Title: The Higgs as a portal to New Physics

Date: Apr 01, 2015 11:00 AM

URL: http://pirsa.org/15030126

Abstract: <p>The discovery of the Higgs boson at the Large Hadron Collider marks the culmination of a decades-long hunt for the last ingredient of the Standard Model. At the same time, this discovery has started a new era in the search for more fundamental physics. In this talk, I will discuss what we have learned from the Higgs discovery about the mechanism of electroweak symmetry breaking and the implications for the existence of additional Higgs bosons. I will then highlight the future prospects of the Higgs boson in shedding light on New Physics and in particular on the nature of Dark Matter.</p>

# The Higgs as a portal to New Physics

Stefania Gori
Perimeter Institute for Theoretical Physics

**Perimeter Institute**
Colloquium

Waterloo,
April 1st 2015

# Discovery!

The first elementary particle discovery of 21st century


CERN, July 4th 2012, ~11am

After ~30 years of experimental searches
(LEP, SLC, Tevatron, LHC)

# Discovery!

The first elementary particle discovery of 21st century

~6000 experimentalists involved

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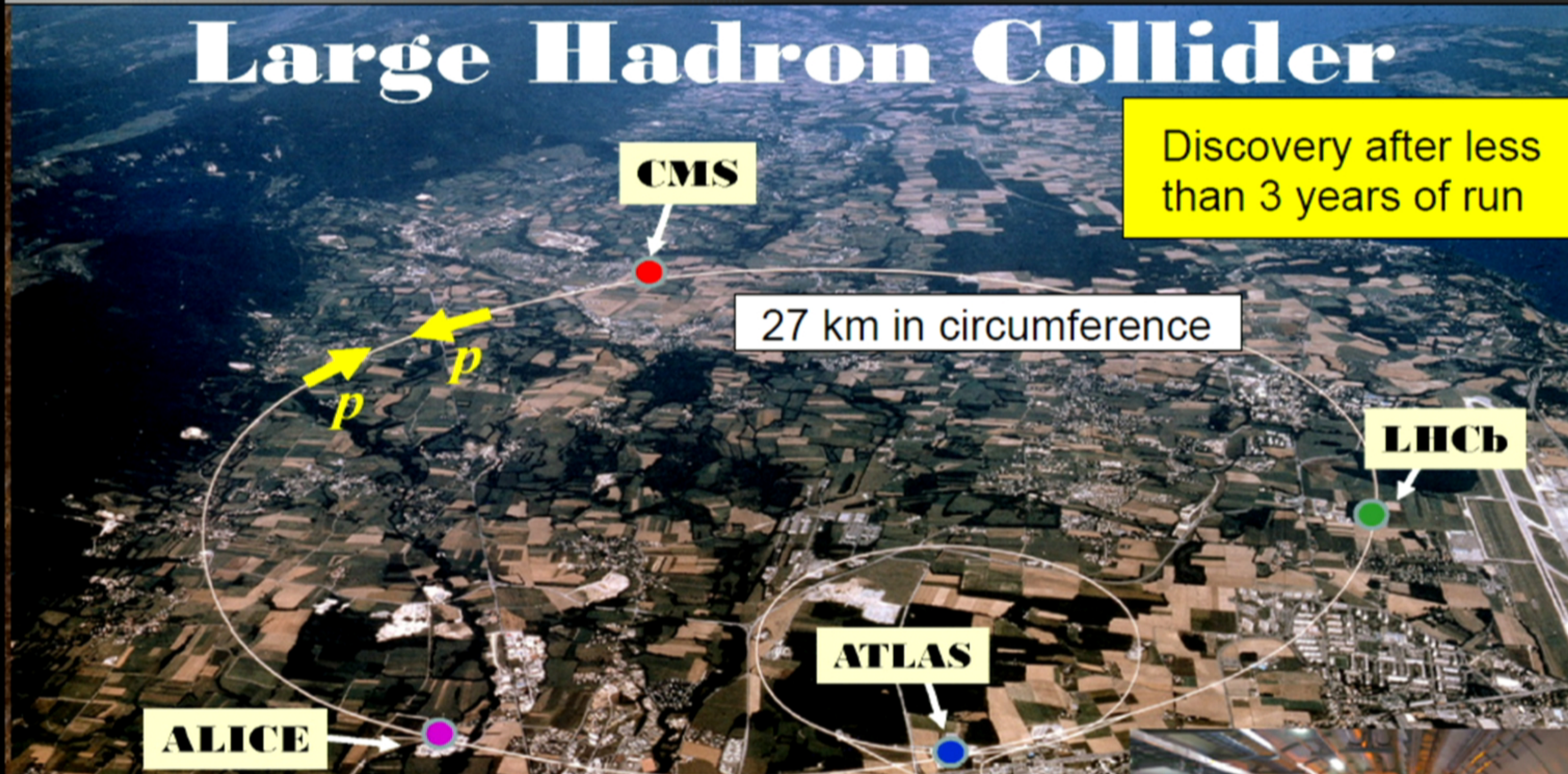
# What lead to the discovery?

## Large Hadron Collider




- Protons collide at 99.9999991% of the speed of light
- At 14 TeV, each of the two proton beams will have a energy equivalent to a 400 t train travelling at 100 mi/h
- Superconductive electromagnets chilled at a temperature of 1.9°K: colder than deep outer space (2.7°K)

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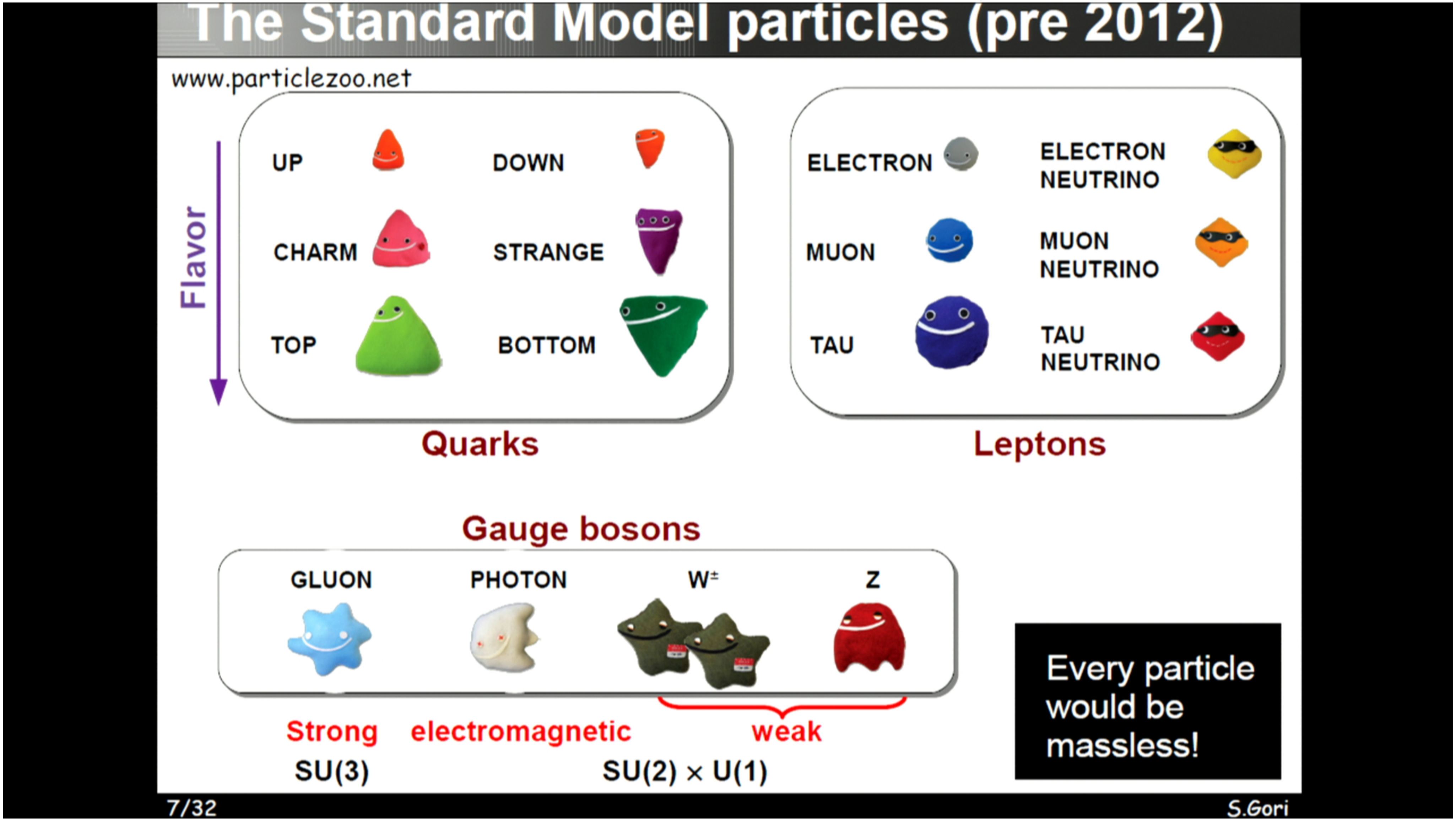
# Still many big questions in particle physics

- Particle content of the Standard Model ✓ **PART I.**
- Hierarchy problem ✗
- Dark matter ✗
- Flavor problem ✗
- Matter-antimatter asymmetry ✗
- Neutrino masses ✗
- Dark energy ✗
- ...

# PART I

1. Self-consistency
   of the Standard Model (SM)


The Standard Model particles (pre 2012)
www.particlezoo.net
Flavor
UP
DOWN
CHARM
STRANGE
TOP
BOTTOM
Quarks
ELECTRON
ELECTRON NEUTRINO
MUON
MUON NEUTRINO
TAU
TAU NEUTRINO
Leptons
Gauge bosons
GLUON
PHOTON
W±
Z
Strong
electromagnetic
weak
SU(3)
SU(2) × U(1)
Every particle would be massless!
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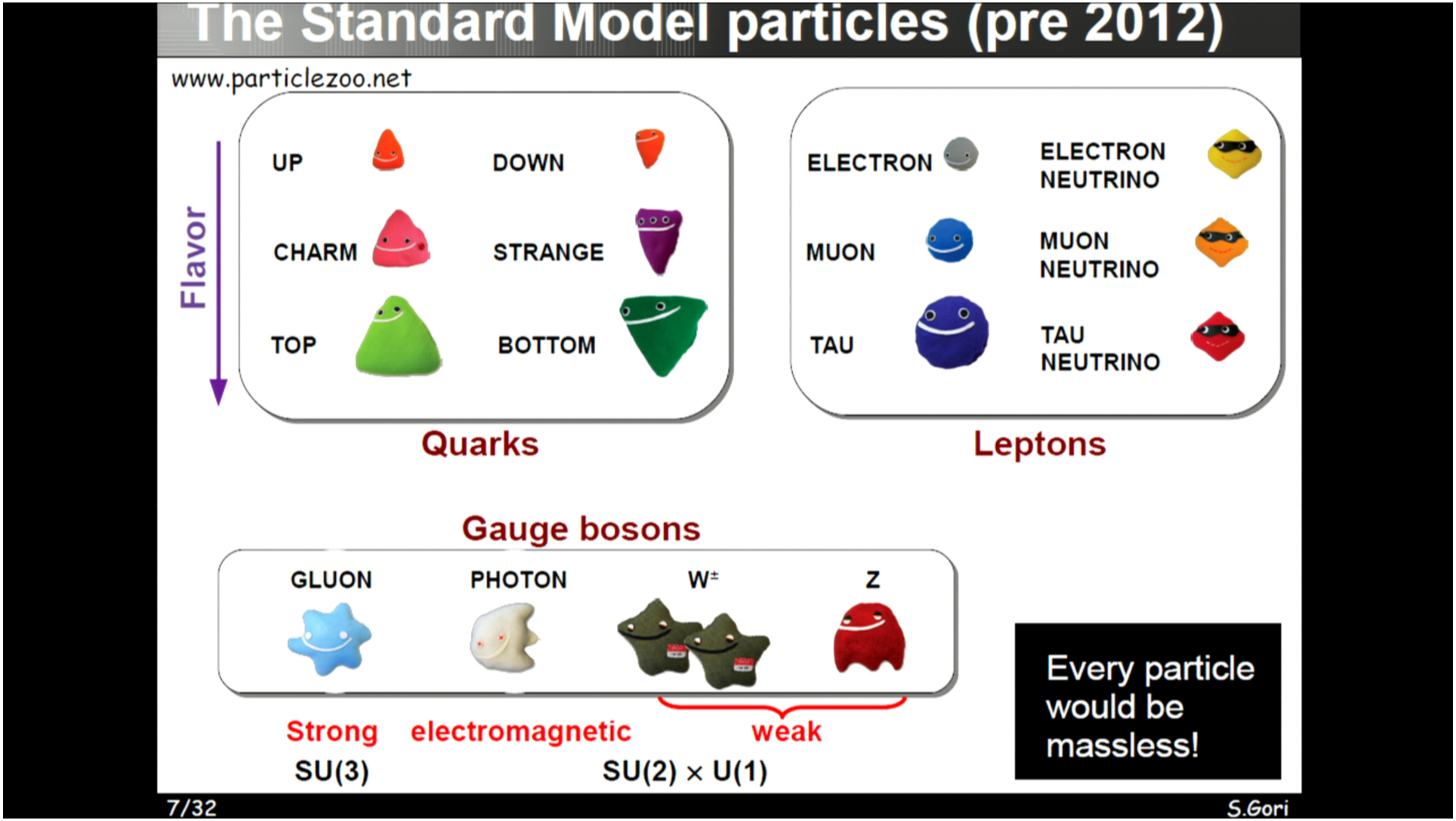
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7/32
S.Gori

# Testing the Electroweak Theory

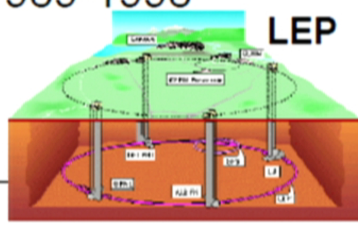

## Discovery

- Hint for the existence of the Z boson at Gargamelle bubble chamber, at CERN in 1973.
- Discovery of Z and W bosons at Super Proton Synchrotron, at CERN in 1983.

## Precision measurements

Z boson properties at the

- Large Electron–Positron Collider at CERN in 1989-2000
- Stanford Linear Collider in 1989-1998



LEP


**Experiments**

Z properties depend on the Higgs mass

**Standard Model Prediction**

# The Higgs mass in the Standard Model

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John Ellis, Mary K. Gaillard *) and D.V. Nanopoulos +)

CERN -- Geneva

Nucl. Phys. B 106, 292 (1976)

We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3),4)] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

We need to measure the Higgs mass!

# Higgs: not the easiest search

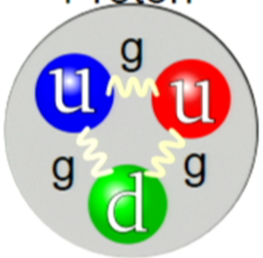
The production of the Higgs is a relatively rare event at the LHC

Motivation:

Higgs couplings $\propto$ particle mass
and the constituents of the protons are pretty light!

Primary reason for which the Higgs boson
has not been discovered long ago

Proton



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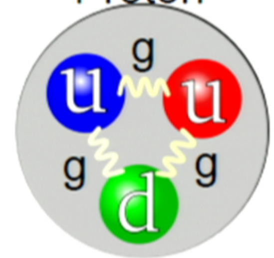
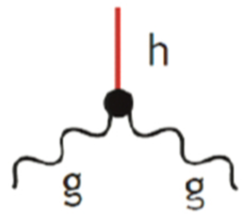
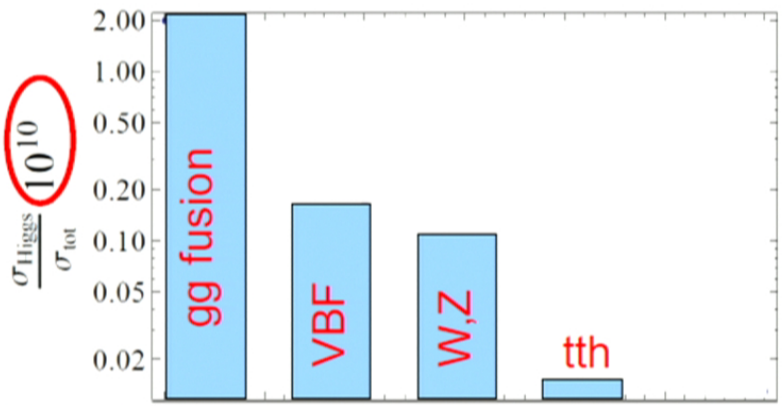



Gluons can react through the higher-order ggh coupling to produce the Higgs boson.

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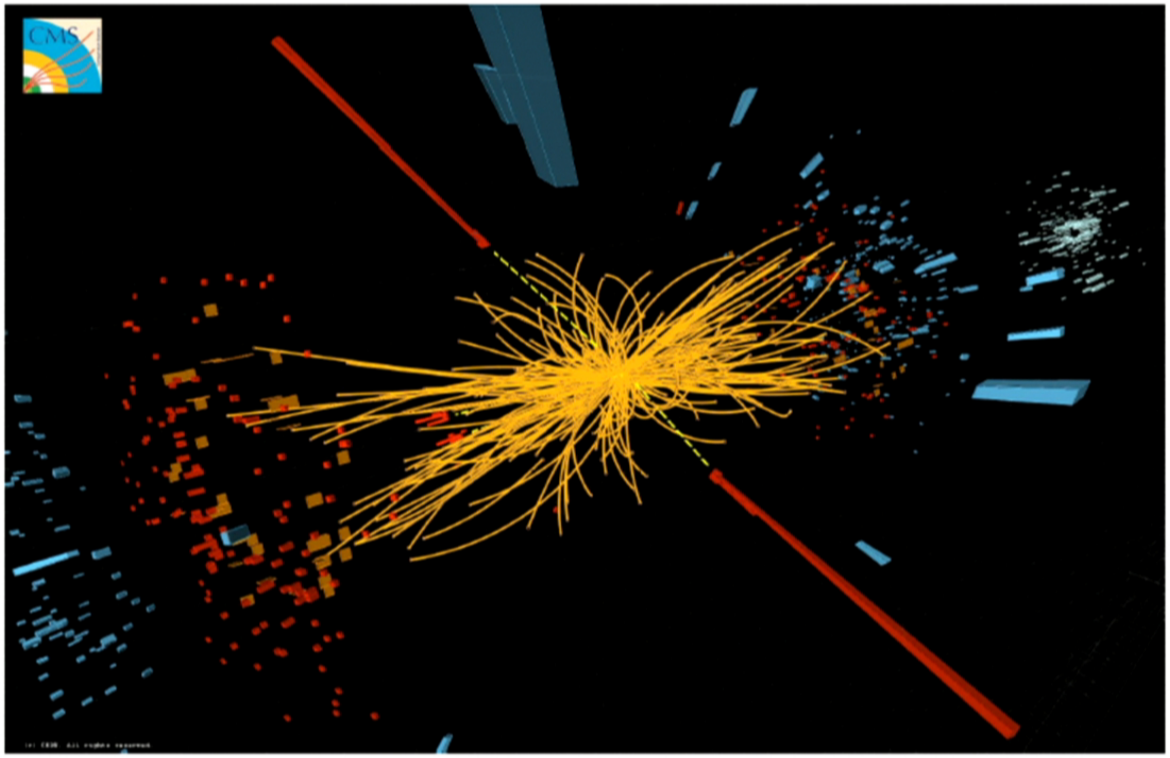
# What do we see?

The Higgs decays in $10^{-22}$ s



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# Self-consistency!

Higgs mass
Z properties

If the Higgs is the one of the SM...

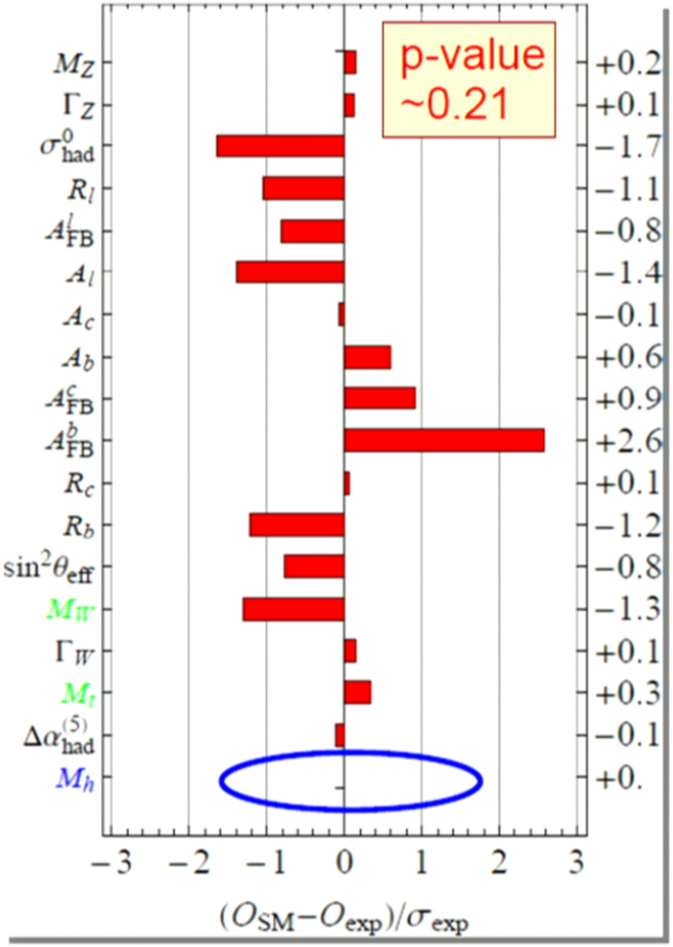
For the first time we have
the measurement of
a self-consistent electro-weak sector

Batell, SG, Wang, 1209.6382

It would not be the case if
the Higgs was heavier:

eg. $M_h$ = 300 GeV ⇒ $p_{value} \sim 3 \times 10^{-5}$

Result of decades of
experimental & theory efforts





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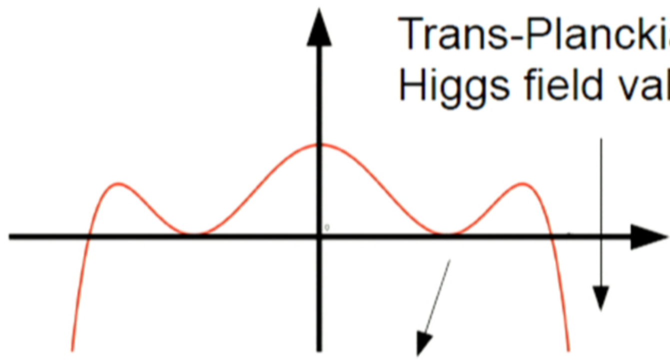
# The stability of our Universe

$M_h$: just one number and yet …

If the SM is the full story:



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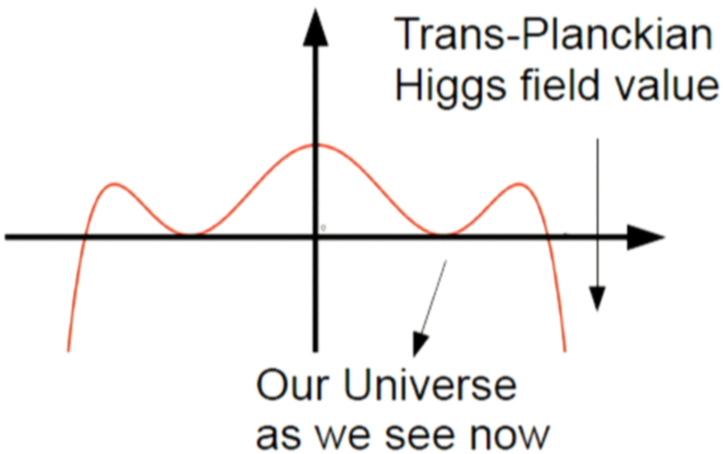
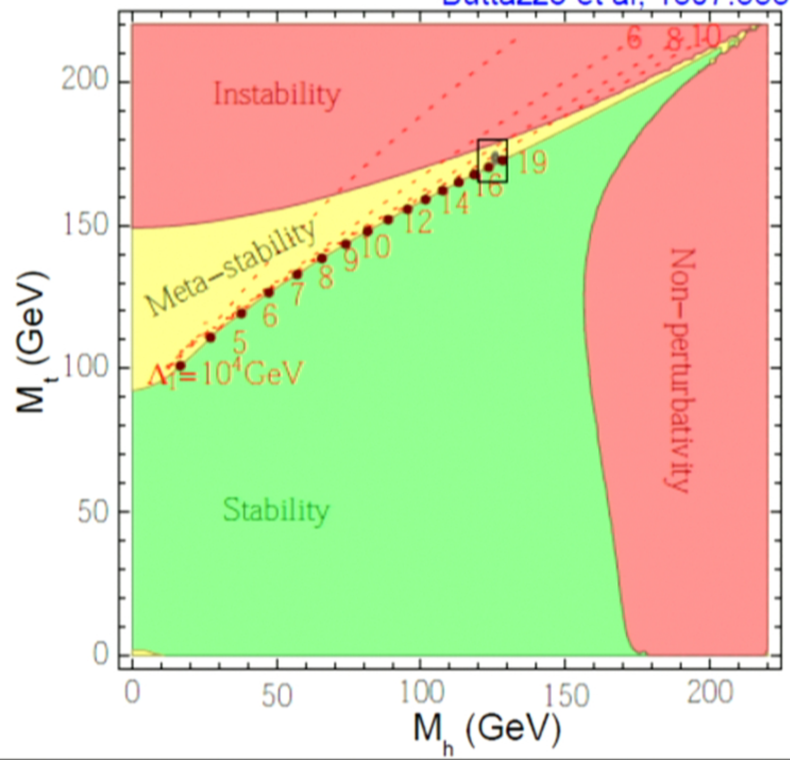


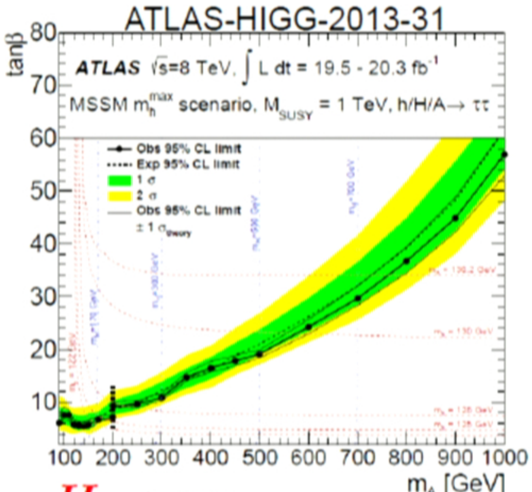

The Universe
on a "knife-edge"

Buttazzo et al, 1307.3536

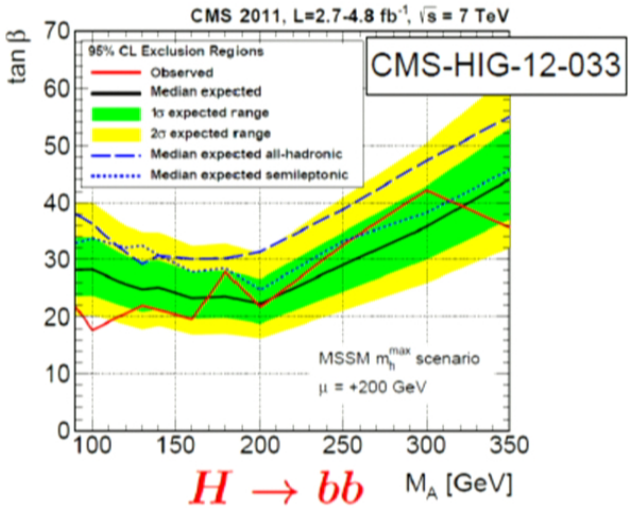


# A full picture for EW symmetry breaking?

Neutral Higgs bosons




$H \to \tau\tau$




$H \to bb$

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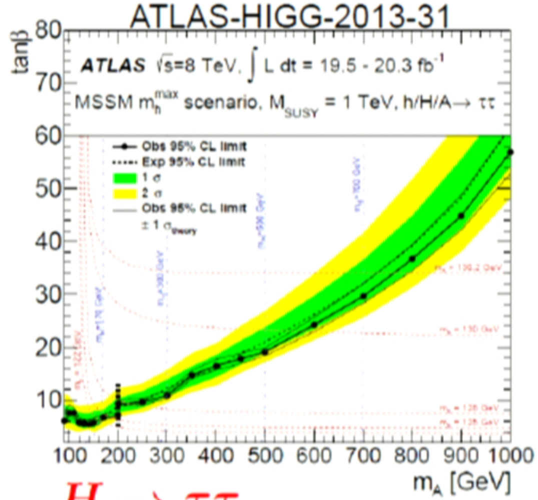
Neutral Higgs bosons

ATLAS-HIGG-2013-31

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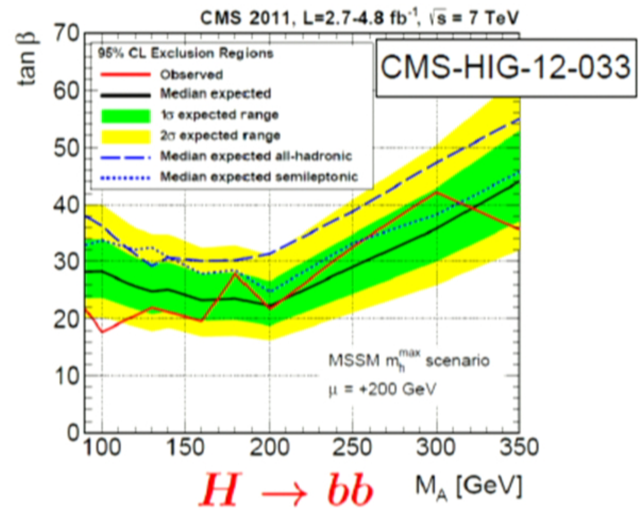
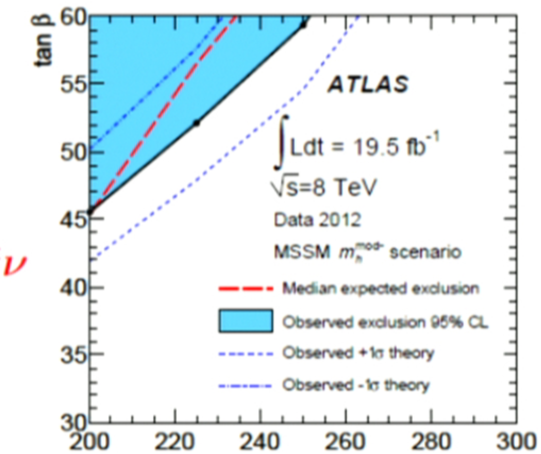



$H \to bb$

Carena, SG, Juste, Menon, Wagner, Wang, 1203.1041

Charged Higgs bosons

$H^{\pm} \to \tau^{\pm}\nu$




ATLAS-HIGG-2013-30

**Theorists:**

More searches to propose to Experimentalists! And more theories to test

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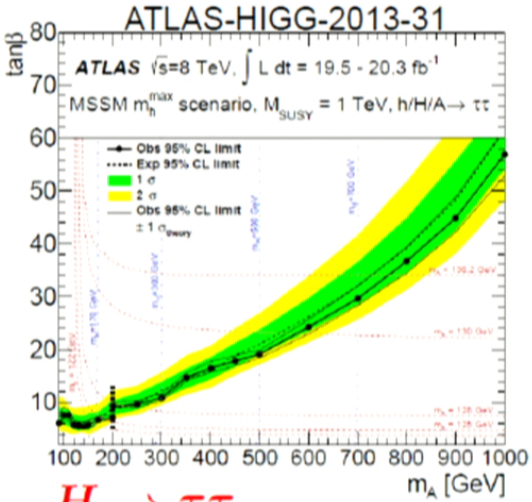
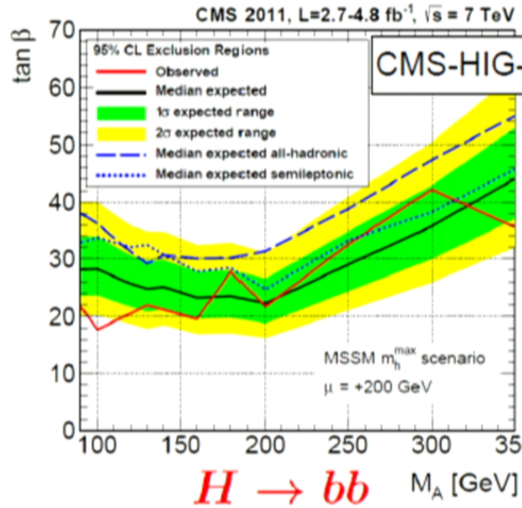
Neutral Higgs bosons

ATLAS-HIGG-2013-31




$H \to \tau\tau$

CMS-HIG-12-033

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Carena, SG, Juste, Menon, Wagner, Wang, 1203.1041

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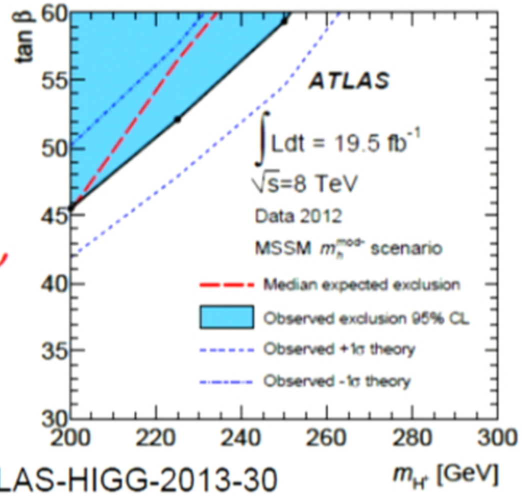


ATLAS-HIGG-2013-30

**Theorists:**

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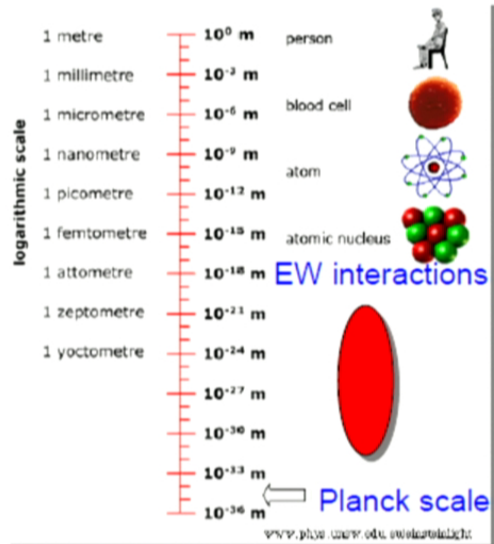
# 1. The hierarchy problem

With the <u>Higgs discovery</u>,
the SM is <u>more puzzling</u> than ever




Gravity << Electroweak interactions

The electric force between two electrons
is $\sim 10^{43}$ times larger than
their gravitational interaction!

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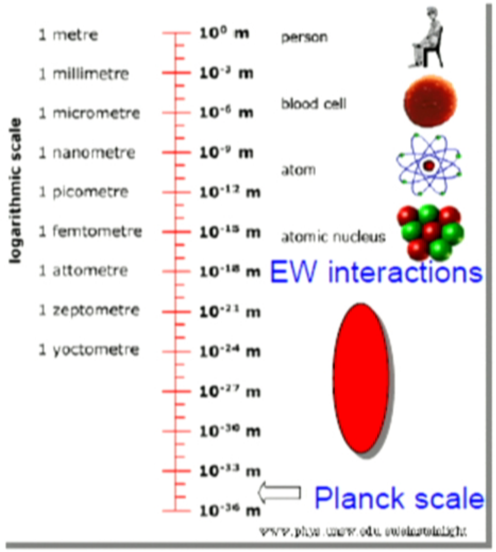


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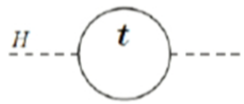
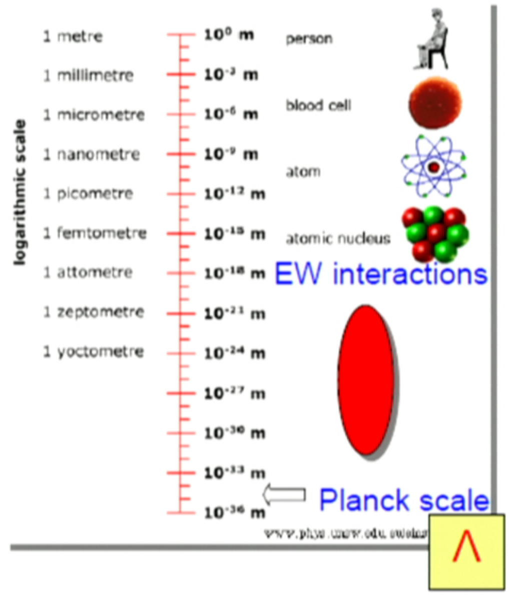
$$m_h^2 \sim \mu^2 + c\,\Lambda^2,\;\; c = \mathcal{O}(0.01)$$

$$V(H) = -(\mu^2 + c\,\Lambda^2)H^\dagger H + \lambda(H^\dagger H)^2$$




What is $\Lambda$?

- Some fundamental scale beyond the Standard Model. Ex. $\Lambda \approx M_{Pl} = 10^{19}$ GeV

# Global symmetries & the hierarchy problem

- An extension of space-time symmetry:

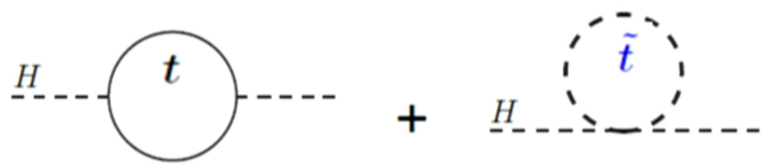
Supersymmetry: (SUSY) $|\text{boson}\rangle \Leftrightarrow |\text{fermion}\rangle$

More particles!

Theorists love symmetries ...

Quadratic dependence on the cutoff is canceled:

$$m_h^2 = \mu^2 + m_{\text{SUSY}}^2 \left( \frac{y_t^2}{8\pi^2} \log\left( \frac{\Lambda}{m_{\text{SUSY}}} \right) + \cdots \right)$$




**Generically,**
**Fine-tuning is smaller for smaller values of $m_{\text{SUSY}}$** (~TeV scale?)

The argument holds also for other theories based on global symmetries. Eg. Twin Higgs models

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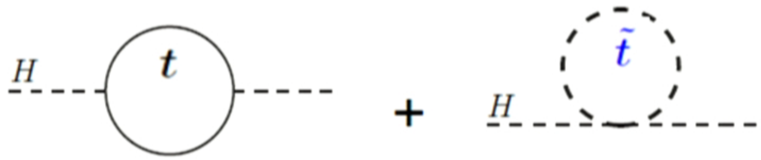


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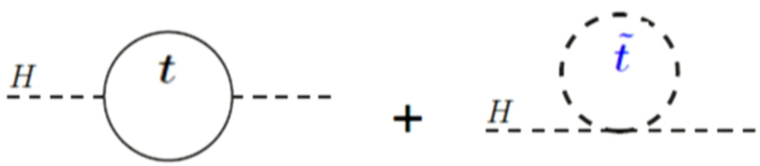


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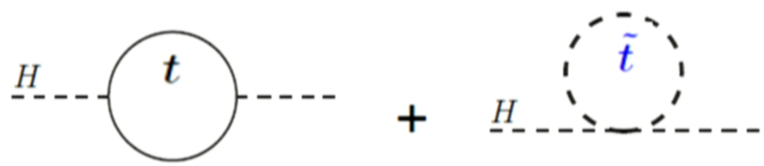


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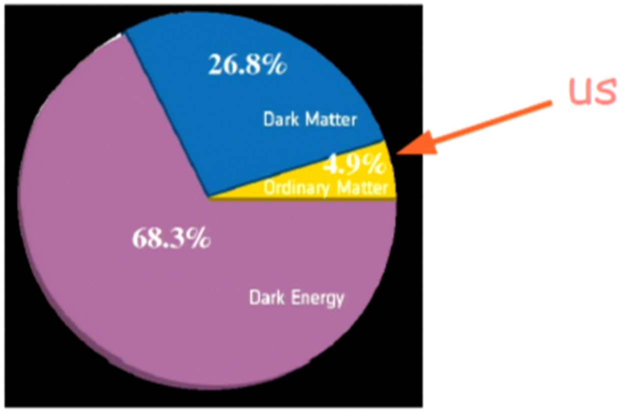
# 2. "Observational" problem: Dark Matter




Plenty of evidence for the existence of a new form of matter: Dark Matter (DM)

(Galactic Rotation Curves, Galaxy Clusters, Cosmic Microwave Background, Bullet Cluster, Large-Scale Structure Formation, ...)

No particle of the Standard Model can be Dark Matter

# To summarize...

We have two deep problems in fundamental particle physics

Theoretical:
The hierarchy problem

Observational:
The Dark Matter problem

Both of them might be telling us that we have more particles at around the electroweak scale

How do we see these particles?

The Higgs is at the electroweak scale:
It might be The Key to open the door to our understanding ...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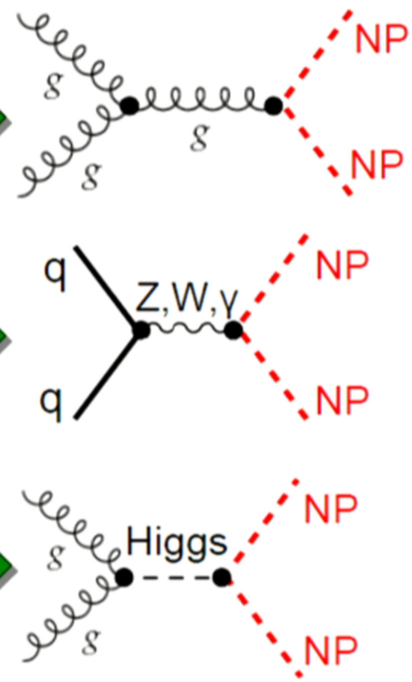
# LHC produces them!

**Gauge group**

More difficult

**Number of events @ LHC up to now**

| Gauge group | | $M_{NP}$ = 200 GeV | 400 GeV |
|---|---|---|---|
| Charged under strong interactions (SU(3)) | | ~500K | ~10K |
| Charged under electroweak interactions (SU(2) × U(1)) | | ~200 | ~10 |
| Not charged | | <1 | <1 |




100 GeV | 500 GeV | 1000 GeV — **Mass of the NP particle**

# LHC produces them!

Gauge group

More difficult

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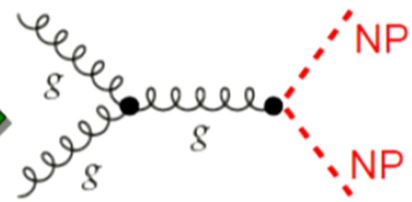


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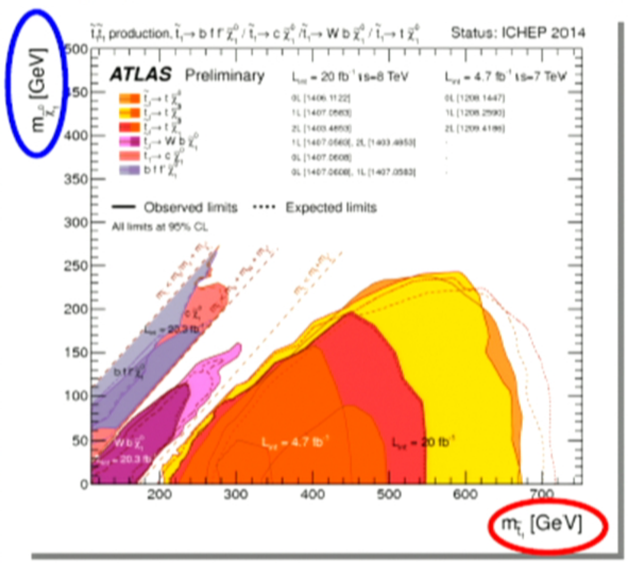
~500K

~10K

"Stop quark" (addresses the hierarchy problem): $\tilde{t} \to \mathrm{LSP}\ \mathrm{SM}$, **LSP** = lightest SUSY particle



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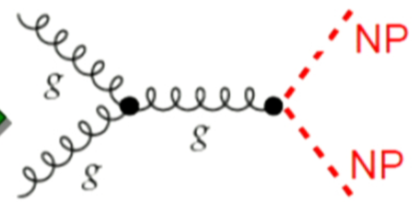


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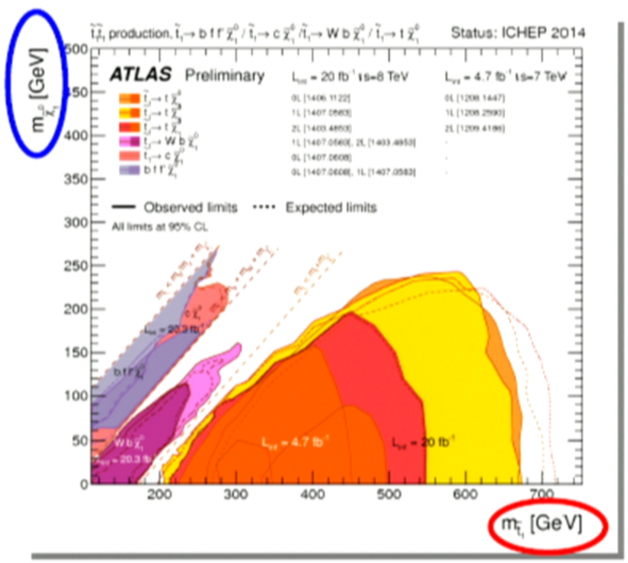


Caveat: 100% branching ratios.

The bound will be weaker in theories with "more complicated" decay modes

- Ex. $\tilde{t} \to \tilde{\tau}\nu b$ Carena, SG, Shah, Wagner, Wang, 1303.4414
- R-parity violation

Role of the theorists in the LHC era: improve on the coverage, identifying new characteristic signatures of NP particles

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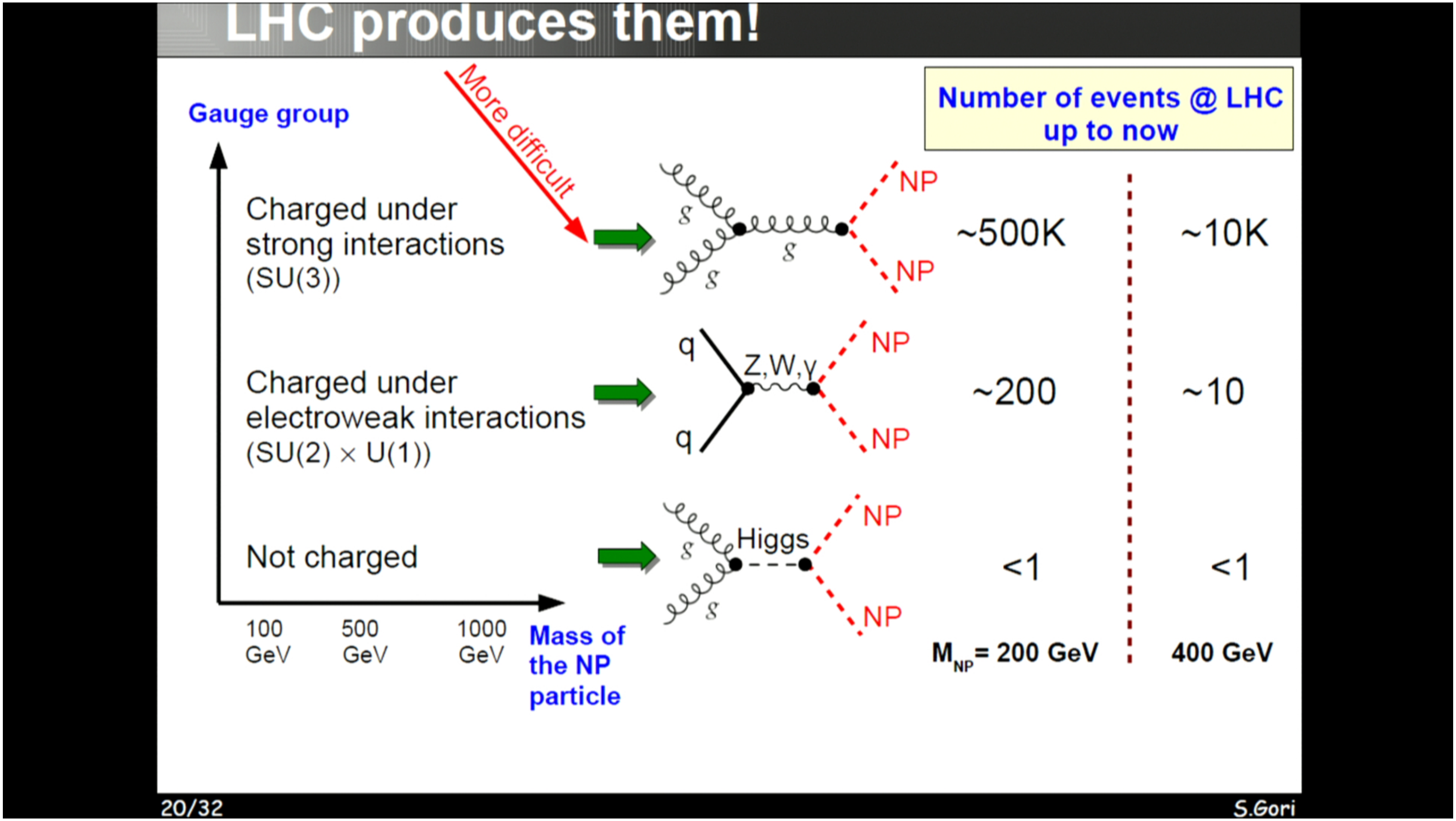
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g
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NP
~500K
~10K
Charged under electroweak interactions (SU(2) × U(1))
q
q
Z,W,γ
NP
NP
~200
~10
Not charged
g
g
Higgs
NP
NP
<1
<1
100 GeV
500 GeV
1000 GeV
Mass of the NP particle
M_NP = 200 GeV
400 GeV
20/32
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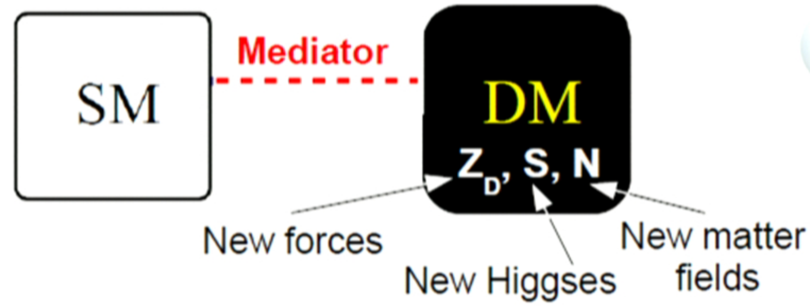
# The most hidden New Physics particles

**Not charged**





## Why are these particle of so central interest?

- Framework used for Dark Matter model building
- Some theories addressing the hierarchy problem have singlet particles (eg. Twin Higgs models)

## How do these particles interact with us?

Thanks to (a few) renormalizable "portals":

$$Z_{\mu\nu} Z_D^{\mu\nu},\ |H|^2 |S|^2,\ H L N$$



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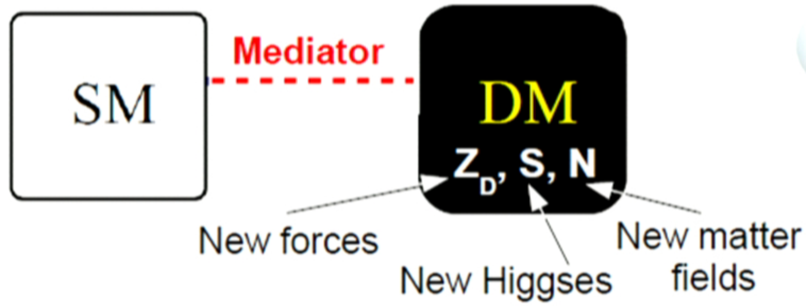



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# The most hidden New Physics particles

**Not charged**

SM — Mediator — DM

$Z_D$, S, N

New forces

New Higgses

New matter fields


The Higgs offers a unique opportunity to probe these new particles!

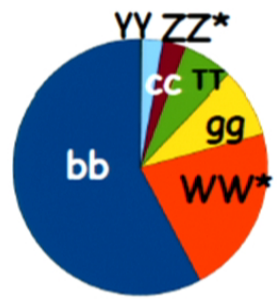
Completely new decay modes of the Higgs

$Z_{\mu\nu} Z_D^{\mu\nu}$ ⇨ $H \to Z Z_D$ ($Z_D$= Dark photon)

$|H|^2 |S|^2$ ⇨ $H \to ss$

$HLN$ ⇨ $H \to LN$

SM:




Almost no searches in the first three years of the LHC!

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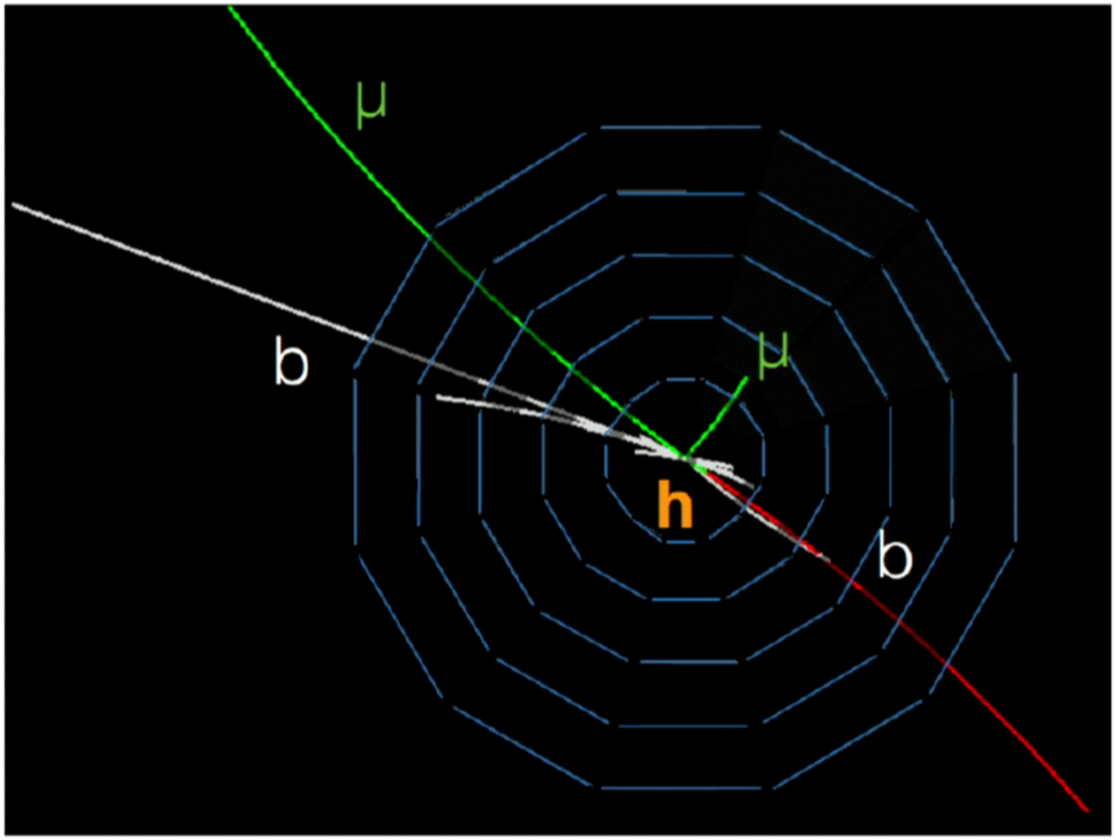
# New events to be seen





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# PART III

3. Indirect searches
for new particles

# A bit of history...

Historically,
several measurements of rare processes
led to the indirect discovery of new particles

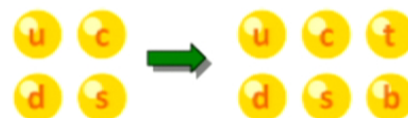
e.g.

- Measurement of the tiny branching ratio of the decay $K_L \to \mu^+\mu^-$

  ➡ prediction of the charm quark to suppress the process
  (Glashow, Iliopoulos, Maiani, 1970)


- Observation of CP violation in kaon anti-kaon oscillations

  ➡ prediction of the 3rd generation of quarks
  (Kobayashi, Maskawa, 1973)



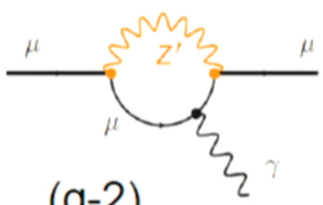

Kaon

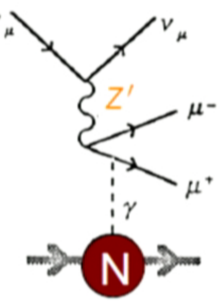
# Discovery potential of indirect searches

## High intensity experiments

- $(g\text{-}2)_\mu$ experiment at Fermilab
- Neutrino facilities
- B-factories/LHCb
- ...

Great potential
to discover new forces of nature




$$\nu_\mu N \to \nu_\mu N \mu^+ \mu^-$$

New measurement
proposed for
neutrino near detectors
(@ MINOS+, LBNF, ...)

Altmannshofer, SG, Pospelov, Yavin, 1406.2332

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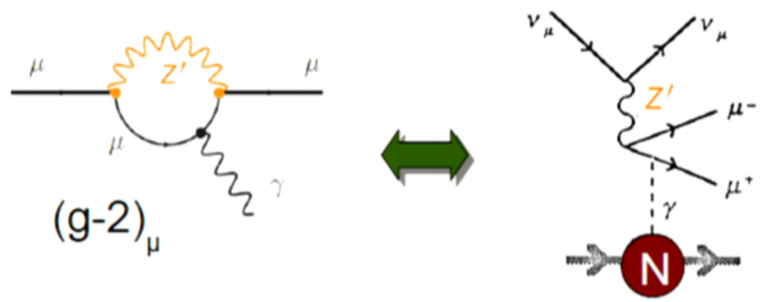


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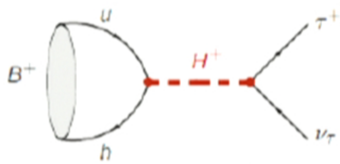
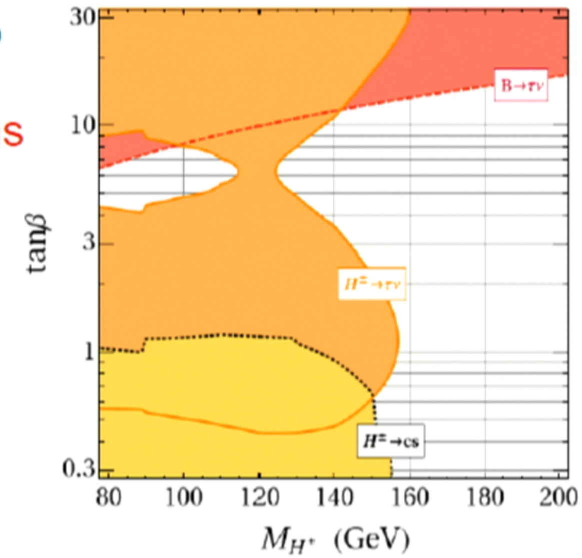



$B^\pm \to \tau^\pm \nu$

Altmannshofer, SG, Kribs, 1210.2465



# Discovery potential of indirect searches

## High intensity experiments

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- Neutrino facilities
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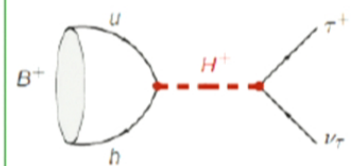
- ...

Great potential to discover new Higgs bosons

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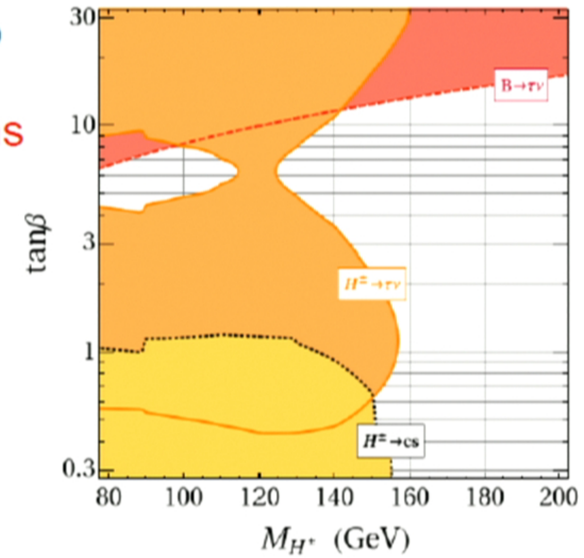
Altmannshofer, SG, Kribs, 1210.2465

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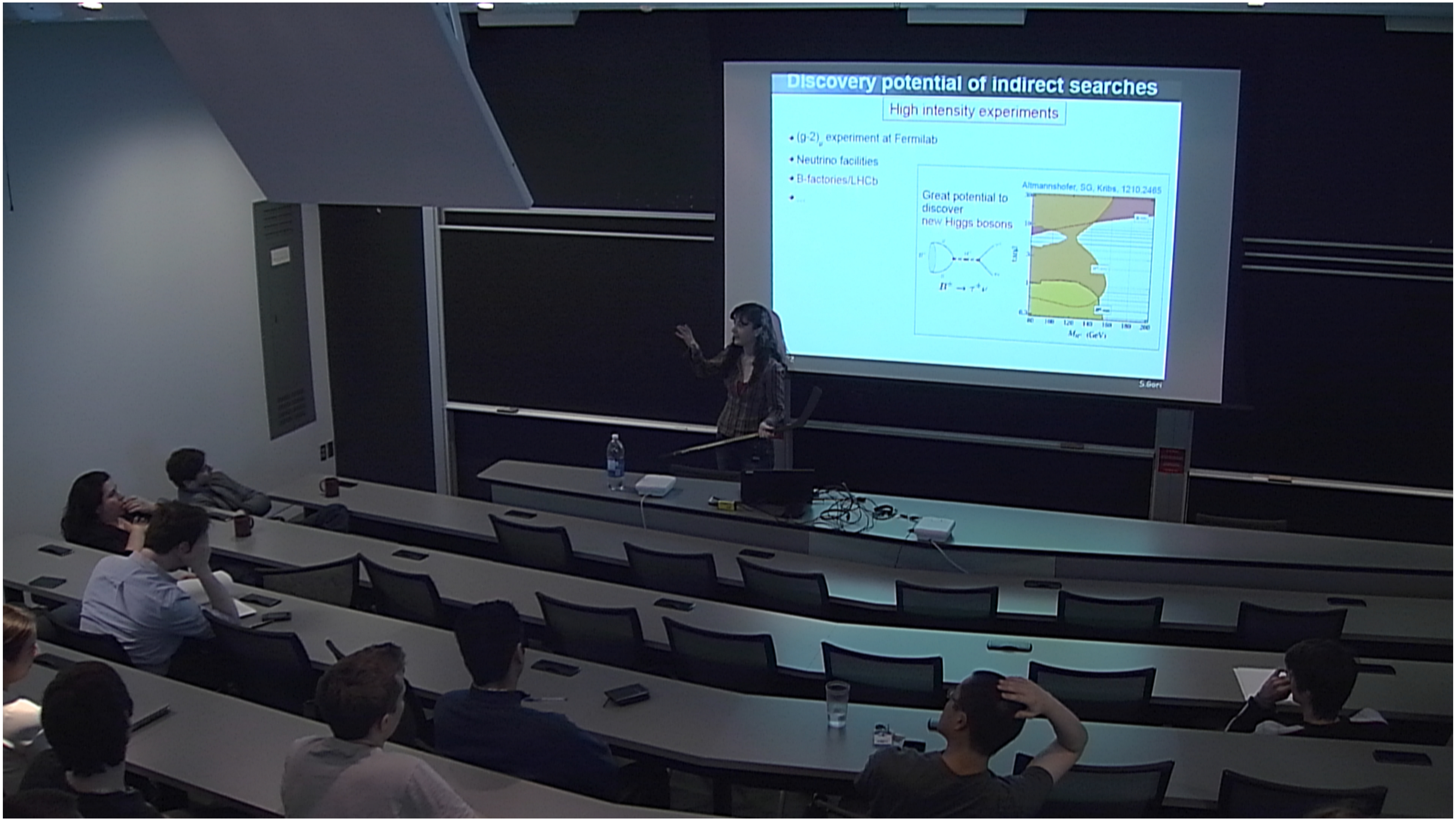

Discovery potential of indirect searches
High intensity experiments
(g-2) experiment at Fermilab
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# Discovery potential of indirect searches

## High intensity experiments

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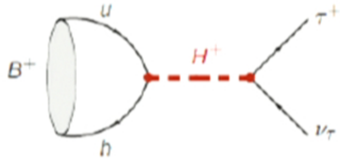
Great potential to discover new Higgs bosons

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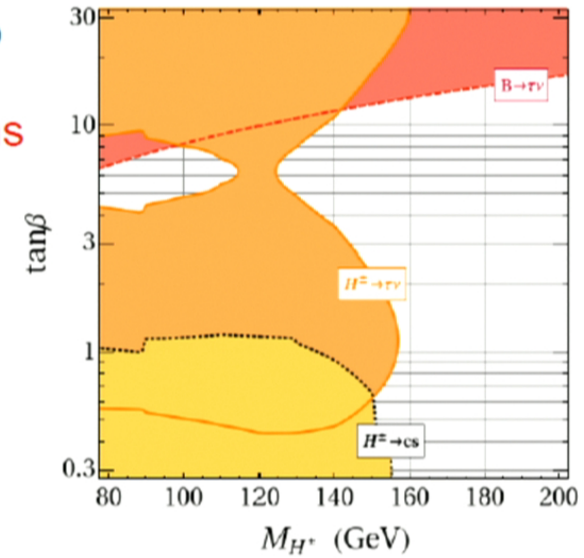


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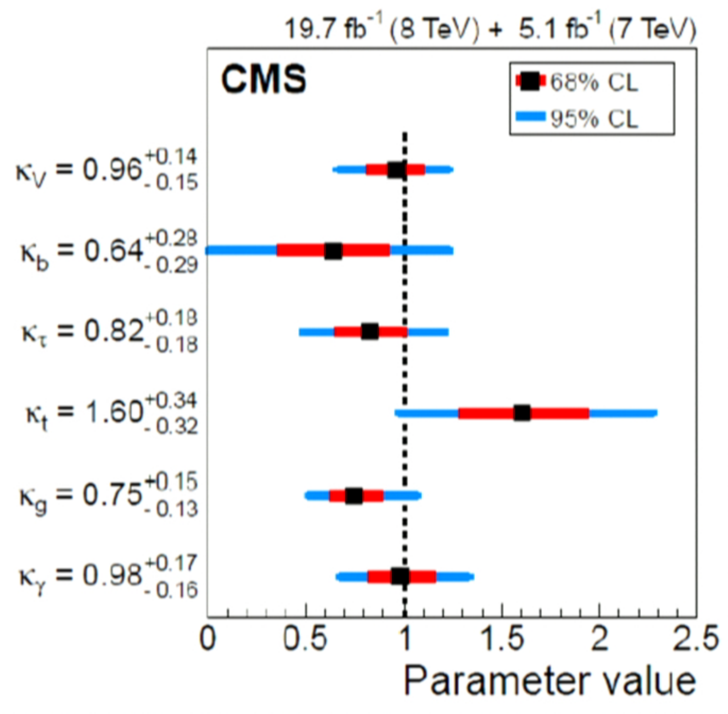
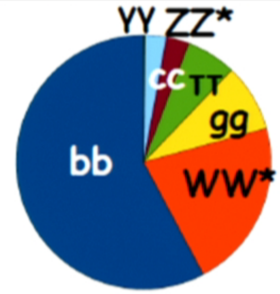
# Experimental prospects

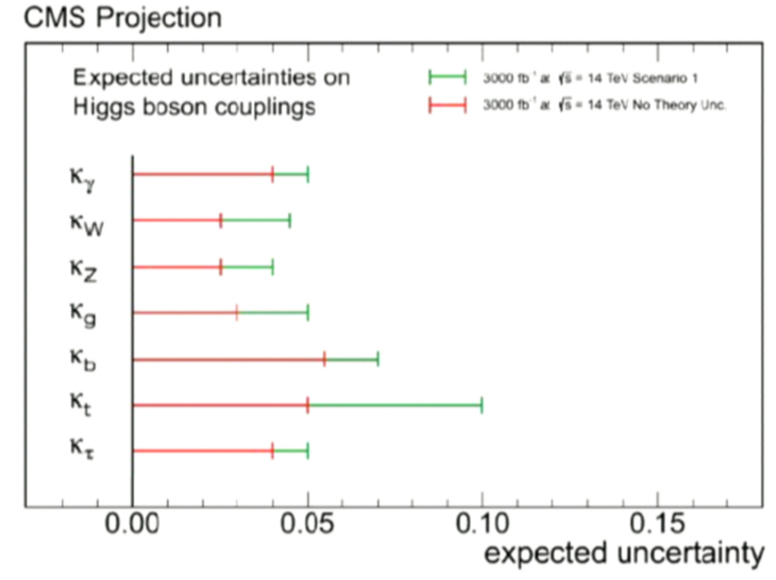
## Now




CMS-HIG-14-009

## Future



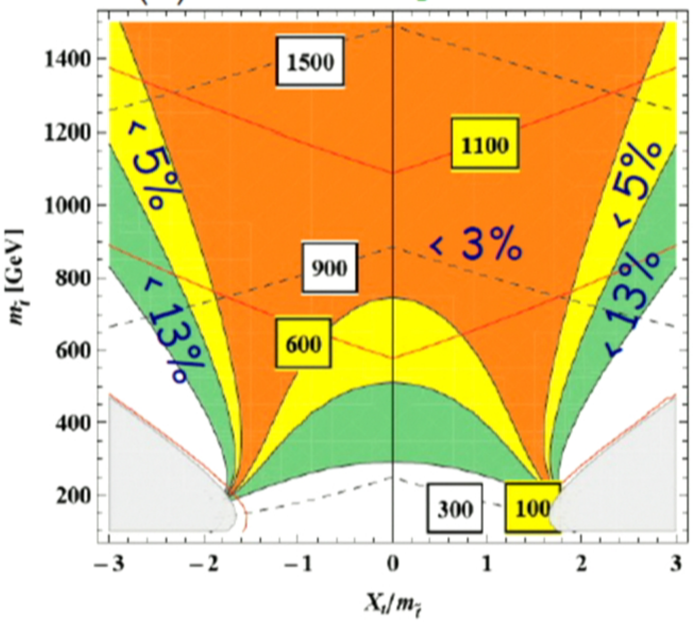




CMS-NOTE-13-002

# Higgs couplings to test New Physics

**hgg coupling**

SU(3) **Stops**




$$|\text{boson}\rangle \Leftrightarrow |\text{fermion}\rangle$$

$\text{stop}_1, \text{stop}_2 \Leftrightarrow \text{Top}_L, \text{Top}_R$

SG,Low,1307.0496

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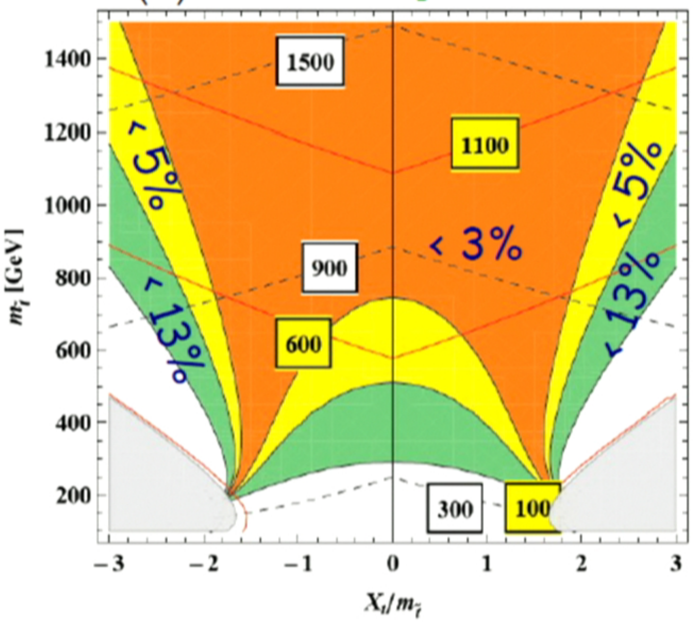


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SG,Low,1307.0496

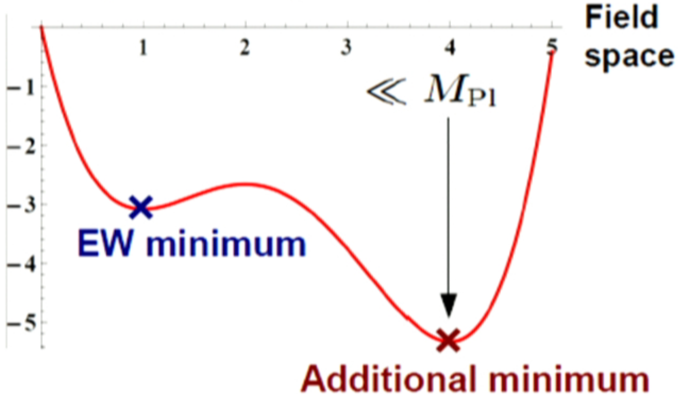
# Deep connection to the vacuum structure

It is not just a matter of measuring the properties of the newly discovered particle ...

Suppose in the coming couple of years, we measure a deviation from the SM prediction for the hγγ coupling

➡ hint for (some) new light particle

The structure of the universe will generically change:





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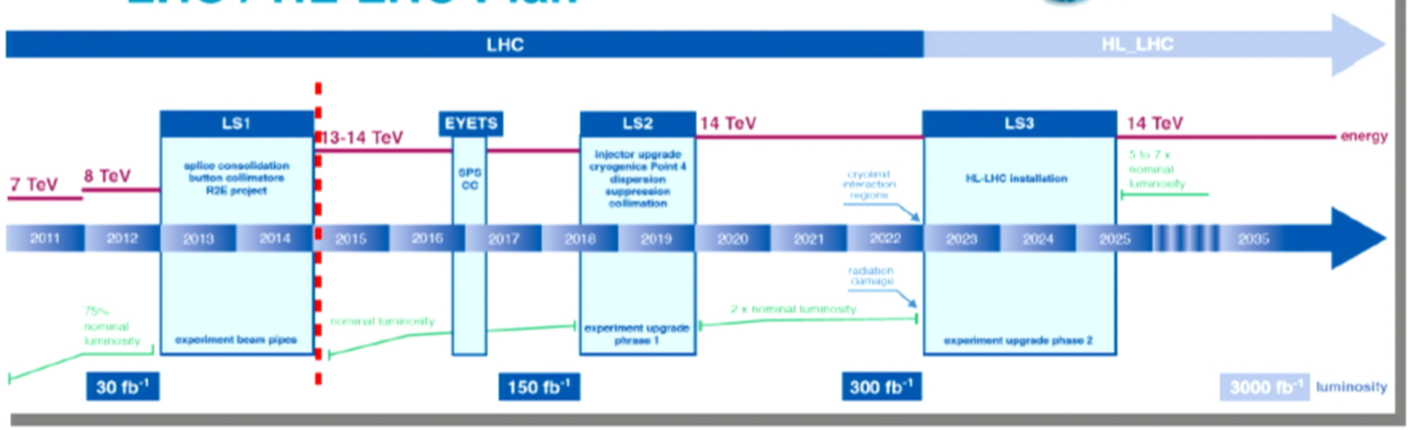
# Conclusions: Exciting times ahead

Great times for particle physics!
Open theoretical problems and a lot of experimental data

**1.The highest energy ever reached before!**

## LHC / HL-LHC Plan





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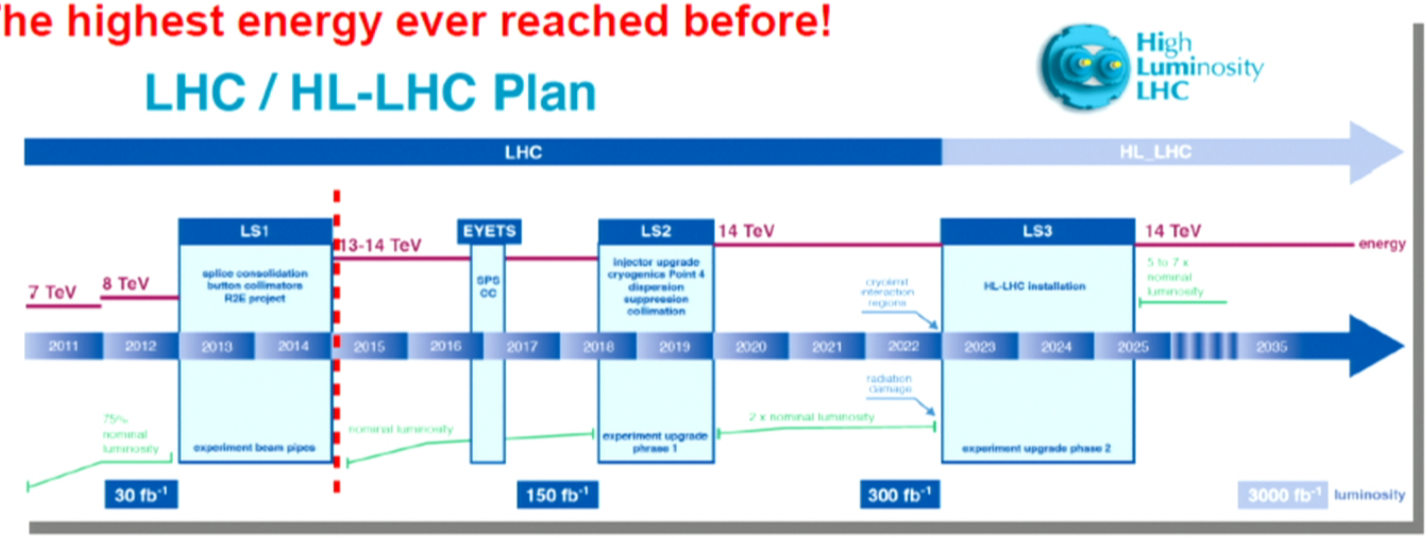



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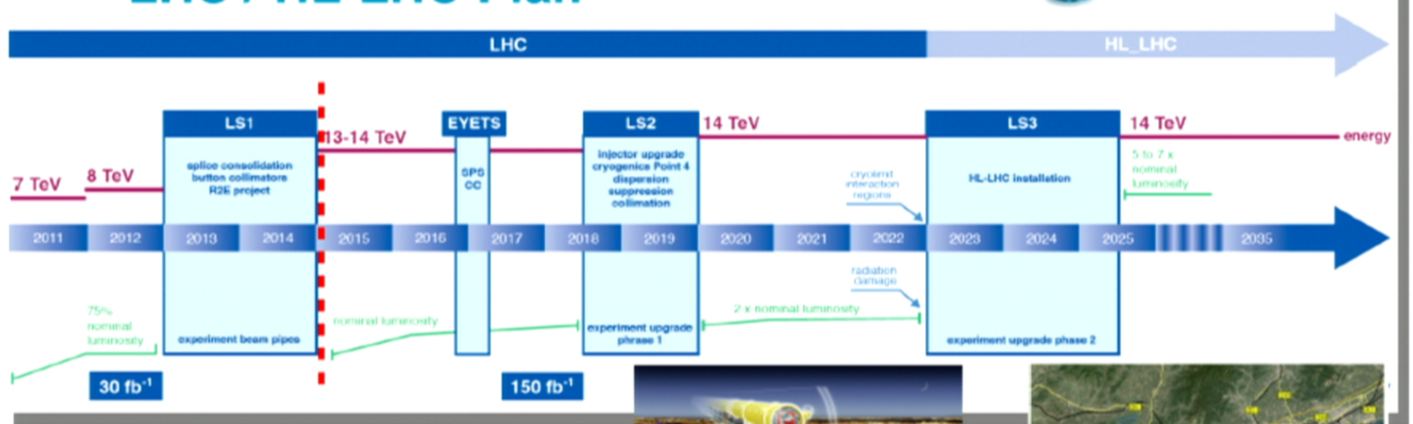
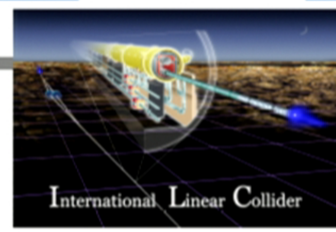
High Luminosity LHC




Thinking forward:
New high energy machines




Super proton-proton
Collider (SppC), 100 TeV

**2.The best indirect searches for NP ever!**
**3.The best Dark Matter experiments ever!**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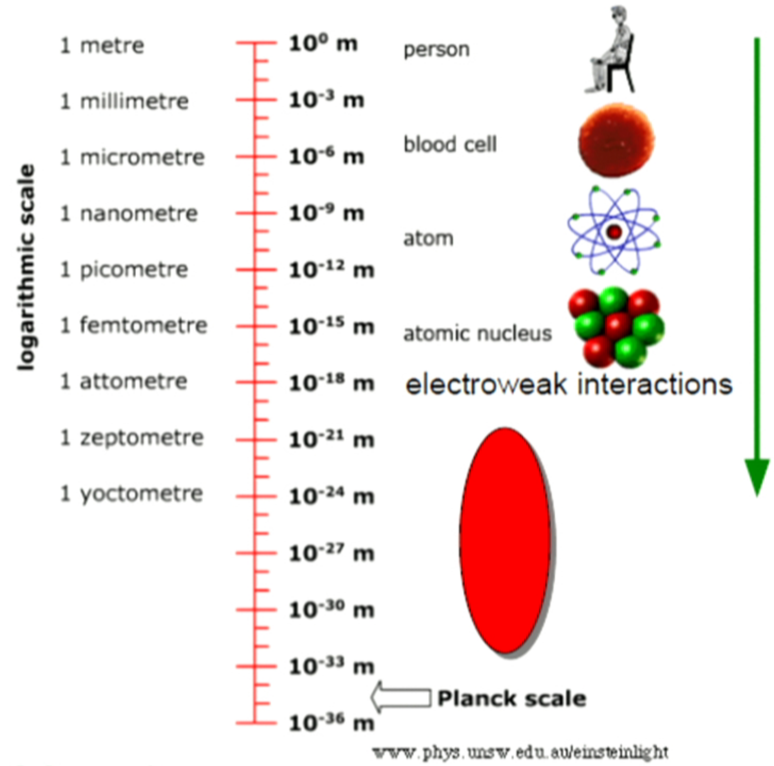
# The expedition to the next physics scale




- Hierarchy problem
- Dark matter
- Flavor problem
- Matter-antimatter asymmetry
- Neutrino masses
- Dark energy

Unique opportunity to test a new energy scale both

- directly at present and future colliders
- indirectly at high intensity machines

Brand new route: the Higgs boson

## My role:

- Propose new solutions to these outstanding theoretical problems
- Work in close contact with particle physics experimentalists to maximize the potential of the collider (LHC and beyond), of high intensity precision, and of dark matter experiments

The expedition to the next physics scale
electroweak interactions
Planck scale
- Hierarchy problem
- Dark matter
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32/32
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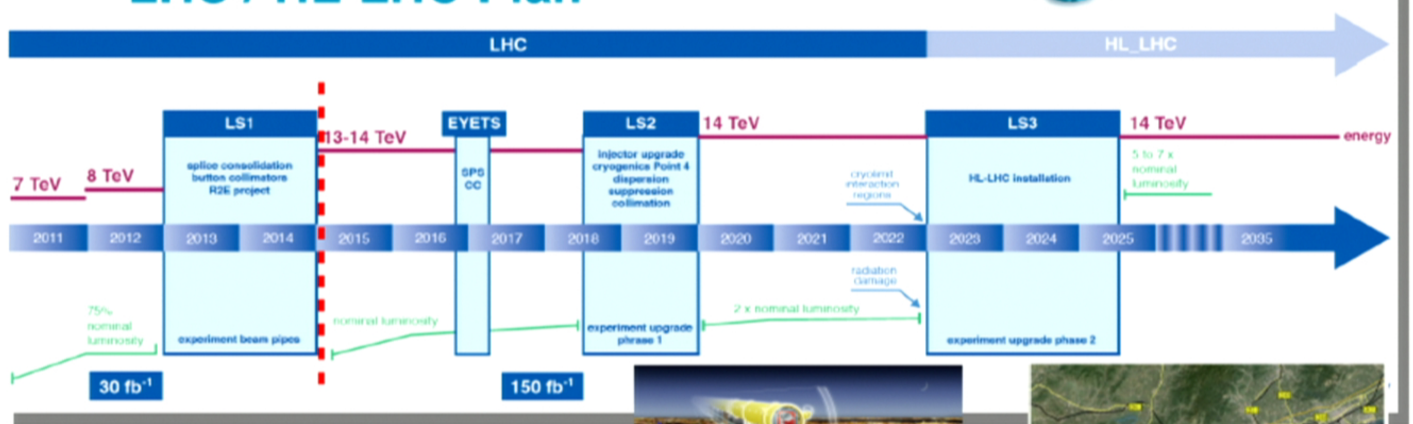


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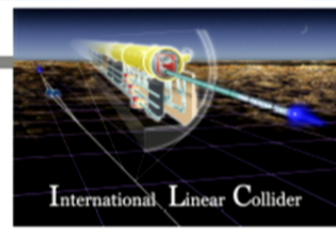


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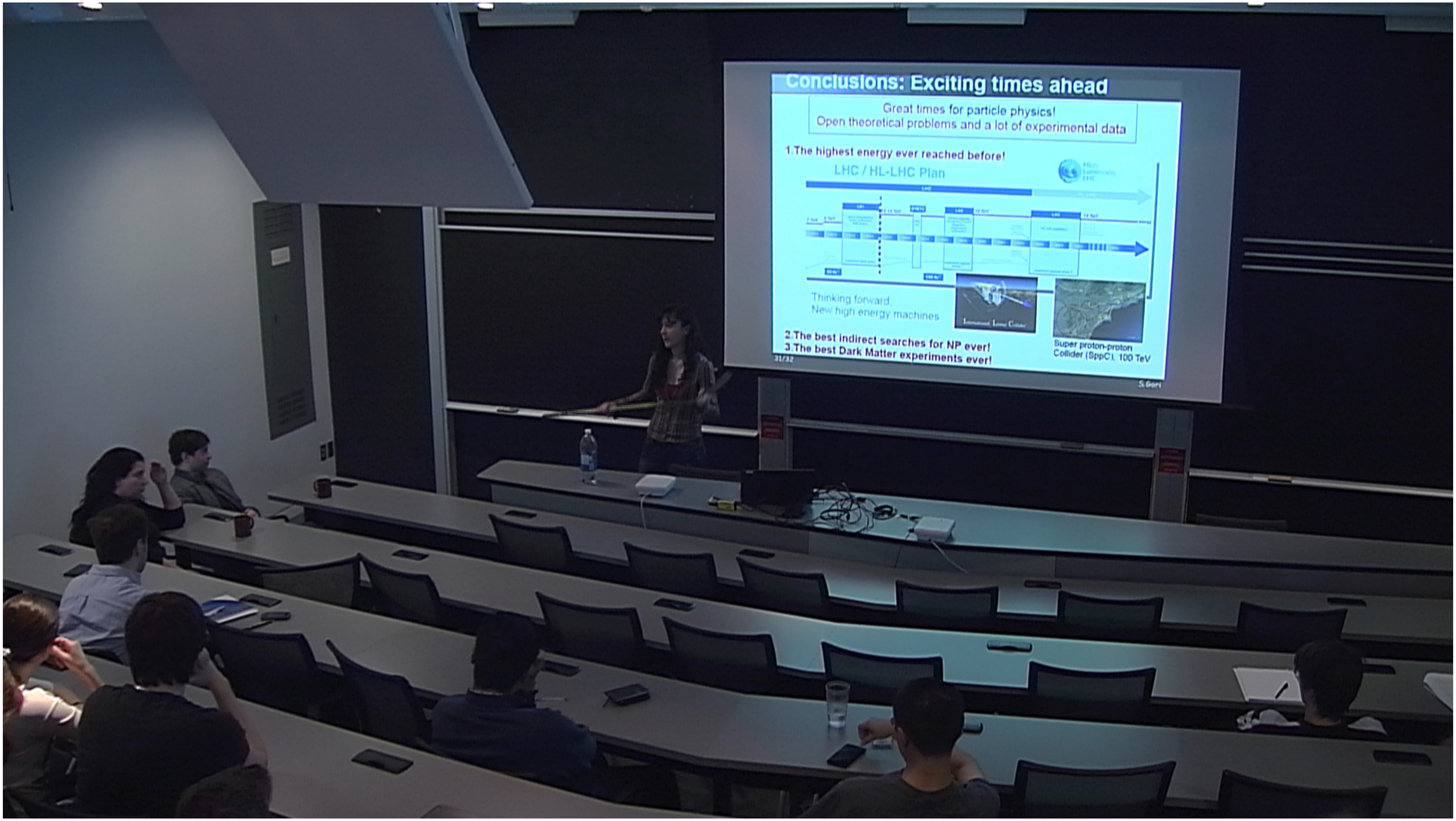
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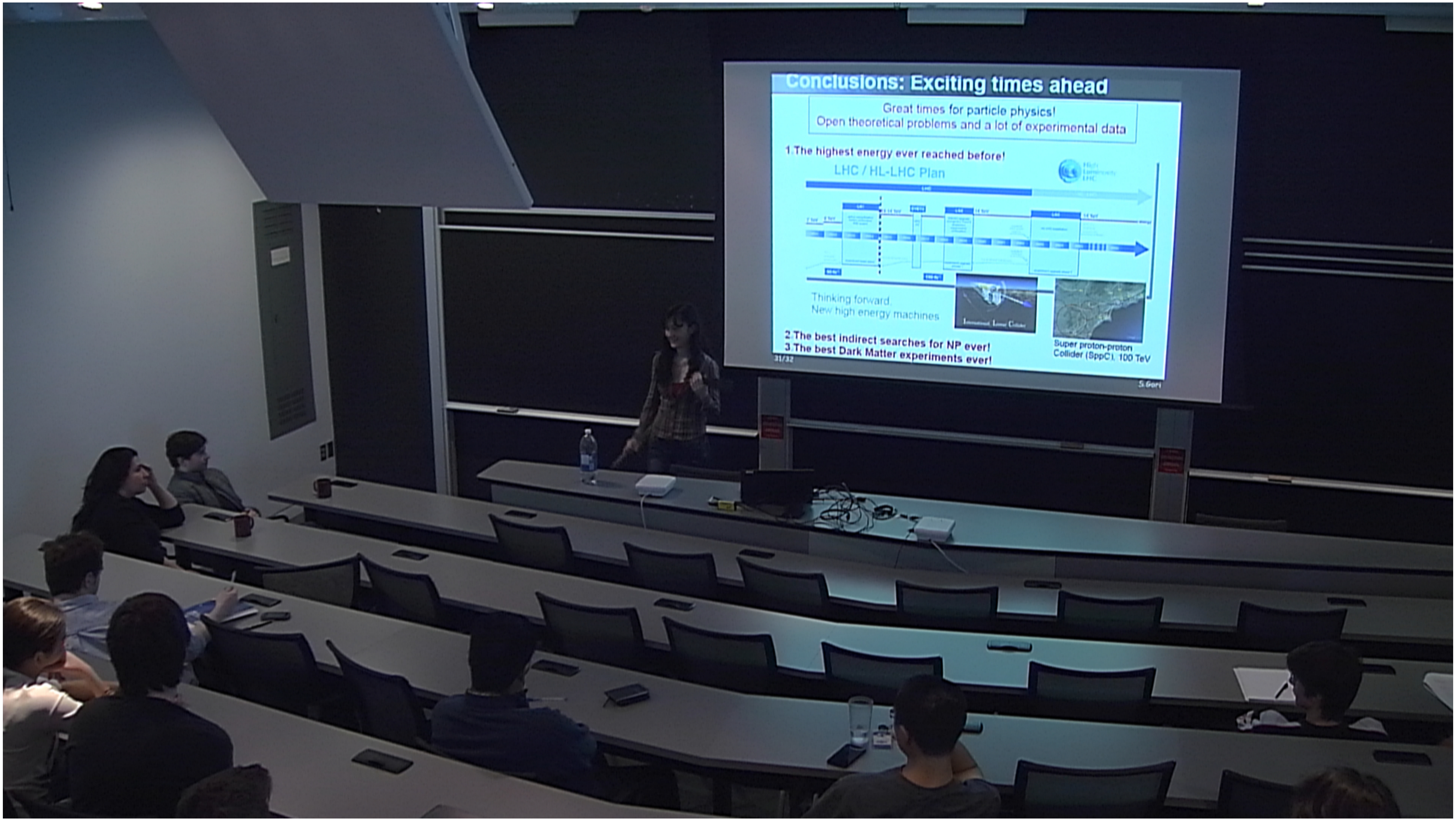
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