Theory and phenomenology of physics with extra dimensions

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IXth Rencontres du Vietnam: Windows on the Universe
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- Mass hierarchy, low energy SUSY and 126 GeV Higgs
- Live with the hierarchy
- Low scale strings and extra dimensions
H⁰ (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.

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<td>CMS</td>
<td>pp, 7 and 8 TeV</td>
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<td></td>
<td>2 AAD 12Al</td>
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<td>pp, 7 and 8 TeV</td>
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<td>125.8 ± 0.4 ± 0.4</td>
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<td>126.0 ± 0.4 ± 0.4</td>
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<tr>
<td>126.2 ± 0.6 ± 0.2</td>
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<tr>
<td>125.3 ± 0.4 ± 0.5</td>
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We do not use the following data for averages, fits, limits, etc.

HTTP://PDG.LBL.GOV

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Created: 7/31/2013
$H^0$ Mass $m = 125.9 \pm 0.4$ GeV

$H^0$ signal strengths in different channels $[n]$

Combined Final States $= 1.07 \pm 0.26$ (S = 1.4)
$WW^*$ Final State $= 0.88 \pm 0.33$ (S = 1.1)
$ZZ^*$ Final State $= 0.89^{+0.30}_{-0.25}$
$\gamma\gamma$ Final State $= 1.65 \pm 0.33$
$b\bar{b}$ Final State $= 0.5^{+0.8}_{-0.7}$
$\tau^+\tau^-$ Final State $= 0.1 \pm 0.7$
Couplings of the new boson vs SM

exclusion: spin 2 and pseudoscalar at $\gtrsim 95\%$ CL

Agreement with Standard Model expectation at $\sim 2\sigma$
Beyond the Standard Theory of Particle Physics: 
driven by the mass hierarchy problem

Standard picture: low energy supersymmetry

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

Problems:
- too many parameters: soft breaking terms
- MSSM: already a $\% - \%_0$ fine-tuning  ‘little’ hierarchy problem

Natural framework: Heterotic string (or high-scale M/F) theory
Remarks on the value of the Higgs mass $\sim 126$ GeV

- consistent with expectation from precision tests of the SM
- favors perturbative physics
  
  $$\text{quartic coupling } \lambda = \frac{m_H^2}{v^2} \simeq 1/8$$

- 1st elementary scalar in nature signaling perhaps more to come

Window to new physics?

- compatible with supersymmetry
  
  but appears fine-tuned in its minimal version \cite{10}

  early to draw a general conclusion before LHC13/14 \cite{11}

  e.g. an extra singlet or split families can alleviate the fine tuning \cite{12}

- very important to measure its properties and couplings

  any deviation of its couplings to top, bottom and EW gauge bosons

  implies new light states involved in the EWSB altering the fine-tuning
$\Delta \alpha_{\text{had}} = \Delta \alpha^{(5)} = 0.02761 \pm 0.00036$

$région exclue$

$I. Antoniadis (CERN)$
Upper bound on the lightest scalar mass:

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

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

\[
\Rightarrow \% \text{ to a few } \%	ext{0 fine-tuning}
\]

Minimum of the potential:

\[
m_Z^2 = 2 \frac{m_1^2 - m_2^2 \tan^2 \beta}{\tan^2 \beta - 1} \sim -2m_2^2 + \cdots
\]

RG evolution:

\[
m_2^2 = m_2^2(M_{\text{GUT}}) - \frac{3\lambda_t^2}{4\pi^2} m_t^2 \ln \frac{M_{\text{GUT}}}{m_\tilde{t}} + \cdots \quad [20]
\]

\[
\sim m_2^2(M_{\text{GUT}}) - O(1)m_\tilde{t}^2 + \cdots \quad [8]
\]
Reduce the fine-tuning

- minimize radiative corrections

\[ M_{\text{GUT}} \rightarrow \Lambda : \text{low messenger scale (gauge mediation)} \]

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

- extend the MSSM

  extra fields beyond LHC reach \( \rightarrow \) effective field theory approach

\[ \cdots \]
**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:**

\[ \mathcal{L}^{(5)} = \frac{1}{M} \int d^2 \theta \left( \eta_1 + \eta_2 S \right) (H_1 H_2)^2 \]

\( \eta_1 \): 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

\( \eta_2 \): corresponding soft breaking term

Spurion \( S \equiv m_S \theta^2 \)
Physical consequences of MSSM$_5$: Scalar potential

\[ \mathcal{V} = m_1^2|h_1|^2 + m_2^2|h_2|^2 + B\mu(h_1 h_2 + \text{h.c.}) + \frac{g_2^2 + g_Y^2}{8} (|h_1|^2 - |h_2|^2)^2 \]

\[ + (|h_1|^2 + |h_2|^2) (\eta_1 h_1 h_2 + \text{h.c.}) + \frac{1}{2} [\eta_2 (h_1 h_2)^2 + \text{h.c.}] \]

\[ + \eta_1^2 |H_1 H_2|^2 (|H_1|^2 + |H_2|^2) \]

- $\eta_{1,2} \Rightarrow$ 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.
dim-6 operators can have an independent scale from dim-5

Classification of all dim-6 contributing to the scalar potential

\[ \delta_6 m_h^2 = f v^2 + \cdots \]

large tan $\beta$ expansion: constant receiving contributions from several operators

\[ f \sim f_0 \times (\mu^2/M^2, m_S^2/M^2, \mu m_S/M^2, v^2/M^2) \]

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

\[ m_h \simeq 103 - 119 \text{ GeV} \]

\[ \Rightarrow \text{MSSM with dim-5 and dim-6 operators: possible resolution of the MSSM fine-tuning problem} \]
Can the SM be valid at high energies?

Degrassi-Di Vita-Elias Miró-Espinosa-Giudice-Isidori-Strumia ’12

Instability of the SM Higgs potential $\Rightarrow$ metastability of the EW vacuum
SUSY: $\lambda = 0 \Rightarrow \sin \beta = 1$

$$H_{SM} = \sin \beta \, H_u - \cos \beta \, H_d^*$$

$$\lambda = \frac{1}{8}(g_2^2 + g'^2) \cos^2 2\beta$$

$\lambda = 0$ at a scale $\geq 10^{10}$ GeV $\Rightarrow m_H = 126 \pm 3$ GeV

Ibanez-Valenzuela '13

- e.g. for universal $\sqrt{2} m = M = M_{SS}, \ A = -3/2M$
If the weak scale is tuned $\Rightarrow$ split supersymmetry is a possibility

Arkani Hamed-Dimopoulos '04, Giudice-Romaninio '04

- natural splitting: gauginos, higgsinos carry R-symmetry, scalars do not
- main good properties of SUSY are maintained
gauge coupling unification and dark matter candidate
- also no dangerous FCNC, CP violation, . . .
- experimentally allowed Higgs mass $\Rightarrow$ ‘mini’ split

$$m_S \sim \text{few - thousands TeV}$$

- gauginos: a loop factor lighter than scalars ($\sim m_{3/2}$)
- natural string framework: intersecting (or magnetized) branes

IA-Dimopoulos '04

D-brane stacks are supersymmetric with massless gauginos

intersections have chiral fermions with broken SUSY & massive scalars
Predicted range for the Higgs mass

- $\tan\beta = 50$
- $\tan\beta = 4$
- $\tan\beta = 2$
- $\tan\beta = 1$

Split SUSY
High-Scale SUSY
Experimentally favored

Higgs mass $m_h$ in GeV

Supersymmetry breaking scale in GeV

$10^4$ $10^6$ $10^8$ $10^{10}$ $10^{12}$ $10^{14}$ $10^{16}$ $10^{18}$
An extra $U(1)$ can also cure the instability problem

usually associated to known global symmetries of the SM: $B, L, \ldots$

- $B$ anomalous and superheavy
- $B - L$ massless at the string scale (no associated 6d anomaly)
  but broken at TeV by a scalar VEV with the quantum numbers of $N_R$
- $L$-violation from higher-dim operators suppressed by the string scale
- $U(3)$ unification, $Y$ combination $\Rightarrow$ 2 parameters: 1 coupling + $m_{Z''}$
- perturbativity $\Rightarrow$ $0.5 \lesssim g_{U(1)_R} \lesssim 1$
- interesting LHC phenomenology and cosmology
Alternative answer: Low UV cutoff $\Lambda \sim \text{TeV}$

- low scale gravity $\Rightarrow$ extra dimensions: large flat or warped
- low string scale $\Rightarrow$ low scale gravity, ultra weak string coupling

$M_s \sim 1 \text{ TeV} \Rightarrow$ volume $R^n_\perp = 10^{32} l_s^n \ (R_\perp \sim .1 - 10^{-13} \text{ mm for } n = 2 - 6)$

- 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 \(^{[10]}\)

$\Lambda \sim \text{a few TeV}$ and $m_H^2 = \text{a loop factor} \times \Lambda^2 \ \ ^{[25]}$

But unification has to be probably dropped

New Dark Matter candidates e.g. in the extra dims
2 types of compact extra dimensions:

- **parallel** ($d_{||}$): $\lesssim 10^{-16}$ cm (TeV)
- **transverse** ($\perp$): $\lesssim 0.1$ mm (meV)
$R_\perp \lesssim 45 \, \mu m$ at 95\% CL

- dark-energy length scale $\approx 85 \, \mu m$
Origin of EW symmetry breaking?

possible answer: radiative breaking

\[ V = \mu^2 H^\dagger H + \lambda (H^\dagger H)^2 \]

\[ \mu^2 = 0 \text{ at tree but becomes } < 0 \text{ at one loop} \quad \text{non-susy vacuum} \]

simplest case: one scalar doublet from the same brane

⇒ tree-level \( V \) same as susy: \( \lambda = \frac{1}{8} (g_2^2 + g'^2) \) \quad \text{D-terms}

\[ \mu^2 = -g^2 \varepsilon^2 M_s^2 \quad \text{effective UV cutoff} \]

\[ \varepsilon^2(R) = \frac{R^3}{2\pi^2} \int_0^\infty d\eta^{3/2} \frac{\theta_2^4}{16l^4\eta^{12}} \left( il + \frac{1}{2} \right) \sum_n n^2 e^{-2\pi n^2 R^2 l} \]
$R \to 0 : \quad \varepsilon(R) \simeq 0.14 \quad \text{large transverse dim} \quad R_\perp = l_s^2 / R \to \infty$

$R \to \infty : \quad \varepsilon(R)M_s \sim \varepsilon_\infty / R \quad \varepsilon_\infty \simeq 0.008 \quad \text{UV cutoff: } M_s \to 1 / R$

Higgs scalar = component of a higher dimensional gauge field

$\Rightarrow \varepsilon_\infty$ calculable in the effective field theory

$\lambda = g^2 / 4 \sim 1 / 8 \quad \Rightarrow \quad M_H \simeq v / 2 = 125 \text{ GeV}$

$M_s$ or $1 / R \sim$ a few or several TeV \cite{25}
Accelerator signatures: 4 different scales

- Gravitational radiation in the bulk $\Rightarrow$ missing energy
  
  present LHC bounds: $M_\star \gtrsim 3 - 5$ TeV

- Massive string vibrations $\Rightarrow$ e.g. resonances in dijet distribution \cite{27}
  
  \[ M_j^2 = M_0^2 + M_s^2 j \quad ; \quad \text{maximal spin} : j + 1 \]

  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
  
  \[ M_k^2 = M_0^2 + k^2 / R^2 \quad ; \quad k = \pm 1, \pm 2, \ldots \]

  experimental limits: $R^{-1} \gtrsim 0.5 - 4$ TeV (UED - localized fermions) \cite{29}

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

  masses suppressed by a loop factor from $M_s$ \cite{32}
CMS EXOTICA 95% CL Exclusion Limits (TeV)

- q^+ (qg), dijet
- q^- (qgW)
- q^- (qZ)
- q^+, dijet pair
- q^+, boosted Z
- e^+, τ = 2 TeV
- μ^+, τ = 2 TeV
- Z'SSM (ee, μμ)
- Z'SSM (ττ)
- Z' (tt hadronic) width=1.2%
- Z' (dijet)
- Z' (tt lep+jet) width=1.2%
- Z'SSM (ll) fβ=0.2
- G (dijet)
- G (ttbar hadronic)
- G (jett+MET) k/M = 0.2
- G (yy) k/M = 0.1
- G (Zll/Zqq) k/M = 0.1
- W' (lv)
- W' (dijet)
- W' (td)
- W' → WZ(lep+jet)
- WR, MNR=MWR/2
- WKK μ = 10 TeV
- pTC, nTC > 700 GeV
- String Resonances (qq)
- s8 Resonance (gg)
- E6 diquarks (qq)
- Axigluon/Coloron (qbar)
- gluino, 3jet, RPV

- gluino, Stopped Gluino
- stop, Stopped Gluino
- stau, HSCP, GMSB
- hyper-K, hyper-p=1.2 TeV
- neutralino, cτ<50cm

Compositeness

Heavy Resonances

Contact Interactions

LeptoQuarks

4th Generation

Extra Dimensions & Black Holes

C.I. A, X analysis, λ+ LL/RR
C.I. A, X analysis, λ- LL/RR
C.I., μμ, destructive LLM
C.I., μμ, constructive LLM
C.I., single e (HnCM)
C.I., single μ (HnCM)
C.I., incl. jet, destructive
C.I., incl. jet, constructive

LQ1, β=0.5
LQ1, β=1.0
LQ2, β=0.5
LQ2, β=1.0
LQ3 (bτ), Q±1/3, β=0.0
LQ3 (bτ), Q±2/3 or ±4/3, β=1.0
stop (bτ)

b' → tw, (3l, 2l) + b-jet
q', b'/t degenerate, Vtb=1
b' → tw, l+jets
B' → bZ (100%)
T' → tZ (100%)
t' → bW (100%), l+jets
t' → bW (100%), l+l

Ms, yy, HLZ, nED = 3
Ms, yy, HLZ, nED = 6
Ms, ll, HLZ, nED = 3
Ms, ll, HLZ, nED = 6
MD, monojet, nED = 3
MD, monojet, nED = 6
MD, mono-l, nED = 3
MD, mono-l, nED = 6
MBH, rotating, MD=3TeV, nED = 2
MBH, no-rot, MD=3TeV, nED = 2
MBH, boil. remn., MD=3TeV, nED = 2
MBH, stable remn., MD=3TeV, nED = 2
MBH, Quantum BH, MD=3TeV, nED = 2
Universal deviation from Standard Model in jet distribution

\[ M_s = 2 \text{ TeV} \]

Width = 15-150 GeV

Anchordoqui-Goldberg-Lüst-Nawata-Taylor-Stieberger '08
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 emission
Universal sum over infinite exchange of string (Regge) excitations

Parton luminosities in pp above TeV are dominated by $gq, gg$
$\Rightarrow$ model independent
$gq \rightarrow gq, gg \rightarrow gg, gg \rightarrow q\bar{q}$
Localized fermions (on 3-brane intersections)

⇒ single production of KK modes

\[ f \]
\[ \bar{f} \]

• strong bounds
• new resonances

but at most \( n = 1 \)

Otherwise KK momentum conservation

⇒ pair production of KK modes (universal dims)

\[ f \]
\[ \bar{f} \]

• weak bounds
• no resonances

• lightest KK stable ⇒ dark matter candidate

I.A.-Benakli ’94

Servant-Tait ’02
**UED hadron collider phenomenology**

- Large rates for KK-quark and KK-gluon production
- Cascade decays via KK-$W$ bosons and KK-leptons
  - Determine particle properties from different distributions
- Missing energy from LKP: weakly interacting escaping detection
- Phenomenology similar to supersymmetry
  - Spin determination important for distinguishing SUSY and UED

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<th>Spin</th>
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<td>KK-quark</td>
<td>1/2</td>
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<td>1/2</td>
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<td>Neutralino</td>
<td>1/2</td>
<td>KK-$Z$ boson</td>
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SUSY vs UED signals at LHC

Example: jet dilepton final state

SUSY

UED
Extra $U(1)$’s and anomaly induced terms

masses suppressed by a loop factor

usually associated to known global symmetries of the SM

(anomalous or not) such as (combinations of)

Baryon and Lepton number, or PQ symmetry

Two kinds of massive $U(1)$’s: I.A.-Kiritsis-Rizos ’02

- 4d anomalous $U(1)$’s: $M_A \simeq g_A M_s$

- 4d non-anomalous $U(1)$’s: (but masses related to 6d anomalies)

$$M_{NA} \simeq g_A M_s V_2 \leftarrow (6d \rightarrow 4d) \text{ internal space} \quad \Rightarrow \quad M_{NA} \geq M_A$$

or massless in the absence of such anomalies
Standard Model on D-branes: SM$^+$

3-Baryonic

2-Left

1-Right

1-Leptonic

Sp(1) ≡ SU(2)

U(1) \_L

U(1) \_R

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

I. Antoniadis (CERN)
\begin{itemize}
  \item $B$ and $L$ become massive due to anomalies
    Green-Schwarz terms
  \item the global symmetries remain in perturbation
    - Baryon number $\Rightarrow$ proton stability
    - Lepton number $\Rightarrow$ protect small neutrino masses
  \item no Lepton number $\Rightarrow \frac{1}{M_s} LLHH \rightarrow$ Majorana mass: $\langle H \rangle^2_{M_s} LL \sim \text{GeV}$
  \item $B, L \Rightarrow$ extra $Z$'s
    with possible leptophobic couplings leading to CDF-type $Wjj$ events
    \[ Z' \sim B \text{ lighter than 4d anomaly free } Z'' \sim B - L \]
\end{itemize}
microgravity experiments

- change of Newton’s law at short distances
detectable only in the case of two large extra dimensions

- new short range forces

light scalars and gauge fields if SUSY in the bulk
or broken by the compactification on the brane

I.A.-Dimopoulos-Dvali ’98, I.A.-Benakli-Maillard-Laughier ’02

such as radion and lepton number

volume suppressed mass: \((\text{TeV})^2/M_P \sim 10^{-4} \text{ eV} \rightarrow \text{mm range}

- Light \(U(1)\) gauge bosons: no derivative couplings

\(\Rightarrow\) for the same mass much stronger than gravity: \(\gtrsim 10^6\)
Experimental limits on short distance forces

\[ V(r) = -G \frac{m_1 m_2}{r} \left( 1 + \alpha e^{-r/\lambda} \right) \]

Radion \( \Rightarrow M_* \gtrsim 6 \text{ TeV} \) 95\% CL  Adelberger et al. '06
spacetime = slice of AdS$_5$ : $ds^2 = e^{-2k|y|} \eta_{\mu\nu} dx^\mu dx^\nu + dy^2 ~ k^2 \sim \Lambda/M_5^3$

- UV-brane: $y = 0$
- bulk: $-|\Lambda|$ with $M_P$ and $M_W$
- IR-brane: $y = r_c$

- fine-tuned tensions: $T = -T' = 24M_5^3 k$

- exponential hierarchy: $M_W = M_P e^{-2kr_c} ~ M_P^2 \sim M_5^3/k$

- 4d gravity localized on the UV-brane, but KK gravitons on the IR
• main prediction: spin-2 resonances at the TeV scale
  \[ m_n = c_n k e^{-2krc} \sim \text{TeV} \quad c_n \simeq \left( n + \frac{1}{4} \right) \text{ for large } n \]
  \[ \Rightarrow \text{ spin-2 TeV resonances in di-lepton or di-jet channels} \]

• weakly coupled for \( m_n < M_5 e^{-2krc} \) \( \Rightarrow k < M_5 \)

• viable models: SM gauge bosons in the bulk, Higgs on the IR-brane

• AdS/CFT duals to strongly coupled 4d field theories

  composite Higgs models, technicolor-type \[ g_{YM} = \frac{M_5}{k} > 1 \]
Conclusions

- Confirmation of the EWSB scalar at the LHC: an 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.
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.

*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.*