All Other Scenarios

Giacomo Cacciapaglia IPN Lyon

UK HEP FORUM "Higgs and BSM" Corsener's House, 22–23 November 2012

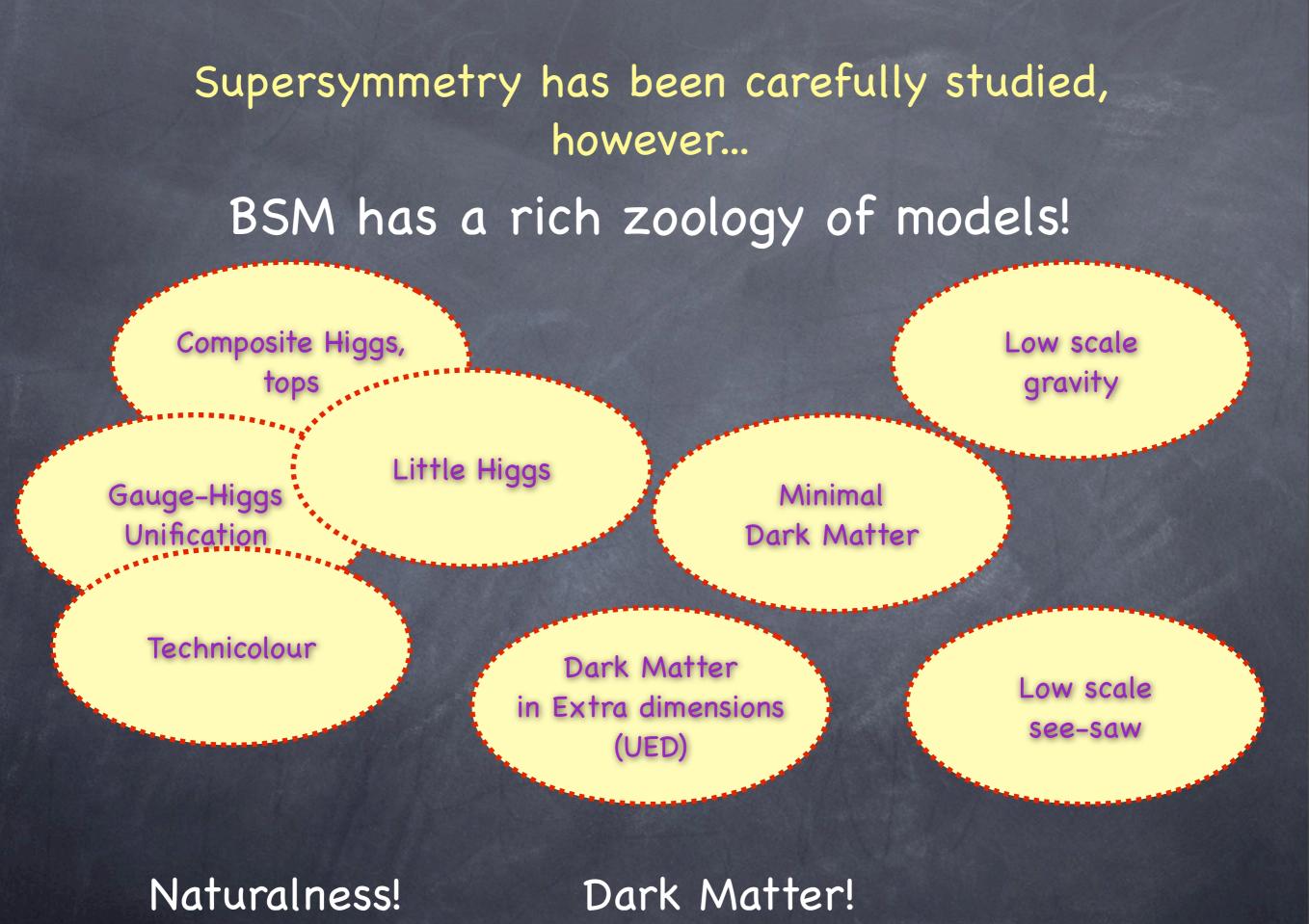
All Other Scenarios The veritable BSM*

* Beyond Sypersymmetry Models

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Supersymmetry has been carefully studied, however...



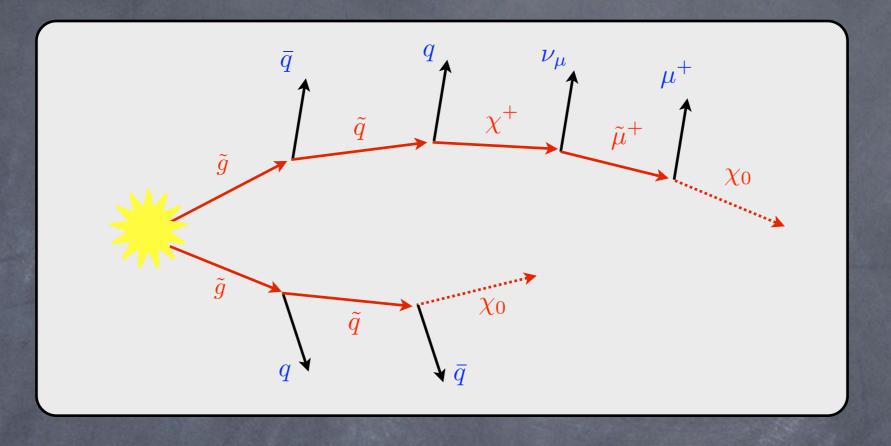
LHC results:

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

		ATLAS Exotics Searches* - 95% CL Lower Limits (Status: HCP 2012)	
	Ζ' (ŚSM) : m _{ee/μμ}	L=5.9-6.1 fb ⁻¹ , 8 TeV (ATLAS-CONF-2012-129) 2.49 TeV Z' mass	
	Z' (SSM) : m		
5	W' (SSM) : m		- 1
2	$W' (\rightarrow tq, q = 1) : m$	L =4.7 (b ⁻¹ , 7 TeV [1209.6593] 430 GeV W' mass	
	$W'_{B} (\rightarrow tb, SSM) : m_{B}$	L=1.0 fb ⁻¹ , 7 TeV [1205.1016] 1.13 TeV W' mass	
	W* : m _{T.80}	L=4.7 fb ⁻¹ , 7 TeV [1209.4446] 2.42 TeV W* mass	
ŝ	A th concretion : this : M/b)A/b	1-47 Ib ¹ 7 TeV (1210 5488) 858 CeV 1 mass	
ž	4 th generation : b'b'(T T T S 3) → WtW	L=4.7 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-130] 670 GeV b' (T) mass	
quarks	New quark b' : b'b' -> Zb+X, m_	L=2.0 fb ⁻¹ , 7 TeV [1204.1265] 400 GeV b' mass	
6	4 th generation : b'b'(T ₅₃ T ₅₃) \rightarrow WtWi New quark b' : b'b' \rightarrow Zb+X, m ₂ Top partner : TT \rightarrow tt + A ₀ A ₀ (dilepton, M ₁₂)	L=4.7 fb ⁻¹ , 7 TeV [1209.4186] 483 GeV T mass (m(A _n) < 100 GeV)	
New	Vector-like guark : CC, m	L=4.6 fb ⁺ , 7 TeV [ATLAS-CONF-2012-137] 1.12 TeV VLQ mass (charge -1/3, coupling $\kappa_{qQ} = v/m_Q$)	
N	Vector-like quark : NC, m		
		ATLAS SUSY Searches* - 95% CL Lower Limits (Status: HCP 2012)	
	MSUGRA/CMSSM : 0 lep + j's + E _{T,miss} L=5.8 f	b ¹ , 8 TeV [ATLAS-CONF-2012-109] 1.50 TeV $\widetilde{q} = \widetilde{g}$ mass b ¹ , 8 TeV [ATLAS-CONF-2012-104] 1.24 TeV $\widetilde{q} = \widetilde{g}$ mass b ¹ , 8 TeV [ATLAS-CONF-2012-109] 1.18 TeV \widetilde{g} mass (m(\widetilde{q}) < 2 TeV, light $\widetilde{\chi}_{1}^{0}$) ATLAS b ¹ , 8 TeV [ATLAS-CONF-2012-109] 1.38 TeV \widetilde{q} mass (m(\widetilde{g}) < 2 TeV, light $\widetilde{\chi}_{1}^{0}$) Preliminary	
		b ¹ , s TeV [ATLAS-CONF-2012-104] 1.24 TeV q = g mass b ¹ , s TeV [ATLAS-CONF-2012-109] 1.18 TeV g mass (mg) < 2 TeV, light χ ⁰) ATLAS	
8		b ¹ , 8 TeV [ATLAS-CONF-2012-109] 1.18 TeV [G mass (m(q) < 2 TeV, light χ̃) Preliminary	
. 5	Pheno model : 0 lep + j's + $E_{T,miss}$ L=5.8 f	1.38 TeV [ATLAS-CONF-2012-109] 1.38 TeV [q mass (m(g) < 2 TeV, light χ)] Preliminary	
3rd gen. sq. :hes gluino med.	g bb/m (midding) to top to b jo t 27,miss	1.24 TeV [ATLAS-CONF-2012-145] 1.24 TeV g mass (m(x)) < 200 GeV)	
E E	$g \rightarrow tt \chi_1$ (virtual t) : 2 lep (SS) + j's + $E_{T,miss}$	B50 GeV \widetilde{g} Mass $(m(\widetilde{\chi}^2) < 300 \text{ GeV})$ 8 TeV results	
ge No	$g \rightarrow tt \chi_1$ (virtual t) : 3 lep + j's + $E_{T,miss}$ L=13.6	(a) a let [Alcosecon variation]	
p.g	$g \rightarrow tt \chi_{4,0}$ (virtual t): 0 lep + multi-j's + $E_{T,miss}$	b ⁻¹ , 8 TeV [ATLAS-CONF-2012-103] 1.00 TeV ğ mass (m(χ ⁰) < 300 GeV) 7 TeV results	
0, 0	g→ttx, (virtualt): 0 lep + 3 b-j's + E _{T,miss} . L=128	1.15 TeV [ATLAS-CONF-2012-145] 1.15 TeV g̃ mass (m(χ)) < 200 GeV)	
8 5	$DD, D_1 \rightarrow D_{\chi_1}$: U lep + 2-b-jets + $E_{\gamma,miss}$	$m_{\chi_1}^{-1}$ 7 TeV [ATLAS-CONF-2012-106] 480 GeV b mass $(m_{\chi_1}^{-2}) < 150 \text{ GeV}$	
ark do	$\frac{\text{DD}, D_1 \rightarrow \text{ty} : 3 \text{ lep } + \text{j's} + E_{T,\text{miss}}}{\text{ff} (\text{very light}) + 1 + b_1^{-1} + 2 \text{ lep } + F}$	(b), 8 TeV [ATLAS-CONF-2012-151] 405 GeV D mass $(m(\tilde{\chi}_{1}^{*}) = 2 m(\tilde{\chi}_{1}^{0}))$	
3rd gen. squarks direct production	$\frac{1}{4} (\text{light}) + \frac{1}{2} + 1$	b ¹ , 7 TeV [1208.4305] 130 GeV t̃ mass (m(χ ²) < 70 GeV) b ¹ , 7 TeV [1209.2102] 123-167 GeV t̃ mass (m(χ ²) = 55 GeV)	
2.5	the (ingrid) to $1/2$ lep + b-jet + $E_{T,miss}$	b ¹ , 7 TeV [1209.2102] 123-167 GeV [THASS $(m(\chi_i) = 56 \text{ GeV})$ b ¹ , 7 TeV [1209.4186] 298-305 GeV [THASS $(m(\chi_i^0) = 0)$	
36l	true (medium), $t \rightarrow t\chi$: 2 lep + D-jet + $E_{T,miss}$		
ire ir	(1) (neavy), $1 \rightarrow i\chi$: 1 lep + b-jet + $E_{T,miss}$	b ⁻¹ , 7 TeV [1208.2590] 230-440 GeV t mass $(m(\tilde{\chi}_1) = 0)$ b ⁻¹ , 7 TeV [1208.1447] 370-465 GeV t mass $(m(\tilde{\chi}_2) = 0)$	
00	200 / 10 / 10 / 10 / 10 / 10 / 10 / 10 /	b ¹ , 7 TeV [1204.6736] 310 GeV T THASS $(m(\chi_1) = 0)$ b ¹ , 7 TeV [1204.6736] 310 GeV T THASS $(115 < m(\chi_1^0) < 230 \text{ GeV})$	
		all dev (110,5 (10,5 m)X, (5,20,064)	

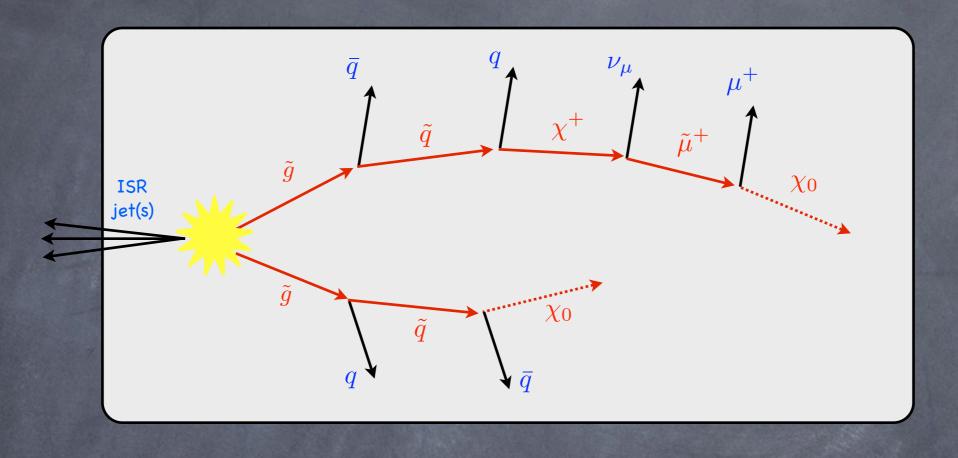
We went after the "easy catch"... what about tougher guys?

Search for Supersymmetry:



- Susy searches mostly based on energetic jets + MET (missing transverse momentum.
- Classic spectra have enough splitting! (from running or couplings)
 ⇒ 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!

100

80

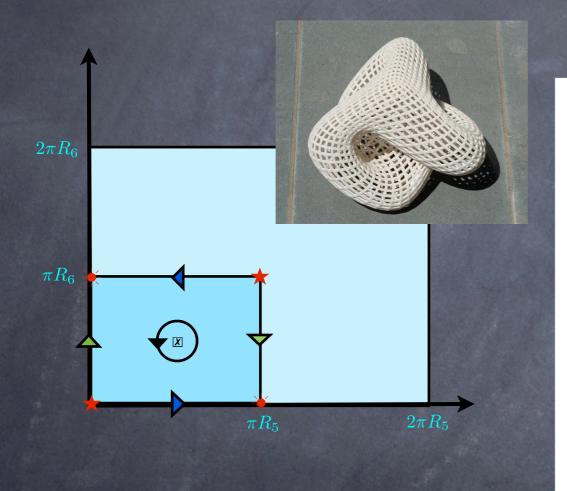
60

40

 $\delta \text{ m [GeV]}$

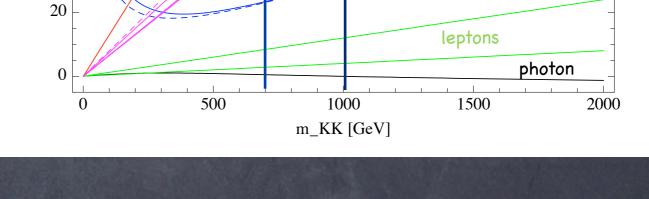
tops

gluo



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

Z, W



WMAP

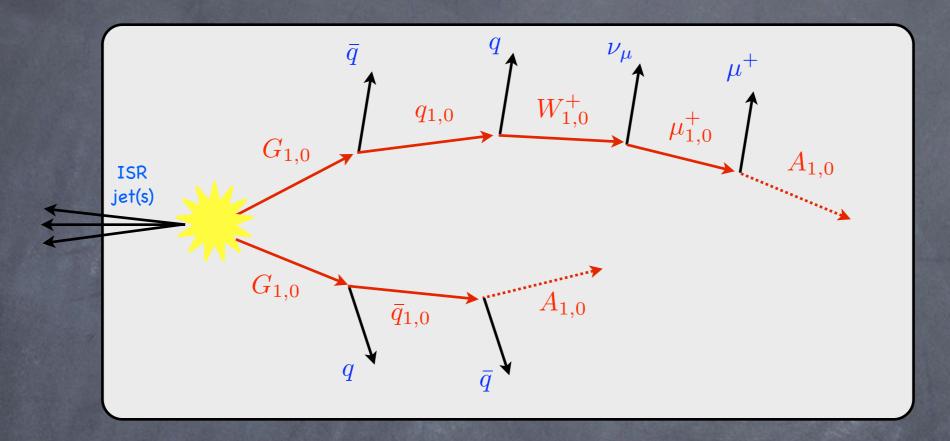
O(10

symmetry of the space ⇔ parity

bulk field ⇔ same-spin recurrences

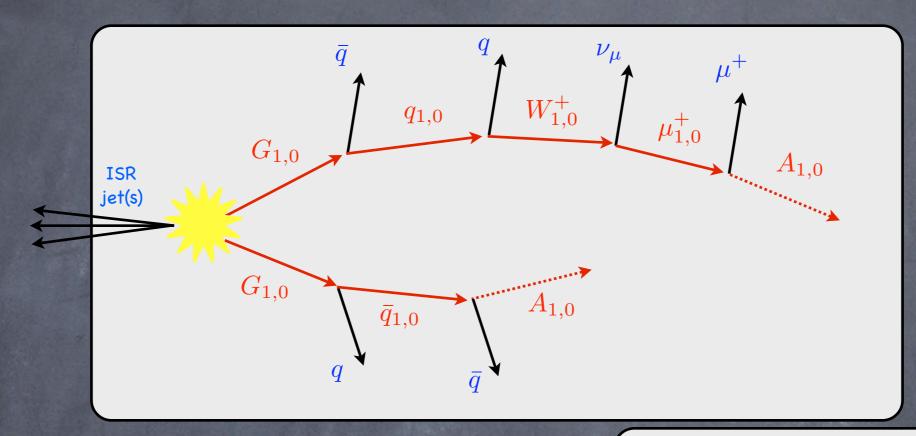
Loop induced splittings are smaller than typical SUSY, and smaller than other UED models (5D, T2/Z2...)

Dark Matter in extra Dimensions:

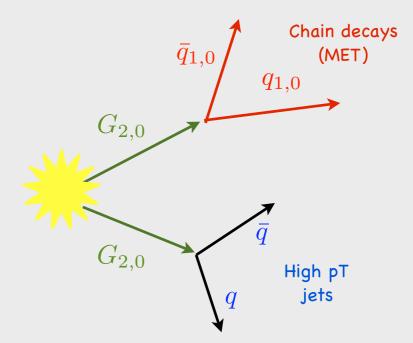


- Same topology as Susy, different spins!
- Small splitting! Searches based on ISR!
- Distinctive signatures from even tiers...

Dark Matter in extra Dimensions:

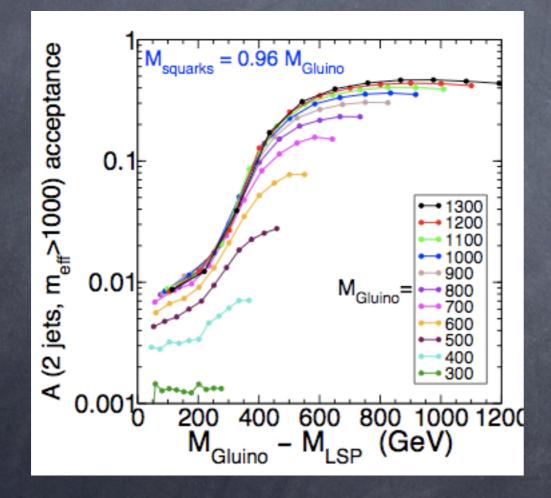


- Same topology as Susy, different spins!
- Small splitting! Searches based on ISR!
- Ø Distinctive signatures from even tiers...



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!!!

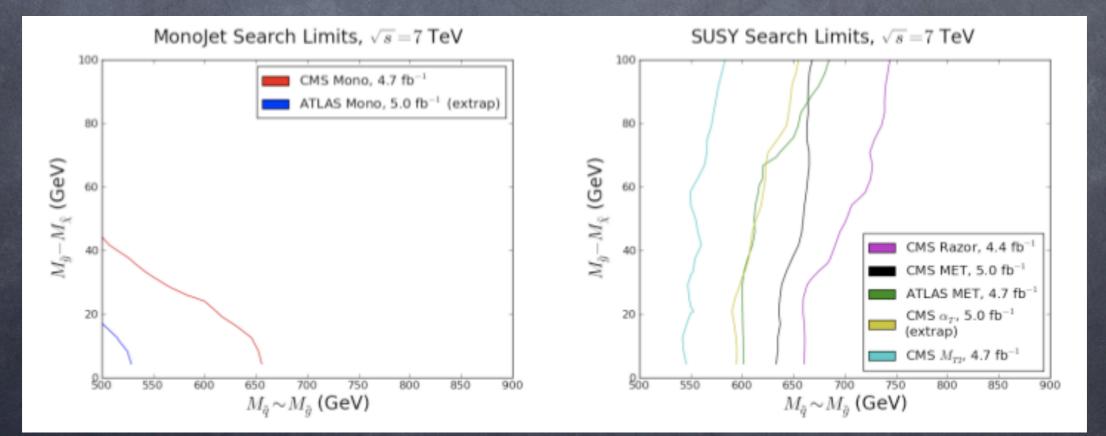
Le Compte, Martin, 1105.4304 & 1111.6897

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)

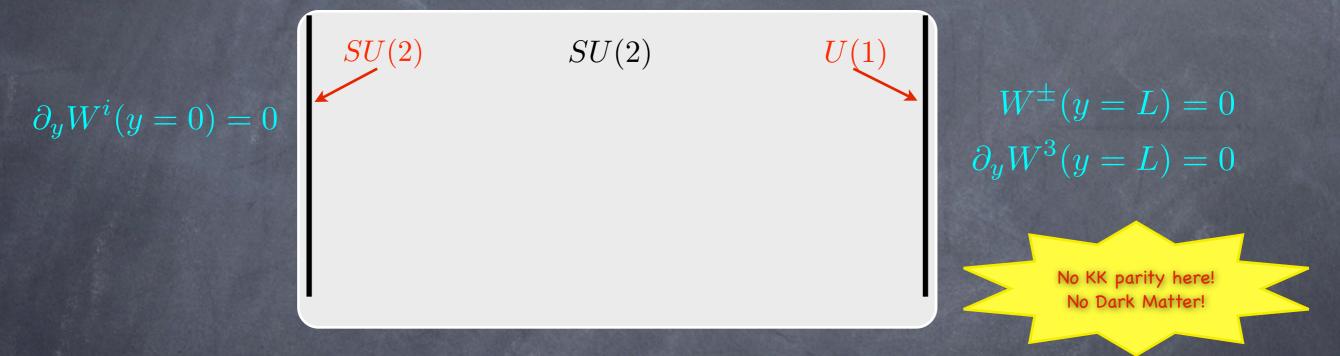
Generate hierarchies (fermion masses)



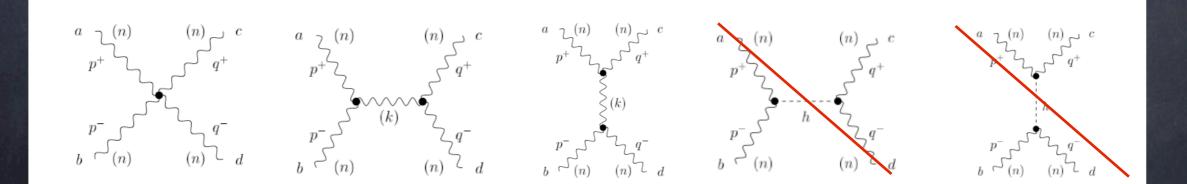
Breaking gauge symmetries

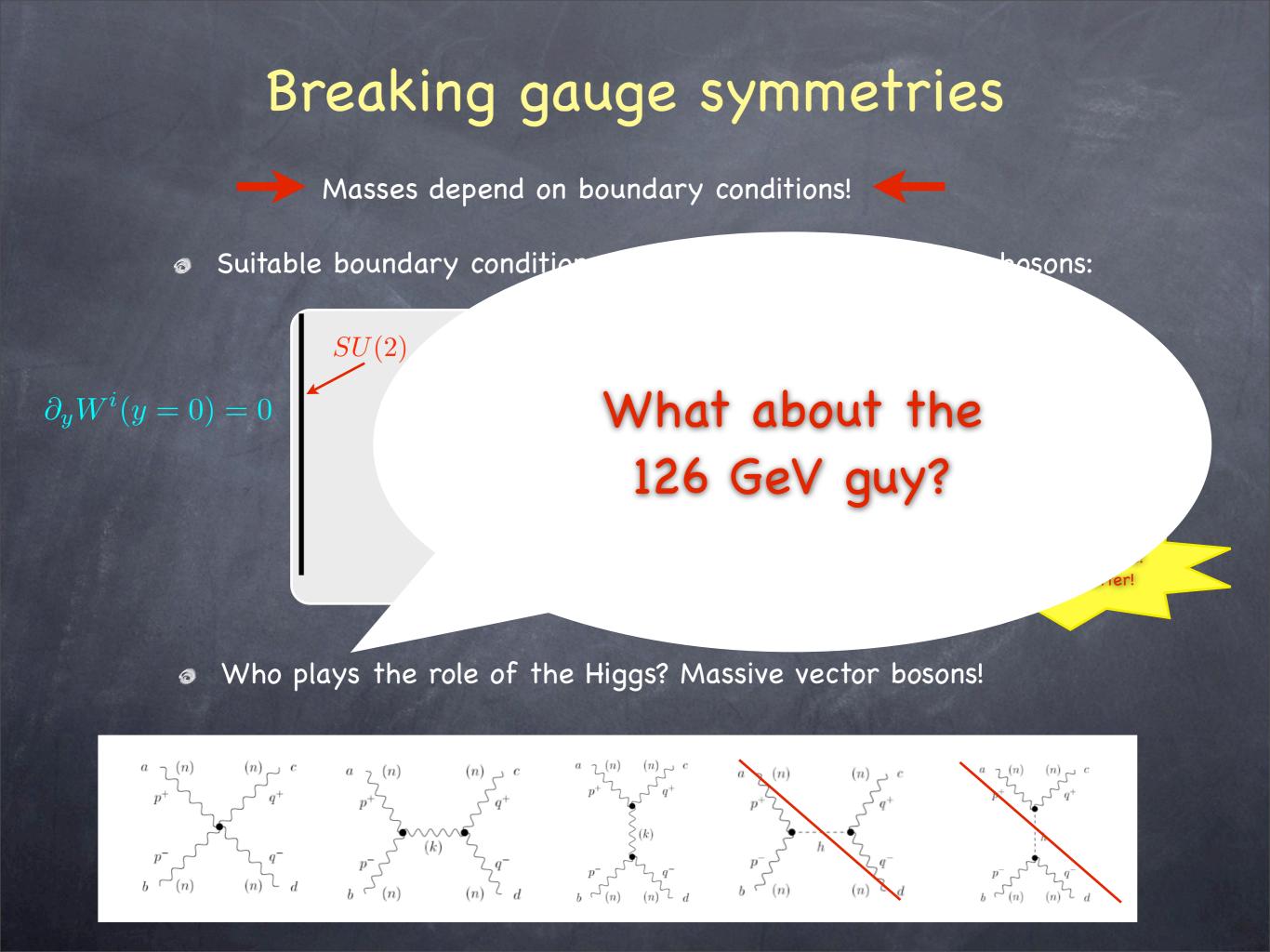
Masses depend on boundary conditions!

Suitable boundary conditions can generate massive gauge bosons:



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





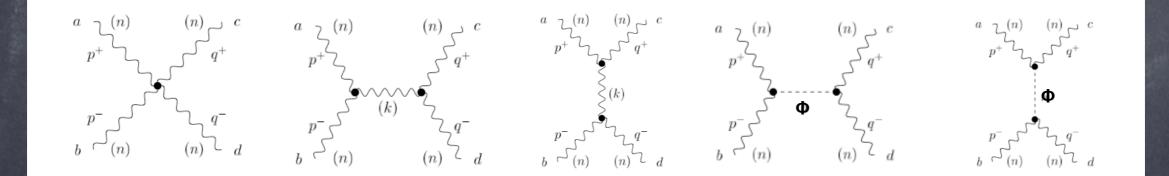
Breaking gauge symmetries

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!)

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

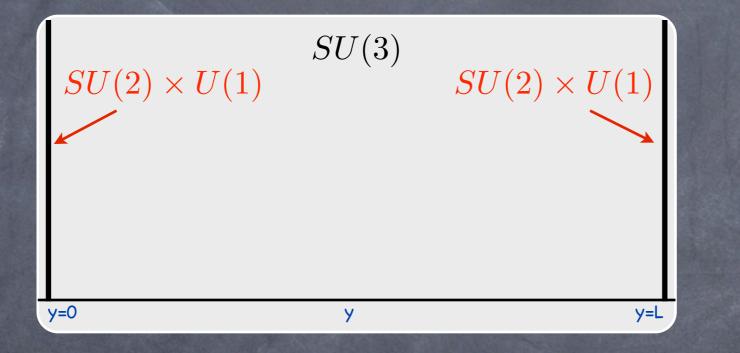


- Reduced tree level couplings to gauge bosons and fermions!
- Somewhat enhanced loop induced couplings (gluons and photons)!



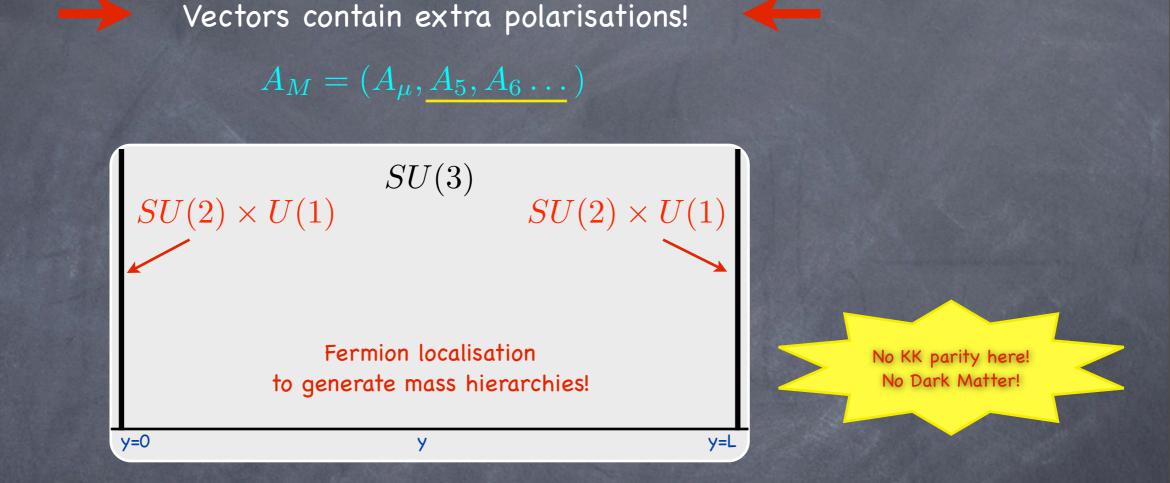
Vectors contain extra polarisations!

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



A massless scalar appears in the coset space $SU(3)/SU(2) \times U(1)$

It's an SU(2) doublet! New gauge-Higgs boson?



A massless scalar appears in the coset space $SU(3)/SU(2) \times U(1)$

- It's an SU(2) doublet! New gauge-Higgs boson?
- No tree level potential, and loops are finite!
- All interactions are gauge (including yukawas)!

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:

Coupling to all (massive) particles:

 $V(H) \sim -\sin(\#H) \Rightarrow \langle H \rangle = \frac{\pi}{2}$ $g_H \sim \sin(\#H) \sim 1 - \#\cos(\#\langle H \rangle) h$ $-\#^2 \sin^2(\#\langle H \rangle) h^2 + \dots$

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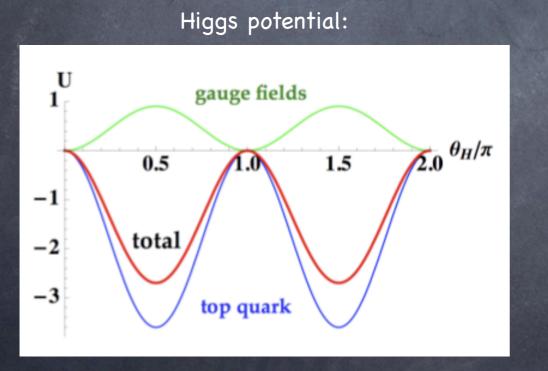
The Higgs is stable and can play the role of the Dark Matter!

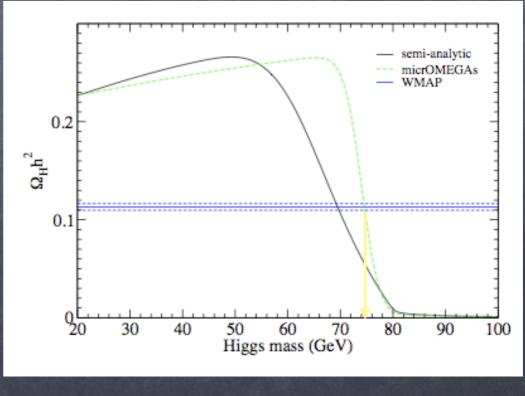
Mr. Radion @ 125 GeV?

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

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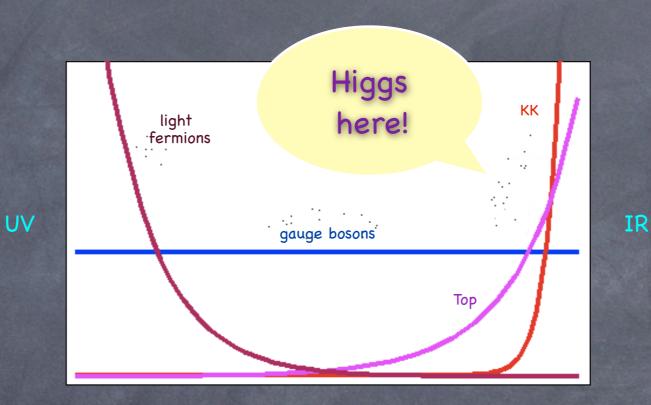


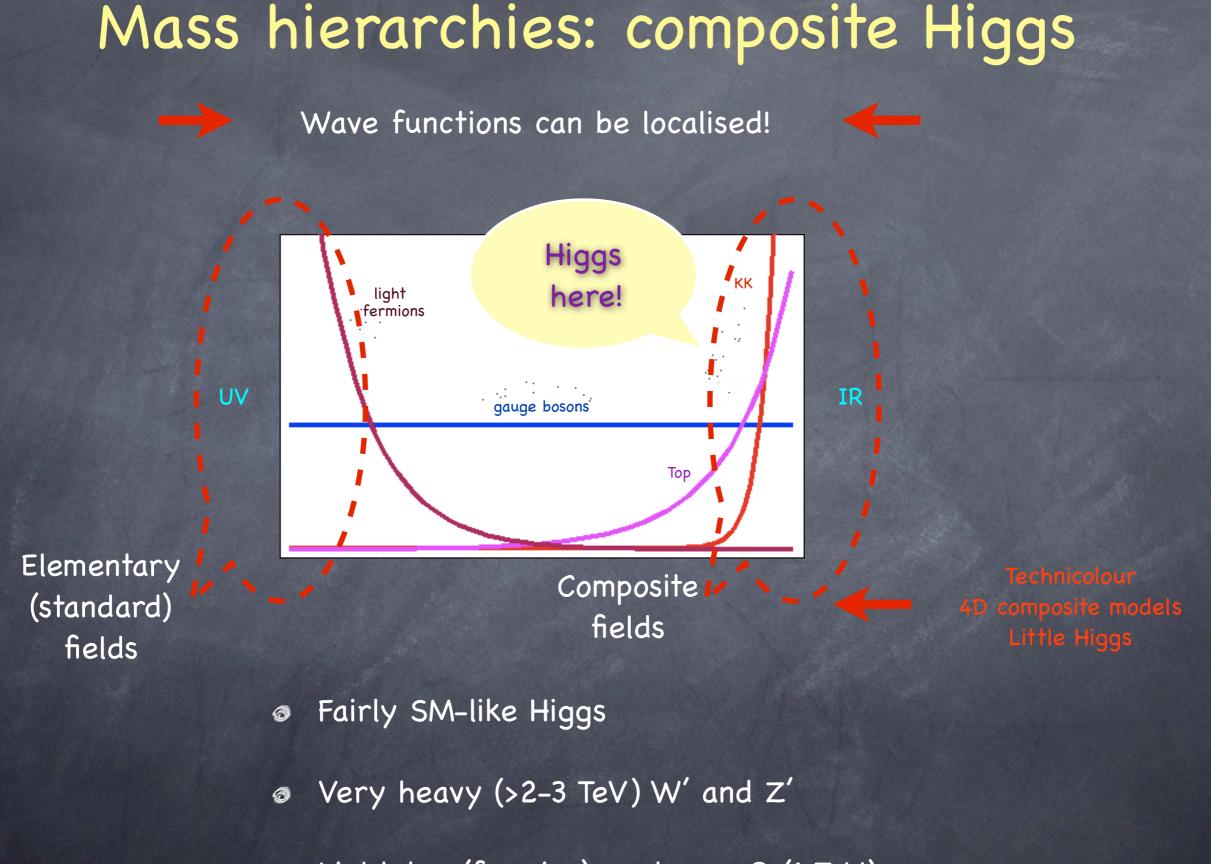


mH = 75 GeV !

Mass hierarchies: composite Higgs

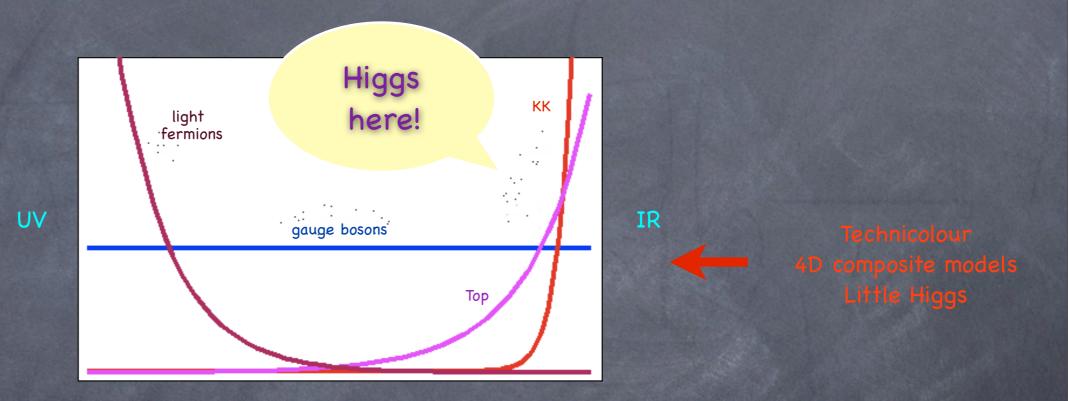
Wave functions can be localised!





Light top (fermion) partners, O (1 TeV)





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

$$\mathcal{L}_{\text{Yuk}} \sim y_{\text{top}} \, \bar{t}_R \, \text{Tr} \left(\begin{array}{cc} h^+ & h_0 \\ h_0^* & -h^- \end{array} \right) \cdot \left(\begin{array}{cc} x_L \\ t'_L \end{array} \right) \, \frac{t_L}{b_L}$$

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 composite models Little Higgs

ections:

Impose a cust

$$\mathcal{L}_{\text{Yuk}} \sim y_{\text{top}} \, \bar{t}_R \, \text{Tr} \left(\begin{array}{cc} h^+ & h_0 \\ h_0^* & -h^- \end{array} \right) \cdot \left(\begin{array}{cc} x_L \\ t'_L \end{array} \right) \, t_L \\ b_L \end{array} \right)$$

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

They have a Dirac mass without the Higgs.

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

They couple to SM quarks via Yukawa-type interactions.

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

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

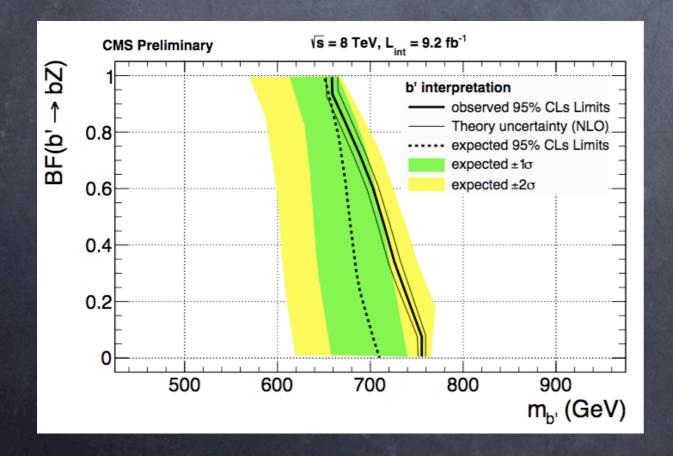
 $\mathcal{L}_{\text{singlet}} \sim \frac{g}{\sqrt{2}} V_L^{4i} W_\mu^+ \bar{t}'_L \gamma^\mu d_L^i + \frac{g}{2\cos\theta_W} V_L^{4i} Z_\mu \bar{t}'_L \gamma^\mu u_L^i + h.c.$

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

		ATLAS Exotics Searches* - 95% CL Lower Limits (Status: HCP 2012)
sylt	4 th generation : t't'→ WbWb 4 th generation : b'b'($T_{s,a}T_{5,3}$)→ WtWt	L=4.7 fb ⁻¹ , 7 TeV [1210.5468] 656 GeV t' mass L=4.7 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-130] 670 GeV b' (T _{erc}) mass
n dn	4 th generation : b'b'(T ₅₃ T ₅₃)→ WtWt New quark b' : b'b'→ Zb+X, m Top partner : TT → tt + A ₀ A ₀ (dilepton, M _{T2})	L=4.7 fb ⁻¹ , 7 TeV [1209.4186] 483 GeV T mass (m(A _n) < 100 GeV)
Neı	Vector-like quark : CC, m _{ivq} Vector-like quark : NC, m _{iiq}	L=4.6 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-137] 1.12 TeV VLQ mass (charge -1/3, coupling $\kappa_{qQ} = v/m_Q$) L=4.6 fb ⁻¹ , 7 TeV [ATLAS-CONF-2012-137] 1.08 TeV VLQ mass (charge 2/3, coupling $\kappa_{qQ} = v/m_Q$)

Bounds are below the TeV.

With few exceptions, 100% BR into a single channel assumed.



BR(Wt) = 1 - BR(Zb)

Search for multilepton signals

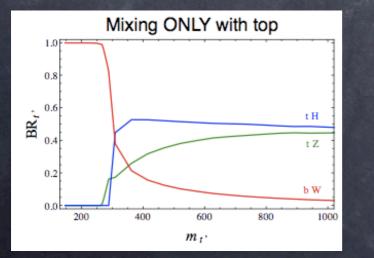
> branchings are never 100% in one channel!

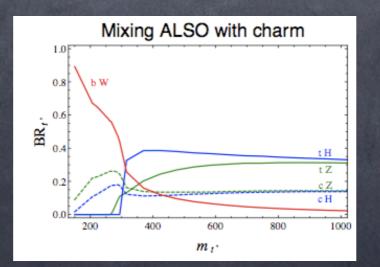
t'	Wb	Zt	ht
Single, Triplet Y=2/3	50%	25%	25%
Doublets, Triplet Y=-1/3	~ 0%	50%	50%

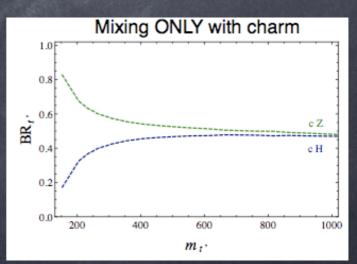
EQUIVALENCE THEOREM: at large VL masses, BR(Zt) = BR(ht)!!!

> decays into light quarks may not be negligible!

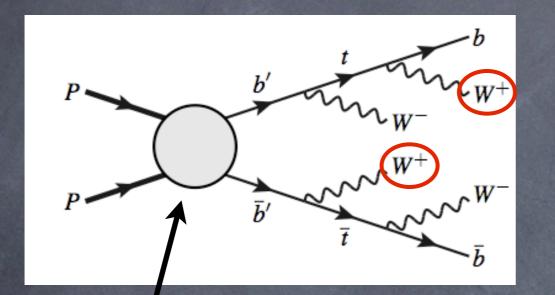
Flavour bounds: however, BRs are NOT proportional to the mixing matrices nor to the Yukawa couplings!







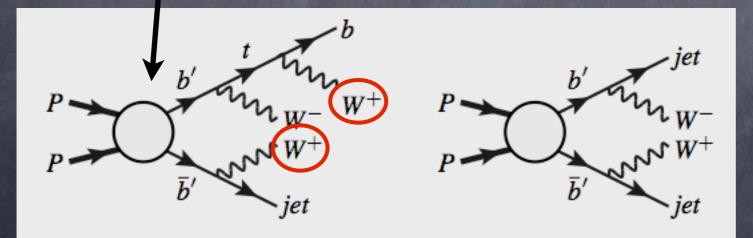
Example: same sign dilepton in b' decays



Assuming 100% decays into Wt

ss dilepton from W's b-tagging

Different efficiencies!!!!



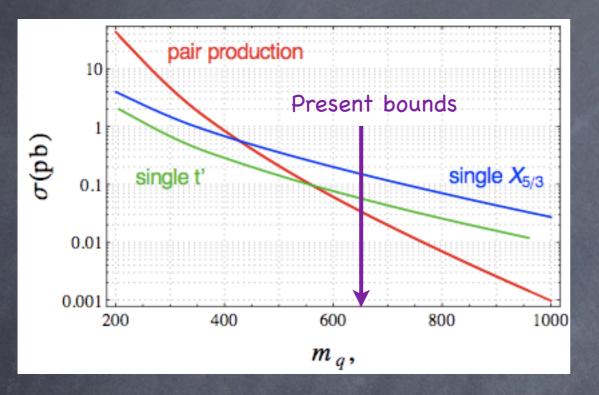
Decays in W q should also be included in the same search!

Example: same sign dilepton in b' decays

	t'	<i>b</i> ′	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!



Single production: $pp \rightarrow q' + \{q, V, H\}$ $q_i \longrightarrow q' \quad q_i \longrightarrow q' \quad g \mod q' \quad g \mod q' \quad g \mod q' \quad g \mod q' \quad q' \quad q \longrightarrow V \quad q$

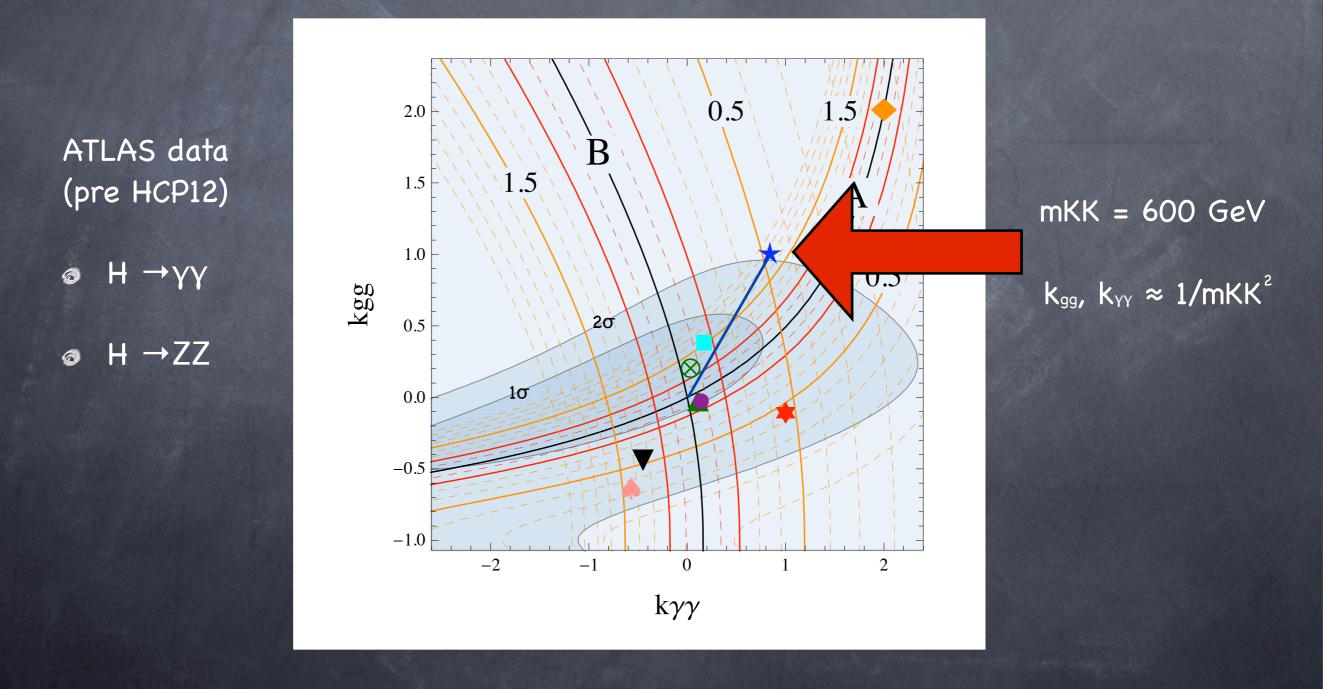
Couplings proportional to the mixing i.e. sensitive to the Yukawa couplings!

- 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 $H \rightarrow gg$ and $H \rightarrow \gamma\gamma$ loops!



Conclusions:



 A lot of information is still to be extracted by the data.

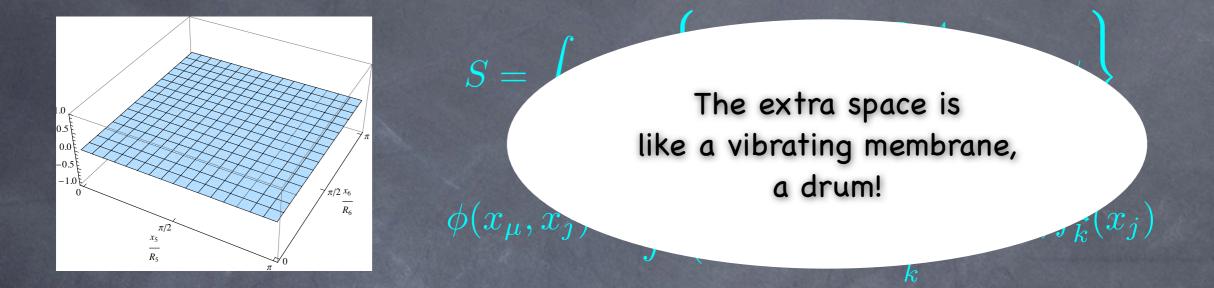
New physics may be there: are we properly looking for it?

Action for a massless scalar in D-dimensions

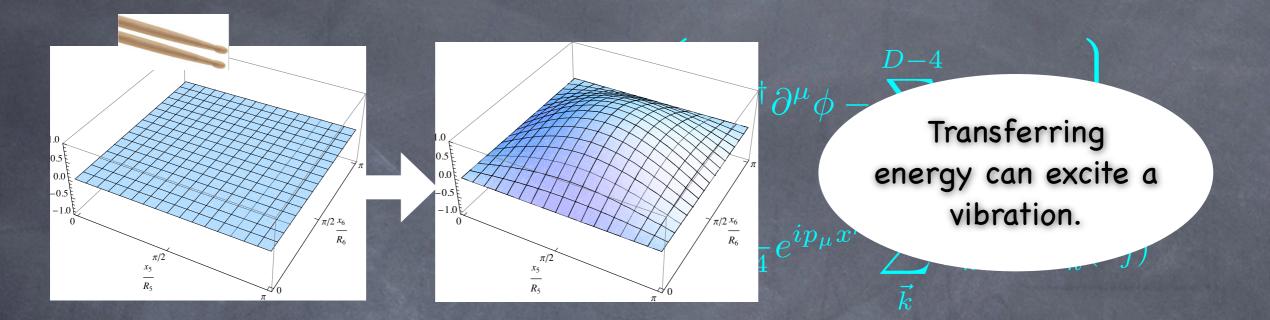
Expansion in 4-dim fields on compact extra space:

$$S = \int d^{D}x \left\{ \partial_{\mu} \phi^{\dagger} \partial^{\mu} \phi - \sum_{j=5}^{D-4} \partial_{j} \phi^{\dagger} \partial_{j} \phi \right\}$$
$$\phi(x_{\mu}, x_{j}) = \int \frac{d^{4}p}{(2\pi)^{4}} e^{ip_{\mu}x^{\mu}} \sum_{\vec{k}} \varphi_{\vec{k}}(p_{\mu}) f_{\vec{k}}(x_{j})$$

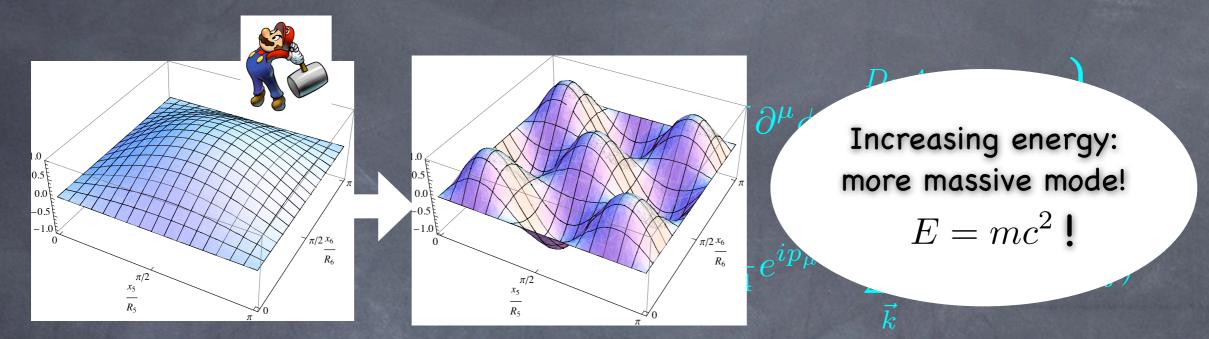
- D-dim fields correspond to tower of massive 4-dim fields
- k's are like <u>frequencies</u> of vibrating membrane!
- Masses and interactions determined by the wave functions $f_{\overrightarrow{k}}(x_i)$!
- Symmetries of the compact space = global symmetries of 4-dim fields: transformation properties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



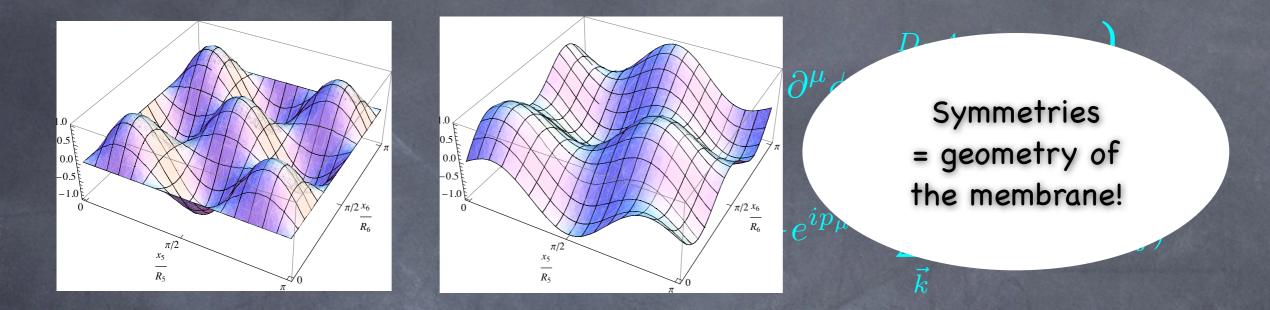
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