Hunting for New Physics: Higgs, SUSY and beyond

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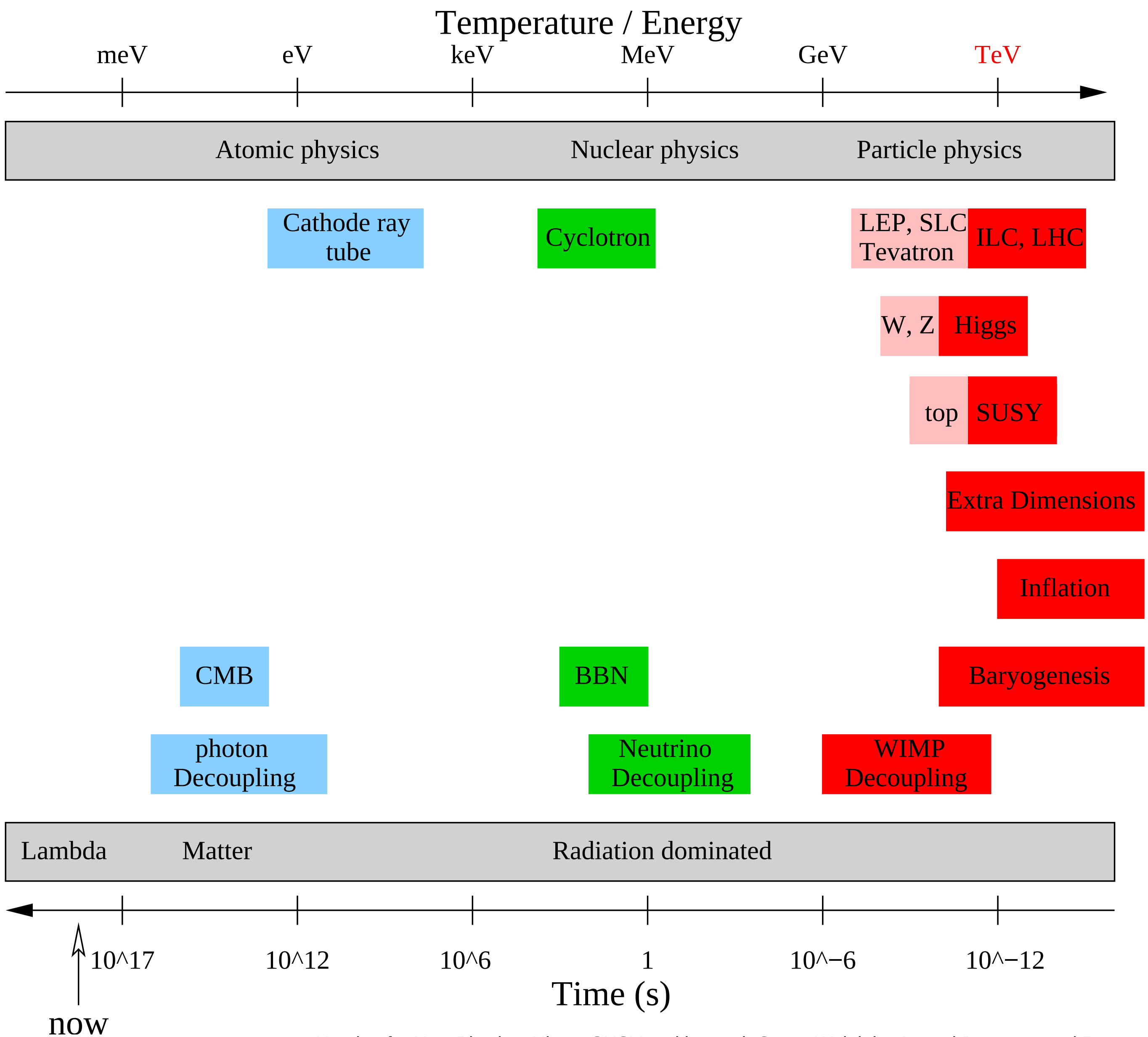
On the way to the TeV scale

$$1\ \text{TeV} \approx 1000 \times m_{\text{proton}} \Leftrightarrow 2 \times 10^{-19}\ \text{m}$$



High-energy colliders: viewing the early Universe

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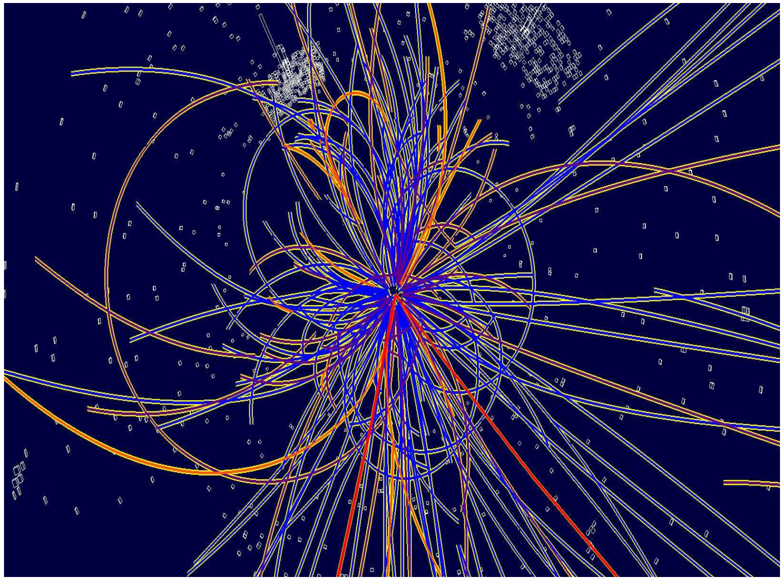

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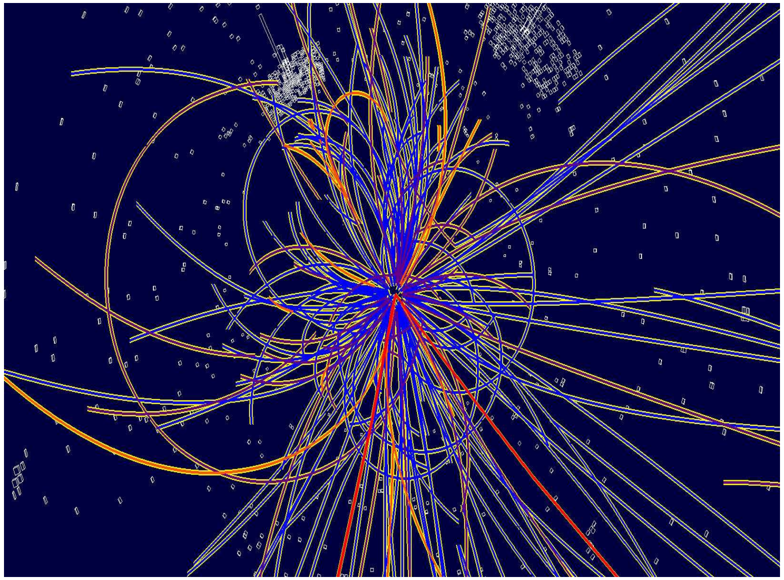

⇒ The LHC probes not only the structure of matter but also the structure of space-time

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- How do elementary particles obtain the property of mass: what is the mechanism of electroweak symmetry breaking?
- Do all the forces of nature arise from a single fundamental interaction?
- Are there more than three dimensions of space?
- Are space and time embedded into a “superspace”?
- What is dark matter? Can it be produced in the laboratory?
- . . .

Probing the electroweak symmetry breaking mechanism at the LHC

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⇒ The mechanism of electroweak symmetry breaking will manifest itself at the TeV scale

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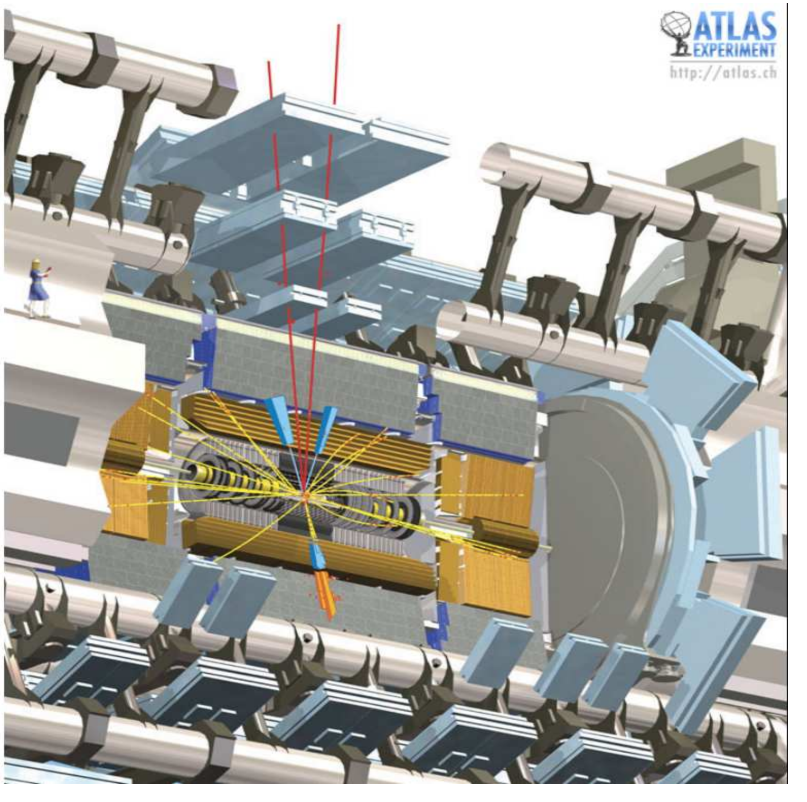
Simulation of a Higgs event in the ATLAS detector



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- Strong electroweak symmetry breaking:
  a new kind of strong interaction
- Higgsless models in extra dimensions: boundary conditions for SM gauge bosons and fermions on Planck and TeV branes in higher-dimensional space

$\Rightarrow$ New phenomena required at the TeV scale

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- Nature has found a way to prevent this
  The Standard Model provides no explanation

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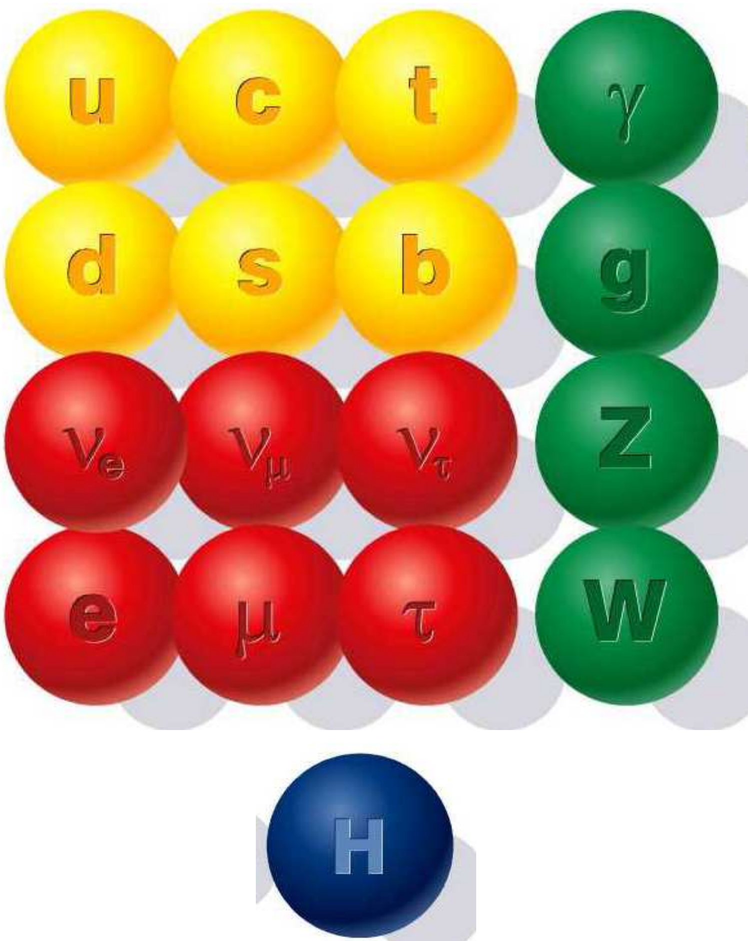
Extra dimensions of space:

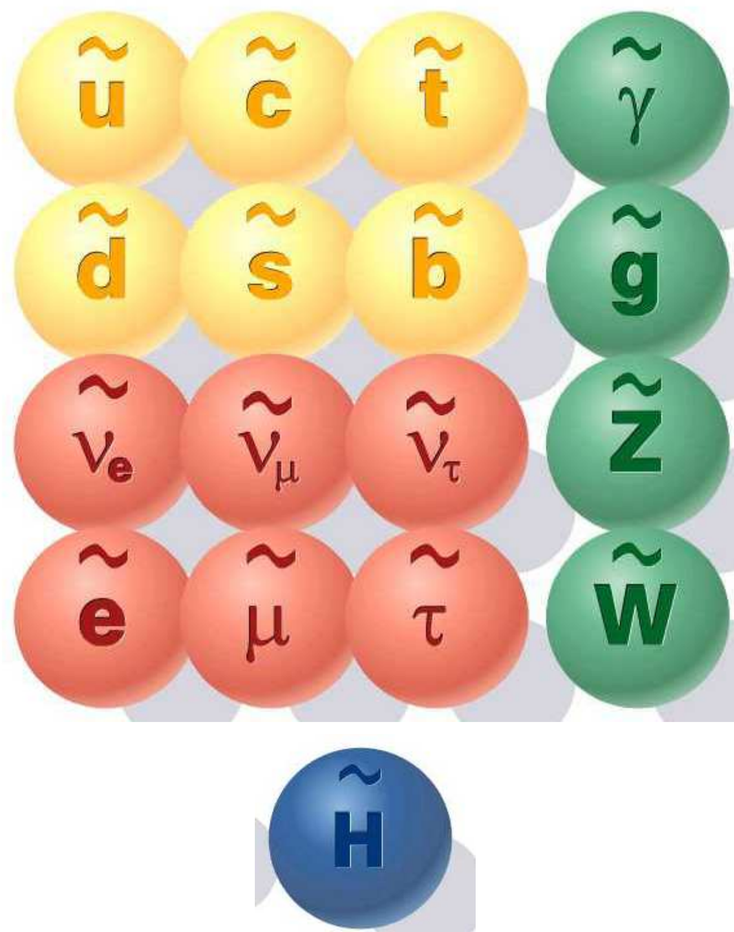
Fundamental Planck scale is $\sim \mathrm{TeV}$ (large extra dimensions),

hierarchy of scales is related to a “warp factor”
(“Randall–Sundrum” scenarios)

Supersymmetry (SUSY)

Supersymmetry: fermion $\longleftrightarrow$ boson symmetry,
leads to compensation of large quantum corrections





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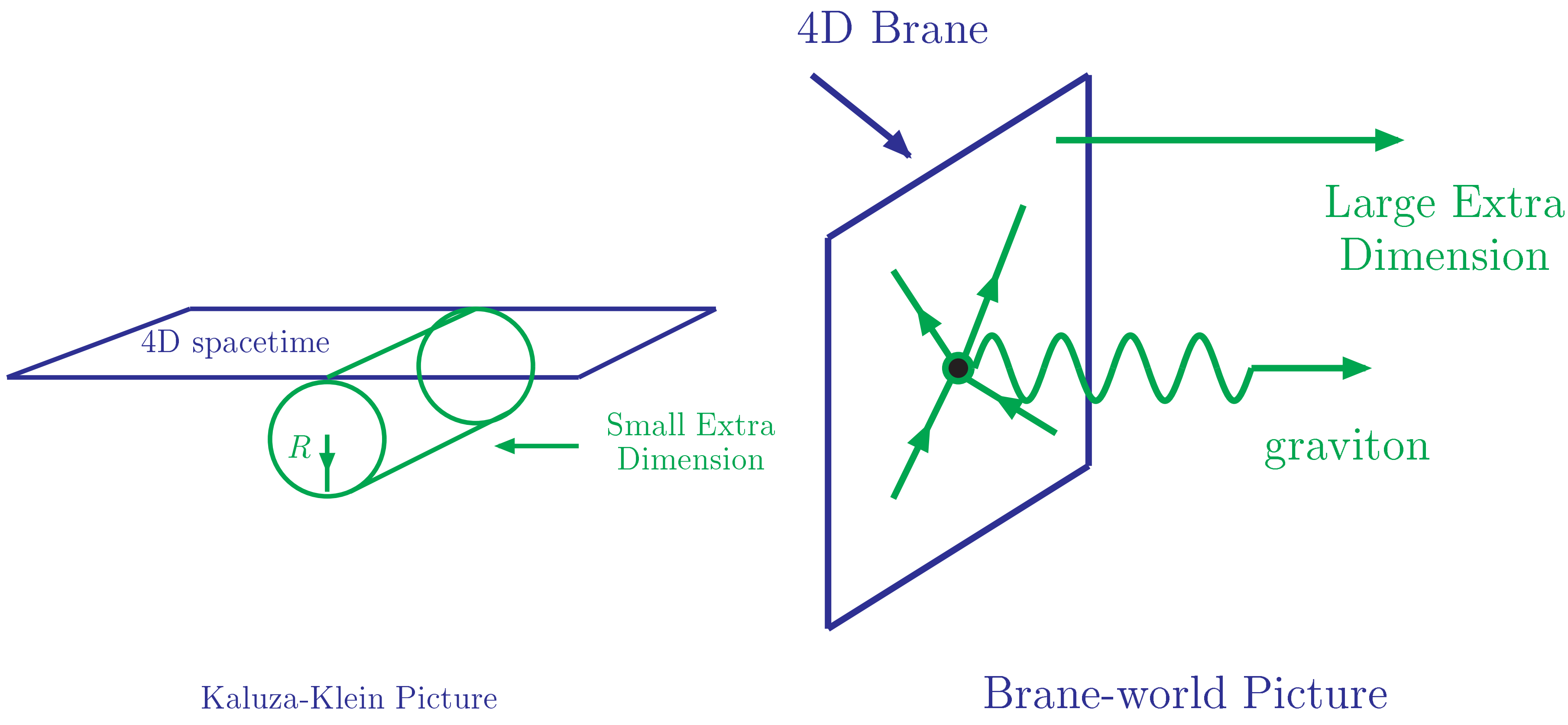
Gauge coupling unification, $M_{\mathrm{GUT}} \sim 10^{16}\ \mathrm{GeV}$

neutrino masses: see-saw scale $\sim .01$–$.1\, M_{\mathrm{GUT}}$

Models with extra dimensions of space



Hierarchy between M_{Planck} and M_{weak} is related to the volume or the geometrical structure of additional dimensions of space

$\Rightarrow$ observable effects at the TeV scale

Why extra dimensions?

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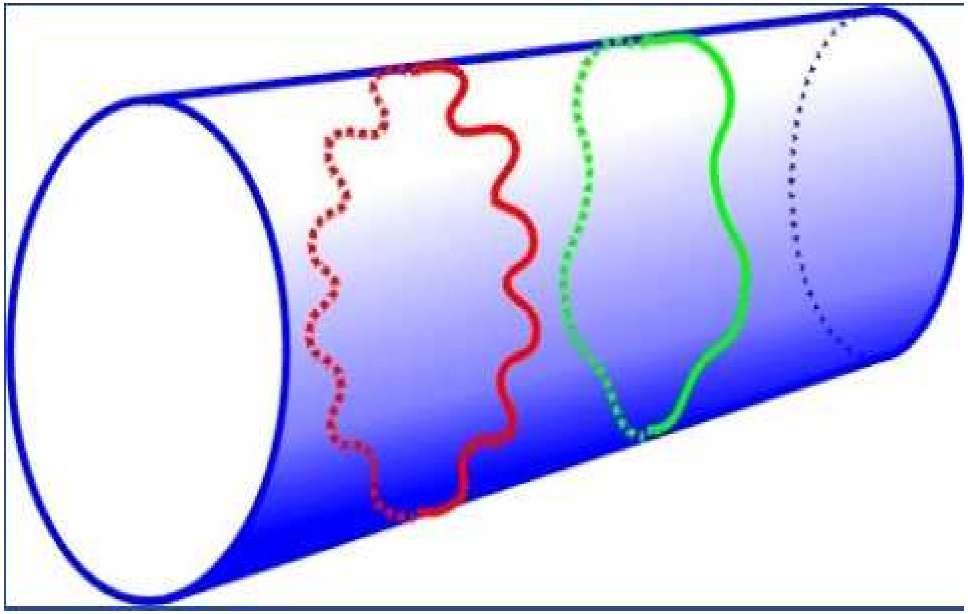
To a tightrope walker, the tightrope is one-dimensional: he can only move forward or backward

But to an ant, the rope has an extra dimension: the ant can travel around the rope as well

Phenomenological consequences of extra dimensions

The wave function of a free particle must be $2\pi R$ periodic



$$e^{ip.x_5} = e^{ip.(x_5+2\pi R)}$$

$$p = \frac{n}{R}$$

$\Rightarrow$ momentum is quantised

$\Rightarrow$ Looks in 4-dim like a series of new, more massive partners associated with each known particle: “Kaluza–Klein tower”

Phenomenological consequences of extra dimensions

We may be trapped on a $(3+1)$-dimensional brane in a higher-dimensional space-time, while gravity can enter the extra dimensions

Extra dimensions could be large, even infinite

$\Rightarrow$ Could explain the apparent weakness of gravity in our 4-dimensional world

$\Rightarrow$ At the LHC, gravitons could be emitted into the extra dimensions

$\Rightarrow$ “missing energy” signals

If gravity is strong at the TeV scale, particle collisions at the LHC may form “mini black holes”

The Institute for Particle Physics Phenomenology

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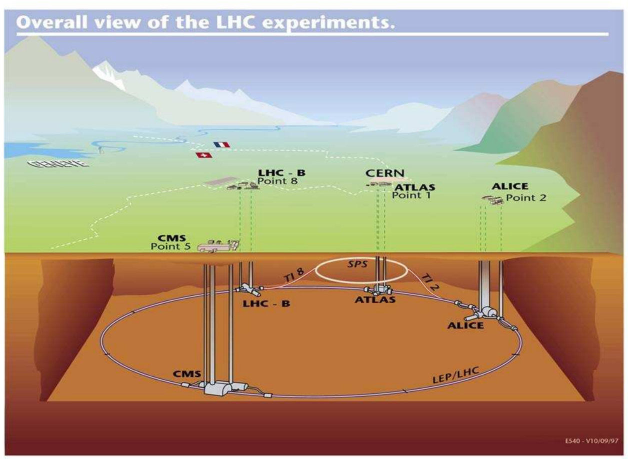
Particle Physics Phenomenology

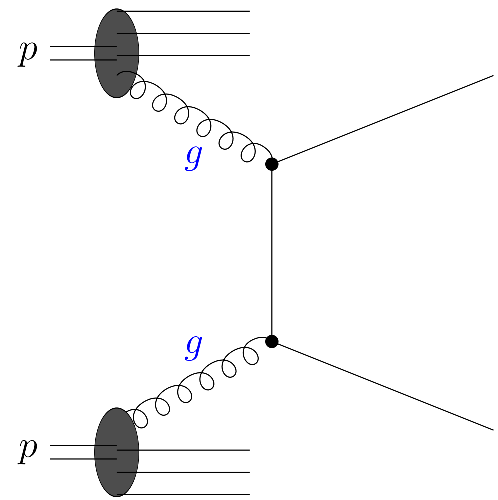
- Develop theoretical models / derive theoretical predictions that can be tested experimentally

- Identify the underlying physics from comparison of theory with experiment

The Large Hadron Collider (LHC)

Proton–proton scattering at $14\,(10)$ TeV: composite objects of quarks and gluons, bound together by strong interaction





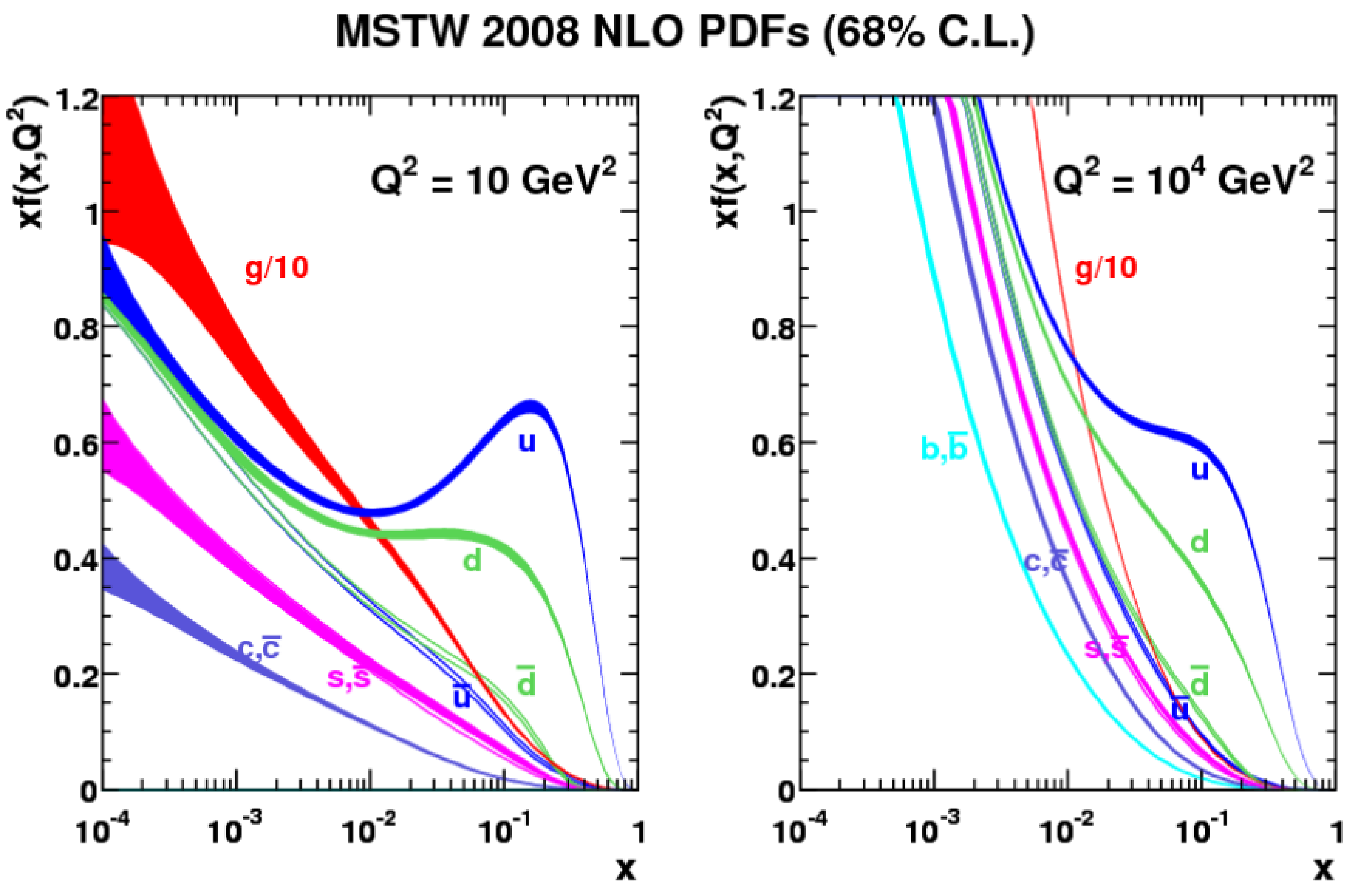
$\Rightarrow$ Opens up new energy domain

complicated scattering processes

10^9 scattering events$/s$

The quark and gluon content of the proton

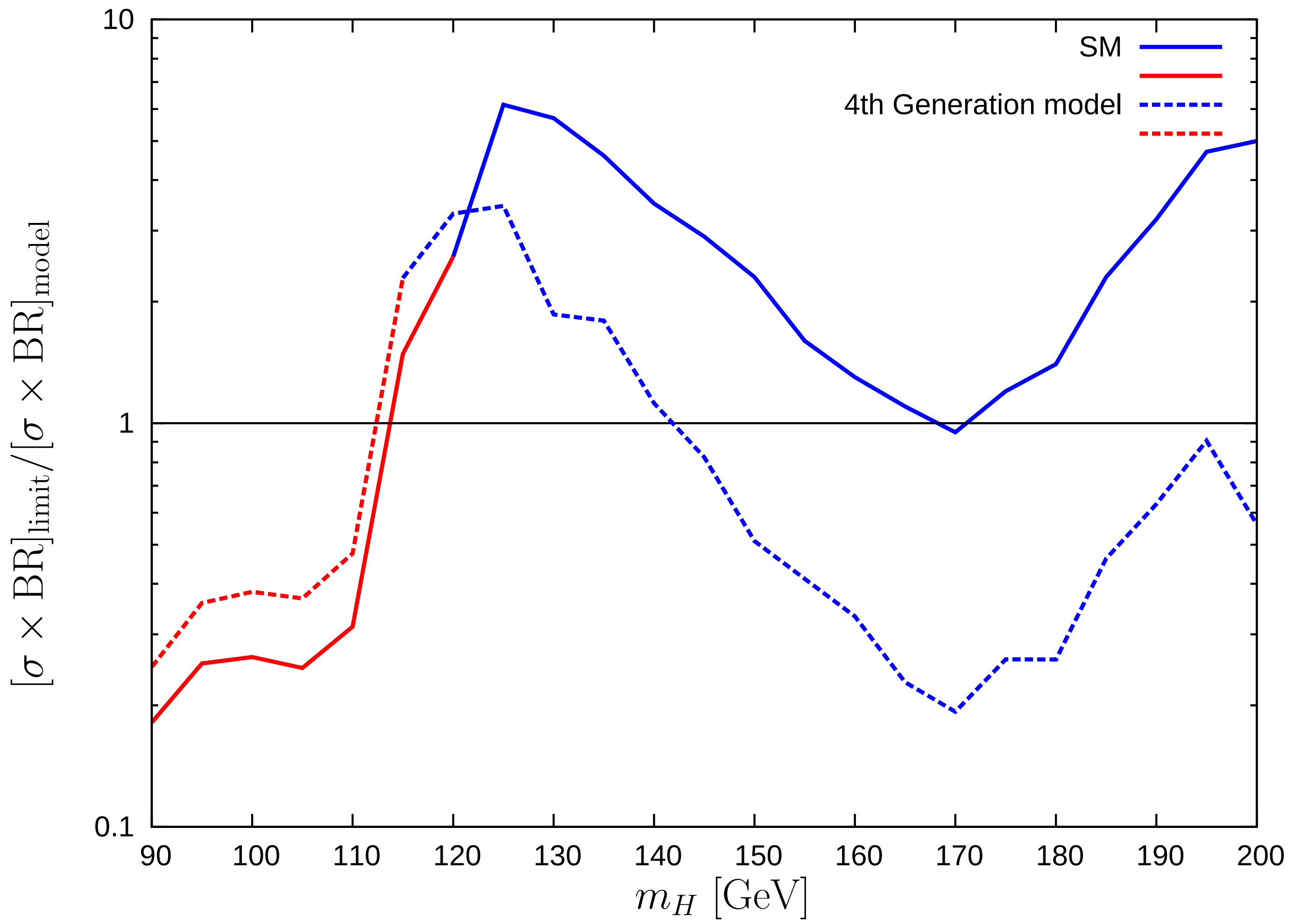
[A. Martin, W.J. Stirling, R. Thorne, G. Watt '08]



⇒ MSTW parton distribution functions

Higgs physics: current limits from LEP and Tevatron for the SM and an extension of the SM with a 4th generation

HiggsBounds [P. Bechtle, O. Brein, S. Heinemeyer, G. W., K. Williams '08]



⇒ Closing in on the Higgs

Prospects for the LHC: Information from high-precision physics

EW precision data:

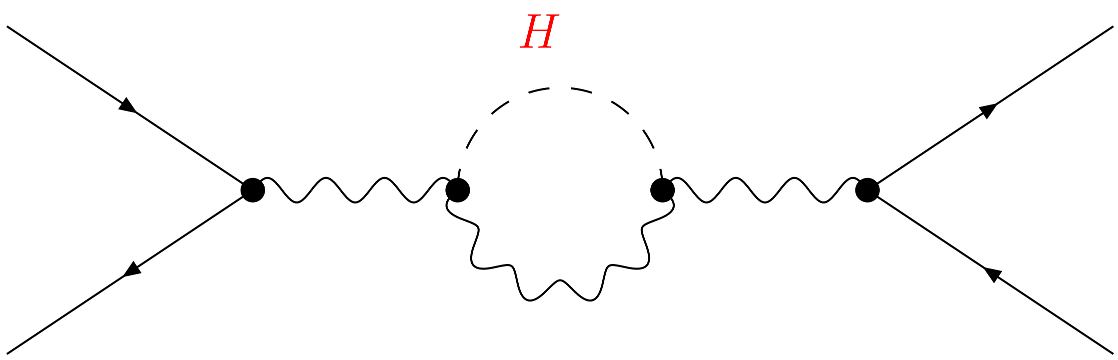
$M_Z, M_W, \sin^2\theta^{\rm lept}_{\rm eff}, \ldots$

Theory:

SM, MSSM, . . .

$\Downarrow$

Test of theory at quantum level: loop corrections



$\Downarrow$

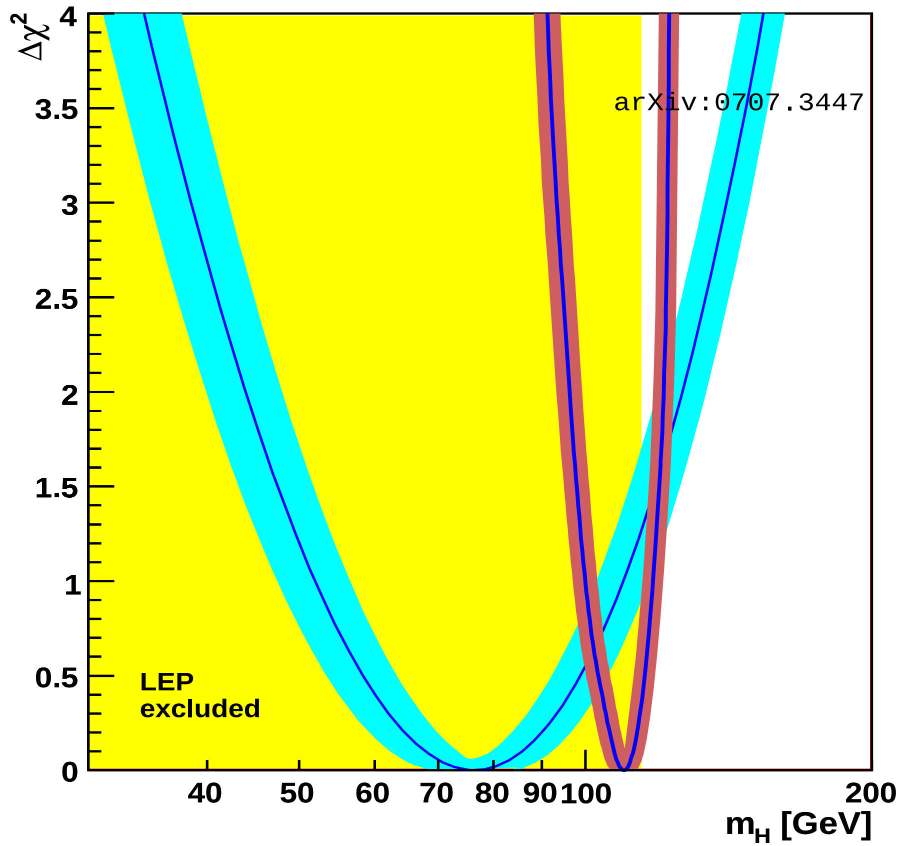
Sensitivity to effects from unknown parameters: M_H, $M_{\tilde{t}}$, . . .

Window to “new physics”

Indirect prediction for the Higgs mass in the SM and the constrained MSSM (CMSSM) from precision data

χ^2 fit for M_h, without imposing direct search limit [*O. Buchmueller, R. Cavanaugh, A. De Roeck, S. Heinemeyer, G. Isidori, P. Paradisi, F. Ronga, A. Weber, G. W. '07*]

SM CMSSM

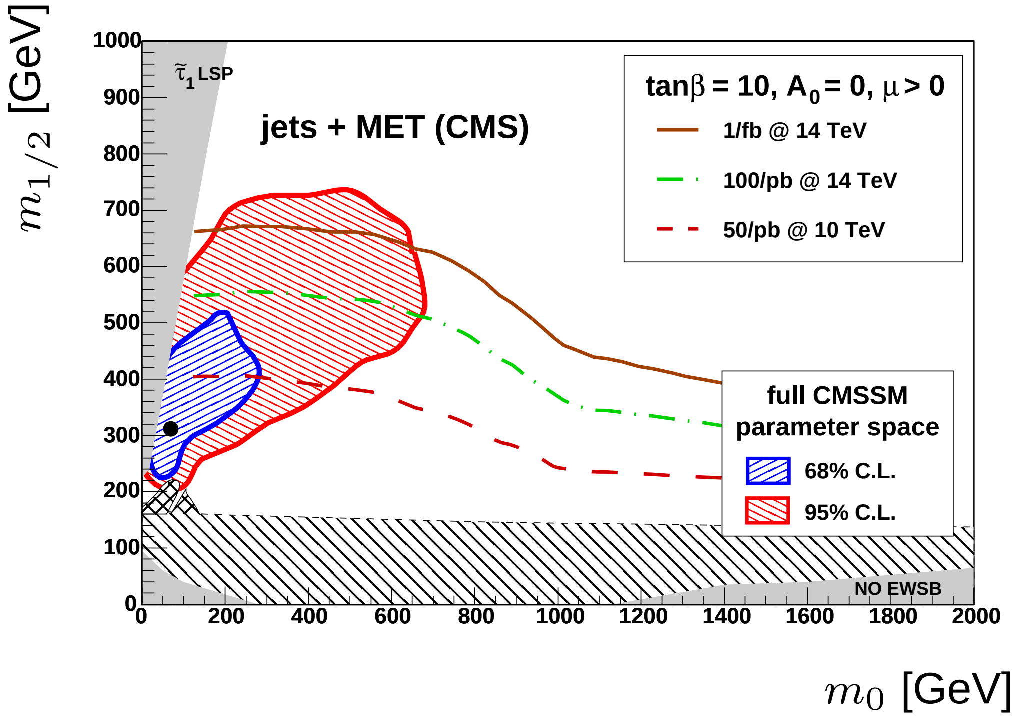


⇒ Accurate indirect prediction; Higgs "just around the corner"?

Comparison: preferred region for the SUSY mass scale vs. LHC discovery reach

68% and 95% C.L. contours from the fit vs. LHC discovery reach for $1, 0.1, 0.05\ \mathrm{fb}^{-1}$ of understood data

[*O. Buchmueller, R. Cavanaugh, A. De Roeck, J. Ellis, H. Flächer, S. Heinemeyer, G. Isidori, K. Olive, P. Paradisi, F. Ronga, G. W. '08*]



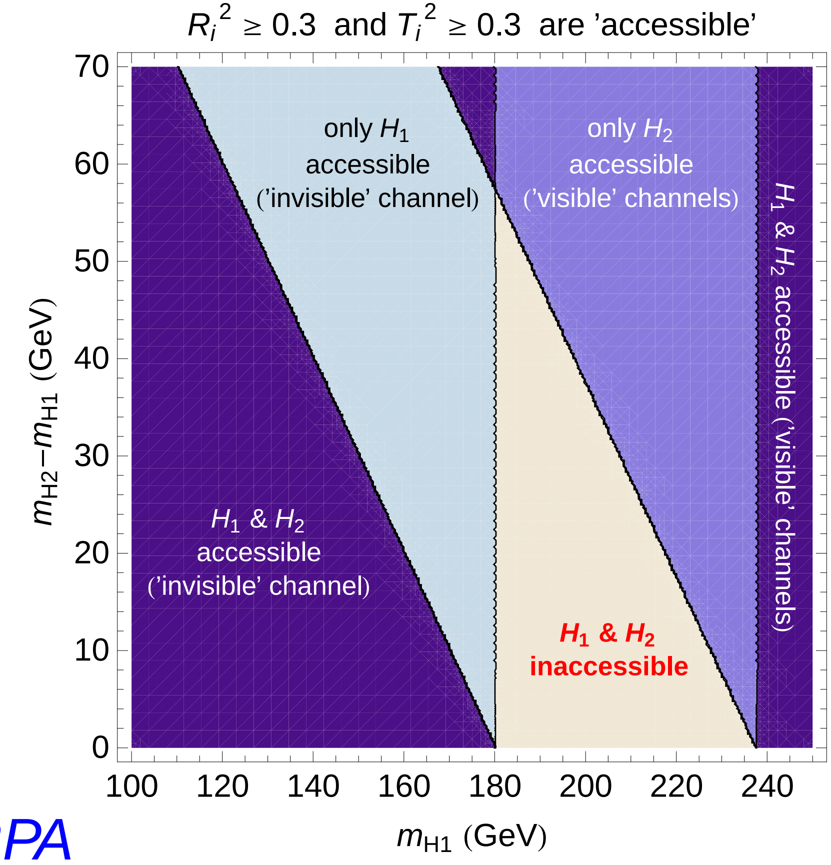
⇒ Preferred region would lead to early discovery

Invisibly decaying Higgs at the LHC

Minimal extension of SM with spontaneously broken global U(1) symmetry; yields small neutrino masses, correct baryon asymmetry [*A. Dedes, T. Figy, S. Höche, F. Krauss, T. Underwood '08*]

Mixing between SM Higgs and singlet field

⇒ predominantly invisible decays



MC simulation studies with *SHERPA*

⇒ Good prospects for ZH production and weak boson fusion

$\mathcal{CP}$ *properties of SUSY particles*

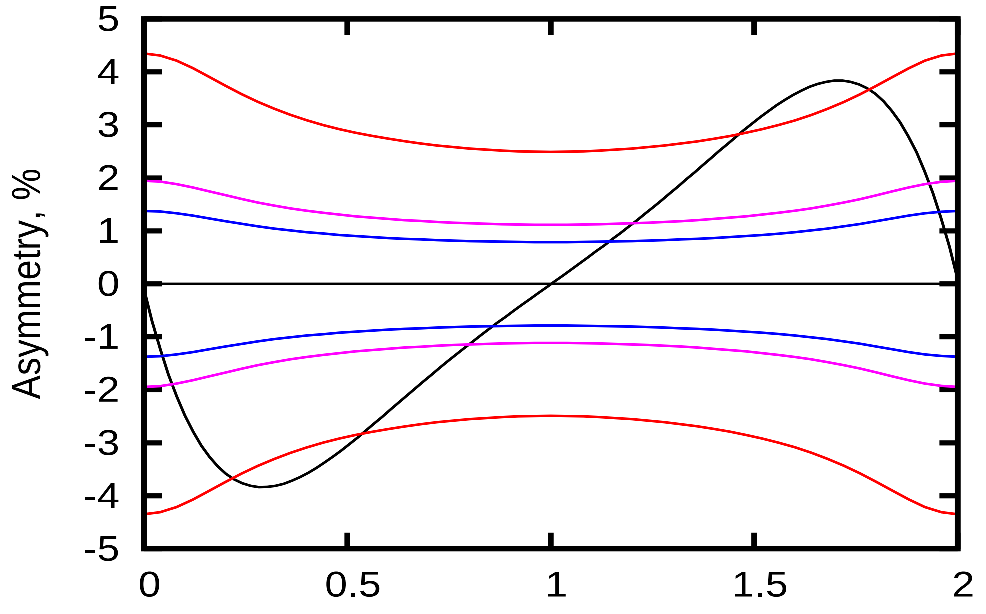
Baryon asymmetry in the Universe $\Leftrightarrow$ additional sources of $\mathcal{CP}$-violation required beyond the SM

$\Rightarrow$ It is important to test the $\mathcal{CP}$ properties of new physics

Example: scalar top production at the LHC

$gg \to \tilde{t}_i \tilde{t}_j \to \tilde{t}_i + \tilde{\chi}^0_k t \to \tilde{t}_i + \tilde{\chi}^0_1 l^+ l^- + W^+ b$

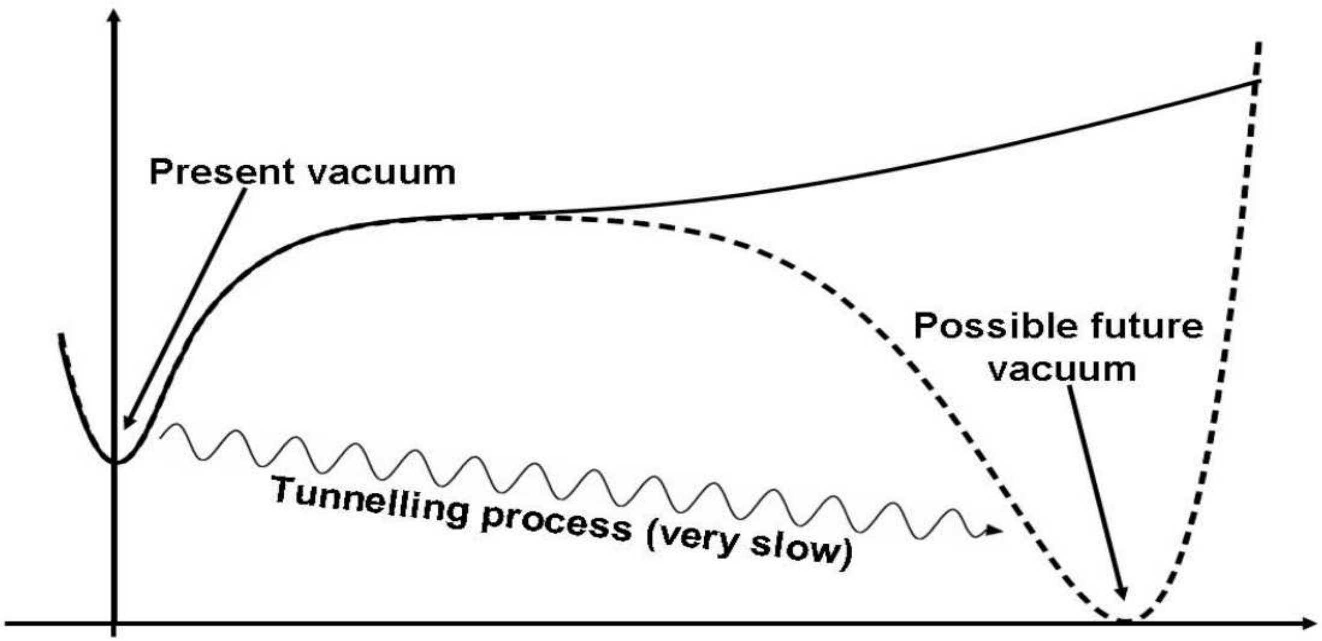
[*J. Ellis, F. Moortgat, G. Moortgat-Pick, J. Smillie, J. Tattersall '08*]



$\Rightarrow$ Need to measure $\mathcal{CP}$ asymmetries

The fate of the Universe — do we live in a meta-stable vacuum?

Detection of supersymmetric particles at the LHC could yield hints that the global minimum of the Universe has unbroken SUSY, while we currently live in a meta-stable vacuum that breaks SUSY [*S. Abel, C. Durnford, J. Ellis, J. Jaeckel, V.V. Khoze*]



Meta-stable SUSY-breaking vacua are "generic" in local SUSY / string theory, can have cosmologically long life times

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Looking forward to very exciting times
for particle physics phenomenology!