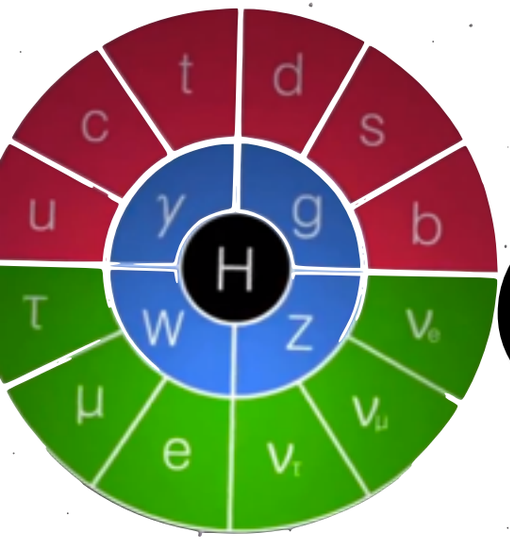
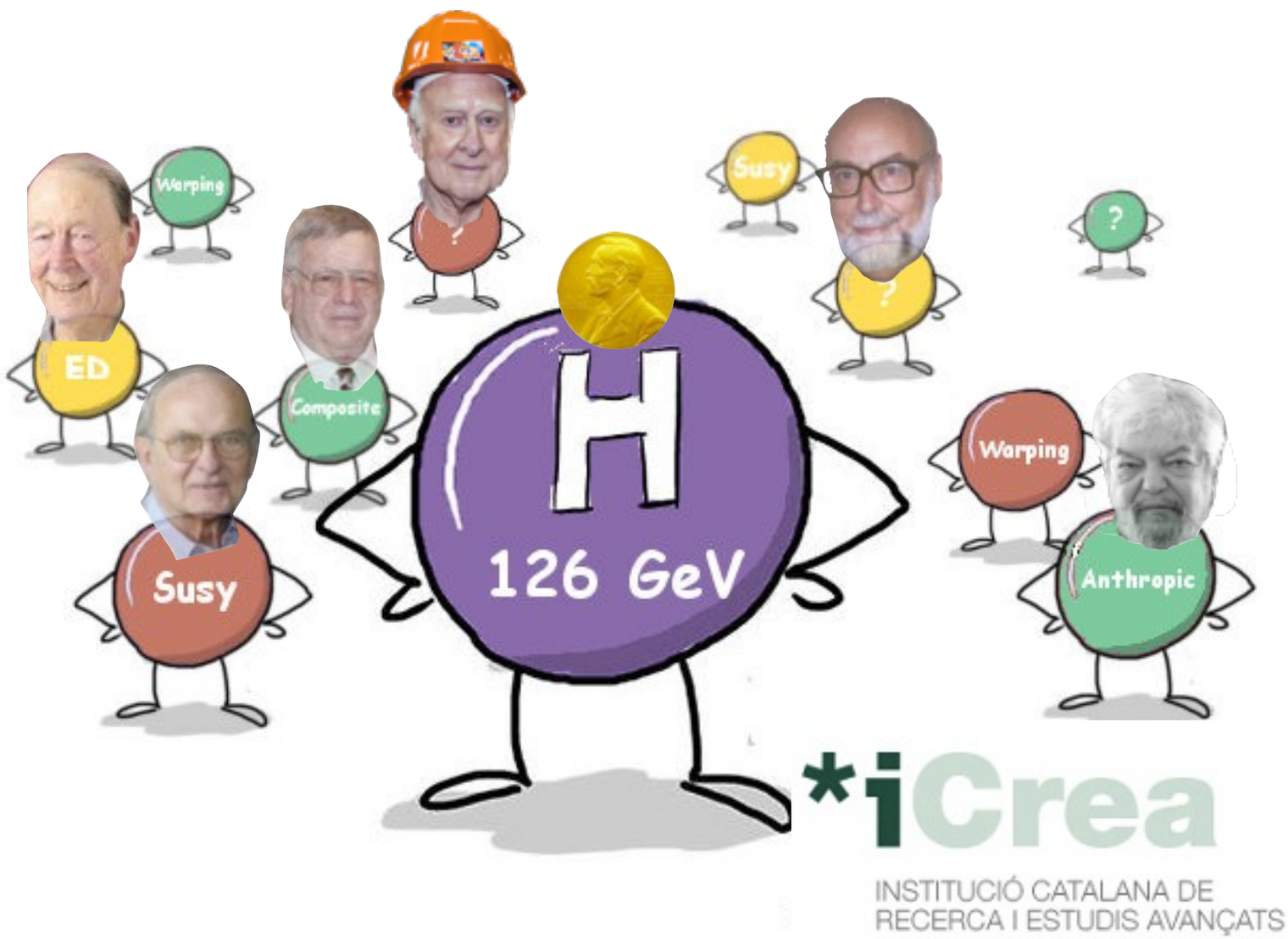


Quo Vadis Higgs?

Fermilab

November 5, 2014



Christophe Grojean

ICREA@IFAE/Barcelona

(christophe.grojean@cern.ch)

Creating matter from energy

~ Particle physics is special ~

Creating matter from energy

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- ***Chemistry : matter reorganization***

  the various blocks of matter reorganize themselves

Creating matter from energy

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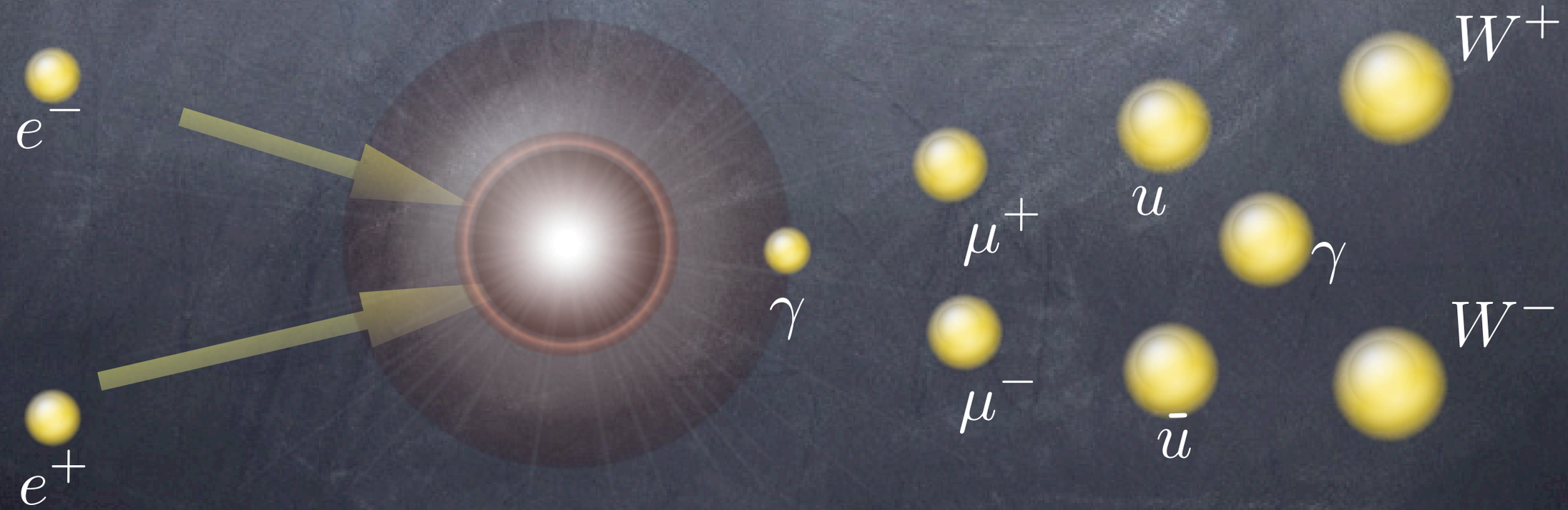

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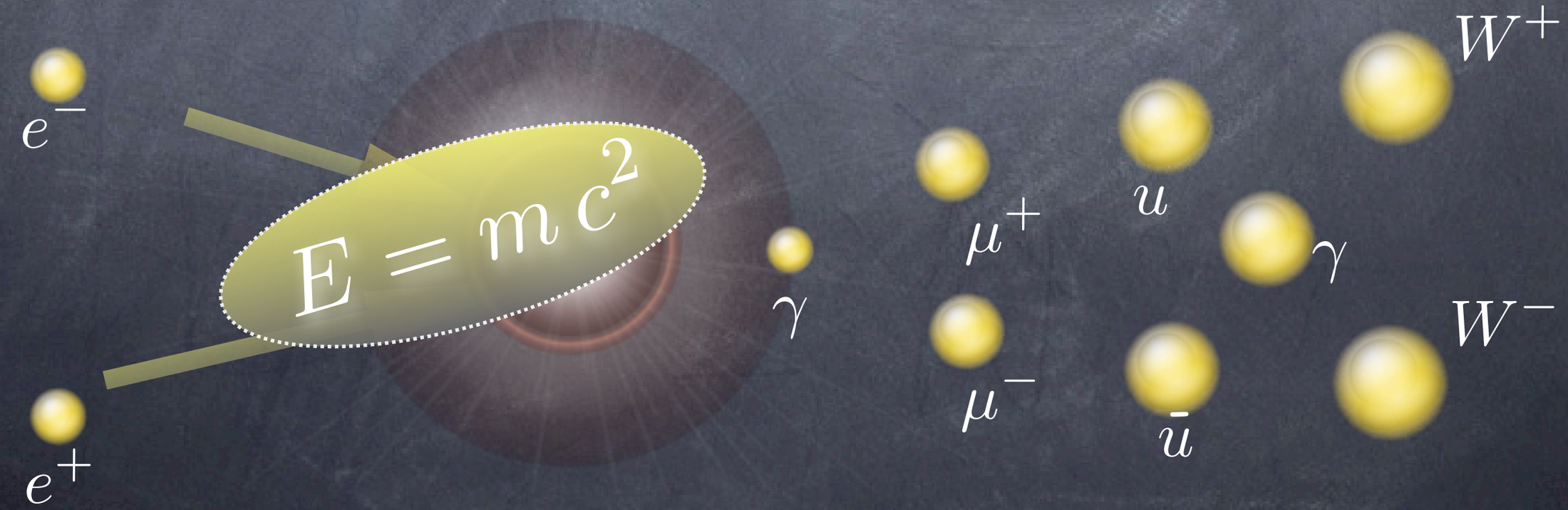


Classical versus quantum collissions

Classical versus quantum collissions

quantum size of an object of mass m (Compton wave-length)

$$\lambda = \frac{h}{mc}$$

h = Planck constant = 6.6×10^{-34} $m^2 kg/s$

Classical : $\lambda \ll R$

strawberry : m~30 g ➲ $\lambda \sim 10^{-40}$ m

quantum : $\lambda \gg R$

e^- : $m \sim 9.1 \times 10^{-31}$ kg ➲ $\lambda \sim 10^{-12}$ m

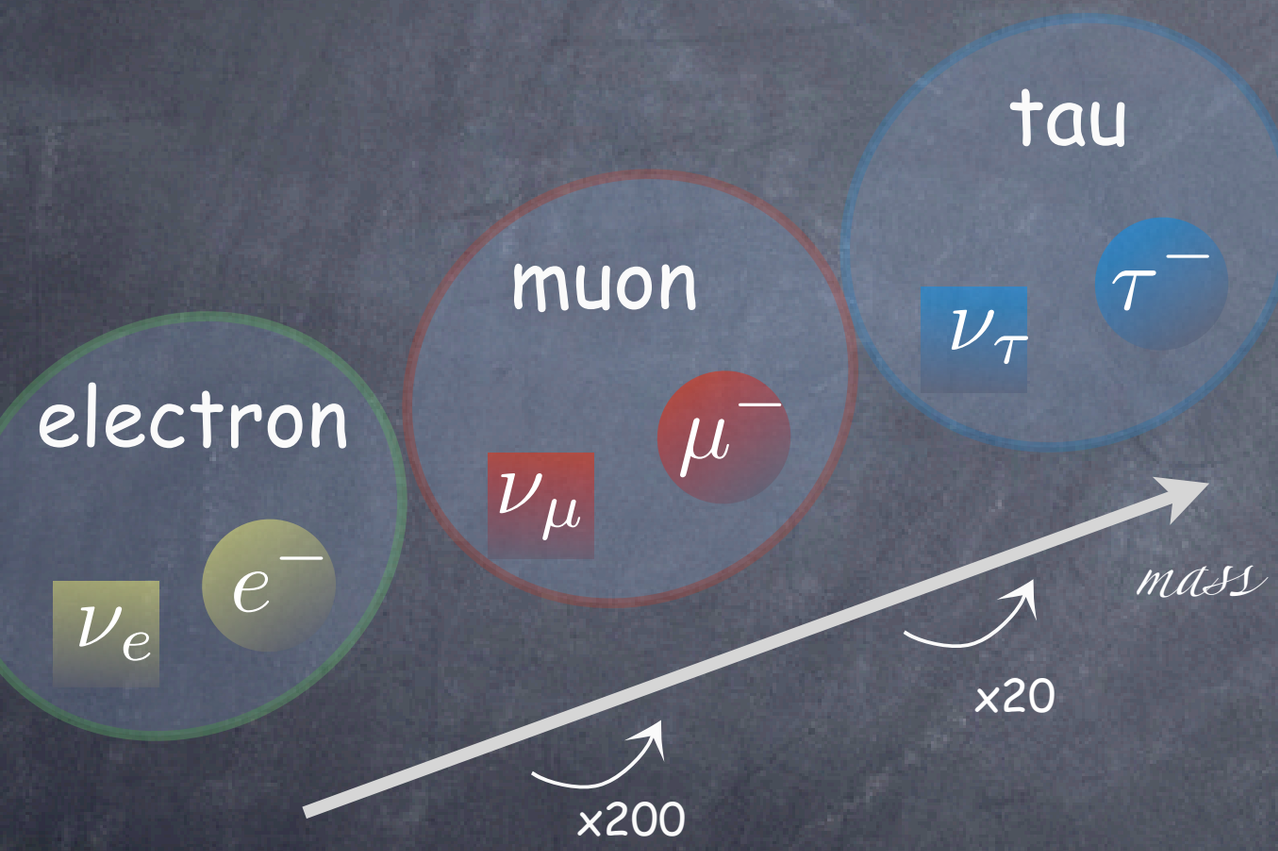
p : $m \sim 1.6 \times 10^{-27}$ kg ➲ $\lambda \sim 10^{-15}$ m

The Standard Model: Matter

The genetic code of matter

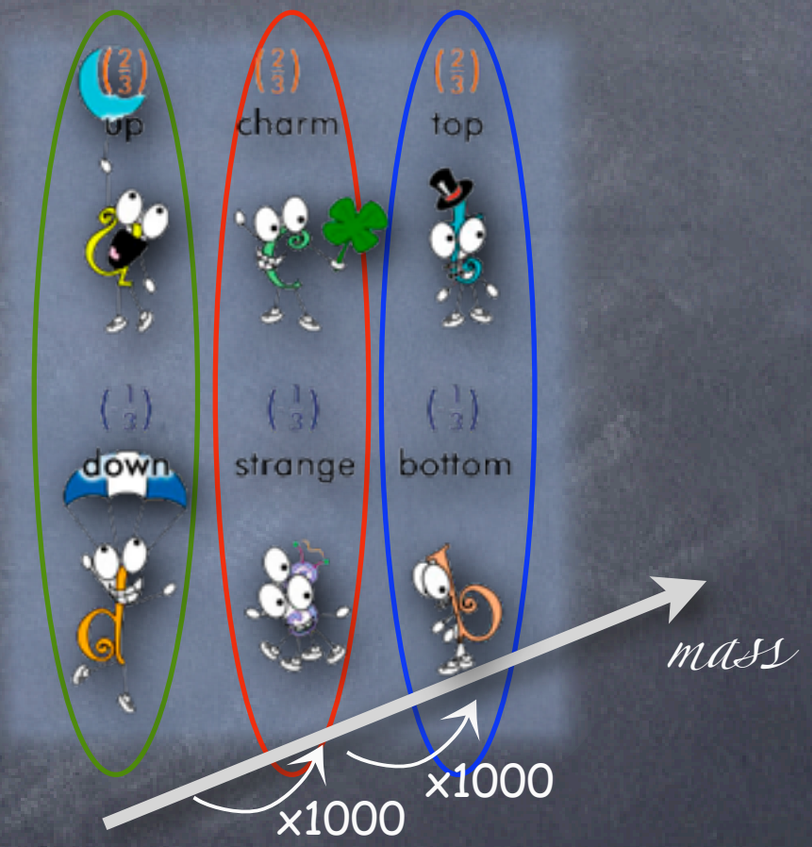
The elementary building blocks that everything is made of

LEPTONS



⇨ no composite states made of leptons

QUARKS



⇨ composite states=hadrons

- baryons
  - proton $p = (u, u, d)$
  - neutron $n = (u, d, d)$
- mésons

Fundamental Interactions

How do the elementary particles talk to each other?

Fundamental Interactions

How do the elementary particles talk to each other?

Fundamental Interactions

How do the elementary particles talk to each other?

universality of interactions: iPhone's and Galaxy's exchange photons!

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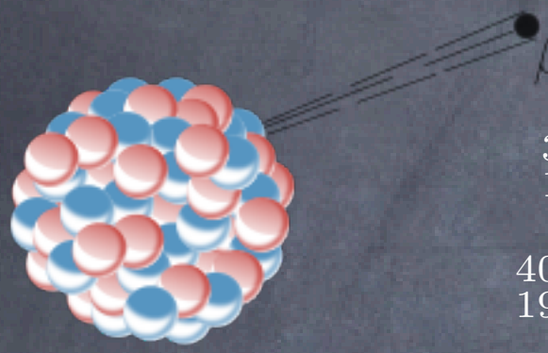
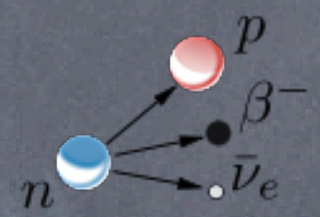


β decay

$$^{3}_{1}\mathrm{H} \rightarrow {}^{3}_{2}\mathrm{He}^{+} + e^{-} + \bar{\nu}_e$$

$$^{40}_{19}\mathrm{K} \rightarrow {}^{40}_{20}\mathrm{Ca}^{+} + e^{-} + \bar{\nu}_e$$

$$^{64}_{29}\mathrm{Cu} \rightarrow {}^{64}_{30}\mathrm{Zn}^{+} + e^{-} + \bar{\nu}_e$$



$$n \rightarrow p + e^{-} + \bar{\nu}_e$$

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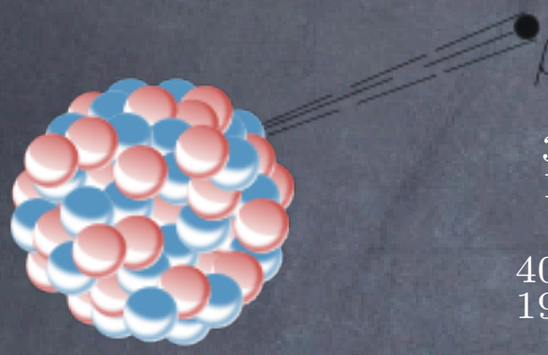

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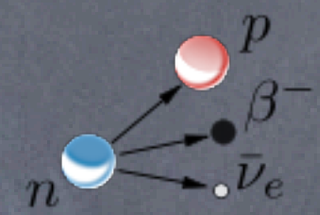

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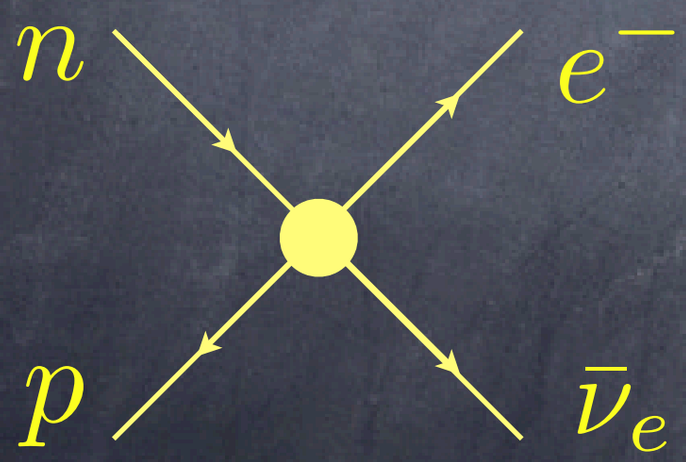
E. Fermi in the '30 described this interaction by a contact force



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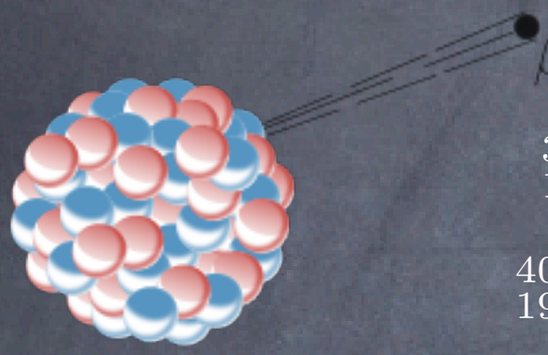

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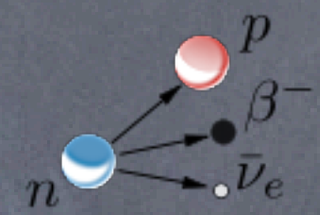

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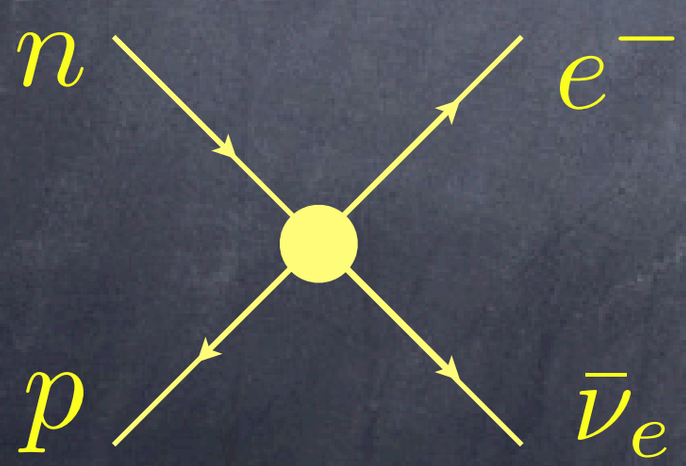

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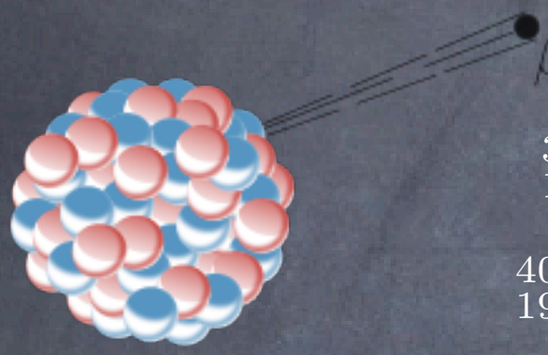

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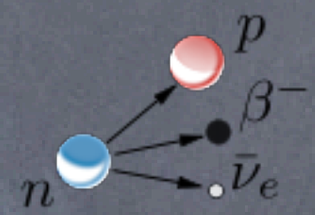

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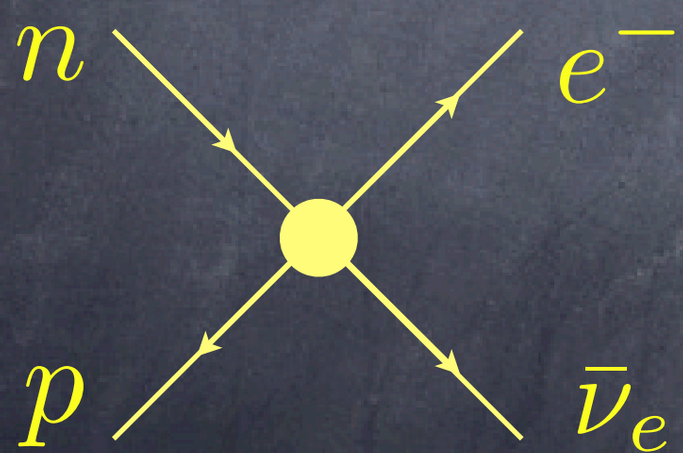

works fine for nuclear physics
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$$\sigma = \frac{G_F^2 \, E^2}{\pi}$$

E > 100 GeV
probability of interaction > 1

Dynamics and Symmetry

Forces create symmetries

Dynamics and Symmetry

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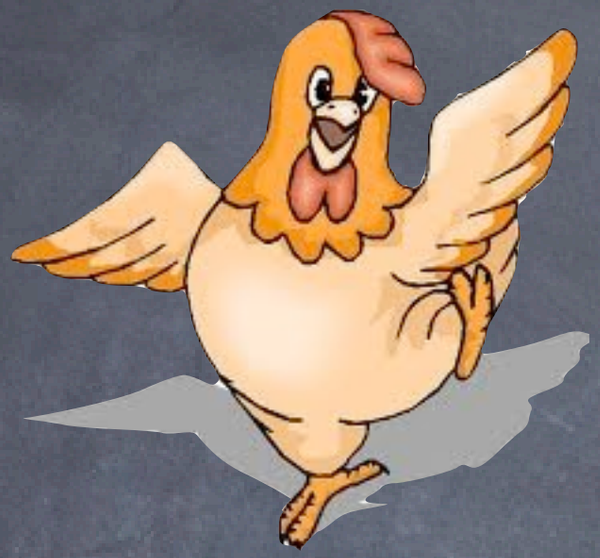

the dynamics
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dictates the shape of the eggs

Dynamics and Symmetry

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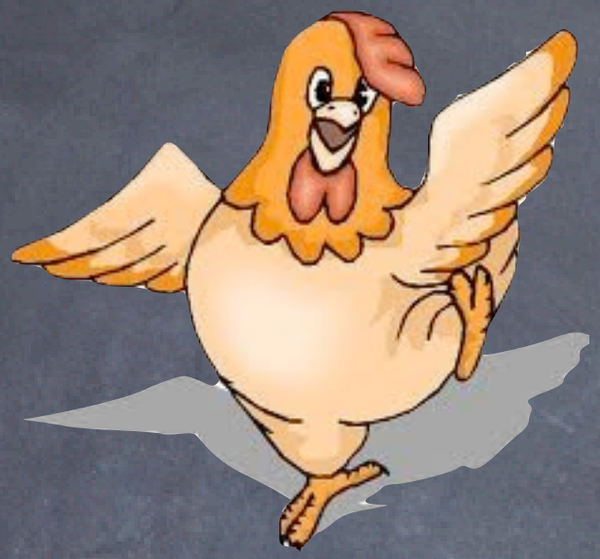

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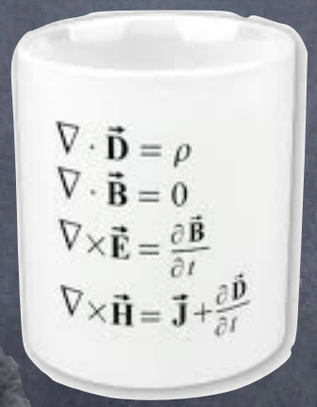
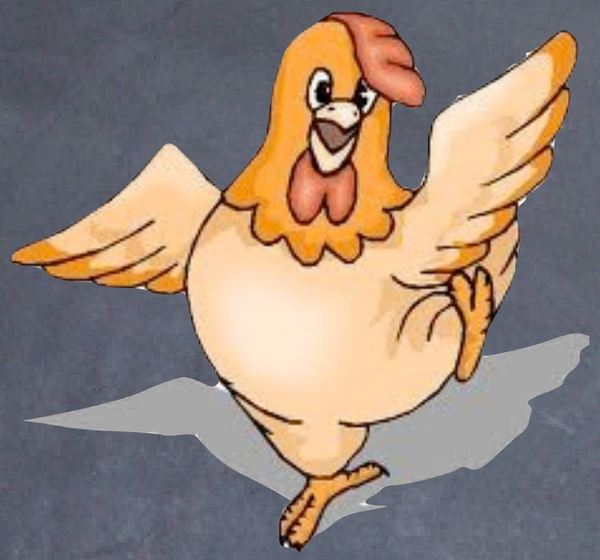


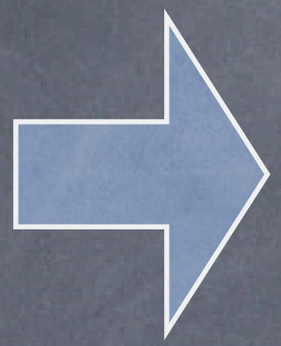
speed of light
in vacuum
is constant

the dynamics
of Maxwell eqs
controls light propagation

Dynamics and Symmetry

Symmetries create forces





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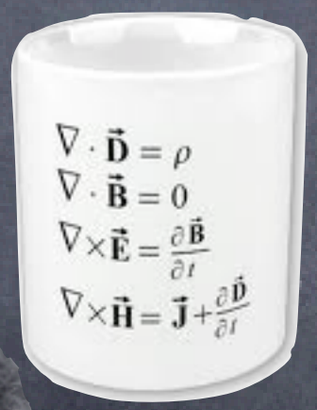

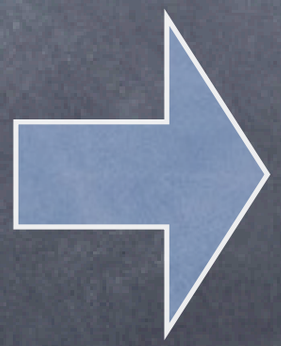

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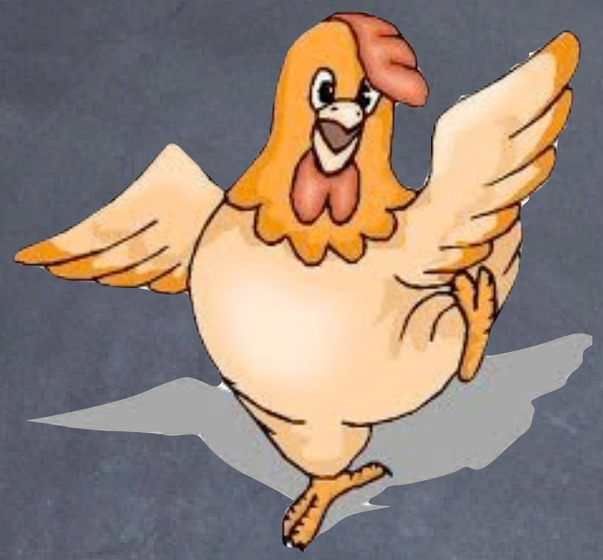

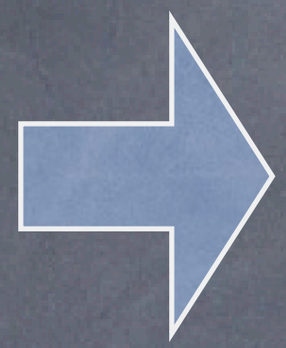

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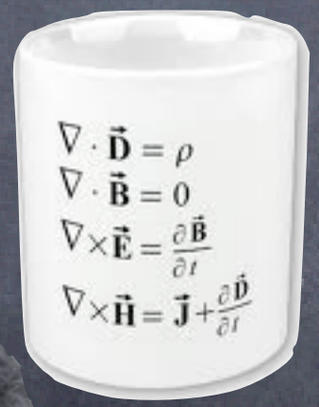

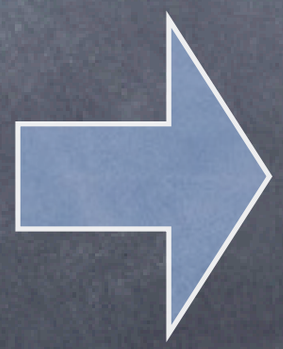

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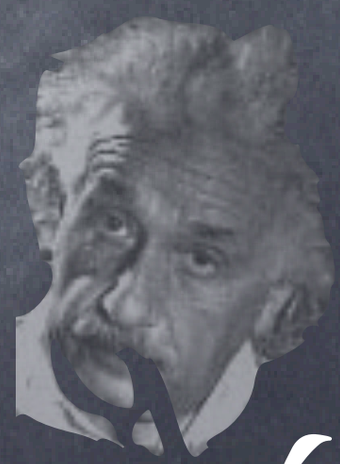

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Symmetry and Dynamics

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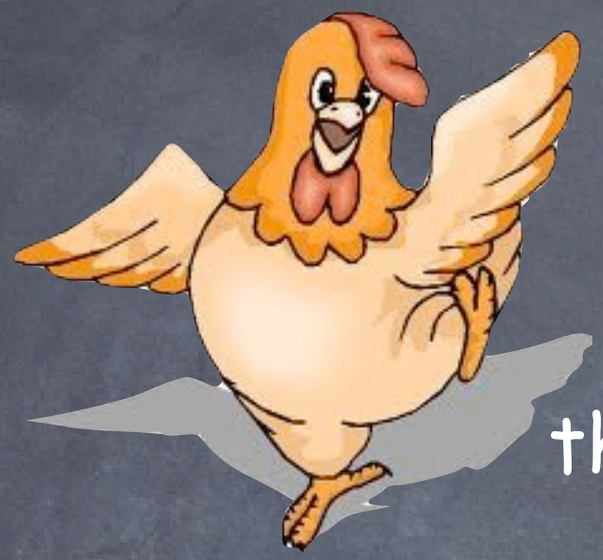

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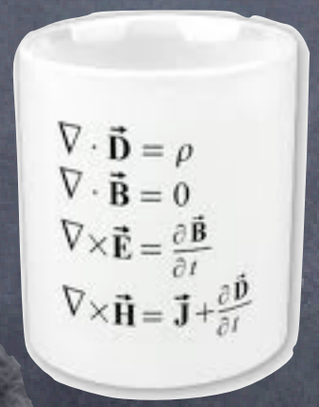

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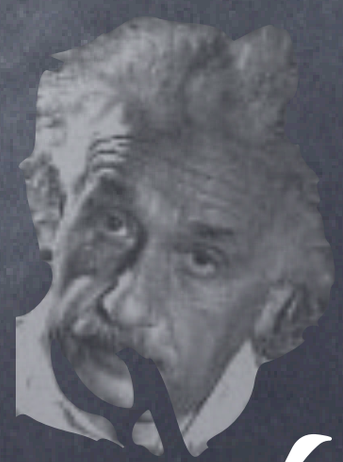

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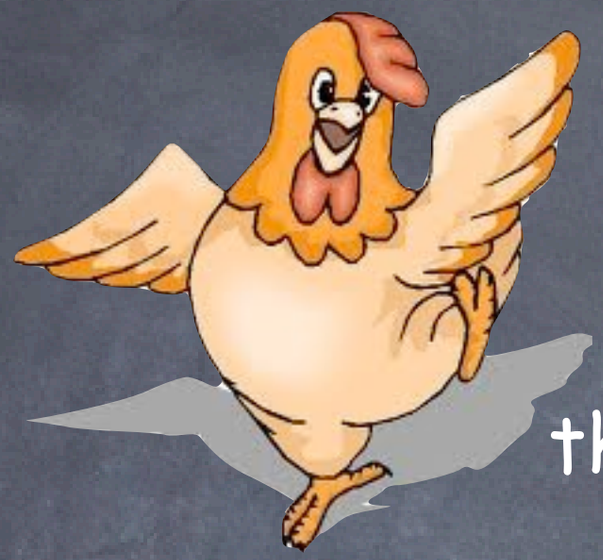

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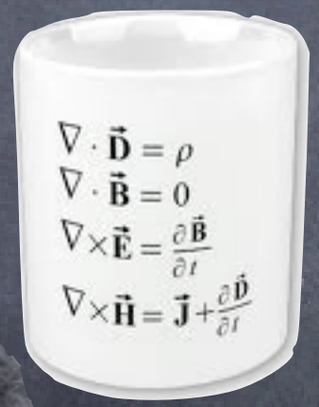

the requirement of
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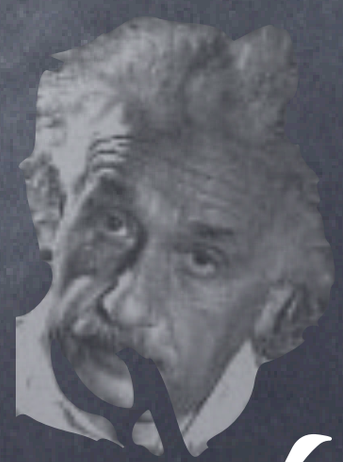

!

Symmetry and Dynamics

How do the elementary particles talk to each other?

an electron is described by a complex number

(the electron "wavefunction" i.e. the probability to find the electron at every point in spacetime)

Symmetry Principle

the phase of this number can be rotated away

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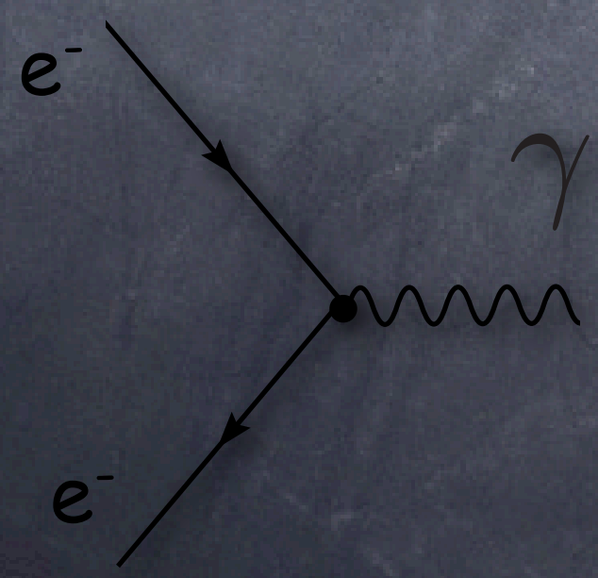

force carrier: photon

"memory" of how the electron phase is changing from one point to another in space-time

Forces and Symmetries

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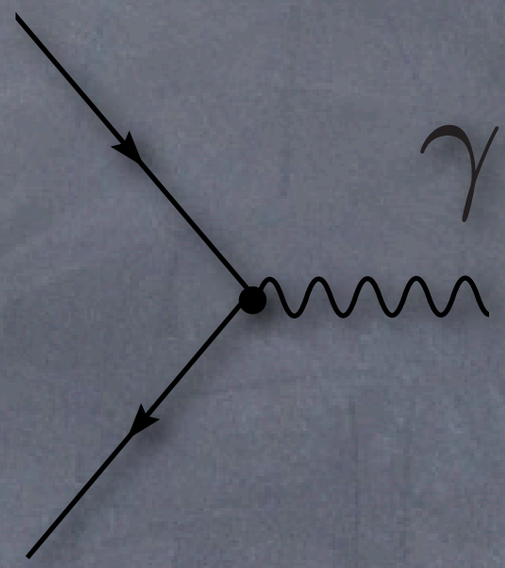

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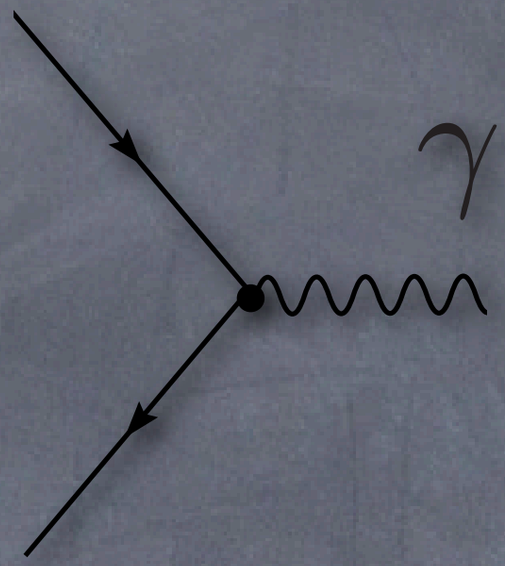

Universality of the interactions

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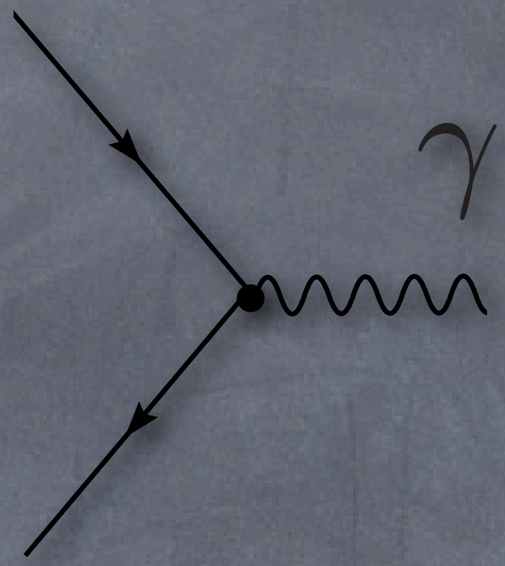

Universality of the interactions

- all the electrons interact with the photons in the same way

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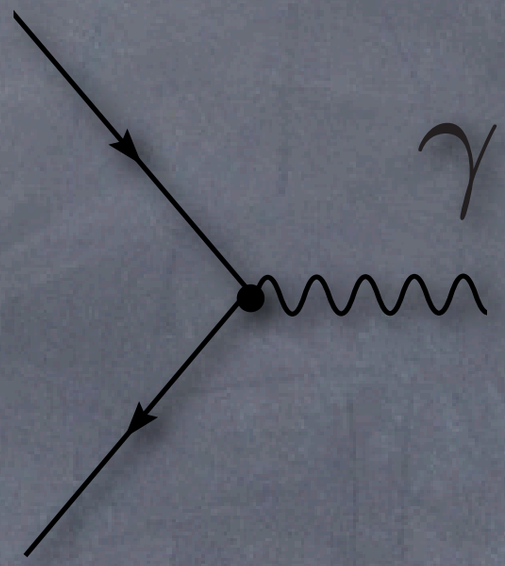

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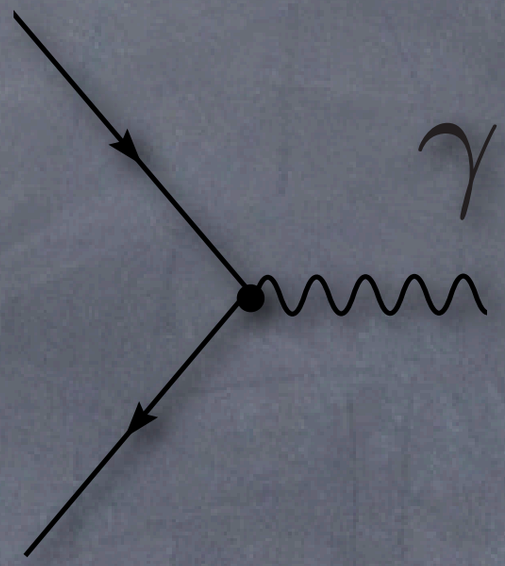

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probability for an electron to "produce" a photon

$$\alpha = \frac{e^2}{4\pi\epsilon_0\hbar c} \sim \frac{1}{137}$$

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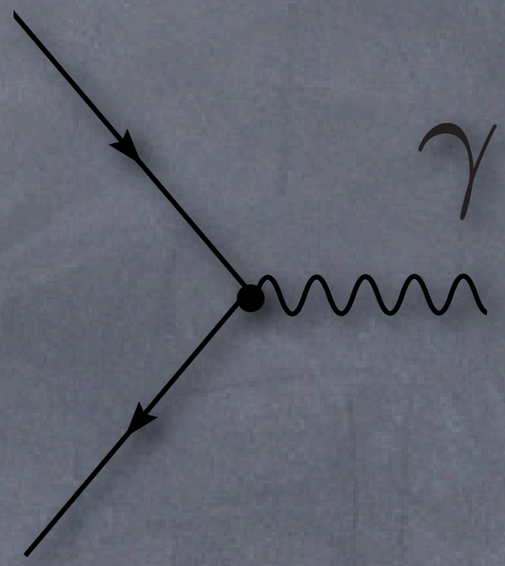

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all fundamental interactions are associated to symmetries

The Standard Model: Interactions

How do the elementary particles talk to each other?

- ***electromagnetic interactions***

  (1873, Maxwell)

  tested with an accuracy of 10^{-8}

  { light, atoms, molecules

- ***weak interactions***

  (1933, Fermi)

  tested with an accuracy of 10^{-3}

  { β decay

  $n \xrightarrow{W^\pm} p + e^- + \bar{\nu}_e$

  $e^+ + e^- \xrightarrow{Z^0} D^+ + D^-$

- ***strong interactions***

  tested with an accuracy of 10^{-1}

  { atomic nuclei, α decay

  $^{238}_{92}U \rightarrow ^{234}_{90}Th + ^{4}_{2}He$

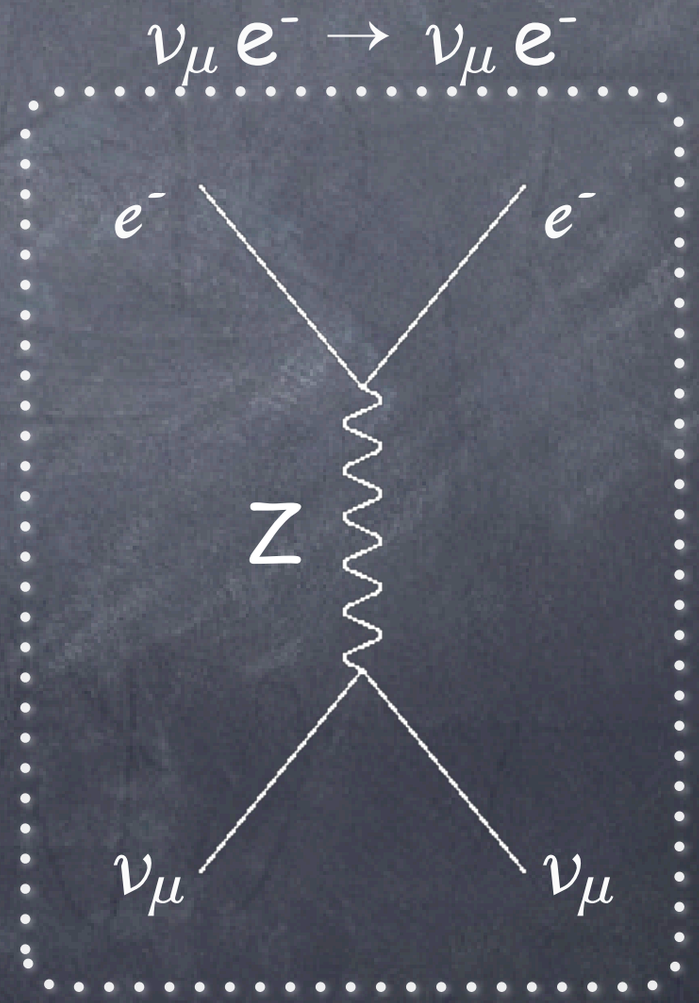
(1911, Rutherford ; 1921, Chadwick et Biesler)

The Standard Model

the strong, weak and electromagnetic interactions of the elementary particles are described by gauge interactions

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

[Gargamelle collaboration, '73]



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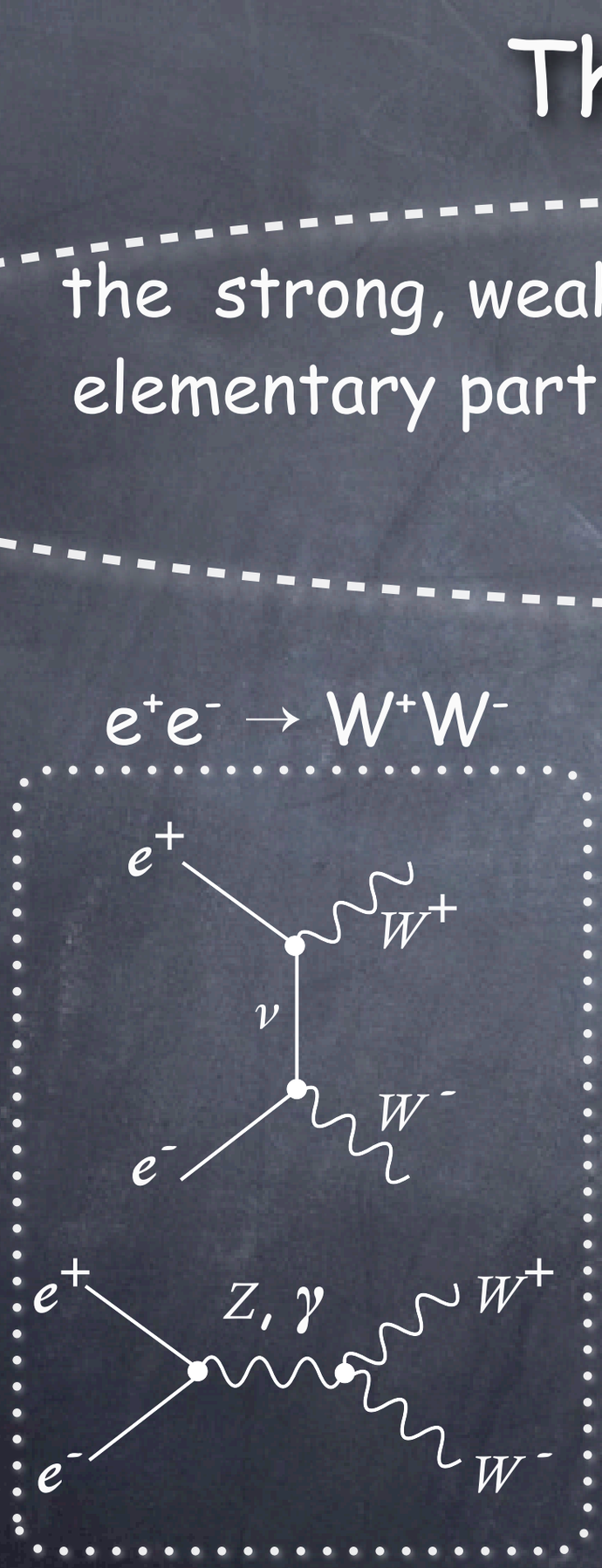
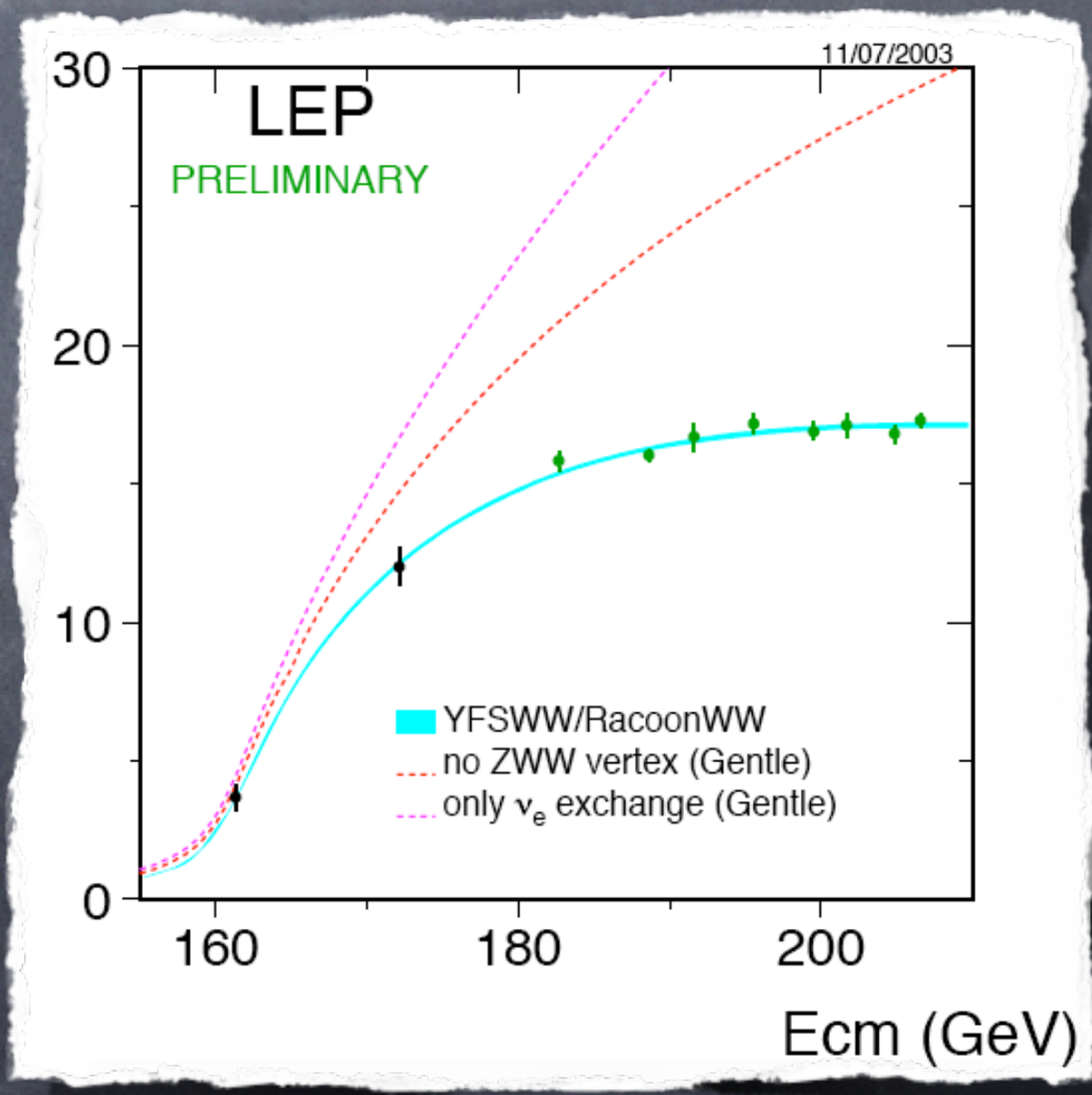
$e^+e^- \to W^+W^-$





Electroweak Symmetry

All fundamental interactions are associated to symmetries

Which symmetries?

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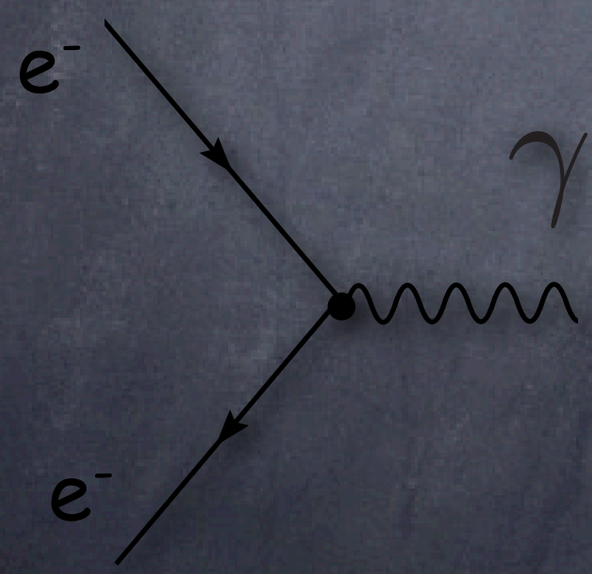
Which symmetries?

electromagnetism

change of electron phase



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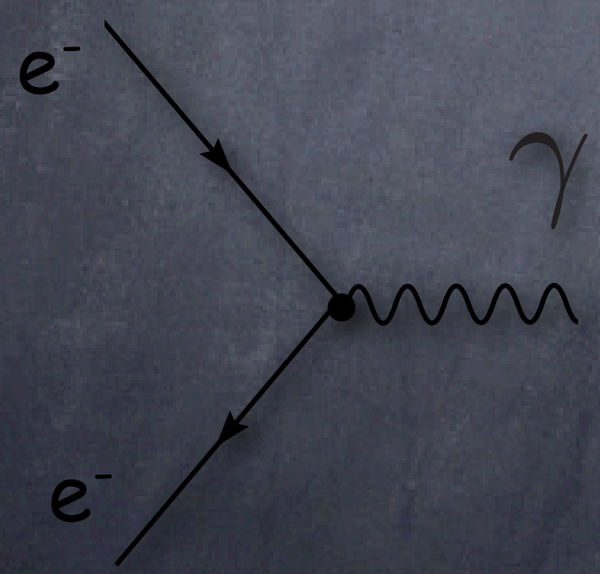
electron $\rightleftarrows$ neutrino



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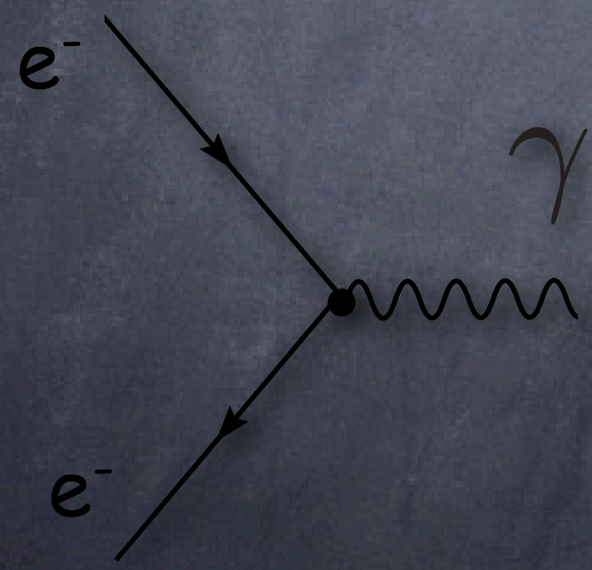

Prix Nobel '79

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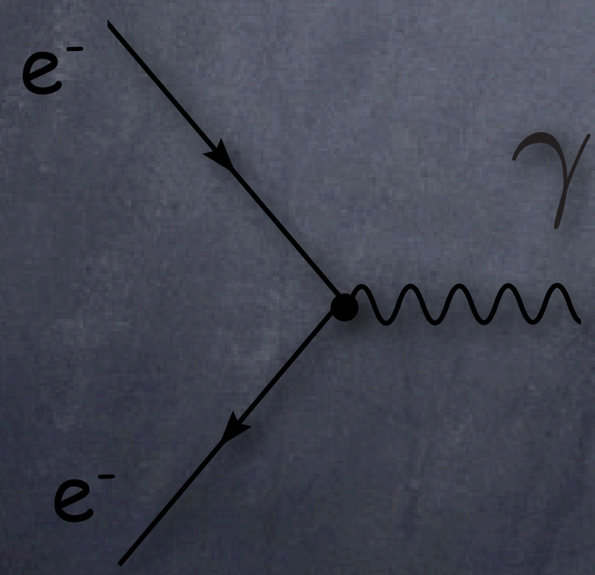

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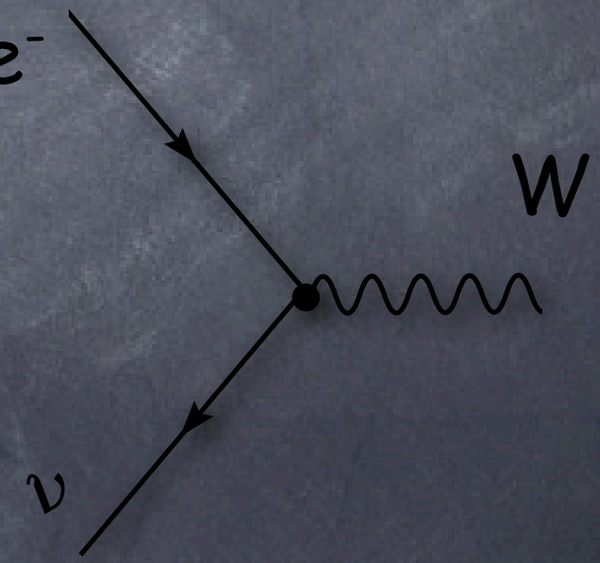

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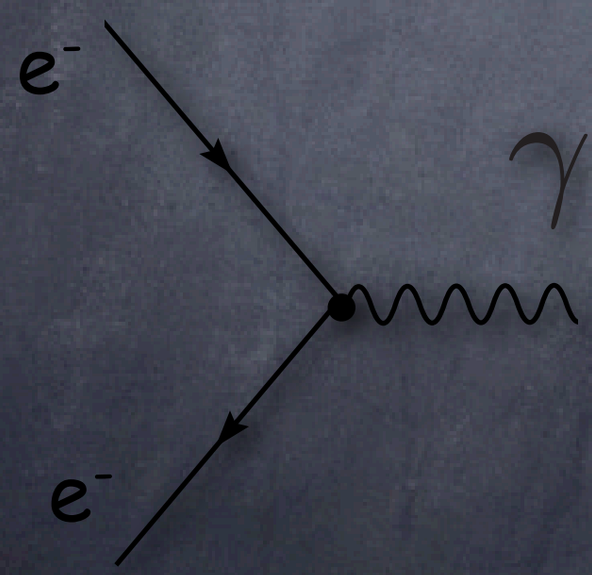

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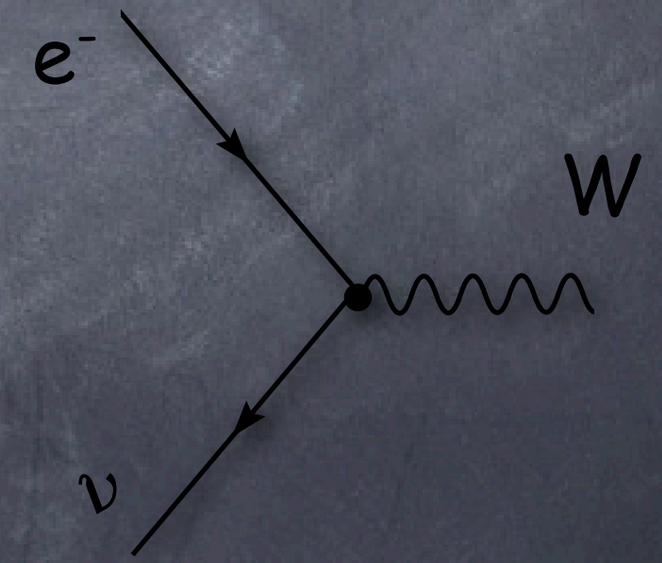

W boson discovered @ CERN in '83

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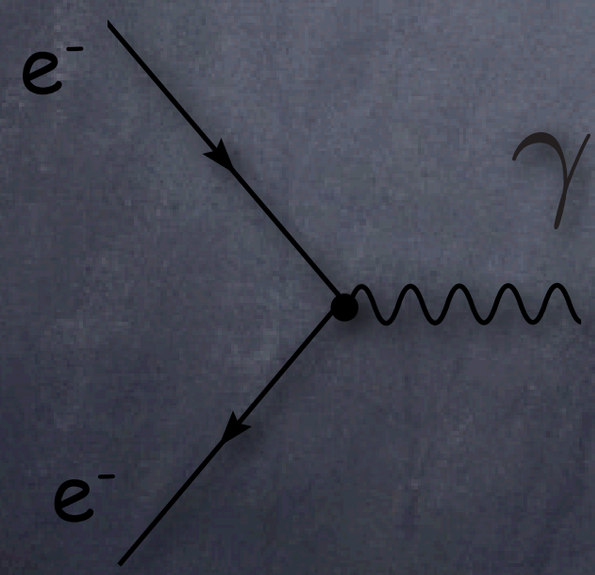

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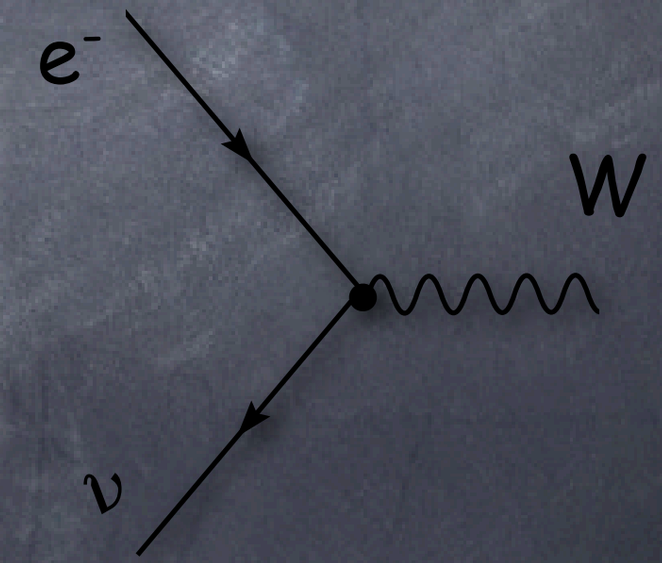


W boson discovered @ CERN in '83

Is it really a symmetry? e and ν are so different!

A second issue: the mass problem

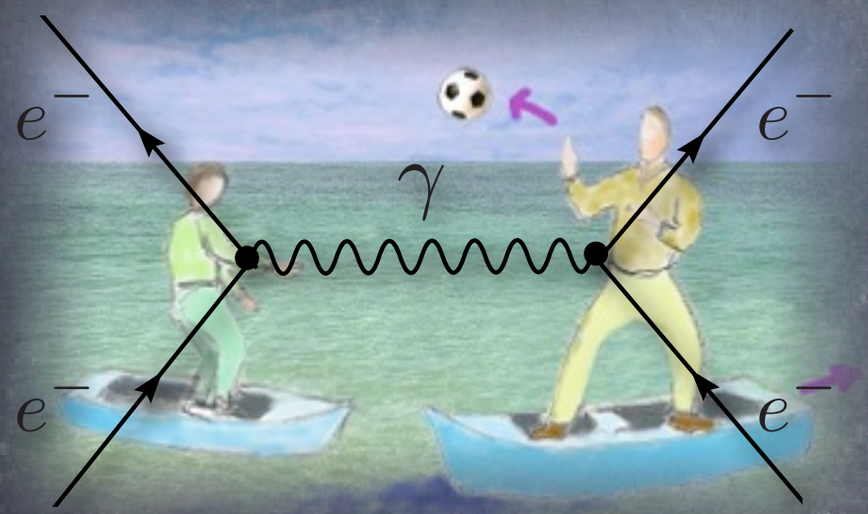
Electromagnetism

Strong Interactions

A second issue: the mass problem

Electromagnetism

long range force
exchange of photons



Dirac's equation
fully consistent with
the laws of QM and SR

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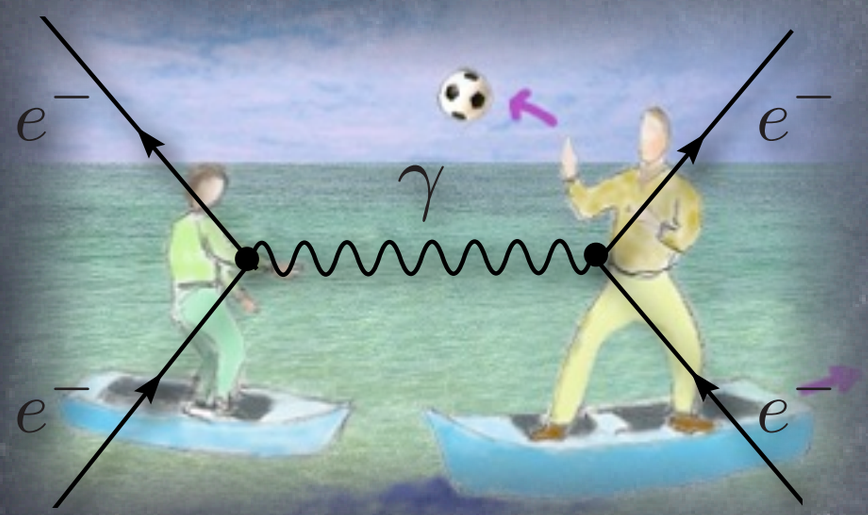

Dirac's equation
fully consistent with
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Strong Interactions

short range force

pion exchange
(formulated by Yukawa in '35
discovered by Powell in '47)

⇩

no consistent
quantum field theory
description

Yang-Mills
gauge invariance

⇩

Pauli's masslessness
nightmare

The mass conundrum

SM=triumph of Quantum Mechanics + Special Relativity

particles = representations of Poincaré group

these representations are labelled by

(spin, mass)

quantized ↑ ↖ continuous

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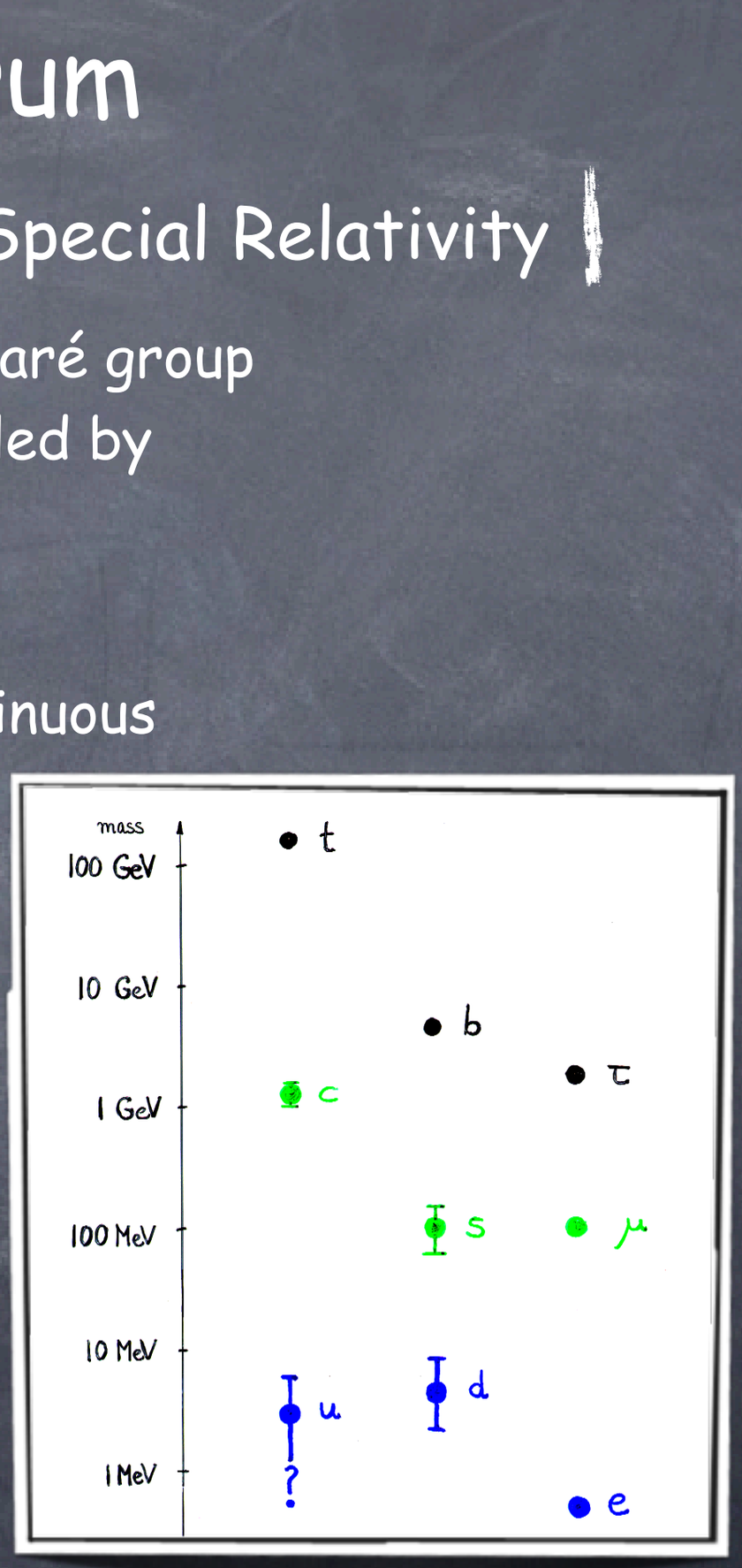

(pictures: courtesy of A. Weiler)

The mass conundrum

SM=triumph of Quantum Mechanics + Special Relativity

particles = representations of Poincaré group
these representations are labelled by

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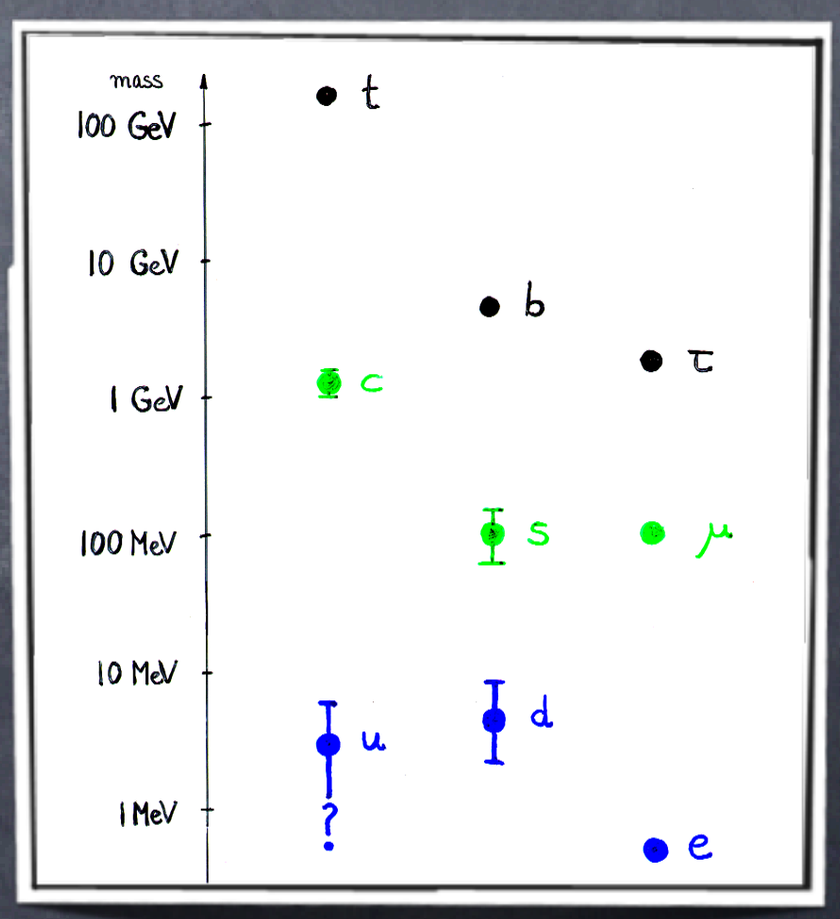
quantized ↑ ↑ continuous

A priori in agreement with data ⇔

but

incompatible with symmetry structure
chiral fermion ⇏ m=0 only
gauge boson ⇏ m=0 only



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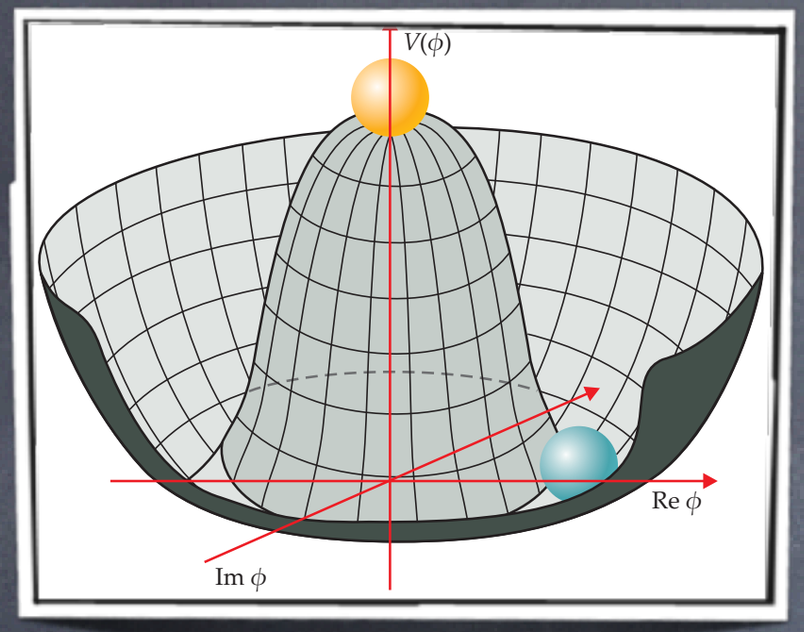
Spontaneous Symmetry Breaking

The masses are emergent due to a non-trivial structure of the vacuum



vacuum = a space entirely devoid of matter

Oxford English

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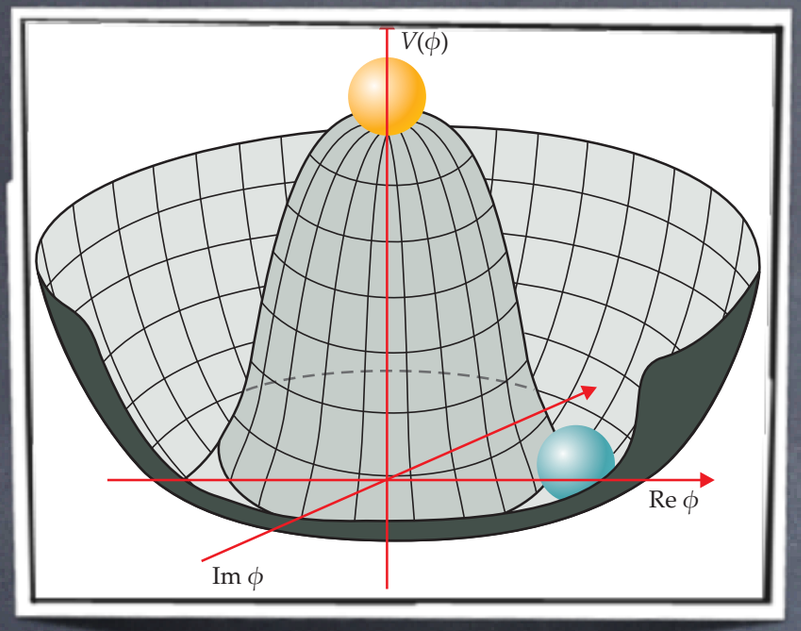

~~vacuum = a space entirely devoid of matter~~

Oxford English

vacuum = a space filled with Higgs substance

Physics English

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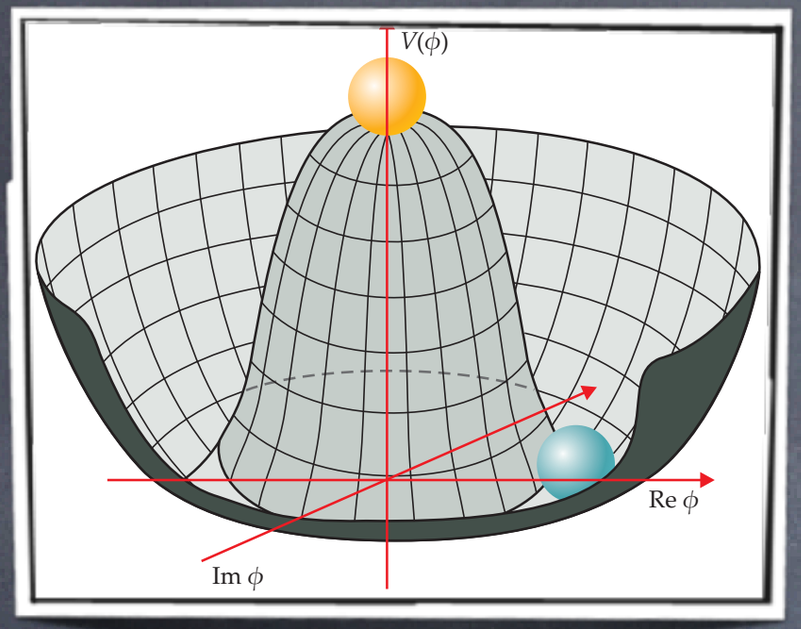

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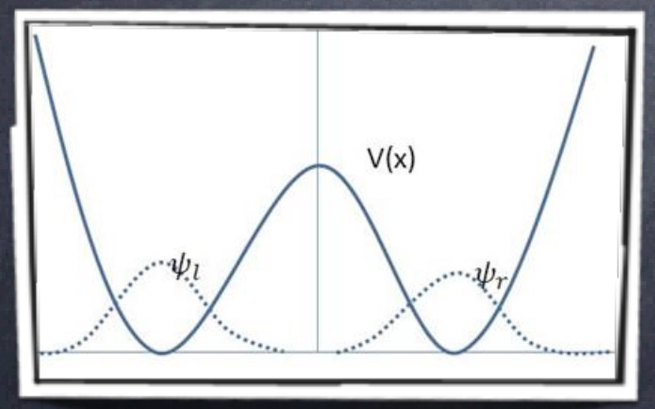
The Brout-Englert-Higgs mechanism is not a trivial thing

(courtesy of J. Lykken@Aspen2014)



ground state of QM double well potential
is a superposition of two states localized on one minimum,
and this superposition preserves the Z_2 symmetry of the potential

the vacuum of the SM breaks SU(2)xU(1) to $U(1)_{em}$

Spontaneous Symmetry Breaking

Isotropy in
the 3 spatial directions

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Isotropy in
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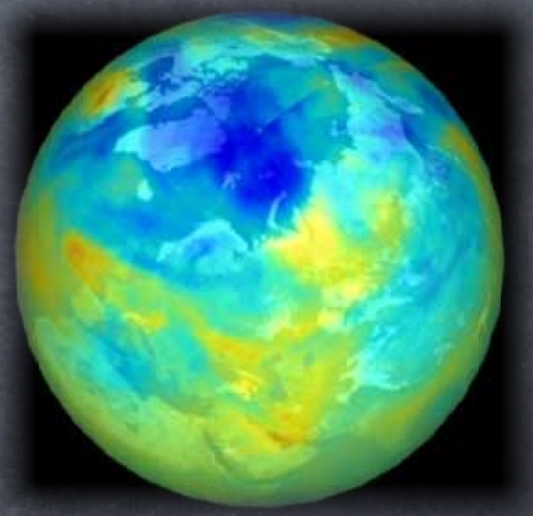

On Earth:
isotropy in the 2 horizontal directions only

Spontaneous Symmetry Breaking

Isotropy in
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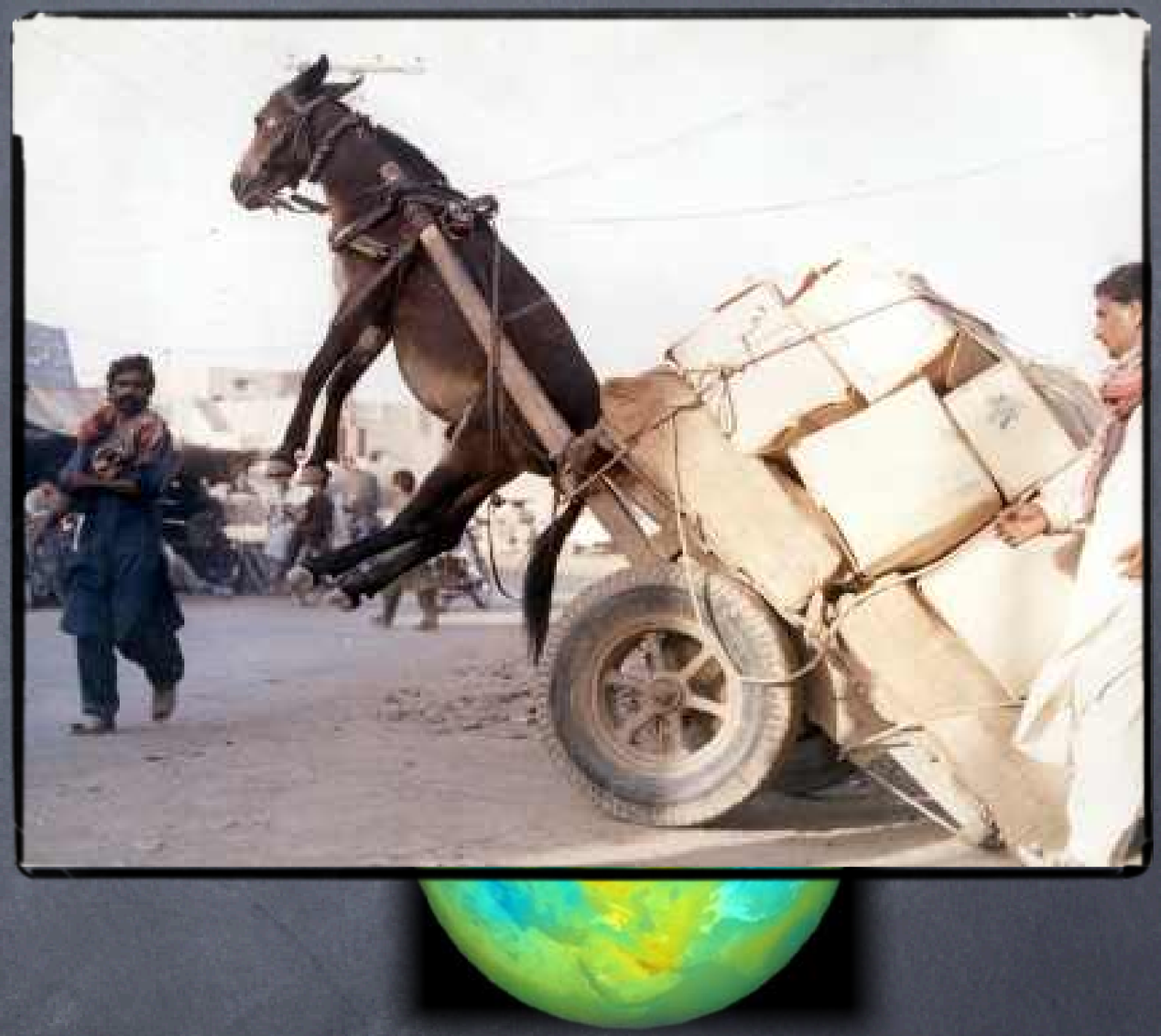

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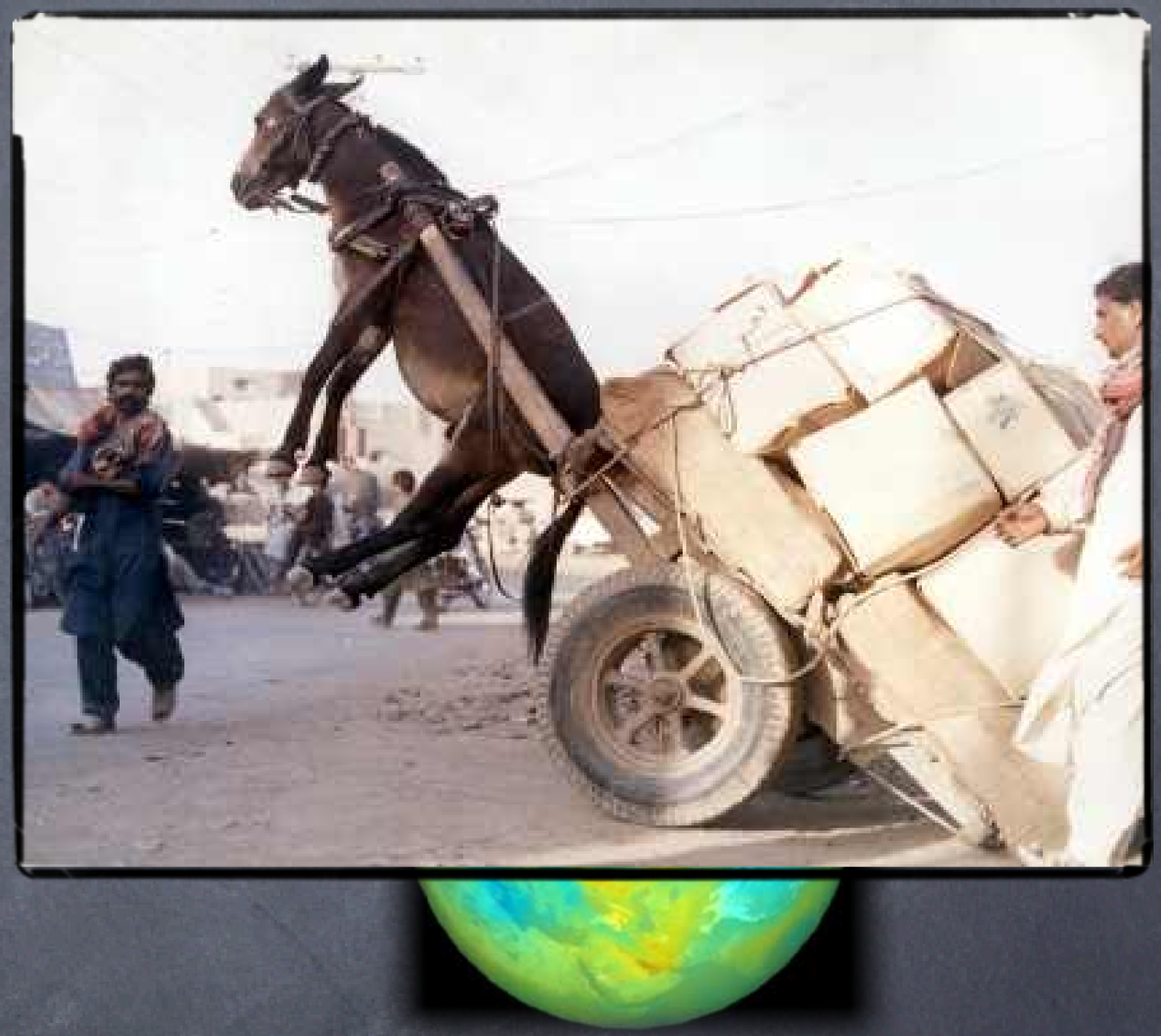
SO(3)



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SO(3) → SO(2)

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~ 10^{-10}s after Big-Bang
space-time crystallized into a new form/state

Why did Nature fill vacuum with Higgs substance?
because it saved energy!

(courtesy @ G. Giudice)

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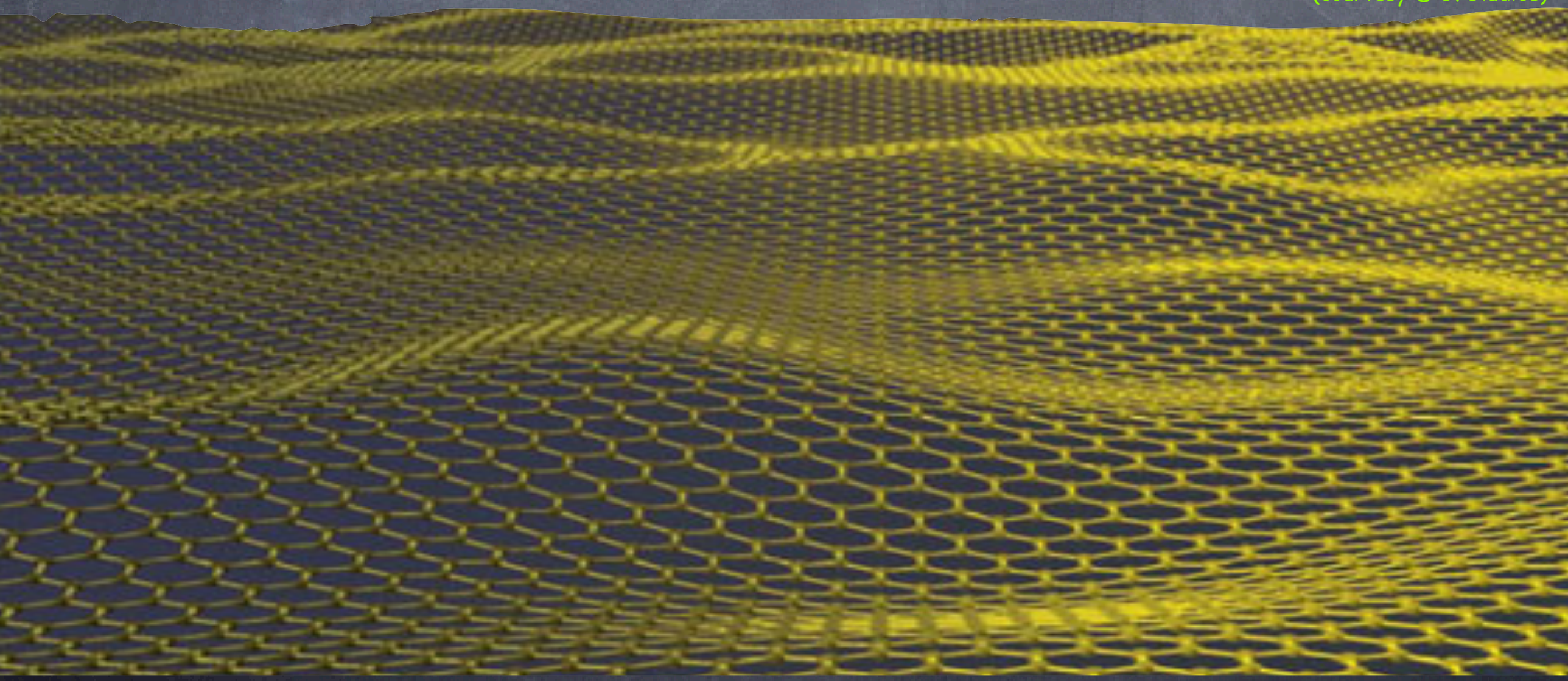

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This Higgs substance is the same
in every point and direction in space time
But it breaks the symmetry between electrons and neutrinos

Electroweak Symmetry Breaking

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space-time crystallized into a new form/state

Why did Na[illegible] vacuum with Higgs substance?

(courtesy @ G. Giudice)

Cosmologists think that it is during this phase transition that matter could have taken over antimatter

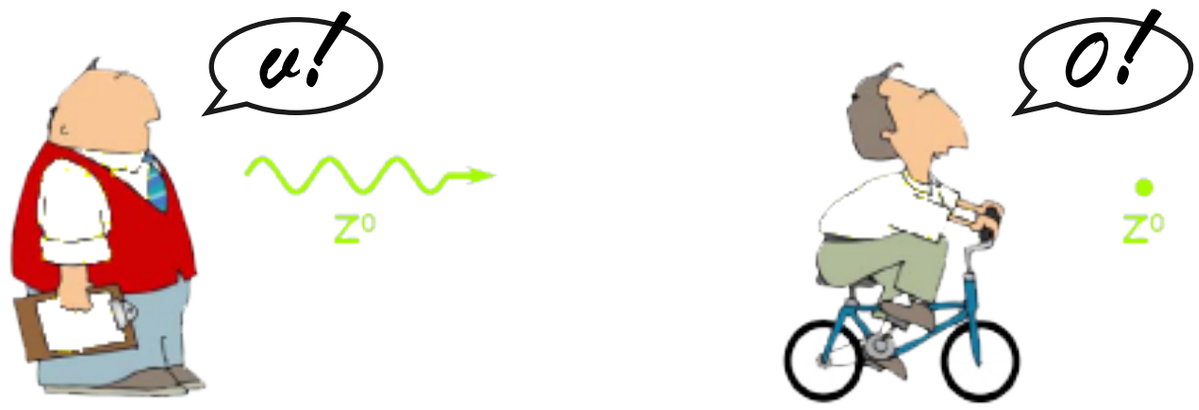
1

The importance of being Higgs

… or "why the Higgs boson is not just yet another particle?"

The longitudinal polarization of massive W, Z

a massless particle is never at rest: always possible to distinguish (and eliminate!) the longitudinal polarization



the longitudinal polarization is physical for a massive spin-1 particle

(pictures: courtesy of G. Giudice)

symmetry breaking: new phase with more degrees of freedom

$$\epsilon_{\parallel} = \left(\frac{|\vec{p}|}{M}, \frac{E}{M} \frac{\vec{p}}{|\vec{p}|} \right)$$ polarization vector grows with the energy

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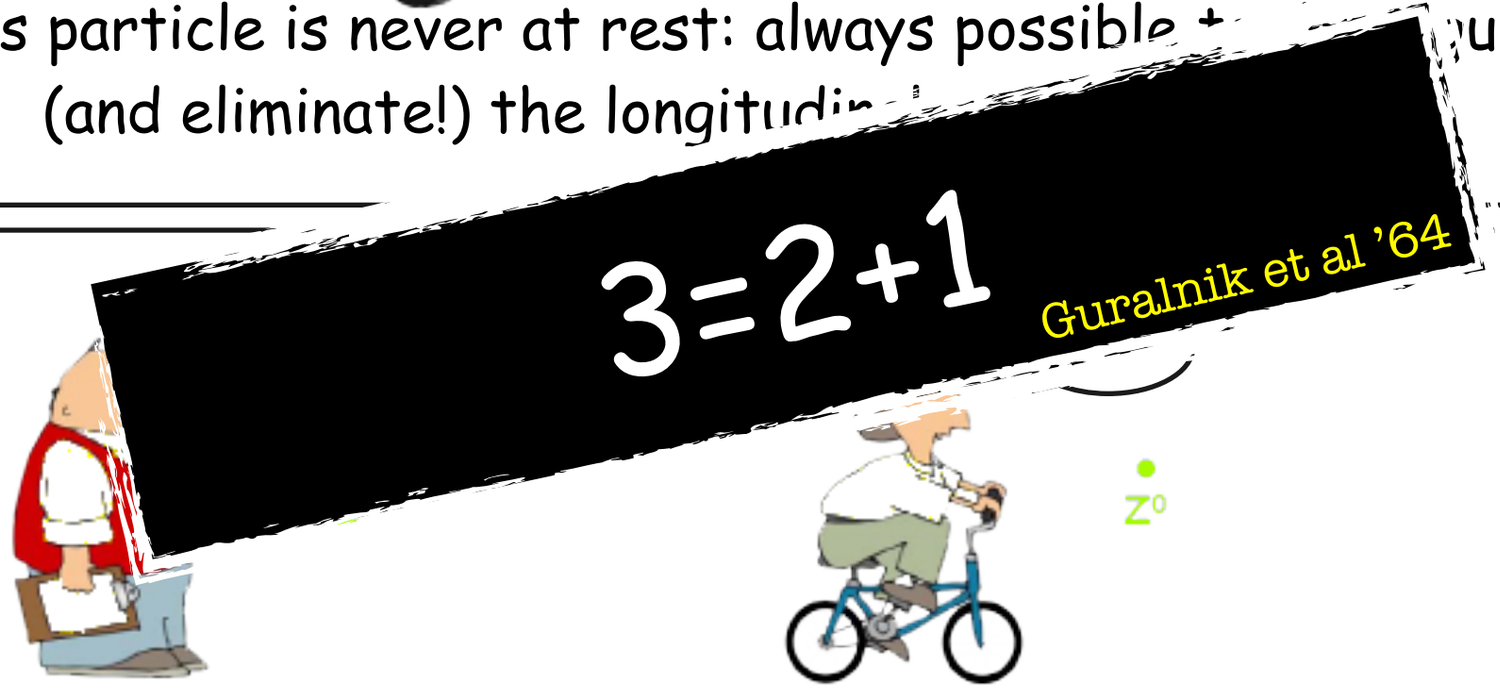

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The UV behavior of the weak Goldstone

symmetry breaking: new phase with more degrees of freedom

massive $W^{\pm}$, Z: 3 physical polarizations=eaten Goldstone bosons $\frac{SU(2)_L \times SU(2)_R}{SU(2)_V}$

$\Rightarrow$ UV behavior of these Goldstone's? $\Leftarrow$

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$$\Sigma = e^{i\sigma^a \pi^a / v}$$

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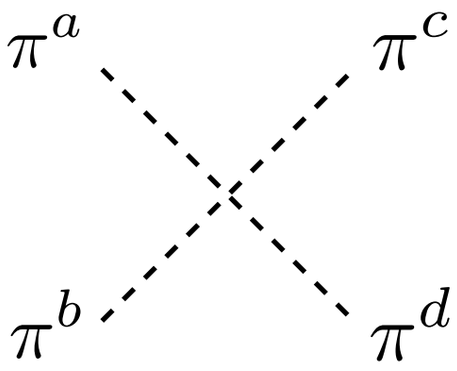
$$\mathcal{L}_{\rm mass} = \frac{1}{2}(\partial_\mu \pi^a)^2 - \frac{1}{6v^2}\left((\pi^a \partial_\mu \pi^a)^2 - (\pi^a)^2 (\partial_\mu \pi^a)^2\right) + \dots$$

contact interaction growing with energy



$$\mathcal{A}\left(\pi^a \pi^b \to \pi^c \pi^d\right) = \mathcal{A}(s,t,u)\delta^{ab}\delta^{cd} + \mathcal{A}(t,s,u)\delta^{ac}\delta^{bd} + \mathcal{A}(u,t,s)\delta^{ad}\delta^{bc}$$

$$\mathcal{A}(s,t,u) = \frac{s}{v^2}$$ Weinberg's LET

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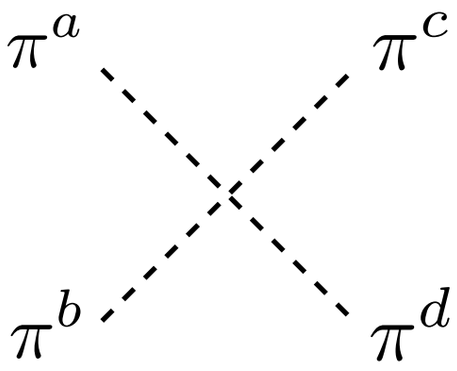

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the behavior of this amplitude is not consistent above $4\pi v$ (≈1÷3 TeV)

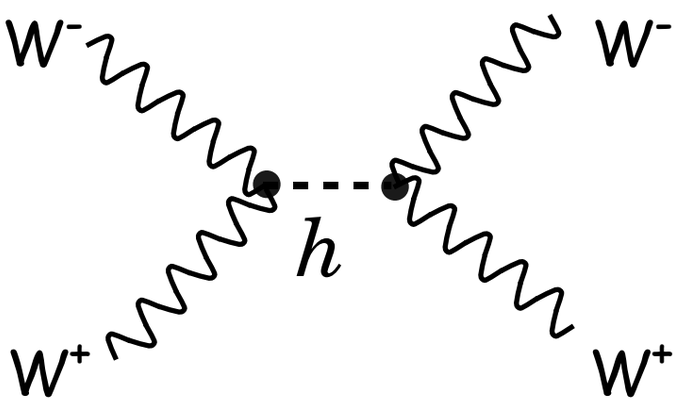
Lee, Quigg & Thacker '77

What is the Higgs the name of?

A single scalar degree of freedom neutral under $SU(2)_L \times SU(2)_R/SU(2)_V$

$$\mathcal{L}_{\rm EWSB} = \frac{v^2}{4}{\rm Tr}\left(D_\mu \Sigma^\dagger D_\mu \Sigma\right)\left(1+2a\frac{h}{v}+b\frac{h^2}{v^2}\right) - \lambda \bar{\psi}_L \Sigma \psi_R \left(1+c\frac{h}{v}\right)$$

'a', 'b' and 'c' are arbitrary free couplings



$$\mathcal{A} = \frac{1}{v^2}\left(s - \frac{a^2 s^2}{s-m_h^2}\right)$$

growth cancelled for
a = 1
restoration of
perturbative unitarity

Cornwall, Levin, Tiktopoulos '73

Contino, Grojean, Moretti, Piccinini, Rattazzi '10

$\Sigma = e^{i\sigma^a \pi^a / v}$ Goldstone of $SU(2)_L \times SU(2)_R/SU(2)_V$ $D_\mu \Sigma \approx W_\mu$

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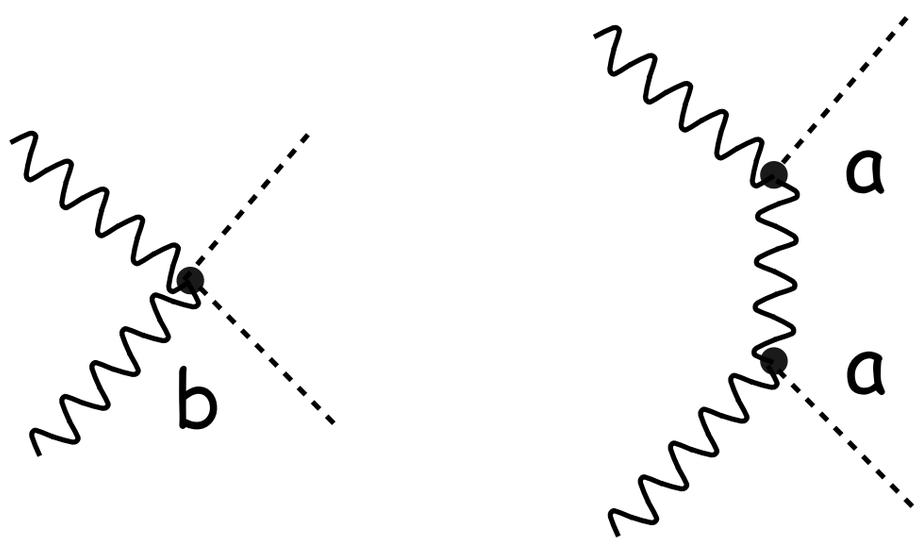
For a=1: perturbative unitarity in elastic channels $WW \to WW$

For $b = a^2$: perturbative unitarity in inelastic channels $WW \to hh$

Cornwall, Levin, Tiktopoulos '73

Contino, Grojean, Moretti, Piccinini, Rattazzi '10



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Cornwall, Levin, Tiktopoulos '73

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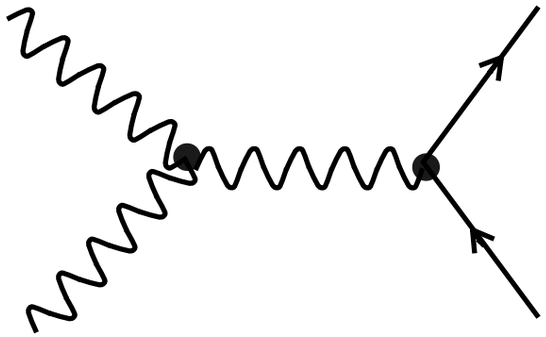
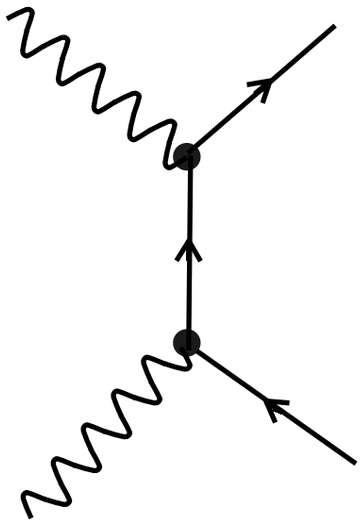
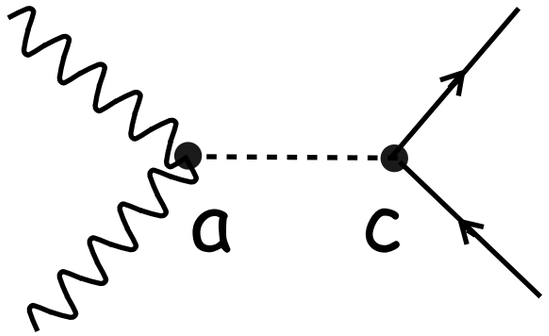






What is the Higgs the name of?

A single scalar degree of freedom neutral under $SU(2)_L \times SU(2)_R / SU(2)_V$

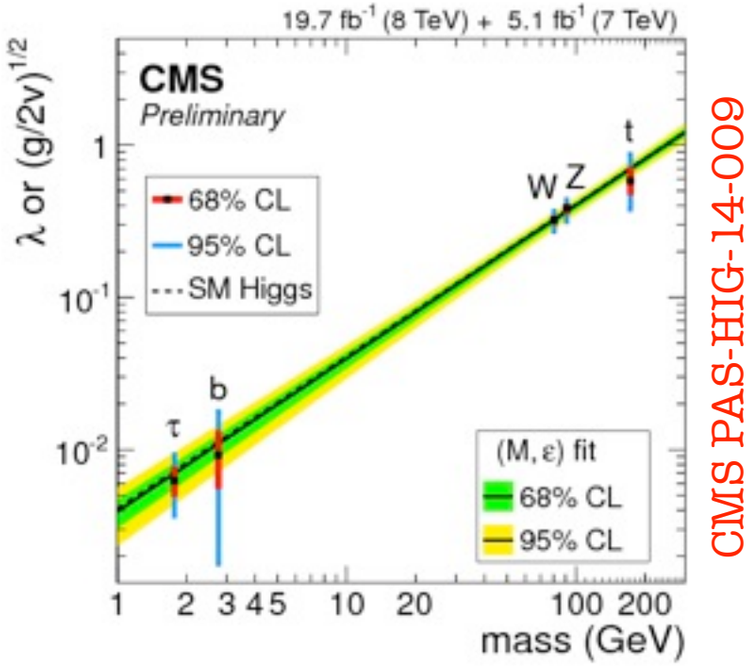
$$\mathcal{L}_{\rm EWSB} = \frac{v^2}{4}{\rm Tr}\left(D_\mu \Sigma^\dagger D_\mu \Sigma\right)\left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2}\right) - \lambda \bar{\psi}_L \Sigma \psi_R \left(1 + c\frac{h}{v}\right)$$

'a', 'b' and 'c' are arbitrary free couplings

For a=1: perturbative unitarity in elastic channels $WW \to WW$

For $b = a^2$: perturbative unitarity in inelastic channels $WW \to hh$

For ac=1: perturbative unitarity in inelastic $WW \to \psi\,\psi$



CMS PAS-HIG-14-009

Higgs couplings
are proportional
to the masses of the particles

$$\lambda_\psi \propto \frac{m_\psi}{v}\,, \qquad \lambda_V^2 \equiv \frac{g_{VVh}}{2v} \propto \frac{m_V^2}{v^2}$$

What is the Higgs the name of?

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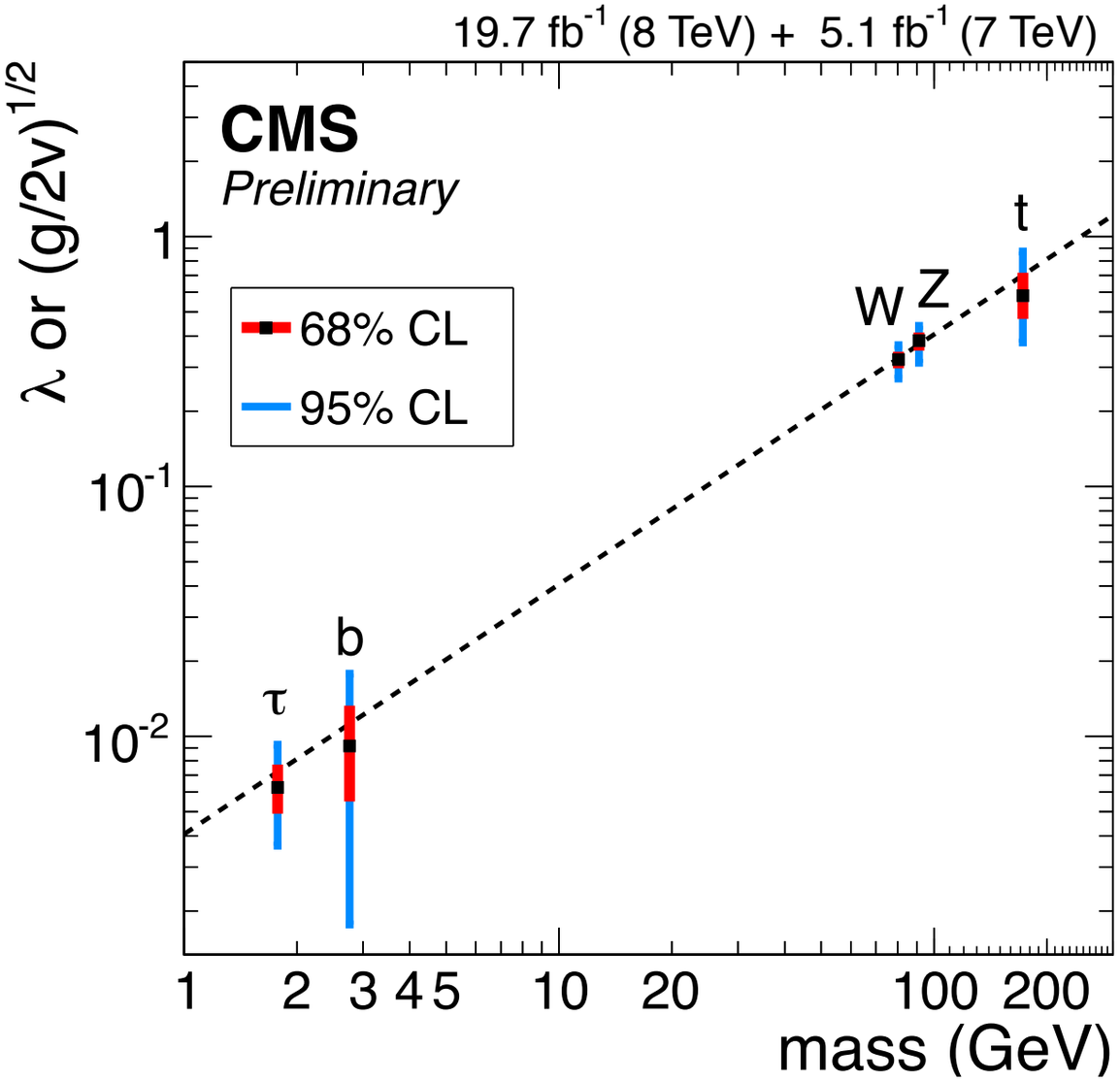

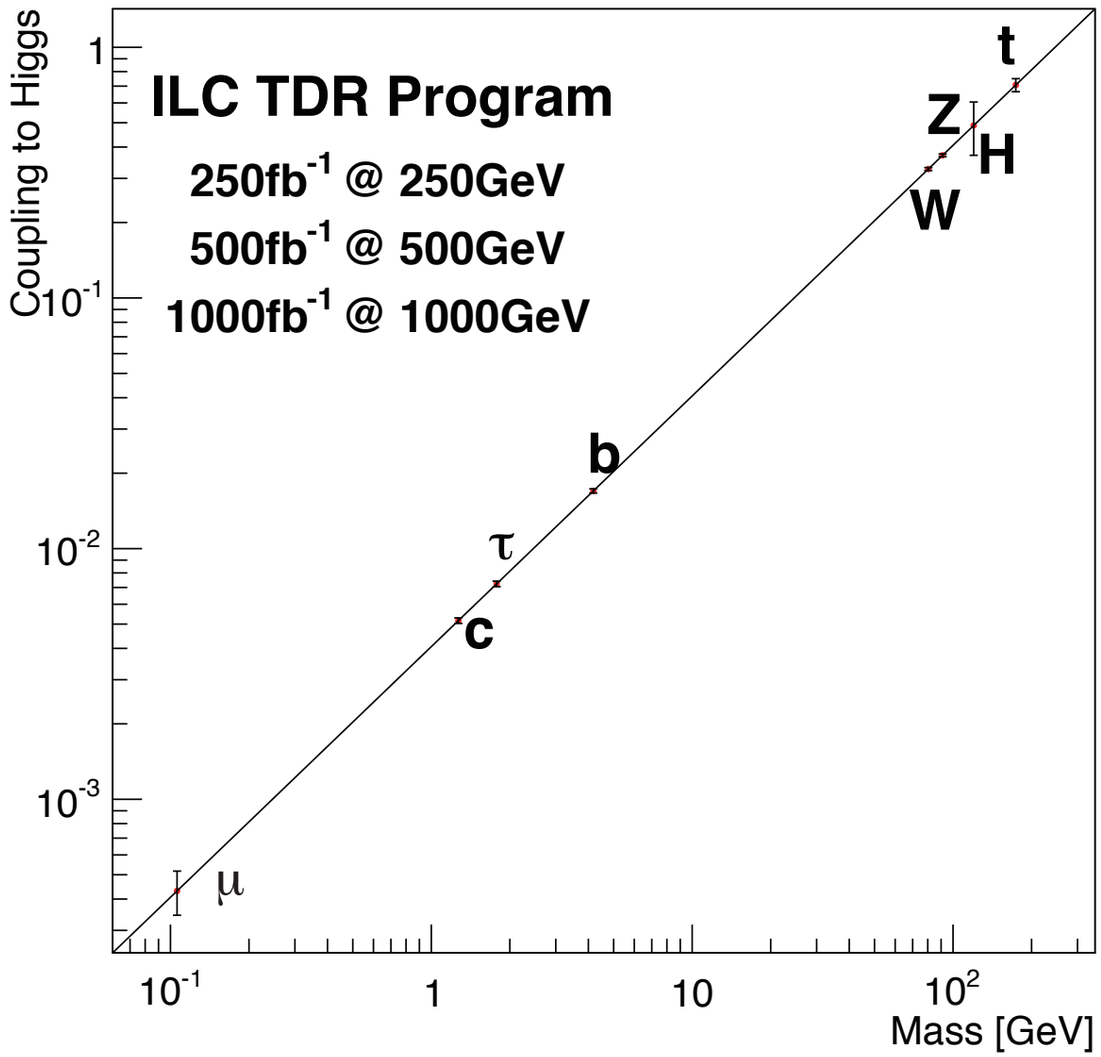

The LHC cannot fully confirm this picture

(no model-independent measurements of the couplings, no access to the couplings to light particles...)

Higgs boson at the LHC

producing a Higgs boson is a rare phenomenon

since its interactions with particles are proportional to masses

and ordinary matter is made of light elementary particles

NB: the proton is not an elementary particle,

its mass doesn't measure its interaction with the Higgs substance

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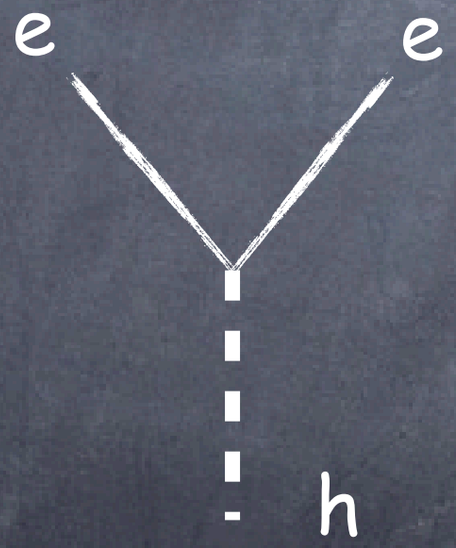
From electrons



probability ~ 10^{-11}

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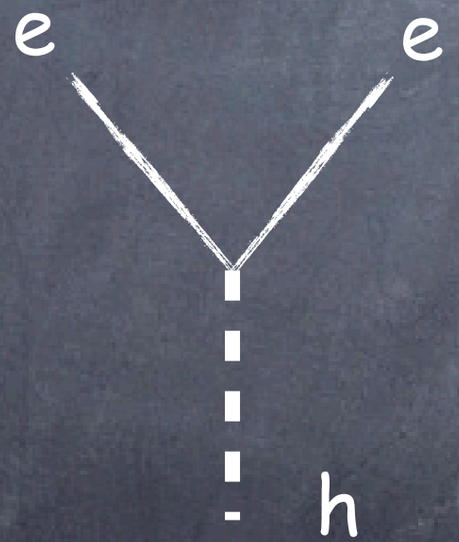
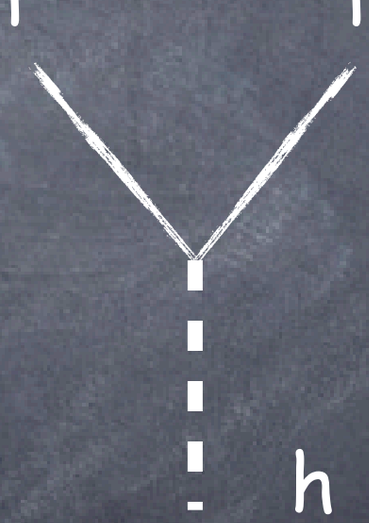


probability ~ 10^{-11}

From top quarks

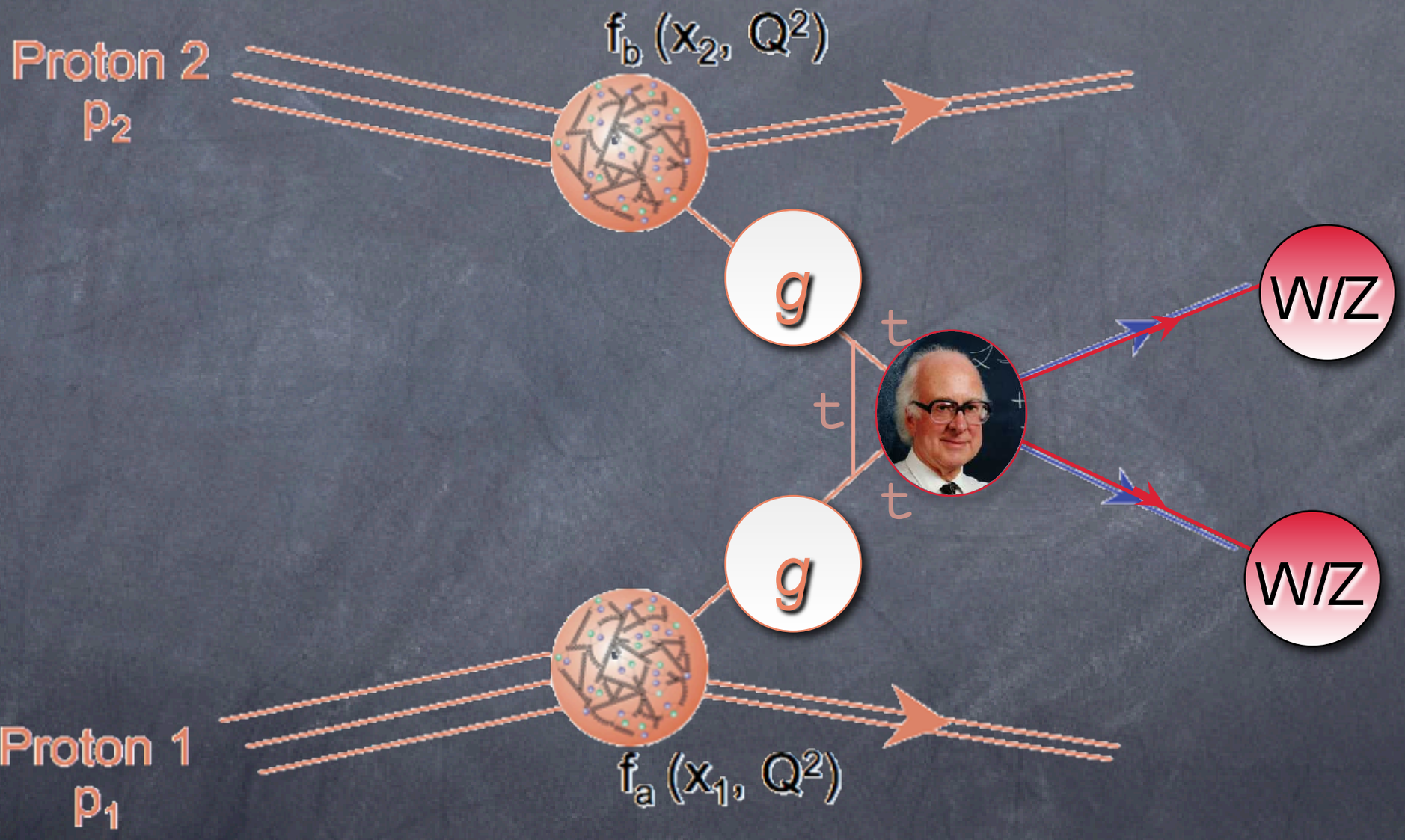


probability ~ 1

but no top quark at our disposal

Higgs boson at the LHC

Higgs boson at the LHC



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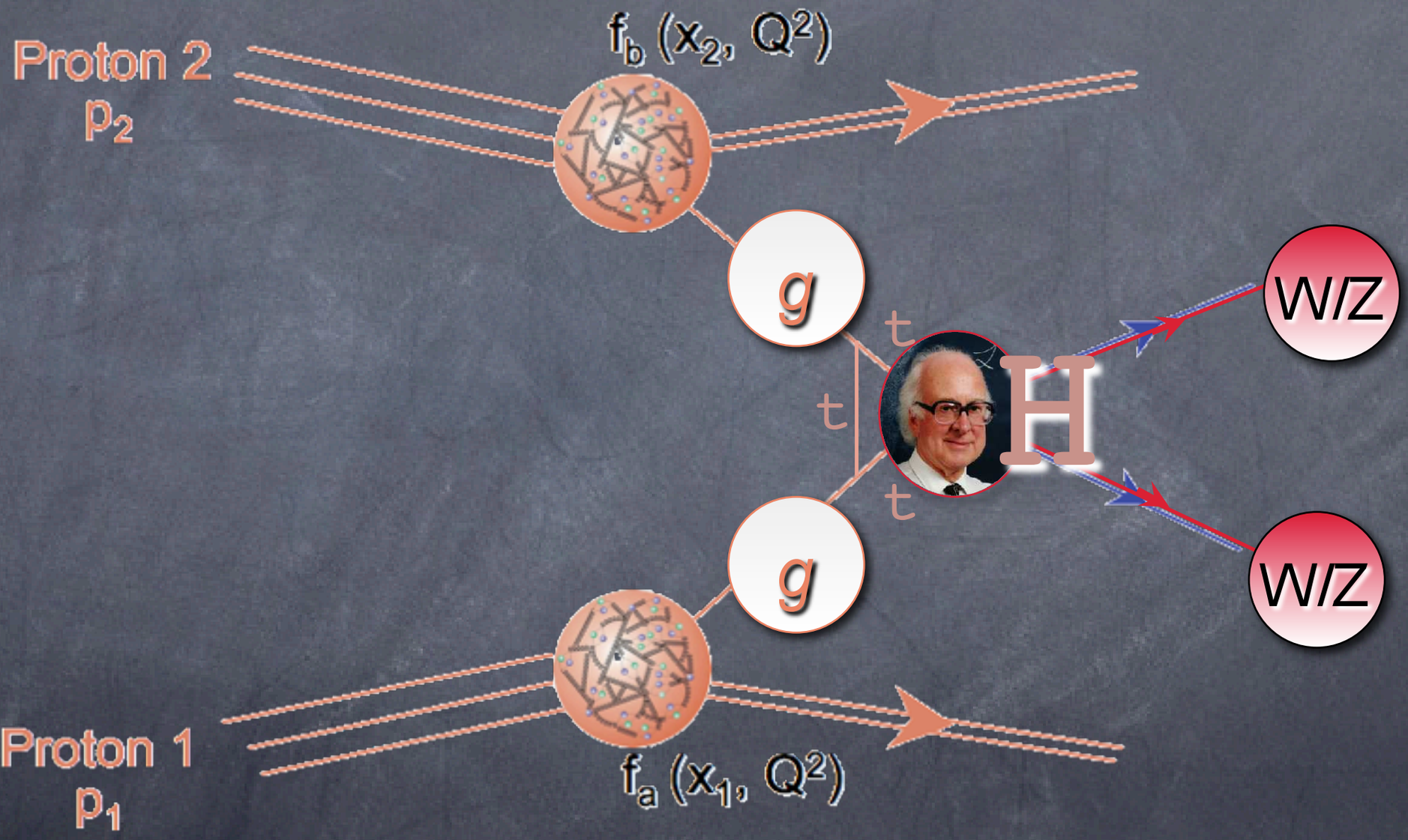

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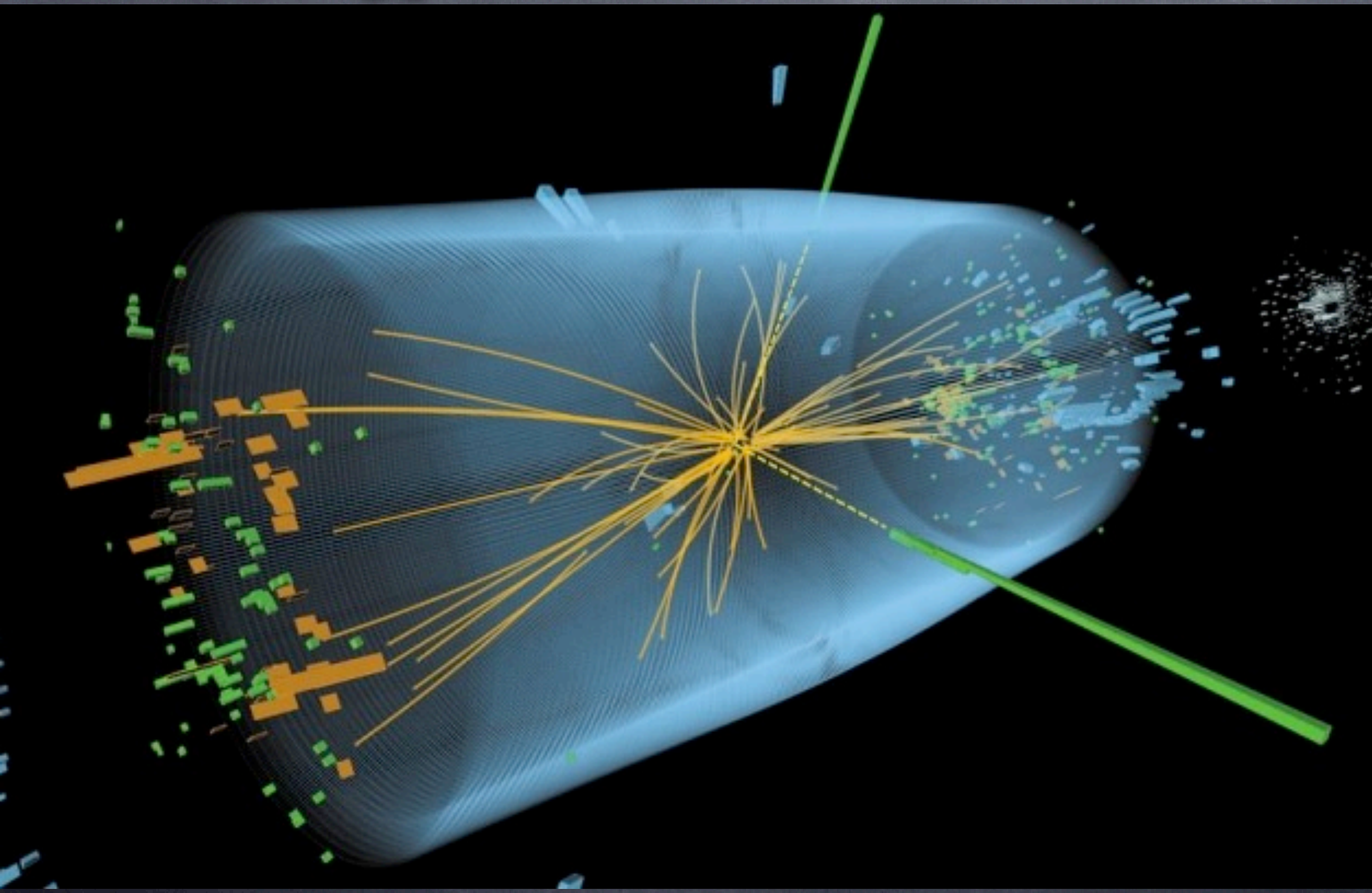
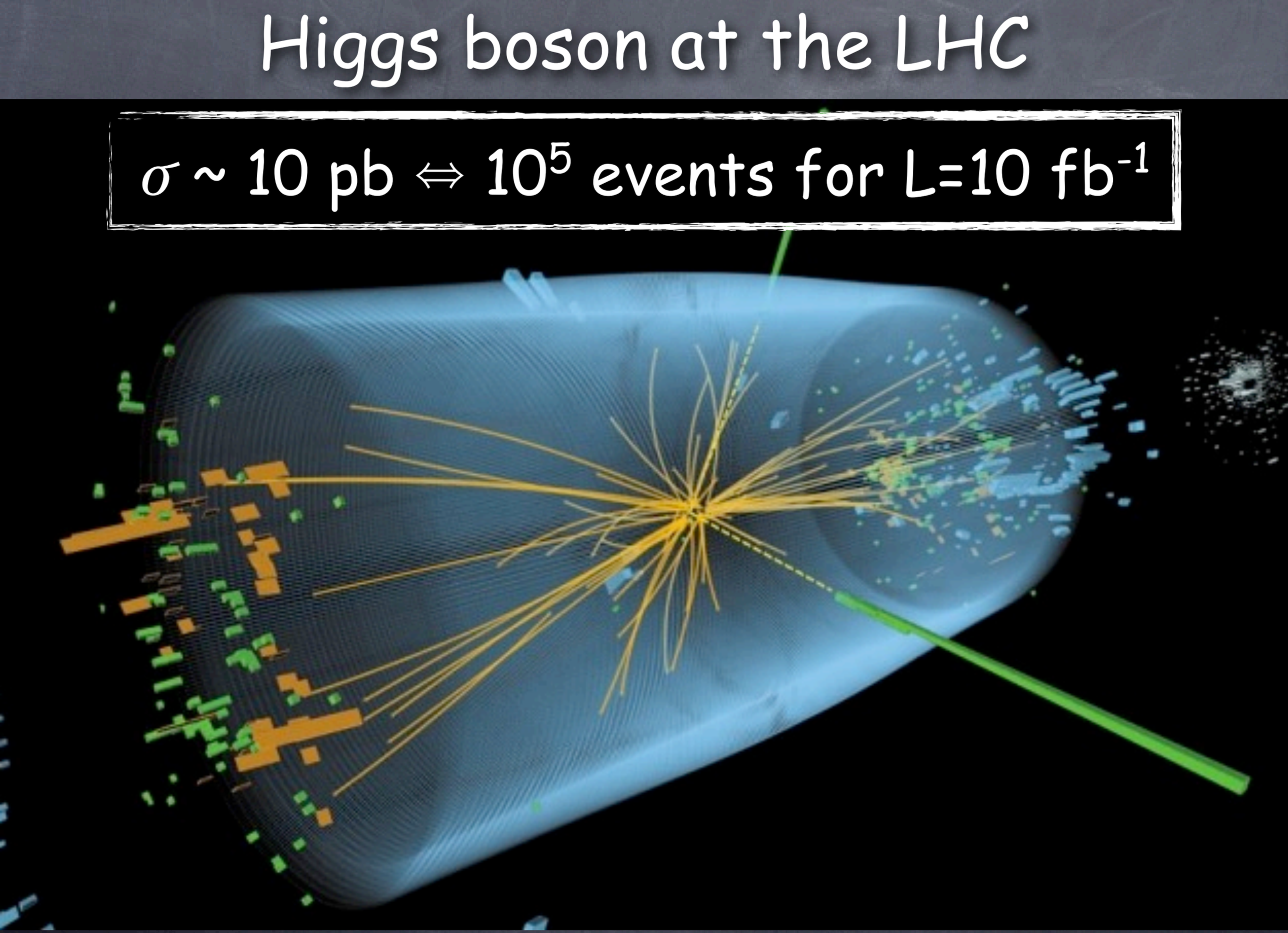


Higgs boson at the LHC

$\sigma \sim 10$ pb $\Leftrightarrow 10^5$ events for L=10 fb^{-1}



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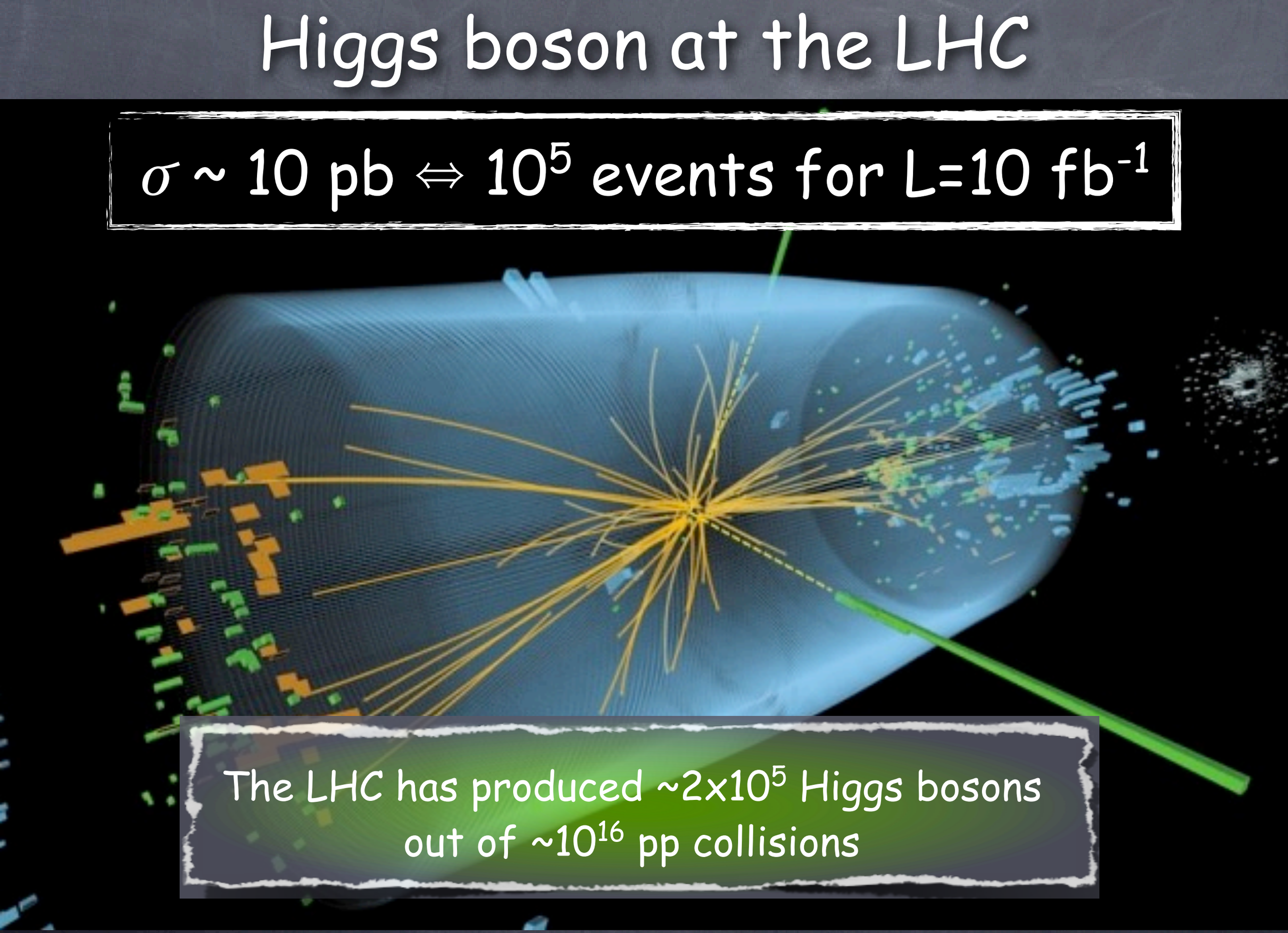
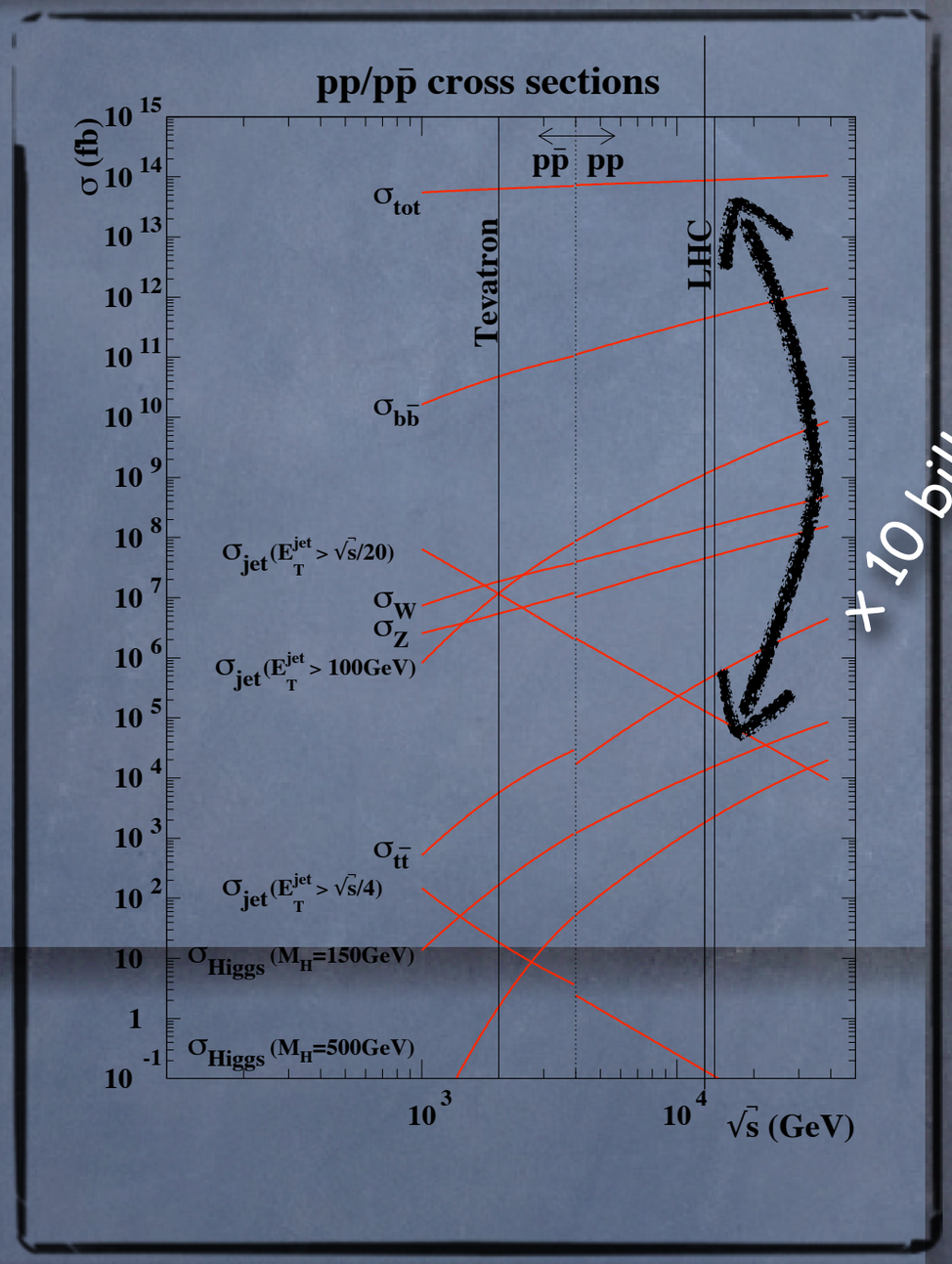
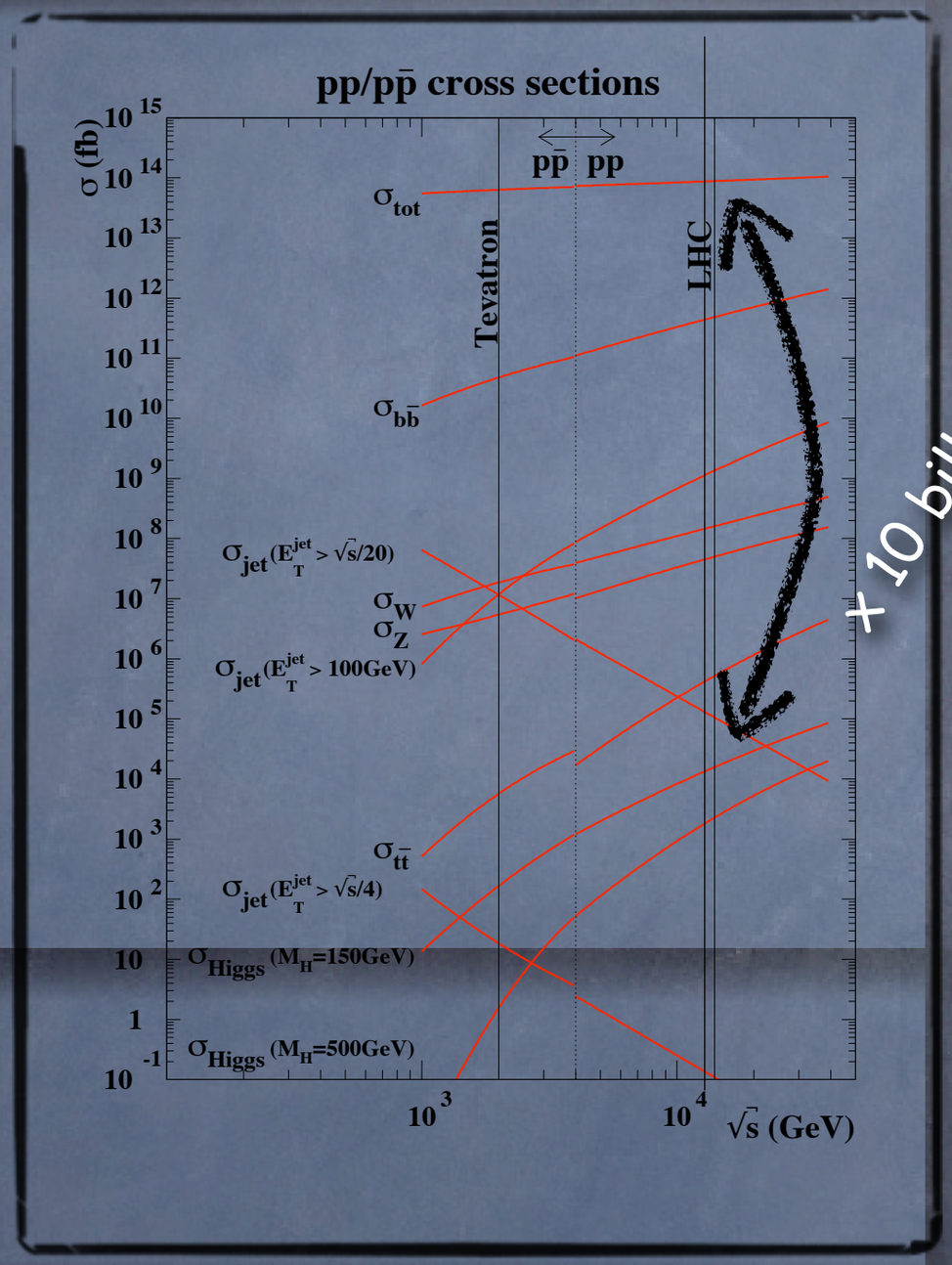


The LHC has produced ~2×10^5 Higgs bosons
out of ~10^{16} pp collisions

The search for the Higgs boson



The search for the Higgs boson



only
1 collision out of 10 billons
produces a Higgs boson

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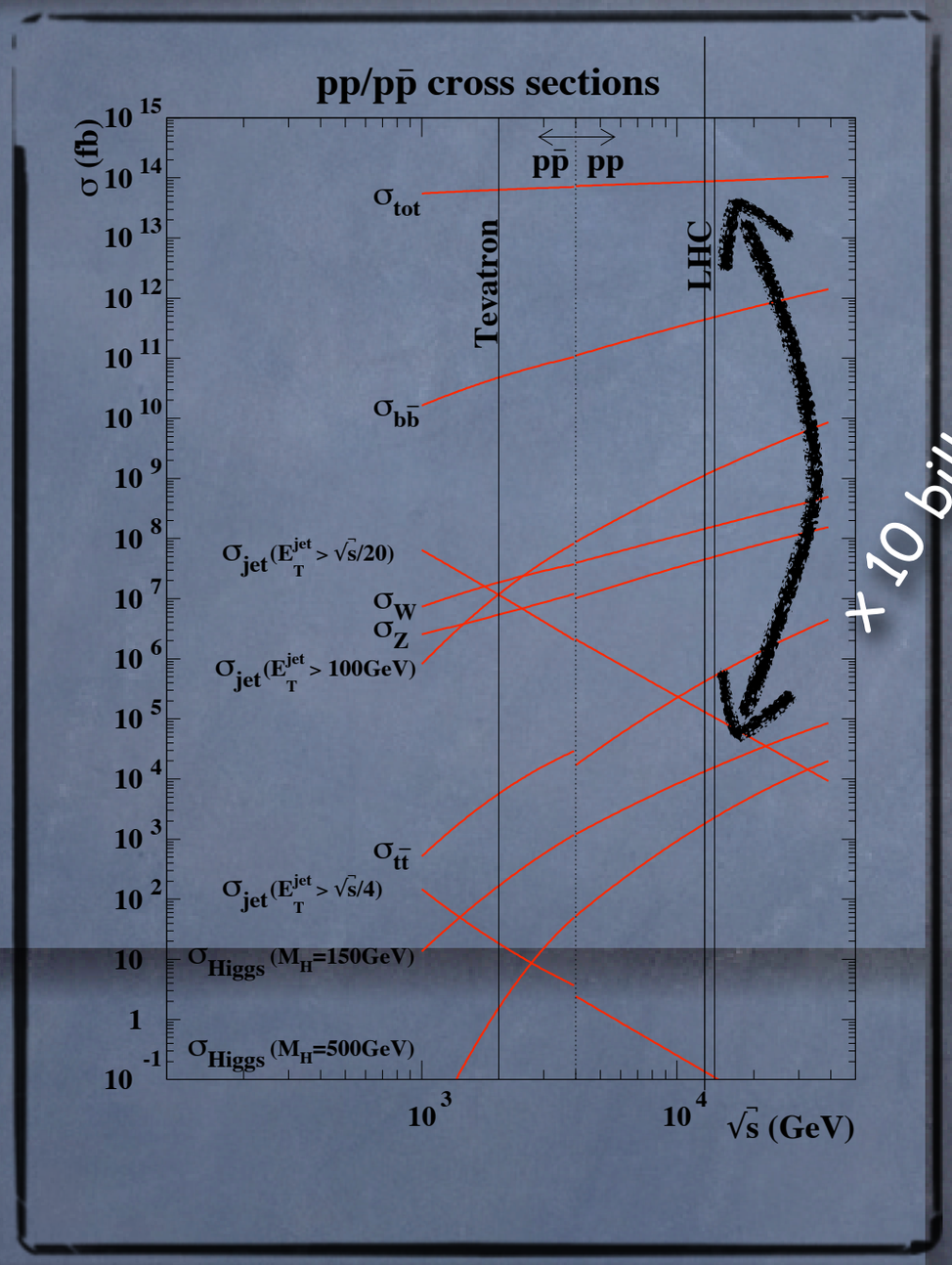

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finding a Higgs boson is like...

The search for the Higgs boson

only
1 collision out of 10 billons
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finding a Higgs boson is like...

... finding the interesting paper
in John Ellis' office at CERN

... finding a book in a library 1000 times
as large as the French Library
while all the books have the same size,
the same cover, the same color...

2

What exactly has the LHC found?
How to know? What to measure?

Now what? What's next?

Now what? What's next?

" With great power comes great responsibility"

Voltaire & Spider-Man

Now what? What's next?

"With great power comes great responsibility"

which, in particle physics, really means

Voltaire & Spider-Man

"With great discoveries come great measurements"

BSMers desperately looking for anomalies

(true credit: F. Maltoni)

The Higgs has access to EW coupled New Physics

which is less constrained by direct searches than strongly coupled NP

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1

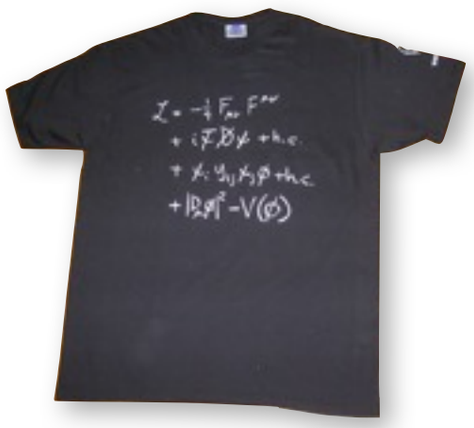
Higgs properties

J^{PC}

Important & nice to see progresses but "this question carries a similar potential for surprise as a football game between Brazil and Tonga" Resonaances

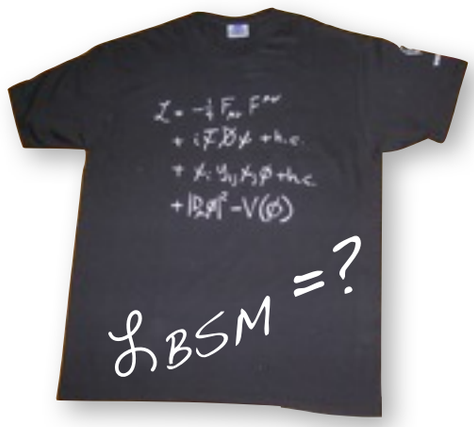
2

Higgs couplings



3

BSM implications



HEP with a Higgs boson

" If you don't have the ball, you cannot score"

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Now with the Higgs boson in their hands,
particle physicists can... play as well as Germans against Brazilians

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Higgs as a target

- observe it in as many channels as possible to measure its properties
- check of the coupling structure of the SM and its deformations
- interpret deviations of Higgs couplings as a sign of NP

Higgs as a tool

- a portal to New Physics
- in initial states: rare decays

e.g., $h \to \mu\tau$, $h \to J/\Psi+\gamma$

- in final states as an object that can be reconstructed and tagged

e.g., $t \to h+c$, $H \to hh$

HEP with a Higgs boson

" If you don't have the ball, you cannot score"

Now with the Higgs boson in their hands,
particle physicists can... play as well as Germans against Brazilians

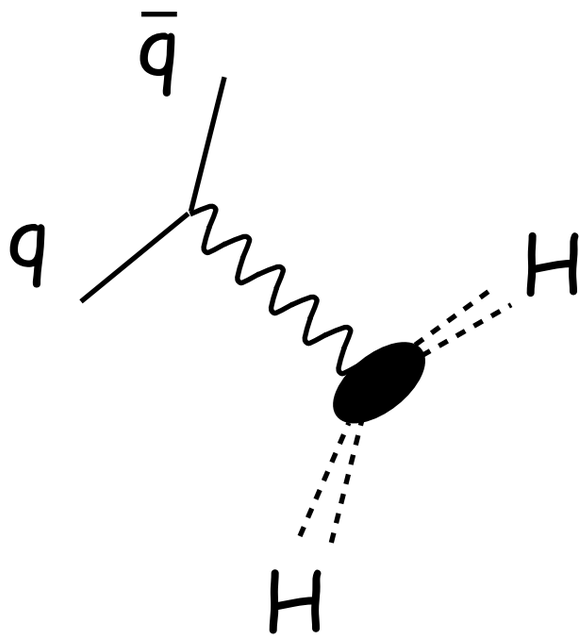
- Is it the SM Higgs?
- Is it an elementary/composite particle?
- Is it unique/solitary?
- Is it eternal/temporary?
- Is it natural?
- Is it the first supersymmetric particle ever observed?
- Is it really "responsible" for the masses of all the elementary particles?
- Is it mainly produced by top quarks or by new heavy vector-like quarks?
- Is it a portal to a hidden world/Dark Matter?
- Is it at the origin of the matter-antimatter asymmetry?
- Is it responsible for the inflationary expansion of the Universe?

Is the Higgs the first elementary scalar?

Unlikely that we'll ever see the fundamental constituents of the Higgs

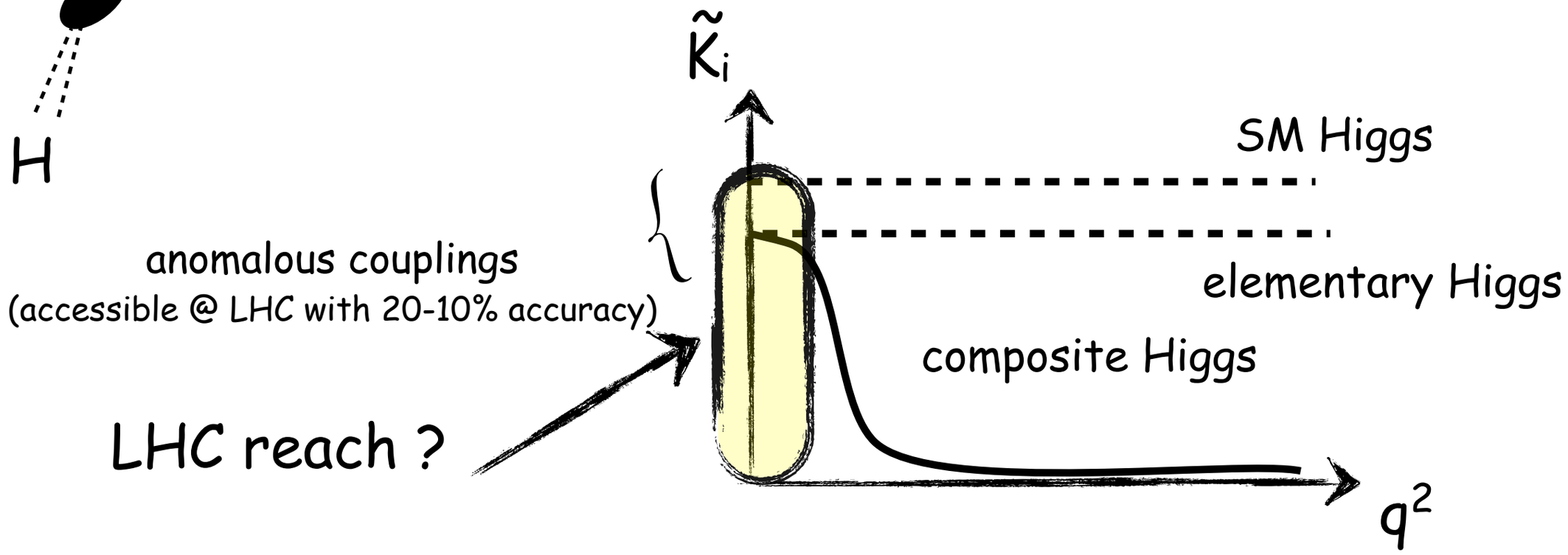
But we can infer that it is not an elementary particle

by measuring its couplings to SM particles

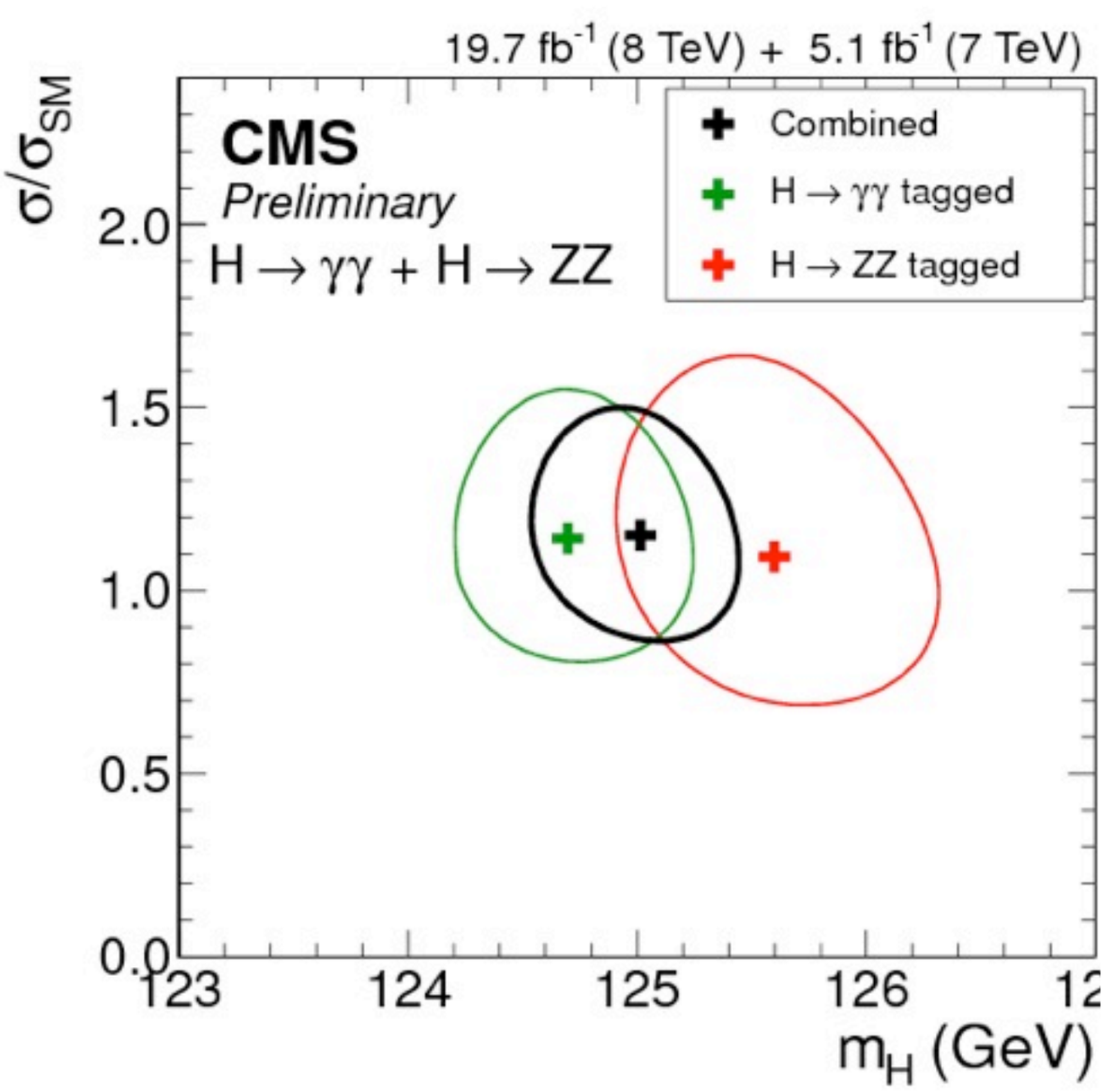


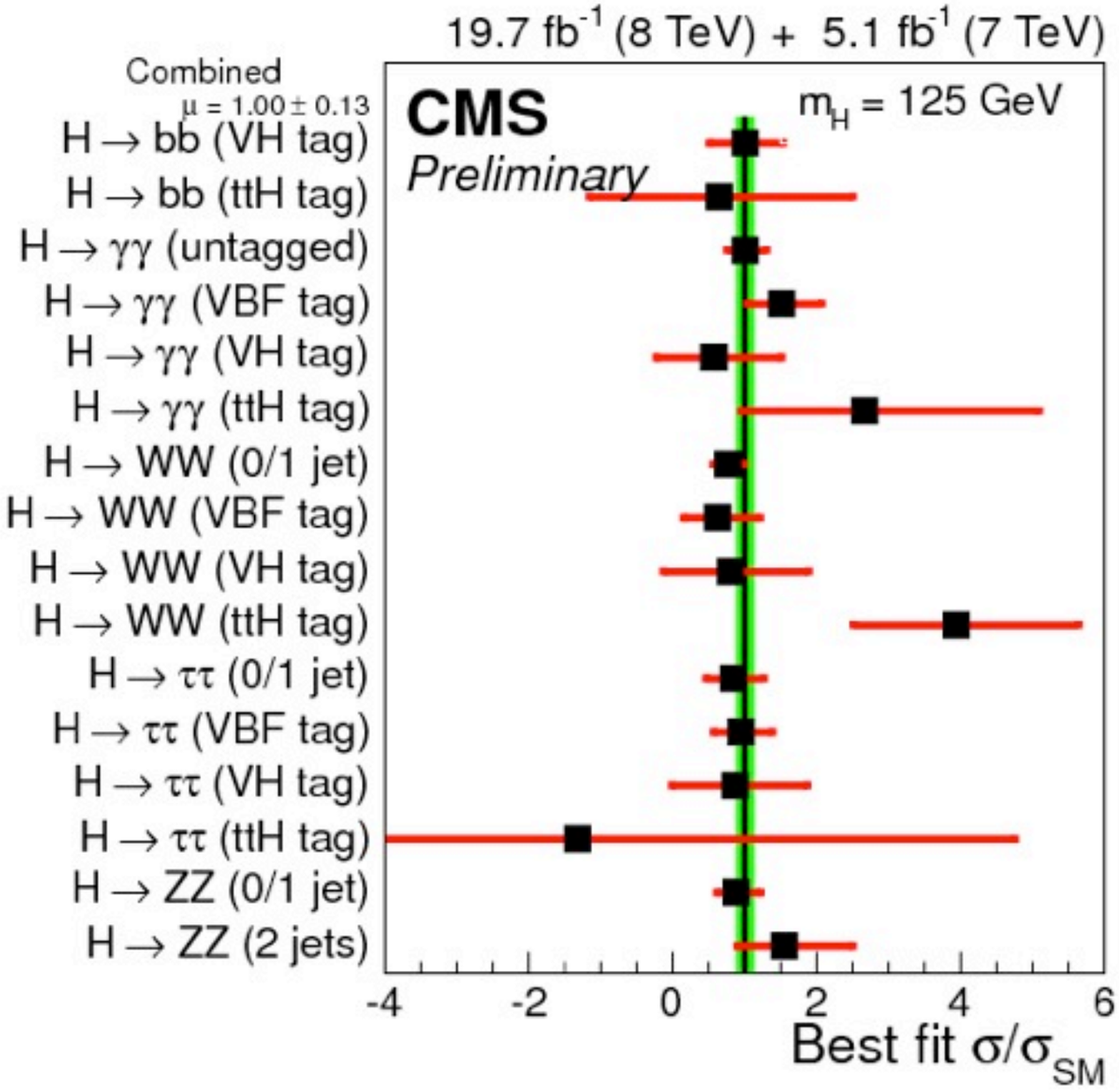
$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{16 m_H^2 \sin^4\theta/2} \frac{E'}{E^3} \left(2\tilde{K}_1 q^2 \sin^2\theta/2 + \tilde{K}_2 \cos^2\theta/2 \right)$$

Rosenbluth-type cross-section



Taming the beast





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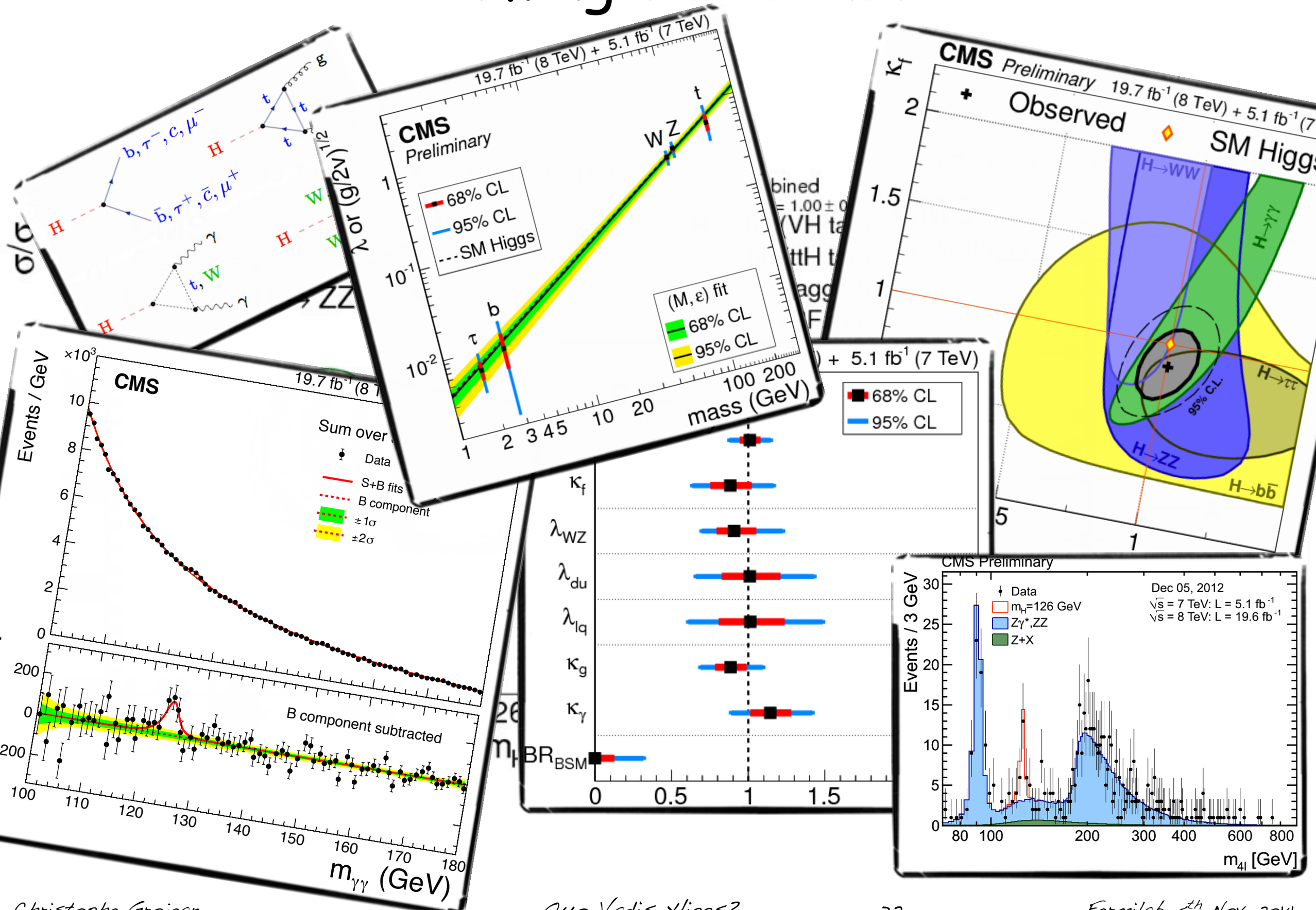
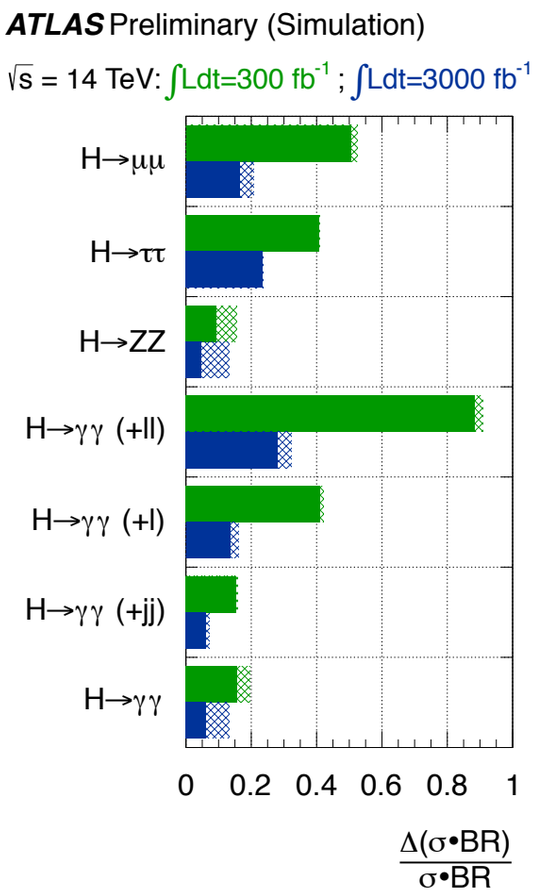
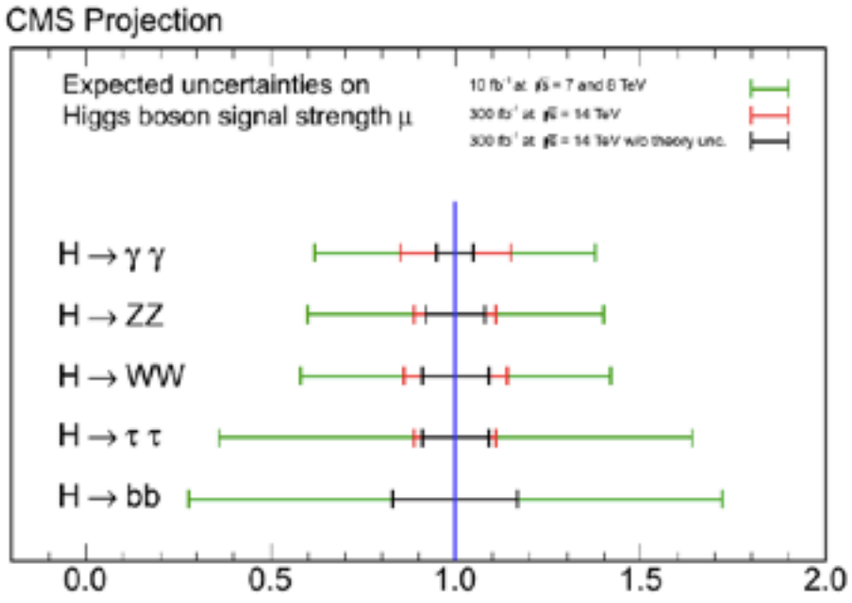
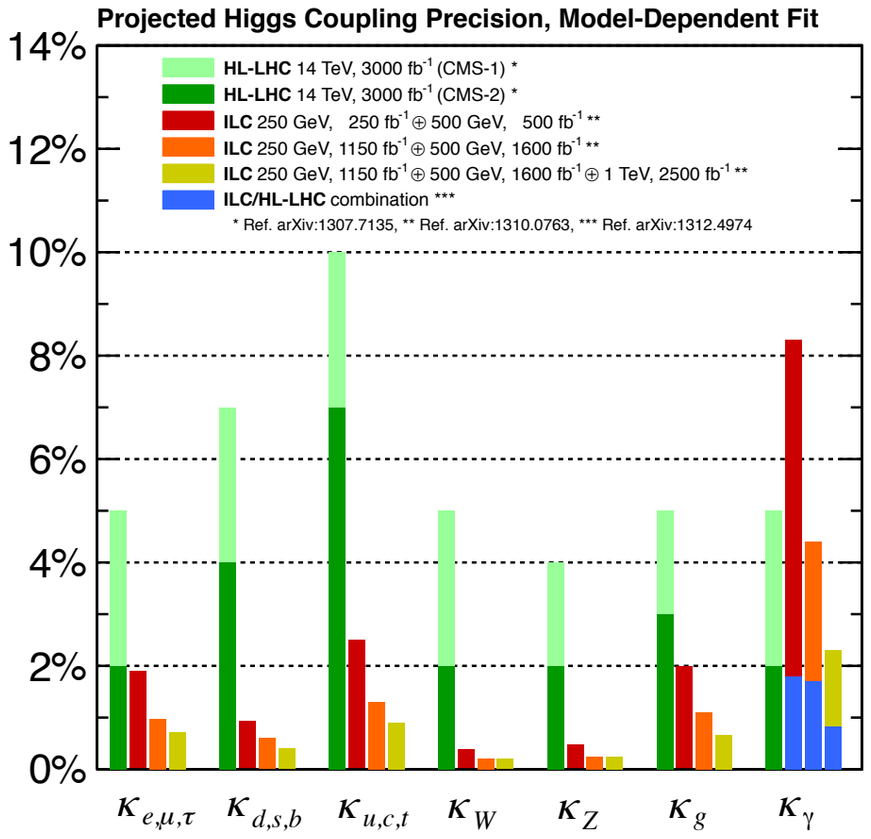


Higgs couplings measurements

$LHC_{300/fb}$, HL-LHC, ILC, CLIC
will measure Higgs couplings with good/excellent precision







5-10% @ $LHC^{14TeV}_{300/fb}$

1-5% @ ILC/CLIC

direct access to Γ_{inv}

Higgs and Flavor

In SM, the Yukawa interactions are the only source of the fermion masses

$$y_{ij}\bar{f}_{L_i}Hf_{R_j} = \frac{y_{ij}v}{\sqrt{2}}\bar{f}_{L_i}f_{R_j} + \frac{y_{ij}}{\sqrt{2}}h\bar{f}_{L_i}f_{R_j}$$

mass

higgs-fermion interactions

both matrices are simultaneously diagonalizable

no tree-level Flavor Changing Current induced by the Higgs

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⇓ ⇓ ⇓

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Not true anymore if the SM fermions mix with vector-like partners(*) or for non-SM Yukawa

$$y_{ij}\left(1+c_{ij}\frac{|H|^2}{f^2}\right)\bar{f}_{L_i}Hf_{R_j} = \frac{y_{ij}v}{\sqrt{2}}\left(1+c_{ij}\frac{v^2}{2f^2}\right)\bar{f}_{L_i}f_{R_j} + \left(1+3c_{ij}\frac{v^2}{2f^2}\right)\frac{y_{ij}}{\sqrt{2}}h\bar{f}_{L_i}f_{R_j}$$

(*) e.g. Buras, Grojean, Pokorski, Ziegler '11

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Look for SM forbidden Flavor Violating decays $h \to \mu\tau$ and $t \to hc$

- weak indirect constrained by flavor data (e.g. $\mu \to e\gamma$): BR<10%
- ATLAS and CMS have the sensitivity to set bounds O(1%)
- ILC/CLIC/FCC-ee can certainly do much better

Blankenburg, Ellis, Isidori '12

Harnik et al '12
Davidson, Verdier '12
CMS-PAS-HIG-2014-005

(*) e.g. Buras, Grojean, Pokorski, Ziegler '11

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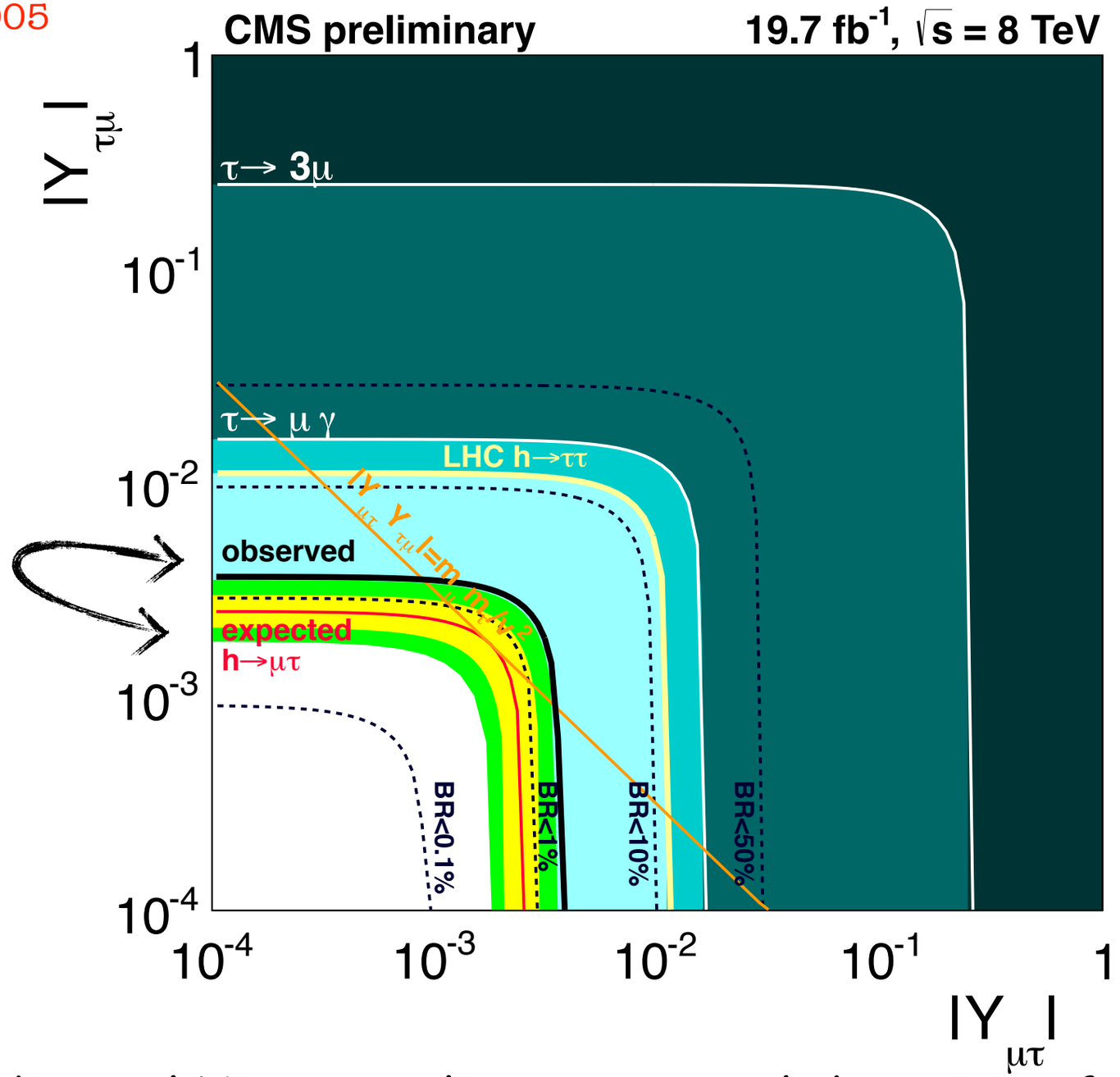
CMS-PAS-HIG-2014-005



by the way:
2.3σ excess!

Off-diagonal Higgs couplings can reveal the origin of flavor

We need to know the prospects to measure them at lepton colliders!

3

Multi Higgs, boosted and off-shell Higgs channels

Beyond single Higgs processes

Producing one Higgs is good. Producing H+X is better

@ 14 TeV

Higgs multiplicty →

Jet multiplicty ↓

Single h		Double h		Triple H	
h	$\sim 50\ \mathrm{pb}^{gg}$	hh	$\sim 34\ \mathrm{fb}^{gg}$	hhh	$\sim 44\ \mathrm{ab}^{gg}$
h+j	$\sim 2\ \mathrm{pb}^{p_T(j)>100}$	hh+j			
h+jj	$\sim 4.2\ \mathrm{pb}^{VBF}$	hh+jj	$\sim 2\ \mathrm{fb}^{VBF}$		

- also roughly indicates possible initial states/related kinematics
- Jet multiplicity might be replaced with V=W,Z, top, etc…

(adapted from M. Son@Planck2014)

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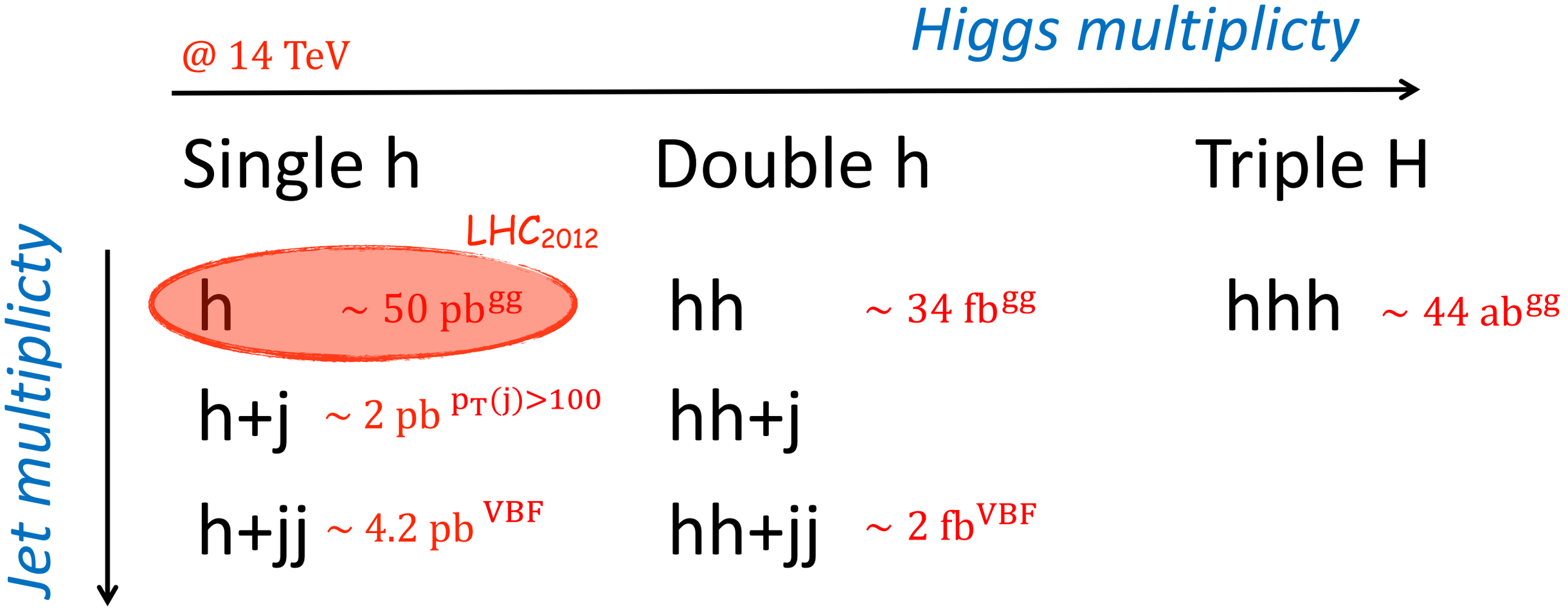

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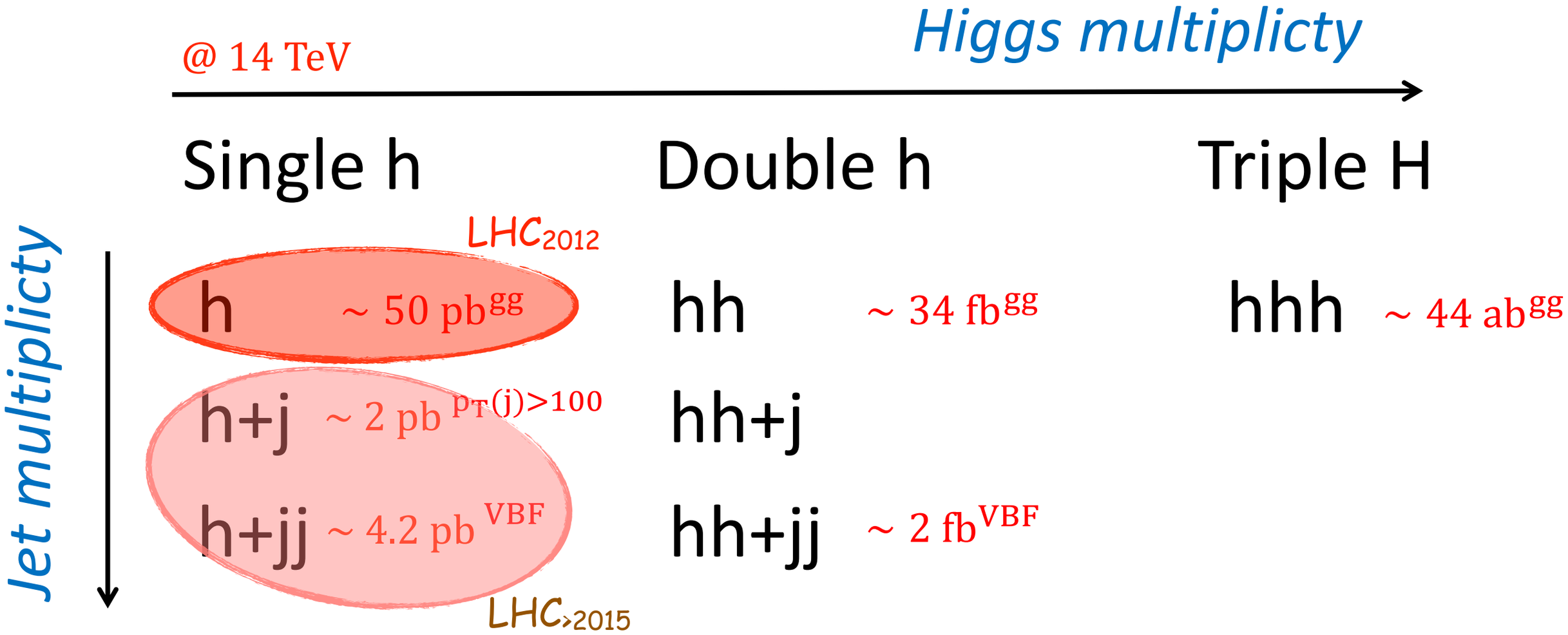

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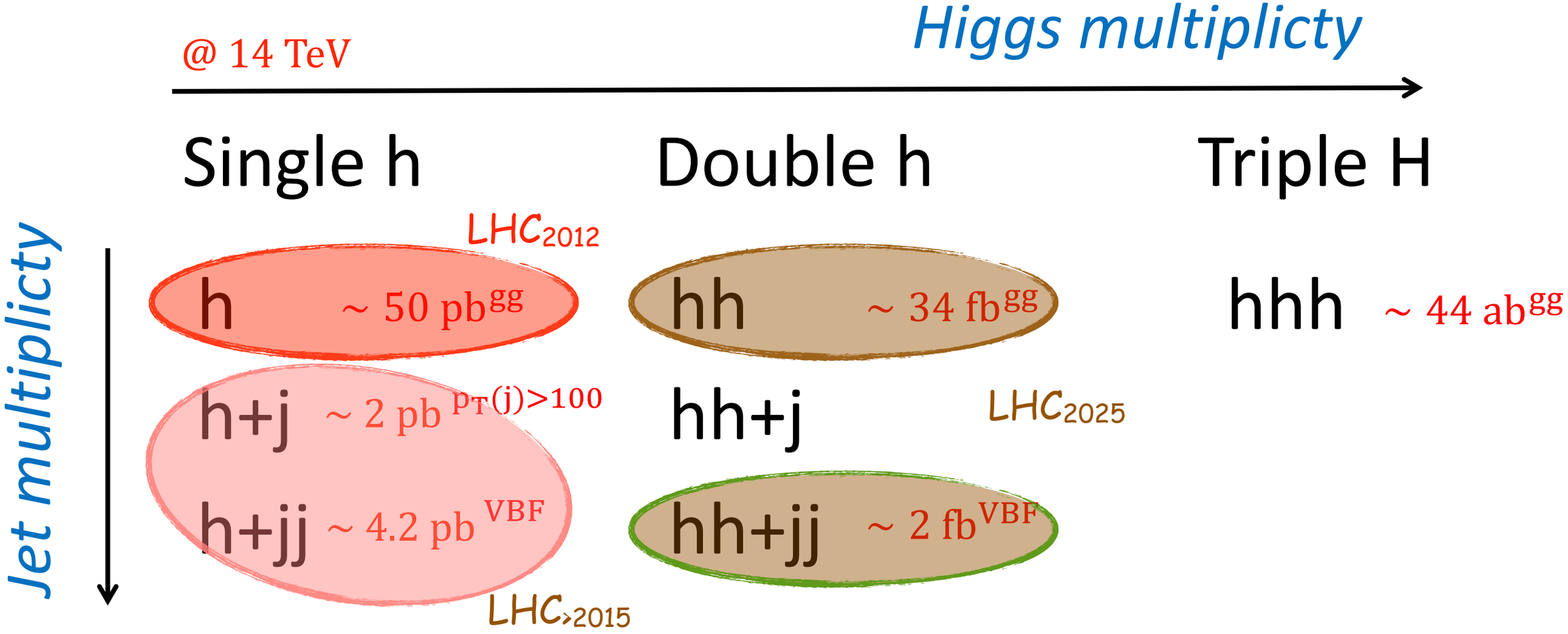

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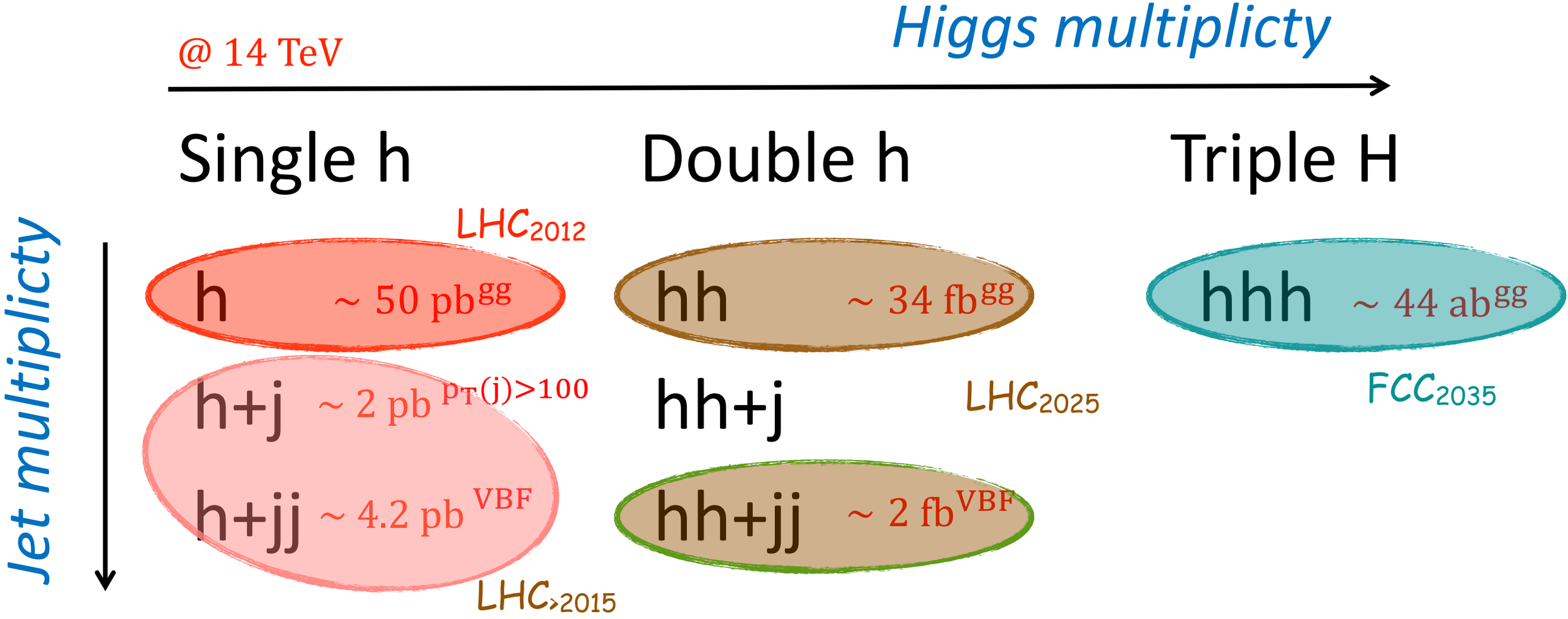

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Beyond single Higgs processes

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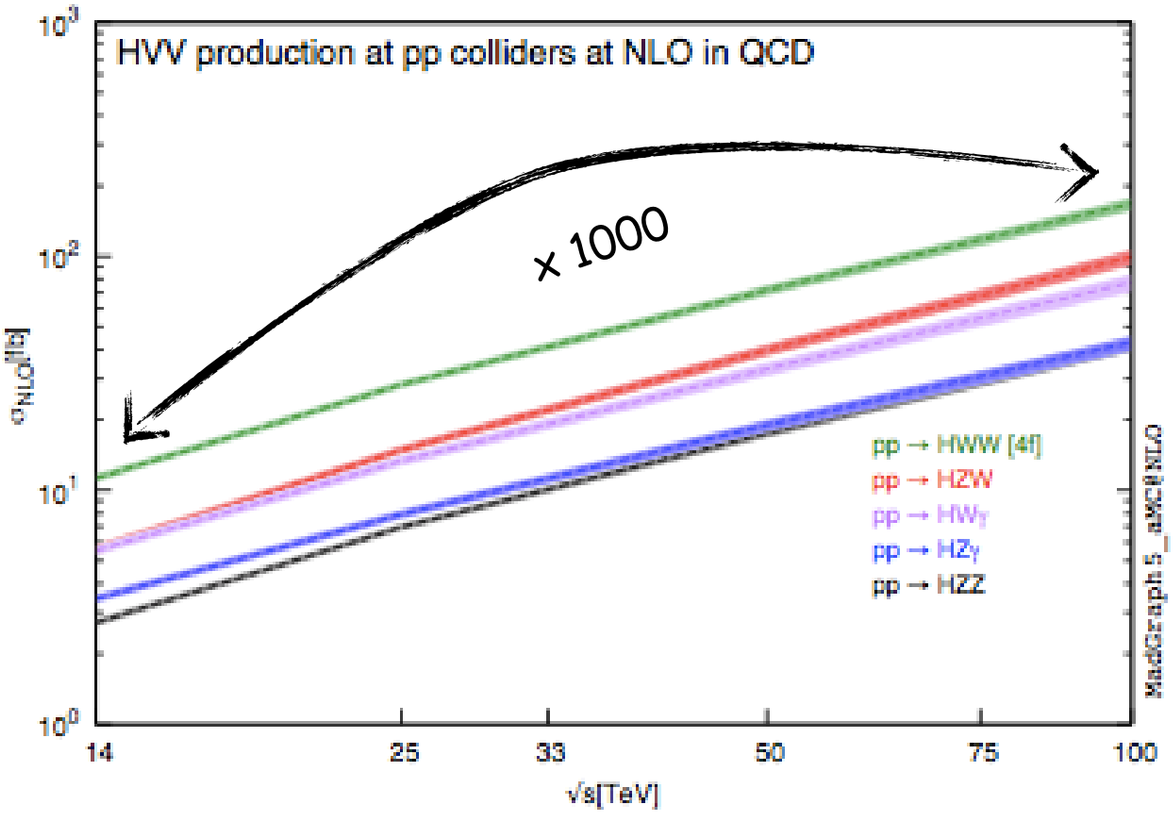
A long term plan?

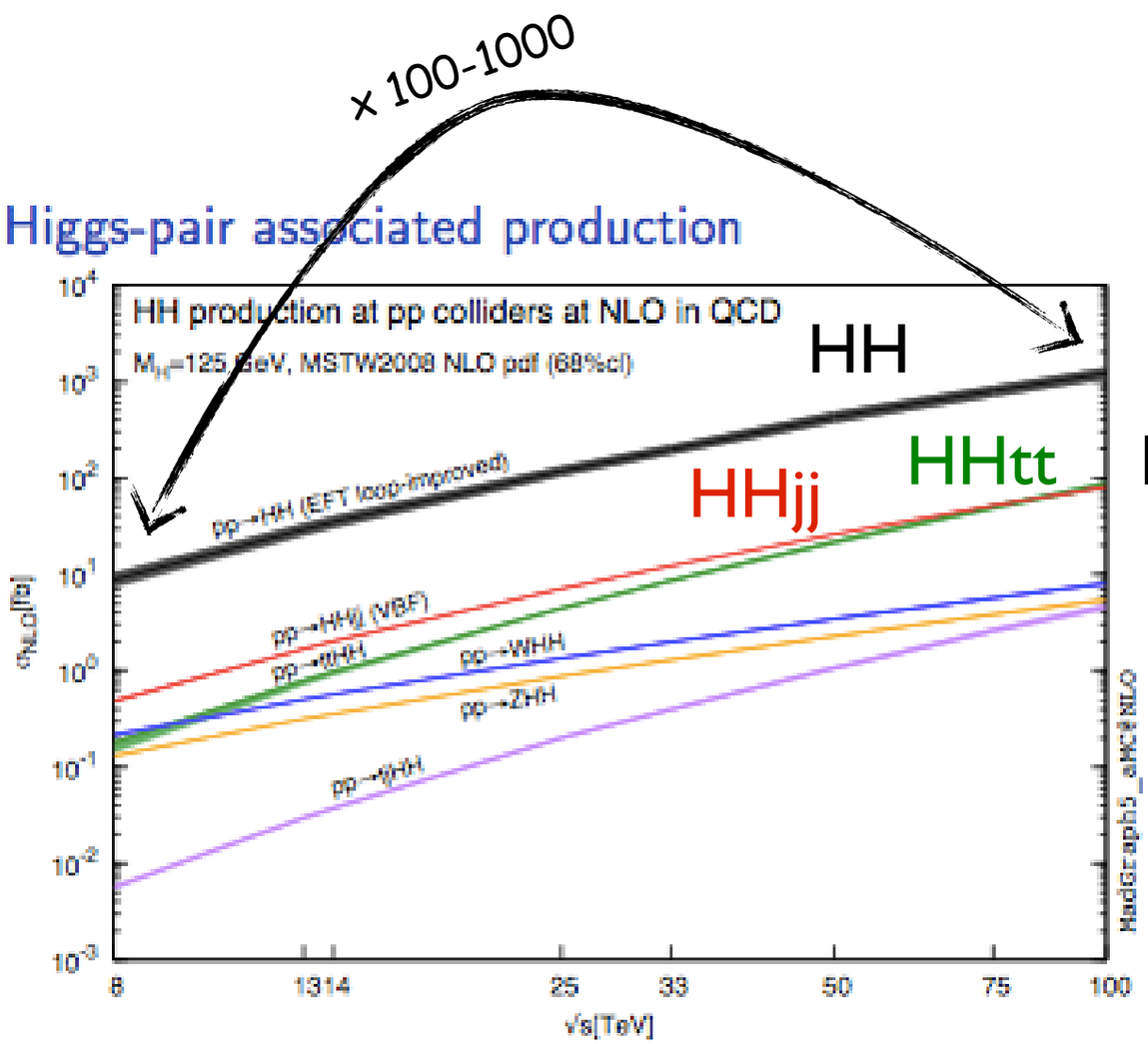
Higgs-diboson associated production



100 fb

FCC = H+X factory

Higgs-pair associated production



1000 fb

100 fb

(Plots from P. Torrielli and MLM, CERN'14)

Why going beyond single Higgs processes?

So far the LHC has mostly produced Higgses on-shell
in processes with a characteristic scale $\mu \approx m_H$

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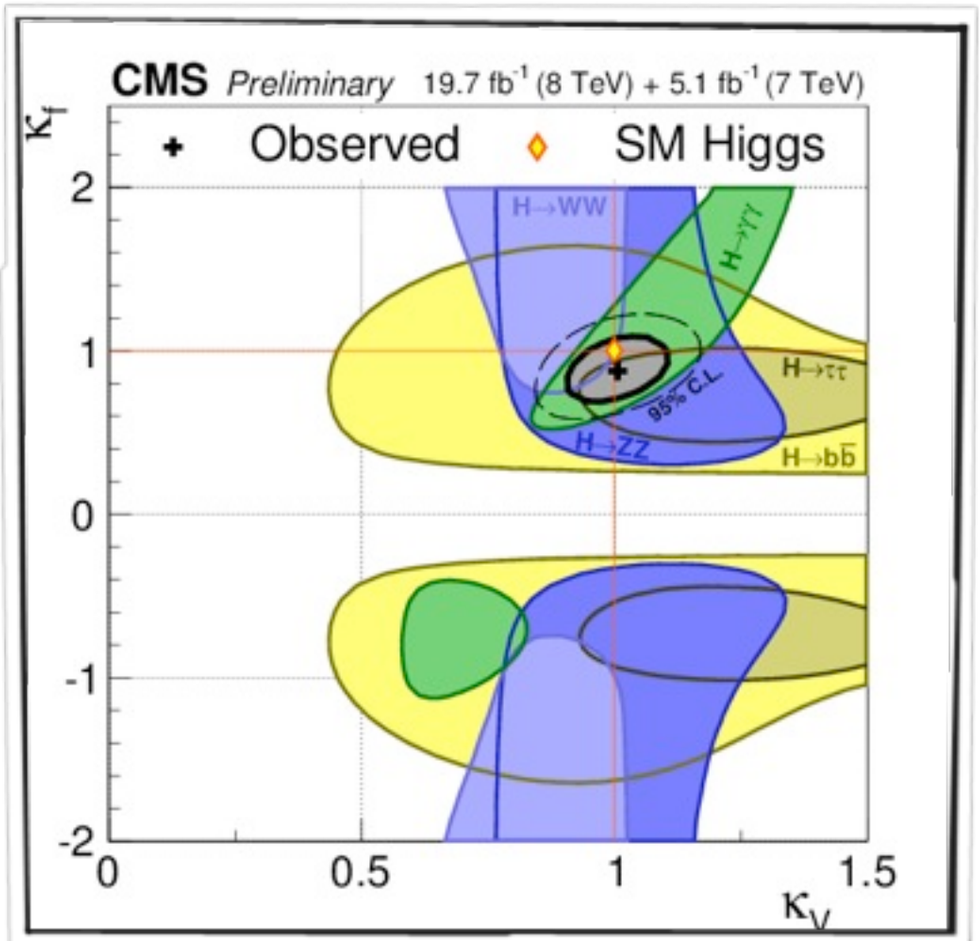
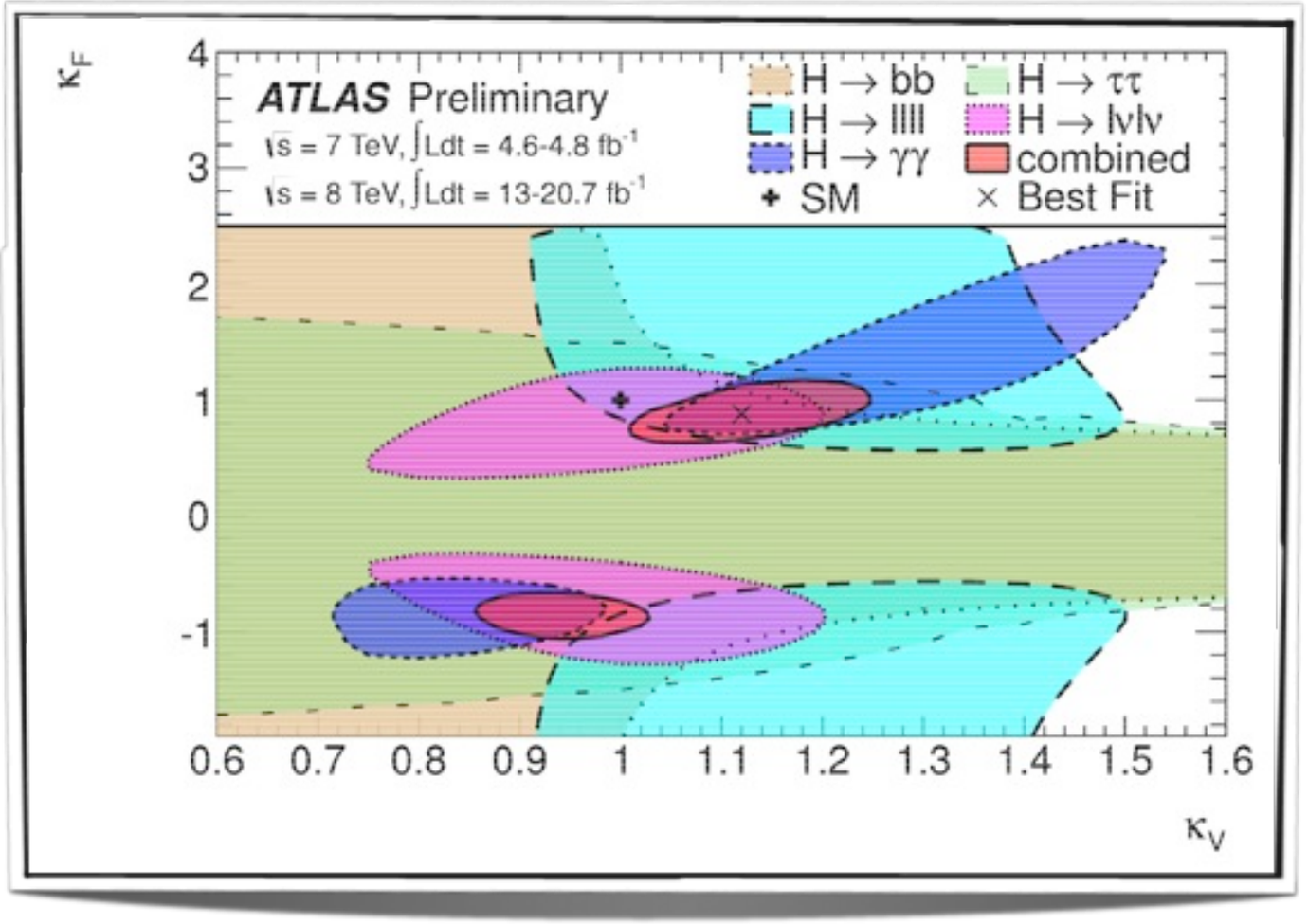
⇩ ⇩

access to Higgs couplings @ m_H





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Producing a Higgs with boosted additional particle(s)
probe the Higgs couplings @ large energy
(important to check that the Higgs boson ensures perturbative unitarity)

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probe the Higgs couplings @ large energy
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Probing new corrections to the SM Lagrangian?

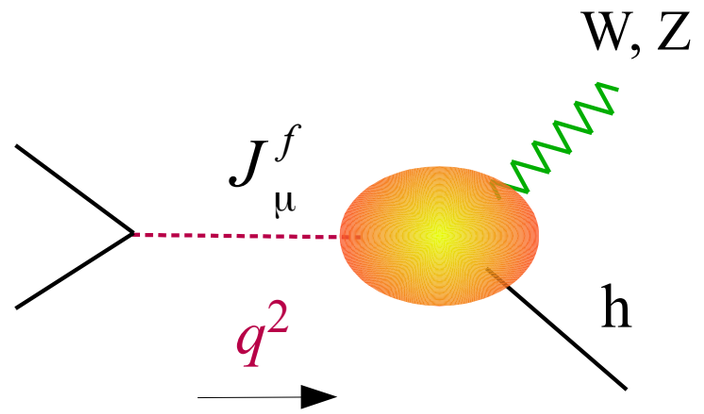
on-shell Z @ LEP1	off-shell Z @ LEP2
constraints on S and T oblique corrections	constraints on W and Y oblique corrections (same order as S and T but cannot be probed @ LEP1)

off-shell Higgs data does not probe new corrections
that are not already constrained by on-shell data

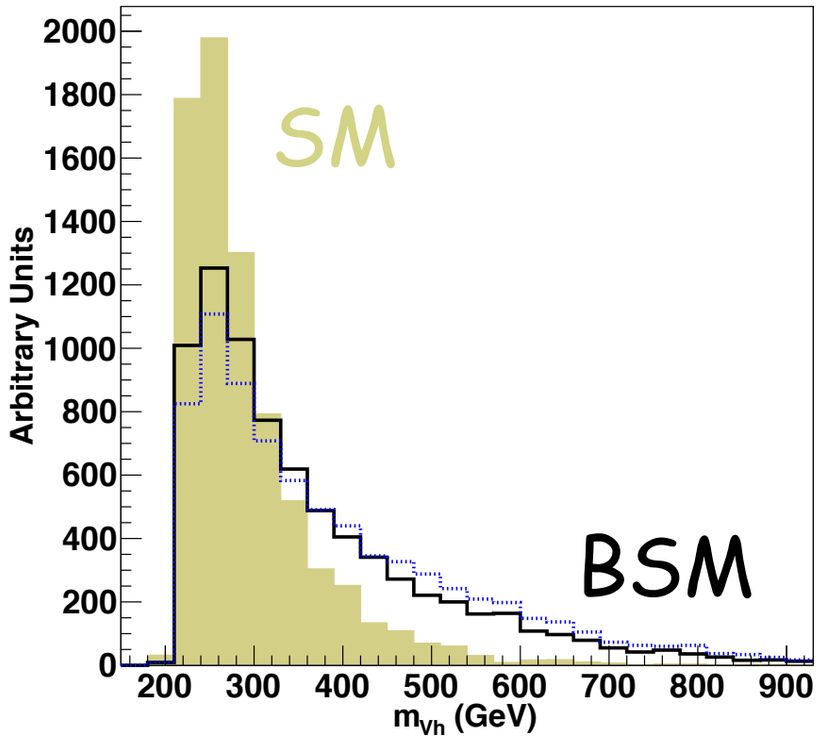
Boosted Higgs in HV production

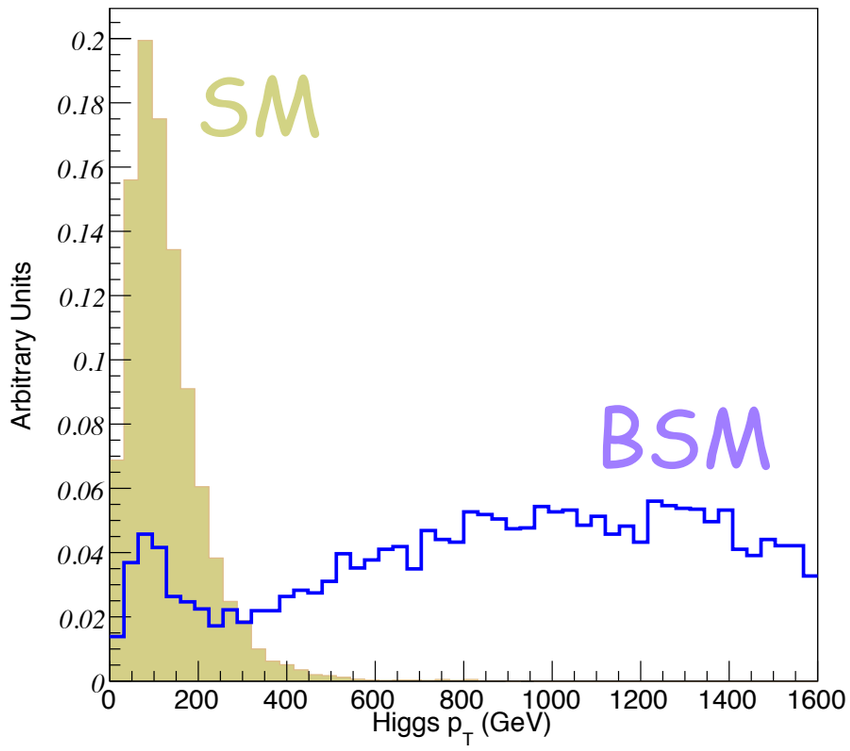
Associate production ff→Vh probe
the high q^2 dependence of the form factors

Isidori, Trott '13



Alloul, Fuks, Sanz '13





The large effects at high p_T or m_{VH} have been used to probe higher dimensional derivative operators

Ellis, Sanz, You '13

Beneke, Boito, Wang '13

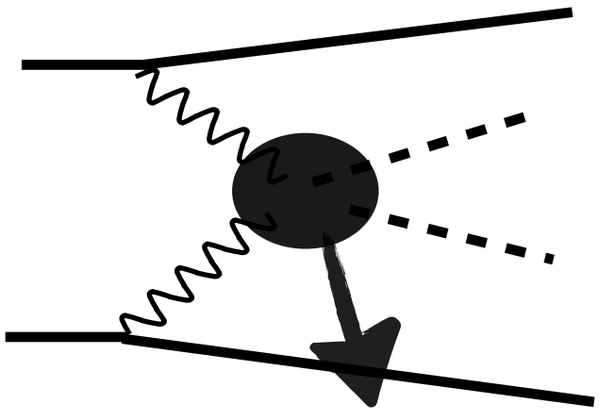
but the validity of the EFT approach is endangered

Biekoetter et al '14

Multiple Higgs interactions in WW→HH

in the SM, the Higgs is essential to prevent strong interactions in EWSB sector

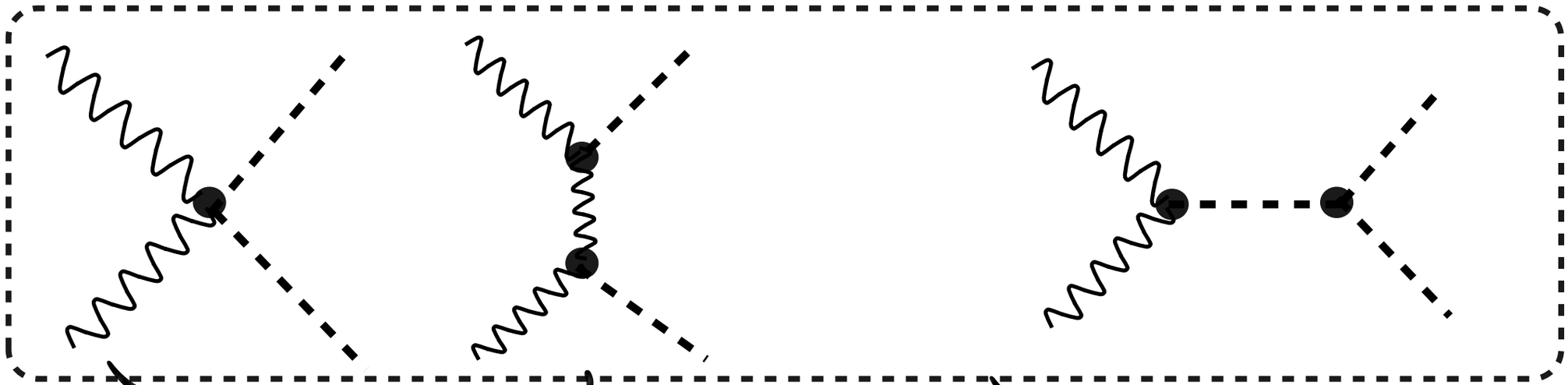
(e.g. WW scattering)



$$\mathcal{L}_{\text{EWSB}} = \frac{v^2}{4}\text{Tr}\left(D_\mu \Sigma^\dagger D_\mu \Sigma\right)\left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2}\right)$$

SM: $a=b=d_3=d_4=1$

$$V(h) = \frac{1}{2}m_h^2 h^2 + d_3\frac{1}{6}\left(\frac{3m_h^2}{v}\right)h^3 + d_4\frac{1}{24}\left(\frac{3m_h^2}{v^2}\right)h^4 + \dots$$



$$\mathcal{A} \underset{m_{hh}^2 \gg m_W^2}{\sim} \left(b - a^2\right)\frac{4m_{hh}^2}{v^2}$$

asymptotic behavior
sensitive to strong interaction

$$\mathcal{A} \underset{m_{hh}^2 \sim 4m_h^2}{\sim} \text{cst.} + 3ad_3\frac{m_h^2}{v^2}$$

threshold effect
anomalous coupling'

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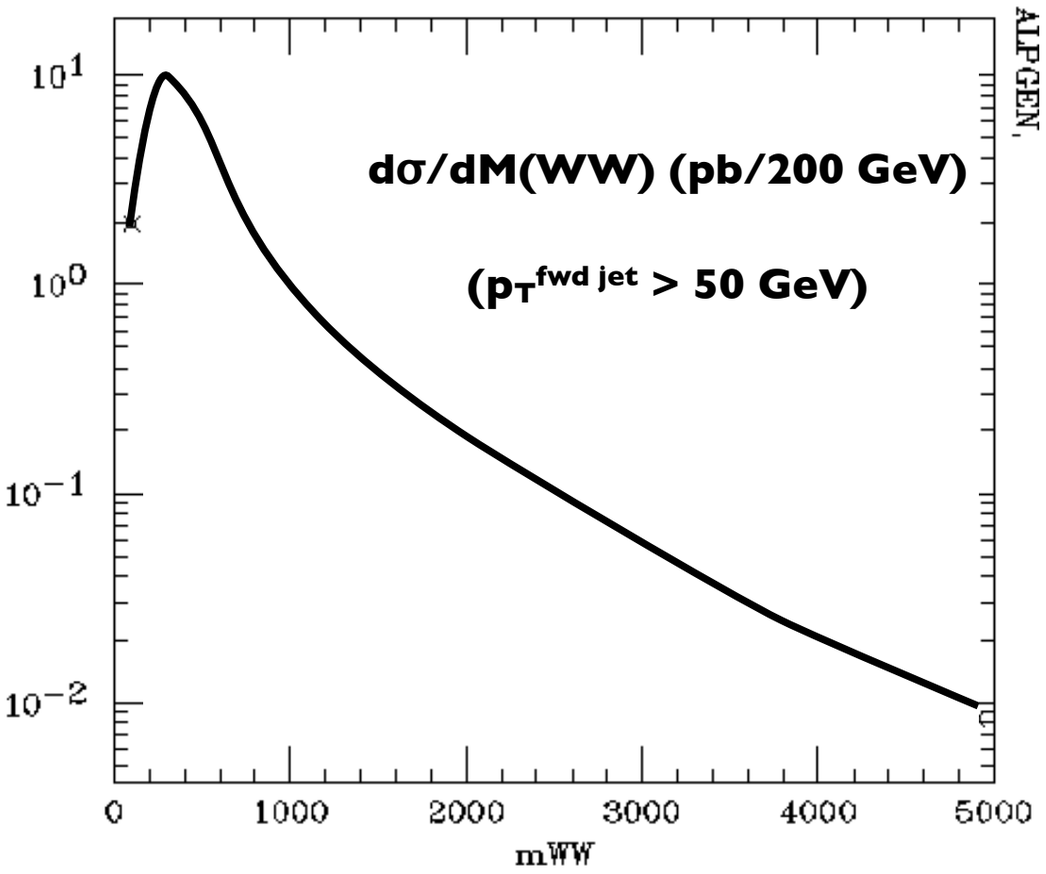
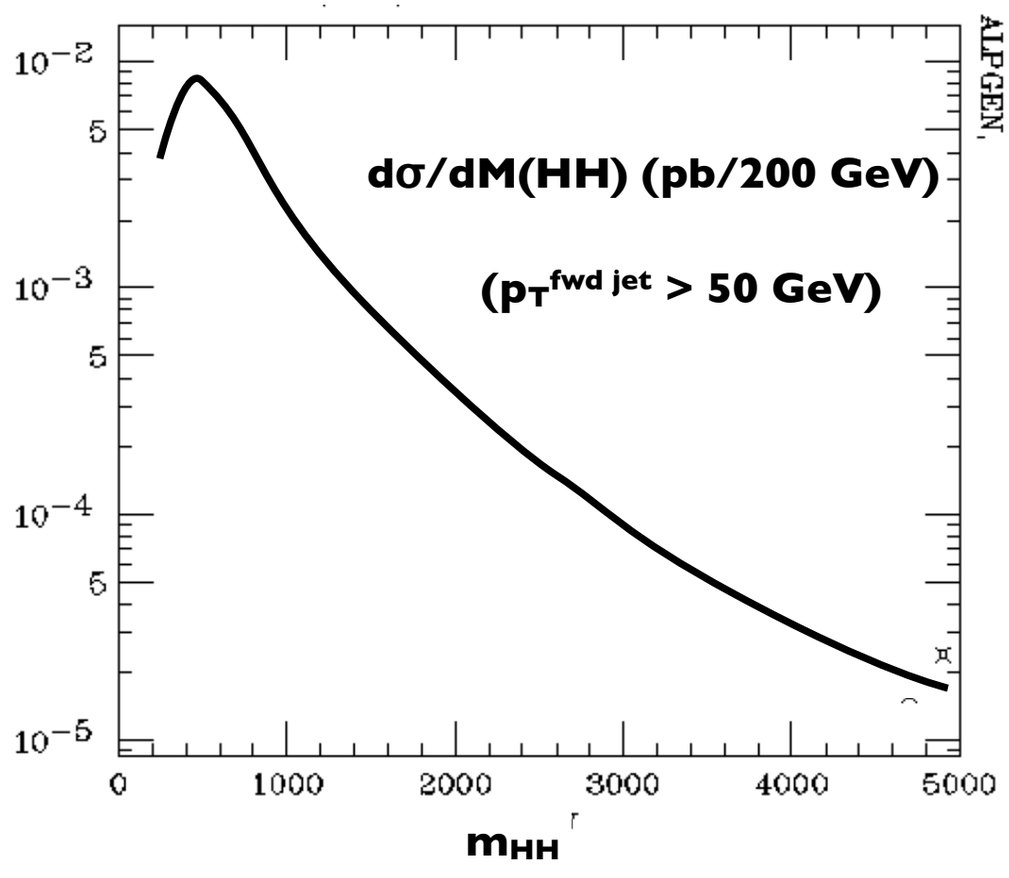
(e.g. WW scattering)

SM rates at 100 TeV



100 fb with M(WW) > ~3 TeV

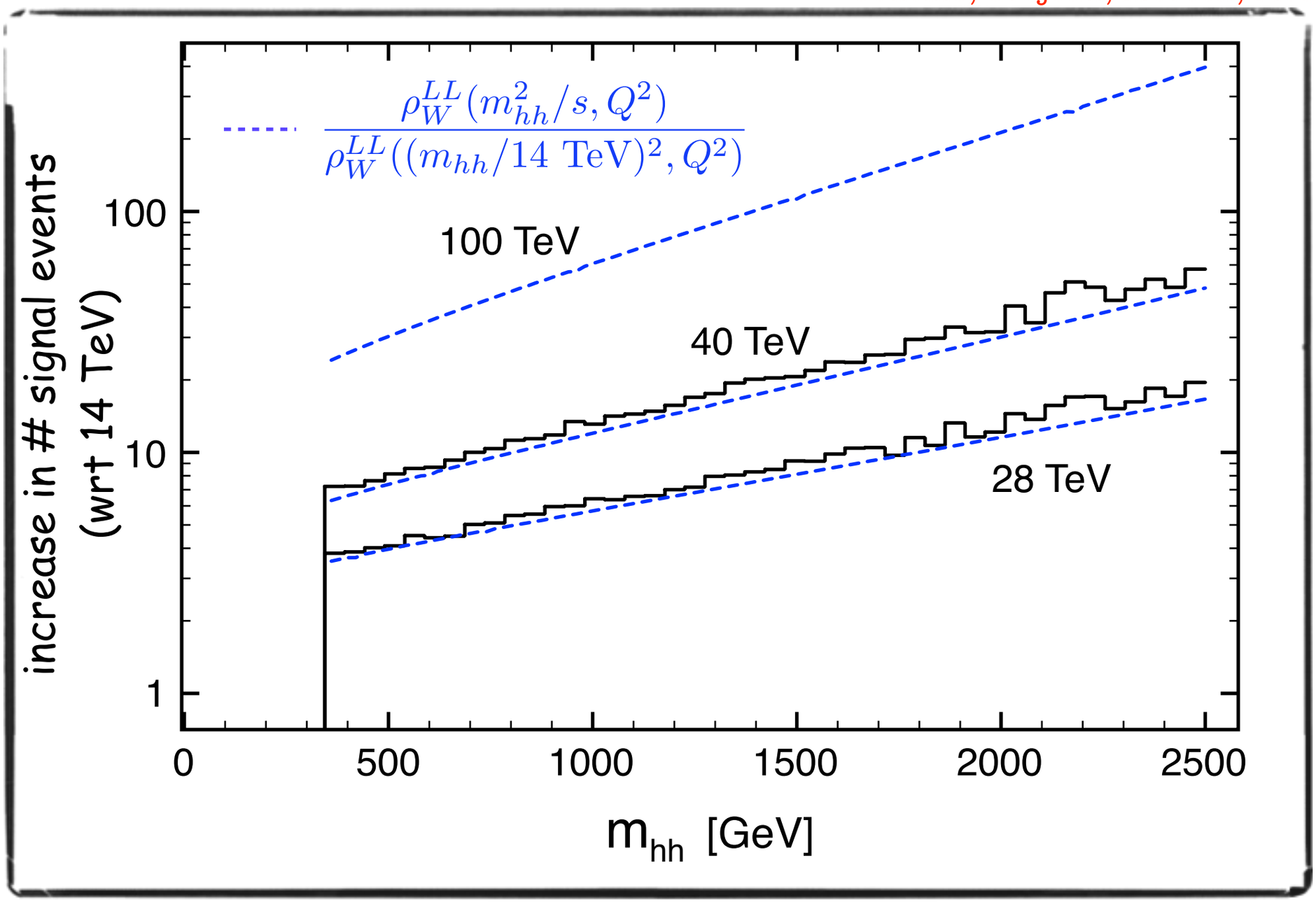


1 fb with M(HH) > ~2 TeV

M. Mangano @ Fermilab '14

Multiple Higgs interactions in WW→HH

Contino, Grojean, Moretti, Piccini, Rattazzi '10



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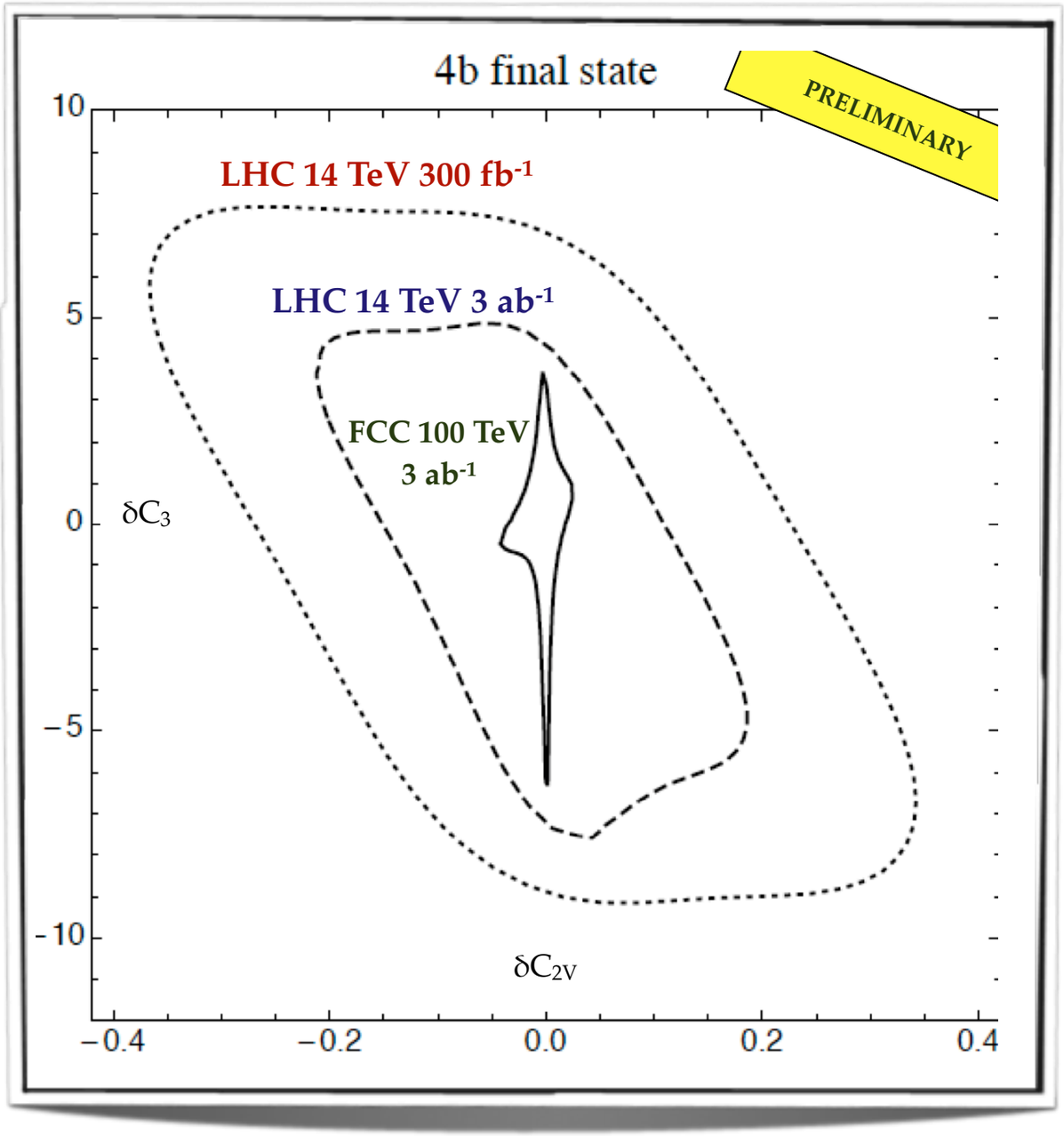
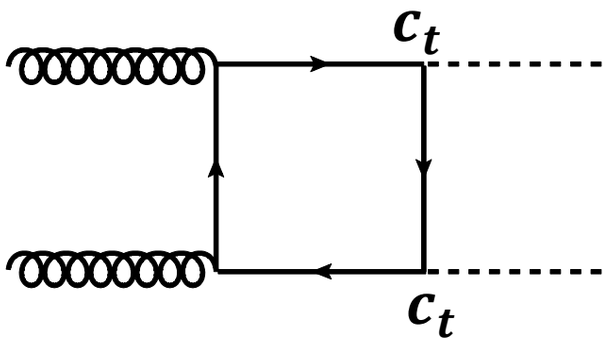
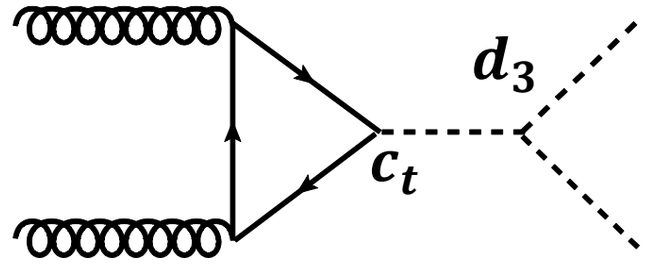


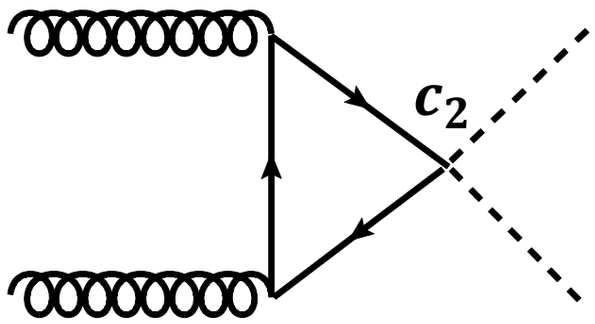
Bondu, Contino, Massironi, Rojo 'to appear

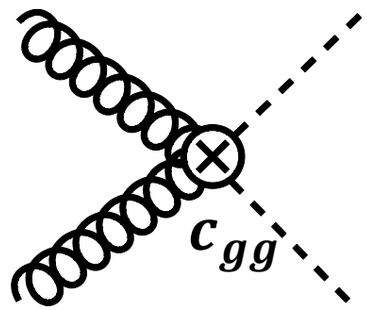
What do we learn from gg→HH?

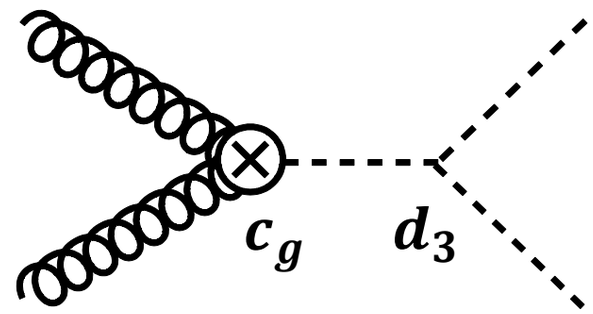
in principle gg→HH gives access to many new couplings, including non-linear couplings











In practice, if the Higgs is part of an EW doublet,
these new couplings are related to single-Higgs couplings

$$c_2 = 3(c_t - 1) \qquad\qquad c_{gg} = c_g$$

In reality single-Higgs processes is unable to differentiate c_t from c_g

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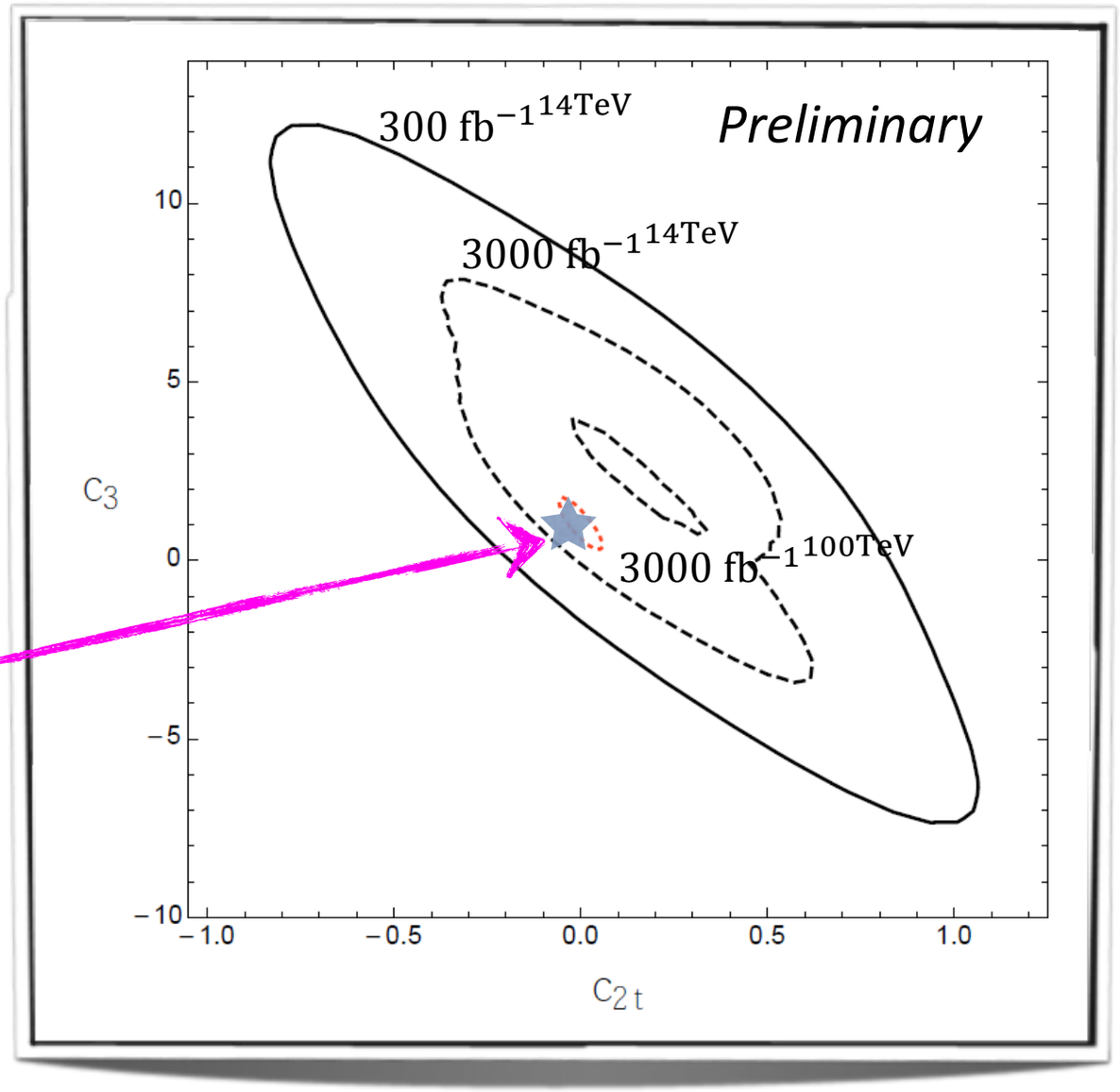

Azatov, Contino, DelRe, Meridiani, Micheli, Panico, Son 'to appear

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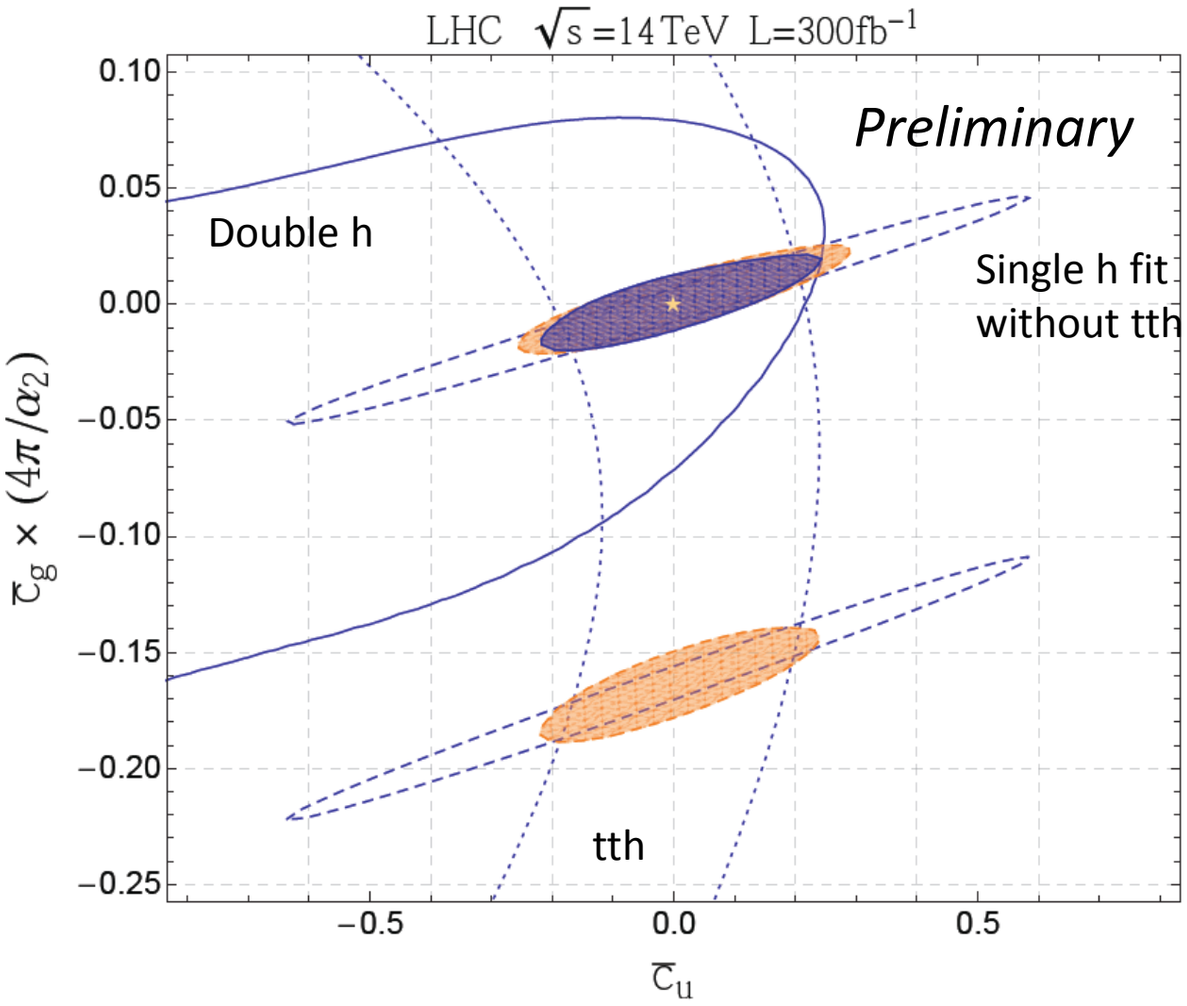
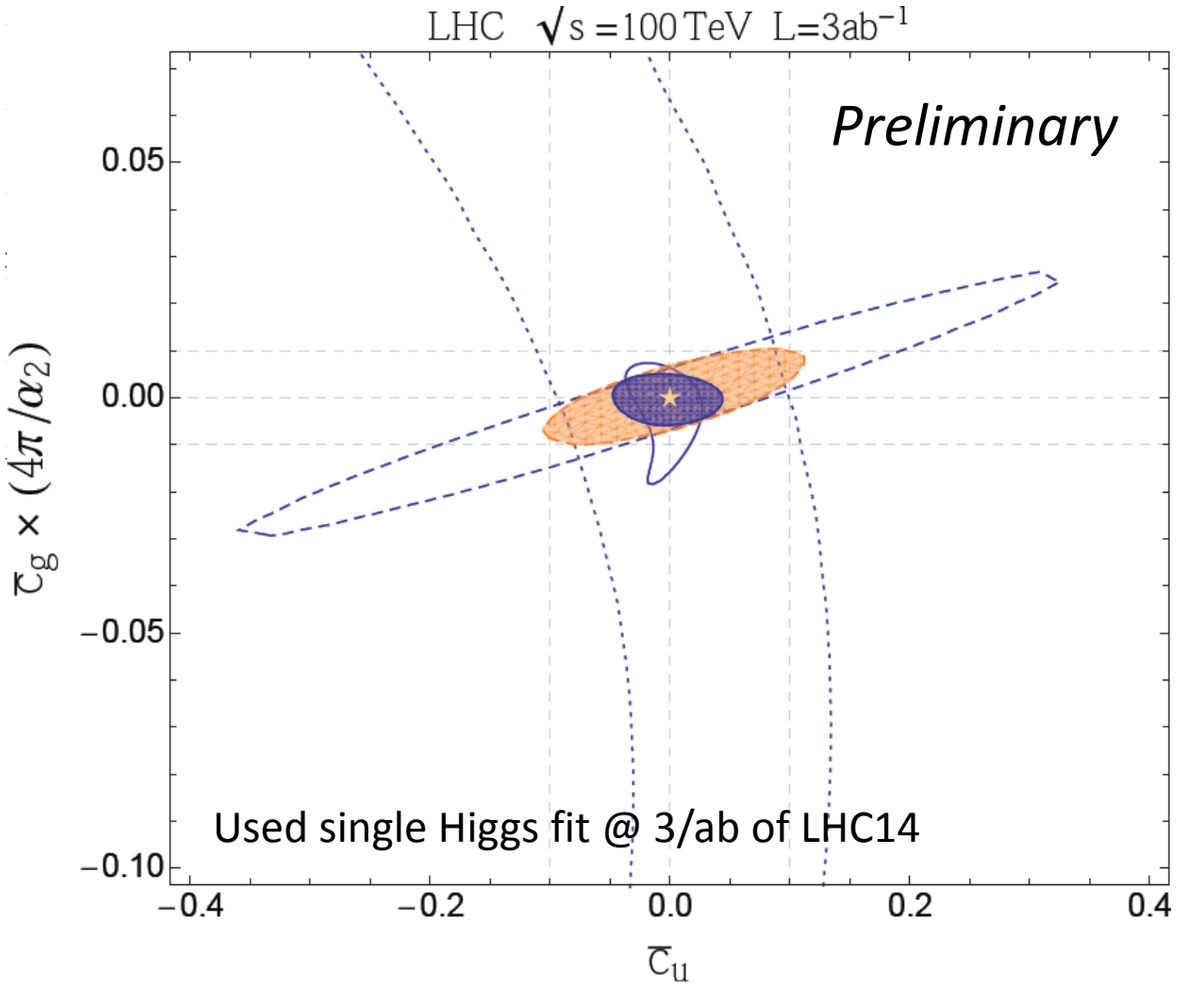
after marginalizing over c_3, hh channel provides additional info on single Higgs couplings





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Boosted Higgs: $gg \to h$+jet

inability to resolve the top loops

- the bearable lightness of the Higgs: rich spectroscopy w/ multiple decays channels
- the unbearable lightness: loops saturate and don't reveal the physics @ energy physics (*)

$m_H(\mathrm{GeV})$	$\frac{\sigma_{NLO}(m_t)}{\sigma_{NLO}(m_t\to\infty)}$	$\frac{\sigma_{NLO}(m_t,m_b)}{\sigma_{NLO}(m_t\to\infty)}$
125	1.061	0.988
150	1.093	1.028
200	1.185	1.134

e.g. Grazzini, Sargsyan '13

the inclusive rate
doesn't "see" the finite mass of the top

(*) unless it doesn't decouple
(e.g. 4th generation)

$\Rightarrow$ cannot disentangle
- long distance physics (modified top coupling)
- short distance physics (new particles running in the loop)

$\Leftarrow$

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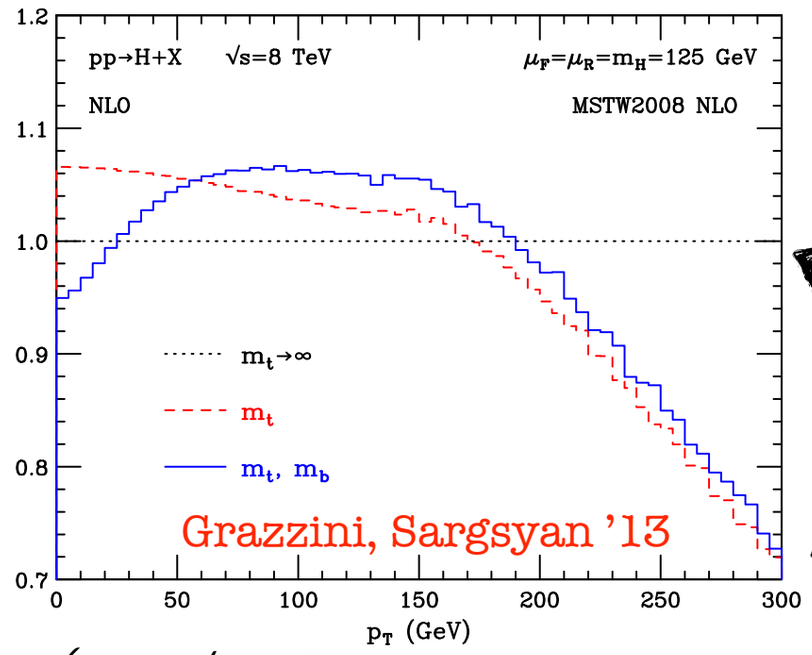
⇐

cut open the top loops

high p_T ≈ Higgs off-shell
we "see" the details of the particles
running inside the loops

Baur, Glover '90
Langenegger, Spira, Starodumov, Trueb '06



Note: LO only
NLO_{m_t} is not known
$1/m_t$ corrections known $O(\alpha_s^4)$
few % up to p_T~150 GeV

Harlander et al '12

the high p_T tail
is tens' % sensitive
to the mass of top

Boosted Higgs: $gg \to h$+jet

Don't think it is easy to produce a Higgs with high p_T

$\sqrt{s}$ [TeV]	$p_T^{\min}$ [GeV]	$\sigma^{\rm SM}_{p_T^{\min}}$ [fb]	δ	ϵ	gg, qg [%]
	100	2200	0.016	0.023	67, 31
	150	830	0.069	0.13	66, 32
	200	350	0.20	0.31	65, 34
	250	160	0.39	0.56	63, 36
	300	75	0.61	0.89	61, 38
	350	38	0.86	1.3	58, 41
	400	20	1.1	1.8	56, 43
14	450	11	1.4	2.3	54, 45
	500	6.3	1.7	2.9	52, 47
	550	3.7	2.0	3.6	50, 49
	600	2.2	2.3	4.4	48, 51
	650	1.4	2.6	5.2	46, 53
	700	0.87	3.0	6.2	45, 54
	750	0.56	3.3	7.2	43, 56
	800	0.37	3.7	8.4	42, 57

× 1000 reduction

resolve the top loops

h spectroscopy w/ multiple decays channels
e and don't reveal the physics @ energy physics (*)

g. Grazzini, Sargsyan '13

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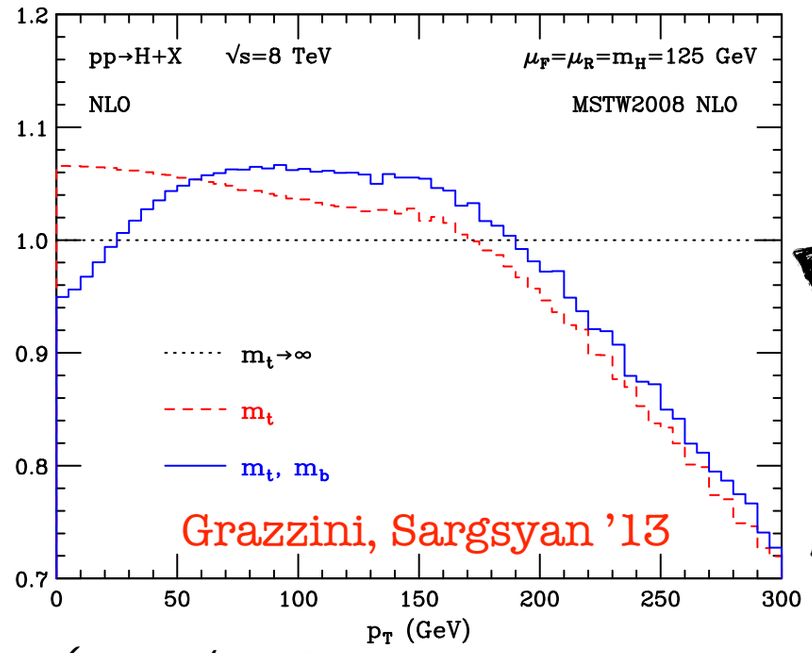

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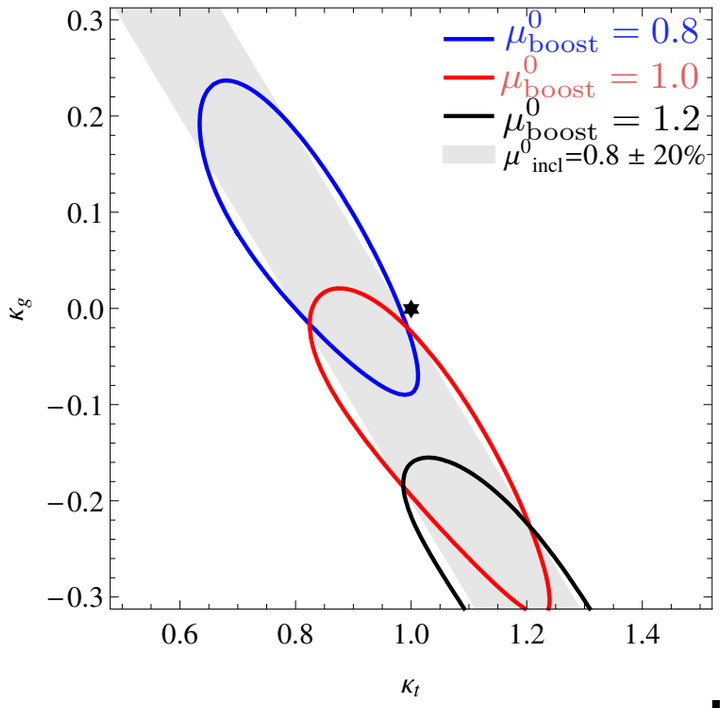
cut open the top loops

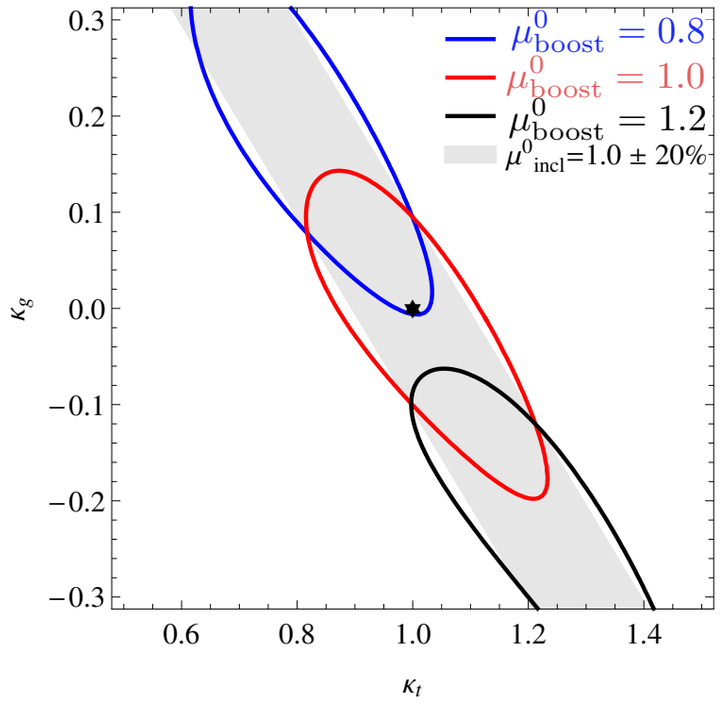
Grojean, Salvioni, Schlaffer, Weiler '13

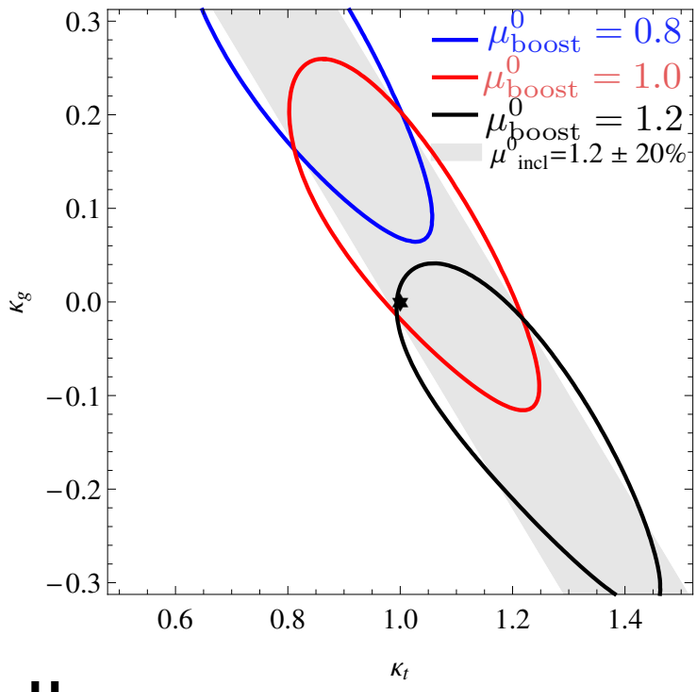
see also Azatov, Paul '13

high p_T tail discriminates short and long distance physics contribution to $gg \to h$

$$\sqrt{s} = 14 \text{ TeV}, \int dt\, \mathcal{L} = 3\text{ab}^{-1}, p_T > 650 \text{ GeV}$$







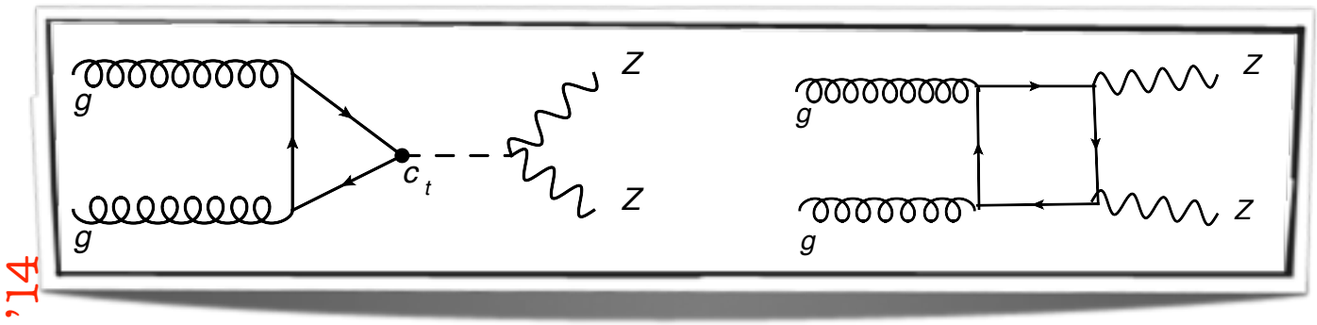
Competitive/complementary to htt channel to measure the top-Higgs coupling

Are the NLO_m QCD corrections (not known) going to destroy all the sensitivity?
Frontier priority: $\text{N}^3\text{LO}_\infty$ for inclusive xs or NLO_{mt} for pT spectrum?

Off-shell Higgs: $gg \to h^* \to ZZ \to 4l$

off-shell effects enhanced by the particular couplings of H to V_L

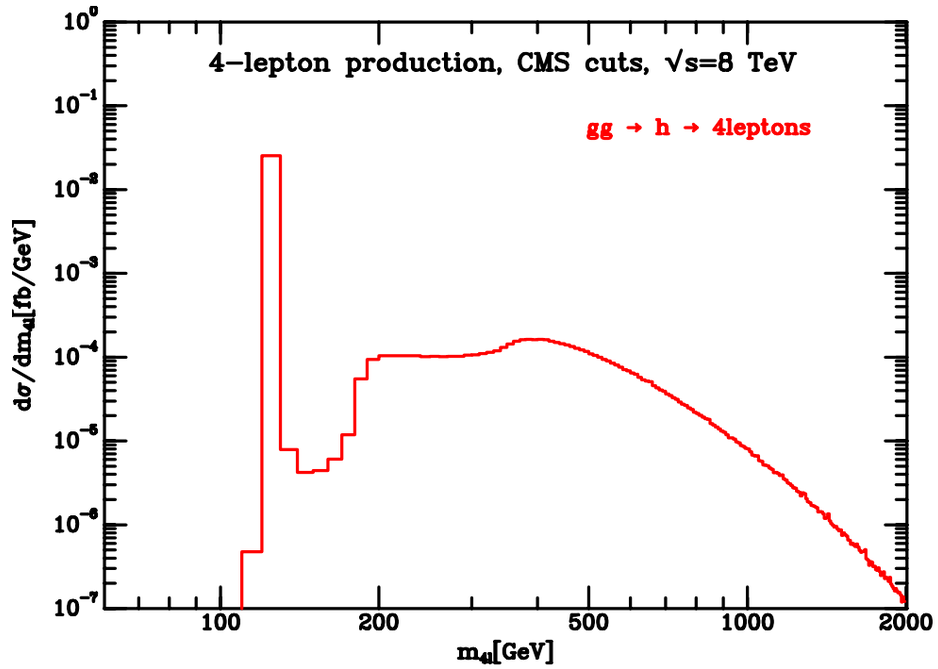
Glover, van der Bij '89



$$\mathcal{M}^{++00}_{\text{Higgs}} \sim \log^2 \frac{\hat{s}}{m_t^2} \qquad \mathcal{M}^{++00}_{\text{box}} \sim -\log^2 \frac{\hat{s}}{m_t^2}$$

SM: cancelation forced by unitarity

BSM: deviations of Higgs couplings at large $\hat{s}$ will be amplified



Azatov, Grojean, Paul, Salvioni '14

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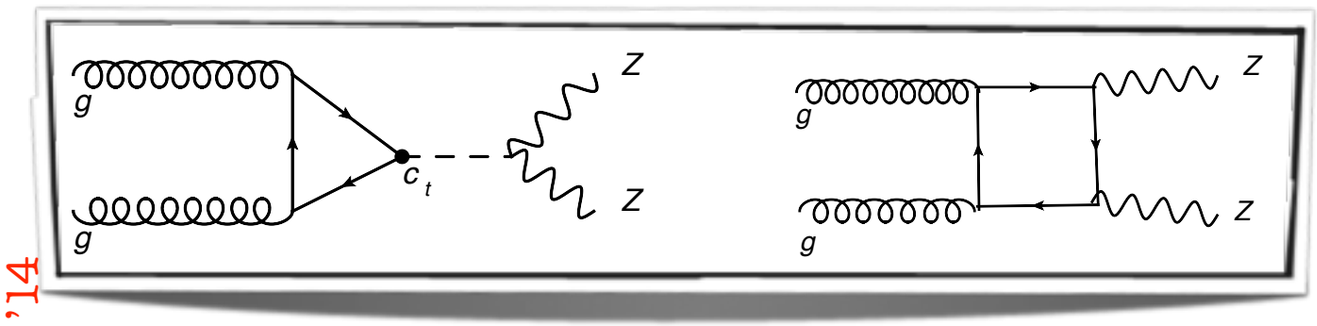

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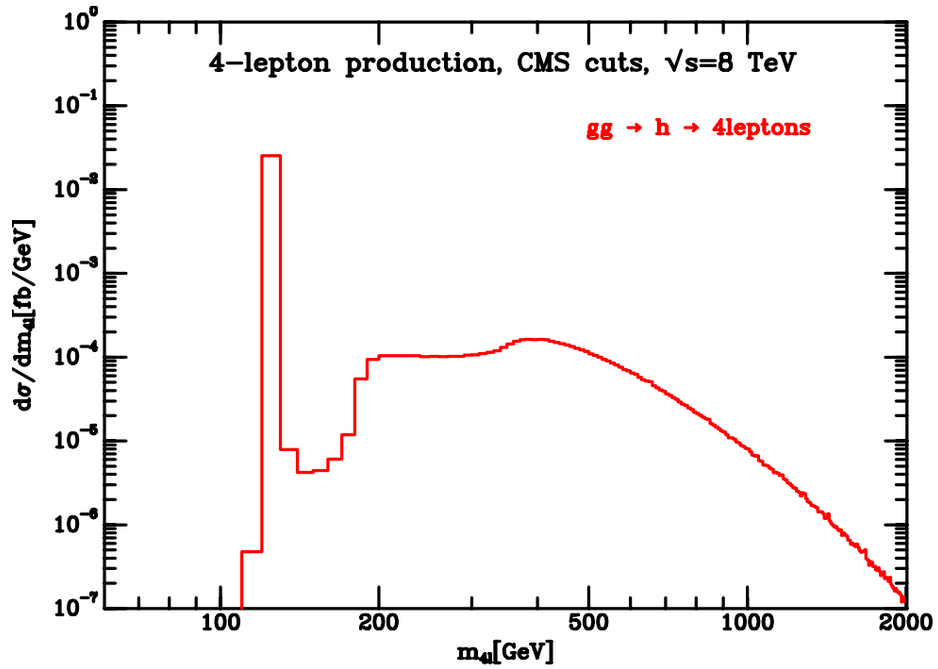

Azatov, Grojean, Paul, Salvioni '14

CMS interpretation in terms of bounds of the Higgs width is limited

data can be better used to measure the top Yukawa coupling

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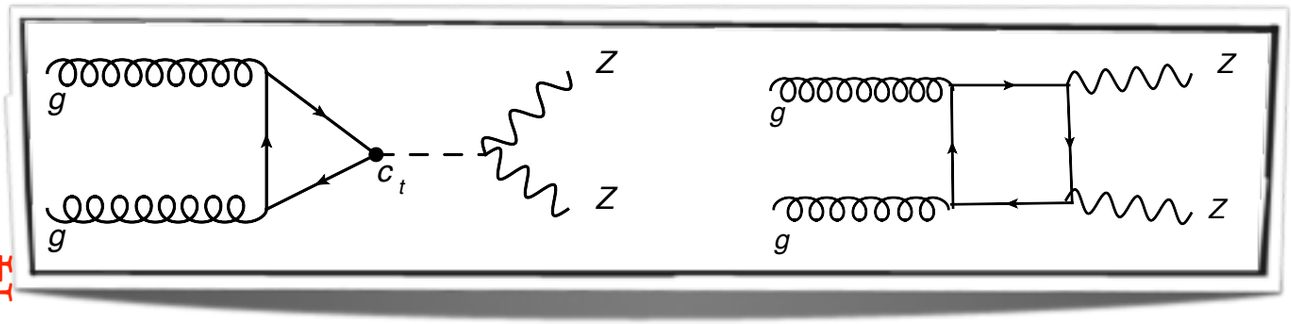

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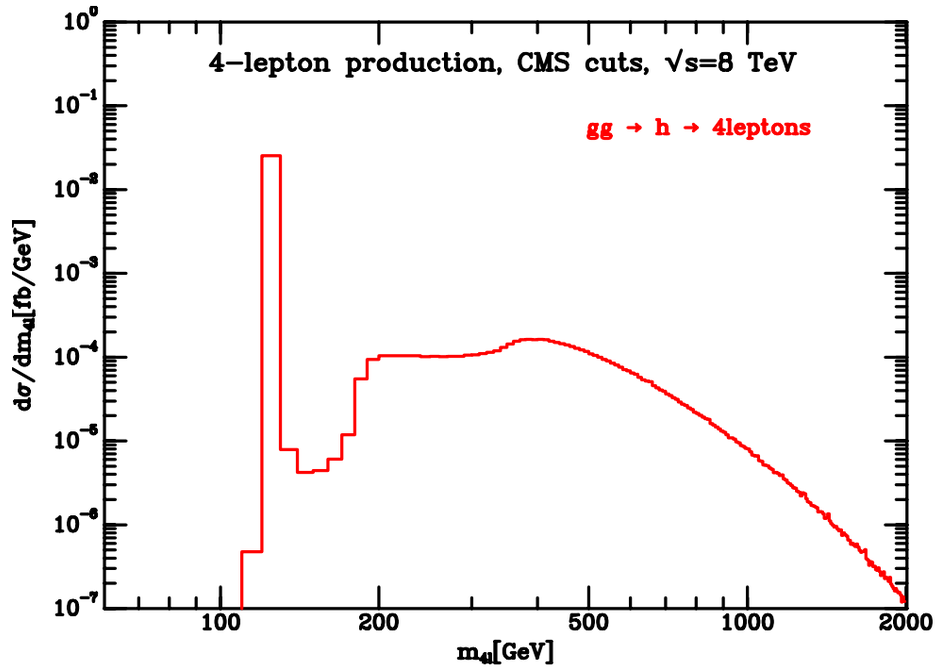

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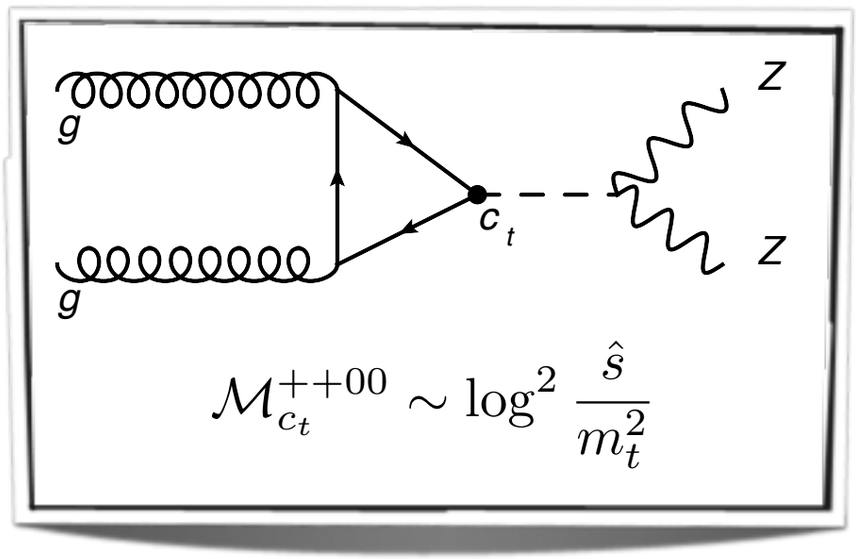

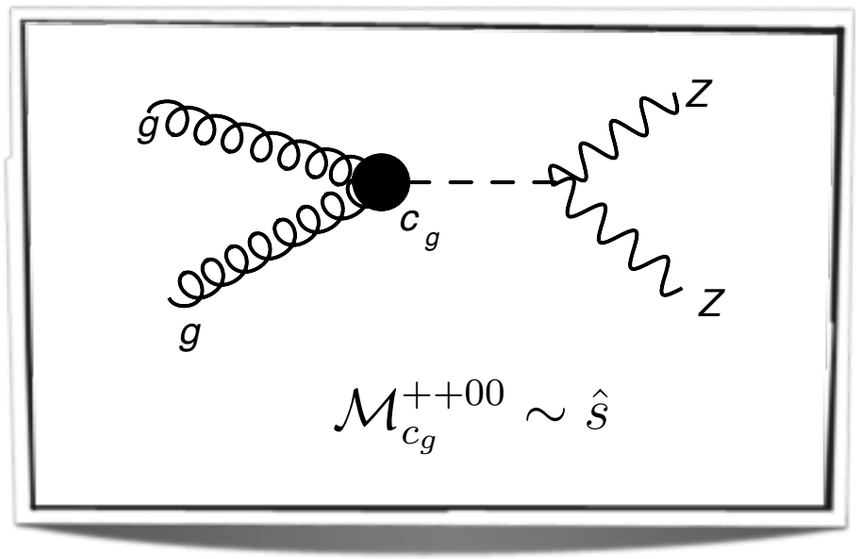

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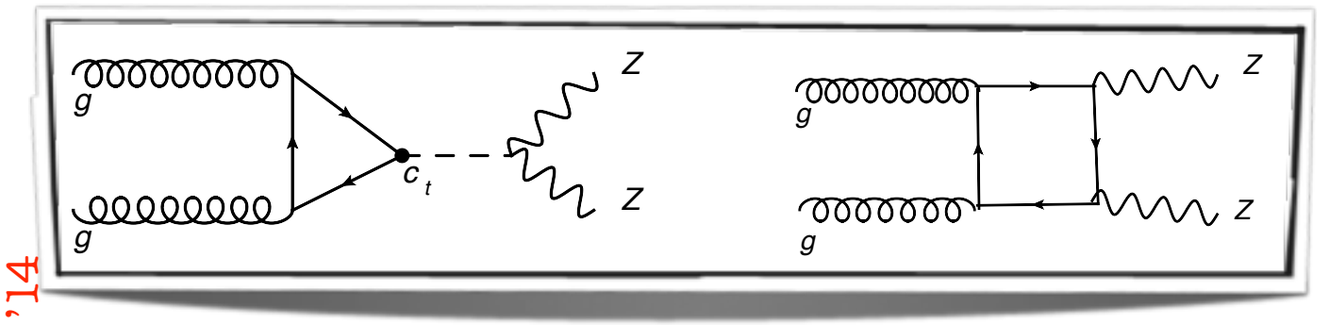

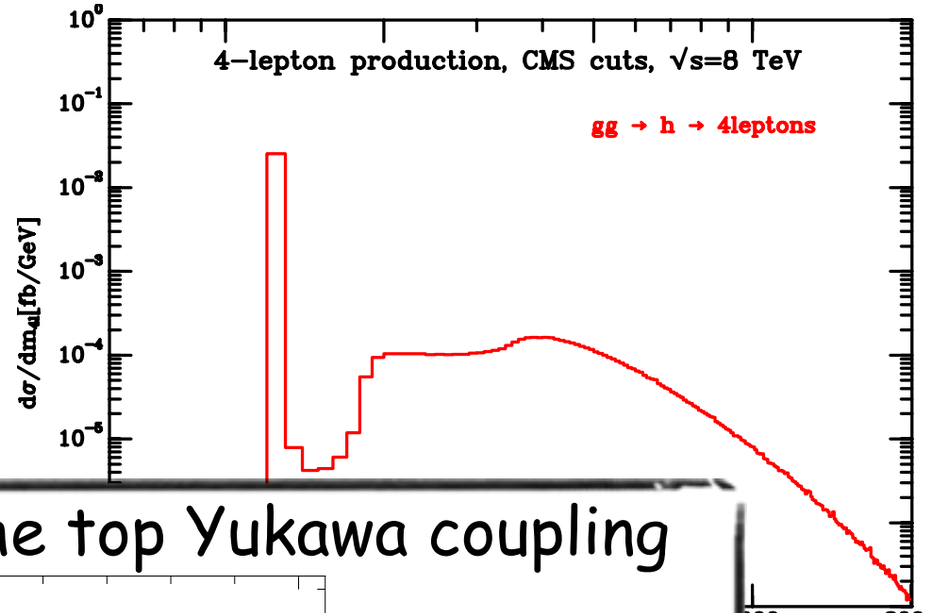

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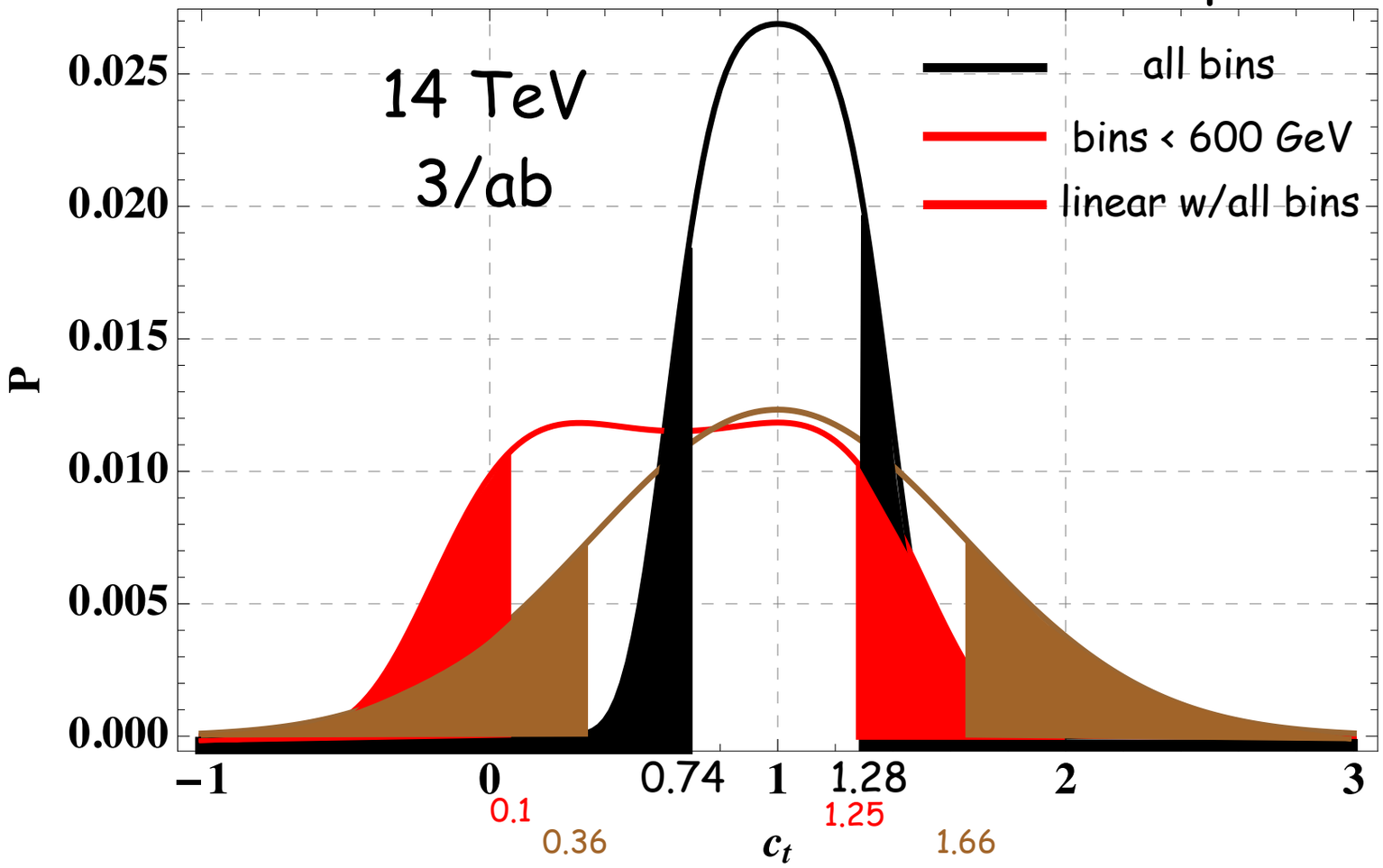
provides an alternative to ttH to measure the top Yukawa coupling

Azatov, Grojean, Paul, Salvioni '14



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My key message

MLM@Aspen'14

- The days of "guaranteed" discoveries or of no-lose theorems in particle physics are over, at least for the time being ....
- .... but the big questions of our field remain wild open (hierarchy problem, flavour, neutrinos, DM, BAU, ...)
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Where and how does the SM break down?
Which machine(s) will reveal this breakdown?

What's next?

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only a few eletrons are enough to lift your hair (~ 10^{25} mass of e^-)

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Several theoretical hypothesis

new space-time structure?

modification of special relativity? of quantum mechanics?

Beyond the Higgs

Beyond the Higgs

" Higgs = emergency tire of the SM"

Altarelli @ Blois'10

[picture courtesy to Andreas Weiler]

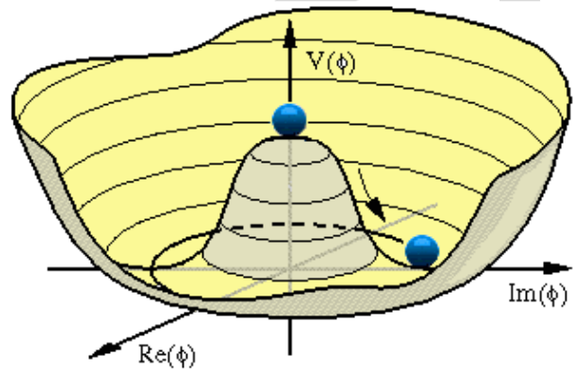
EXTRA SLIDES

Is the Higgs a portal to New Physics?

Higgs physics vs BSM

$$\phi = v + h$$

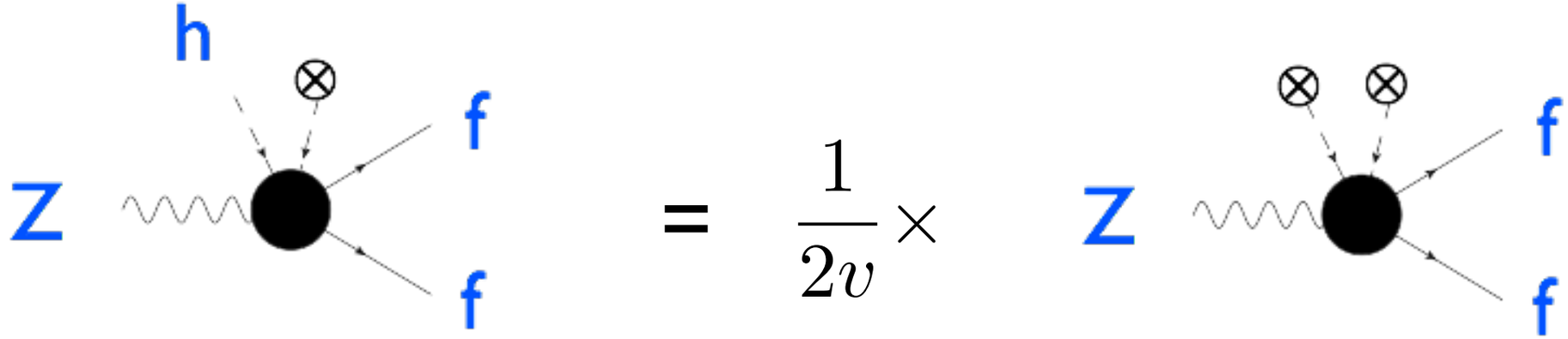
vacuum



Potentially new BSM-effects in h physics
could have been already tested in the vacuum

(courtesy of A. Pomarol@Moriond2014)

e.g.



$$\frac{1}{2v} \times$$

$$H^\dagger D_\mu H \bar{f} \gamma^\mu f$$

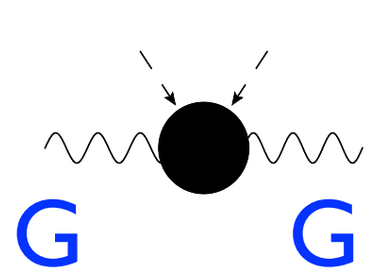
Modifications in h→Zff related to Z→ff

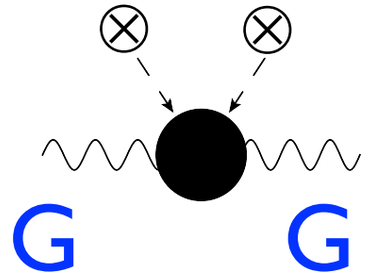
Higgs/BSM Primaries

Effects that on the vacuum, **H = v**, give only a redefinition of the SM couplings:

e.g. $$\frac{1}{g_s^2}G_{\mu\nu}^2 + \frac{|H|^2}{\Lambda^2}G_{\mu\nu}^2 \to \left(\frac{1}{g_s^2} + \frac{v^2}{\Lambda^2}\right) G_{\mu\nu}^2$$

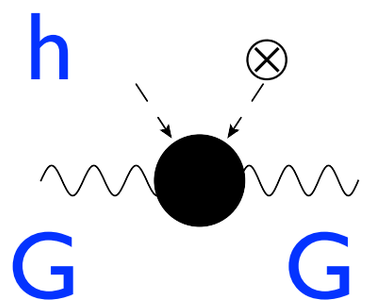
operator is not visible in the vacuum





Not physical!

But can affect h physics:



affects GG →h!

this BSM operator is visible only in Higgs physics!

(courtesy of A. Pomarol@HiggsHunting2014)

Higgs/BSM Primaries

How many of these effects can we have?

Pomarol, Riva '13
Elias-Miro et al '13
Gupta, Pomarol, Riva '14

As many as parameters in the SM: **8**

for one family

(assuming CP-conservation)

(courtesy of A. Pomarol@HiggsHunting2014)

g_s	$\lvert H\rvert^2 G^A_{\mu\nu} G^{A\mu\nu}$	→ GGh coupling
g	$\lvert H\rvert^2 B_{\mu\nu} B^{\mu\nu}$	→ hγγ coupling
g'	$\lvert H\rvert^2 W^a_{\mu\nu} W^{\mu\nu\, a}$	→ hZγ coupling
m_W	$\lvert H\rvert^2 \lvert D_\mu H\rvert^2$	→ hVV* (custodial invariant)
m_h	$\lvert H\rvert^6$	→ h^3 coupling
m_f (f=t,b,τ)	$\lvert H\rvert^2 \bar{f}_L H f_R + h.c.$	→ htt, hbb, h$\tau\tau$

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m_h	$\lvert H\rvert^6$	→ **h³ coupling**
m_f (f=t,b,τ)	$\lvert H\rvert^2 \bar{f}_L H f_R + h.c.$	→ **htt, hbb, hττ**

yet to be measured at the LHC

the 6 others have been measured (~15%) up to a flat direction between between the top/gluon/photon couplings

(courtesy of A. Pomarol@HiggsHunting2014)

Higgs/BSM Primaries

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8 for one family

(assuming CP-conservation)

Almost a 1-to-1 correspondence with the 8 κ's in the Higgs fit

see A. Apyan's talk

Coupling	300 fb^{-1} Theory unc.: All	Half	None	3000 fb^{-1} Theory unc.: All	Half	None
κ_Z	8.1%	7.9%	7.9%	4.4%	4.0%	3.8%
κ_W	9.0%	8.7%	8.6%	5.1%	4.5%	4.2%
κ_t	22%	21%	20%	11%	8.5%	7.6%
κ_b	23%	22%	22%	12%	11%	10%
κ_τ	14%	14%	13%	9.7%	9.0%	8.8%
κ_μ	21%	21%	21%	7.5%	7.2%	7.1%
κ_g	14%	12%	11%	9.1%	6.5%	5.3%
κ_γ	9.3%	9.0%	8.9%	4.9%	4.3%	4.1%
$\kappa_{Z\gamma}$	24%	24%	24%	14%	14%	14%

Atlas projection

With some important differences:

1) width approximation built-in

2) κ_W/κ_Z is not a primary
(constrained by $\Delta\rho$ and TGC)

3) $\kappa_g, \kappa_\gamma, \kappa_{Z\gamma}$ do not separate UV and IR contributions

GGh coupling

hγγ coupling

hZγ coupling

hVV* (custodial invariant)

h^3 coupling

yet to be measured at the LHC

htt, hbb, hττ

Don't forget LEP!

The parameter 'a' controls the size of the one-loop IR contribution to the LEP precision observables

$$\mathcal{L} \supset \frac{1}{f^2}|H|^2|D_\mu H|^2$$

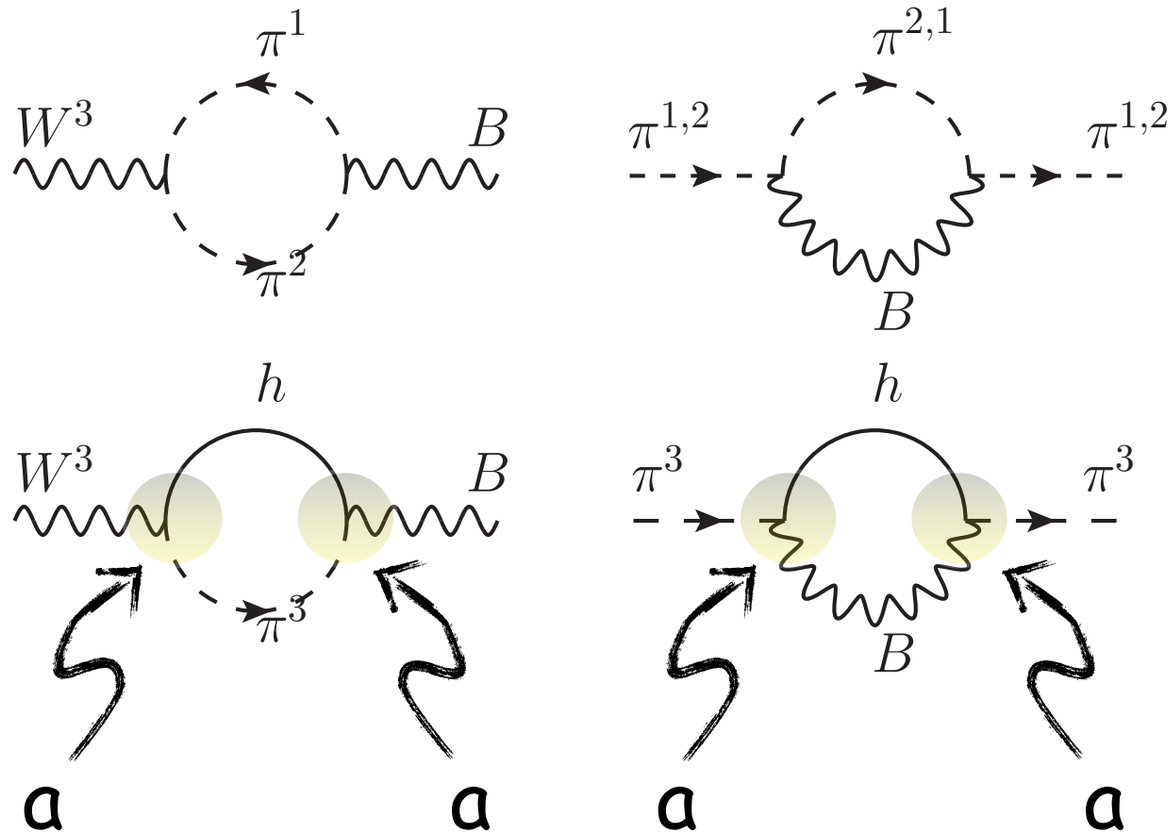
$$\Rightarrow a = \kappa_V = 1 + \frac{v^2}{2f^2}$$

$$\epsilon_{1,3} = c_{1,3}\log(m_Z^2/\mu^2) - c_{1,3}\,a^2\log(m_h^2/\mu^2) - c_{1,3}\left(1-a^2\right)\log(m_\rho^2/\mu^2) + \text{finite terms}$$

$$c_1 = +\frac{3}{16\pi^2}\frac{\alpha(m_Z)}{\cos^2\theta_W} \qquad c_3 = -\frac{1}{12\pi}\frac{\alpha(m_Z)}{4\sin^2\theta_W}$$

$$\Delta\epsilon_{1,3} = -c_{1,3}\left(1-a^2\right)\log(m_\rho^2/m_h^2)$$

Barbieri, Bellazzini, Rychkov, Varagnolo '07



Log. div. cancel only for a=1 (SM)

a≠1 log. sensitivity on the scale of new physics

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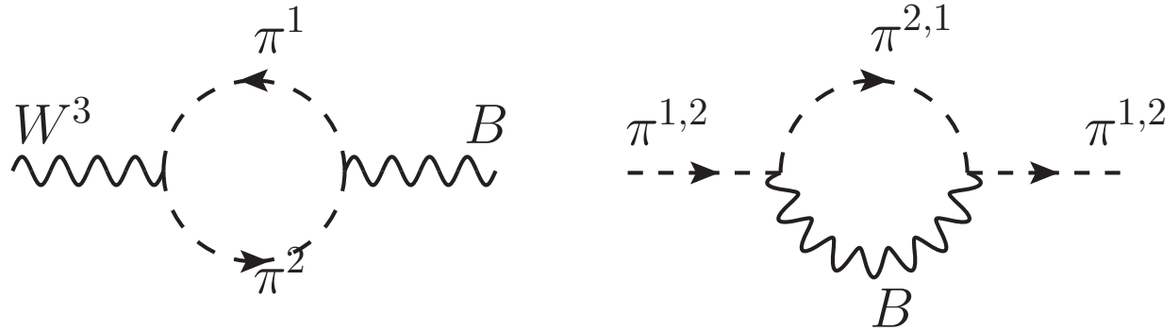
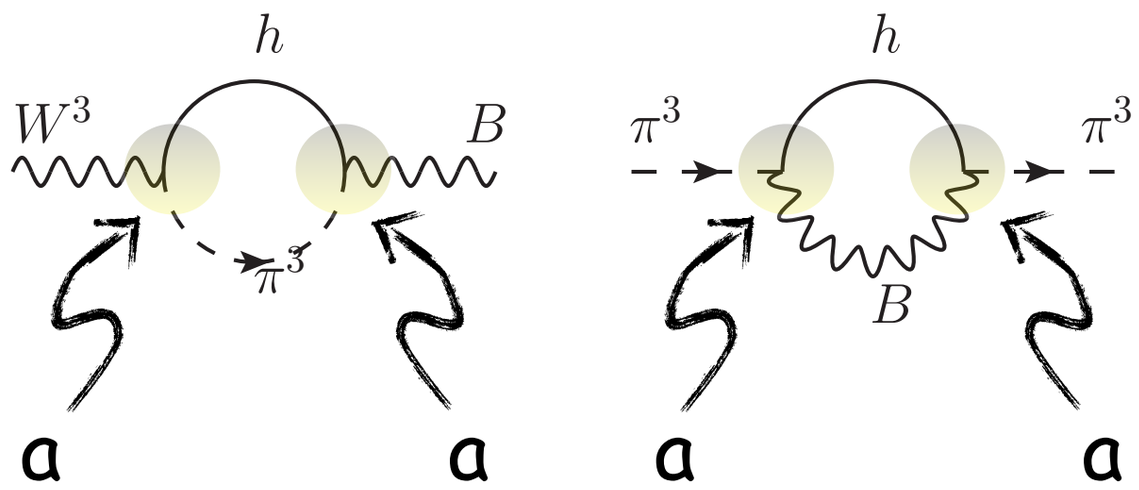




Log. div. cancel only for a=1 (SM)

a≠1 log. sensitivity on the scale of new physics

EW fit:

$$0.98 \leq a^2 \leq 1.12$$

Ciuchini et al '13

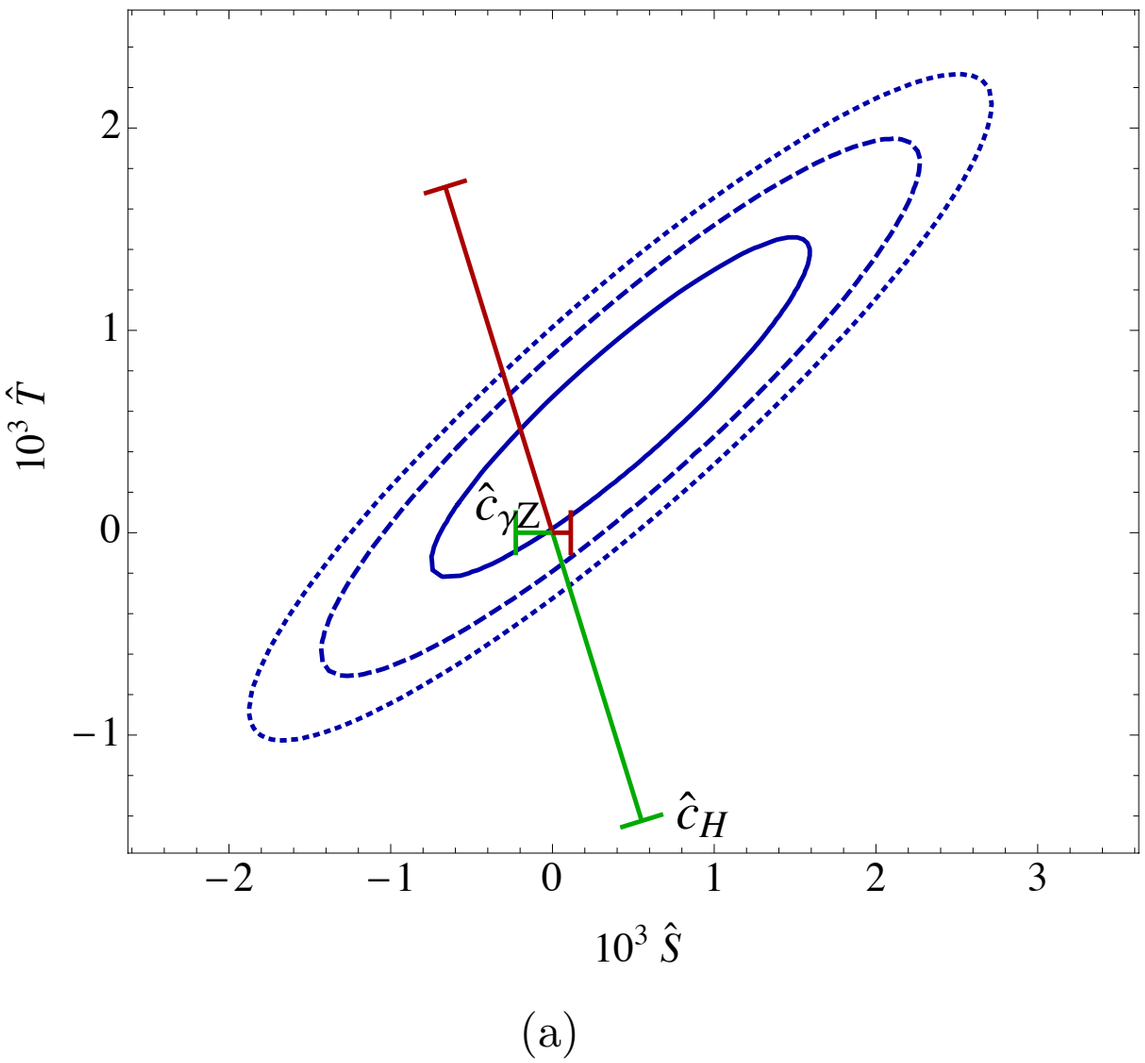
see also Grojean et al '13

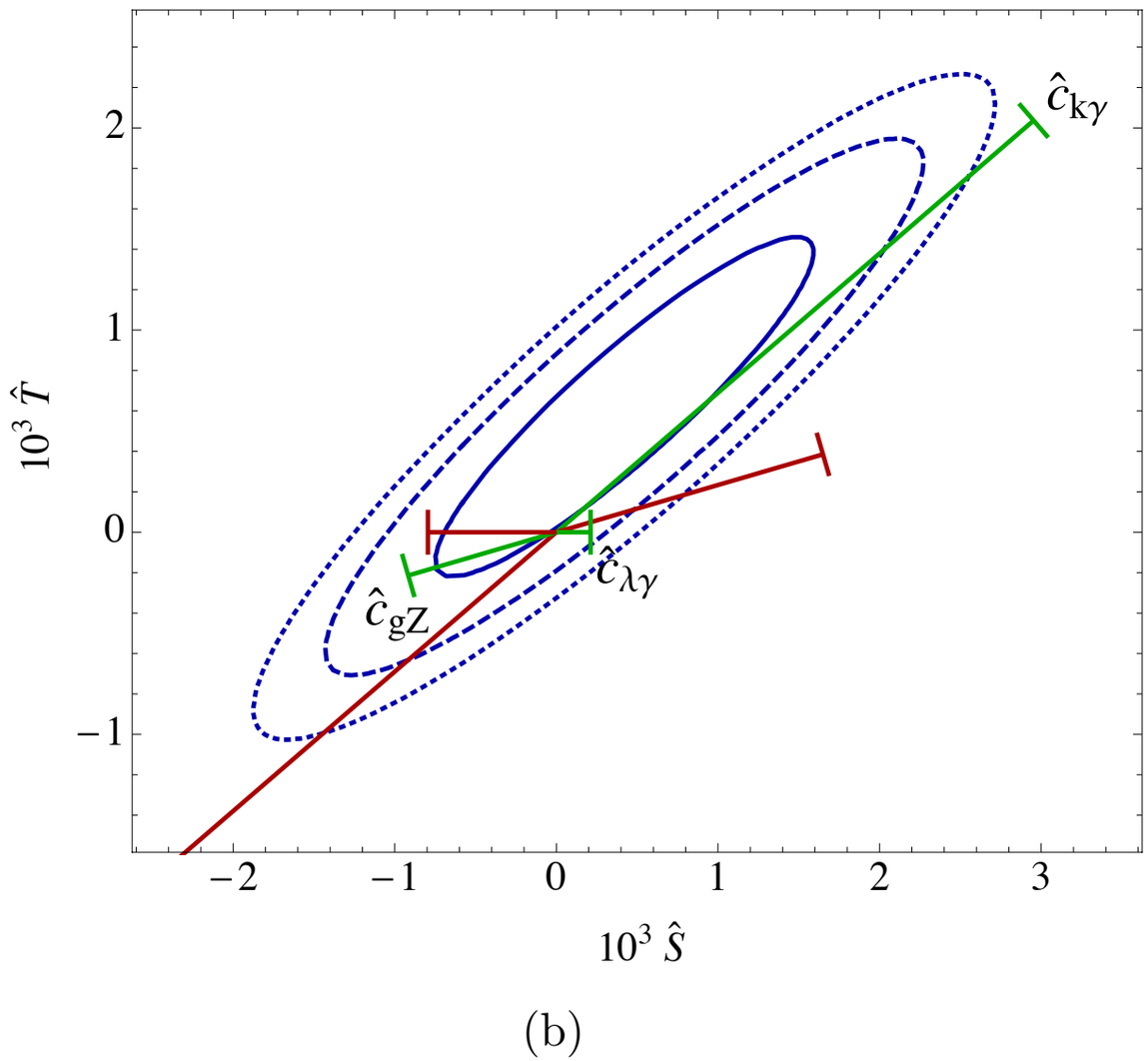
The LEP indirect constraints on the other BSM primaries are not competitive

Elias-Miro et al '13

Don't forget LEP!

Elias-Miro, Grojean, Gupta, Marzocca '14





The blue ellipses represent the 68% (solid), 95% (dashed) and 99% (dotted) CL bounds on S and T.
The straight lines represent the RG-induced contribution to the oblique parameters
from the weakly constrained observable couplings, divided in Higgs couplings (a) and TGC couplings (b).
The length of the lines corresponds to their present 95% CL direct bounds.

EW/Higgs data: the TLEP improvement

LEP: 10^6 Z's ➠ TLEP: 10^{12} Z's

TLEP (physics case) '13

Quantity	Physics	Present precision	Measured from	Statistical uncertainty	Systematic uncertainty	Ratio TLEP/LEP
m_Z (keV)	Input	91187500 ± 2100	Z Line shape scan	5 (6)	< 100	20
Γ_Z (keV)	$\Delta\rho$ (not $\Delta\alpha_{had}$)	2495200 ± 2300	Z Line shape scan	8 (10)	< 100	20
R_ℓ	α_s, δ_b	20.767 ± 0.025	Z Peak	0.00010 (12)	< 0.001	25
N_ν	PMNS Unitarity, ...	2.984 ± 0.008	Z Peak	0.00008 (10)	< 0.004	
N_ν	... and sterile ν's	2.92 ± 0.05	$Z\gamma$, 161 GeV	0.0010 (12)	< 0.001	
R_b	δ_b	0.21629 ± 0.00066	Z Peak	0.000003 (4)	< 0.000060	10
A_{LR}	$\Delta\rho$, ϵ_3, $\Delta\alpha_{had}$	0.1514 ± 0.0022	Z peak, polarized	0.000015 (18)	< 0.000015	100
m_W (MeV)	$\Delta\rho$, ϵ_3, ϵ_2, $\Delta\alpha_{had}$	80385 ± 15	WW threshold scan	0.3 (0.4)	< 0.5	3
m_{top} (MeV)	Input	173200 ± 900	$t\bar{t}$ threshold scan	10 (12)	< 10	100

Table 9. Selected set of precision measurements at TLEP. The statistical errors have been determined with *(i)* a one-year scan of the Z resonance with 50% data at the peak, leading to 7×10^{11} Z visible decays, with resonant depolarization of single bunches for energy calibration at O(20min) intervals; *(ii)* one year at the Z peak with 40% longitudinally-polarized beams and a luminosity reduced to 20% of the nominal luminosity; *(iii)* a one-year scan of the WW threshold (around 161 GeV), with resonant depolarization of single bunches for energy calibration at O(20min) intervals; and *(iv)* a five-years scan of the $t\bar{t}$ threshold (around 346 GeV). The statistical errors expected with two detectors instead of four are indicated between brackets. The systematic uncertainties indicated below are only a "first look" estimate and will be revisited in the course of the design study.

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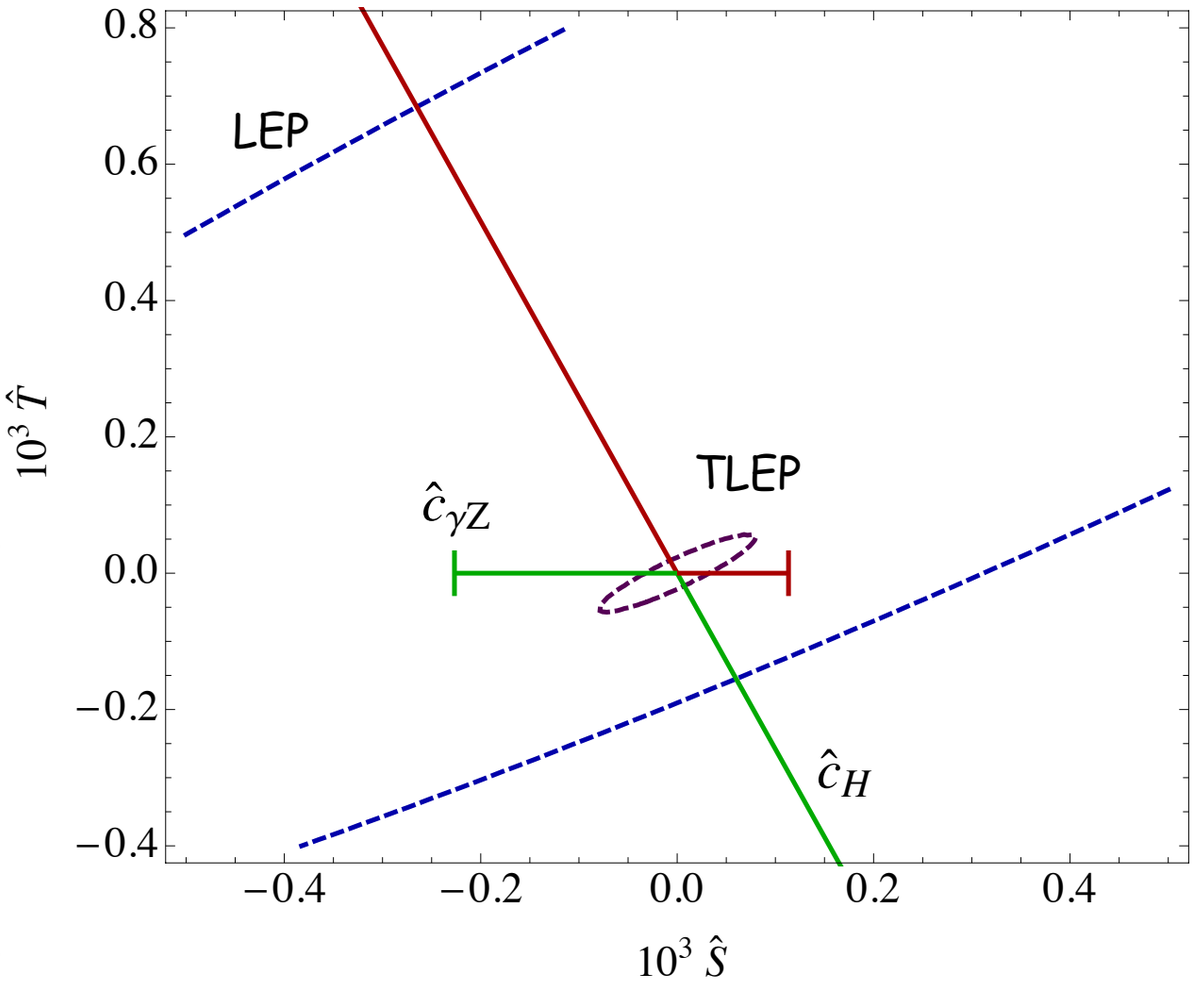
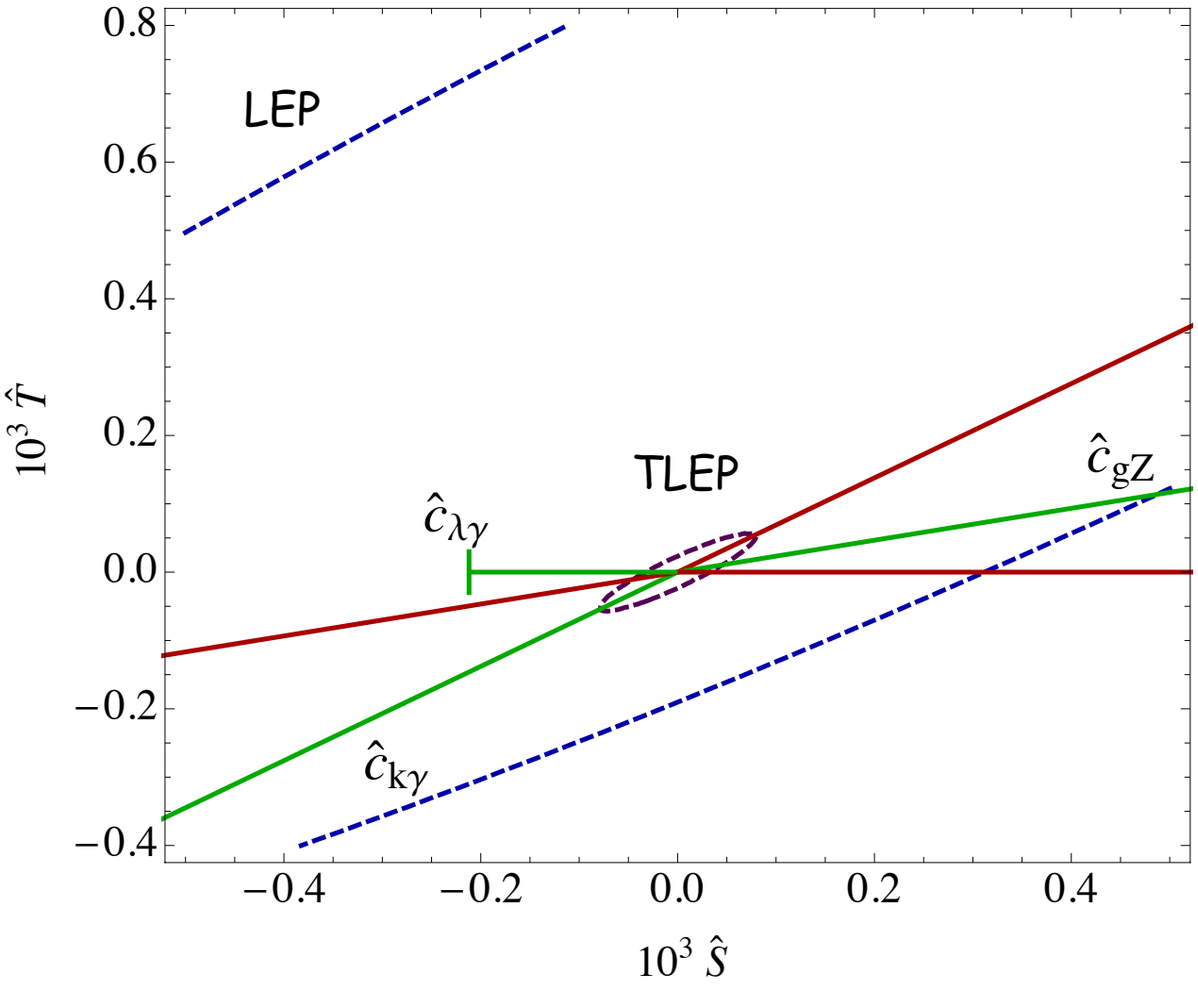
Elias-Miro, Grojean, Gupta, Marzocca '14





O(20-30) improvement in EW oblique parameters measurement

(ILC/now ≈ 2÷3 improvement only)

CP violation in Higgs physics?

Is CP a good symmetry of Nature? 2 CP-violating couplings in the SM:

V_{CKM} (large, O(1)), but screened by small quark masses) and θ_{QCD} (small, $O(10^{-10})$)

EXTRA SLIDES

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Can the 0^+ SM Higgs boson have CP violating couplings?

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Can the 0^+ SM Higgs boson have CP violating couplings?

Among the 59 irrelevant directions, 6 CP Higgs/BSM primaries

$$\Delta\mathcal{L}_{\rm BSM} = i\delta\tilde{g}_{hff}\, h\bar{f}_L f_R + h.c. \qquad \text{(f=b, } \tau\text{, t)}$$

$$+\tilde{\kappa}_{GG}\frac{h}{v}G^{\mu\nu}\tilde{G}_{\mu\nu} \qquad \left(\tilde{F}_{\mu\nu} \equiv \epsilon_{\mu\nu\rho\sigma}F^{\rho\sigma}\right)$$

$$+\tilde{\kappa}_{\gamma\gamma}\frac{h}{v}F^{\gamma\,\mu\nu}\tilde{F}^{\gamma}_{\mu\nu}$$

$$+\tilde{\kappa}_{\gamma Z}\frac{h}{v}F^{\gamma\,\mu\nu}\tilde{F}^{Z}_{\mu\nu}$$

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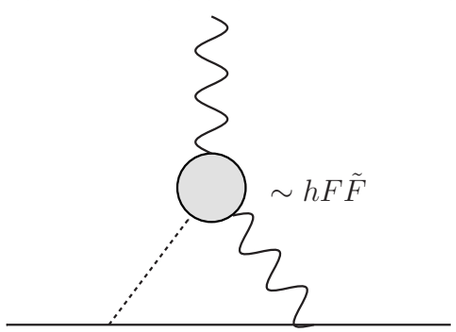
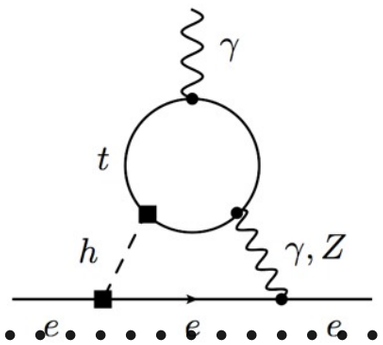
operators with γ:
already severely constrained
by e and q EDMs
McKeen, Pospelov, Ritz '12



$$\tilde{\kappa}_{\gamma\gamma} \sim \tilde{\kappa}_{\gamma Z} \leq 10^{-4}$$

Λ_{CP} > 25 TeV

operators with top:
already severely constrained
by e and q EDMs
Brod, Haisch, Zupan '13



$$\delta\tilde{g}_{htt} \leq 0.01$$

Λ_{CP} > 2.5 TeV

Last hopes in $h\tau\tau$ or hbb?