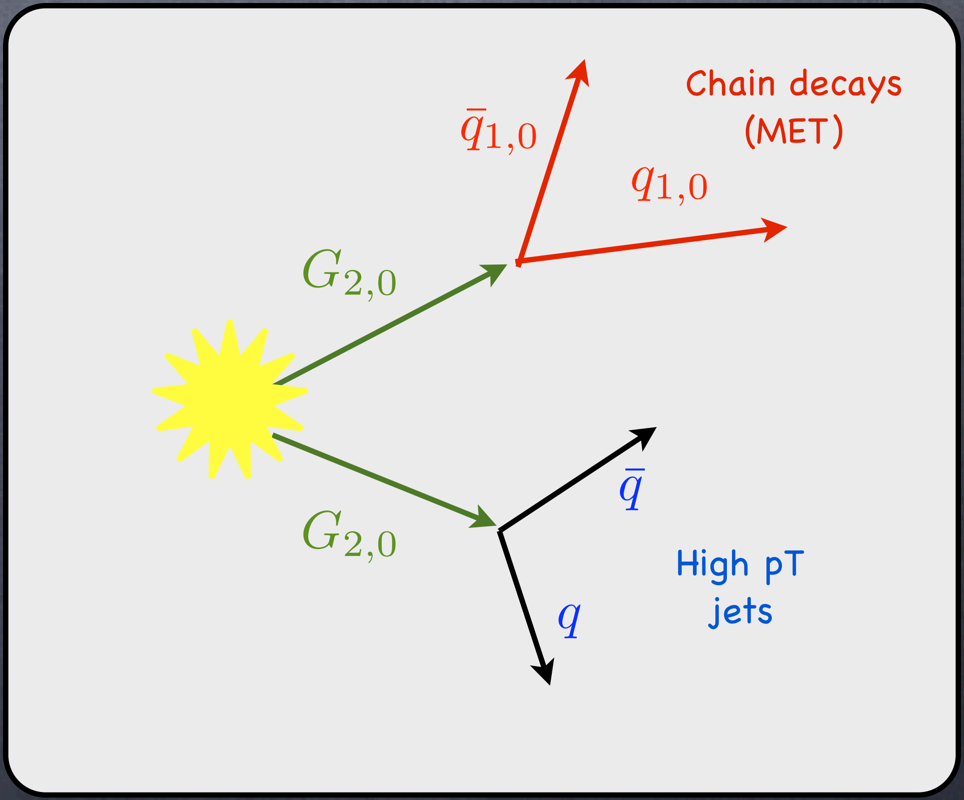
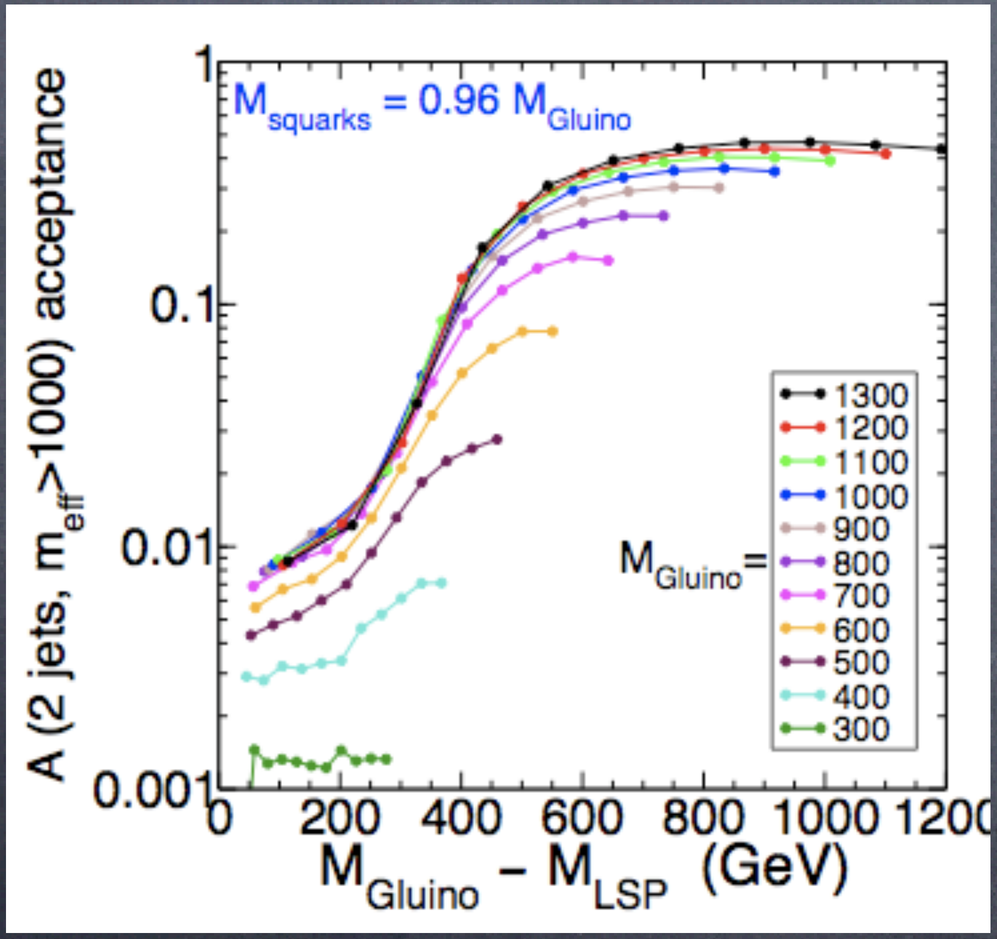


Compressed Susy searches

- Acceptance of standard SUSY searches are very low!



ATLAS jets+MET searches: acceptance drops to 1÷0.1%

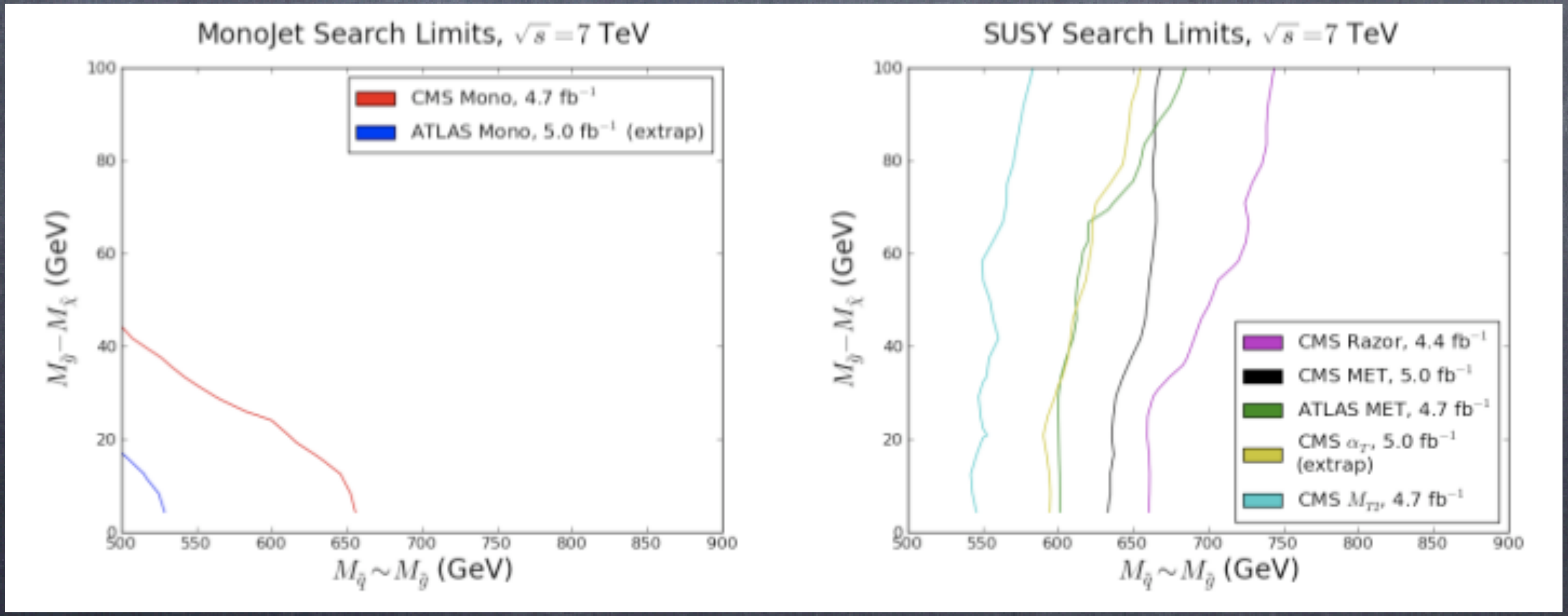
pT leading jet > 120 GeV!!!

Le Compte, Martin, 1105.4304 & 1111.6897

Compressed Susy searches

- Acceptance of standard SUSY searches are very low!
- Bounds on SUSY masse drop significantly!

$$M_{\tilde{g}} > 650\ GeV$$



Monojet: 1 high-pT jet + jet-veto!

Dreiner et al, 1207.1613

What else can Extra Dimensions do?

A personal list:

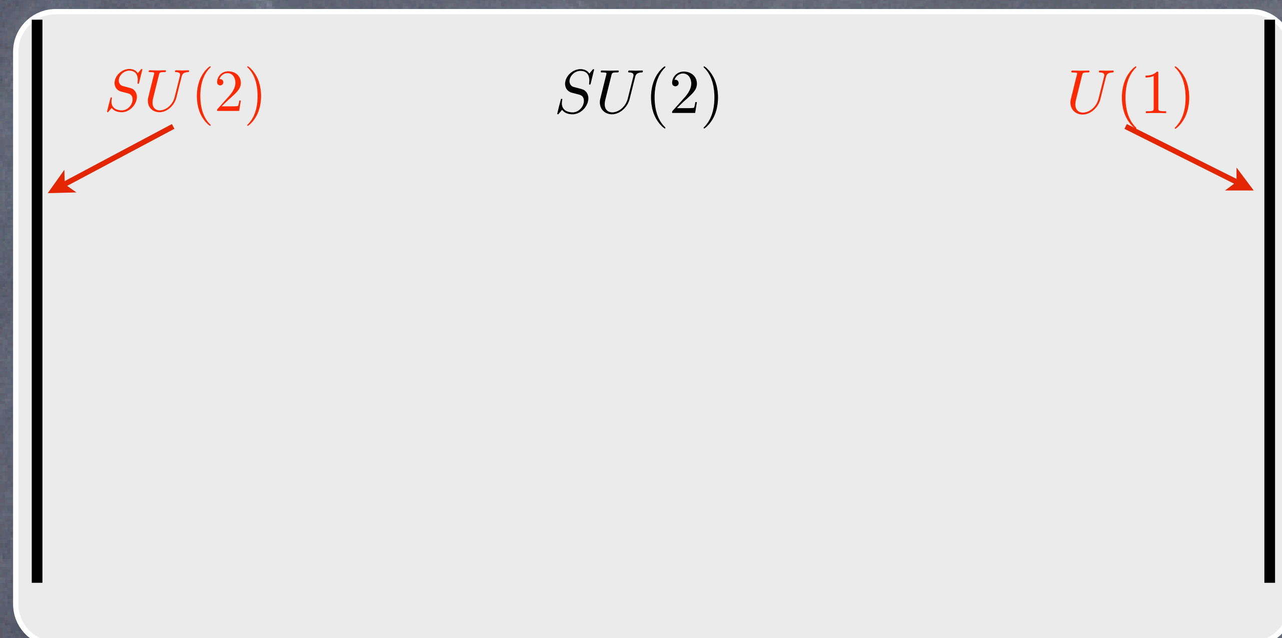
- Provide symmetries (KK parity/Dark Matter)
- Break gauge symmetries (Higgsless models)
- Protect the Higgs mass (Gauge-Higgs unification, composite Higgs models, Little Higgs models)
- Generate hierarchies (fermion masses)
- ...

Breaking gauge symmetries

Masses depend on boundary conditions!

- Suitable boundary conditions can generate massive gauge bosons:

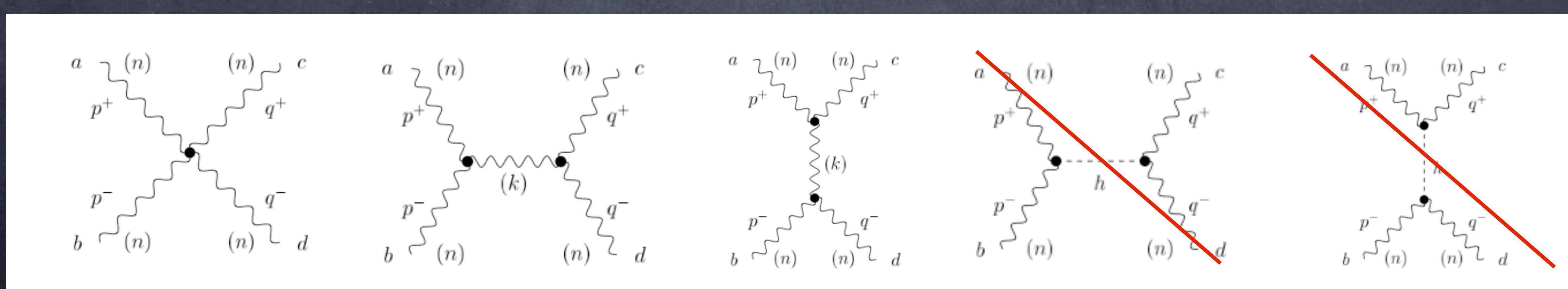
$$\partial_y W^i(y=0) = 0$$



$$W^\pm(y=L) = 0$$
$$\partial_y W^3(y=L) = 0$$

No KK parity here!
No Dark Matter!

- Who plays the role of the Higgs? Massive vector bosons!



Breaking gauge symmetries

Masses depend on boundary conditions!

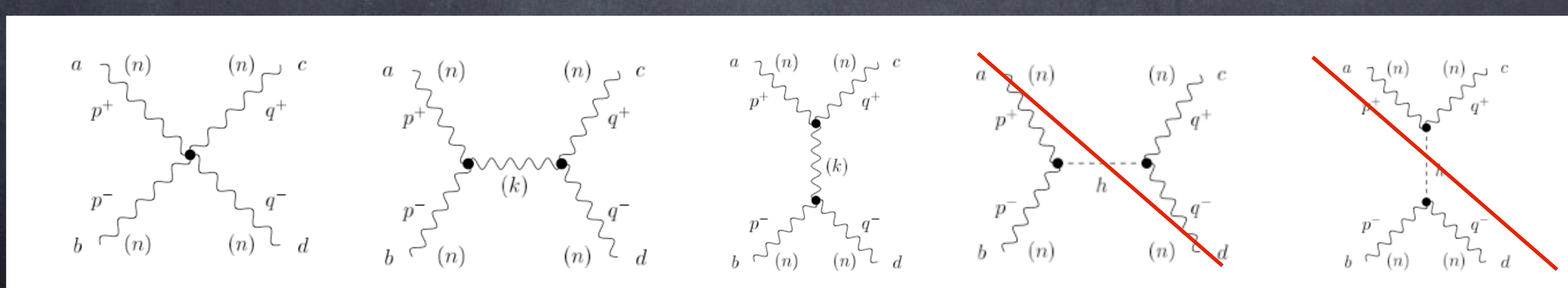
- Suitable boundary conditi... bosons:

$$\partial_y W^i(y=0) = 0$$

$SU(2)$

What about the 126 GeV guy?

- Who plays the role of the Higgs? Massive vector bosons!

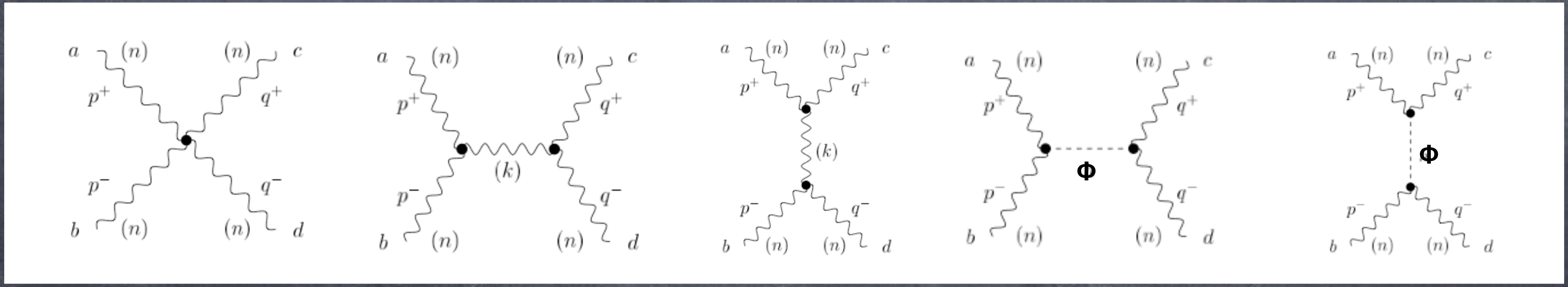


Breaking gauge symmetries

Here enters Mr. Radion:

- Scalar degree of freedom associated with the stabilisation of the XD size! It's a gravity field!
- Its couplings are proportional to the masses (like for the Higgs!)

$$\mathcal{L}_{\text{Radion}} = \frac{\phi}{f}\left\{ m_W^2 W^+W^- + \frac{1}{2} m_Z^2 Z^2 + \ldots \right\}$$

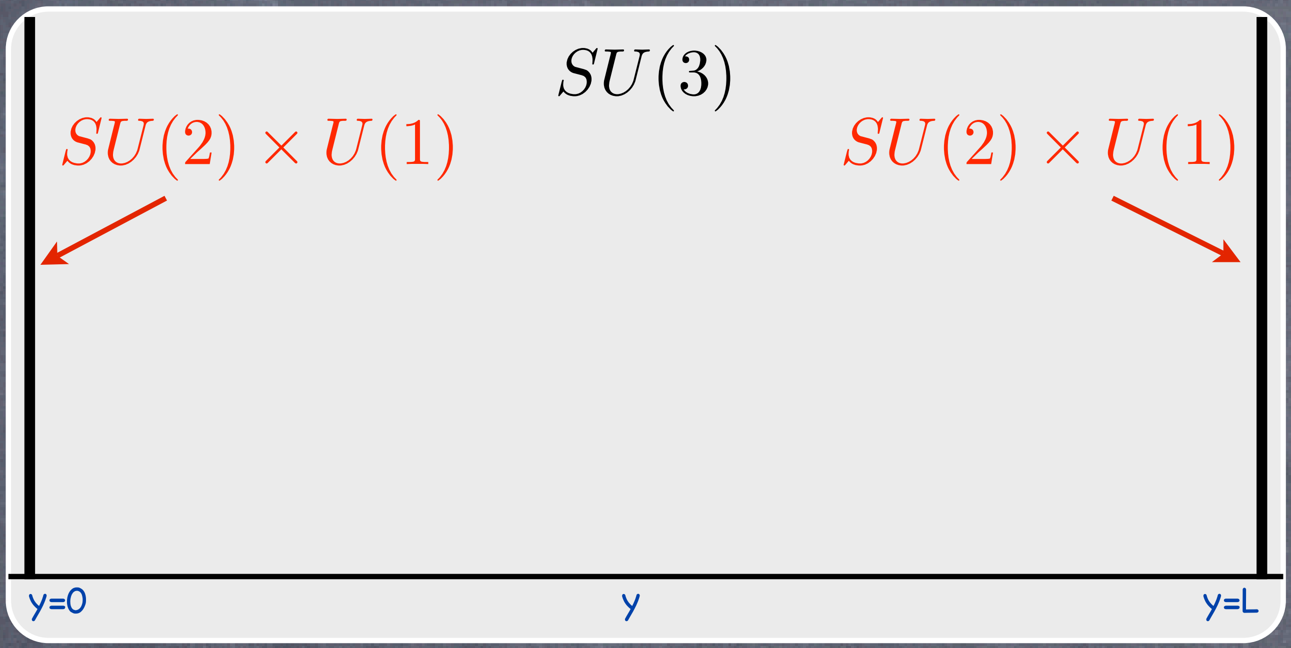


- Reduced tree level couplings to gauge bosons and fermions!
- Somewhat enhanced loop induced couplings (gluons and photons)!

New kinds of scalars

Vectors contain extra polarisations!

$$A_M = (A_\mu, \underline{A_5, A_6 \ldots})$$



- A massless scalar appears in the coset space SU(3)/SU(2)xU(1)
- It's an SU(2) doublet! New gauge-Higgs boson?

New kinds of scalars

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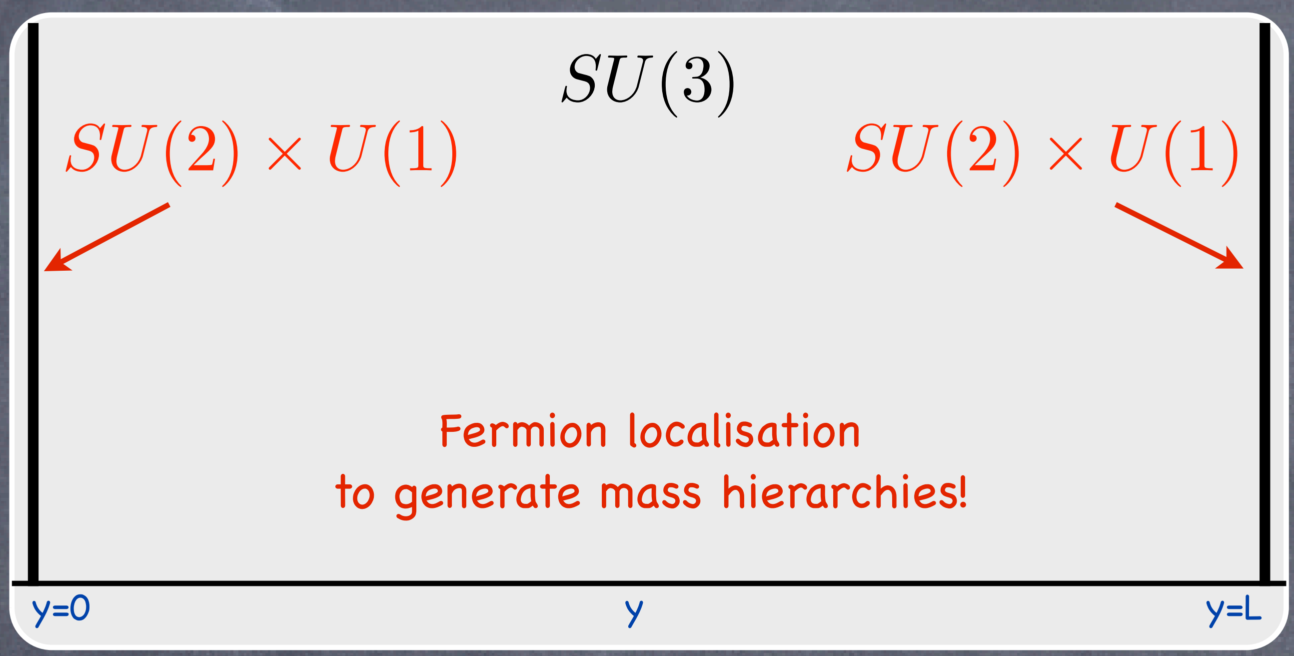

No KK parity here!
No Dark Matter!

- A massless scalar appears in the coset space SU(3)/SU(2)xU(1)
- It's an SU(2) doublet! New gauge-Higgs boson?
- No tree level potential, and loops are finite!
- All interactions are gauge (including yukawas)!

New kinds of scalars

An interesting development: Higgs as Dark Matter?!?!

Y.Hosotani, P.Ko, M.Tanaka, 0908.0212

- As the Higgs is a gauge field, it can be removed from the Action with a gauge transformation.
- Thus, the VEV of the field appears in the Boundary Conditions! (Hosotani Mechanism!)

Loop induced potential: $$V(H) \sim -\sin(\# H) \;\Rightarrow\; \langle H \rangle = \frac{\pi}{2}$$

Coupling to all (massive) particles: $$g_H \sim \sin(\# H) \sim 1 - \# \cos(\# \langle H \rangle)\, h \\ -\#^2 \sin^2(\# \langle H \rangle) h^2 + \ldots$$

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- The Higgs is stable and can play the role of the Dark Matter!

- Mr. Radion @ 125 GeV?

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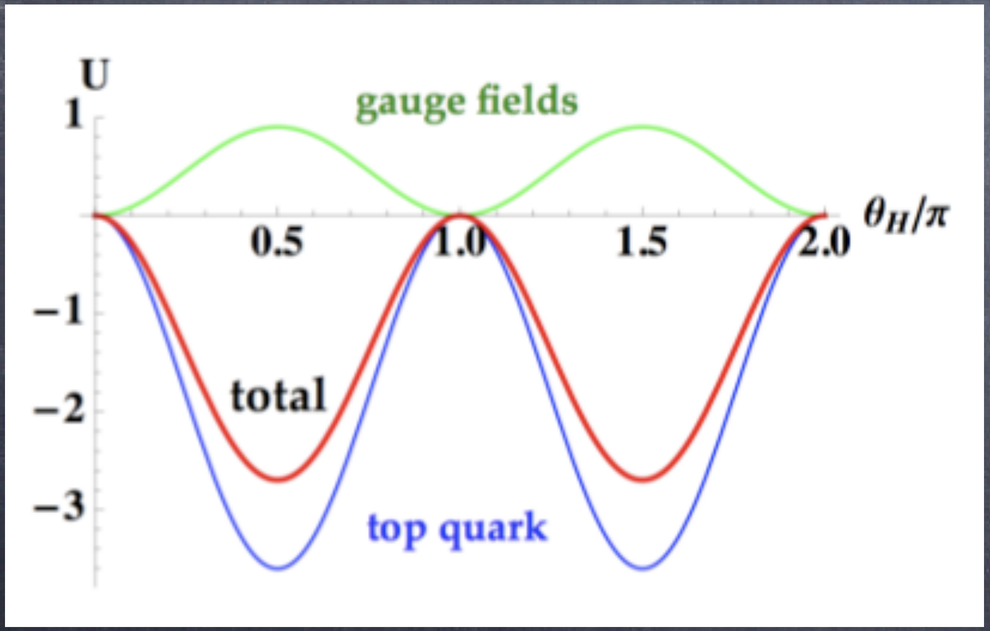
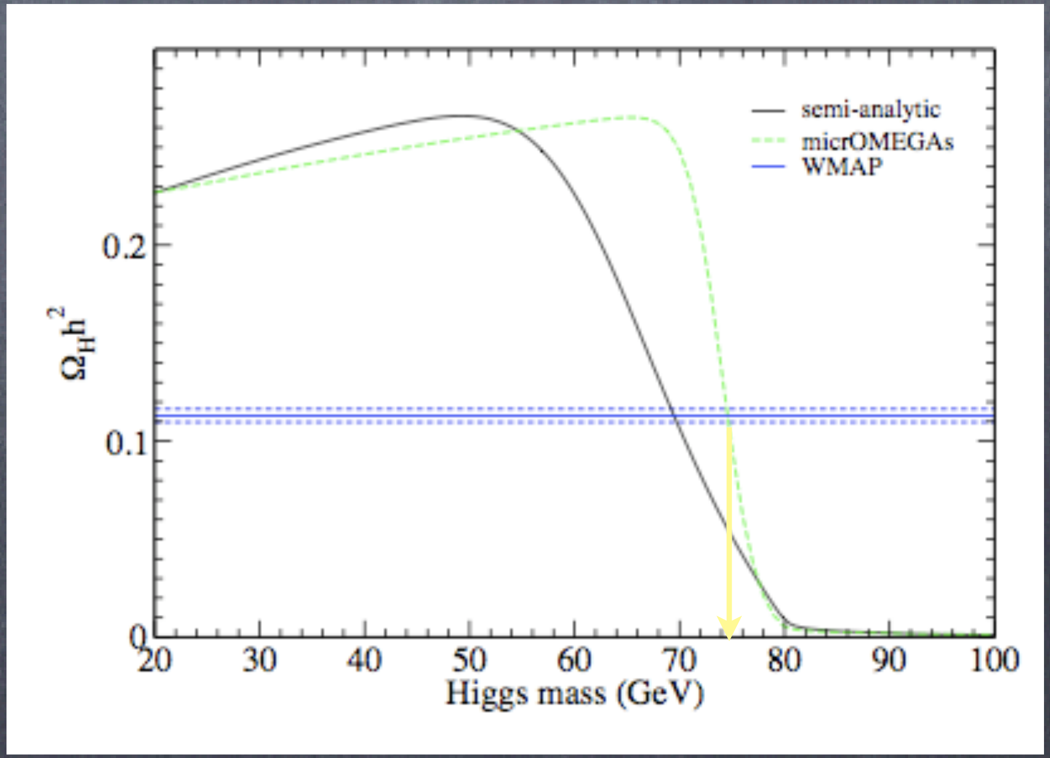
Higgs potential:

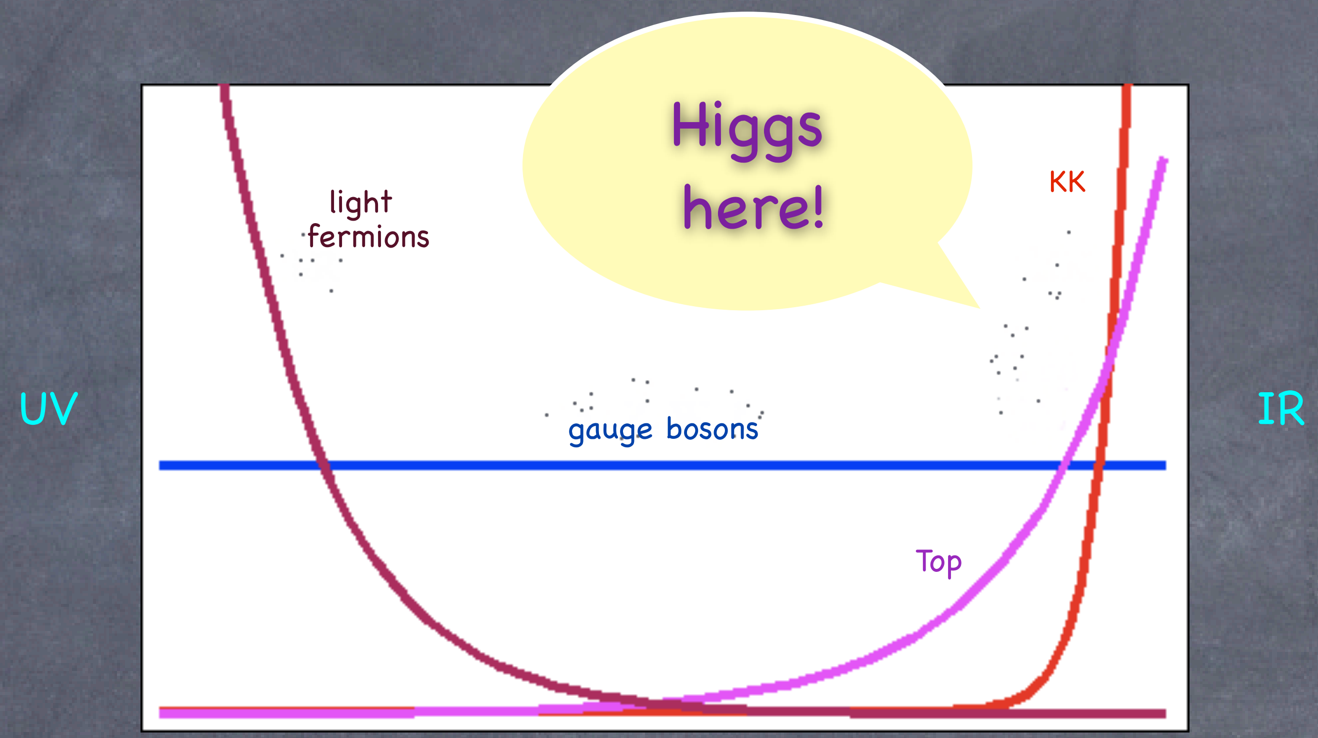




mH = 75 GeV !

Mass hierarchies: composite Higgs

Wave functions can be localised!



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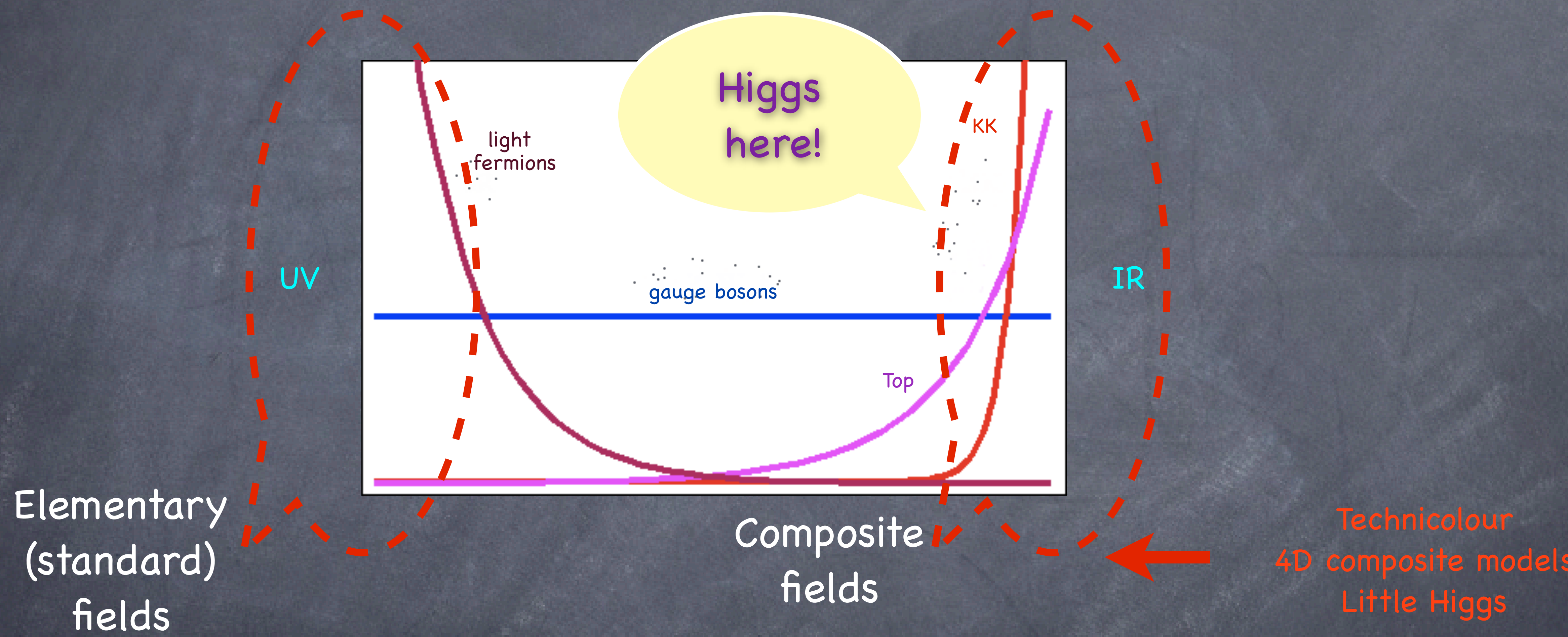
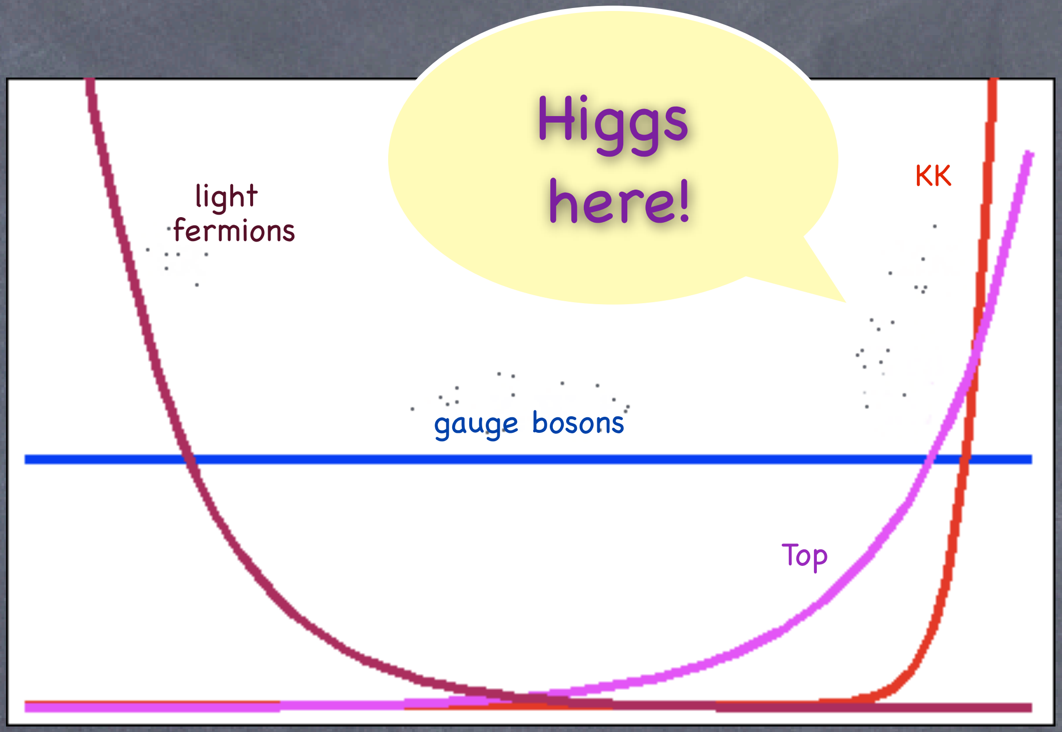


- Fairly SM-like Higgs
- Very heavy (>2-3 TeV) W′ and Z′
- Light top (fermion) partners, O (1 TeV)

Mass hierarchies: composite Higgs

Wave functions can be localised!

UV



IR

Technicolour
4D composite models
Little Higgs

Impose a custodial symmetry in the bulk to avoid EWPTs and Zbb corrections:

$$\mathcal{L}_{\rm Yuk} \sim y_{\rm top}\, \bar{t}_R\, {\rm Tr} \begin{pmatrix} h^+ & h_0 \\ h_0^* & -h^- \end{pmatrix} \cdot \begin{pmatrix} x_L & t_L \\ t'_L & b_L \end{pmatrix}$$

New Vector-Like quark doublet with hypercharge 7/6!

Mass hierarchies: composite Higgs

Wave functions can be localised!

Vector-like quarks (top partners) are a common prediction of:

- x dimensions
- composite Higgs models
- Little Higgs
- ...

Technicolour
4D composite models
Little Higgs

Impose a cust ... rections:

$$\mathcal{L}_{\rm Yuk} \sim y_{\rm top}\, \bar{t}_R\, \mathrm{Tr} \begin{pmatrix} h^+ & h_0 \\ h_0^* & -h^- \end{pmatrix} \cdot \begin{pmatrix} x_L & t_L \\ t'_L & b_L \end{pmatrix}$$

New Vector-Like quark doublet with hypercharge 7/6!

What is a VL quark?

- They have a Dirac mass without the Higgs.

$$\mathcal{L}_{\rm mass} \sim -M\left(\bar{\psi}_L \psi_R + \bar{\psi}_R \psi_L\right)$$

- They couple to SM quarks via Yukawa-type interactions.

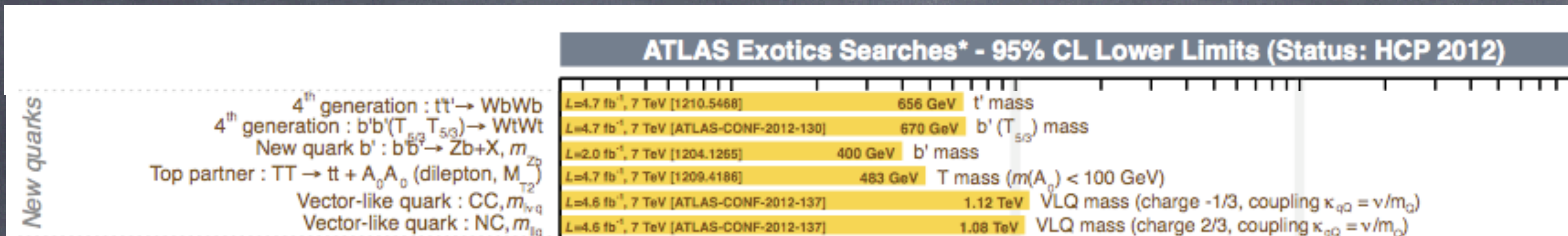
$$\mathcal{L}_{\rm Yuk} \sim -\frac{\lambda v}{\sqrt{2}}\left(\bar{q}_L \psi_R + \bar{\psi}_R q_L\right) \quad \text{or} \quad \left(\bar{\psi}_L q_R + \bar{q}_R \psi_L\right)$$

- The couplings depend on the representation of SU(2) - few possible choices!

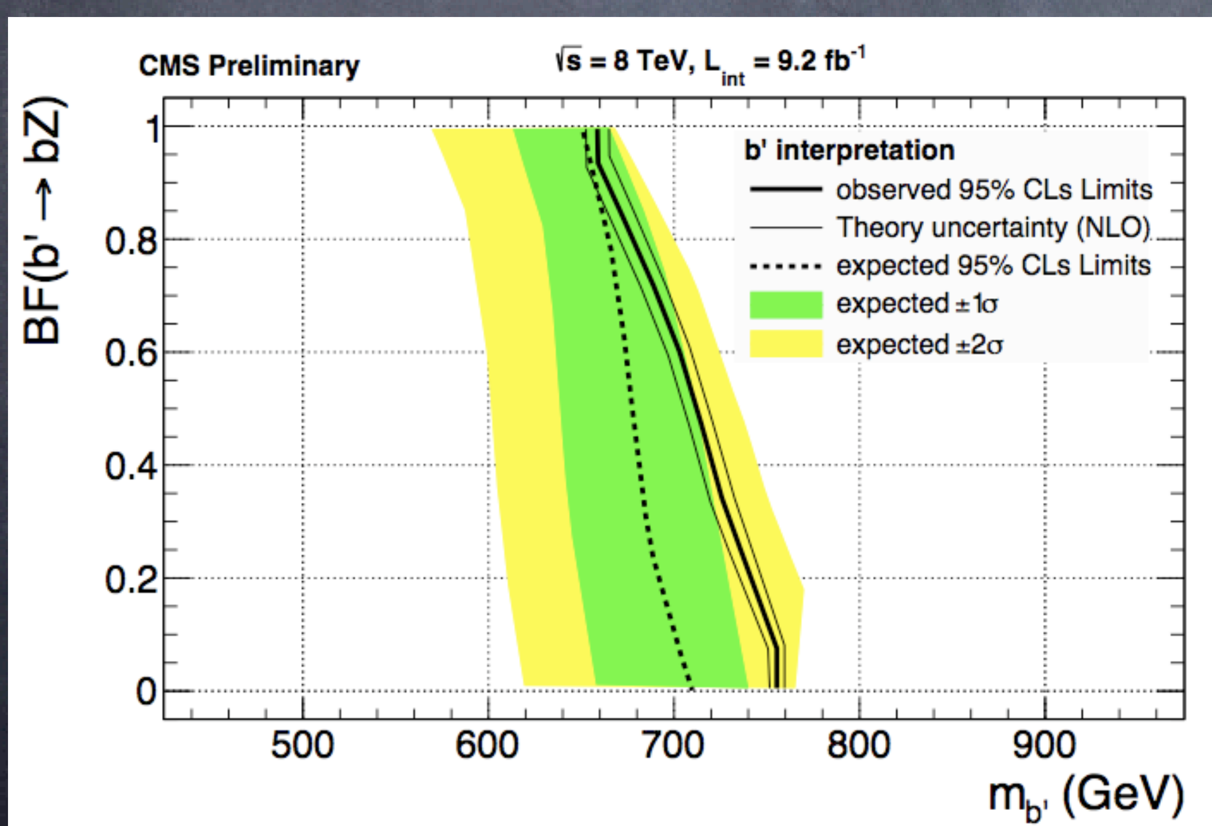
$$\mathcal{L}_{\rm singlet} \sim \frac{g}{\sqrt{2}} V_L^{4i}\, W_\mu^+\, \bar{t}'_L \gamma^\mu d_L^i + \frac{g}{2\cos\theta_W} V_L^{4i}\, Z_\mu\, \bar{t}'_L \gamma^\mu u_L^i + h.c.$$

$$\mathcal{L}_{\rm doublets} \sim \pm \frac{g}{2\cos\theta_W} V_R^{4i}\, Z_\mu\, \bar{t}'_R \gamma^\mu u_R^i + h.c.$$

What is a VL quark?



- Bounds are below the TeV.
- With few exceptions, 100% BR into a single channel assumed.



BR(Wt) = 1 - BR(Zb)

Search for multilepton signals

What is a VL quark?

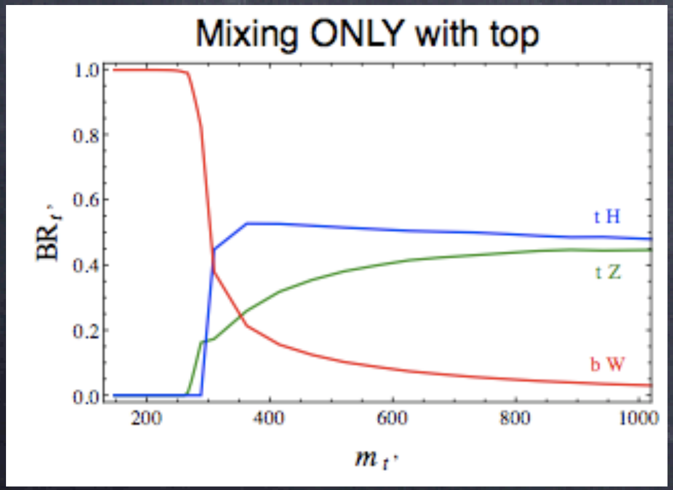
➤ branchings are never 100% in one channel!

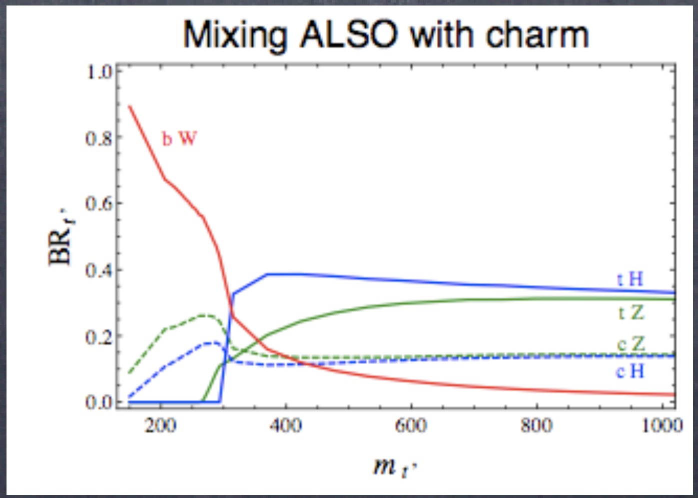
t′	Wb	Zt	ht
Single, Triplet Y=2/3	50%	25%	25%
Doublets, Triplet Y=-1/3	~ 0%	50%	50%

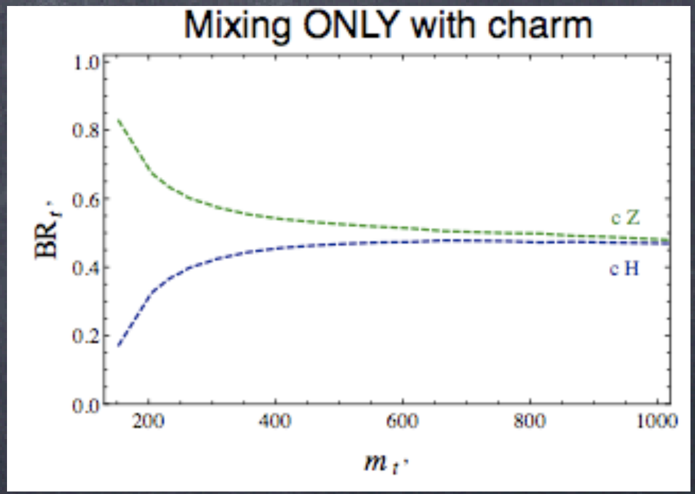
EQUIVALENCE THEOREM: at large VL masses, BR(Zt) = BR(ht)!!!

➤ decays into light quarks may not be negligible!

Flavour bounds: however, BRs are NOT proportional to the mixing matrices nor to the Yukawa couplings!

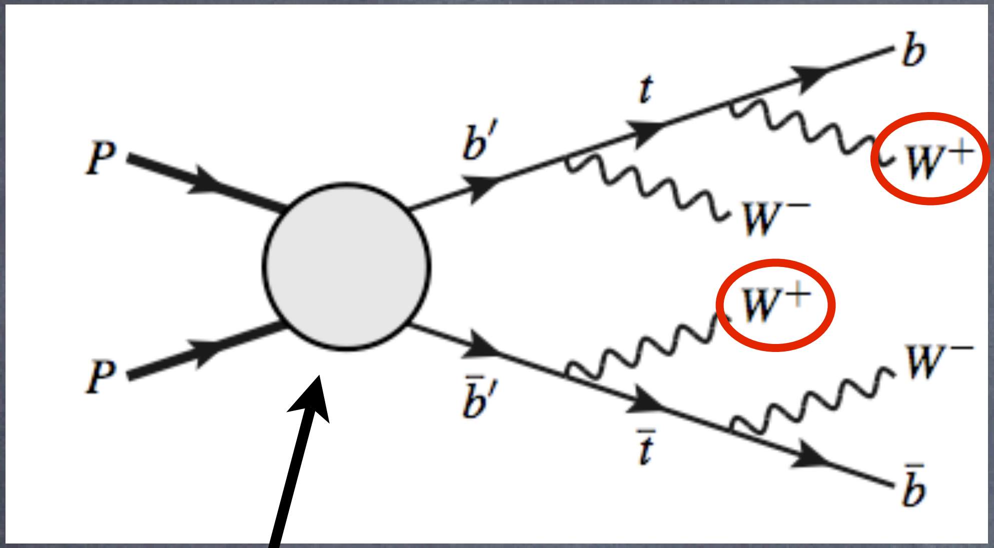






What is a VL quark?

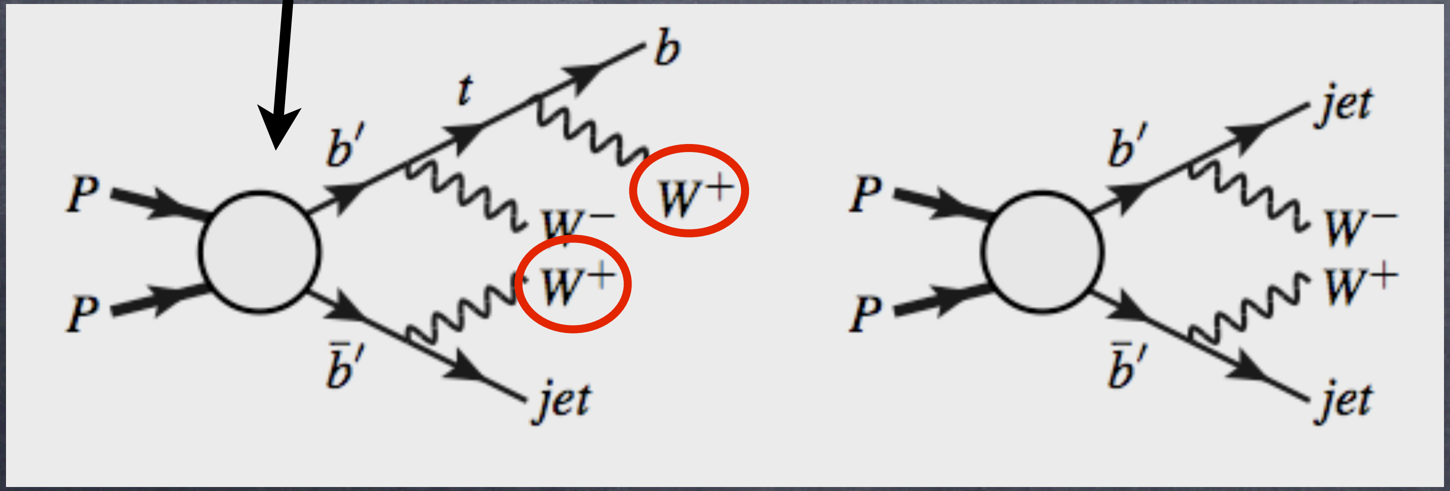
Example: same sign dilepton in b′ decays



Assuming 100% decays into Wt

ss dilepton from W's
b-tagging

Different efficiencies!!!!



Decays in W q
should also be included
in the same search!

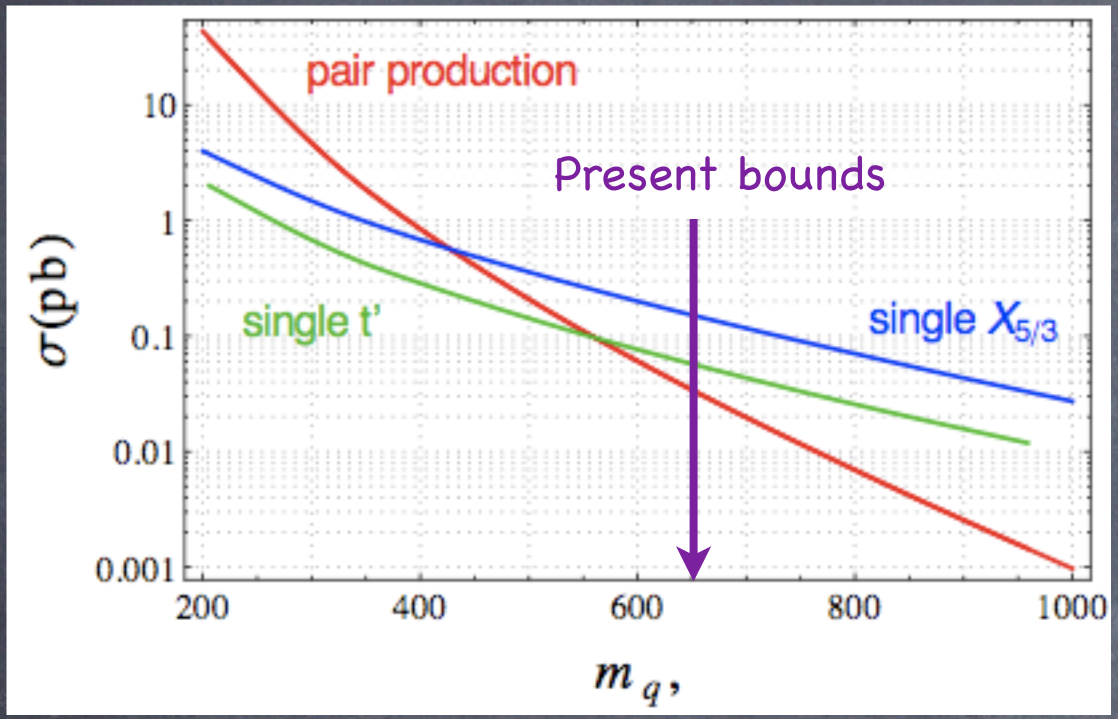
What is a VL quark?

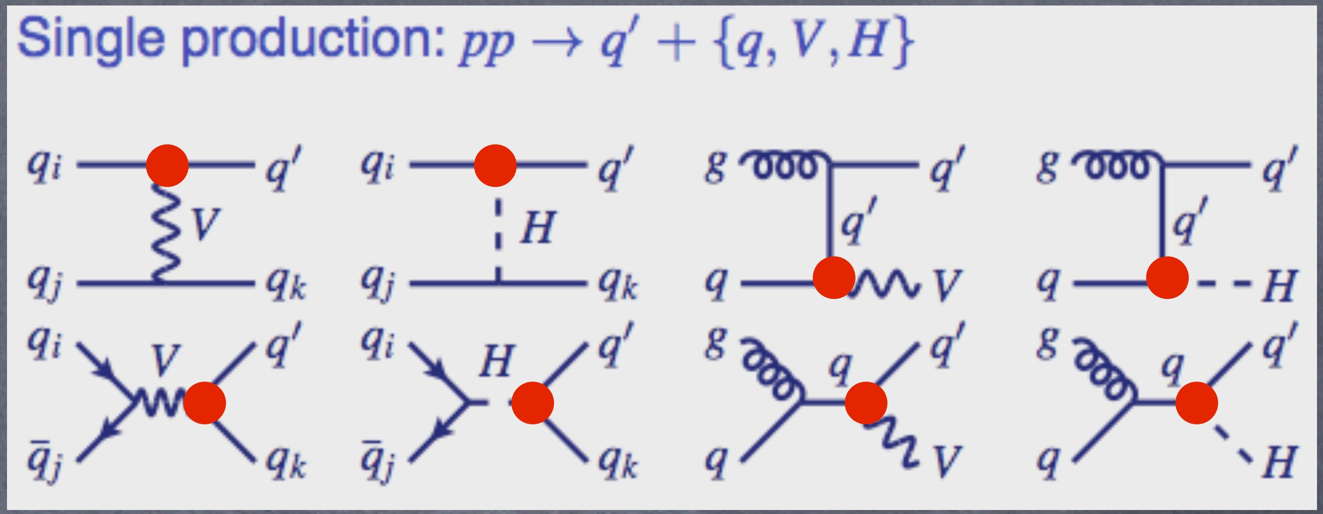
Example: same sign dilepton in b′ decays

	t'	b'	ss 2l	3l+	tot
(WW)	$WqWq$	$WjWj$	0	0	0 %
(WWW)	–	$WtWj$	4.77	1.61	6.38
$(WWWW)$	–	$WtWt$	7.13	5.22	12.35
(WZ)	$WqZj$	$WjZq$	0.19	1.80	2.00
(WWZ)	$WqZt$	$WtZq$	0.29	3.25	3.54
(Wh)	$Wqhj$	$Wjhq$	1.40	0.65	2.04
(WWh)	$Wqht$	$Wthq$	2.09	1.82	3.91
(ZZ)	$ZjZj$	$ZqZq$	0.01	0.73	0.74
(WZZ)	$ZjZt$	–	0.36	4.03	4.39
$(WWZZ)$	$ZtZt$	–	0.53	6.67	7.21
(hh)	$hjhj$	$hqhq$	0.61	0.65	1.26
(Whh)	$hjht$	–	2.87	2.04	4.92
$(WWhh)$	$htht$	–	3.95	4.30	8.26
(Zh)	$Zjhj$	$Zqhq$	0.09	1.02	1.11
(WZh)	$Zjht$	–	1.51	3.20	4.71
$(WWZh)$	$Ztht$	–	2.20	4.85	7.05

Relevance of Single Production!

Pair production is "model independent", being dominated by QCD!





Couplings proportional to the mixing
i.e. sensitive to the Yukawa couplings!

- Potential window to size of Yukawa couplings/mixing!
- Potentially relevant at high masses.
- It needs to be included in a consistent way (flavour bounds!!!)

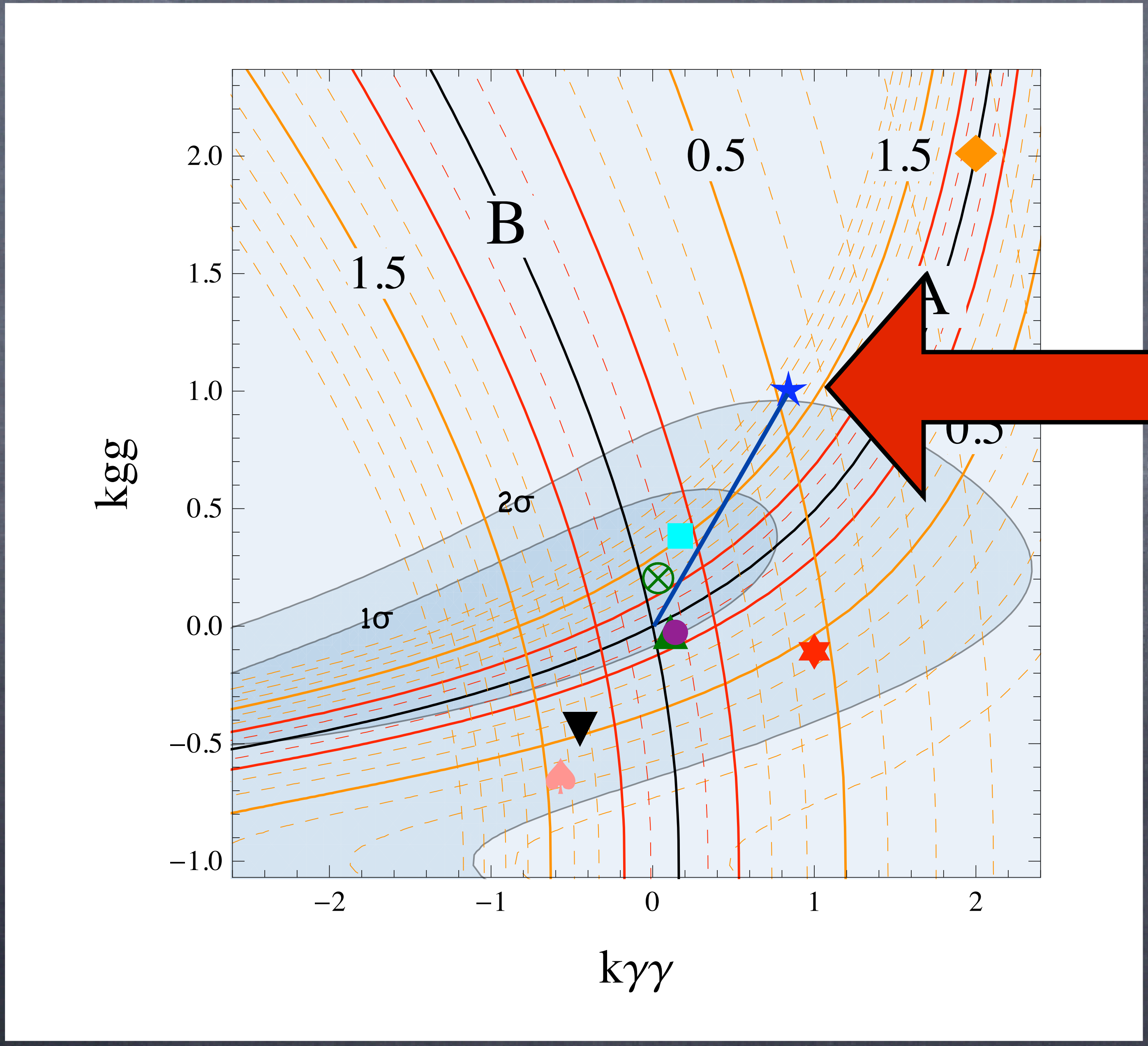
The Higgs discovery and BSM

G.C., A.Deandrea, J.Llodra-Perez 0901.0927
G.C., A.Deandrea, G.Drieu La Rochelle, J.B.Flament 1210.8120

- The KK resonances of W and top contribute to H→gg and H →γγ loops!

ATLAS data (pre HCP12)

- H →γγ
- H →ZZ



mKK = 600 GeV

k_{gg}, $k_{\gamma\gamma} \approx 1/mKK^2$

Conclusions:

- A lot of information is still to be extracted by the data.
- New physics may be there: are we properly looking for it?

A closer look to Extra Dimensions

Action for a massless scalar in D-dimensions

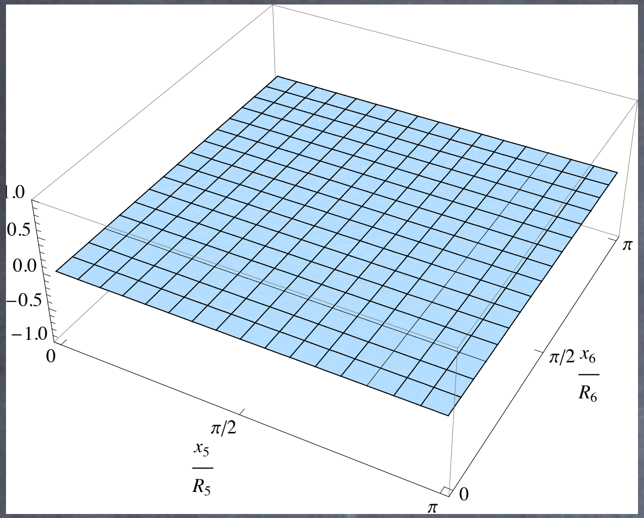
$$S = \int d^D x \left\{ \partial_\mu \phi^\dagger \partial^\mu \phi - \sum_{j=5}^{D-4} \partial_j \phi^\dagger \partial_j \phi \right\}$$

Expansion in 4-dim fields on compact extra space:

$$\phi(x_\mu, x_j) = \int \frac{d^4 p}{(2\pi)^4} e^{i p_\mu x^\mu} \sum_{\vec{k}} \varphi_{\vec{k}}(p_\mu) f_{\vec{k}}(x_j)$$

- D-dim fields correspond to tower of massive 4-dim fields
- k's are like frequencies of vibrating membrane!
- Masses and interactions determined by the wave functions $f_{\vec{k}}(x_i)$!
- Symmetries of the compact space = global symmetries of 4-dim fields: transformation properties of the wave functions!
- Can such symmetry stabilise the Dark Matter?

A closer look to Extra Dimensions



$S = \int$

The extra space is
like a vibrating membrane,
a drum!

$\phi(x_\mu, x_j)$ … $f_{\vec{k}}(x_j)$

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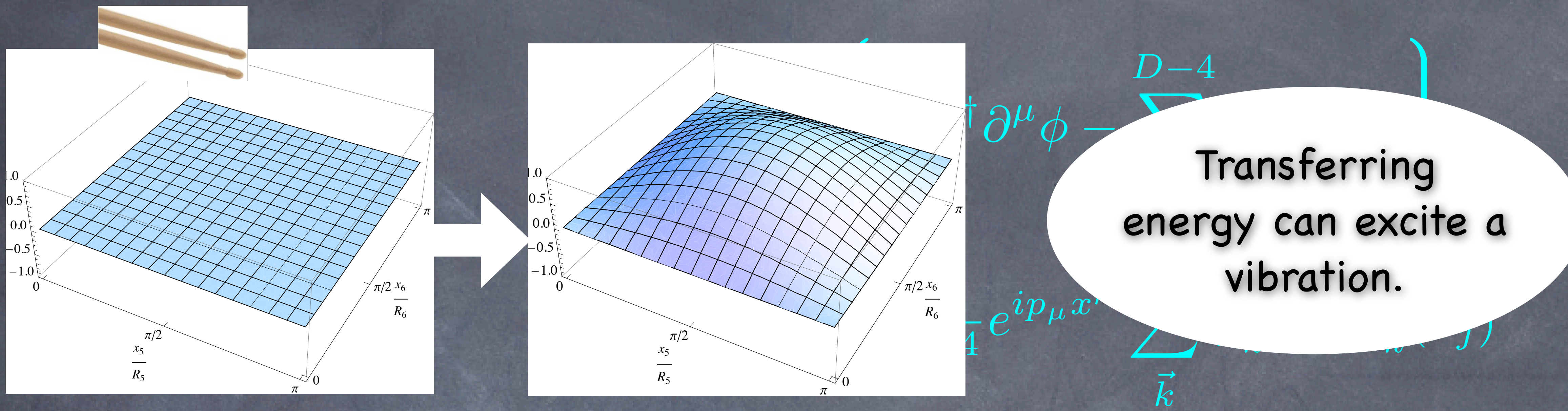

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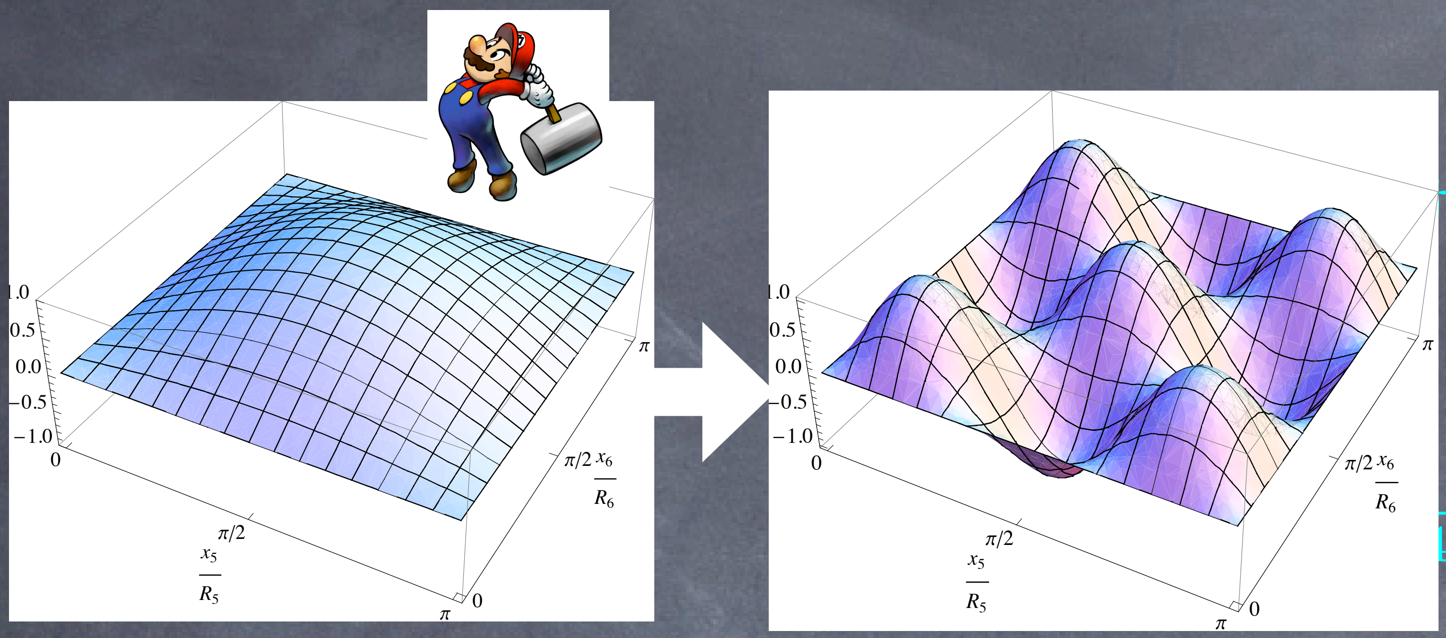

Increasing energy:
more massive mode!
$E = mc^2$!

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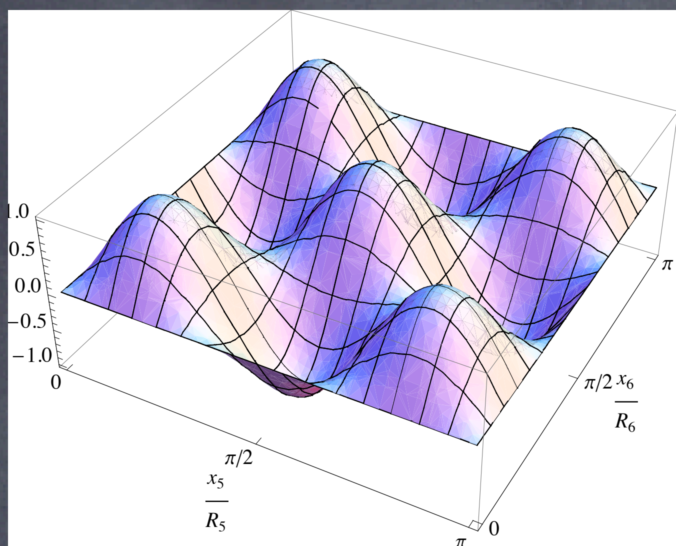

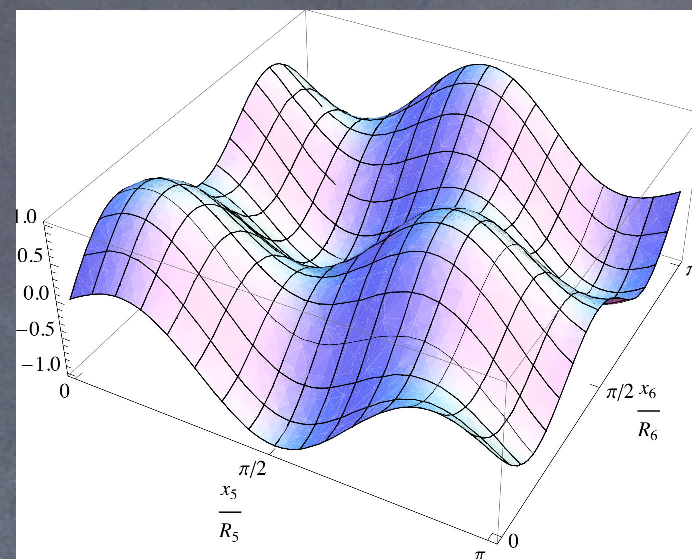

Symmetries
= geometry of
the membrane!

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- Masses and interactions determined by the wave functions $f_{\vec{k}}(x_i)$!
- Symmetries of the compact space = global symmetries of 4-dim fields: transformation properties of the wave functions!
- Can such symmetry stabilise the Dark Matter?