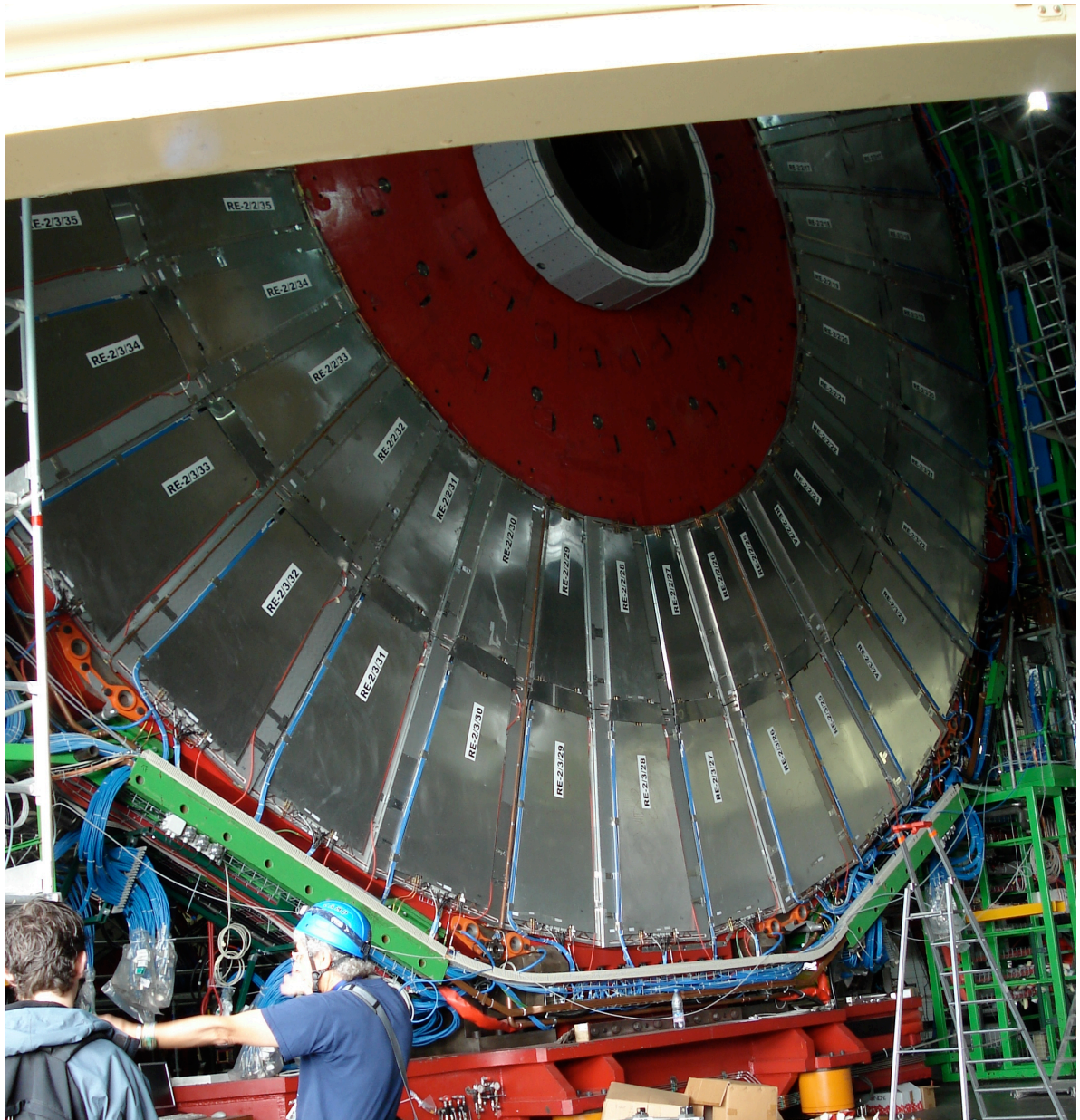
Higgs Fysica

Lydia Brenner

Brout-Englert-Higgs Fysica

Lydia Brenner

2007 op CERN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RE-2/3/28

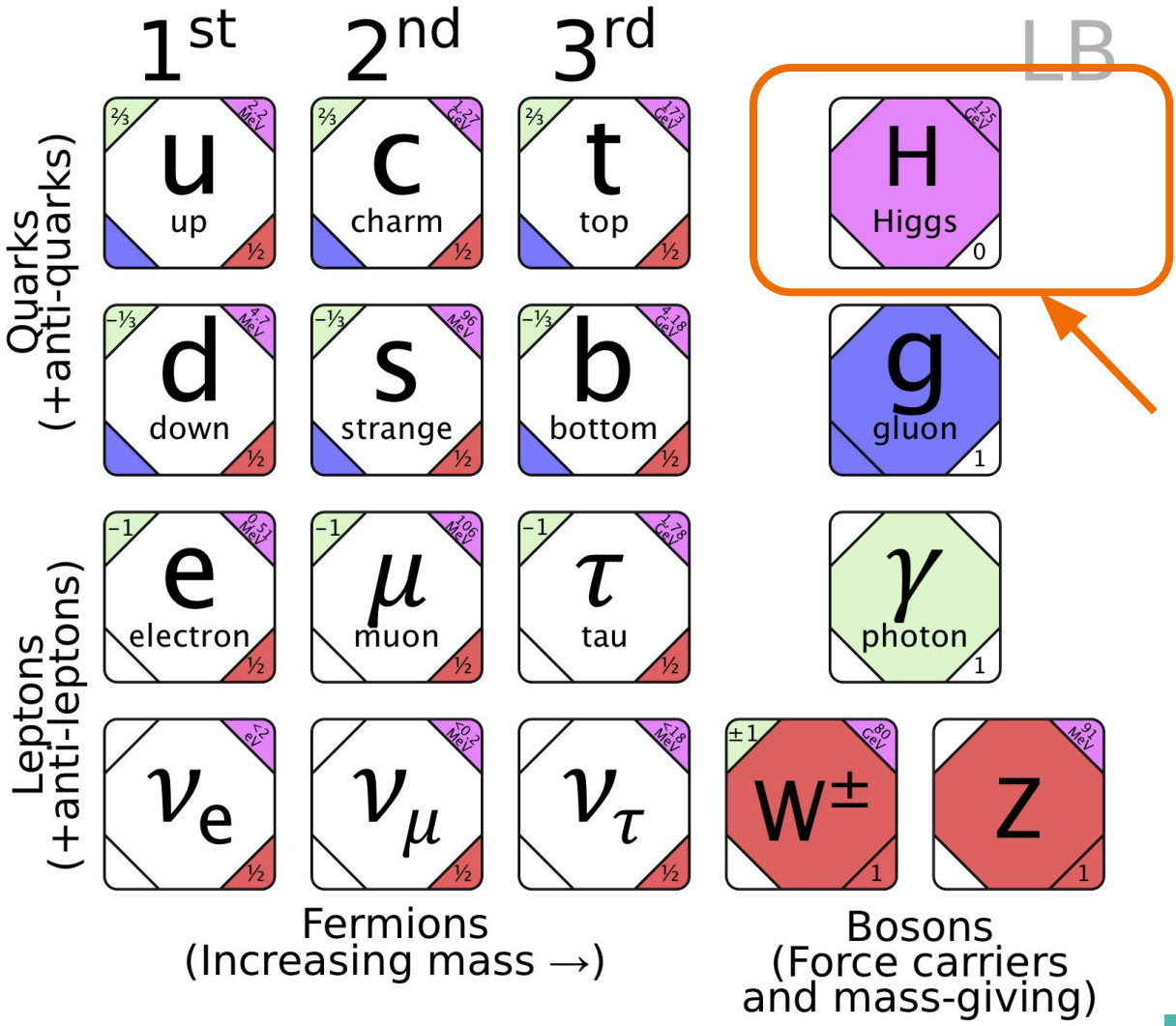
Het standaard model

$$-\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \tfrac{1}{2}ig_s^2(q^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu + G^a\partial^2 G^a + g_s f^{abc}\partial_\mu G^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \tfrac{1}{2}\partial_\mu H \partial_\mu H - \tfrac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2\phi^+\phi^- - \tfrac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \tfrac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h[\tfrac{2M^2}{g^2} + \tfrac{2M}{g}H + \tfrac{1}{2}(H^2+\phi^0\phi^0+2\phi^+\phi^-)] + \tfrac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + A_\mu(W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - \tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] - \tfrac{1}{8}g^2\alpha_h[H^4+(\phi^0)^4+4(\phi^+\phi^-)^2+4(\phi^0)^2\phi^+\phi^-+4H^2\phi^+\phi^-+2(\phi^0)^2H^2] - gMW^+_\mu W^-_\mu H - \tfrac{1}{2}g\tfrac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \tfrac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \tfrac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)] + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\tfrac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_w MA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\tfrac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \tfrac{1}{4}g^2W^+_\mu W^-_\mu[H^2+(\phi^0)^2+2\phi^+\phi^-] - \tfrac{1}{4}g^2\tfrac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2+(\phi^0)^2+2(2s_w^2-1)^2\phi^+\phi^-] - \tfrac{1}{2}g^2\tfrac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) - \tfrac{1}{2}ig^2\tfrac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) + \tfrac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c_w^2-1)Z^0_\mu A_\mu\phi^+\phi^- - g^1 s_w^2 A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial + m^\lambda_e)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m^\lambda_u)u^\lambda_j - d^\lambda_j(\gamma\partial + m^\lambda_d)d^\lambda_j + igs_w A_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \tfrac{1}{3}(d^\lambda_j\gamma^\mu d^\lambda_j)] + \tfrac{ig}{4c_w}Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2-1-\gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\tfrac{4}{3}s_w^2 - 1-\gamma^5)u^\lambda_j) + (\bar{d}^\lambda_j\gamma^\mu(1-\tfrac{8}{3}s_w^2-\gamma^5)d^\lambda_j)] + \tfrac{ig}{2\sqrt{2}}W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \tfrac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1+\gamma^5)u^\lambda_j)] + \tfrac{ig}{2\sqrt{2}}\tfrac{m^\lambda_e}{M}[-\phi^+(\bar{\nu}^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] - \tfrac{g}{2}\tfrac{m^\lambda_e}{M}[H(\bar{e}^\lambda e^\lambda) + i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \tfrac{ig}{2M\sqrt{2}}\phi^+[-m^\kappa_d(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m^\lambda_u(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j] + \tfrac{ig}{2M\sqrt{2}}\phi^-[m^\lambda_d(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m^\kappa_u(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j] - \tfrac{g}{2}\tfrac{m^\lambda_u}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \tfrac{g}{2}\tfrac{m^\lambda_d}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2}\tfrac{m^\lambda_u}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \tfrac{ig}{2}\tfrac{m^\lambda_d}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \tfrac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0X^- - \partial_\mu\bar{X}^+X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- - \partial_\mu\bar{X}^+Y) + igc_w W^-_\mu(\partial_\mu\bar{X}^-X^0 - \partial_\mu\bar{X}^0X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^-Y - \partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+X^+ - \partial_\mu\bar{X}^-X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+X^+ - \partial_\mu\bar{X}^-X^-) - \tfrac{1}{2}gM[\bar{X}^+X^+H + \bar{X}^-X^-H + \tfrac{1}{c_w^2}\bar{X}^0X^0H] + \tfrac{1-2c_w^2}{2c_w}igM[\bar{X}^+X^0\phi^+ - \bar{X}^-X^0\phi^-] + \tfrac{1}{2c_w}igM[\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-] + igMs_w[\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-] + \tfrac{1}{2}igM[\bar{X}^+X^+\phi^0 - \bar{X}^-X^-\phi^0]$$

Introduction

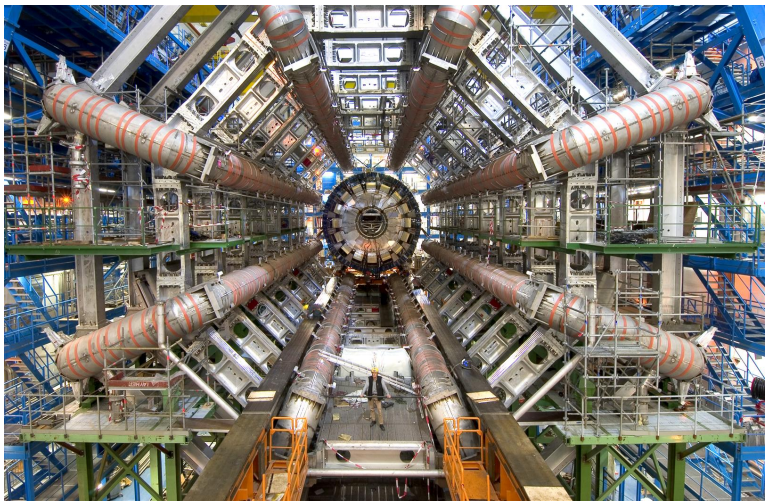
The Higgs boson

- Origin of mass
- Electroweak symmetry breaking
- Potential link to new physics

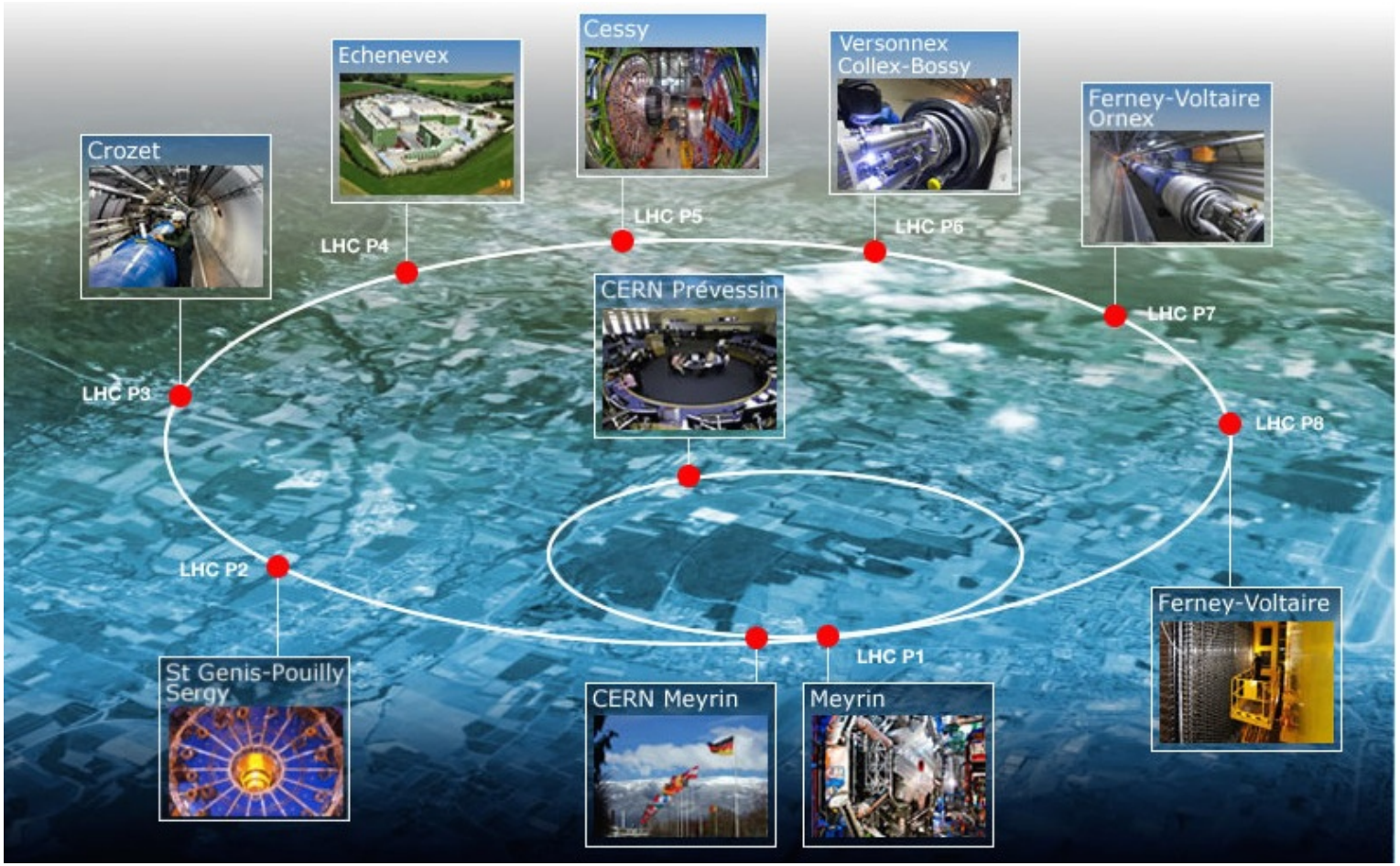


"Er zijn electromagnetische golven om ons heen die stemmen en plaatjes bevatten"

"Er is een Higgs veld waardoor deeltjes een massa kunnen krijgen"

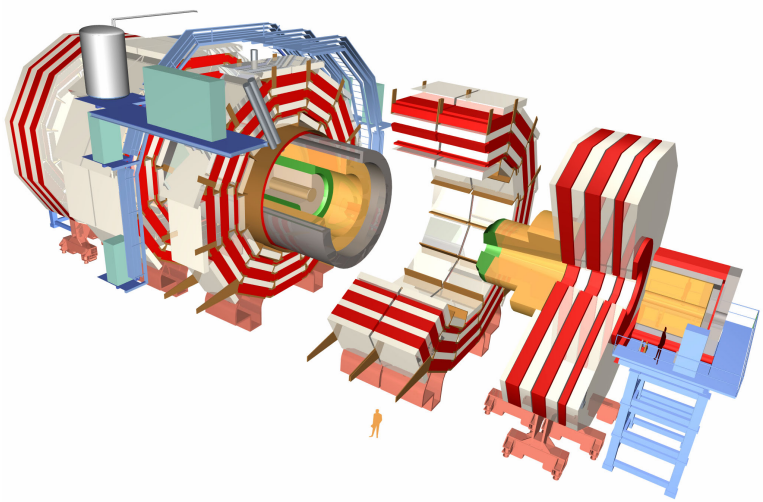


CERN

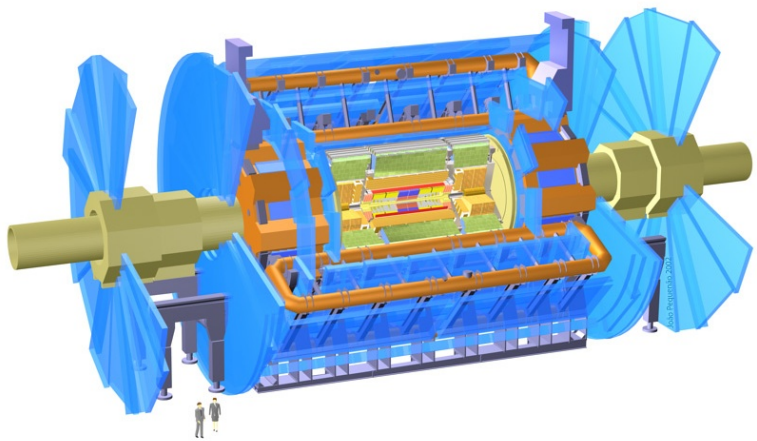

Cessy
Echenevex
Versonnex
Collex-Bossy
Ferney-Voltaire
Ornex
Crozet
LHC P5
LHC P4
LHC P6
CERN Prévessin
LHC P7
LHC P3
LHC P8
LHC P2
Ferney-Voltaire
LHC P1
St Genis-Pouilly
Sergy
CERN Meyrin
Meyrin

De CMS en Atlas detectors

CMS (Compact Muon Solenoid)
Diameter 15 m ; Lengte 21 m;
Gewicht 14000ton



ATLAS (A ToroidaL ApparatuS)
Diameter 25 m; Lengte 46 m;
Gewicht 7000 ton
Hoeveel kilometer kabel zit er in Atlas?



De Atlas detector

Atlas heeft 3000 km kabels

Hoe ver kan je komen met 3000 km vanaf Nederland?

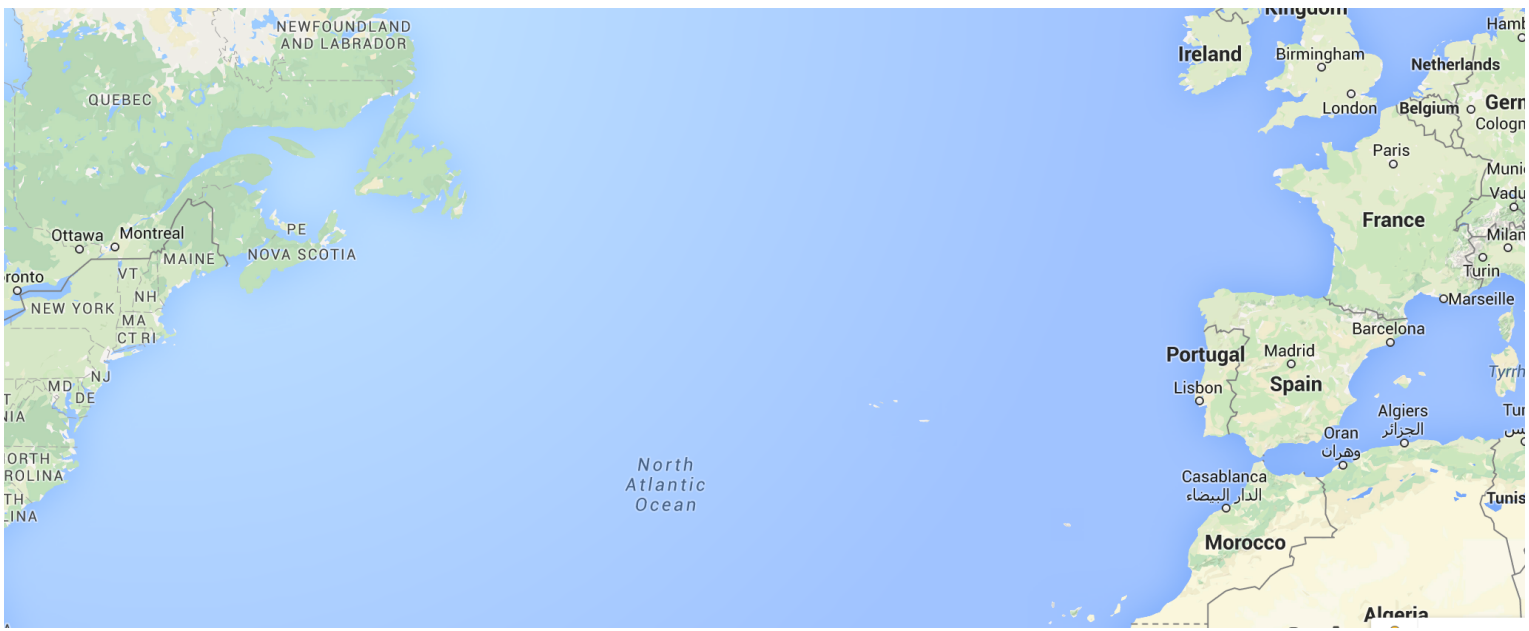
A Tot Amsterdam

B Tot Cern

C Tot Marokko

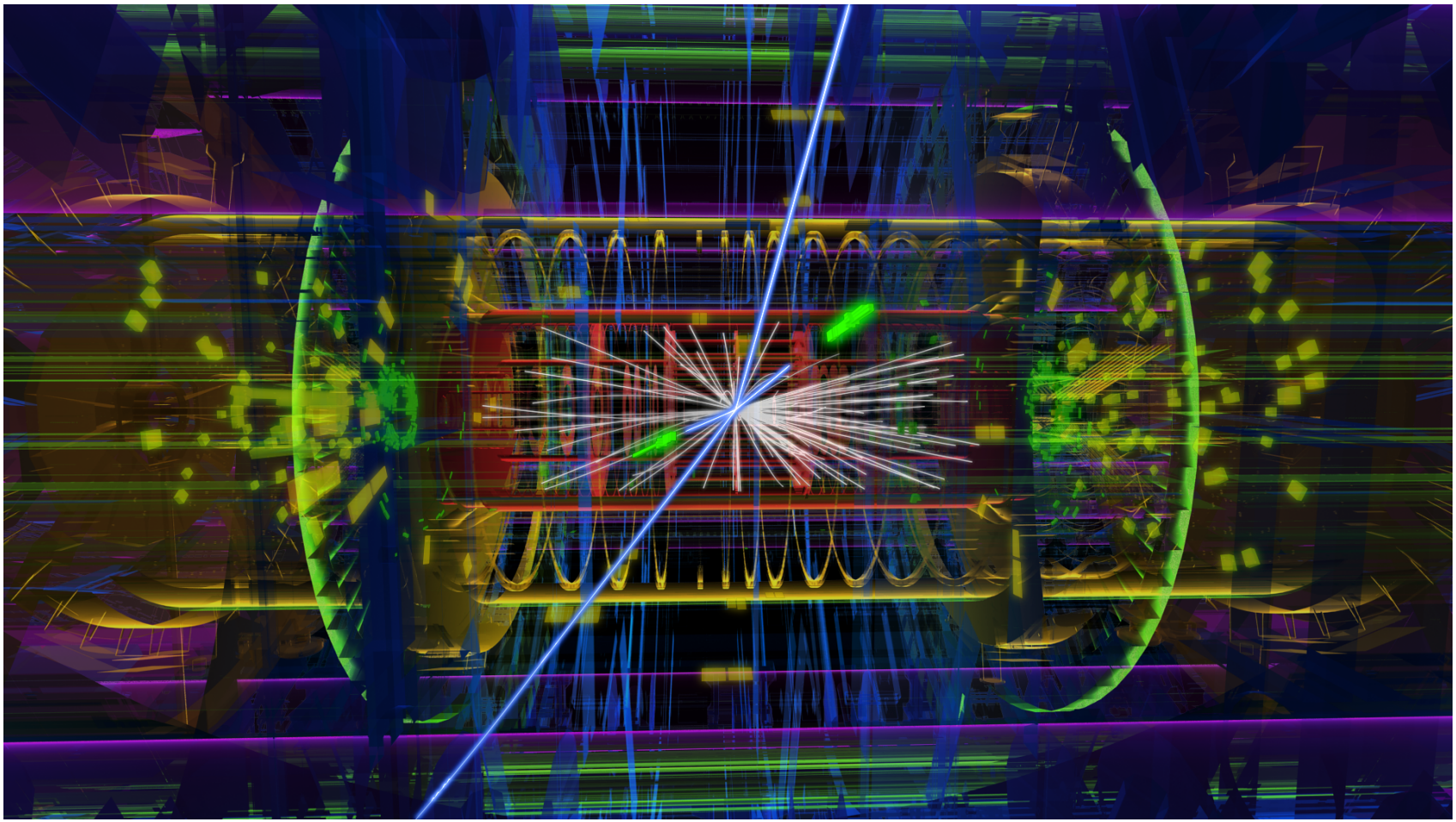
D Tot New York

E De aarde rond

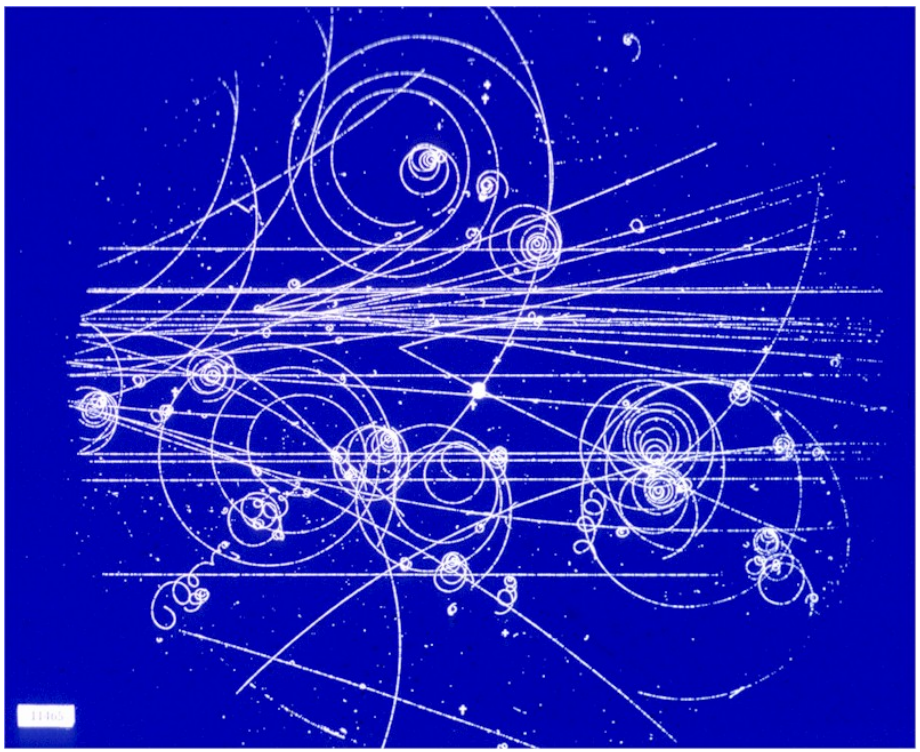


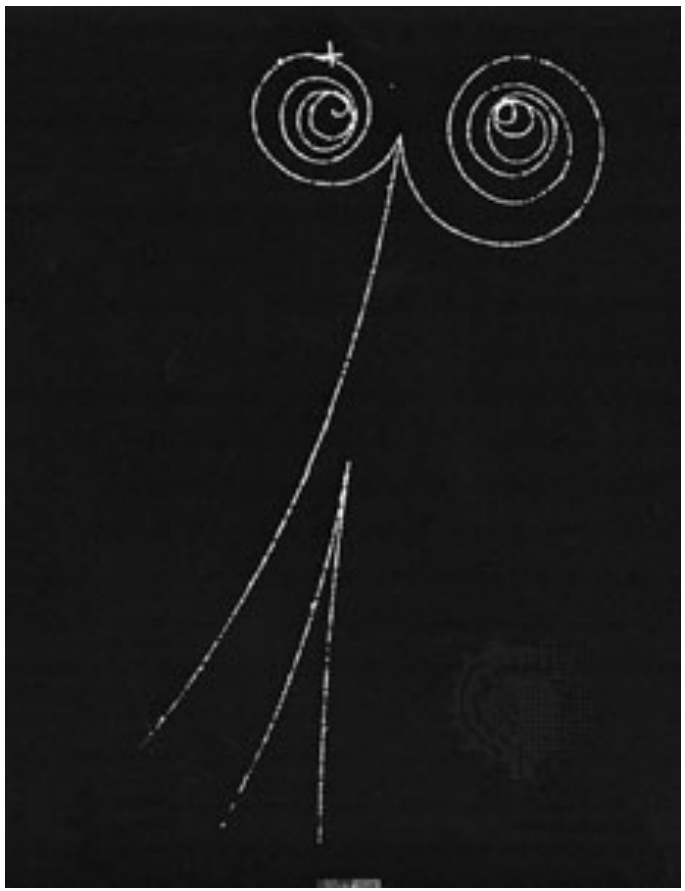
Tracks identificeren

100 miljoen kanalen

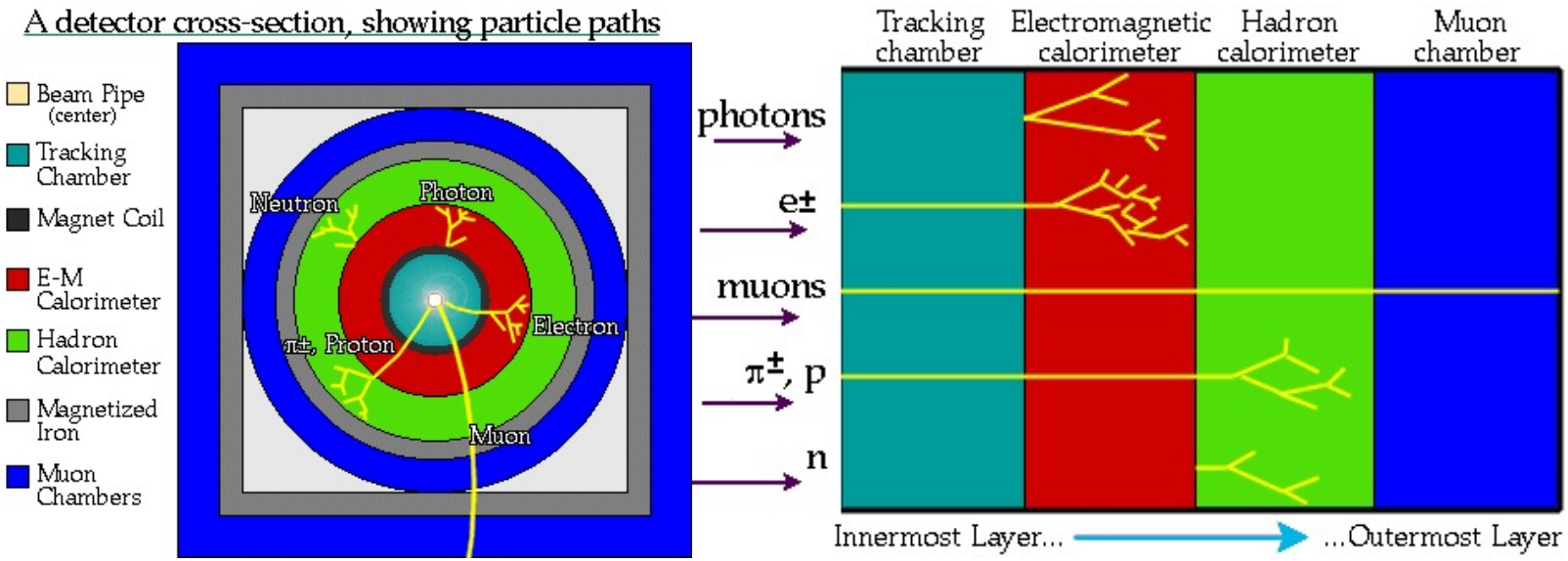


Tracks identificeren



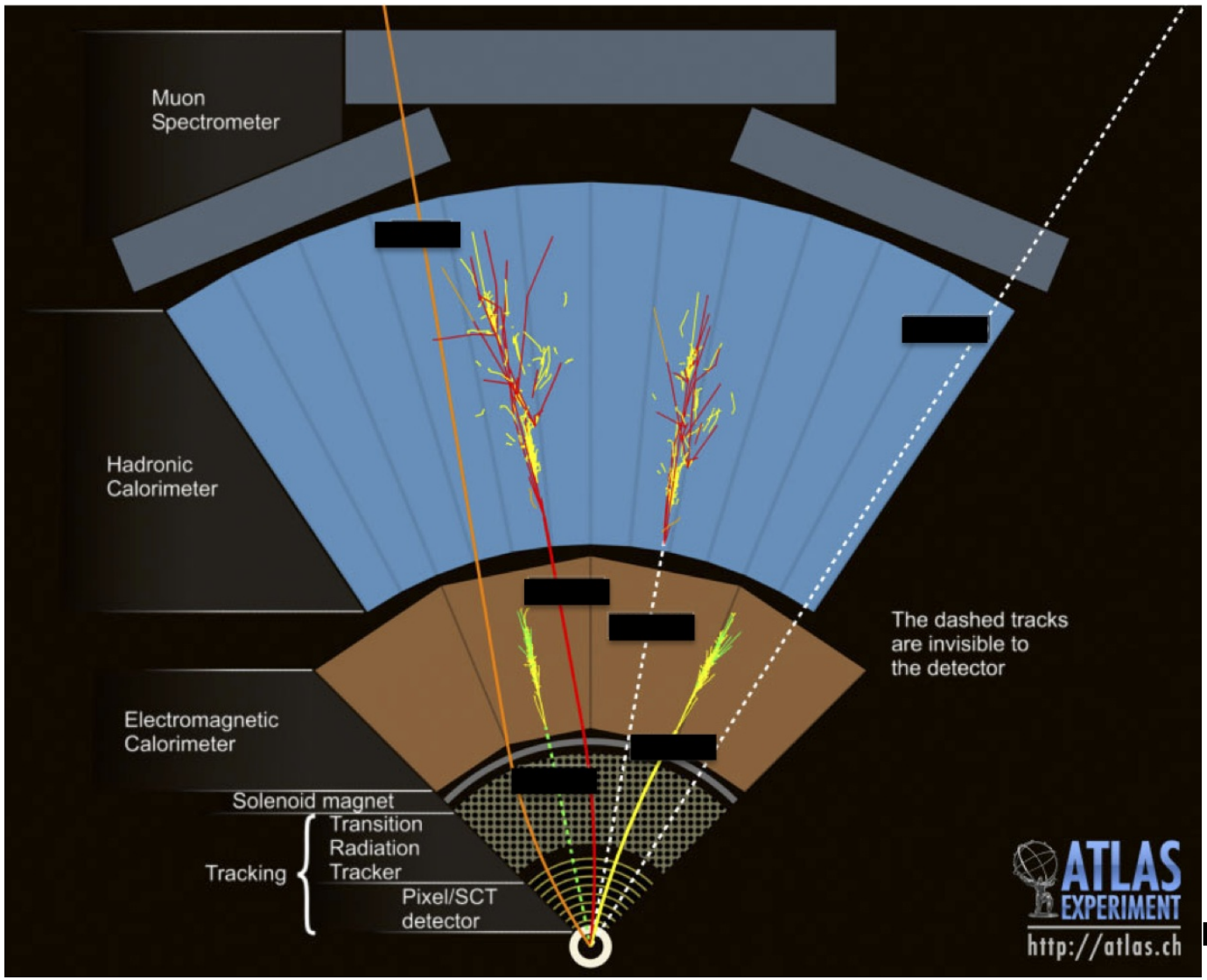


Tracks identificeren

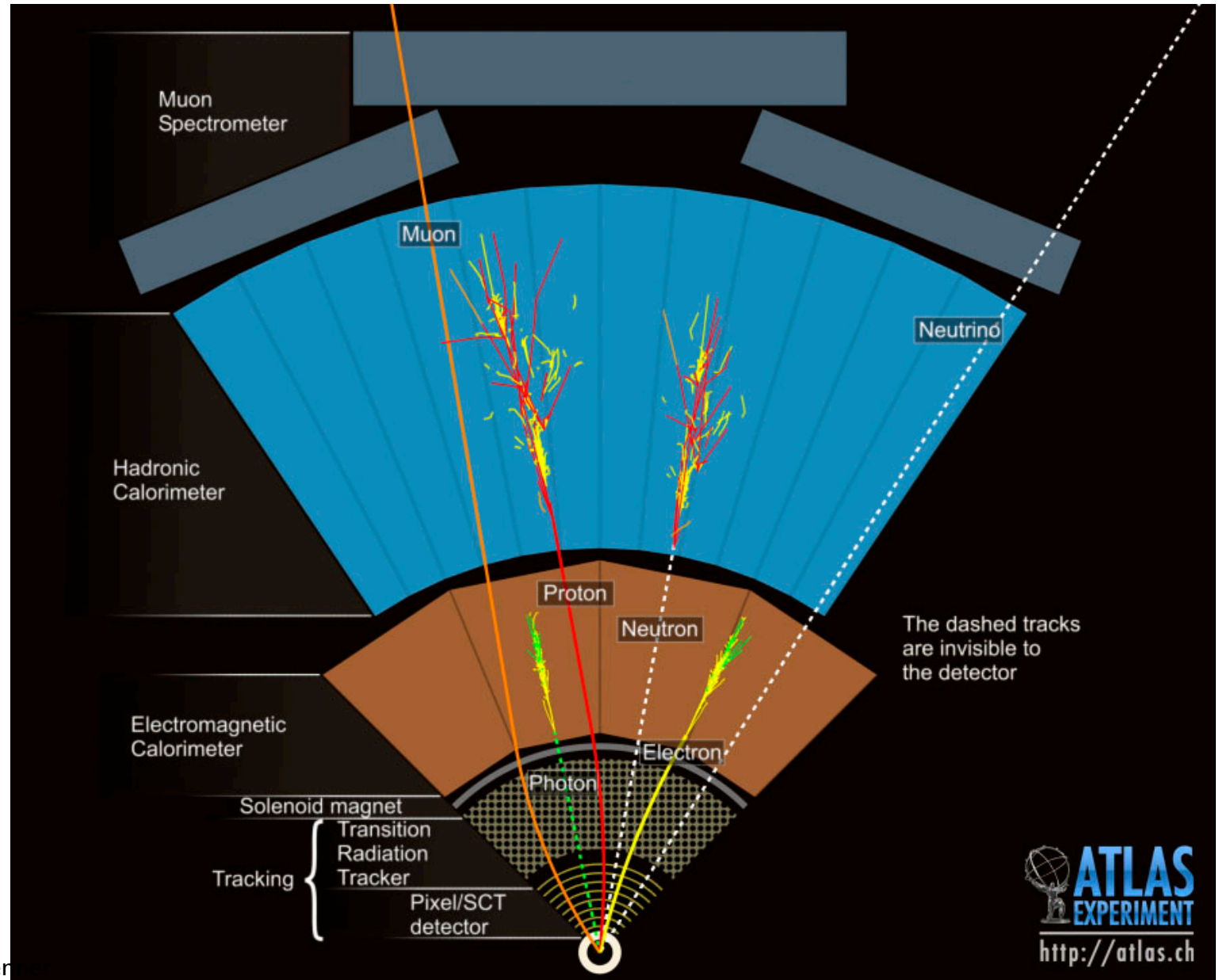


Tracks identificeren

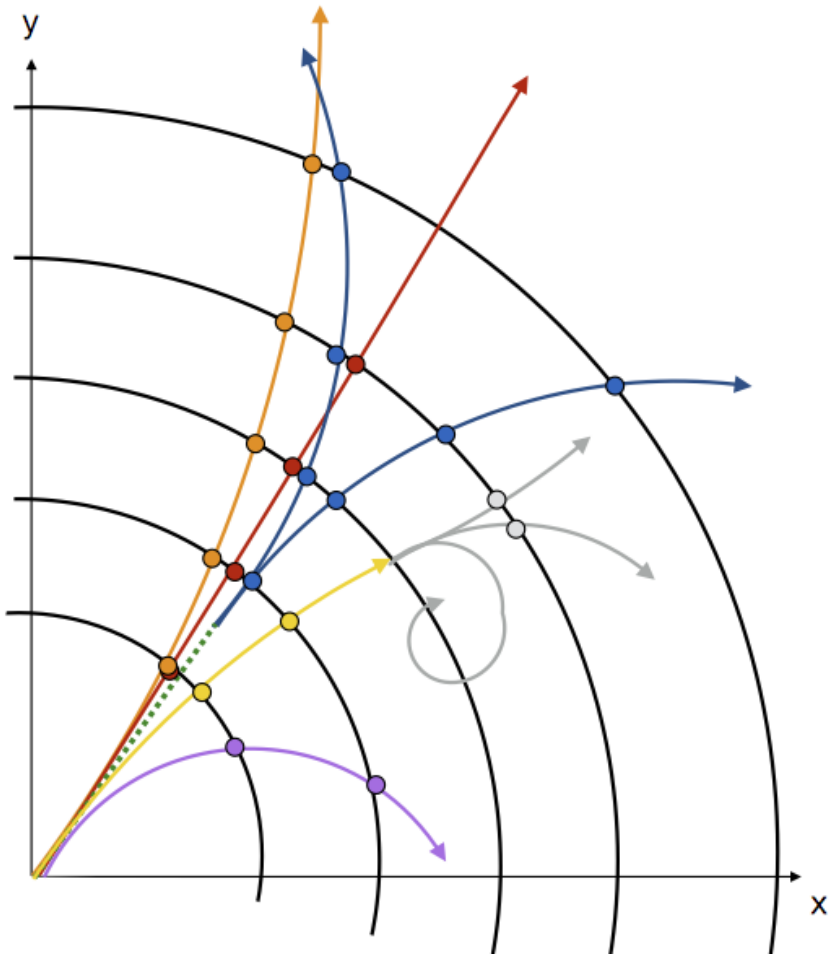
Foton
Electron
Muon
Proton
Neutron
Neutrino



Tracks identificeren



Higgs identificeren

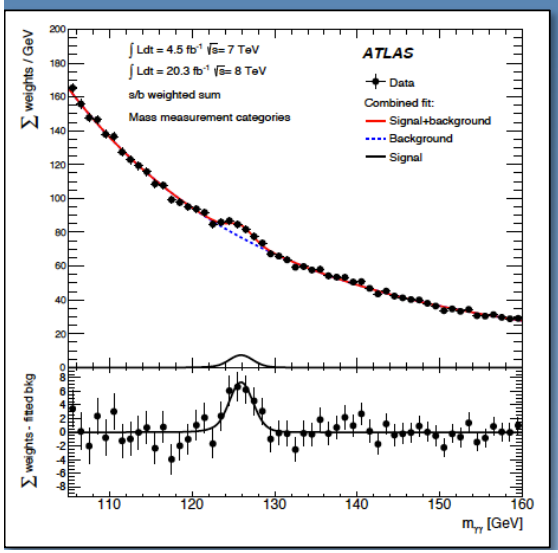


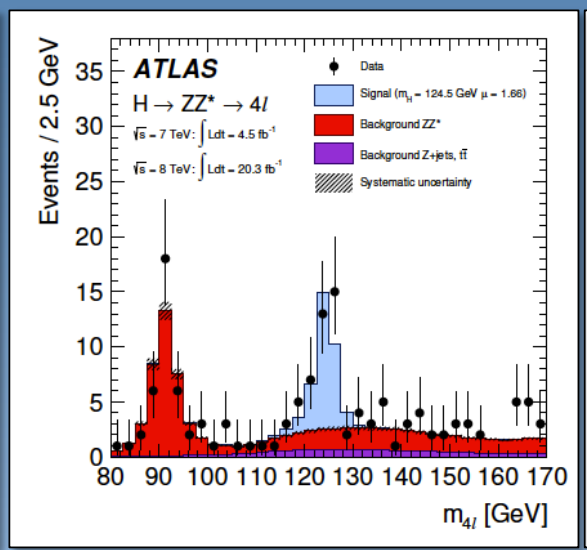
Ontdekking van een nieuw deeltje

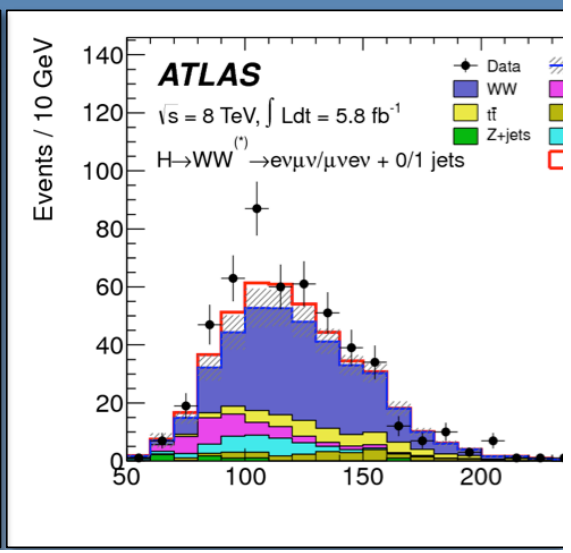
https://twiki.cern.ch/twiki/pub/AtlasProtected/HiggsWorkingGroup/WW-FixedScale.gif

Ontdekking van een nieuw deeltje

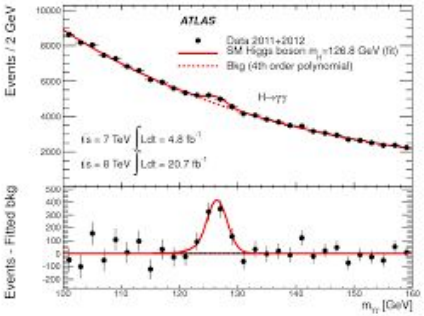
h→γγ	h→ZZ→4 leptonen	h→WW$^{(*)}$→lνlν







Higgs timeline at the LHC



Higgs boson observation

LHC

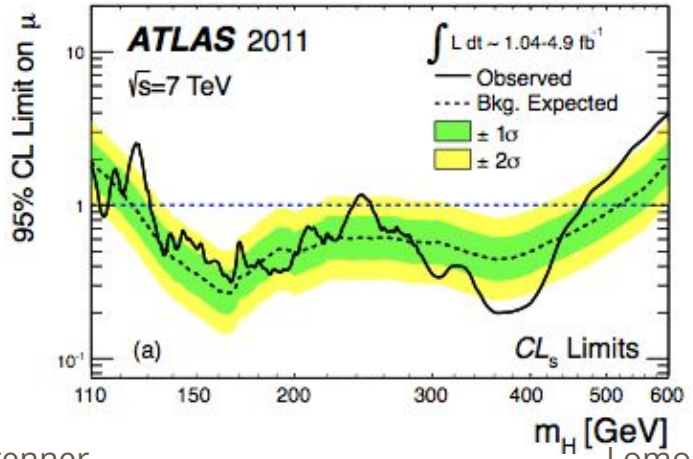
Run 1
7-8 TeV
21 fb^{-1}

Run 2
13 TeV
139 fb^{-1}

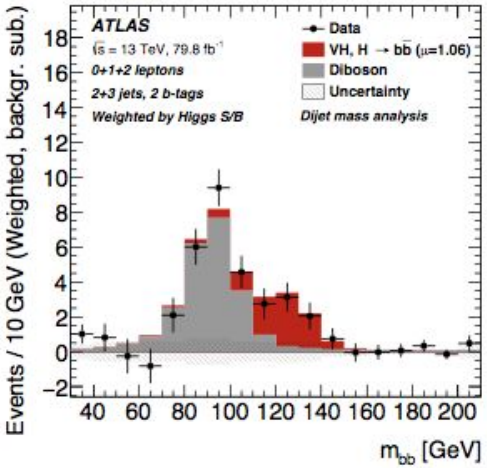
High Luminosity LHC

2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | …2038

Higgs boson searches

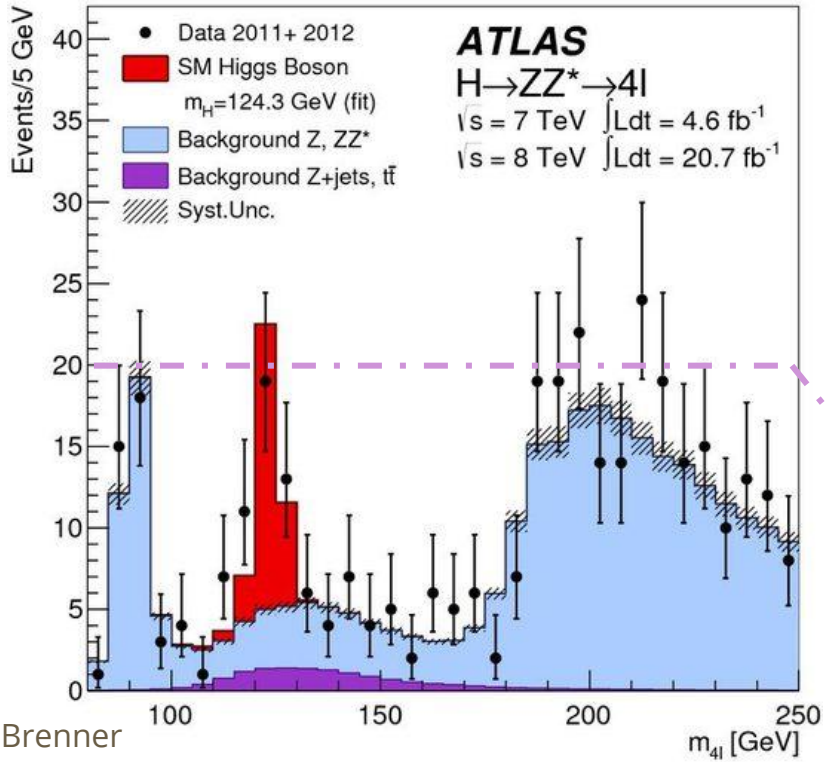


Observation of 3rd generation Yukawa couplings
- H-t, H-b

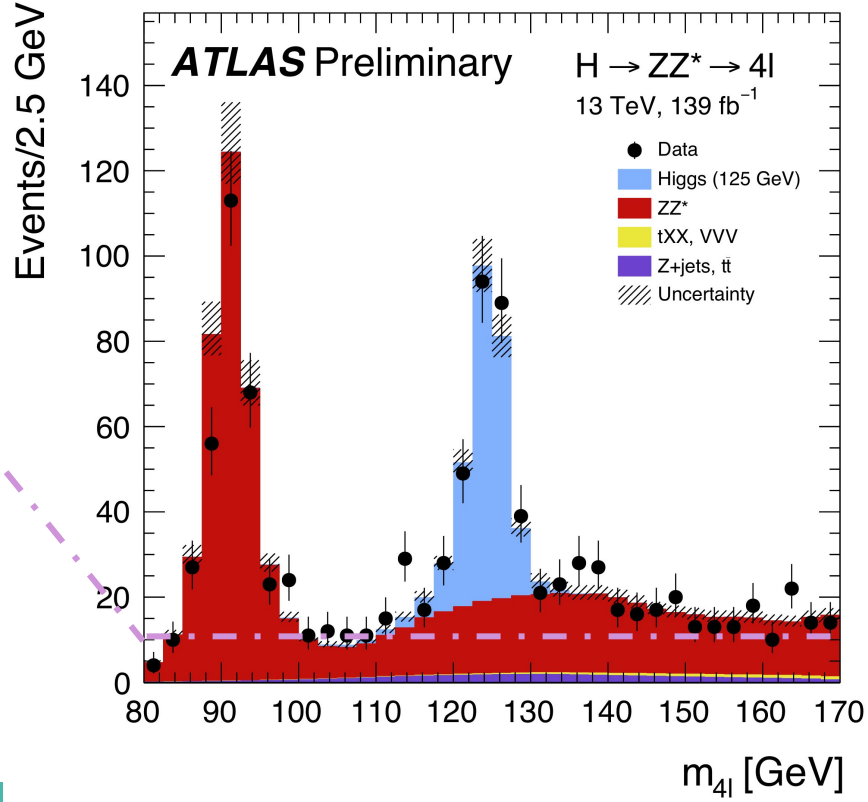


Towards precision physics

Run 1



Run 2



Introduction

The Higgs boson landscape

- Mass and width
- Coupling properties
  - Fermion interactions New
- Inclusive/differential cross-sections New

- Quantum numbers
  - Spin/CP
- Self coupling New
  - HH production
- Rare / Exotic / Invisible decays New

Particle	Produced in 139 fb^{-1} at $\sqrt{s}$=13 TeV
Higgs Boson	7.7 million
Top quark	275 million
Z Boson	2.8 billion
W Boson	12 billion

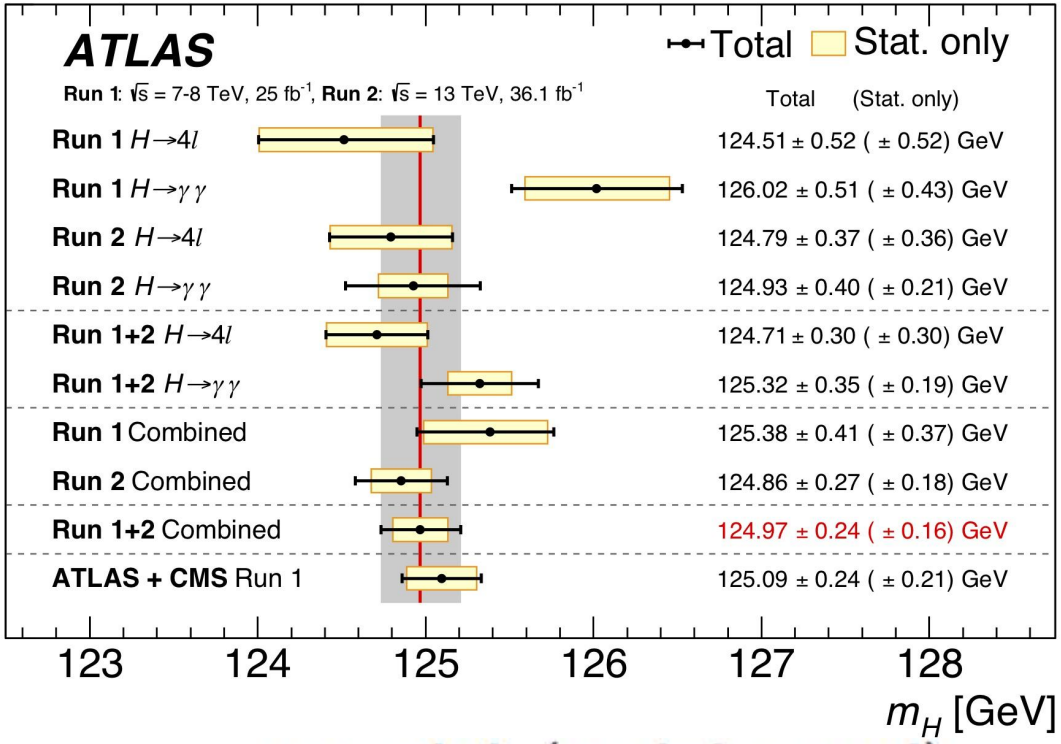
Higgs Boson mass

PLB 784(2018)345

One free parameter in the Standard Model: m_H

Among the most precise EWK parameters

- 240 MeV precision



$m_H \pm$ tot ($\pm$ stat $\pm$ syst)

$4\ell+\gamma\gamma$ (Run1 + 36/fb Run2) $124.97 \pm 0.24\ (\pm 0.16 \pm 0.18)$ GeV

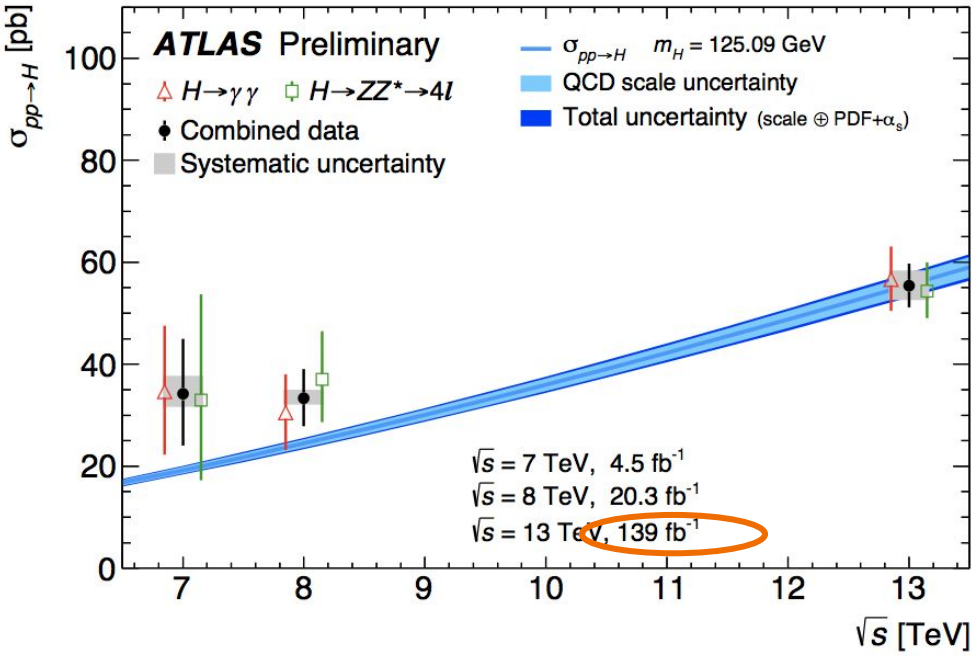
Total cross section measurement

ATLAS-CONF-2019-032

Obtained from H→ZZ→4l, H → $\gamma\gamma$, and their combination.

√s=13 TeV	Total H production xsec
$\gamma\gamma$ (full Run2)	$56.7^{+6.4}_{-6.2}$ pb
4ℓ (full Run2)	$54.4^{+5.6}_{-5.4}$ pb
Combination	$55.4^{+3.1}_{-3.1}$ (stat) $^{+3.0}_{-2.8}$ (syst) pb
SM prediction	55.6 ± 2.5 pb

Use SM BRs as input

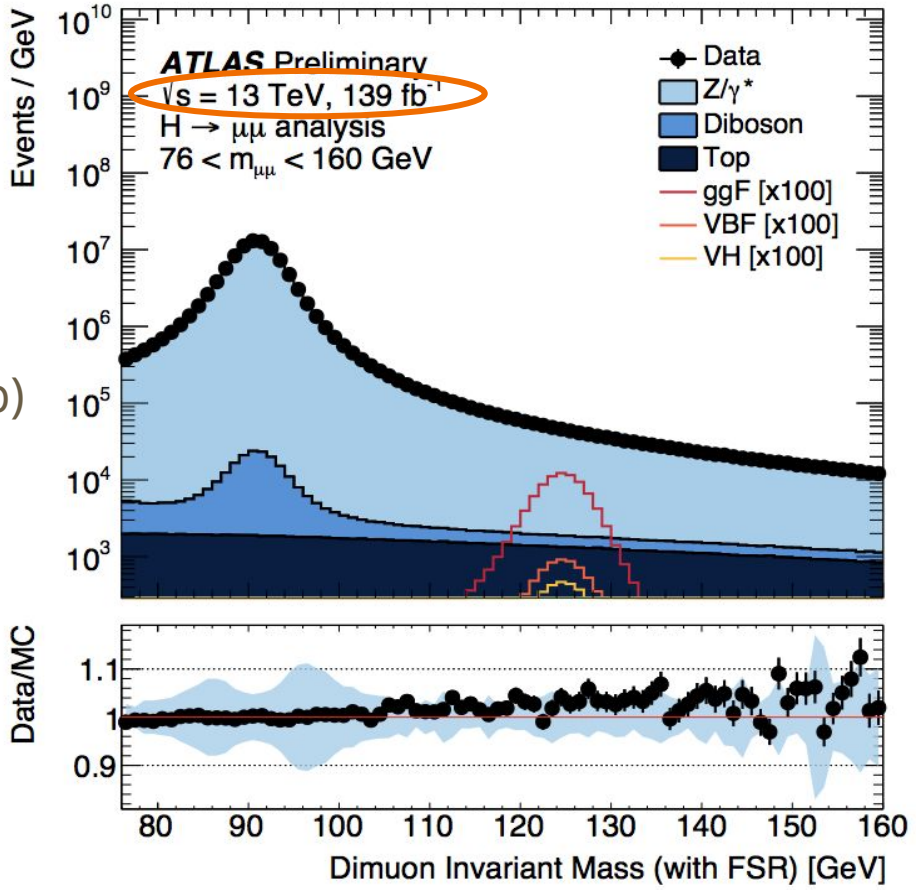


Second generation fermion couplings: H→$\mu\mu$

ATLAS-CONF-2019-028

Identifying and measuring μ
is not the problem, difficulties are

- Small BR (2×10^{-4})
- Large backgrounds (Z/γ^*, diboson, top)

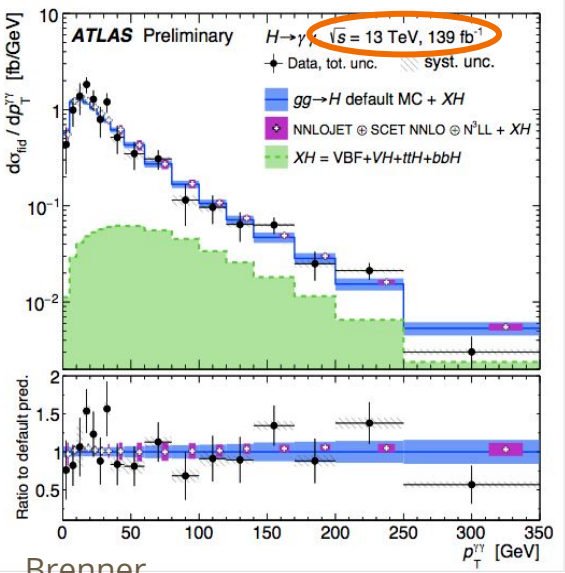


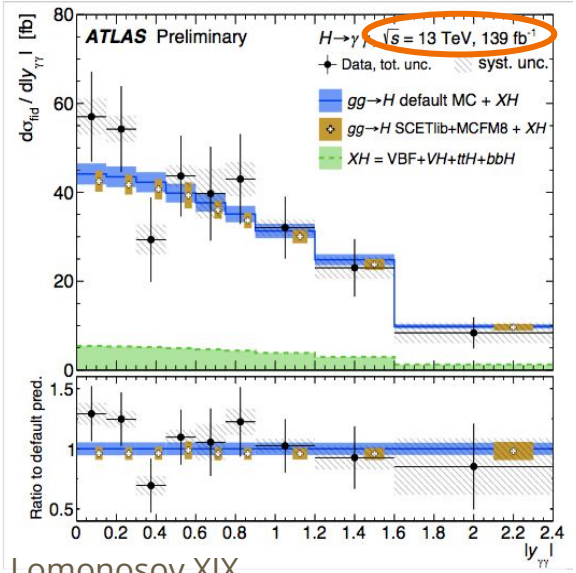
Differential cross section measurement

ATLAS-CONF-2019-029

Finer granular measurements for specific observables

Measure a large numbers of distributions ($pT_{\gamma\gamma}$, pT_{4l}, $|Y_{\gamma\gamma}|$, N_{jets}, p_T^{j1}, m_{jj}, $\Delta\varphi_{jj}$) and compare with various predictions

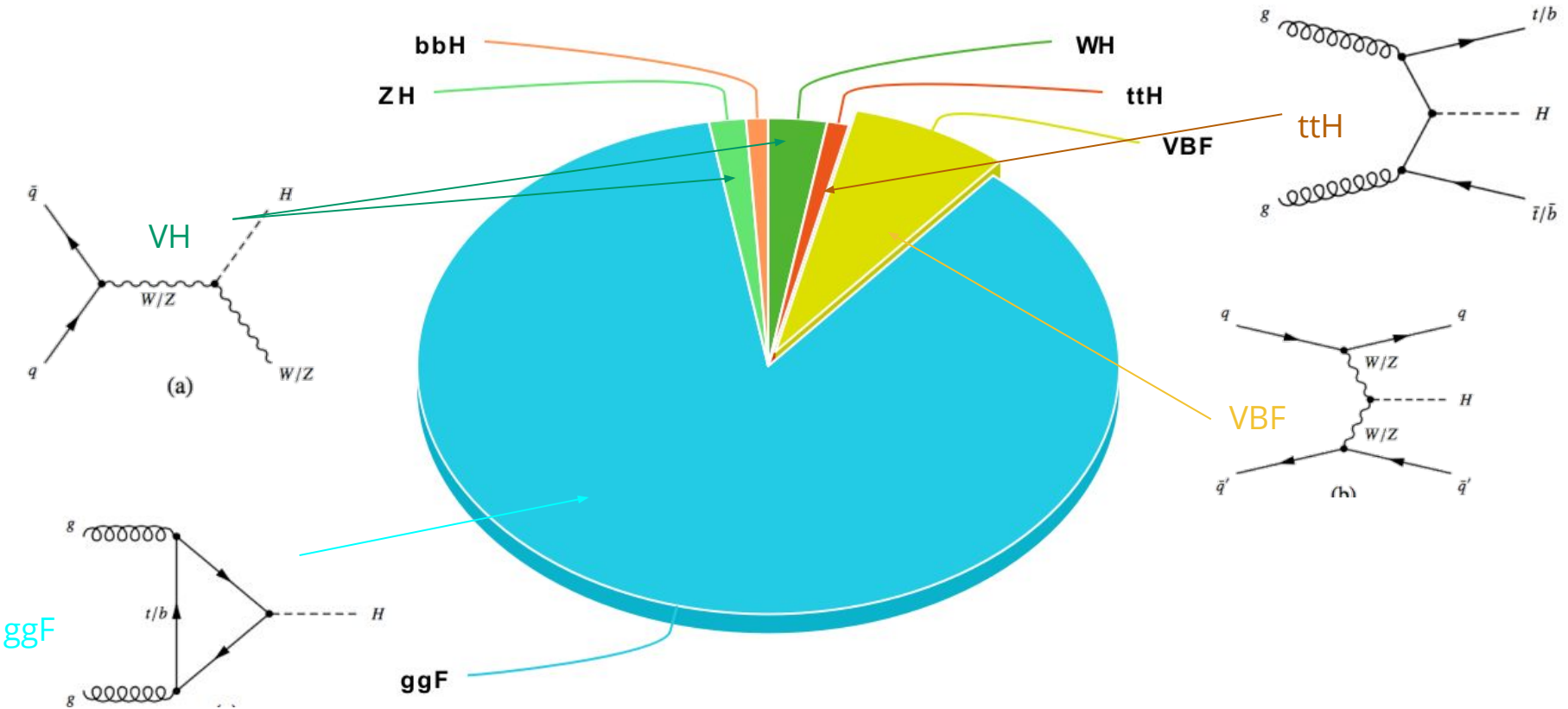




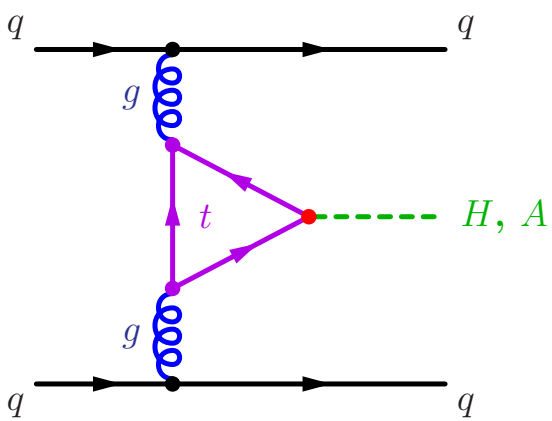
These measurements allow to constrain

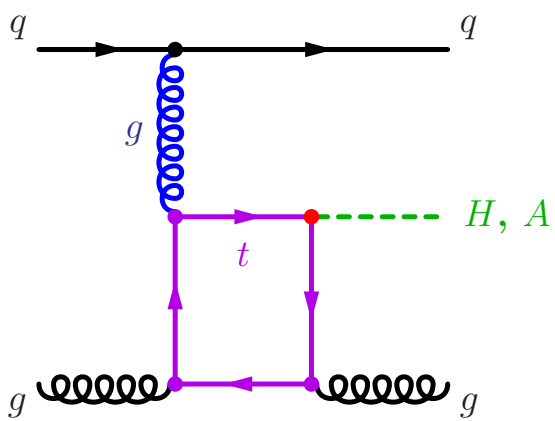
- Couplings not directly accessible (e.g charm-H interaction)
- Wilson coefficients of an effective Lagrangian

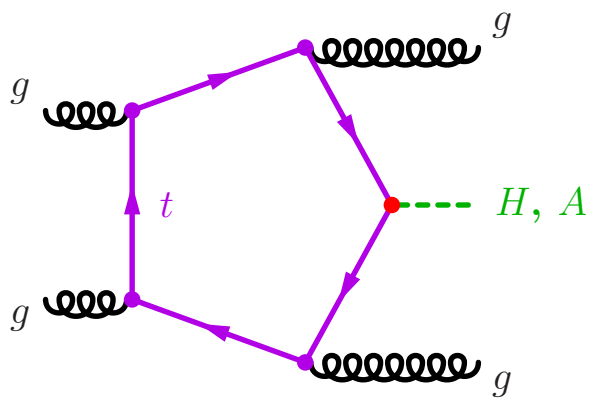
Introduction



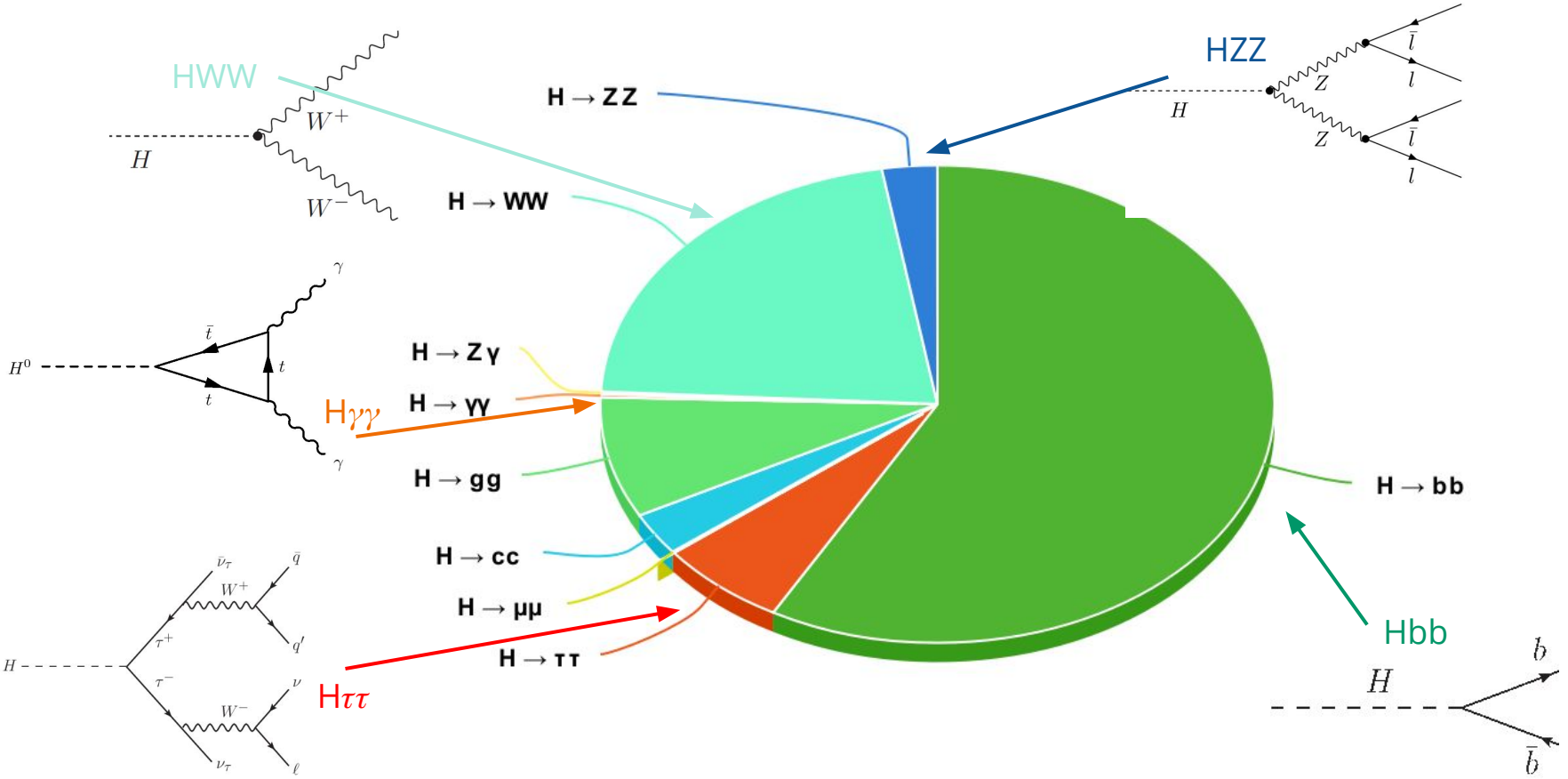
Mijn onderzoek - productie van Higgs



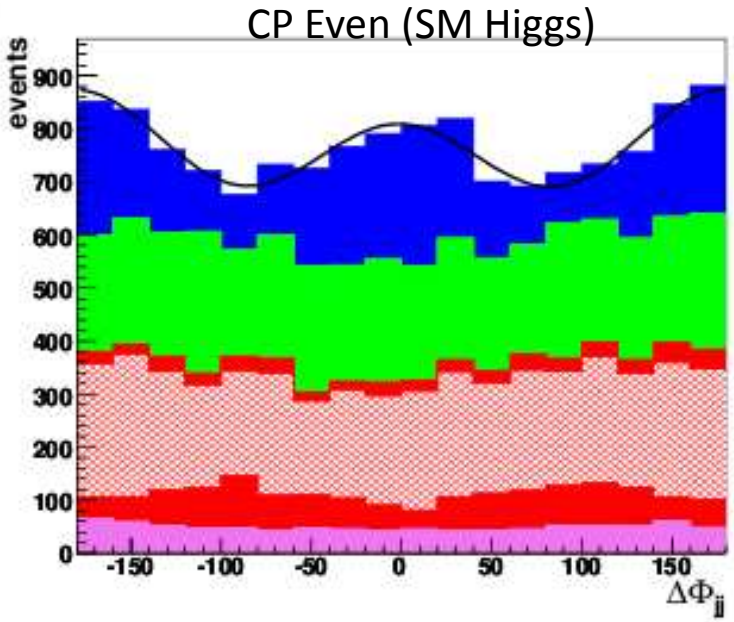


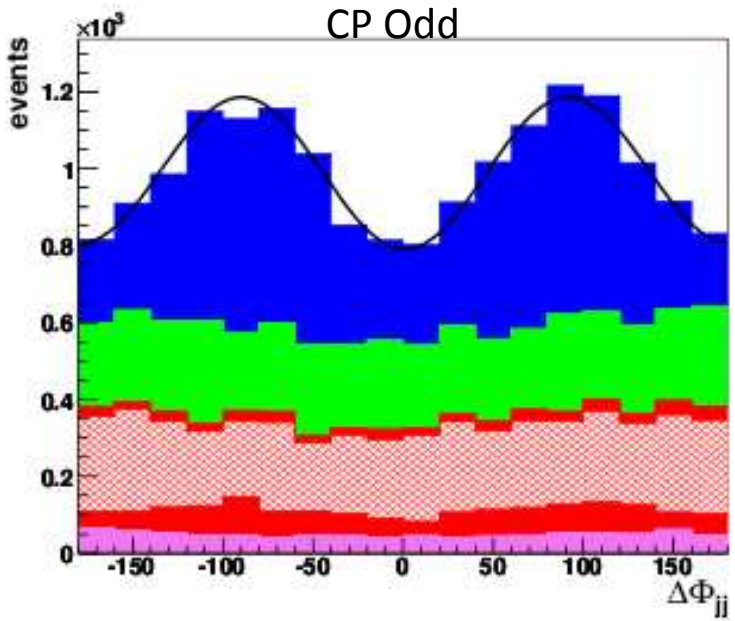


Introduction



Mijn onderzoek - Wat onderzoeken?





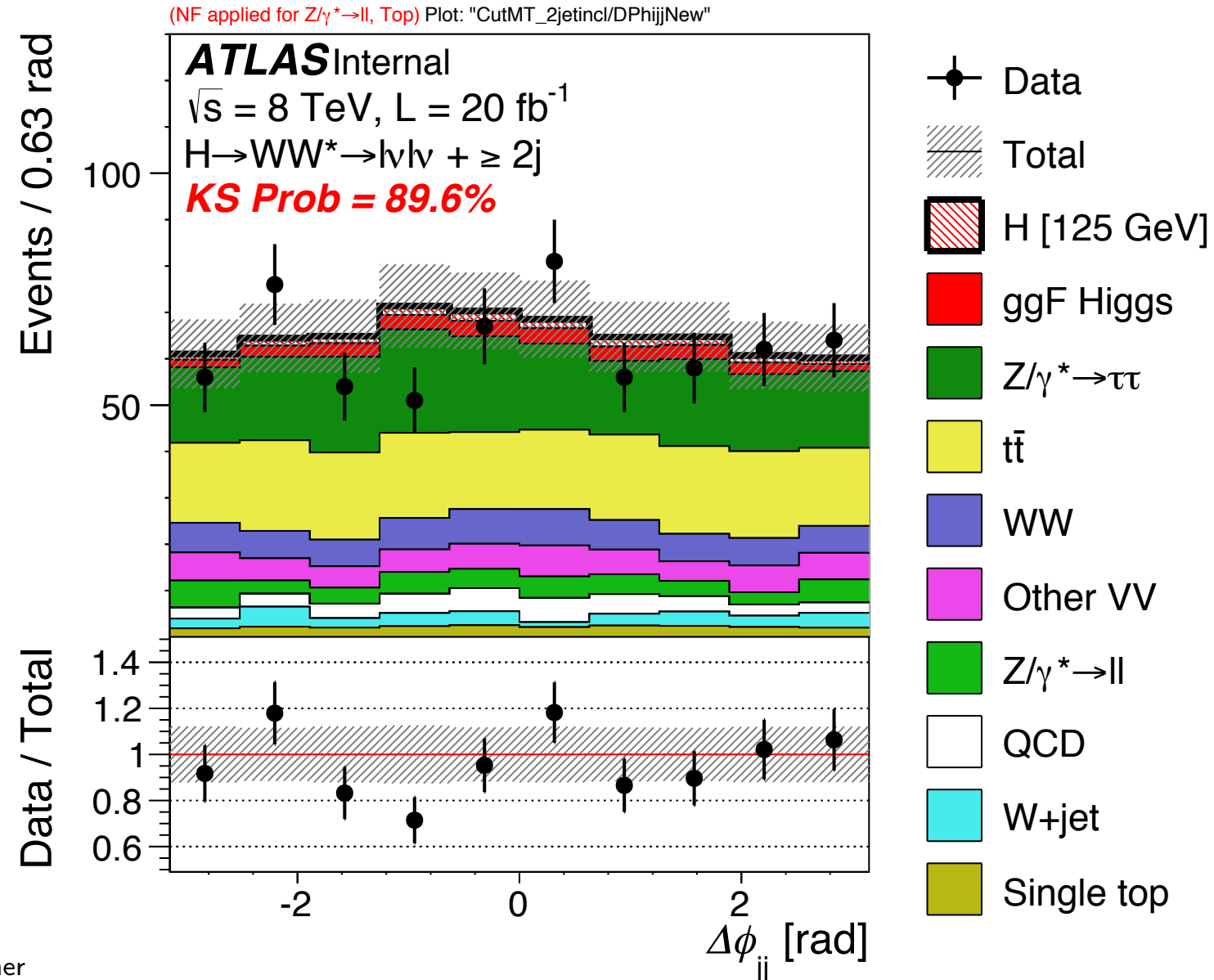
ggF

EW-WW +2j
(Dominated by VBF
Higgs production)

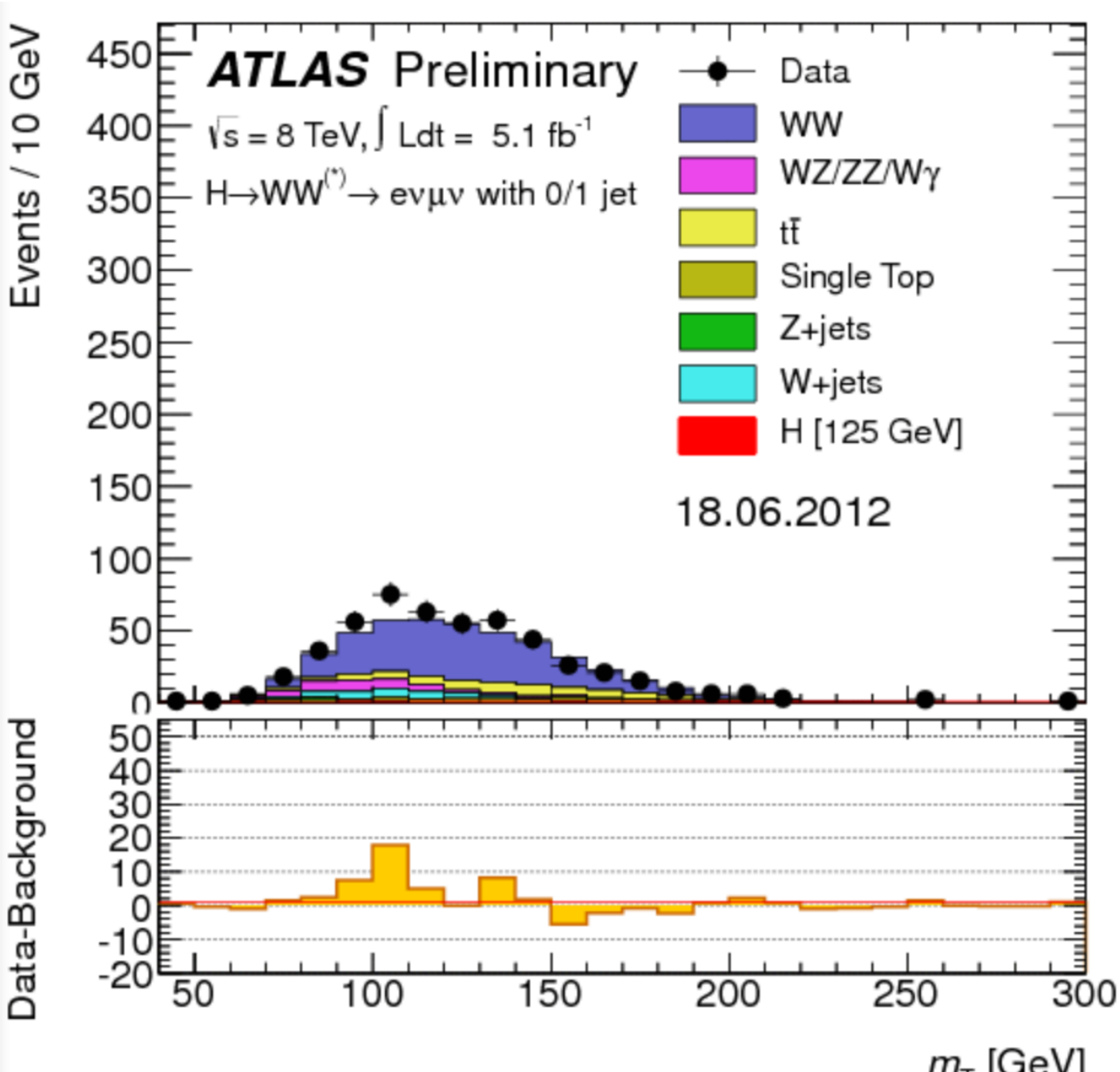
Top background

QCD-WW+2j

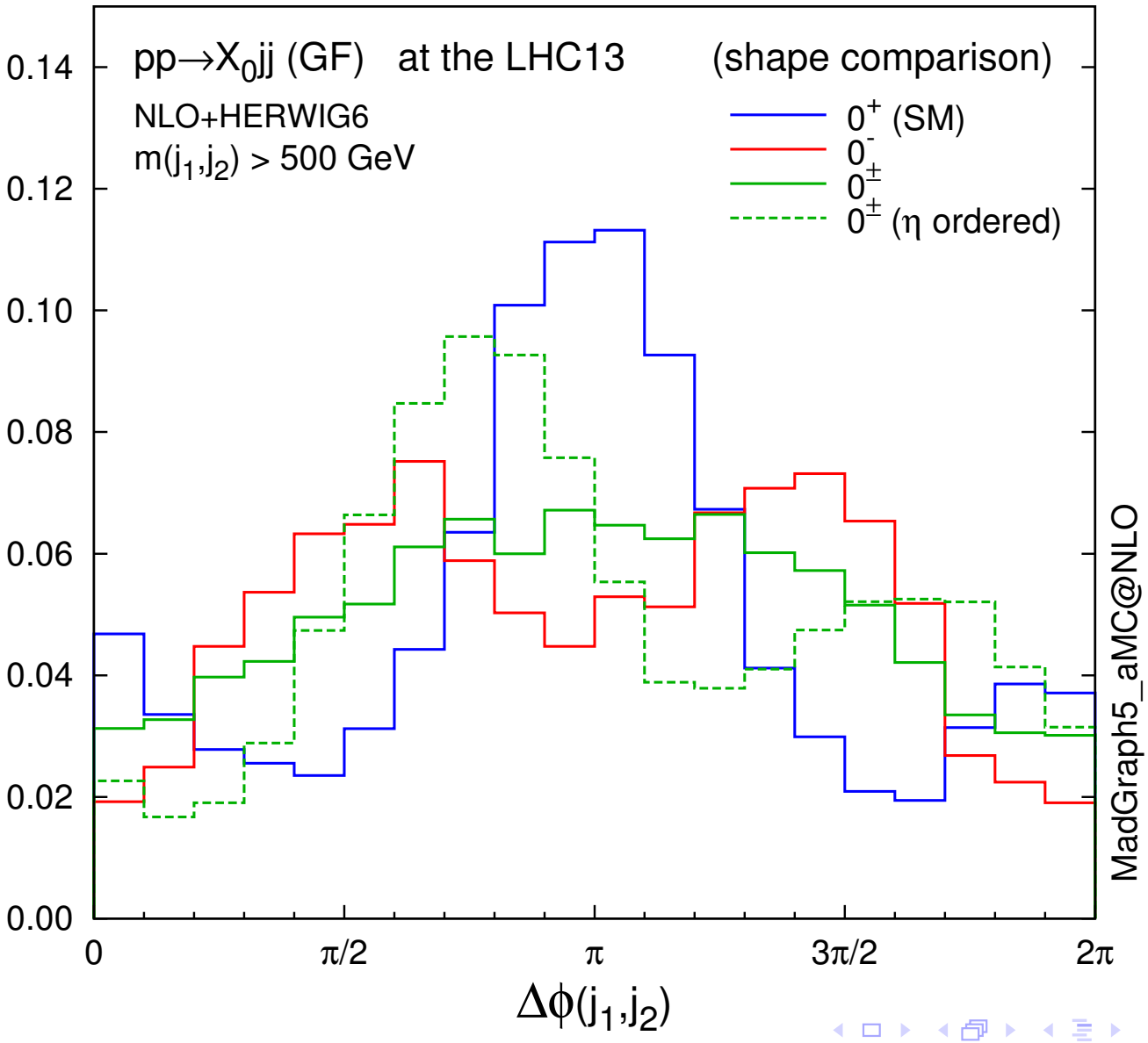
Mijn onderzoek - Resultaten vorige run



Mijn onderzoek - Wat nu?



Simulatie hogere energie



Combination

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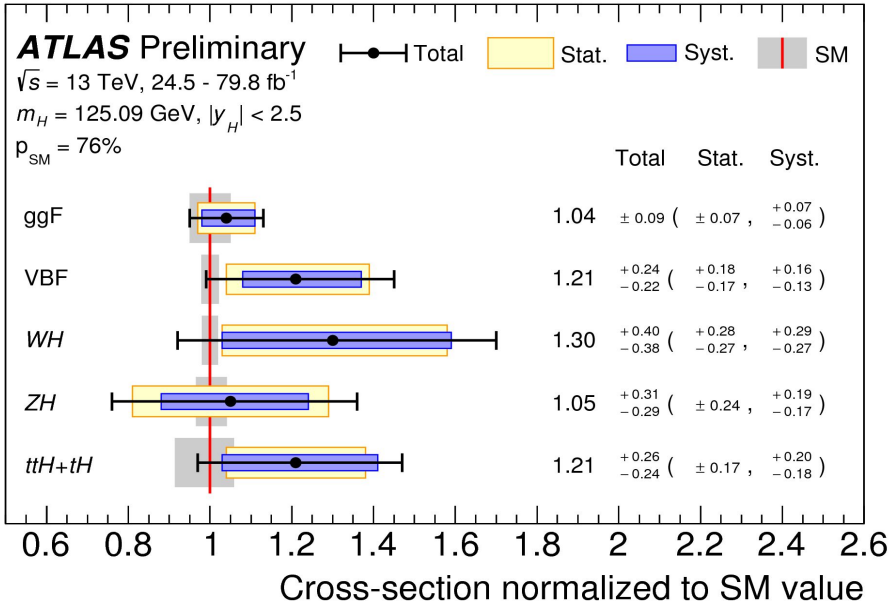
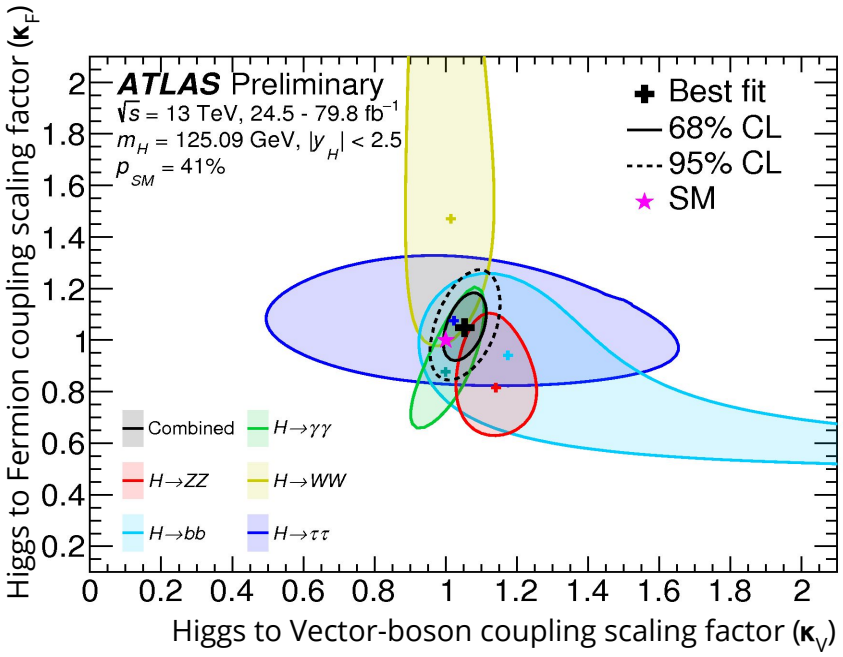
Extracting more information by combining decay channels





Combination: Reinterpretations

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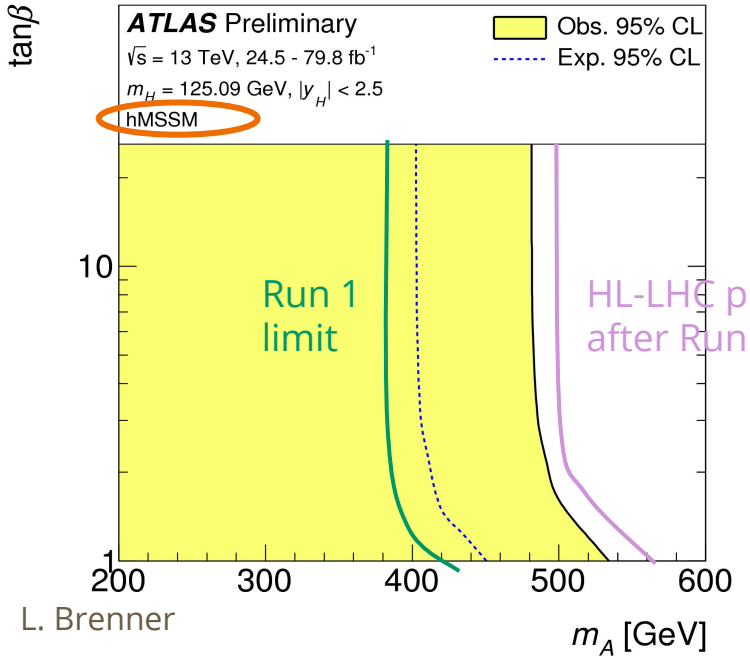
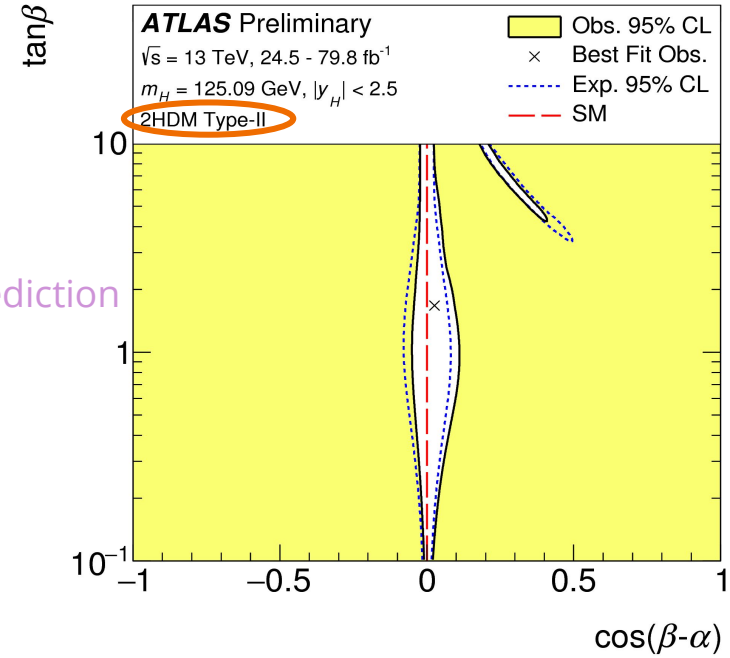
Additional Higgs field → 5 Higgs bosons

Map couplings to new parameters

Coupling	Type I	Type II
κ_V	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
κ_u	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$
κ_d	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$
κ_l	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$

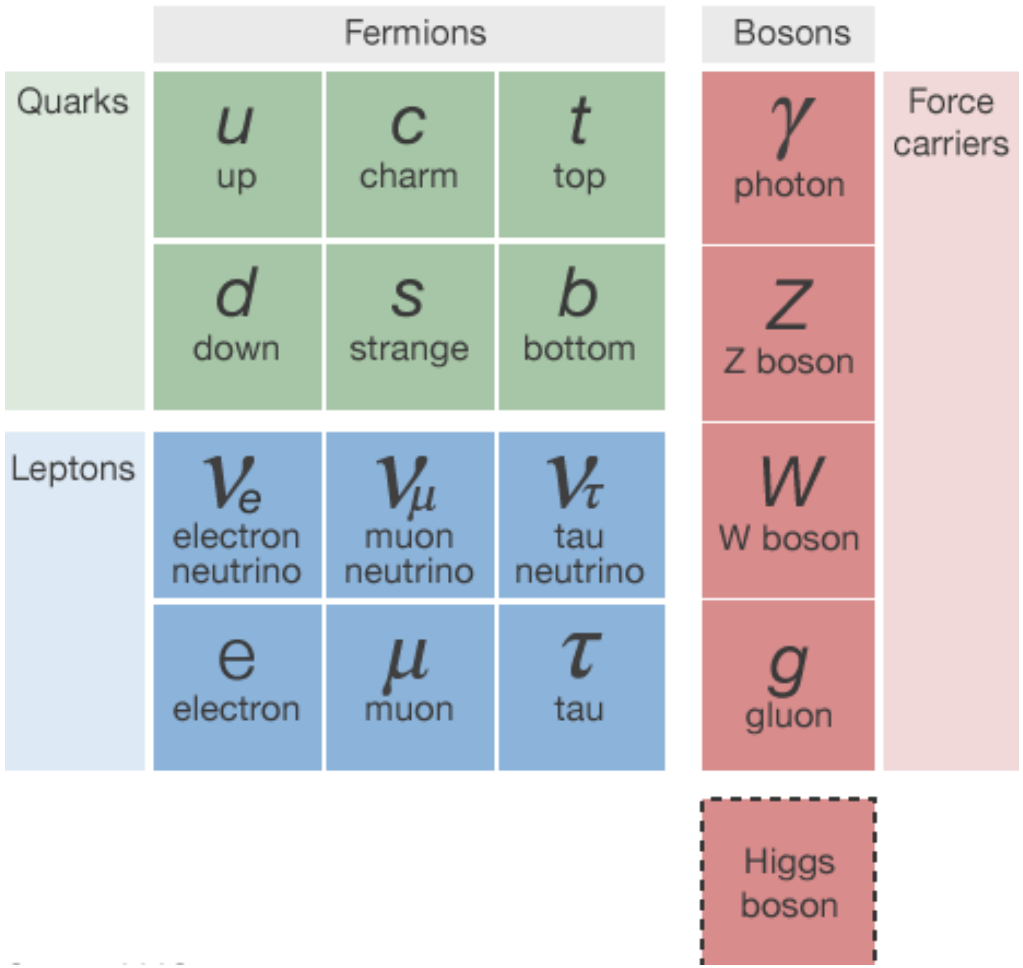
2 New free parameters
- tan **β**: ratio of the two vacuum expectation values
- **α**: mixing angle between two neutral CP even Higgs states





Vragen?

"Zijn we nu klaar?"



Met veel dank aan Ivo van Vulpen en Marco van Woerden!