

Update on String Phenomenology



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Strings 2012

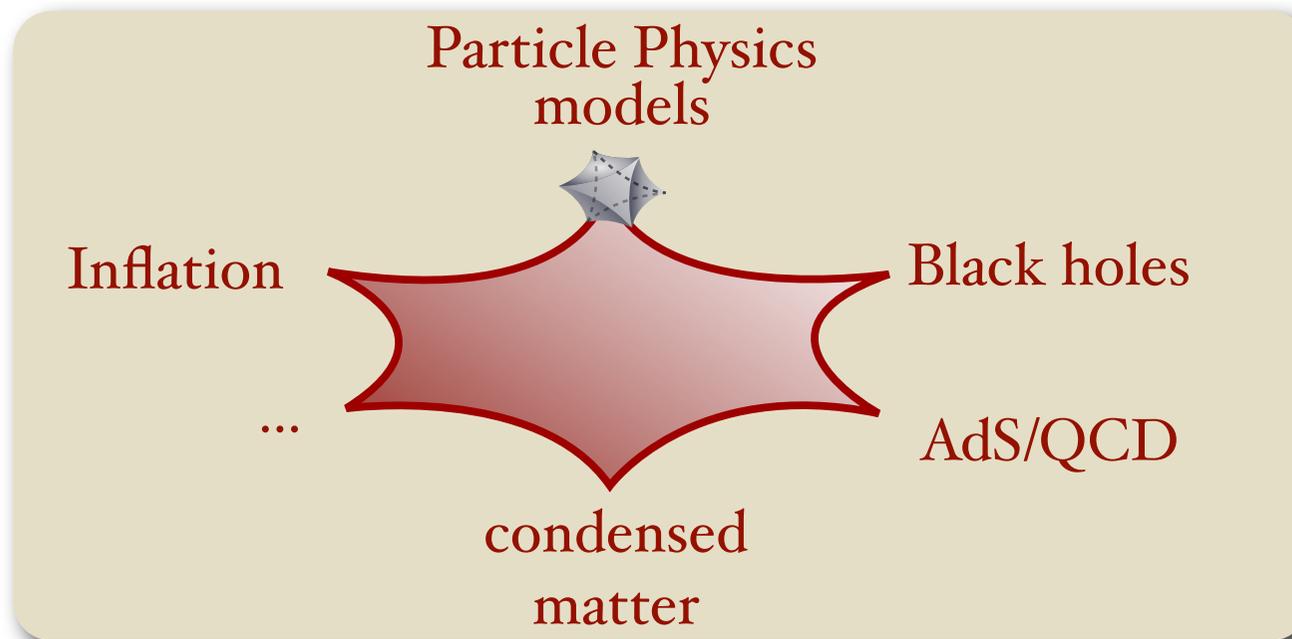
'Landscape' of string theory applications

'70s Early string theory

'80s The superstring revolution

'90s Non-perturbative string theory

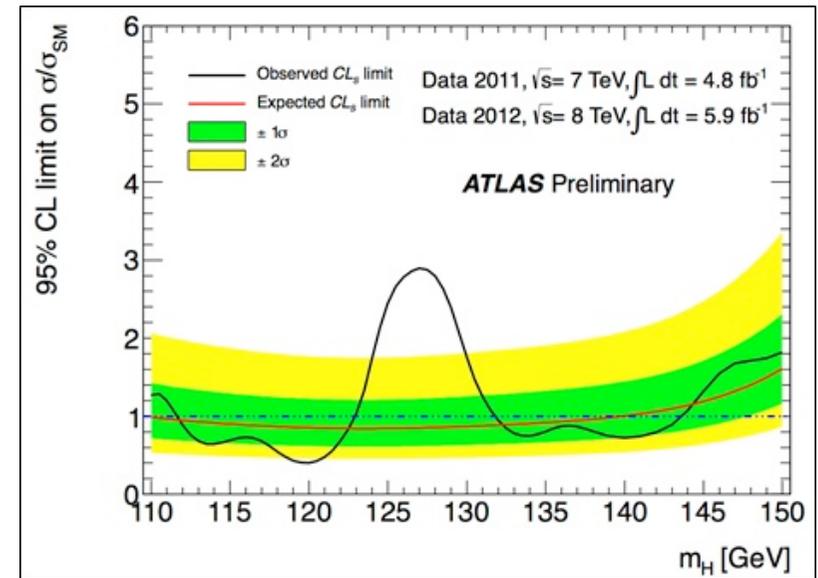
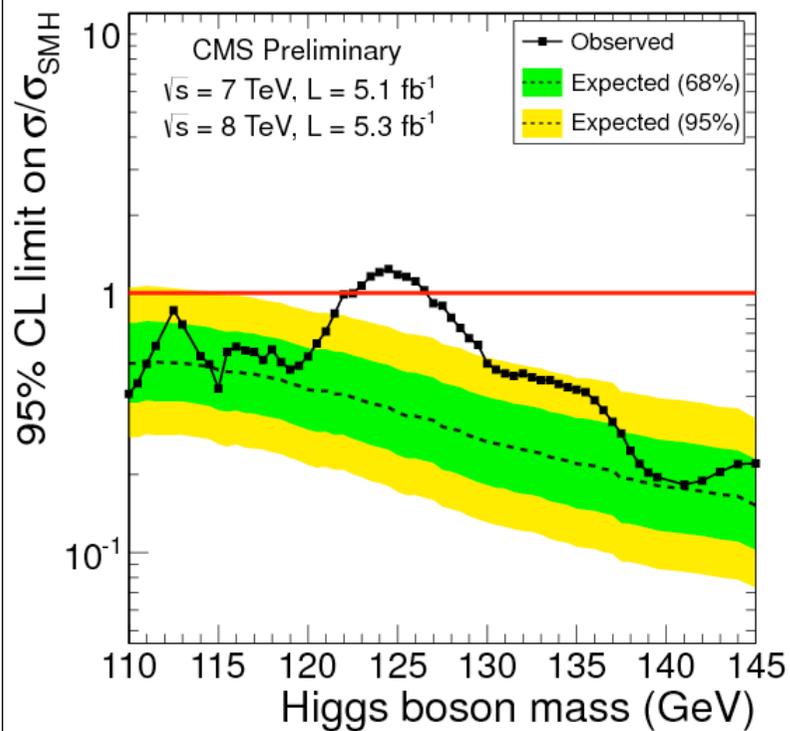
📌 Since 2000 we are having a great “decade” of ‘applied string theory’



📌 Zoom into Particle Physics model building

String Phenomenology

- 🎤 String theory describes gravitational and gauge interactions in a unified framework, consistent at the quantum level
- 🎤 What about the **Standard Model** ? (or whatever extension)
- 🎤 **Aim of String Phenomenology:**
 - Understand basic mechanisms realizing interesting properties
Chirality, susy, gauge symm, moduli stab, flat potentials, instantons...
 - Determine classes of constructions incorporating subsets of them
Non abelian gauge interactions, replicated charged fermions, Higgs scalars, Yukawas, moduli stabilization, tuning of cc, ...
 - Within each class, obtain explicit models as close to SM as possible with the hope of learning more about the high energy regime of SM in string theory
- 🎤 Old program, yet sustained progress, following formal developments...



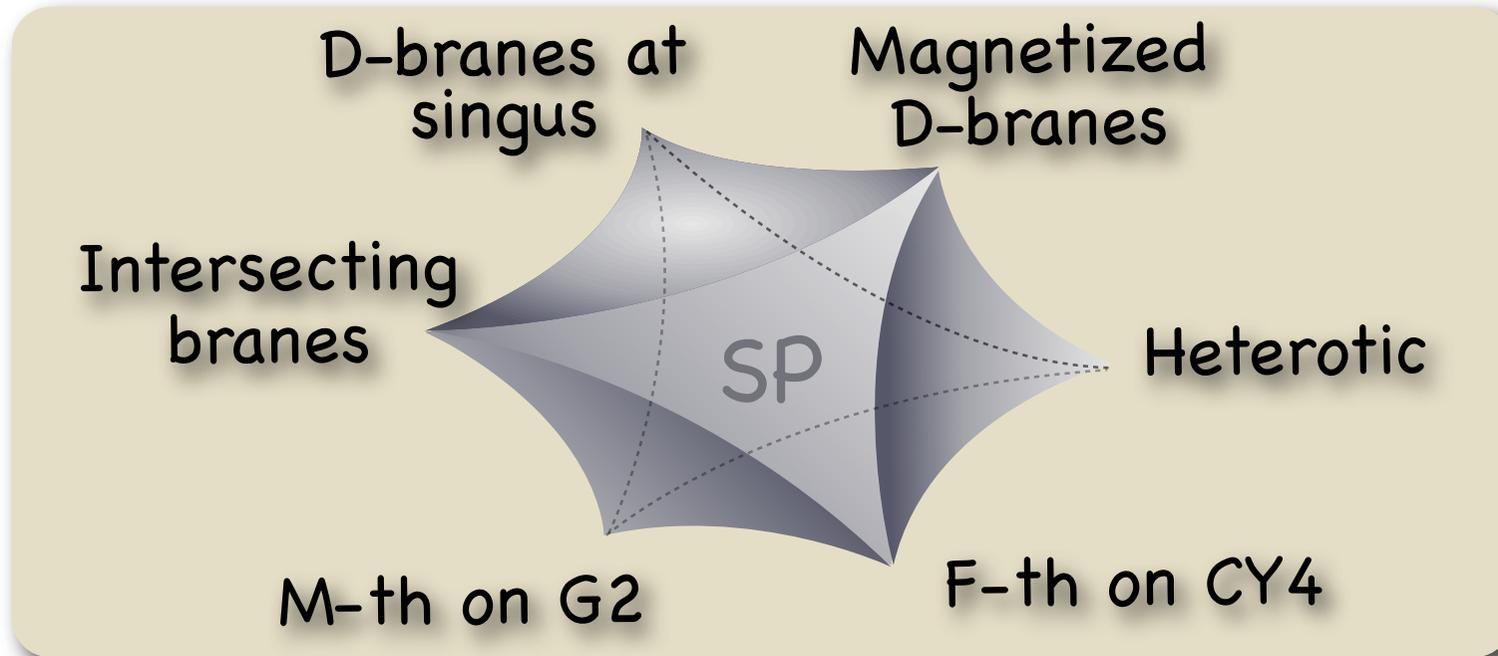
In summary

We have observed a new boson with a mass of
 $125.3 \pm 0.6 \text{ GeV}$
 at
 4.9σ significance !

 Old program, yet sustained progress, following formal developments...
 ... and hopefully to an data-driven era, just started

'Landscape' of String Phenomenology tools

- Plenty of (related) constructions to 'engineer' SM in string theory



Remarkably, generic 4d compactifications are chiral

- Overview with an eye on recent developments

Disclaimer: Necessarily incomplete

Follow particular path: not an ordered set

Outline

-  Introduction
-  D-brane models
-  F-theory developments
-  Fluxes, de Sitter and all that
-  Heterotic models
-  Higgs
-  Conclusions

Prototype: Intersecting IIA D6's

[Berkooz, Douglas, Leigh '96;
Blumenhagen, Gorlich, Kors, Lust '00;
Aldazabal, Franco, Ibáñez, Rabadán, AU '00]

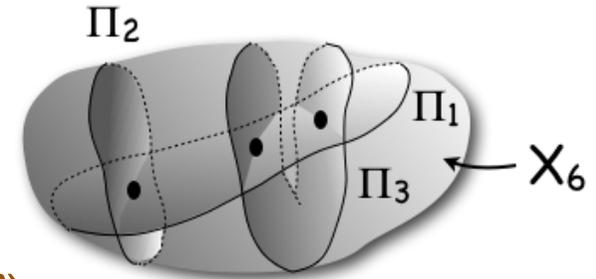
Illustrate a few points in model building

Type IIA on CY orientifold with O6's and D6's

Susy conditions on 3-cycles Π_a : **Special Lagrangian**

$$J|_{\Pi} = 0 \quad , \quad \text{Im } \Omega|_{\Pi} = 0$$

F-term
D-term
(“A-branes”)

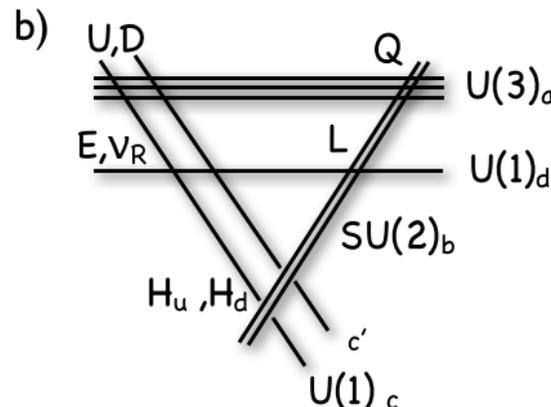
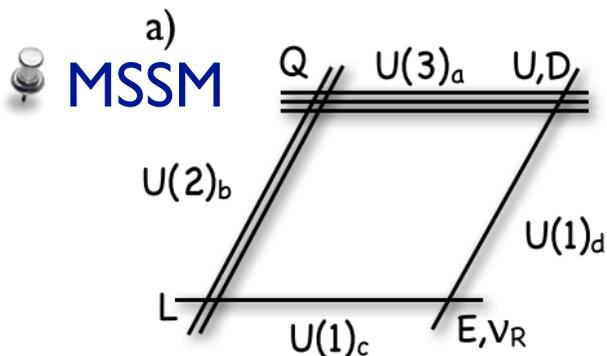


Open string spectrum: Chiral piece is topological

Gauge group $\prod_a U(N_a)$

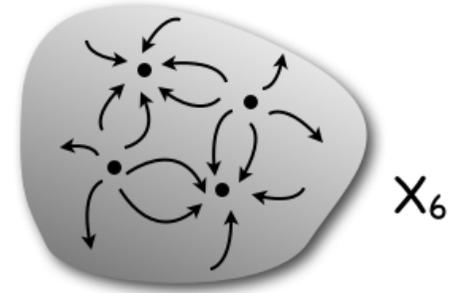
Chiral mults $\sum_{a,b} I_{ab}(N_a, \bar{N}_b) + \sum_{a,b'} I_{ab'}(N_a, N_b)$ (& 2-index tensors)

Intersection number $I_{ab} = [\Pi_a] \cdot [\Pi_b] = \text{topological family replication}$
(Fight chiral exotics, perhaps live with non-chiral ones)



[Ibáñez, Marchesano, Rabadán '01;
Cvetic, Shiu, AU '01;
Cremades, Ibáñez, Marchesano '03;
...; Schellekens et al '04, '06;
Honecker et al '04, '08;
...]

Tadpoles, Green-Schwarz, U(1)'s

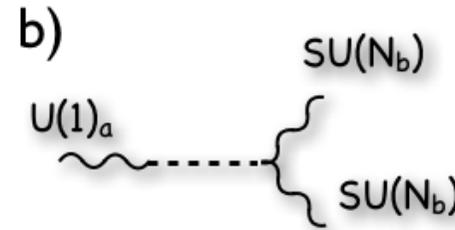
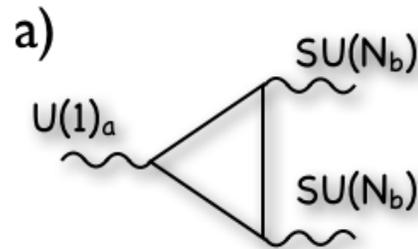


X_6

RR tadpoles: total D6-brane charge must be zero

4d anomaly cancellation, with Green-Schwarz for U(1)'s

$$\sum_{k,a} \int_{4d} B_k \wedge \text{tr} F_a \quad \& \quad \sum_{k,a} \int_{4d} a_k \text{tr} (F_b \wedge F_b)$$



BF terms give mass to all 'anomalous' and some 'non-anomalous' U(1)'s

$$\sum_{k,a} \int_{4d} B_k \wedge \text{tr} F_a = - \sum_{k,a} \int_{4d} \partial_\mu a_k A_\mu^a$$

- Must require that hypercharge remains massless
- Massive U(1)'s are perturbatively exact global symmetries
- (Field dependent) FI term = deviation from sLag condition (D-term)
- Non-perturbative U(1) violation by D-brane instantons

[Blumenhagen, Cvetič, Weigand '06; Ibáñez, AU '06; Florea, Kachru, McGreevy, Saulina '06]

- Possible Z_n discrete gauge symmetry remnants

[Berasaluce-González, Ibáñez, AU '11]

Type IIB models

(motivations: Flux moduli stabilization, holomorphic tools, ...)

Mirror to earlier IIA: Type IIB on CY orientifold with “B-branes”

- 🔍 Orbifolds etc: D-branes at singularities [Douglas, Moore '96]
- D3s at toric singus: dimers [Franco, Hanany, Kennaway, Vegh, Wecht '05]
- Early local model building [Aldazabal, Ibáñez, Quevedo, AU '00; Berenstein, Jejjala, Leigh '01; Verlinde, Wijnholt '05]
- Global embeddings (dP's) [Buican, Malyshev, Morrison, Verlinde, Wijnholt '06; Cicoli, Krippendorf, Mayrhofer, Quevedo, Valandro '12]

🔍 Large volume: wrapped branes

Susy conditions: Holomorphic cycles with holomorphic & Π -stable bundles

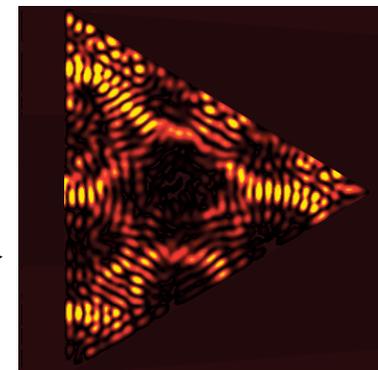
$$F_{(2,0)} = 0 \quad , \quad \text{Im}(e^{J+i(B+F)})|_{\Pi} = 0$$

F-term

D-term

At large volume, reproduces Donaldson, Uhlenbeck, Yau, slope stability, etc [cf. heterotic on CY]

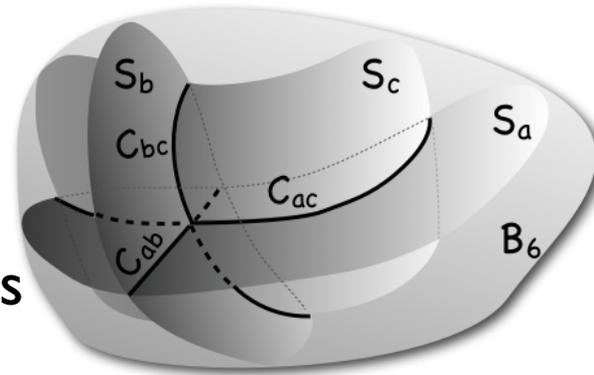
Magnetized branes: Chirality & replication from index of Dirac operator (Landau groundstates)



Type IIB D7's and F-theory

D7-brane models

- D7brane on 4-cycle: Gauge group
- Intersections over 2-cycles: Matter
- Triple intersections at points: Yukawas

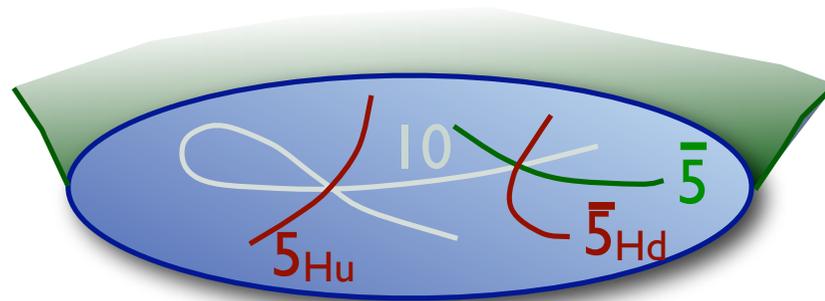


In models with underlying $SU(5)$, top Yukawa $10.10.5$ forbidden in by pert. $U(1)$'s
 \Rightarrow Go non-perturbative

Instantons (D3's on 4-cycles): but must explain non-suppression

F-theory (E6 point yield order one Yukawa)

[Beasley, Heckman, Vafa '08;
... many ...]



(Still, much interesting physics in D3-brane instantons in F-theory)

Much formal work in matching F-theory and IIB (when applicable [Sen'97])

F-theory flavour and unification

Developments in pheno aspects of F-theory

Flavour

- Use of wavefunction profiles

Yukawas

Non-commutative deformation $G_{1,2}$ -flux [Cecotti, Cheng, Heckman, Vafa '09]

Distant instanton effects [Marchesano, Martucci '09]

Equivalence (SW map) [Aparicio, Font, Ibáñez, Marchesano '11]

KK modes: FCNC, proton decay, ... [Cámara, Dudas, Palti '11]

...

- Gluing morphism (vevs at intersections) [Donagi, Wijnholt '11]

Unification

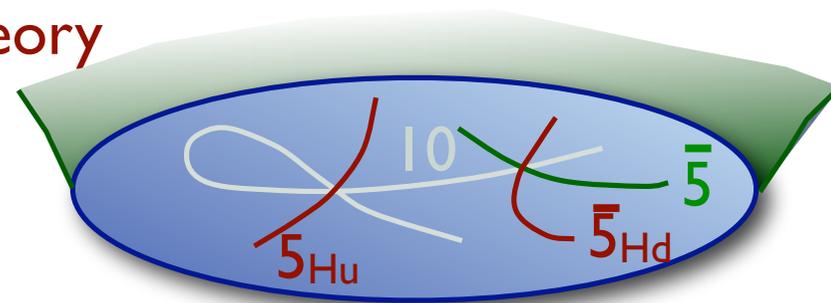
- Early: Hypercharge flux distortion: IIB perspective [Blumenhagen '08]

- Derivation within F-th due to G4 warping [Grimm, Klevers, Poretschkin '12]

- Fix with thresholds, exotics, ... [...many...]

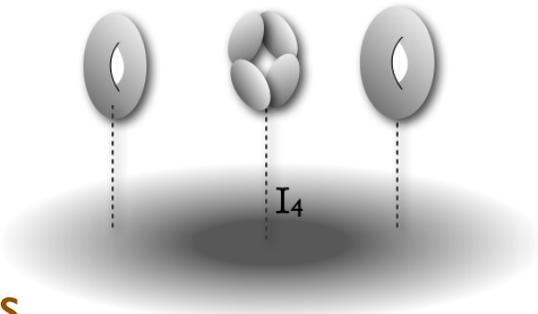
- Alternatives: Wilson line breaking? [eg. Clemens, Marsano, Pantev, Raby, Tseng '12]

Dust not fully settled



F-theory

Physics of G4-flux and U(1)'s. Sensitive to global



📌 “Early”: semilocal models via spectral cover

[Donagi, Wijnholt '09; Marsano, Schafer-Nameki, Saulina, c. '10]

📌 U(1)'s Mth con resolved CY4, blowup PIs on deg. fibers

- Massless U(1)'s from restricted Tate models: e.g. $SU(5) \times U(1)_X$

contain additional cycles from extra singus

[Grimm, Weigand '10]

- Geometrically massive U(1)'s: non-harmonic forms & non-Kähler blowups

[Grimm, Weigand '10; + Kerstan, Palti '11]

associated to IIB U(1)'s with Stueckelberg mass [Krause, Mayrhofer, Weigand '12]

📌 Fluxes

Chirality formulas from 3d CS

[Grimm, Hayashi '12]

Match with IIB

[Krause, Mayrhofer, Weigand '12]

- G4 on usual blowup cycles: flux for massless U(1)'s

- Spectral cover fluxes [Marsano, Schafer-Nameki '11; Kuntzler, Schafer-Nameki '12]

correspond to geometrically massive U(1)'s

- ‘Non-generic’ fluxes: Rigidifying 7-branes

[Braun, Collinucci, Valandro, '12]

G4 quantization & IIB Freed-Witten

[Collinucci, Savelli, '10-'12]

Instantons

Efforts in fundamental aspects F-theory instantons

$$W = \sum_D A(z, z_i) e^{-T_D}$$

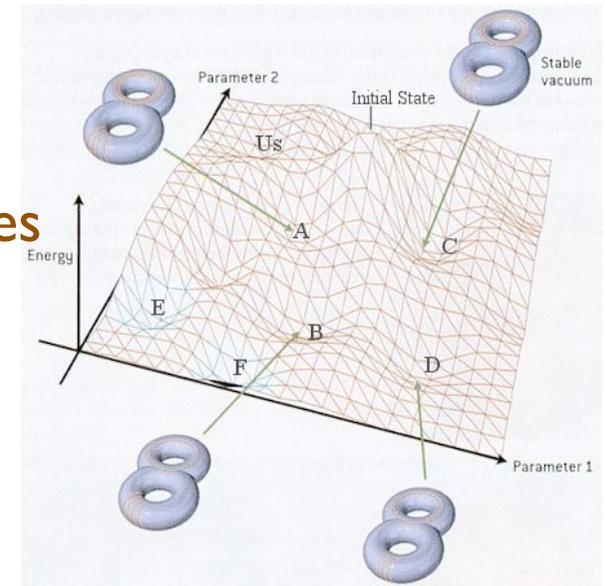
- 📌 **Early:** M5s on divisors D of elliptic CY4: $\chi(D) = 1$ [Witten '96]
Zeroes from D3-7 zero modes [Ganor '97]
Partial results on effects of bulk fluxes in IIB & M [many ... c.2005]
- 📌 **Matching with D3's on divisor of CY orientifold**
(string junctions, anomaly inflow, $SL(2, \mathbb{Z})$ covariant action on D3's, ...)
[Blumenhagen, Collinucci, Jurke '10], [Cvetic, Garcia-Etxebarria, Halverson '10-'11]
[Bianchi, Collinucci, Martucci '11]
- 📌 **Worldvolume fluxes (M5's and D3's)**
rigidification & lifting zero modes, [Bianchi, Collinucci, Martucci '11]
sum over flux sectors [Grimm, Weigand, Kerstan, Palti '11; Weigand, Kerstan '12]
- 📌 **U(1) violation and charged zero modes**
- FW anomaly from G4 requires M2 brane legs [Weigand, Kerstan '12]
selection rules for massless and geometrically massive U(1)'s
- Duality with heterotic ws instantons. [Donagi, Wijnholt '10]
Zeroes from D3-7 zero modes [Cvetic, Garcia-Etxebarria, Halverson '11]

Moduli stabilization & deSitter

Standard ingredients (IIB):

3-form fluxes, instantons, corrections $(\alpha', g_s), \dots$

(continuous development of formal aspects of fluxes not yet in use for model building)



Large Volume scenario

- Systematic search for Swiss-cheese CYs

[Gray, He, Jejjala, Jurke, Nelson, Simón '12]

- with appropriate cycles to support instantons, SM, ...

Uplift (localized sources)

- Explorations of backreaction of antiD3's

[Bena, Giecold, Graña, Kuperstein, Halmagyi, Massai '11, '12]

- Alternatives?

e.g. S-dependent non-pert effects (in addition to T-dependent)

[Cicoli, Maharana, Quevedo, Burgess '12]

Statistics

- Random supergravity and matrix models suggest exponential (Gaussian) suppression of deSitter [Chen, Shiu, Sumimoto, Tye '11]

[Marsh, McAllister, Wrase '11 + Bachlechner '12]

Heterotic on CY

[cf. Lara Anderson's talk]

Line bundle MSSM

[Anderson, Gray, Lukas, Palti]

(analogous to IIB magnetized branes)

- Break E_8 with bunch of line bundles $\Rightarrow SU(5) \times U(1)^4$
- Wilson line breaking of $SU(5)$
- Superpotential textures improve by $U(1)$ permutation Wilson lines

[cf. F-theory monodromies]

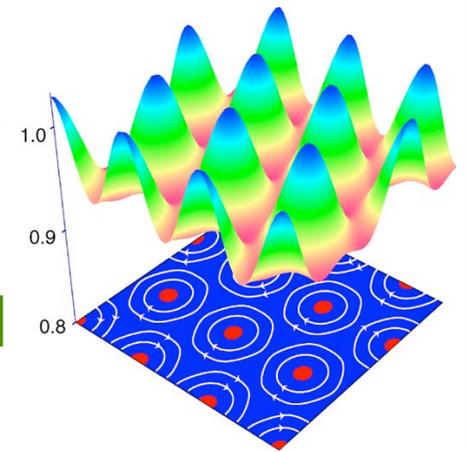
Systematic construction of MSSM-like models

Stabilization of geometric moduli from bundle susy conditions

[Anderson, Gray, Lukas, Ovrut]

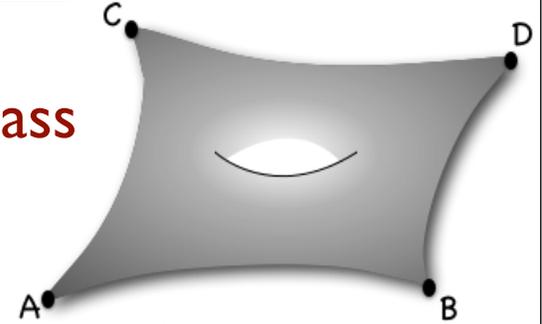
(het. version of earlier F- and D-terms on branes [Antoniadis et al '05-'07])

- Powerful math description of cplx. str. moduli stabilization: Atiyah class
- Explicit models with many (most) moduli stabilized
- Left-over moduli +lift, harder



Heterotic orbifolds

Exploration of features of previously constructed class
Discrete symmetries



- Heterotic orbifold techniques, with improved geometric intuition
higher-dimensional GUT models

[e.g. Lebedev, Nilles, Raby, Ramos-Sánchez, Ratz, Vaudrevange '06]

- Development of computational tools to compute D-, F-flat directions
“anomalous” $U(1)$ FI-term controlled by gs, must restabilize at one-loop
[related: Kappl, Ratz, Staudt '11]

- Identify interesting features and how to preserve them
Discrete symmetries, R-symmetries, either gauge or approximate
E.g. approximate Z_4^R with Z_2 R-parity subgroup

[Lee, Raby, Ratz, Ross, Schieren, Schmidt-Hoberg, Vaudrevange '10]

- Implications of geography for Yukawas, susy breaking soft terms, ...

other CFT models

Computer scans of the flavour landscape

Recall large class of MSSM-like models in Gepner orientifolds

boundary states play “intersecting branes”

[Dijkstra, Huiszoon, Schellekens'04; Anastasopoulos, Kiritsis, Schellekens '06]

Testing ground for many ideas:

Exotic SM embedding, instantons, discrete symmetries, ...

The heterotic story

Heterotic on Gepner models & “weight lifting” [Gato-Rivera, Schellekens '10]

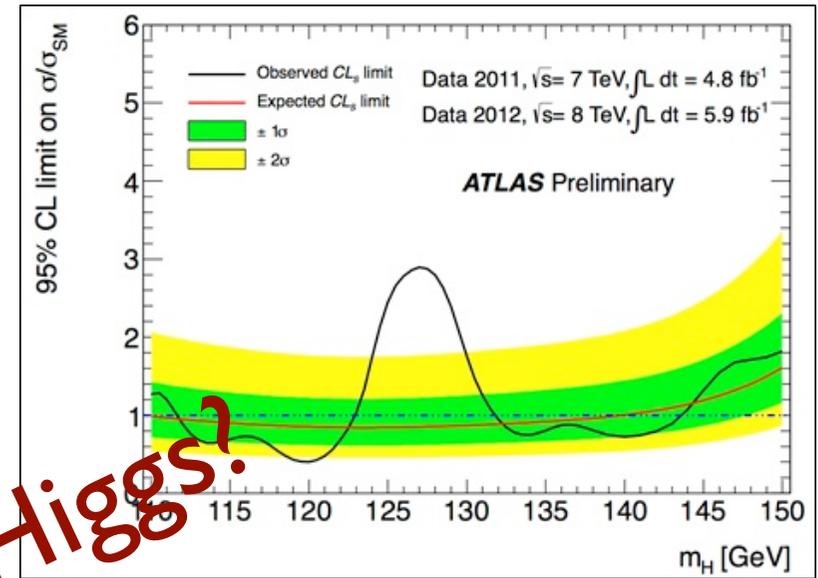
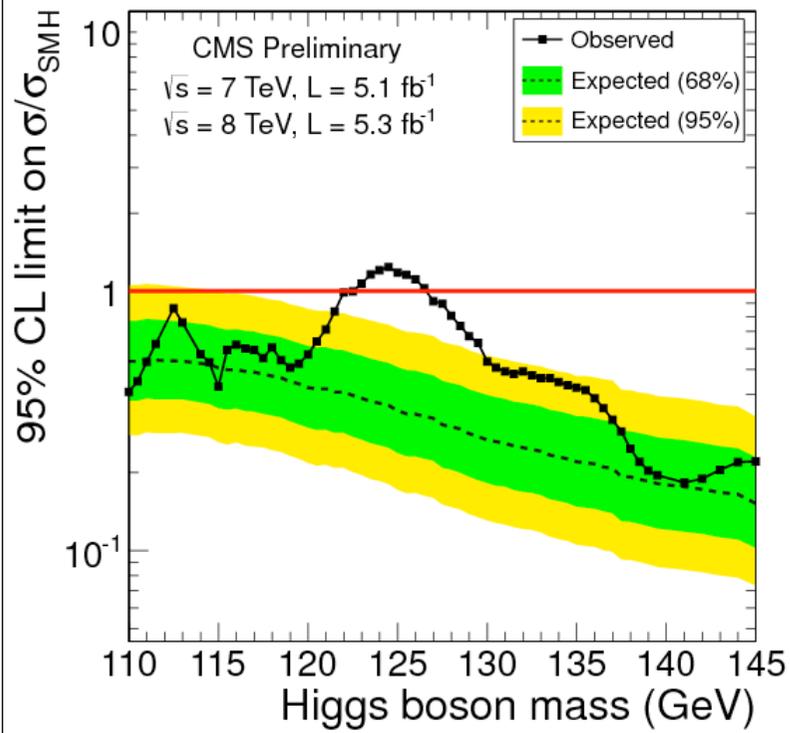
⇒ several hundreds of new MSSM-like models

Fermionic construction

Asymmetric twists and models with very few moduli

some with $SO(10)$ & chirality

[Bianchi, Pradisi, Timirgaziu, Tripodi '12]



What about the Higgs?

In summary

We have observed a new boson with a mass of
 $125.3 \pm 0.6 \text{ GeV}$
 at
 4.9σ significance !

Higgs

Several scenarios explaining/reproducing right Higgs mass

Under certain assumptions on moduli stabilization, susy breaking source
With some inputs e.g. dark matter relic density, cosmological moduli problem,...

[Kane, Kumar, Lu, Zheng; Acharya, Kane, Kumar '11, '12] [deAlwis, Givens '12]

[Aparicio, Cerdeño, Ibáñez '11-'12] [Ibáñez, Marchesano, Regalado, Valenzuela '12]

[Nilles et al]

Turn “prediction” around: Higgs mass suggests high energy scenarios

3-line lesson to take home

Questions on the Higgs sector can be addressed in string theory

General plausible scenarios

They differ slightly in new physics at LHC (testable)

(and keep in mind there is life apart from Higgs and susy
low string scale, Z' resonances, dark sectors, ...)

[... many... e.g. Anchordoqui, Antoniadis, Goldberg, Huang, Lust, Taylor, Vlccek '12]

Two IIB/Fth takes on the Higgs mass

🔍 Try to give some flavour, in setups of IIB/Fth 7-branes with 3-form flux susy breaking soft terms (gravity mediation, modulus domination)
 [Graña '02, Cámara, Ibáñez, AU; Graña, Grimm, Jockers, Louis '03, Lust et al '04...]

Flux susy breaking: few parameters, eg $M = \sqrt{2}m = -(2/3)A = -B$

Scale $M_{SUSY} \sim f \frac{\alpha'}{R^3} \sim f \frac{M_c^2}{M_p}$ f: possible local suppression

TeV scale soft terms

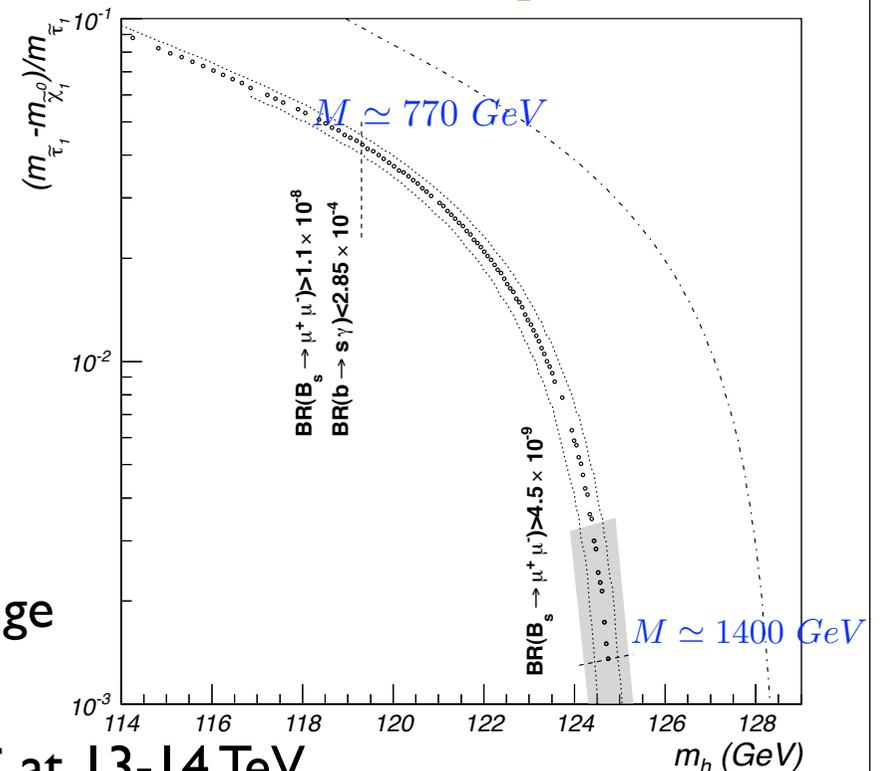
[Aparicio, Cerdeño, Ibáñez '11-'12]

TeV soft terms from $M_c \sim 10^{11} \text{ GeV}$
 or $M_c \sim M_{GUT}$ and suppression f

3 parameter model M, μ, ρ_H

Require radiative electroweak symmetry breaking and neutralino dark matter

$B_s \rightarrow \mu^+ \mu^-$ bounds push $M \geq 1.4 \text{ TeV}$
 and Higgs mass to 125 GeV range



heavy sparticles, but some accessible to LHC at 13-14 TeV

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intermediate scale soft terms [Ibáñez, Marchesano, Regalado, Valenzuela '12]
 $m_h = 126 \text{ GeV}$

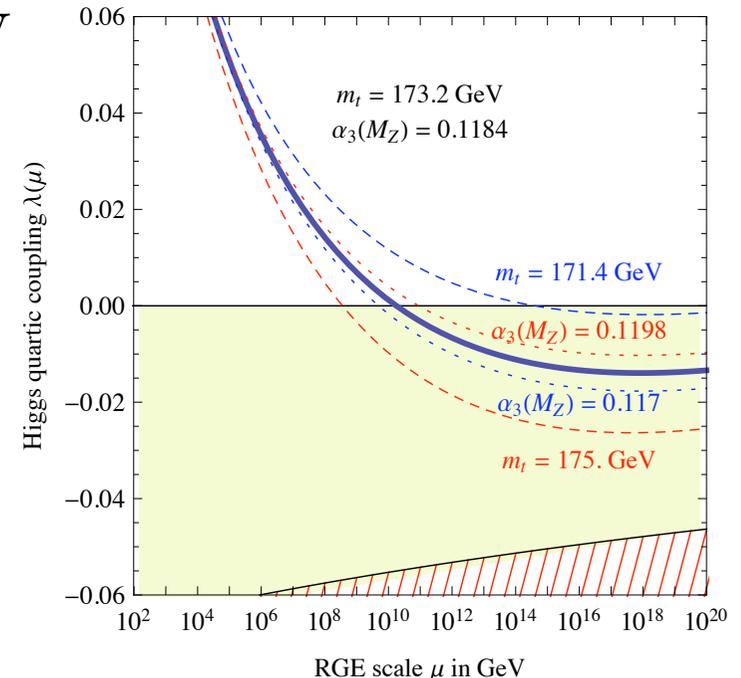
Choose $M_c \sim 10^{14} \text{ GeV}$ then $M_{SUSY} \sim 10^{10} \text{ GeV}$

fine-tune hierarchy
 non-susy unification with F-theory corrections
 must evade dim 6 proton decay

Engineering vanishing quartic coupling at

$M_{SUSY} \sim 10^{10} \text{ GeV}$ in nonsusy SM
 (e.g. shift symmetries [Hebecker, Weigand '12])

produces 125 GeV Higgs



Espinosa, Giudice, Strumia... '11-'12

Conclusions

 Amazing that something close to the SM can be realized in string theory (and just beautiful that building blocks -- gauge symms, chiral fermions, replication --- are generic)

 Continuous progress along different lines

- Good old heterotic models (orbifold and smooth CYs)
- Brane models (D-branes and F-theory)
- Computational scans (CYs, CFTs, ...)

 Getting closer to Particle Physics phenomenology at the LHC

Under reasonable assumptions, pretty solid scenarios for susy breaking, the Higgs, and beyond

(Recall 3-line lesson)

 Much room for improvement to keep up in the LHC era

Some good opportunities...

New Challenges for String Phenomenology

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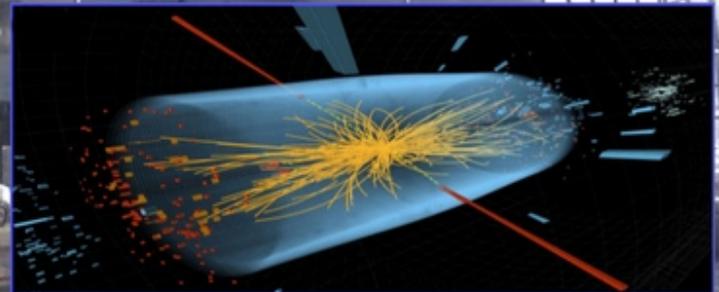
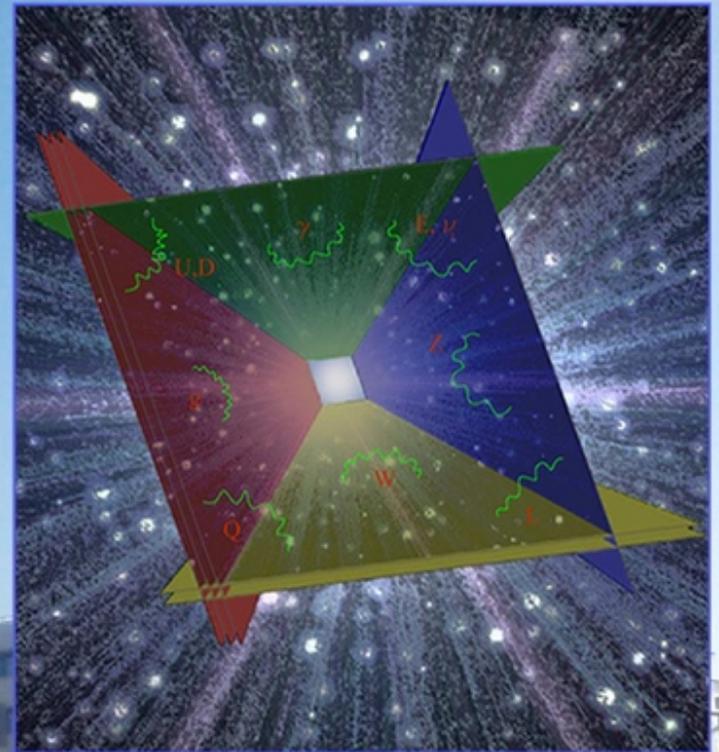
26-28 September 2012

Speakers:

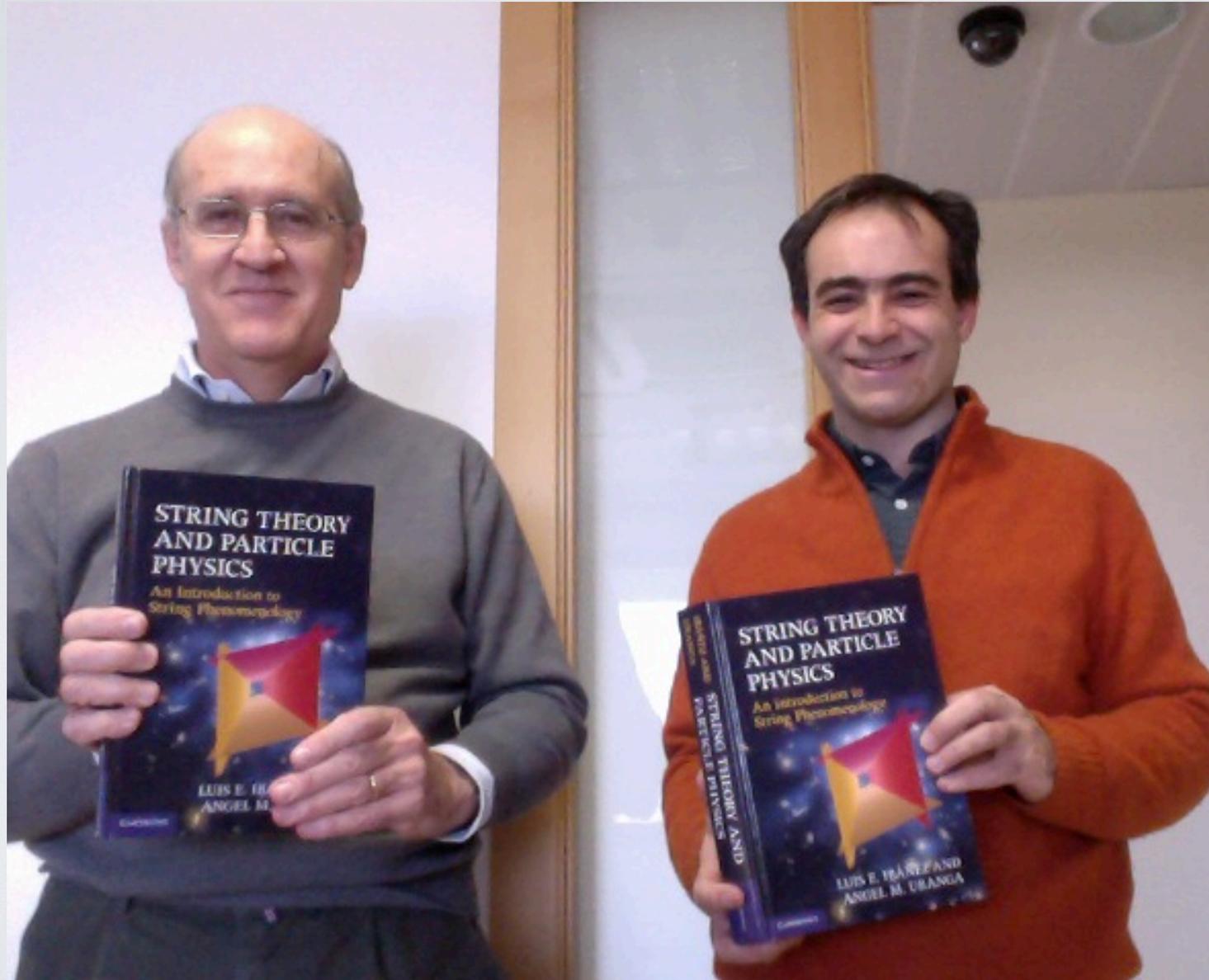
M. Bianchi
R. Blumenhagen
V. Braun
P. Cámara
M. Cicoli
J. Conlon
R. Donagi
I. Garcia-Etxebarria
M. Goodsell
T. Grimm
M. Haack
J. Heckman
S. Krippendorf
J. Marsano
E. Palti
T. Watari

Organizers:

L. Ibáñez
F. Marchesano
A. Uranga



& our book is out :)





Thank you!