Phenomenology of the Supersymmetric Large Extra Dimensions scenario

by
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University of Toronto, decembre 7th, 2004

INTRODUCTION

- **GOAL OF THIS TALK**

The goal of the talk is to demonstrate that the Supersymmetric Large Extra Dimensions scenario (SLED) could provide a deep and fundamental understanding of the structure of the Universe, that it is theoretically and experimentally viable, and that must therefore be considered very seriously.

- **PLAN OF THE TALK**

In order to achieve this goal, the talk will be organized as follow:

1· Motivation of the SLED scenario:

  – set the problem
  – see how it requires fundamental changes in the paradigm of Particle Physics
  – summerize principal SLED features
  – see how SLED is a good candidate for fundamental new physics

2· Present some very general low-energy physics predictions that can be made from this scenario:

  – coupling of a generic bulk scalar with quarks and gluons
  – coupling of a generic bulk scalar with Higgs bosons

3· Study how these specific predictions could be experimentally tested with the ATLAS detector at the LHC.

MOTIVATION

The Standard Model is the most precise and successful theory that has been <u>tested</u> so far.

However, it misses many fundamental ingredients to provide a complete explanation of the structure of Nature:

1- the stability of scalar mass to radiative corrections

2- solution to the hierarchy problem

3- grand unification

4- consistent quantum description of gravity

5- solution to the cosmological constant problem

Other important problems or questions remain unsolved:
CP violation, quark/lepton compositness, number of families, QCD nonperturbative low-energy behaviour, Dark Matter

Solving the first set of problems would require a fundamental theory beyond the SM while the second set of problems could be predictions of this new theory.

- **WHAT KIND OF FUNDAMENTAL CHANGE ARE REQUIRED?**

  Completing the SM with new structures, that could manifest themself at high energies, can help to address these problems.

  Two fundamental changes in the actual paradigm are particularly encouraging:

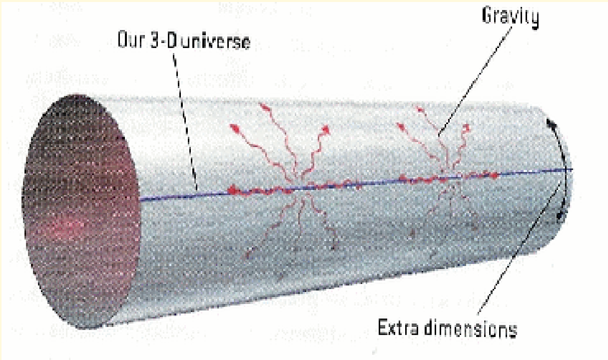
  - SUSY: there is a symmetry between bosons and fermions

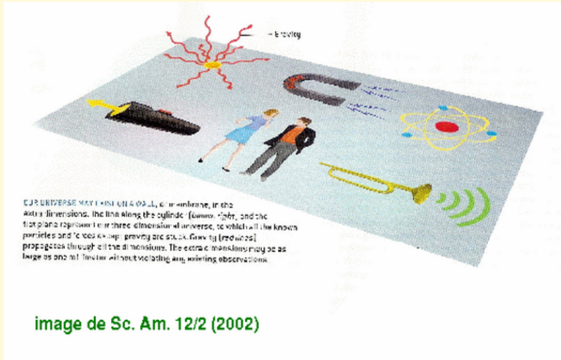
    $\Rightarrow$ help to solve points 2+3+4

  - Extra Dimensions: the Universe has few not-too-small compactified extra-D

    $\Rightarrow$ help to solve point 5

- **FIRST: WHAT DO MEAN BY EXTRA DIMENSIONS**
  - Extra dimensions are new confined degrees of freedom associated with every spacetime coordinates
  - A 3-brane is the hyperplane corresponding to the usual 4D space, embeded in the bulk of extra dimensions





If extra-D are probed by gravity only, then Newton law will change at distance scale $d < R$

$$\Downarrow$$

The D-dimensional Planck scale will be: $M_{\text{Pl}}^2 \sim R^n M_D^{n+2}$

$$R \sim 10\ \mu\text{m} \rightarrow R^{-1} \sim 1\ \text{meV} \rightarrow M_D \sim \text{TeV}$$

WHAT ABOUT THE COSMOLOGICAL CONSTANT PROBLEM?

- **WHAT IS THE COSMOLOGICAL CONSTANT PROBLEM?**

The experimental evaluation of Dark Energy from the anisotropy in c.m.b. (WMAP) has revealed a small but non-zero cosmological constant with:

$$\rho_\Lambda \sim 1\ (\mathrm{meV})^4$$

When we evaluate vacuum energy density from QFT we got $\rho_\Lambda \sim M^4$

$$\Downarrow$$

SM predicts a vacuum energy density 60 orders of magnitude too big!

The Cosmological constant problem is the most cumbersome of SM problems

$$\Leftrightarrow$$

It reveals a profond misunderstanding of the low-energy physics.

Ex.: the electron contributes already to a too big vacuum energy density compared to the measured amount of Dark Energy measurements

- **HOW COULD IT BE SOLVED?**

CLAIM:

$$\text{SUSY} \oplus \text{EXTRA-D.} = \text{SLED}$$

$$\Downarrow$$

May solve the Cosmological Problem!

† Burgess *et al.*: hep-th/0304256
hep-th/0308064
hep-th/0402200
hep-th/0404135

- **WHAT IS SLED?**

SLED is a framework that provides the ingredients for building effective models that doesn't suffer from the Cosmological Constant Problem.

In order to solve this problem SLED requires:

- exactly 2 extra dimensions of $\mathcal{O}(10\mu\mathrm{m})$
- SM particle stuck to a 3-brane
- N=2 SUperGRAvity in the bulk
- SUSY strongly broken on the brane
- bulk SUSY breaking scale of $\mathcal{O}(10^{-3}\mathrm{eV})$

$$\Downarrow$$

We can use this to write a low-energy effective 4D field theory that couples SM particles to bulk modes

- **OUTLINE**

SLED involve fundamental changes in the SM.

It can provide a new fundamental understanding of Nature because:

- it includes gravity at relatively low energies
- it eliminates any hierarchy between fundamental high energy scales
- it has the suitable ingredients to solve the Cosmological Constant Problem!
- it is a new way in which SUSY can be realized at low energies

$$\Downarrow$$

This is a promising new physics candidate which is at the frontier of High Energy theory, experimental particle physics and cosmology.

- **MUST IT BE CONSIDERED SERIOUSLY?**

YES!

SLED framework must be considered seriously because:

- it can be used to solved one of the most refractory problems of physics and could provide a better understanding of the structure of Universe

- its concepts are motivated by a more fundamental theory: Sting Theory

- it predicts a rich phenomenology $\Rightarrow$ can be tested

$$\Downarrow$$

It deserves as much research effort as SUSY!

Assuming that SLED is theoretically viable, ie that it predicts a cosmological constant of the size of the measured Dark Energy

The rest of the talk is to support the claim that SLED is experimentally viable, ie that

it can be tested at the LHC.

PHYSICS PREDICTIONS

- **PHENOMENOLOGY**

To make predictions for colliders, we have to express the model ($\mathcal{L}$) in a low-energy (compare to the Planck scale) 4D point of view.

The fundamental features of SLED modelized in such perspective will provide the following phenomenology:

▷ Extra dimensions are compactified on a torus of external and internal radius of $r \sim 10\mu$m.

$\Downarrow$

Kaluza-Klein modes can be seen as a continuous spectrum in 4D

▷ SM on a 3-brane and SUSY strongly broken on the brane

$\Downarrow$

In MSLED, all the non-gravitational degrees of freedom will exactly be described by SM

- In 4D, bulk space will be described by an extended $N = 4$ SUSY

  $\Downarrow$

  The bulk space will appear to be populated by particles of all spins from 0 to 2

- Small SUSY breaking scale in the bulk

  $\Downarrow$

  Gravity spectrum will be approximately degenerate and massless (zero modes)

- **EFFECTIVE THEORY**

To get the 4D low-energy SLED theory from the exacte and complete 6D Lagrangian, we have to:

1- develop it in term of the bulk Fourier modes (KK modes)

2- integrate on the compactified extra dimension

3- integrate out all the high energetic modes and their quantum fluctuations down to the experimental energy scale

BUT...

We don't have a complete and exact SLED model yet!

Effective field theory framework allow us to get a Model Independant 4D low-energy SLED theory

We simply have to write the most general field theory that:

1- couple massless bulk particles gravitationally to SM particles

2- follow the phenomenological prescription presented above

3- respect all the SM symmetries

The price to pay will be that the coupling constants will be taken as free parameters of the theory (exept for the graviton)

- **PLAN OF THE ANALYSIS**

Choose a particular SLED bulk field and write the effective 4D low-energy Lagrangian describing its couplings to SM fields.

▷ We study the coupling of a bulk scalar ϕ with SM fields

Concentrate on the lowest mass dimension interaction terms to:

-quarks and gluons

-Higgs bosons

Evaluate the possibility to observe a bulk scalar with ATLAS

jet+$\not{E}_T$: Beauchemin *et al.* (hep-ph/0401125)

H+$\not{E}_T$: Beauchemin *et al.* (hep-ph/0407196)

The parameter range of our generic set of couplings needed for discovery

$\Leftrightarrow$

sensitivity of ATLAS to such physics

- **LAGRANGIAN**

$f\bar{f}\phi$ and $gg\phi$ interactions

at lowest orders we have:

$$\mathcal{L}_{\text{EFF}} = \partial_M\phi(x,y)\partial^M\phi(x,y)$$
$$- \delta^n(y)[\sum_Q \frac{1}{\bar{M}_D^{n/2}}\bar{\Psi}(x)(g + ig_5\gamma_5)\Psi(x)\phi(x)$$
$$- \frac{1}{\bar{M}_D^{(n+2)/2}} G^a_{\mu\nu}(x)(cG_a^{\mu\nu}(x) + \tilde{c}\tilde{G}_a^{\mu\nu}(x))\phi(x)]$$

Note:

- We explicitly replaced a SM Higgs factor by its vev and rotated to a fermion eigen-basis.

  $\Rightarrow g$ could be suppressed by an extra $v/\bar{M}_D$ factor

- Even if in SLED $n = 2$, we will keep n general.

  $\Downarrow$

  SLED will phenomenologically be the favored scenario.

Higgs-ϕ

At lowest order, this trilinear coupling is dimensionless in SLED!

$$\Downarrow$$

This is a SLED prediction alone and it will dominate at colliders!

The effective Lagrangian of such an interaction is:

$$\boxed{\mathcal{L}_{int} = -\delta^2(y)[aH^\dagger(x)H(x)\phi(x)]}$$

In unitary gauge, we have $H = \binom{0}{v+h(x)}$

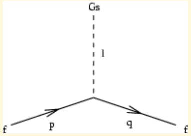
$$\Downarrow$$

$$\mathcal{L}_{int} = -\delta^2(y)[a(v+h)^2\,\phi(x)\;,]$$

We will focus on $hh\phi$

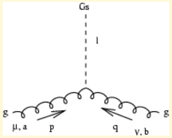
- **FEYNMAN RULES**

$\bar{q}q\phi$:



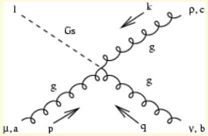
$= -i(g + ig_5\gamma_5)$

$gg\phi$:



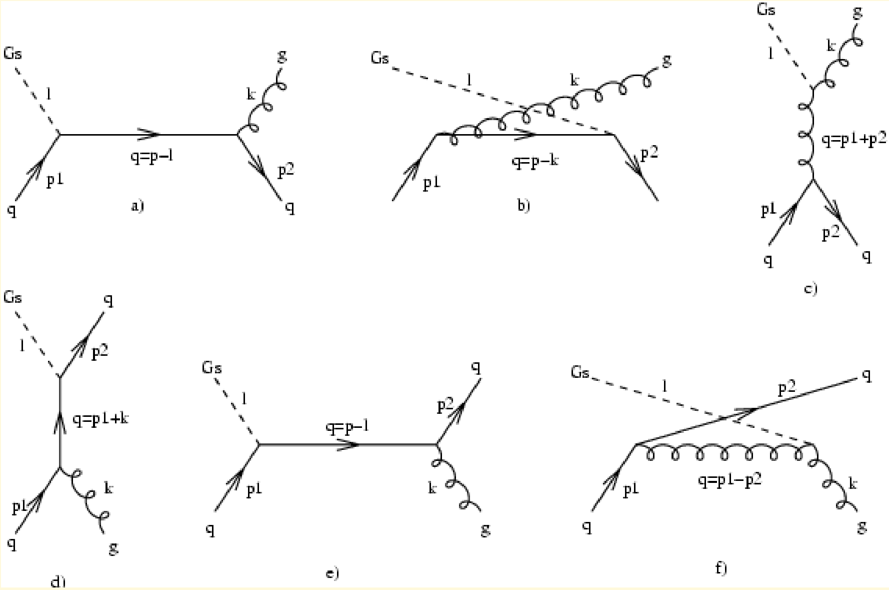
$= 4i[c(p.q)g_{\mu\nu} - cp_\nu q_\mu + \tilde{c}\epsilon_{\mu\nu\alpha\beta}p^\alpha q^\beta]\delta_{ab}$

$ggg\phi$:



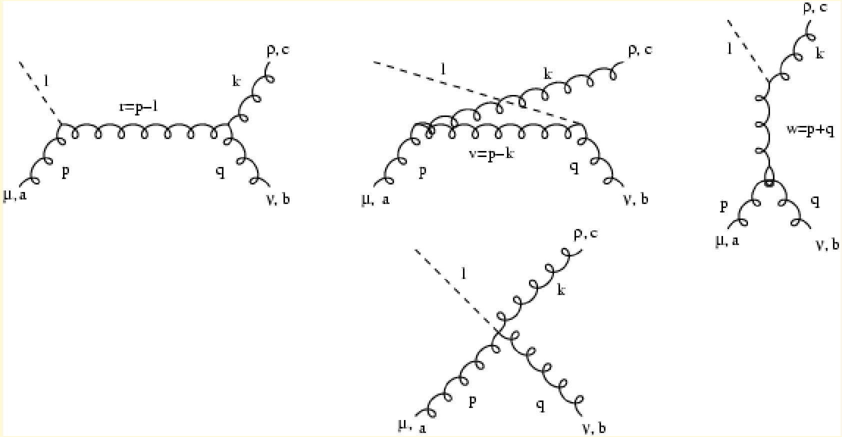
$$= 4g_3 f^{abc}[cg_{\mu\nu}(p_\rho - q_\rho) + cg_{\mu\rho}(k_\nu - p_\nu) + cg_{\nu\rho}(q_\mu - k_\mu) + \tilde{c}\epsilon_{\alpha\mu\nu\rho}(p^\alpha + q^\alpha + k^\alpha]$$

- **PARTON-ϕ CROSS-SECTIONS**



$$\frac{d\sigma(q\bar{q}\to g\phi)}{d\hat{t}\,d\hat{u}\,dM^2} = \frac{\alpha_s(2\pi)^{n/2}(M^2)^{\frac{n-2}{2}}}{18\Gamma(n/2)\hat{s}^2} \times \left[\frac{(g^2+g_5^2)}{M_D^n(2\pi)^{\frac{2n}{2+n}}}\,\frac{2M^2\hat{s}+(\hat{u}+\hat{t})^2}{\hat{u}\hat{t}} + 4\frac{(c^2+\tilde{c}^2)}{M_D^{n+2}}\,\frac{\hat{t}^2+\hat{u}^2}{\hat{s}}\right]$$

$$\frac{d\sigma(qg\to q\phi)}{d\hat{t}\,d\hat{u}\,dM^2} = -\frac{\alpha_s(2\pi)^{n/2}(M^2)^{\frac{n-2}{2}}}{48\Gamma(n/2)\hat{s}^2} \times \left[\frac{(g^2+g_5^2)}{M_D^n(2\pi)^{\frac{2n}{2+n}}}\,\frac{\hat{u}+M^4}{\hat{s}\hat{t}} + 4\frac{(c^2+\tilde{c}^2)}{M_D^{n+2}}\,\frac{\hat{t}^2+\hat{s}^2}{\hat{u}}\right]$$



$$\frac{d\sigma(gg\to g\phi)}{d\hat{t}\,d\hat{u}\,dM^2} = \frac{3\alpha_s(2\pi)^{n/2}(M^2)^{\frac{n-2}{2}}}{16\Gamma(n/2)\hat{s}^3\hat{t}\hat{u}}\frac{(c^2+\tilde{c}^2)}{M_D^{n+2}}\left[(\hat{u}+\hat{t})^4+(\hat{u}+\hat{s})^4+(\hat{t}+\hat{s})^4+12\hat{s}\hat{t}\hat{u}M^2\right]$$

Note: Each cross-section is multiplied by $\delta(\hat{s}+\hat{t}+\hat{u}-M^2)$

Bulk phase space: $\int_{\Omega_n}\frac{d^nL}{(2\pi)^n} = \frac{(M^2)^{(n-2)/2}\,dM^2}{2\,\Gamma(\frac{n}{2})\,(2\pi)^{n/2}}$

Physical picture: a stable particle radiated by the brane in the extra-D

$\Downarrow$

We are looking for pp$\longrightarrow$jet+$\not{E}_T$ events.

• PHASE SPACE INTEGRATION

We want to compute the following integral numerically:

$$\sigma = \int f(x_1, Q^2) f(x_2, Q^2) \frac{d\sigma}{d\hat{t} dM^2} dx_1 dx_2 dM^2 d\hat{t}$$

The integration limits are:

(a) for $\hat{t}$: $P_T^2 = \frac{\hat{t}\hat{u}}{\hat{s}}$ and $P_T^2 \geq P_{cut}^2$

▷ $$t_0 \equiv \frac{(M^2-\hat{s})-\sqrt{(M^2-\hat{s})^2-4P_{cut}^2\hat{s}}}{2} \leq \hat{t} \leq \frac{(M^2-\hat{s})+\sqrt{(M^2-\hat{s})^2-4P_{cut}^2\hat{s}}}{2} \equiv t_1$$

(b) for M^2: $\sqrt{\hat{s}} = E_g + \sqrt{|\vec{P}_G|^2 + M^2}$

▷ $$0 \leq M^2 \leq \hat{s} - 2\sqrt{\hat{s}} P_{cut} \equiv M_{max}^2$$

(c) for x: $\hat{s} = x_1 x_2 s$ and $x_{min} = \frac{2}{\sqrt{s}} P_{cut}$

▷ $$x_{min} \leq x_{1,2} \leq 1$$

The processes have been implemented in PYTHIA.

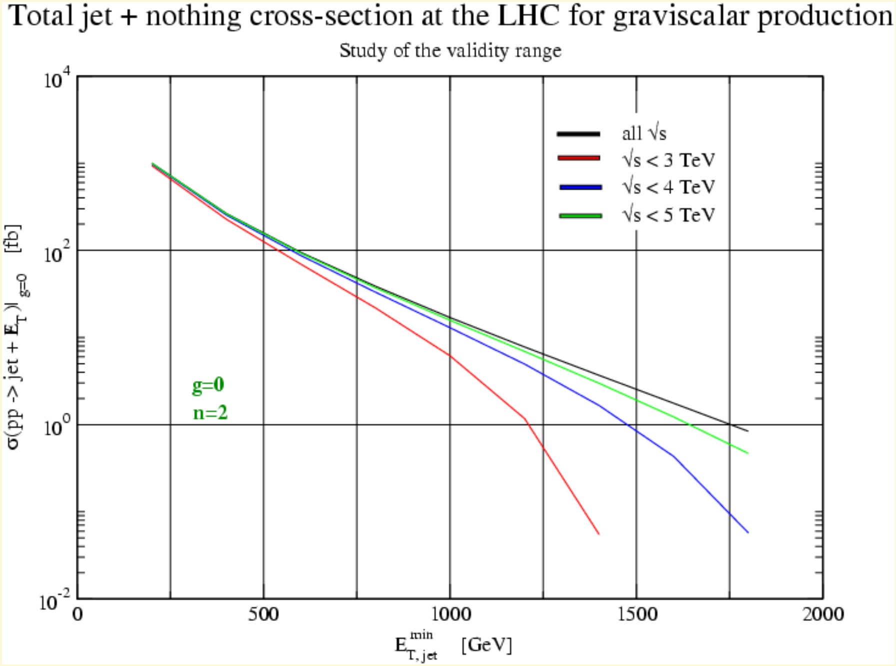
• RELIABILITY

The physical predictions will not be reliable for high energies.

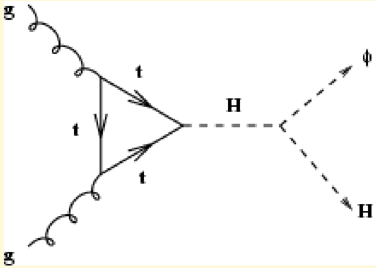
Quantify the UV sensibility by comparing σ vs $E_{T,jet}^{min}$ in two cases:

a: $\frac{d\sigma}{d\hat{t}}$ is fixed to 0 for $\sqrt{\hat{s}} > M_D$

b: compute σ for all $\sqrt{\hat{s}}$



- **H-ϕ CROSS-SECTIONS**



$$\frac{d\sigma}{d\hat{t}\, dM_\phi^2}(gg \to h\phi) = \left(\frac{a^2\alpha_s^2}{144 v^2}\right) \frac{|\mathcal{F}(\frac{m_t^2}{Q^2})|^2}{(\hat{s}-m_h^2)^2}.$$

We follow the conventions of [hep-ph/9912459]:

$$\mathcal{F}(r) = 3[2r + r(4r-1)f(r)]$$

where

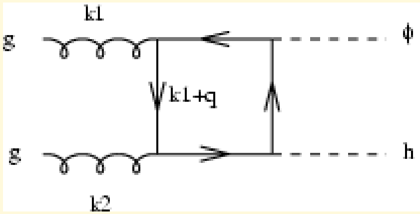
$$f(r) = \begin{cases} -2\left[\arcsin\left(\frac{1}{2\sqrt{r}}\right)\right]^2 & \text{if} \quad r > \frac{1}{4}; \\ \frac{1}{2}\left[\ln\left(\frac{\eta_+}{\eta_-}\right)\right]^2 - \frac{\pi^2}{2} + i\pi \ln\left(\frac{\eta_+}{\eta_-}\right) & \text{if} \quad r < \frac{1}{4}; \end{cases}$$

with

$$\eta_\pm = \frac{1}{2} \pm \sqrt{\frac{1}{4} - r}.$$

Note: contribution of the top-quark loop suffices.

Other Feynman graph contributions are suppressed by powers of $\frac{E}{M_D}$



we study the more rare, but cleaner, $h \to \gamma\gamma$ channel.

$$\Downarrow$$

The desired signal is two photons plus $\not{E}_T$

Higgs mass (GeV)	100	110	120	130	140	150
Cross sect. (pb)	22.5	18.8	15.9	13.6	11.8	10.3
Branch. ratio (%)	0.15	0.19	0.22	0.22	0.19	0.14
$\sigma \times B$ (fb)	35.6	34.9	30.2	22.7	14.2	5.9
SM $pp \to h$ (pb)	31.8	26.7	23.0	20.0	17.4	15.8
Mass resol. (GeV)	1.31	1.37	1.43	1.55	1.66	1.74

$$a = 0.5$$

EXPERIMENTAL ANALYSIS

1- HADRONS-BULK SCALAR COUPLING

$f\bar{f}\phi$ and $gg\phi$

- **PARTON-ϕ ANALYSIS**
  (Using ATLFAST)

The topology of the signal is jet+$\not{E}_T$

The standard background is (following Vacavant & Hinchliffe):

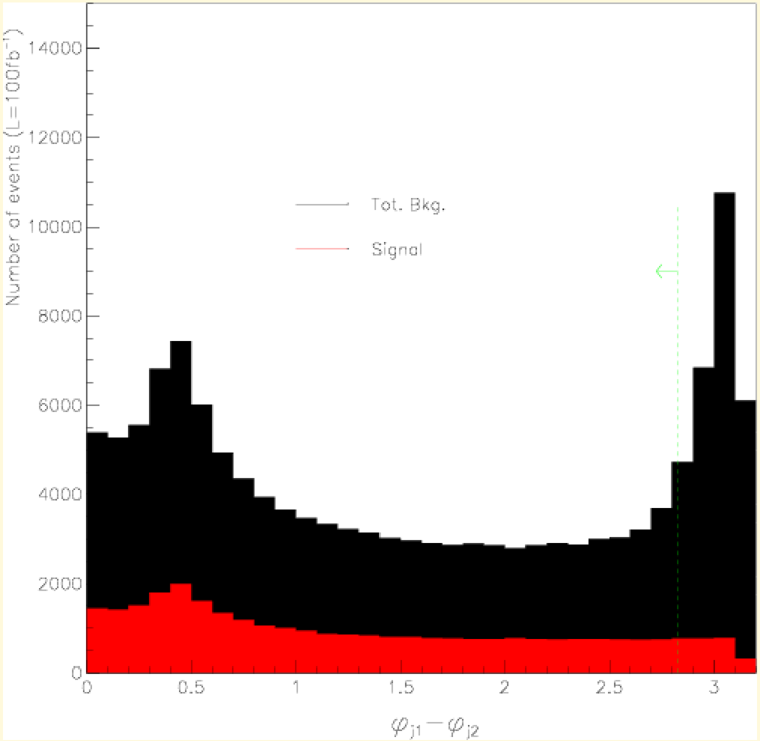
- $pp \to jet + Z(\to \nu\nu)$ (277.6 fb)
- $pp \to jet + W(\to e\nu_e)$ (364.2 fb)
- $pp \to jet + W(\to \mu\nu_\mu)$ (363.7 fb)
- $pp \to jet + W(\to \tau\nu_\tau)$ (363.3 fb)

CUT 1: number of leptons = 0

In the c.m.s. the bulk scalar and the jet are back-to-back

$$\Downarrow$$

CUT 2: accept $|\varphi_{j_1} - \varphi_{j_2}| < 2.83$



Processes	Total	Cut 1	Cut 2
jet+$Z(\to \nu\nu)$	27760	27100	24940
jet+$W(\to e\nu_e)$	36420	5224	1430
jet+$W(\to \mu\nu_\mu)$	36370	957	866
jet+$W(\to \tau\nu_\tau)$	36330	24600	9459
jet+bulk scalar	30960	30090	27720

For a 5σ discovery, we need $\frac{S}{\sqrt{S+B}} > 5$

With $100 fb^{-1}$

$$B = 36700 \text{ events } (P_T > 500 GeV)$$

$$\Downarrow$$

$$S > 970 \text{ events} \Rightarrow \sigma > 10.9 fb$$

$$\Downarrow$$

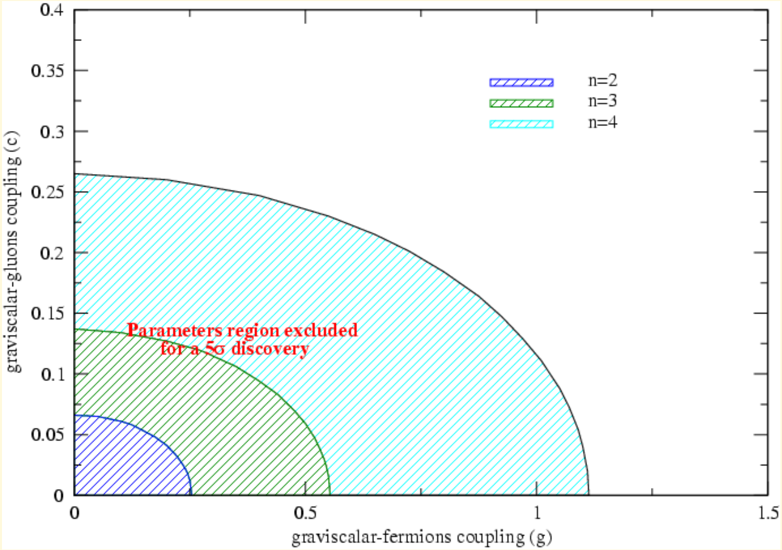
$$\bar{c} = 5.1 \times 10^{-3} TeV^{-2}$$
$$\bar{g} = 7.1 \times 10^{-2} TeV^{-1}$$

where $g = \bar{g} M_D^{\frac{n}{2}}$ and $c = \bar{c} M_D^{\frac{n+2}{2}}$

This analysis applies for any number of extra-D.

- **RESULTS**

To be valid and testable at the LHC, any model of graviscalar must satisfy: $1 \gtrsim g > \bar{g}_0^{(n)}(M_D^{min})^{\frac{n}{2}}$ $\quad 1 \gtrsim c > \bar{c}_0^{(n)}(M_D^{min})^{\frac{n+2}{2}}$



The sensitivity range of ATLAS to M_D is:

ndim	Graviton	bulk scalar	
	M_D^{max}	M_D^{min}	M_D^{max}
2	7.5 TeV	3.60 TeV	14.00 TeV
3	5.9 TeV	4.30 TeV	6.45 TeV
4	5.3 TeV	4.85 TeV	1.45 TeV

- **GRAVITON**

Graviton production rate is have same $\not{p}_T$ behaviour as for the bulk scalar.

$$\Downarrow$$

We cannot use $P_{T,jet}$ or $\not{E}_T$ to discriminate.

But the only handle we have is $P_T(jet)$:

- no angular distribution in cm of parton system;
- no FB asymmetry
- possible discriminating variable: η vs P_T.

$$\Downarrow$$

Even if spins are distinct, the discrimination will be very difficult (possible ???)

- **WHAT CAN WE LEARN?**

a) We find a discriminating distribution, graviton will then be another background

$$\Downarrow$$

increase c and g for discovery.

b) We can't distinguish between these particles

$$\Downarrow$$

Theoretical uncertainty on graviton signal and on M_D, r and n measurement.

c) Other physics give a measurement of M_D, n and r to fix graviton production rate.

$$\Downarrow$$

bulk scalar would appear as an excess of graviton events;

This last case is exactly what SLED offers using the measurement of Dark Energy

$$\Downarrow$$

SLED is more predictive and offers stronger experimental tests than other large extra-D scenario!

2- HIGGS-BULK SCALAR COUPLING

$$hh\phi$$

- **H-ϕ ANALYSIS**
  (Using ATLFAST)

  The standard backgrounds are (following TDR):

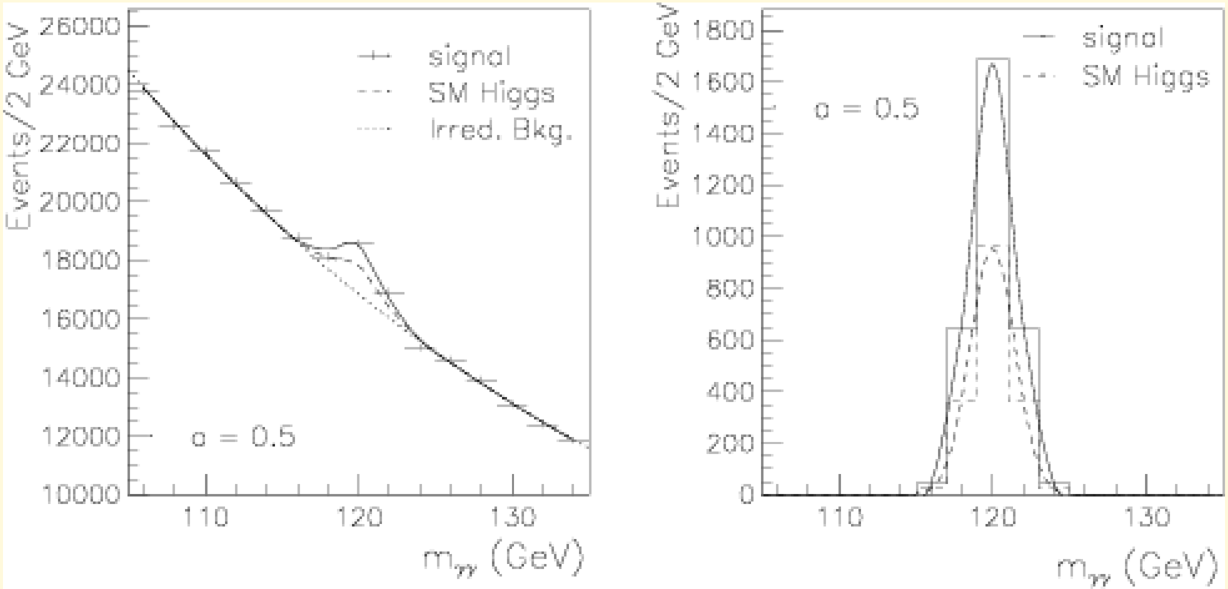
  - $q\bar{q} \longrightarrow \gamma\gamma$ (56.2 pb)
  - $gg \longrightarrow \gamma\gamma$ (49.0 pb)
  - QCD jet-jet (4.9×10^8 pb)
  - QCD γ-jet (1.2×10^5 pb)
  - $q\bar{q} \longrightarrow hZ \longrightarrow \gamma\gamma\ \nu\nu$ (1.22×10^{-3} pb)
  - $q\bar{q} \longrightarrow t\bar{t}h\ h \longrightarrow \gamma\gamma$ (1.28×10^{-3} pb)

  1. add a correction to the total irred. bkg. for quark brems. by a 50% scaling factor
  2. requiring two γs in the final state $\Rightarrow$ rejection factor for red. bakg: 2×10^7 and 8×10^3 respectively.
  3. expected photons reconst. eff. $\Rightarrow$ further reduction factor of 80%/γ
  4. isolated photon if:
     - $P_T^\gamma > 5.0$ GeV
     - < 10 GeV of energy deposited by all other particles within a cone of radius $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} < 0.4$.

The cuts are imposed to optimize the significance of the $h \to \gamma\gamma$ signal for the standard Higgs search at ATLAS (TDR).

- CUT 1: $P_T > 40$ **GeV** for photon 1 and $P_T > 25$ **GeV** for photon 2
- CUT 2: γ candidates must lie in the pseudorapidity interval $|\eta| < 2.4$
- CUT 3: pseudorapidity separation of $\Delta\eta > 0.15$
- CUT 4: final state invariant mass close to Higgs mass:

$$M_H - 1.4\sigma_H < M_{\gamma\gamma} < M_H + 1.4\sigma_H$$


Events/2 GeV
26000
24000
22000
20000
18000
16000
14000
12000
10000
signal
SM Higgs
Irred. Bkg.
a = 0.5
110
120
130
m_γγ (GeV)
Events/2 GeV
1800
1600
1400
1200
1000
800
600
400
200
0
signal
SM Higgs
a = 0.5
110
120
130
m_γγ (GeV)

38% of the initial number of signal events survive these cuts

With $100 fb^{-1}$ we expect:

- 44 700 background events
- 1,500 standard $h \to \gamma\gamma$ events
- 16 $hZ \to \gamma\gamma\ \nu\nu$ events
- 9 $t\bar{t}h\ h \to \gamma\gamma$ events

For a 5σ discovery, we need $\frac{S}{\sqrt{B}} > 5$

$$\Downarrow$$

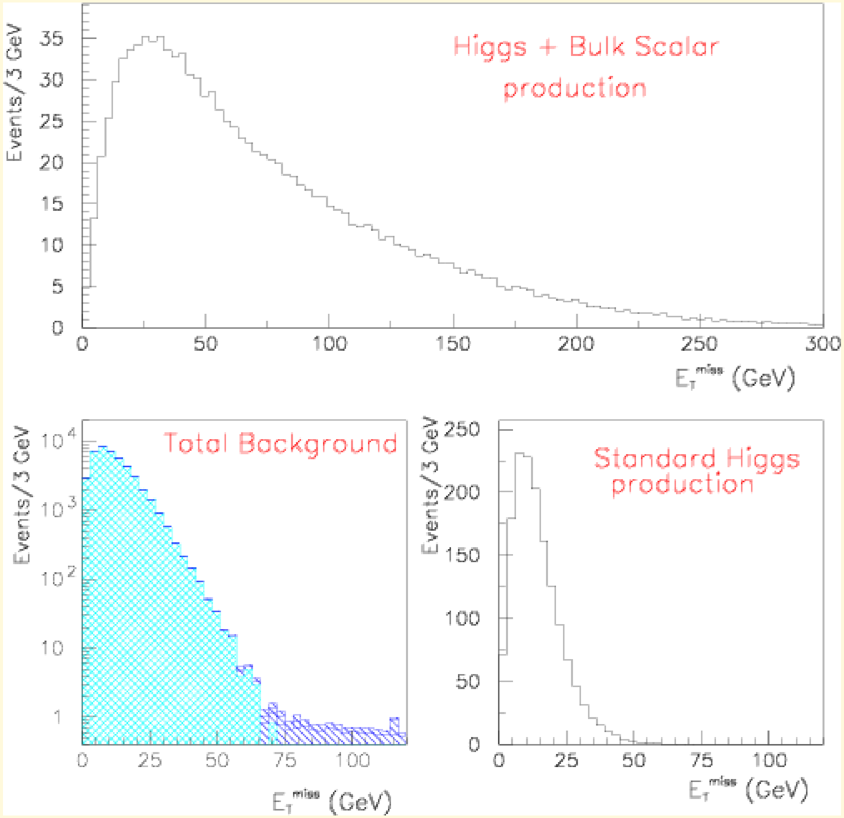
$a = 0.5$ produces roughly the same number of $pp \to h\phi$ events as from the Standard Model $pp \to h$ process ($m_h = 120$ GeV)

$$\Downarrow$$

For couplings this large roughly half of the Higgs particles are produced in association with ϕ emission into the extra dimensions.

- $\not{E}_T$ **CUT**

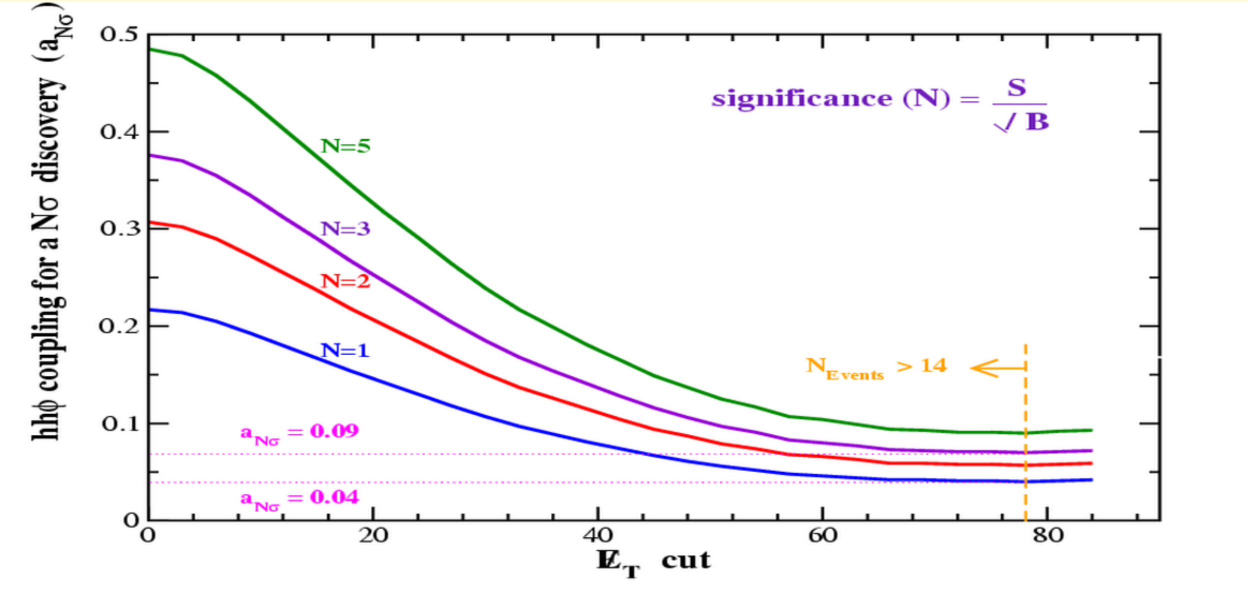
Because of the escaping bulk scalar, we expect much more $\not{E}_T$ in the signal than in the bkg.



RESULTS

- **PARAMETER RANGE**

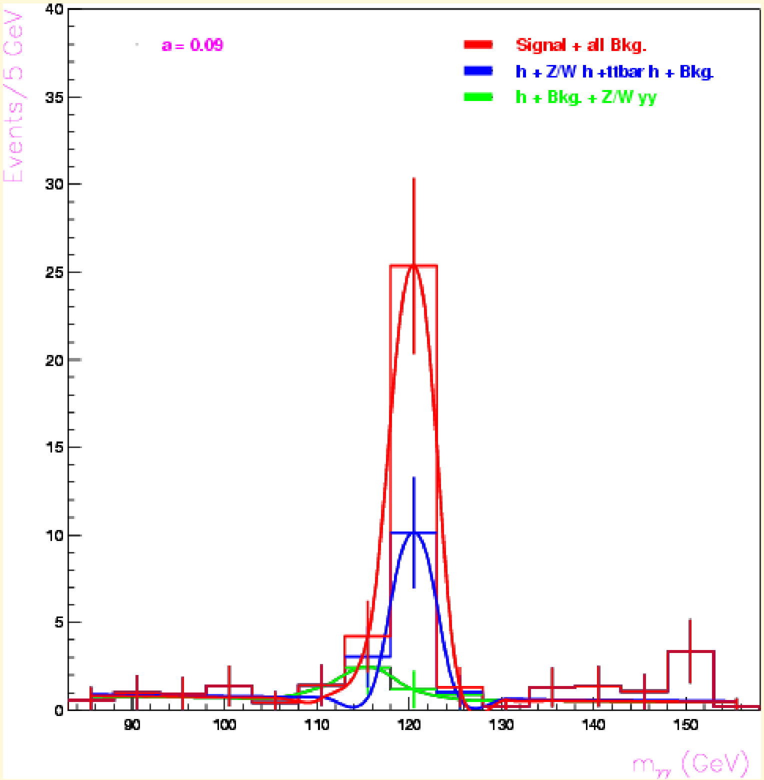
A cut on $\not{E}_T$ allows to increase the parameter range for a discovery from 0.5 to 0.09



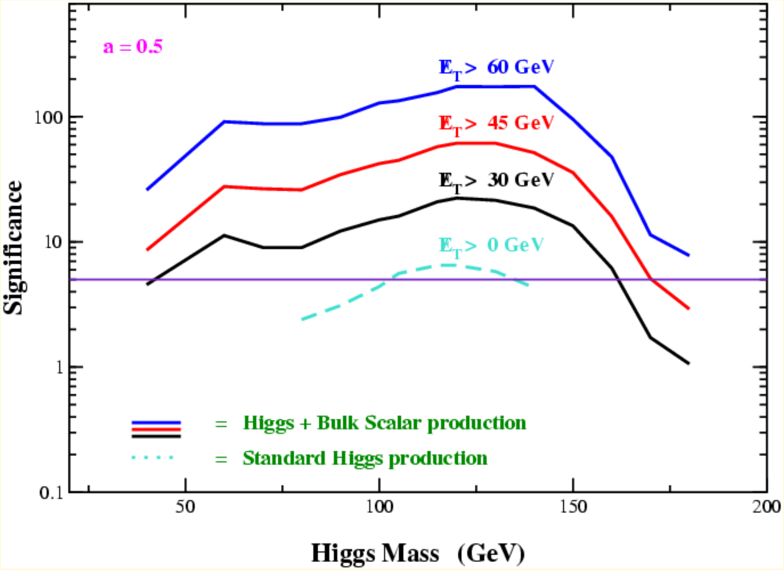
- CUT 5: missing transverse energy of the entire event must satisfy: $\not{E}_T > 78$ GeV.

HIGGS DISCOVERY

The new cut allow for a clear peak for the discovery of the Higgs with the $h\phi \to \gamma\gamma \not{E}_T$ channel



It increases significantly the sensitivity of ATLAS to a Higgs and extends the mass range for a potential discovery.



By itself the process $h + Zh + t\bar{t}h \;\; h \to \gamma\gamma$ has a significance of 8.3 σ when we impose a cut of 66 GeV.
ATLAS note COM-PHYS-2004-056

CONCLUSION

- SLED scenario can provide a fundamentally new understanding of high energy physics and thus deserves to be carefully studied
- SLED has a rich phenomenology. In particular, it predicts coupling of bulk scalars to SM particles.
- We compute physical predictions for a fairly generic bulk scalar-parton and bulk scalar-Higgs interaction
- Using cut on $\not{E}_T$ we evaluated ATLAS sensitivity to:
  -$q\bar{q}\phi$: $0.26 \lesssim g \lesssim 1$
  -$gg\phi$: $0.06 \lesssim c \lesssim 1$
  -$hh\phi$: $0.09 \lesssim a \lesssim 1$
- SLED offers the widest discovery possibility for the ϕ-parton couplings
- The $h\phi$ signal can significantly improve the Higgs discovery