Naturalness and string phenomenology in the LHC era

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8th Mathematical Physics Meeting:

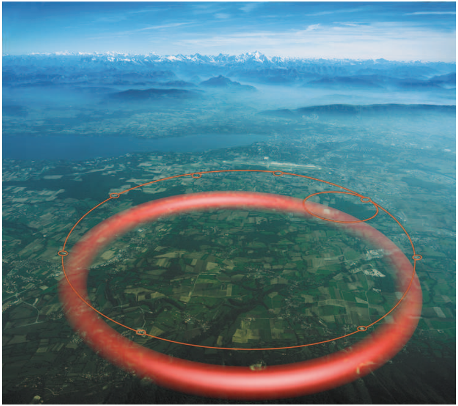
Summer School and Conference on Modern Mathematical Physics

Belgrade, Serbia, 24-31 August 2014

- LHC: where do we stand? where do we go?
- Low energy SUSY after the Higgs discovery
- Non-linear SUSY and MSSM
- Non-linear SUSY and Starobinsky inflation
- Low scale strings and extra dimensions
- Gravity scale and number of species

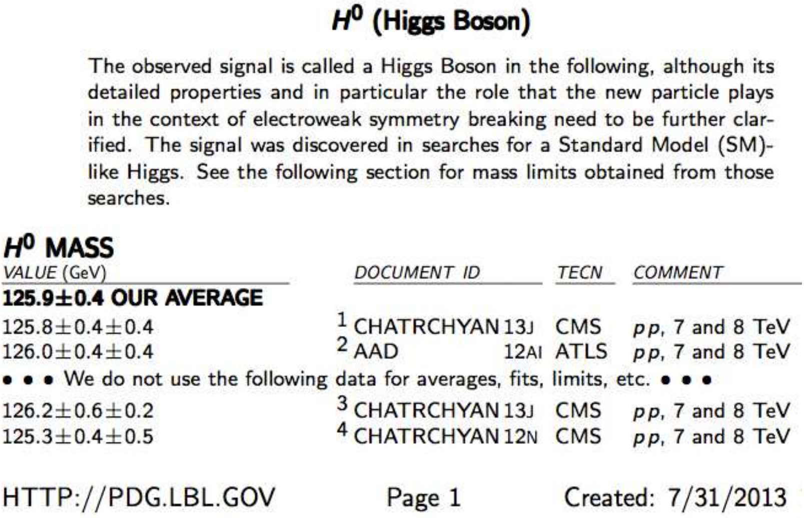
Connect string theory to the real world

- Is it a tool for strong coupling dynamics or a theory of fundamental forces?
- Can string theory describe both particle physics and cosmology?
- What can we hope to learn from LHC and cosmological observations on string phenomenology?



Entrance of a Higgs Boson in the Particle Data Group 2013

particle
listing



H^0 (Higgs Boson)

The observed signal is called a Higgs Boson in the following, although its detailed properties and in particular the role that the new particle plays in the context of electroweak symmetry breaking need to be further clarified. The signal was discovered in searches for a Standard Model (SM)-like Higgs. See the following section for mass limits obtained from those searches.

H^0 MASS

VALUE (GeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
125.9±0.4 OUR AVERAGE				
125.8±0.4±0.4	[1] CHATRCHYAN	13J	CMS	*pp*, 7 and 8 TeV
126.0±0.4±0.4	[2] AAD	12AI	ATLS	*pp*, 7 and 8 TeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
126.2±0.6±0.2	[3] CHATRCHYAN	13J	CMS	*pp*, 7 and 8 TeV
125.3±0.4±0.5	[4] CHATRCHYAN	12N	CMS	*pp*, 7 and 8 TeV

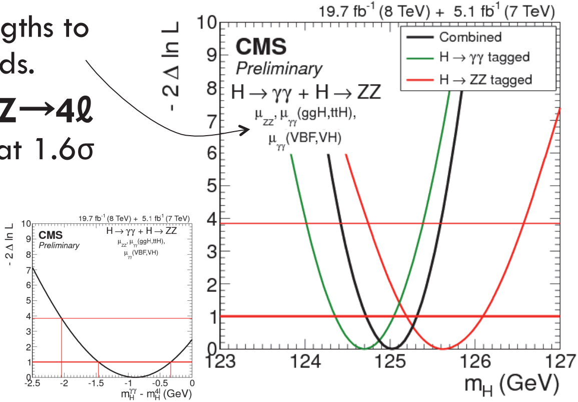
HTTP://PDG.LBL.GOV Page 1 Created: 7/31/2013

Combined mass measurement

[CMS-PAS-HIG-14-009]

$$m_H = 125.03 \pm 0.30 \left[^{+0.26}_{-0.27}(\text{stat.}) ^{+0.13}_{-0.15}(\text{syst.}) \right] \text{GeV}$$

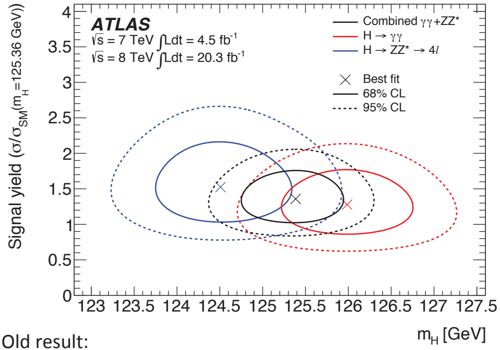
- ☐ Float 3 signal strengths to not depend on yields.
- ☐ **H⟶γγ and H⟶ZZ⟶4ℓ** results compatible at 1.6σ level.



a.david@cern.ch @CMSexperiment @ICHEP2014

Measurement of the Higgs boson mass

(and signal strengths)



Old result:

$$125.5 \ \pm 0.2\ (\text{stat})\ {}^{+0.5}_{-0.6}\ (\text{syst})\ \ \text{GeV}$$

New:

$$\boxed{125.36\ \pm 0.37\ (\text{stat})\ \pm 0.18\ (\text{syst})\ \ \text{GeV}}$$

0.3% Precision measurement (statistical uncertainty dominant)

Note measure channels signal strength

$$\mu^{\gamma\gamma}_{(m_H=125.98\,GeV)} = 1.29\ \pm 0.30$$

$$\mu^{ZZ}_{(m_H=124.51\,GeV)} = 1.66\ {}^{+0.45}_{-0.38}$$

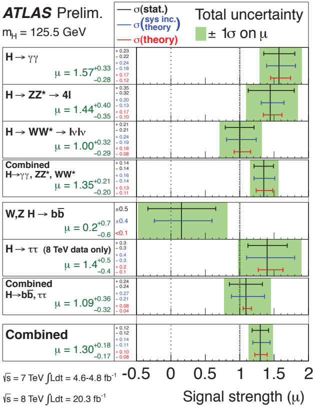
ZZ and γγ compatibity

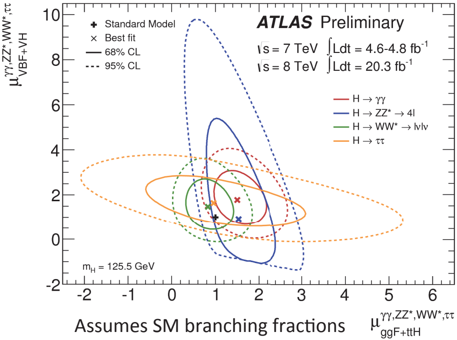
Old $\begin{cases} \Delta m = 2.3 \pm 0.9 \\ \text{Compatibility } 2.4\sigma \end{cases}$

$$\Delta m = 1.47 \pm 0.72$$

Compatibility 1.97σ

Main Decay and Production Modes



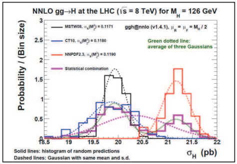


←

Assumes SM branching fractions and production modes

Compatible with SM (at 14%)

$$\mu = 1.30 \pm 0.12\ (\text{stat})\ \pm 0.10\ (\text{th})\ \pm 0.09\ (\text{syst})$$



All channels couplings updated soon

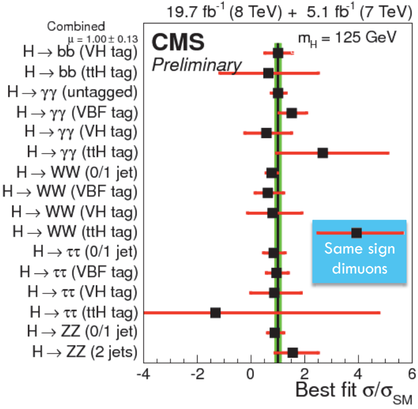
Stay tuned !

Signal strength

[CMS-PAS-HIG-14-009]

$$\sigma/\sigma_{\mathrm{SM}} = 1.00 \pm 0.13 \left[\pm 0.09(\mathrm{stat.})^{+0.08}_{-0.07}(\mathrm{theo.}) \pm 0.07(\mathrm{syst.})\right]$$

- Grouped by production tag and dominant decay:
  - χ^2/dof = 10.5/16
  - p-value = 0.84 (asymptotic)
- ttH-tagged 2.0σ above SM.
  - **Driven by one channel.**



a.david@cern.ch @CMSexperiment @ICHEP2014

The value of its mass ~ 125 GeV

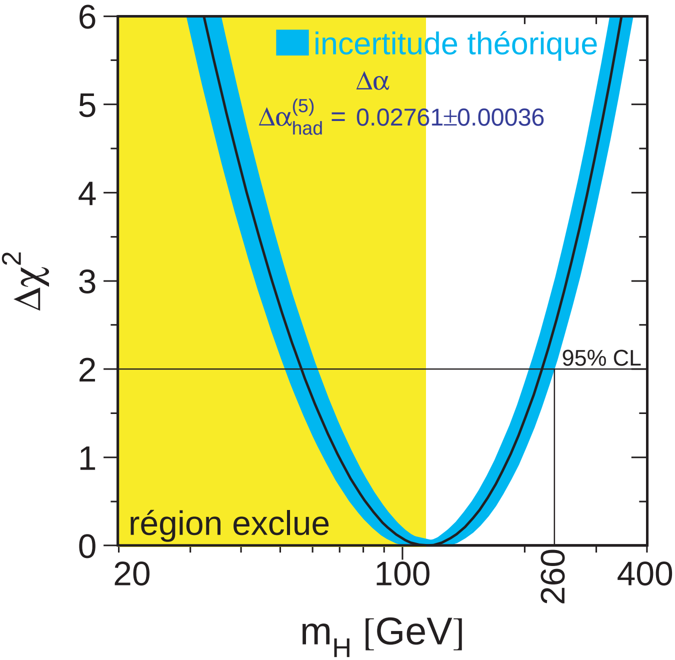
- consistent with expectation from precision tests of the SM
- favors perturbative physics quartic coupling $\lambda = m_H^2/v^2 \simeq 1/8$
- 1st elementary scalar in nature signaling perhaps more to come
- triumph of QFT and renormalized perturbation theory!

  Standard Theory has been tested with radiative corrections

Window to new physics ?

- very important to measure precisely its properties and couplings
- several new and old questions wait for answers

  Dark matter, neutrino masses, baryon asymmetry, flavor physics, axions, electroweak scale hierarchy, early cosmology, . . .


incertitude théorique
Δα
$\Delta\alpha^{(5)}_{had} = 0.02761 \pm 0.00036$
95% CL
région exclue
$\Delta\chi^2$
0
1
2
3
4
5
6
20
100
260
400
m_H [GeV]

Beyond the Standard Theory of Particle Physics: driven by the mass hierarchy problem

Standard picture: low energy supersymmetry

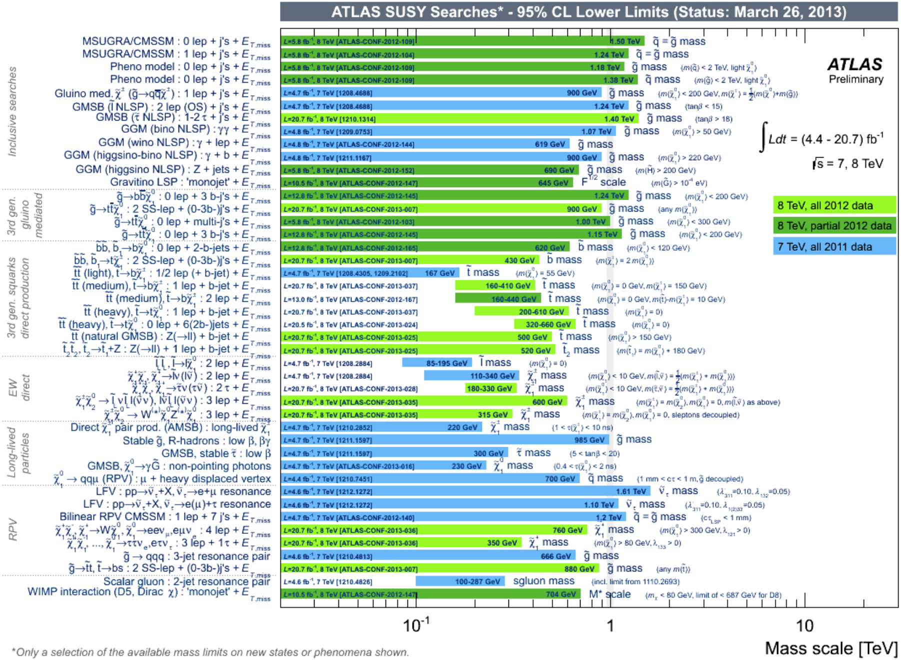
Natural framework: Heterotic string (or high-scale M/F) theory

Advantages:

- natural elementary scalars
- gauge coupling unification
- LSP: natural dark matter candidate
- radiative EWSB

Problems:

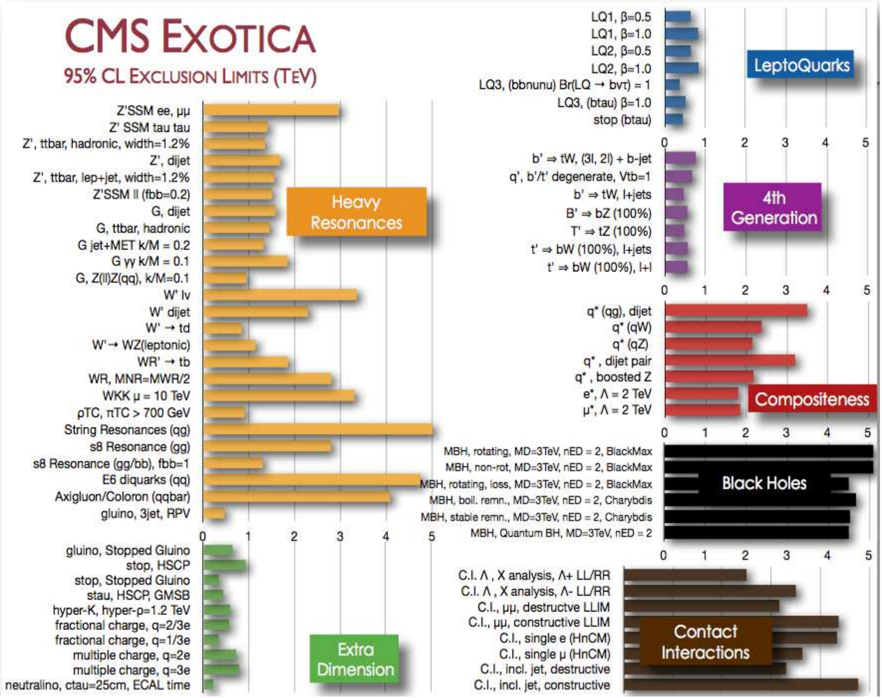
- too many parameters: soft breaking terms
- MSSM : already a % - ‰ fine-tuning 'little' hierarchy problem



*Only a selection of the available mass limits on new states or phenomena shown.
All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

CMS EXOTICA

95% CL EXCLUSION LIMITS (TEV)



What is next?

What is next?

Physics is an experimental science

- Exploit the full potential of LHC
- Go on and explore the multi TeV energy range

The LHC timeline

LS1 Machine Consolidation

LS2 Machine upgrades for high Luminosity

- Collimation
- Cryogenics
- Injector upgrade for high intensity (lower emittance)
- Phase I for ATLAS : Pixel upgrade, FTK, and new small wheel

LS3 Machine upgrades for high Luminosity

- Upgrade interaction region
- Crab cavities?
- Phase II: full replacement of tracker, new trigger scheme (add L0), readout electronics.

European Strategy Update

Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030.

LHC timeline

2009 Start of LHC

Run 1, 7+8 TeV, ~25 fb^{-1} int. lumi

2013/14 Prepare LHC for design *E* & lumi **LS1**

Collect ~30 fb^{-1} per year at 13/14 TeV

2018 Phase-1 upgrade ultimate lumi **LS2**

Twice nominal lumi at 14 TeV, ~100 fb^{-1} per year

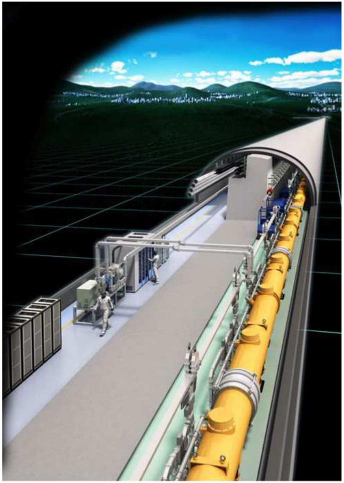
~2022 Phase-2 upgrade to HL-LHC **LS3**

~300 fb^{-1} per year, run up to > 3 ab^{-1} collected

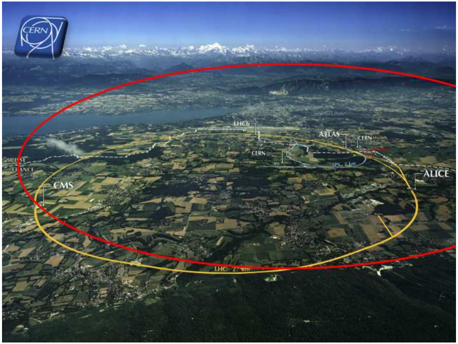
~2030

We must fully explore the 10-100 TeV energy range

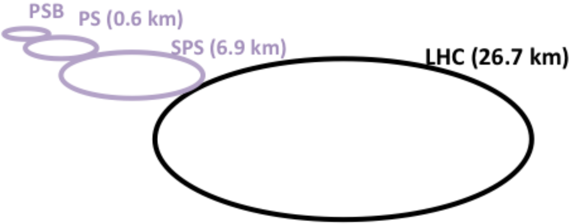
Linear Colliders - ILC project



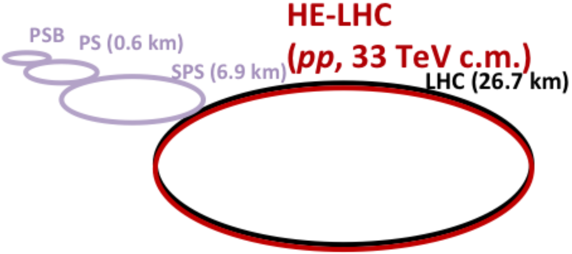
Circular Colliders



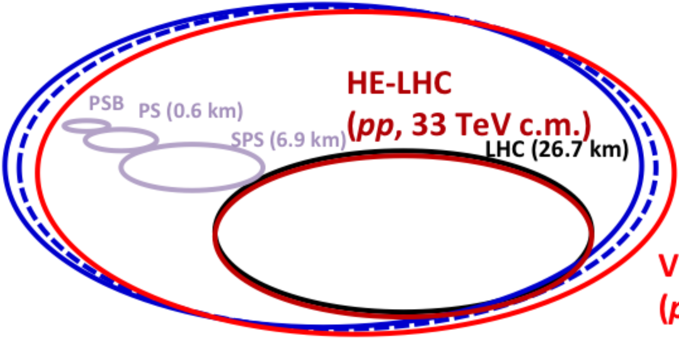
possible long-term strategy



possible long-term strategy



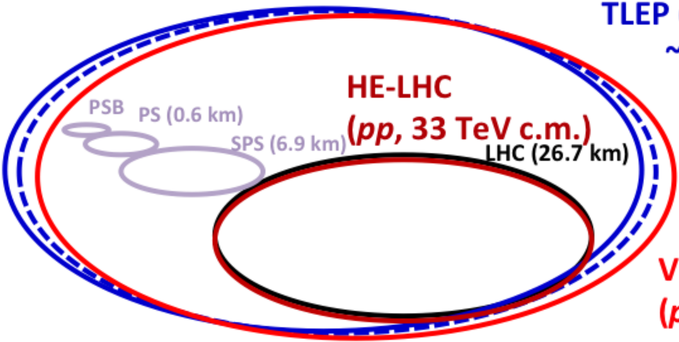
possible long-term strategy



HE-LHC
(*pp*, 33 TeV c.m.)

VHE-LHC
(*pp*, up to
100 TeV c.m.)
same detectors!

possible long-term strategy



HE-LHC
(*pp*, 33 TeV c.m.)

TLEP (*e^+e^-* up to ~350 GeV c.m.)

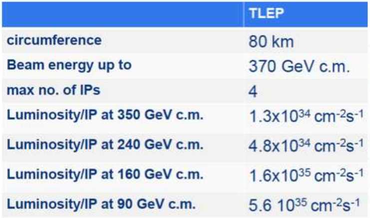
VHE-LHC
(*pp*, up to
100 TeV c.m.)
same detectors!

also: ***$e^{\pm}$* (120 GeV) – *p* (7 & 50 TeV)** collisions

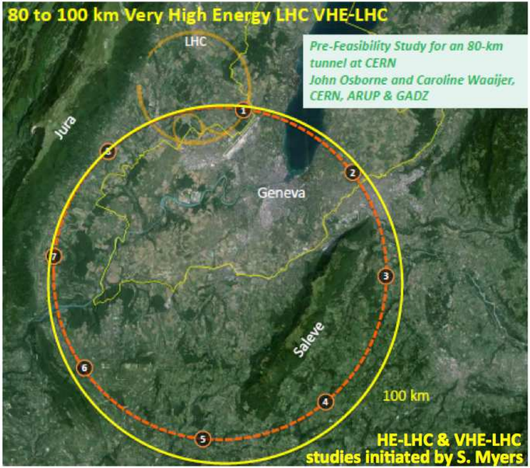
≥50 years of *e^+e^-*, *pp*, *ep/A* physics at highest energies

VHE-LHC: location and size

- 100 TeV p-p collider
- CDR and cost review to be ready for next European Strategy Update
- The tunnel could also house a e^+- e^- Higgs factory (TLEP)



	TLEP
circumference	80 km
Beam energy up to	370 GeV c.m.
max no. of IPs	4
Luminosity/IP at 350 GeV c.m.	$1.3\mathrm{x}10^{34}$ $\mathrm{cm}^{-2}\mathrm{s}^{-1}$
Luminosity/IP at 240 GeV c.m.	$4.8\mathrm{x}10^{34}$ $\mathrm{cm}^{-2}\mathrm{s}^{-1}$
Luminosity/IP at 160 GeV c.m.	$1.6\mathrm{x}10^{35}$ $\mathrm{cm}^{-2}\mathrm{s}^{-1}$
Luminosity/IP at 90 GeV c.m.	$5.6\ 10^{35}$ $\mathrm{cm}^{-2}\mathrm{s}^{-1}$



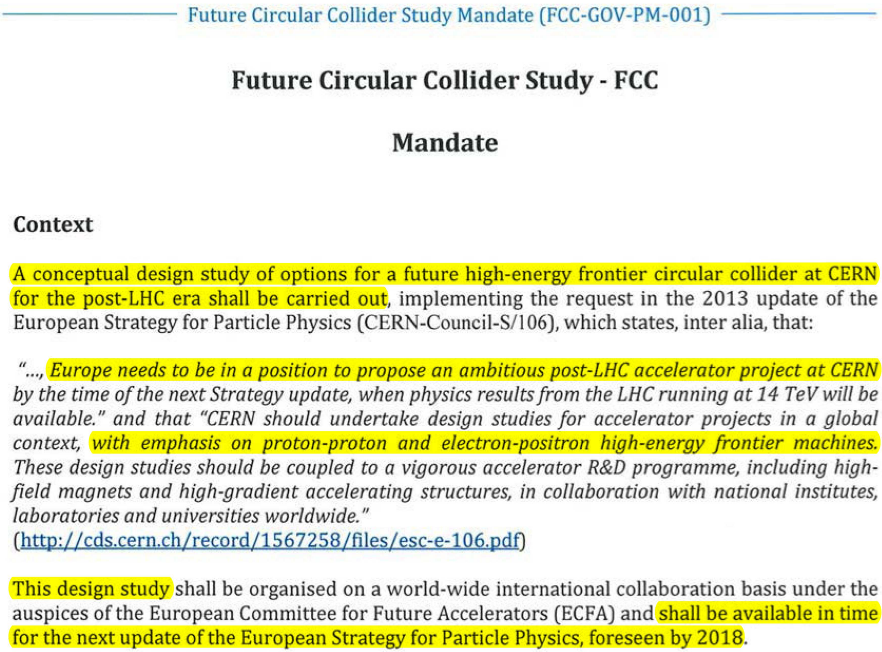
80 to 100 km Very High Energy LHC VHE-LHC

Pre-Feasibility Study for an 80-km tunnel at CERN
John Osborne and Caroline Waaijer, CERN, ARUP & GADZ

HE-LHC & VHE-LHC studies initiated by S. Myers

A circumference of 100 km is being considered for cost-benefit reasons

20T magnet in 80 km / 16T magnet in 100 km → 100 TeV



Future Circular Collider Study - FCC

Mandate

Context

A conceptual design study of options for a future high-energy frontier circular collider at CERN for the post-LHC era shall be carried out, implementing the request in the 2013 update of the European Strategy for Particle Physics (CERN-Council-S/106), which states, inter alia, that:

"..., Europe needs to be in a position to propose an ambitious post-LHC accelerator project at CERN by the time of the next Strategy update, when physics results from the LHC running at 14 TeV will be available." and that "CERN should undertake design studies for accelerator projects in a global context, with emphasis on proton-proton and electron-positron high-energy frontier machines. These design studies should be coupled to a vigorous accelerator R&D programme, including high-field magnets and high-gradient accelerating structures, in collaboration with national institutes, laboratories and universities worldwide."
(http://cds.cern.ch/record/1567258/files/esc-e-106.pdf)

This design study shall be organised on a world-wide international collaboration basis under the auspices of the European Committee for Future Accelerators (ECFA) and shall be available in time for the next update of the European Strategy for Particle Physics, foreseen by 2018.

Future Circular Colliders Study Kickoff Meeting

12-15 February 2014
University of Geneva - UNI MAIL
Europe/Zurich timezone

Webcast: Please note that this event will be available live via the Webcast Service.

Future Circular Collider Kickoff Meeting

This meeting is the starting point of a five-year international design study called "Future Circular Colliders" (FCC) with emphasis on a hadron collider with a centre-of-mass energy of the order of 100 TeV in a new 80-100 km tunnel as a long-term goal. The design study includes a 90-400 GeV lepton collider, seen as a potential intermediate step. It also examines a lepton-hadron collider option. The international kick-off meeting for the FCC design study will be held at the University of Geneva, Unimail site, on 12–15 February 2014. The scope of this meeting will be to discuss the main study topics and to prepare the groundwork for the establishment of international collaborations and future studies. The formal part of the meeting will start at noon on Wednesday 12 February and last until noon on Friday 14 February. It will be followed by break-out sessions on the various parts of the project on the Friday afternoon, with summary sessions until noon on Saturday 15 February.

126 GeV Higgs compatible with supersymmetry

Upper bound on the lightest scalar mass:

$$m_h^2 \lesssim m_Z^2 \cos^2 2\beta + \frac{3}{(4\pi)^2}\frac{m_t^4}{v^2}\left[\ln\frac{m_{\tilde t}^2}{m_t^2} + \frac{A_t^2}{m_{\tilde t}^2}\left(1 - \frac{A_t^2}{12 m_{\tilde t}^2}\right)\right] \lesssim (130\, GeV)^2$$

$m_h \simeq 126$ GeV $\Rightarrow$ $m_{\tilde t} \simeq 3$ TeV or $A_t \simeq 3 m_{\tilde t} \simeq 1.5$ TeV

$\Rightarrow$ % to a few ‰ fine-tuning

minimum of the potential: $m_Z^2 = 2\frac{m_1^1 - m_2^2 \tan_\beta^2}{\tan^2\beta - 1} \sim -2m_2^2 + \cdots$

RG evolution: $m_2^2 = \; m_2^2(M_{\rm GUT}) - \frac{3\lambda_t^2}{4\pi^2} m_{\tilde t}^2 \ln\frac{M_{\rm GUT}}{m_{\tilde t}} + \cdots$ [47]

$$\sim m_2^2(M_{\rm GUT}) - \mathcal{O}(1) m_{\tilde t}^2 + \cdots$$

Reduce the fine-tuning

- minimize radiative corrections

  $M_{\rm GUT} \to \Lambda$: low messenger scale (gauge mediation)

  $$\delta m_{\tilde{t}}^2 = \frac{8\alpha_s}{3\pi} M_3^2 \ln \frac{\Lambda}{M_3} + \cdots$$

- increase the tree-level upper bound ⇛ extend the MSSM

  extra fields beyond LHC reach → effective field theory approach

- Low scale SUSY breaking ⇛ extend MSSM with the goldstino

  → Non linear MSSM [33]

- ...

MSSM with dim-5 and 6 operators

I.A.-Dudas-Ghilencea-Tziveloglou '08, '09, '10

parametrize new physics above MSSM by higher-dim effective operators

relevant super potential operators of dimension-5:

$$\mathcal{L}^{(5)} = \frac{1}{M} \int d^2\theta \, (\eta_1 + \eta_2 S) \, (H_1 H_2)^2$$

η_1 : generated for instance by a singlet

$$W = \lambda \sigma H_1 H_2 + M \sigma^2 \quad \rightarrow \quad W_{\text{eff}} = \frac{\lambda^2}{M} \, (H_1 H_2)^2$$

Strumia '99 ; Brignole-Casas-Espinosa-Navarro '03
Dine-Seiberg-Thomas '07

η_2 : corresponding soft breaking term spurion $S \equiv m_S \, \theta^2$ [30]

Soft supersymmetry breaking

Add all possible breaking terms that preserve the good SUSY behavior

$\Rightarrow$ they should have positive mass dimensions

can be generated if SUSY is spontaneously broken in a different sector

and mediated to the SM by gauge interactions or gravity

$$m_{\rm susy} \sim \frac{\langle F \rangle}{M} \quad \text{or} \quad \frac{\langle D \rangle}{M} \quad \sim \frac{\Lambda^2}{M}$$

M: messengers mass or $M_{\rm Planck}$ Λ: $\text{SU}\!\!\!/\text{SY}$ scale in the extra sector

if $M = M_{\rm Pl} \Rightarrow \Lambda \sim 10^{11}$ GeV so that $m_{\rm susy} \sim 1$ TeV

Obtain the general soft terms

must have positive dimensions: masses and trilinear scalar terms $m\phi^3$

necessary but not sufficient condition → general rule:

- Introduce an auxiliary chiral superfield S with only F-component

$$S \equiv m_{\rm susy}\theta^2 \; : \text{ spurion (dimensionless)}$$

- Promote all couplings of the supersymmetric Lagrangian

  to S-dependent functions/superfields

1) Matter kinetic terms: $\int d^4\theta\, \Phi^\dagger\Phi \to \int d^4\theta\, Z_\Phi(S, S^\dagger)\, \Phi^\dagger\Phi$

$Z_\Phi(S,S^\dagger) = 1 + z_\phi SS^\dagger$ up to analytic/antianalytic redefinitions

$$\Phi \to (1+cS)\Phi,\ \ \Phi^\dagger \to (1+c'S^\dagger)\Phi^\dagger$$

$\Rightarrow$ scalar masses: $m^2_{\rm susy} z_i|\phi_i|^2$ $\quad\to m_0^2$

2) Gauge kinetic terms $\int d^2\theta\,\mathcal{W}^2 \to \int d^2\theta\, Z_{\mathcal{W}}(S)\,\mathcal{W}^2$

$Z_{\mathcal{W}}(S) = 1 + z_{\mathcal{W}} S \Rightarrow$ gaugino masses $m_{\rm susy} z_a \lambda^a \lambda^a \quad \to m_{1/2}$

3) Superpotential $\int d^2\theta\, W(\Phi) \to \int d^2\theta\, w(S) W(\Phi) \qquad w(S) = 1 + \omega S$

$\Rightarrow m_{\rm susy}\omega_i W_i(\phi)$ for $W = \sum_i W_i$

$$W_{\rm SSM} \to B\mu H_1 H_2 + \tilde{q}\underset{\nwarrow}{\mathbf{A_u}}\tilde{u}^c H_2 + \tilde{q}\mathbf{A_d}\tilde{d}^c H_1 + \tilde{\ell}\mathbf{A_e}\tilde{e}^c H_1$$

matrices in flavor space

trilinear analytic scalar interactions $\quad \phi^3$ but not $\phi^2\phi^*$ [26]

Physical consequences of MSSM$_5$: Scalar potential

$$\mathcal{V} = m_1^2|h_1|^2 + m_2^2|h_2|^2 + B\mu(h_1h_2 + \mathrm{h.c.}) + \frac{g_2^2 + g_Y^2}{8}\left(|h_1|^2 - |h_2|^2\right)^2$$

$$+ \left(|h_1|^2 + |h_2|^2\right)\left(\eta_1 h_1h_2 + \mathrm{h.c.}\right) + \frac{1}{2}\left[\eta_2(h_1h_2)^2 + \mathrm{h.c.}\right]$$

$$+ \eta_1^2\,|h_1h_2|^2\left(|h_1|^2 + |h_2|^2\right)$$

- $\eta_{1,2} \Rightarrow$ quartic terms along the D-flat direction $|h_1| = |h_2|$
- tree-level mass can increase significantly
- bigger parameter space for LSP being dark matter

Bernal-Blum-Nir-Losada '09

- last term $\sim \eta_1^2$: guarantees stability of the potential

but requires addition of dim-6 operators

MSSM Higss with dim-6 operators

dim-6 operators can have an independent scale from dim-5

Classification of all dim-6 contributing to the scalar potential

(without $SU\!\!\!/SY$) $\Rrightarrow$

large $\tan\beta$ expansion: $\delta_6 m_h^2 = \underset{\nearrow}{f}\, v^2 + \cdots$

constant receiving contributions from several operators

$$f \sim f_0 \times \left(\mu^2/M^2,\ m_S^2/M^2,\ \mu m_S/M^2,\ v^2/M^2\right)$$

$m_S = 1$ TeV, $M = 10$ TeV, $f_0 \sim 1 - 2.5$ for each operator

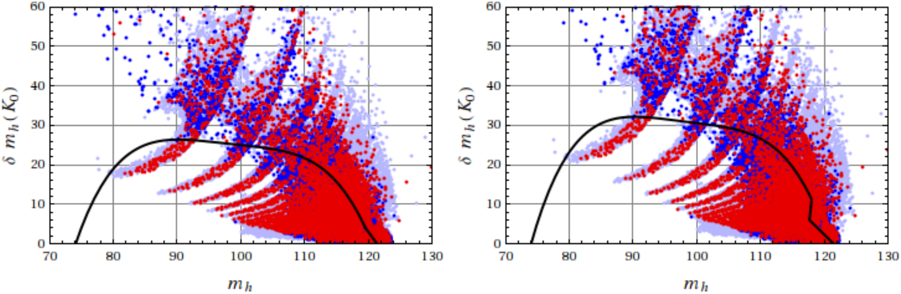
$\Rrightarrow m_h \simeq 103 - 119$ GeV

$\Rrightarrow$ MSSM with dim-5 and dim-6 operators:

possible resolution of the MSSM fine-tuning problem [25]

Fine-tuning in Constrained MSSM$_5$

I.A.-Dudas-Ghilencea-Tziveloglou '11



m_h: 2-loop (LL) CMSSM value; δm_h: correction from dim-5 operator

Left plot: $M = 10$ TeV; Right plot: $M = 8$ TeV;

Below solid line: $\Delta < 200$

Blue to Red: Dark Matter constraint Best to 3σ

Non-linear supersymmetry $\Rightarrow$ goldstino mode χ

Volkov-Akulov '73

- Effective field theory of SUSY breaking at low energies $m_\chi << m_{susy}$

  e.g. gauge mediation dominant vs gravity mediation

  χ: longitudinal gravitino with $m_\chi \simeq \dfrac{m_{susy}^2}{M_{Planck}} \lesssim m_{soft} << m_{susy}$

  $M_{Planck} \to \infty$: SUGRA decoupled

  massless χ coupled to matter $\sim 1/m_{susy}$

- Non-linear SUSY transformations:

$$\delta\chi_\alpha = \frac{\xi_\alpha}{\kappa} + \kappa\,\Lambda_\xi^\mu\,\partial_\mu\chi_\alpha \qquad \Lambda_\xi^\mu = -i\left(\chi\sigma^\mu\bar{\xi} - \xi\sigma^\mu\bar{\chi}\right)$$

κ: goldstino decay constant (*susy* breaking scale) $\quad \kappa = (\sqrt{2}m_{susy})^{-2}$

Constrained superfields

Rocek-Tseytlin '78, Lindstrom-Rocek '79, Komargodski-Seiberg '09

spontaneous global $S\!\!\!/USY$: no supercharge but still conserved supercurrent

$\Rightarrow$ superpartners exist in operator space (not as 1-particle states)

$\Rightarrow$ constrained superfields: 'eliminate' superpartners

Goldstino: chiral superfield X_{NL} satisfying $X_{NL}^2 = 0 \Rightarrow$

$$X_{NL}(y) = \frac{\chi^2}{2F} + \sqrt{2}\theta\chi + \theta^2 F \qquad y^\mu = x^\mu + i\theta\sigma^\mu\bar{\theta}$$

$$= F\Theta^2 \qquad \Theta = \theta + \frac{\chi}{\sqrt{2}F}$$

$$\mathcal{L}_{NL} = \int d^4\theta X_{NL}\bar{X}_{NL} - \frac{1}{\sqrt{2}\kappa}\left\{\int d^2\theta X_{NL} + h.c.\right\} = \mathcal{L}_{Volkov-Akulov}$$

$$F = \frac{1}{\sqrt{2}\kappa} + \dots$$

Goldstino couplings to matter supermultiplets

replace spurion superfield $S = m_{soft}\theta^2$ by goldstino constrained superfield

$$S \to \sqrt{2}\kappa m_{soft} X_{NL} = \frac{m_{soft}}{m_{susy}} X_{NL}$$

$\Rightarrow$ Non-linear MSSM

F-auxiliary in X_{NL}: dynamical field with no derivatives to be solved

$$-\bar{F} = m_{susy}^2 + \frac{B\mu}{m_{susy}^2} h_1 h_2 + \frac{A_u}{m_{susy}^2} \tilde{u}_R \tilde{q} h_2 + \cdots$$

$\Rightarrow$ compact form for all goldstino couplings at linear and non-linear level

Non-linear MSSM

I.A.-Dudas-Ghilencea-Tziveloglou '10

$$\mathcal{L} = \mathcal{L}_{SUSY} + \mathcal{L}_{X_{NL}} + \mathcal{L}_H + \mathcal{L}_m + \mathcal{L}_{AB} + \mathcal{L}_g$$

with

$$\mathcal{L}_H = \sum_{i=1,2} \frac{m_i^2}{m_{susy}^4} \int d^4\theta \; X_{NL}^\dagger X_{NL} \; H_i^\dagger \, e^{V_i} \, H_i$$

$$\mathcal{L}_m = \sum_{\Phi} \frac{m_\Phi^2}{m_{susy}^4} \int d^4\theta \; X_{NL}^\dagger X_{NL} \, \Phi^\dagger e^V \, \Phi \quad ; \quad \Phi = Q, U^c, D^c, L, E^c$$

$$\mathcal{L}_{AB} = \frac{1}{m_{susy}^2} \int d^2\theta \, X_{nl} \, (A_u \, H_2 \, Q \, U^c + A_d \, Q \, D^c \, H_1 + A_e \, L \, E^c \, H_1) + \frac{B\mu}{m_{susy}^2} \int d^2\theta \, X_{NL} \, H_1 \, H_2 + h.c.$$

$$\mathcal{L}_g = \sum_{i=1}^{3} \frac{1}{8g_i^2} \frac{m_{\lambda_i}}{m_{susy}^2} \int d^2\theta \, X_{NL} \, \mathrm{Tr} \, [\, W^\alpha \, W_\alpha]_i + h.c.$$

Phenomenological analysis I.A.-Dudas-Ghilencea-Tziveloglou '10

Higgs potential is modified:

$$V = V_{MSSM} + 2\kappa^2 \left| m_1^2 |h_1|^2 + m_2^2 |h_2|^2 + B\mu h_1 h_2 \right|^2 + \mathcal{O}(\kappa^4) \quad \Rightarrow$$

$m_{1,2}, B\mu$: soft mass parameters, μ: higgsino mass

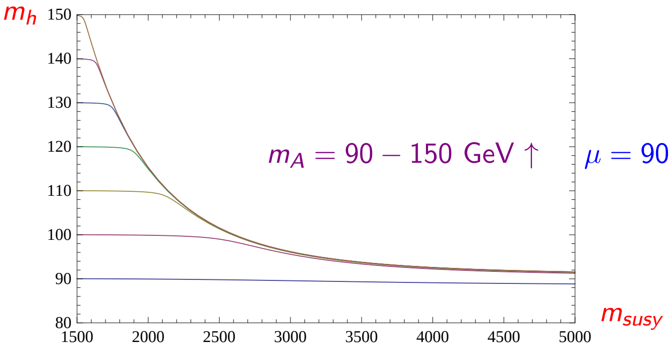
Classical value of light higgs mass can be increased significantly

for $m_{susy} \sim$ a few TeV

large $\tan\beta$ limit: $m_h^2 = m_Z^2 + \frac{v^2}{2m_{susy}^2}(2\mu^2 + m_Z^2)^2 + \cdots$

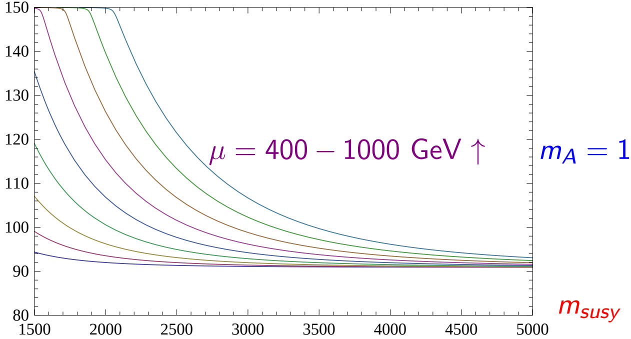
Quartic higgs coupling increases for large soft masses $\Rightarrow$

MSSM 'little' fine tuning of the EW scale is alleviated



$m_A = 90 - 150$ GeV ↑

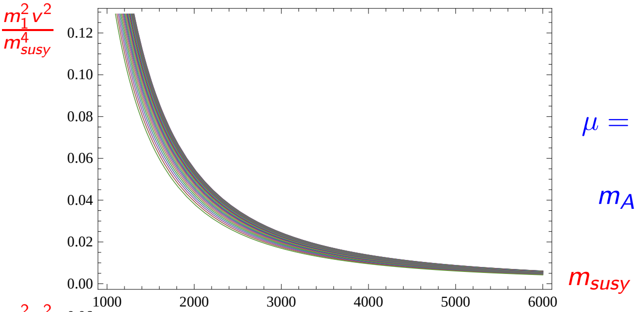
$\mu = 900$ GeV; $\tan\beta = 50$



$\mu = 400 - 1000$ GeV ↑

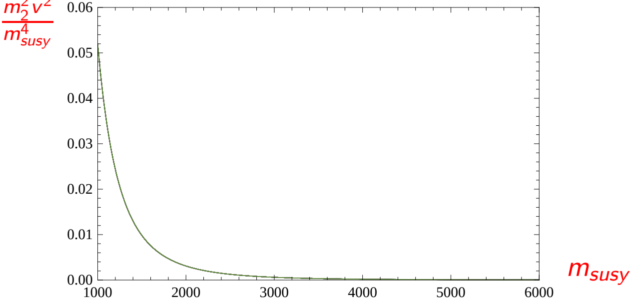
$m_A = 150$ GeV; $\tan\beta = 50$

Validity of perturbative expansion: $m_i^2 v^2 / m_{susy}^4 << 1$



$\mu = 900$ GeV; $\tan\beta = 50$

$m_A = 90 - 650$ GeV ↑



Fine-tuning analysis

I.A.-Babalic-Ghilencea '14

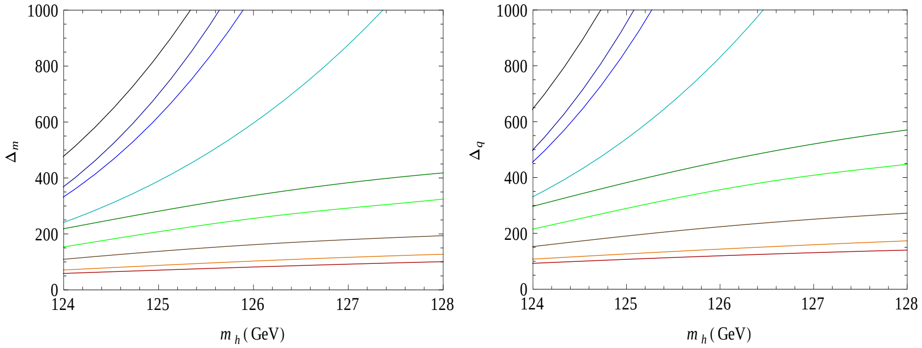
Fine-tuning measures:

Ellis-Enqvist-Nanopoulos-Zwirner '86
Barbieri-Giudice '88, Anderson-Castano '94

$$\Delta_m = \max \left|\Delta_{\gamma^2}\right|, \quad \Delta_q = \Big\{ \sum_\gamma \Delta^2_{\gamma^2} \Big\}^{1/2}, \quad \text{with} \;\; \Delta_{\gamma^2} \equiv \frac{\partial \ln v^2}{\partial \ln \gamma^2}$$

$$\gamma = \{m_0, m_{12}, A_t, B_0, \mu_0\}, \quad v = \text{EW scale}$$

The Constrained Non-Linear MSSM



Minimal values of Δ_m (left) and Δ_q (right) for $\tan\beta = 10$ and m_{susy} from the lowest to the top curve: 2.8 TeV (red), 3.2 TeV (orange), 3.9 TeV (brown), 5 TeV (green), 5.5 TeV (dark green), 6.3 TeV (cyan), 7.4 TeV (blue), 8 TeV (dark blue), 8.7 TeV (black).

$$m_{susy} \simeq 3 \text{ TeV} \Rightarrow \Delta^{NL} \sim \Delta/10$$

Non-liner SUSY in supergravity

I.A.-Dudas-Ferrara-Sagnotti '14

$$K = -3\log(1 - X\bar{X}) \equiv 3X\bar{X} \quad ; \quad W = f\,X + W_0 \qquad\qquad X \equiv X_{NL}$$

$$\Rightarrow \quad V = \frac{1}{3}|f|^2 - 3|W_0|^2 \quad ; \quad m_{3/2}^2 = |W_0|^2$$

- V can have any sign contrary to global NL SUSY
- NL SUSY in flat space $\Rightarrow f = 3\,m_{3/2}M_p$
- Dual gravitational formulation: $\mathcal{R}^2 = 0 \leftarrow$ chiral curvature superfield
- Minimal SUSY extension of R^2 gravity

Starobinsky model of inflation

$$\mathcal{L} = \frac{1}{2}R + \alpha R^2$$

equivalent to a scalar field with exponential potential:

$$\mathcal{L} = \frac{1}{2}R - \frac{1}{2}(\partial\phi)^2 - \frac{M^2}{12}\left(1 - e^{-\sqrt{\frac{2}{3}}\phi}\right)^2 \qquad M^2 = \frac{3}{4\alpha}$$

Note that the two metrics are not the same

supersymmetric extension:

add D-term $\mathcal{R}\bar{\mathcal{R}}$ because F-term $\mathcal{R}^2$ does not contain R^2

$\Rightarrow$ brings two chiral multiplets

SUSY extension of Starobinsky model

$$K = -3\ln(T + \bar{T} - C\bar{C}) \quad ; \quad W = MC(T - \frac{1}{2})$$

- T contains the inflaton: $\mathrm{Re}\, T = e^{\sqrt{\frac{2}{3}}\phi}$
- $C \sim \mathcal{R}$ is unstable during inflation

  $\Rightarrow$ add higher order terms to stabilize it

  e.g. $C\bar{C} \to h(C, \bar{C}) = C\bar{C} - \zeta(C\bar{C})^2$ Kallosh-Linde '13
- SUSY is broken during inflation with C the goldstino superfield

Minimal SUSY extension that evades stability problem:

replace C by the non-linear multiplet X

Non-linear Starobinsky supergravity

$$K = -3\ln(T+\bar{T}-X\bar{X}) \quad ; \quad W = M\,XT + f\,X + W_0 \qquad \Rightarrow$$

$$\mathcal{L} = \frac{1}{2}R - \frac{1}{2}(\partial\phi)^2 - \frac{M^2}{12}\left(1 - e^{-\sqrt{\frac{2}{3}}\phi}\right)^2 - \frac{1}{2}e^{-2\sqrt{\frac{2}{3}}\phi}(\partial a)^2 - \frac{M^2}{18}e^{-2\sqrt{\frac{2}{3}}\phi}a^2$$

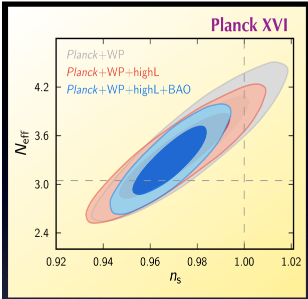
- axion a much heavier than ϕ during inflation, decouples:

  $m_\phi = \frac{M}{3}e^{-\sqrt{\frac{2}{3}}\phi_0} << m_a = \frac{M}{3}$

- inflation scale M independent from NL-SUSY breaking scale f

  $\Rightarrow$ compatible with low energy SUSY

- string realization? [70]



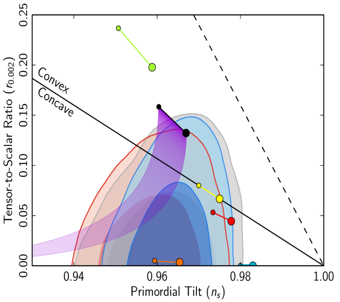
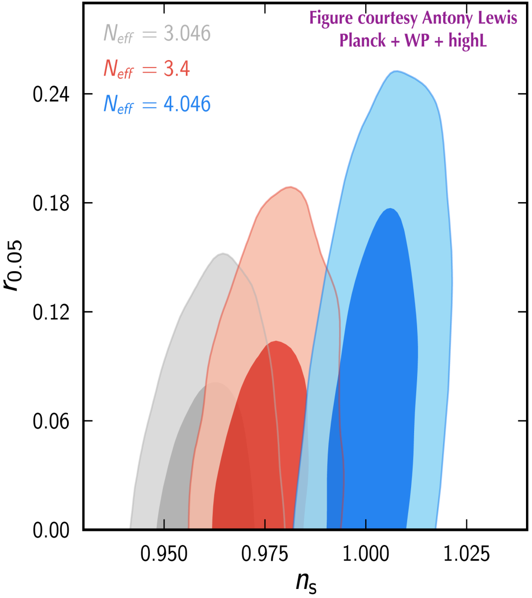


Fig. 1. Marginalized joint 68% and 95% CL regions for n_s and $r_{0.002}$ from *Planck* in combination with other data sets compared to the theoretical predictions of selected inflationary models.



Alternative answer: Low UV cutoff $\Lambda \sim$ TeV

- low scale gravity $\Rightarrow$ extra dimensions: large flat or warped

- low string scale $\Rightarrow$ low scale gravity, ultra weak string coupling

$M_s \sim 1$ TeV $\Rightarrow$ volume $R_\perp^n = 10^{32}\, l_s^n$ [??] ($R_\perp \sim .1 - 10^{-13}$ mm for $n = 2 - 6$)

- spectacular model independent predictions

- radical change of high energy physics at the TeV scale

Moreover no little hierarchy problem:

radiative electroweak symmetry breaking with no logs [24]

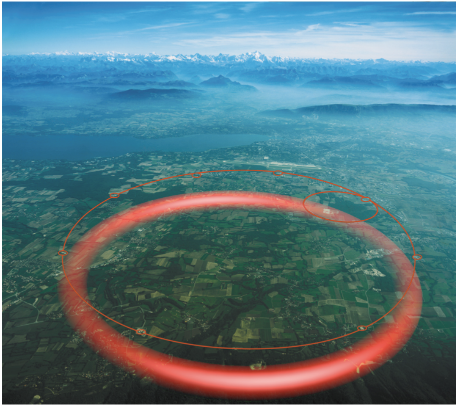
$\Lambda \sim$ a few TeV and $m_H^2 =$ a loop factor $\times\, \Lambda^2$

But unification has to be probably dropped

New Dark Matter candidates e.g. in the extra dims

Connect string theory to the real world

- Is it a tool for strong coupling dynamics or a theory of fundamental forces?
- Are there low energy string predictions testable at LHC?
- What can we hope to learn from LHC on string phenomenology?



At what energies strings may be observed?

Very different answers depending mainly on the value of the string scale M_s

Before 1994: $M_s \simeq M_{\rm Planck} \sim 10^{18}$ GeV $l_s \simeq 10^{-32}$ cm After 1994:

- arbitrary parameter : Planck mass $M_P \longrightarrow$ TeV

- physical motivations $\Rightarrow$ favored energy regions:

- High : $\begin{cases} M_P^* \simeq 10^{18} \text{ GeV} & \text{Heterotic scale} \\ M_{\rm GUT} \simeq 10^{16} \text{ GeV} & \text{Unification scale} \end{cases}$
- Intermediate : around 10^{11} GeV $(M_s^2/M_P \sim \text{TeV})$

  SUSY breaking, strong CP axion, see-saw scale
- Low : TeV (hierarchy problem)

High string scale

perturbative heterotic string : the most natural for SUSY and unification

gravity and gauge interactions have same origin

massless excitations of the closed string

But mismatch between string and GUT scales:

$M_s = g_H\, M_P \simeq 50\, M_{\rm GUT} \qquad g_H^2 \simeq \alpha_{\rm GUT} \simeq 1/25$ [57]

in GUTs only one prediction from 3 gauge couplings unification: $\sin^2\theta_W$

introduce large threshold corrections or strong coupling → $M_s \simeq M_{\rm GUT}$

but loose predictivity

Heterotic string

gravity $+$ gauge kinetic terms [58]

$$\int [d^{10}x]\,\frac{1}{g_H^2}M_H^8\,\mathcal{R}^{(10)} + \int [d^{10}x]\,\frac{1}{g_H^2}M_H^6\,\mathcal{F}_{MN}^2$$

simplified units: $2=\pi=1$

Compactification in 4 dims on a 6-dim manifold of volume $V_6 \Rightarrow$

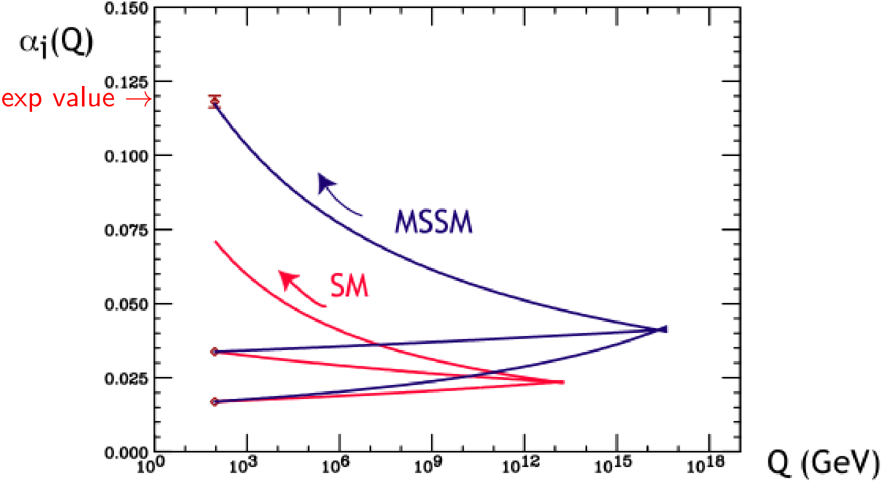
$$\int [d^4x]\,\underset{\substack{||\\ M_P^2}}{\frac{V_6}{g_H^2}M_H^8}\,\mathcal{R}^{(4)} + \int [d^4x]\,\underset{\substack{||\\ 1/g^2}}{\frac{V_6}{g_H^2}M_H^6}\,\mathcal{F}_{\mu\nu}^2 \qquad \Rightarrow$$

$$M_P^2 = \frac{1}{g^2}M_H^2 \quad \frac{1}{g^2} = \frac{1}{g_H^2}V_6 M_H^6 \quad \Rightarrow \quad M_H = gM_P \quad g_H = g\sqrt{V_6}M_H^3$$

$g_H \lesssim 1 \Rightarrow V_6 \sim$ string size

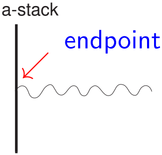
GUT prediction of QCD coupling

input $\alpha_{\rm em}, \sin^2\theta_W \quad \Rightarrow \quad$ output α_3



Open strings and D-branes

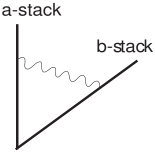
Generic spectrum: N coincident branes $\Rightarrow$ $U(N)$



endpoint transformation: $\mathbf{N}_a$ or $\bar{\mathbf{N}}_a$ $U(1)_a$ charge: $+1$ or -1

$\Rightarrow$ "baryon" number

- open strings from the same stack $\Rightarrow$ adjoint gauge multiplets of $U(N_a)$
- stretched between two stacks $\Rightarrow$ bifundamentals of $U(N_a) \times U(N_b)$



non-oriented strings $\Rightarrow$ also:

- orthogonal and symplectic groups $SO(N), Sp(N)$

- matter in antisymmetric + symmetric reps

Minimal Standard Model embedding

General analysis using 3 brane stacks

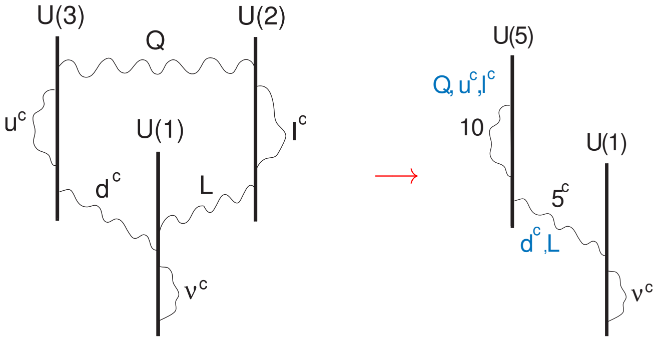
$$\Rightarrow \; U(3) \times U(2) \times U(1)$$

antiquarks u^c, d^c $(\bar{3}, 1)$:

antisymmetric of $U(3)$ or bifundamental $U(3) \leftrightarrow U(1)$

$\Rightarrow$ 3 models: antisymmetric is u^c, d^c or none

$SU(5)$ GUT



Intersecting branes: ‘perfect’ for SM embedding

product of unitary gauge groups (brane stacks) and bi-fundamental reps

but no unification: no prediction for M_s, independent gauge couplings

however GUTs: problematic:

- no perturbative $SO(10)$ spinors
- no top-quark Yukawa coupling in $SU(5)$: $10\,10\,5_H$

  $SU(5)$ is part of $U(5) \Rightarrow U(1)$ charges : 10 charge 2 ; 5_H charge ± 1

  $\Rightarrow$ cannot balance charges with $SU(5)$ singlets

  can be generated by D-brane instantons but . . .

→ Non-perturbative M/F-theory models:

combine good properties of heterotic and intersecting branes

but lack exact description for systematic studies

Type I/II string theory $\Rightarrow$ D-brane world

I.A.-Arkani-Hamed-Dimopoulos-Dvali '98

- gravity: closed strings propagating in 10 dims
- gauge interactions: open strings with their ends attached on D-branes

Dimensions of finite size: n transverse $6-n$ parallel [59]

calculability $\Rightarrow R_{\|} \simeq l_{\rm string}$; $R_\perp$ arbitrary

$M_p^2 \simeq \frac{1}{g_s^2} M_s^{2+n} R_\perp^n$ $g_s = \alpha$: weak string coupling [50]

Planck mass in $4+n$ dims: M_*^{2+n}

small $M_s/M_P \Rightarrow$ extra-large $R_\perp$

$M_s \sim 1$ TeV $\Rightarrow R_\perp^n = 10^{32}\, l_s^n$ [??]

$$R_\perp \sim .1 - 10^{-13} \text{ mm for } n = 2-6$$

distances $< R_\perp$: gravity $(4+n)$-dim $\rightarrow$ strong at 10^{-16} cm

Type I/II strings: gravity and gauge interactions have different origin

gravity + gauge kinetic terms

$$\int [d^{10}x]\, \frac{1}{g_s^2} M_s^8\, \mathcal{R}^{(10)} + \int [d^{p+1}x]\, \frac{1}{g_s} M_s^{p-3}\, \mathcal{F}_{MN}^2$$ [51]

Compactification in 4 dims ⇛

$$\int [d^4x]\, \underbrace{\frac{V_6}{g_s^2} M_s^8}_{M_P^2}\, \mathcal{R}^{(4)} + \int [d^4x]\, \underbrace{\frac{V_\parallel}{g_s} M_s^{p-3}}_{1/g^2}\, \mathcal{F}_{\mu\nu}^2 \qquad V_6 = V_\parallel V_\perp$$

$$\Rrightarrow$$

$$g_s = g^2 V_\parallel M_s^{p-3} \lesssim 1 \Rrightarrow V_\parallel \sim \text{string size}$$

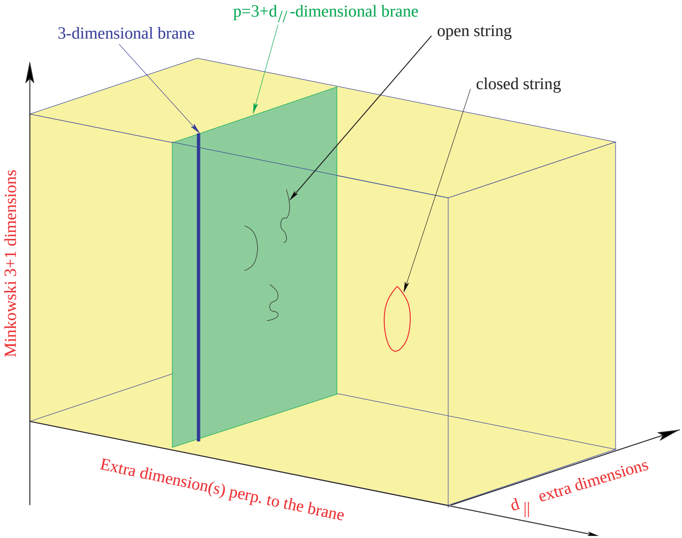
$$\Rrightarrow \quad M_P^2 = \frac{V_\perp}{g_s^2} M_s^{2+n} \qquad g_s \simeq g^2$$

Braneworld

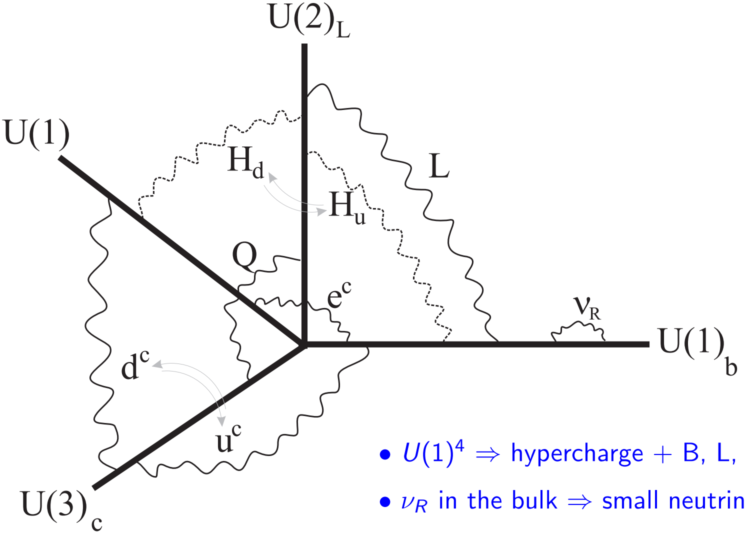
I.A.-Arkani-Hamed-Dimopoulos-Dvali ’98

2 types of compact extra dimensions:

- parallel ($d_{\|}$): $\lesssim 10^{-16}$ cm (TeV)
- transverse ($\perp$): $\lesssim 0.1$ mm (meV)



Standard Model on D-branes I.A.-Kiritsis-Rizos-Tomaras '02



- $U(1)^4 \Rightarrow$ hypercharge + B, L, PQ global
- ν_R in the bulk $\Rightarrow$ small neutrino masses

Accelerator signatures: 4 different scales

- Gravitational radiation in the bulk $\Rightarrow$ missing energy

  present LHC bounds: $M_* \gtrsim 3-5$ TeV

- Massive string vibrations $\Rightarrow$ e.g. resonances in dijet distribution [64]

  $$M_j^2 = M_0^2 + M_s^2\, j \quad ; \quad \text{maximal spin} : j+1$$

  higher spin excitations of quarks and gluons with strong interactions

  present LHC limits: $M_s \gtrsim 5$ TeV

- Large TeV dimensions $\Rightarrow$ KK resonances of SM gauge bosons I.A. '90

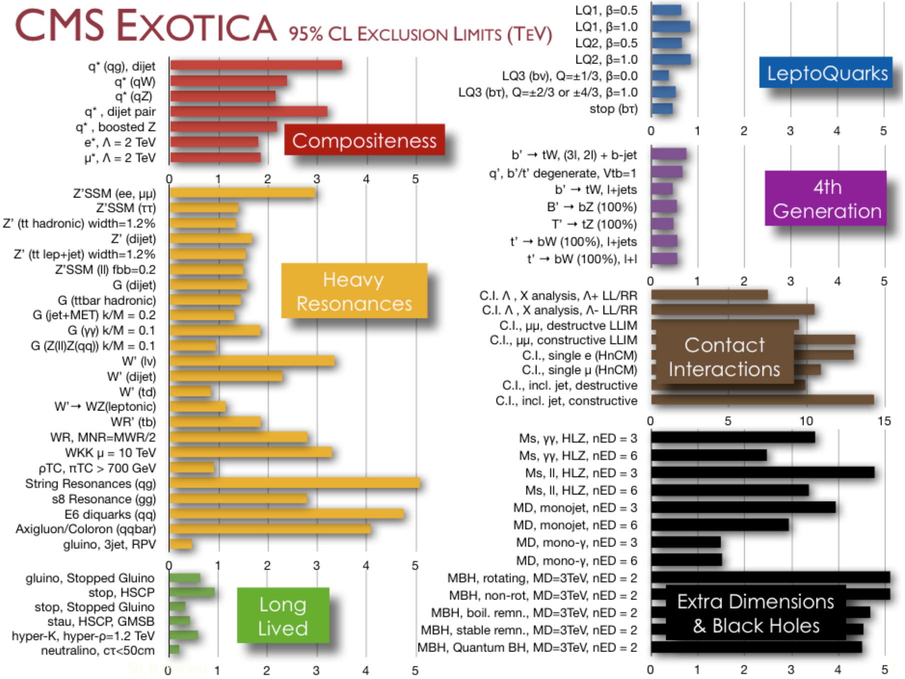
  $$M_k^2 = M_0^2 + k^2/R^2 \;\; ; \;\; k = \pm 1, \pm 2, \ldots$$

  experimental limits: $R^{-1} \gtrsim 0.5-4$ TeV (UED - localized fermions) [67]

- extra $U(1)$'s and anomaly induced terms

  masses suppressed by a loop factor from M_s [68]

CMS EXOTICA 95% CL EXCLUSION LIMITS (TEV)



Micro-black hole production?

String-size black hole energy threshold : $M_{\rm BH} \simeq M_s/g_s^2$

Horowitz-Polchinski '96, Meade-Randall '07

- string size black hole: $r_H \sim l_s = M_s^{-1}$
- black hole mass: $M_{\rm BH} \sim r_H^{d-3}/G_N \qquad G_N \sim l_s^{d-2} g_s^2$

weakly coupled theory $\Rightarrow$ strong gravity effects occur much above M_s, M_*

$g_s \sim 0.1$ (gauge coupling) $\quad \Rightarrow \quad M_{\rm BH} \sim 100 M_s$

Comparison with Regge excitations : $M_j = M_s\sqrt{j} \ \Rightarrow$

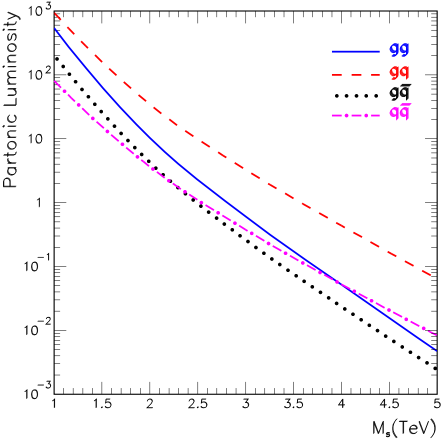
production of $j \sim 1/g_s^4 \sim 10^4$ string states before reach $M_{\rm BH}$ [61]

Tree level superstring amplitudes involving at most 2 fermions and gluons:

model independent for any compactification, # of susy's, even none

no intermediate exchange of KK, windings or graviton emmission

Universal sum over infinite exchange of string (Regge) excitations



Parton luminosities in pp above TeV

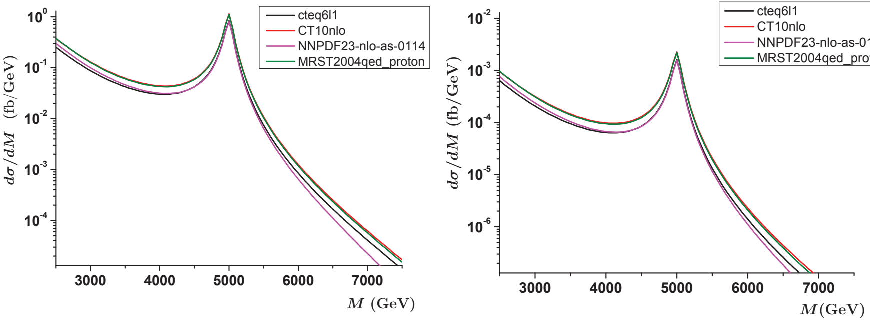
are dominated by gq, gg

$\Rightarrow$ model independent

$gq \to gq$, $gg \to gg$, $gg \to q\bar{q}$

String Resonances production at Hadron Colliders

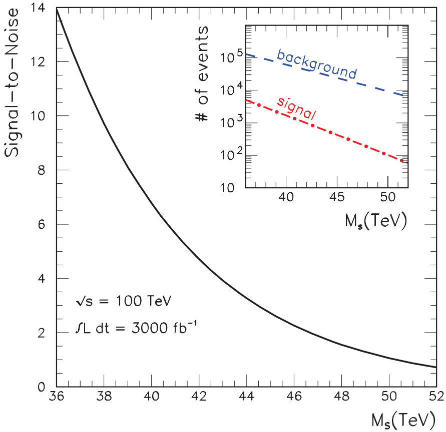
I.A.-Anchordoqui-Dai-Feng-Goldberg-Huang-Lüst-Stojkovic-Taylor '14

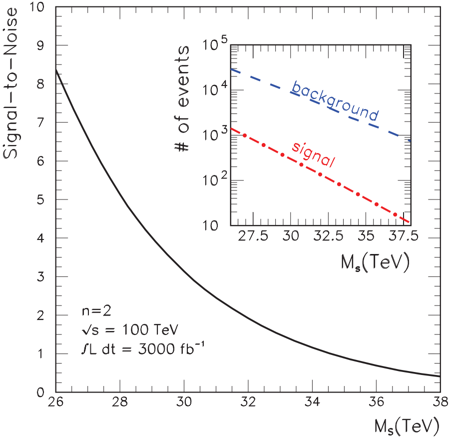


$M_s = 5$ TeV: dijet at LHC14 $\gamma +$ jet

String Resonances production at Hadron Colliders

I.A.-Anchordoqui-Dai-Feng-Goldberg-Huang-Lüst-Stojkovic-Taylor '14

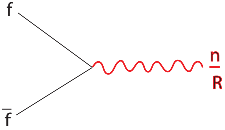




[61]

Localized fermions (on 3-brane intersections)

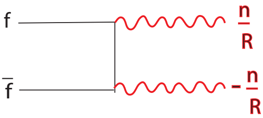
$\Rightarrow$ single production of KK modes I.A.-Benakli '94



- strong bounds indirect effects
- new resonances but at most $n = 1$

Otherwise KK momentum conservation

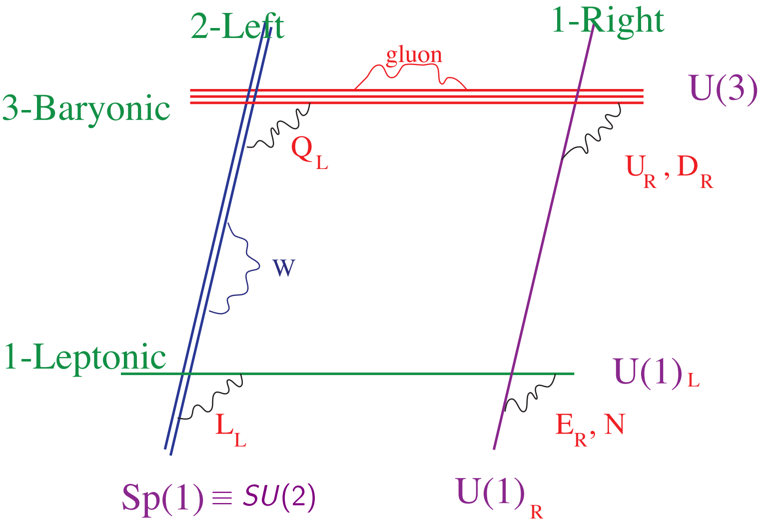
$\Rightarrow$ pair production of KK modes (universal dims)



- weak bounds
- no resonances
- lightest KK stable $\Rightarrow$ dark matter candidate

Servant-Tait '02 [61]

Standard Model on D-branes : SM^{++}



$U(1)^3 \Rightarrow$ hypercharge + B, L

TeV string scale

Anchordoqui-IA-Goldberg-Huang-Lüst-Taylor '11

- B and L become massive due to anomalies

  Green-Schwarz terms

- the global symmetries remain in perturbation

  - Baryon number $\Rrightarrow$ proton stability

  - Lepton number $\Rrightarrow$ protect small neutrino masses

  no Lepton number $\Rrightarrow \frac{1}{M_s} LLHH \rightarrow$ Majorana mass: $\frac{\langle H \rangle^2}{\underset{\nwarrow \sim \text{GeV}}{M_s}} LL$

- $B, L \Rrightarrow$ extra Z's

  with possible leptophobic couplings leading to CDF-type Wjj events

  $Z' \simeq B$ lighter than 4d anomaly free $Z'' \simeq B - L$

Conclusions

- Discovery of a Higgs scalar at the LHC:

  important milestone of the LHC research program

- Precise measurement of its couplings is of primary importance
- Hint on the origin of mass hierarchy and of BSM physics
  - natural or unnatural SUSY?
  - low string scale in some realization?
  - something new and unexpected?

  all options are still open

- LHC enters a new era with possible new discoveries
- Future plans to explore the 10-100 TeV energy frontier