Exploring Electroweak Symmetry Breaking from the LHC to CLIC

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Concluding Colloquium of the Graduiertenkolleg 1504
Mass – Spectrum – Symmetry

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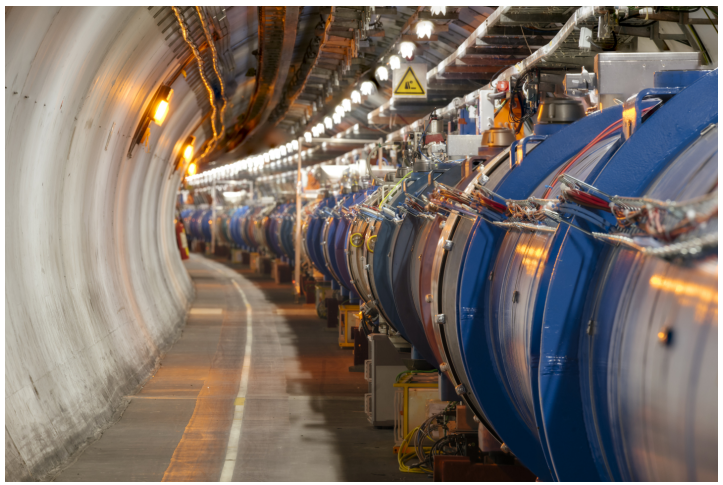
Physics in the Era of the Large Hadron Collider

2009-2018 = Era of LHC Runs 1 & 2

2009 – 2018
GRADUIERTEN KOLLEG
Masse-Spektrum-Symmetrie



CERN

Outline

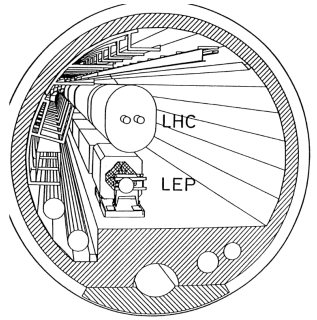
- PhD student in GK Nov 2010 - Jan 2015
- Post-PhD project 2015 in GK
- PostDoc in Freiburg
- Fellow at CERN in CLIC Detector&Physics group

This talk:

- Topics in Electroweak Symmetry Breaking 2009-2018
- Outlook for Electroweak Symmetry Breaking in the future

Before LHC data taking

"Large Hadron Collider in the LEP Tunnel"



Proceedings of the ECFA-CERN Workshop 1984:

the standard model is not complete.

some of the most obvious items which it fails to explain being

- the origin of mass
- the origin of flavour
- the origin of CP violation
- the connection between the electroweak, strong and gravitational forces.

In particular:

What is the deep origin of mass and what are the relations between masses and symmetry breaking processes, such as those which are at work in the Higgs mechanism?

Before LHC data taking

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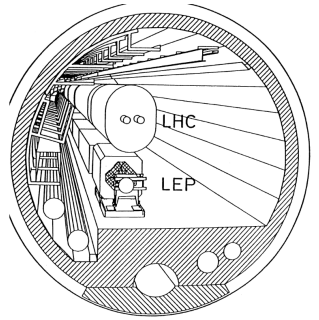
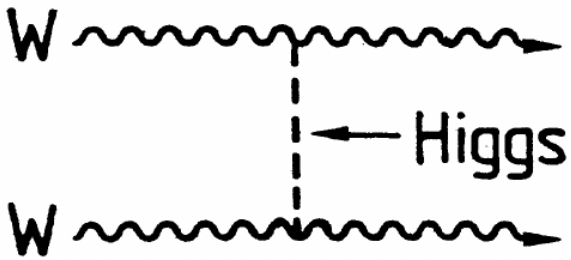


Even if the W and Z do have gauge couplings, the perturbative WW scattering amplitude violates unitarity at $\sqrt{s} \approx 1$ TeV. if the W and Z are simply given ad hoc masse
This indicates the failure of perturbation theory or the occurrence of quite new phenome
at or below 1 TeV. In the standard model, the new physics is provided by adding the Higgs boson. The contribution of the diagram

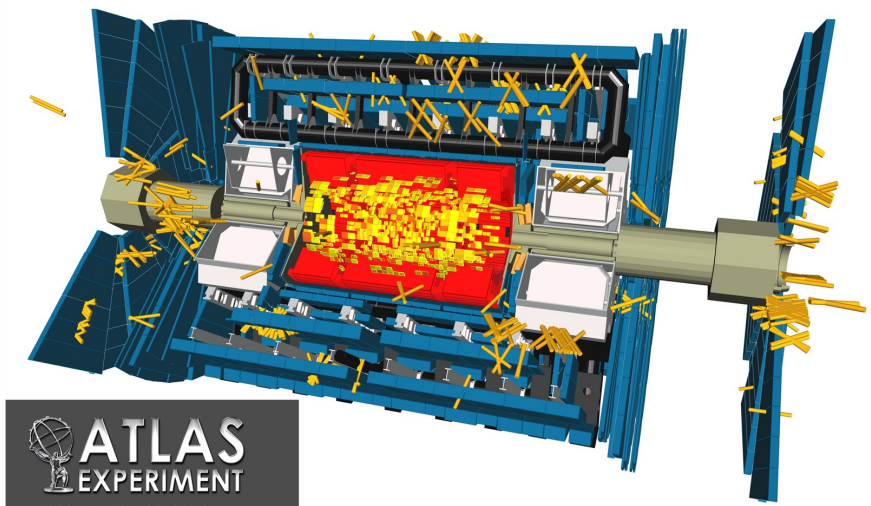


cancels the contributions of the other tree level diagrams which violate unitarity.

Era of the LHC

2009

2009 – 2018
GRADUIERTEN KOLLEG
Masse-Spektrum-Symmetrie



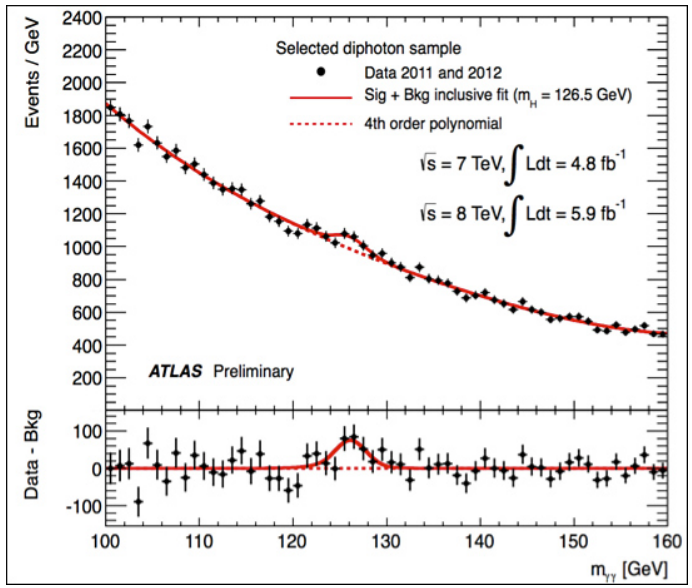
First Splash Event 2009

CERN

Discovery of the Higgs boson

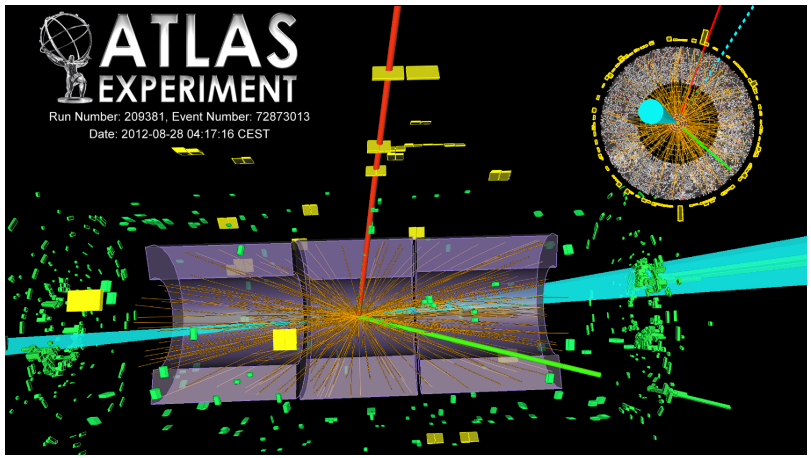
2012

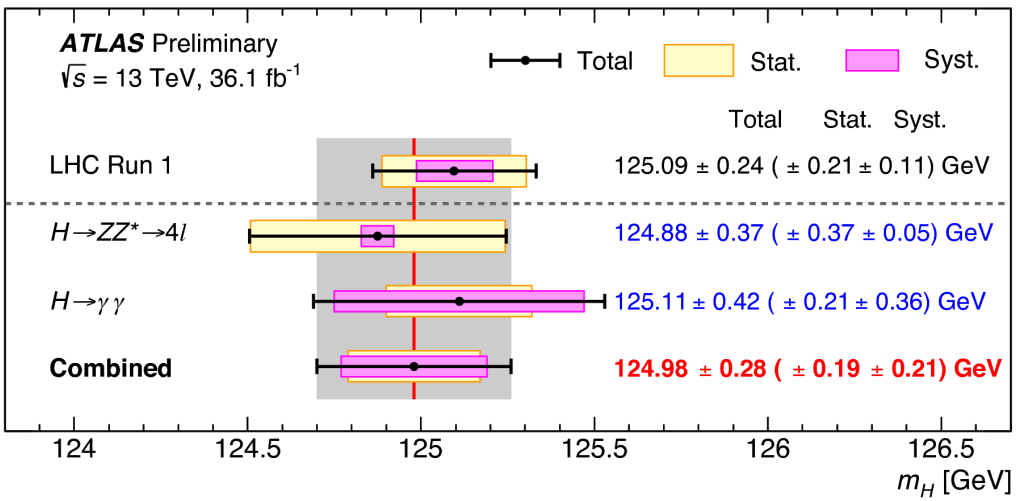
2009 – 2018
GRADUIERTEN KOLLEG
Masse-Spektrum-Symmetrie



Investigation of the Higgs boson

- Discovery of a Higgs boson (2012) at CMS & ATLAS
- Observed decays: WW, ZZ, $\gamma\gamma$, $\tau\tau$



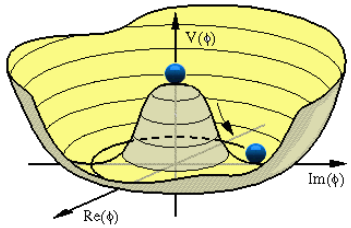


Sparked investigation of the nature of electroweak symmetry breaking

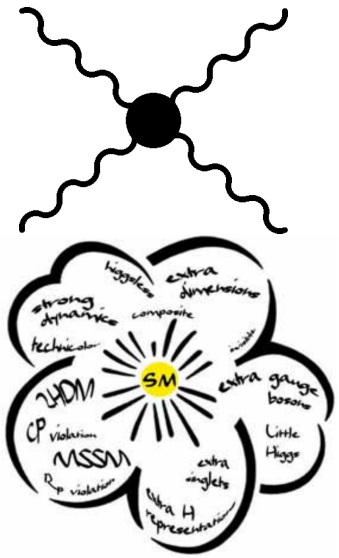
Phys. Rev. Lett. 114 (2015) 191803

Investigating Electroweak Symmetry Breaking

- Measurements of Higgs boson properties

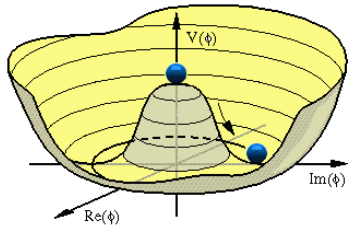


- Scrutiny of electroweak theory: gauge boson self-interactions



- Searches for new physics in the electroweak sector

Higgs properties



Mass: free parameter in SM

Other properties: fixed in SM

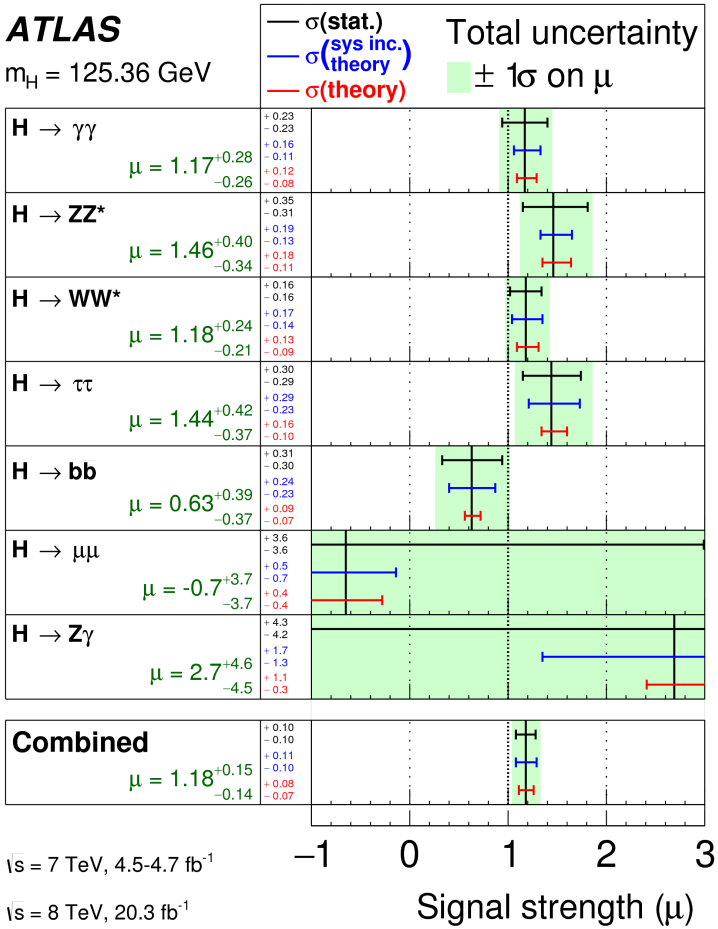
Possible deviations from SM parametrized effectively
e.g. with Effective Field Theories

$$\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_d \sum_i \frac{c_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}^{(d)}$$

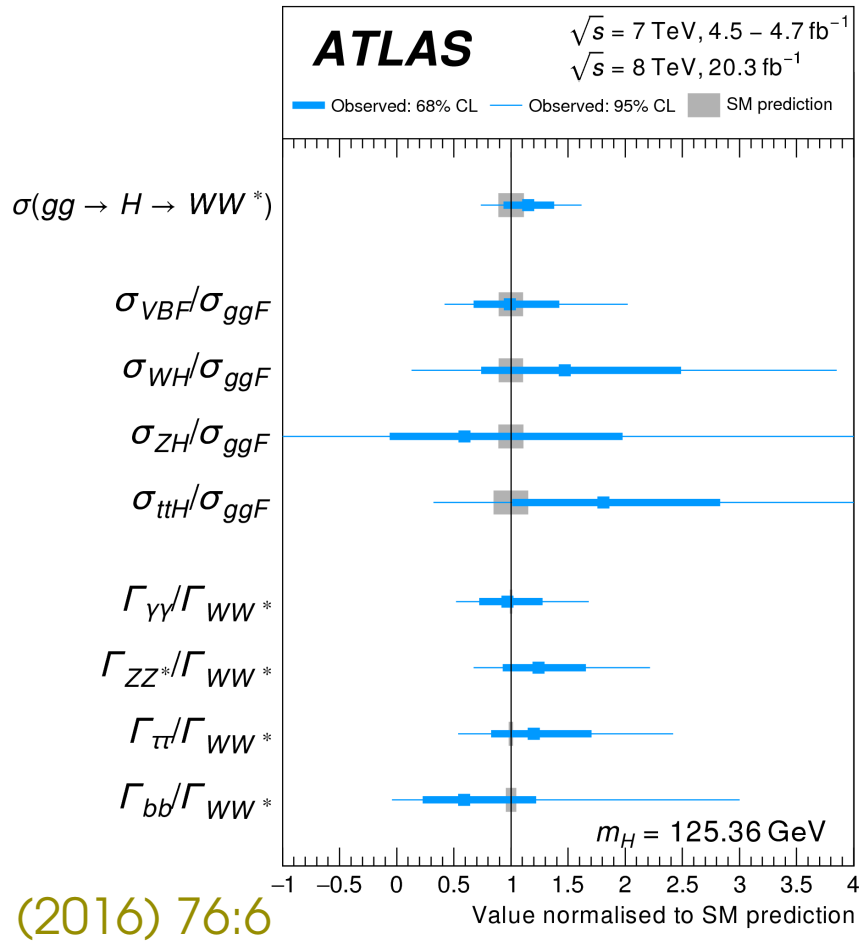
$c_i^{(d)}$: Wilson coefficients
Λ: scale of new physics

$\rightarrow$ low-energy tail of new physics, with limited validity

Higgs Properties (I): Couplings to SM particles



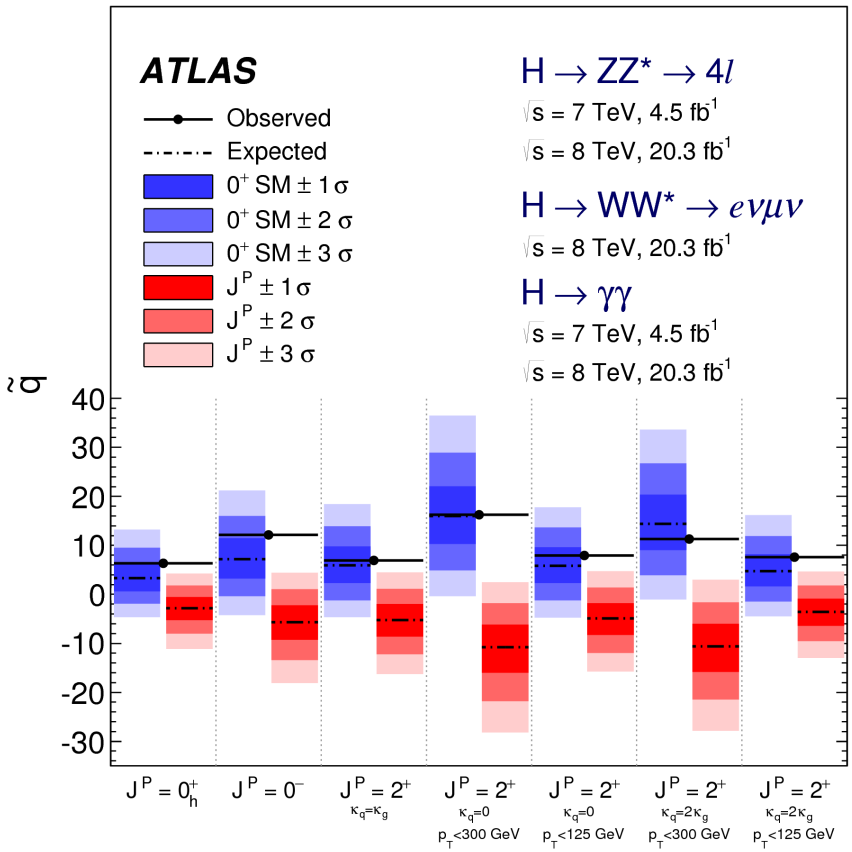
$H \to WW^*$



Eur. Phys. J. C (2016) 76:6

Higgs Properties (II): Spin and parity

J^P of 125 GeV Higgs boson



from signal strengths in $H \to ZZ^*$, $H \to WW^*$, $H \to \gamma\gamma$

Eur. Phys. J. C75 (2015) 476

Higgs properties (III): CP behavior

- CP violation is 1 of 3 Sakharov conditions explaining Baryon asymmetry of the universe

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- CP violation is 1 of 3 Sakharov conditions explaining Baryon asymmetry of the universe
- Effective Lagrangian with CP-violating couplings (dim. 6)

$$\mathcal{L}_{eff} = \mathcal{L}_{\mathrm{SM}} + \tilde{\mathrm{d}}\frac{e}{2m_W \sin\theta_w} H\widetilde{W}^{+}_{\mu\nu} W^{-\mu\nu}$$
$$+ \tilde{\mathrm{d}}\frac{e}{2m_W \sin\theta_w} H\widetilde{Z}_{\mu\nu} Z^{\mu\nu} + \tilde{\mathrm{d}}\frac{e}{2m_W \sin\theta_w} H\widetilde{A}_{\mu\nu} A^{\mu\nu}$$

(L3 Collaboration Phys.Lett. B589 (2004) 89-102; V. Hankele et al. Phys. Rev. D74 (2006))

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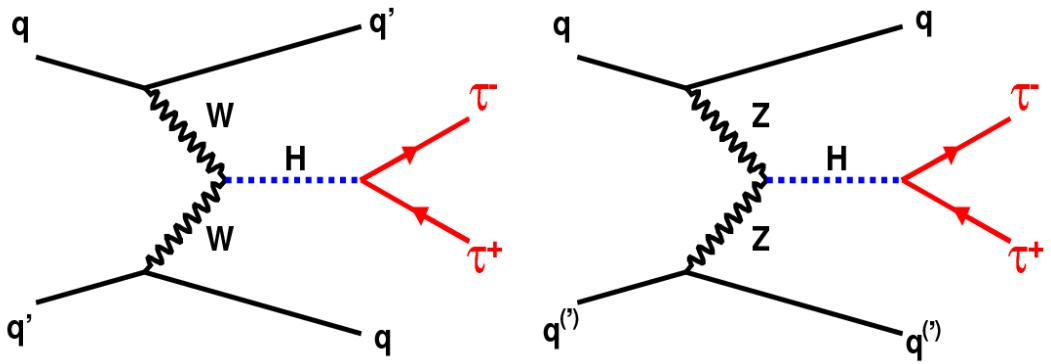
- Measurements $\rightsquigarrow$ Matrix element:

$$\mathcal{M} = \mathcal{M}_{\mathrm{SM}} + \tilde{\mathrm{d}}\mathcal{M}_{\mathrm{CP-odd}}$$

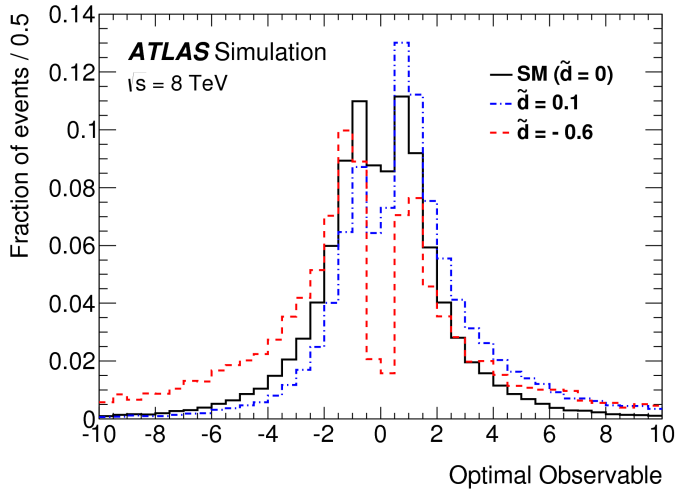
CP in VBF H production

- Total cross section:
  $|\mathcal{M}|^2 = |\mathcal{M}_{\mathrm{SM}}|^2 + \tilde{\mathrm{d}} \cdot 2\Re(\mathcal{M}^*_{\mathrm{SM}}\mathcal{M}_{\text{CP-odd}}) + \tilde{\mathrm{d}}^2 \cdot |\mathcal{M}_{\text{CP-odd}}|^2$
  $\rightsquigarrow$ Observables:
  - CP even (e.g. total cross section)
  - CP-odd observables $\mathcal{O}_{odd}$:
    $\langle \frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{O}_{odd}} \rangle \neq 0 \Rightarrow$ presence of CP violation
- Coupling to weak vector bosons measured in VBF



Optimal Observable

$$\mathcal{OO} = \frac{2\Re(\mathcal{M}^*_{SM}\mathcal{M}_{\mathrm{CP-odd}})}{|\mathcal{M}_{SM}|^2}$$



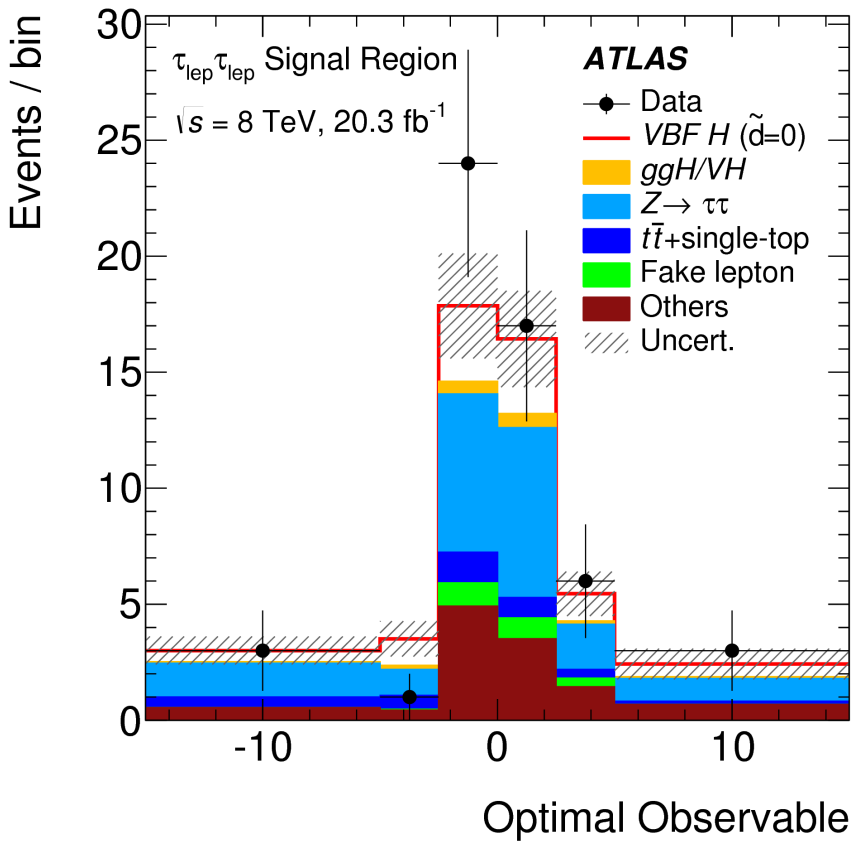
- Defined with the reconstructed four-momenta of particles in the events (tagging jets, reconstructed Higgs momentum)
- Why optimal?
  $\rightarrow$ combines the information on the entire phase space in one scalar variable (for small $\widetilde{\mathrm{d}}$)

  (D. Atwood, A. Soni; Phys. Rev. D45 (1992)), (M. Davier et al.; Phys. Lett. B306 (1993)),

  (M. Diehl, O. Nachtmann; Z. Phys. C62 (1994))

Measurement of $\tilde{\mathrm{d}}$ in VBF $H \to \tau\tau$ 8 TeV

- VBF $H \to \tau\tau$ selection



- no signal strength information
- only shape information
- fit to full $\mathcal{OO}$ distribution to extract exclusion limits on $\tilde{\mathrm{d}}$
- Mean of $\mathcal{OO}$:
  $\langle \mathcal{OO} \rangle = 0.3 \pm 0.5$ $(\tau_{\mathrm{lep}}\tau_{\mathrm{lep}})$
  $\langle \mathcal{OO} \rangle = -0.3 \pm 0.4$ $(\tau_{\mathrm{lep}}\tau_{\mathrm{had}})$
- Observed confidence interval at 68 % C.L.:
  $\tilde{\mathrm{d}} \in [-0.11, 0.05]$

$\to$ no hint for CP violation

(ATLAS Collaboration arXiv:1602.04516 (hep-ex))

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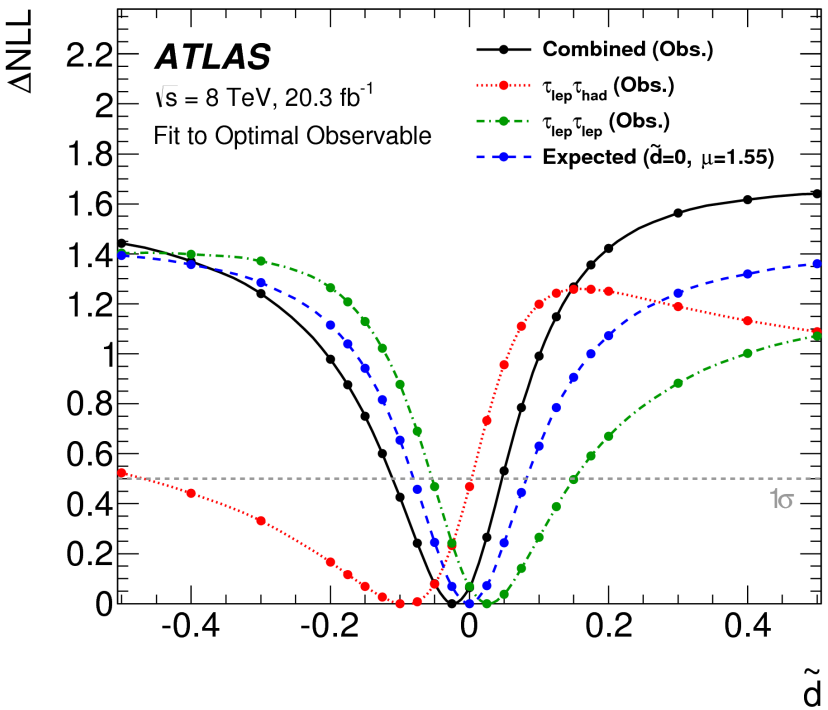

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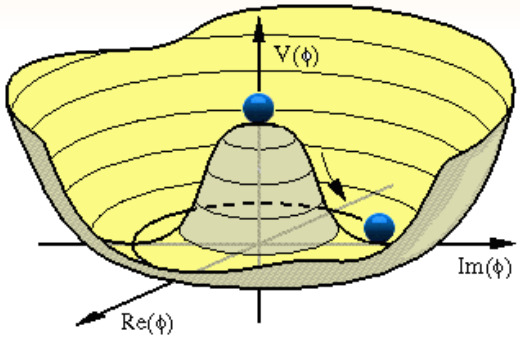
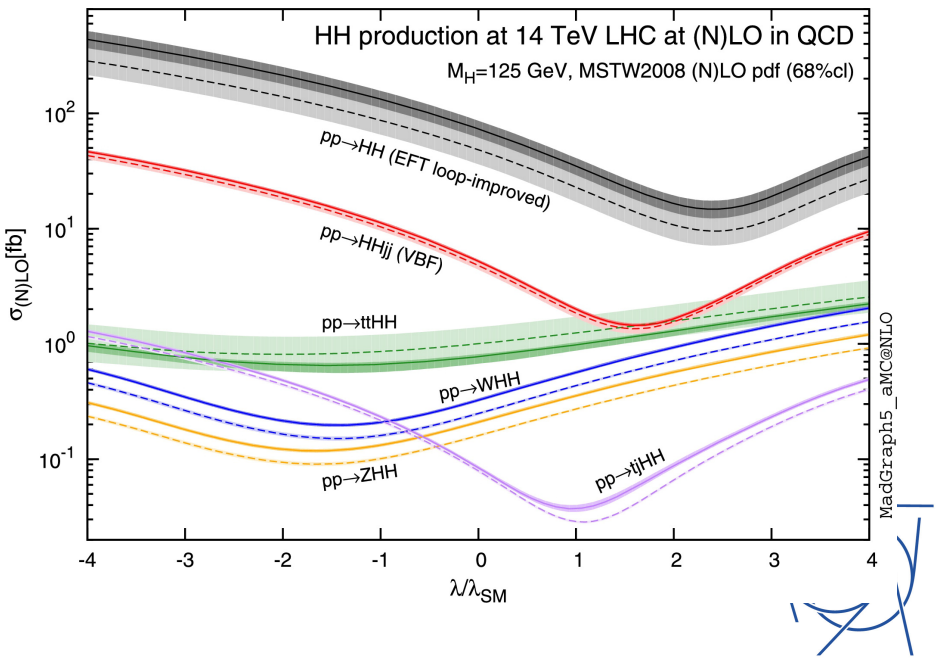
Higgs properties (IV): Self-couplings



SM Higgs mechanism:

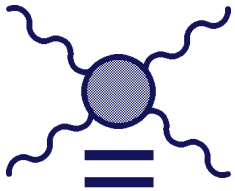
- $V = -\mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$
- μ, λ related to the Higgs Mass

Self-couplings measurement $\rightsquigarrow$ shape of the potential



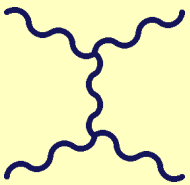
Phys. Lett. B 732 (2014) 142

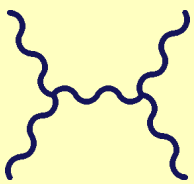
Electroweak gauge boson scattering



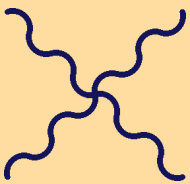
$(V = W/Z)$

$$\mathcal{M}^{W,Z} = -\frac{g_w^2}{4m_W^2}u + const$$

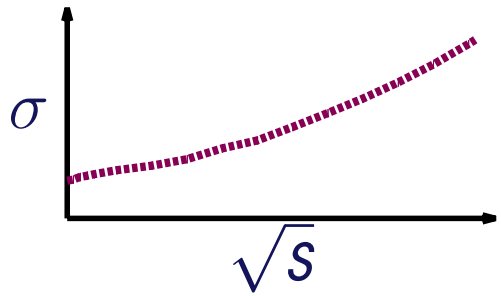




Triple gauge coupling

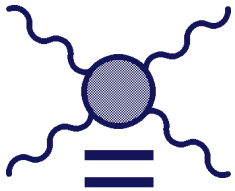


Quartic gauge coupling



Violating unitarity of the scattering matrix ($P > 1$)

Electroweak gauge boson scattering



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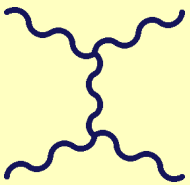
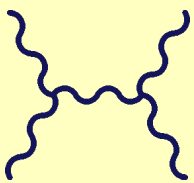

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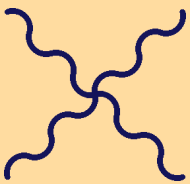

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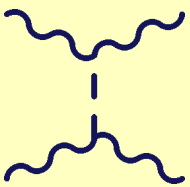
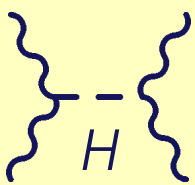
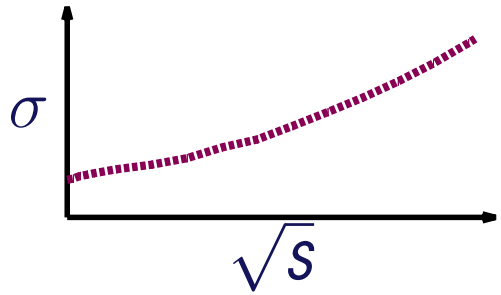
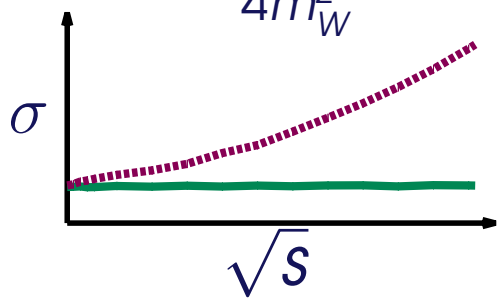



Higgs coupling to gauge bosons



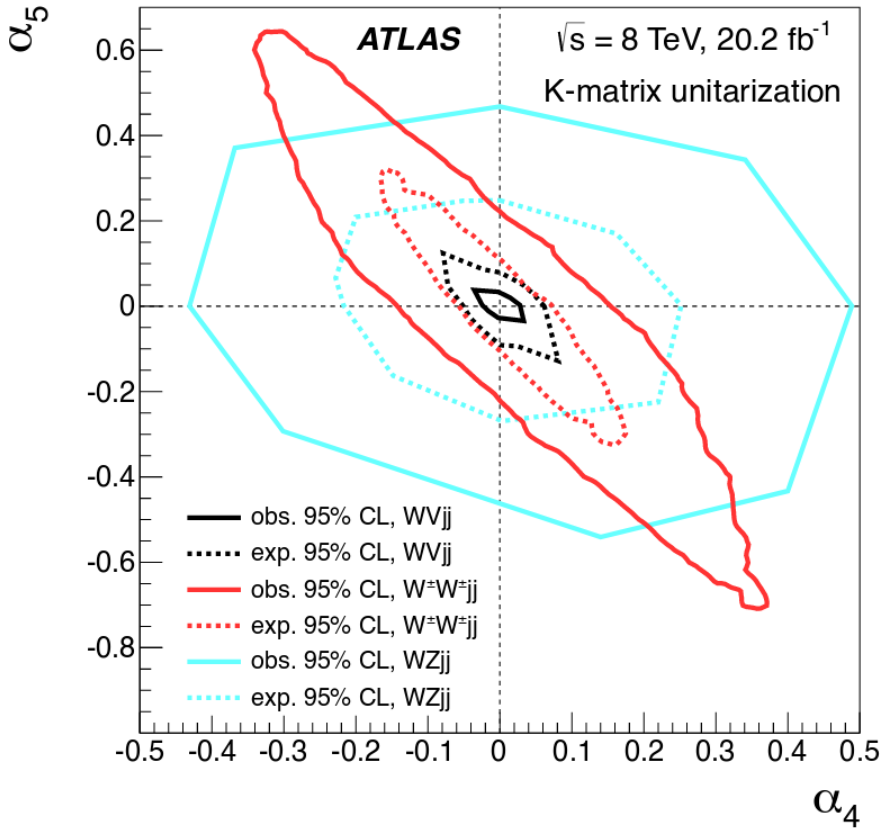
Violating unitarity of the scattering matrix $(P > 1)$

$$\mathcal{M}^{H} = +\frac{g_w^2}{4m_W^2}u$$



Limits on anomalous quartic gauge couplings

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \alpha_4(\mathrm{tr}[\mathbf{V}_\mu \mathbf{V}_\nu])^2 + \alpha_5(\mathrm{tr}[\mathbf{V}_\mu \mathbf{V}^\mu])^2$$



Phys.Rev.D 95(2017) 021001

Status and Prospects

What is the deep origin of mass and what are the relations between masses and symmetry breaking processes, such as those which are at work in the Higgs mechanism?

- ✓ Higgs
- ✓ Electroweak gauge boson scattering
- Many questions still open
  - the origin of mass
  - the origin of flavour
  - the origin of CP violation
  - the connection between the electroweak, strong and gravitational forces.

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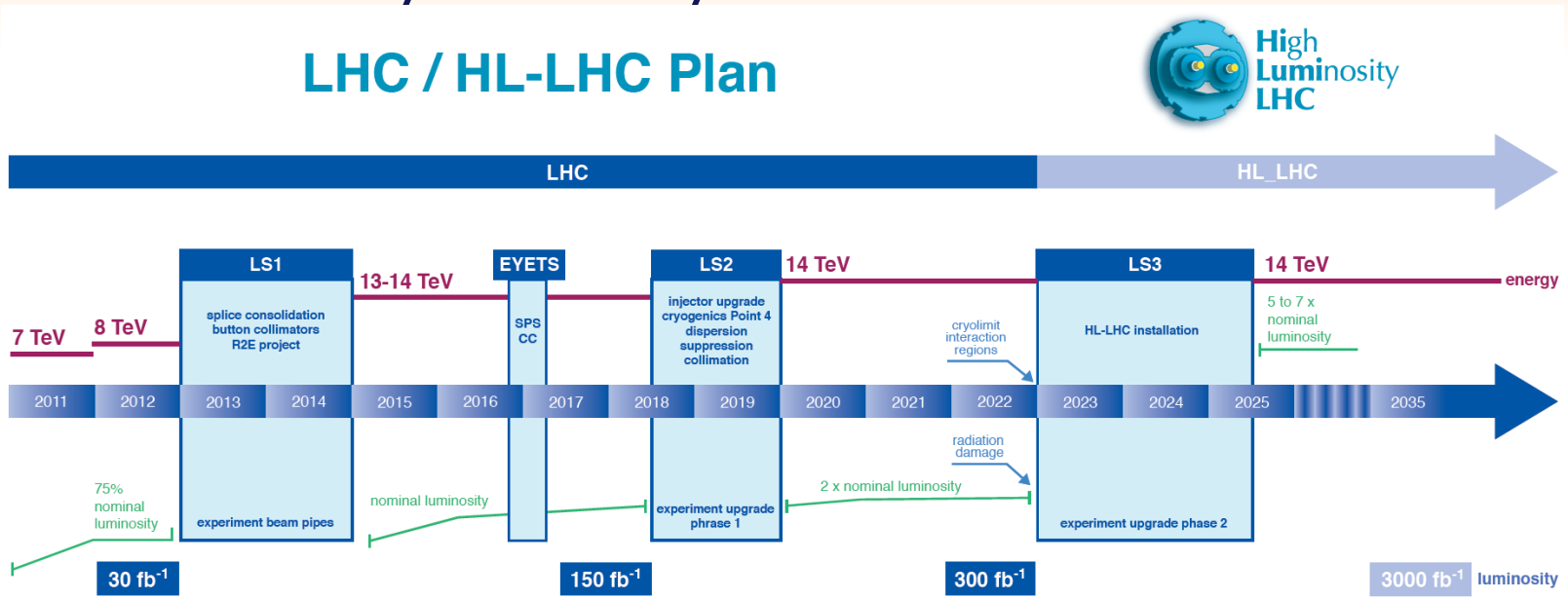
- Many questions still open
  - the origin of mass
  - the origin of flavour
  - the origin of CP violation
  - the connection between the electroweak, strong and gravitational forces.
- New questions: precise nature of the Higgs(125) boson

⇒ Higgs measurements beyond the LHC

- Higgs factory
- Ability to measure self-coupling

Particle Physics beyond the LHC



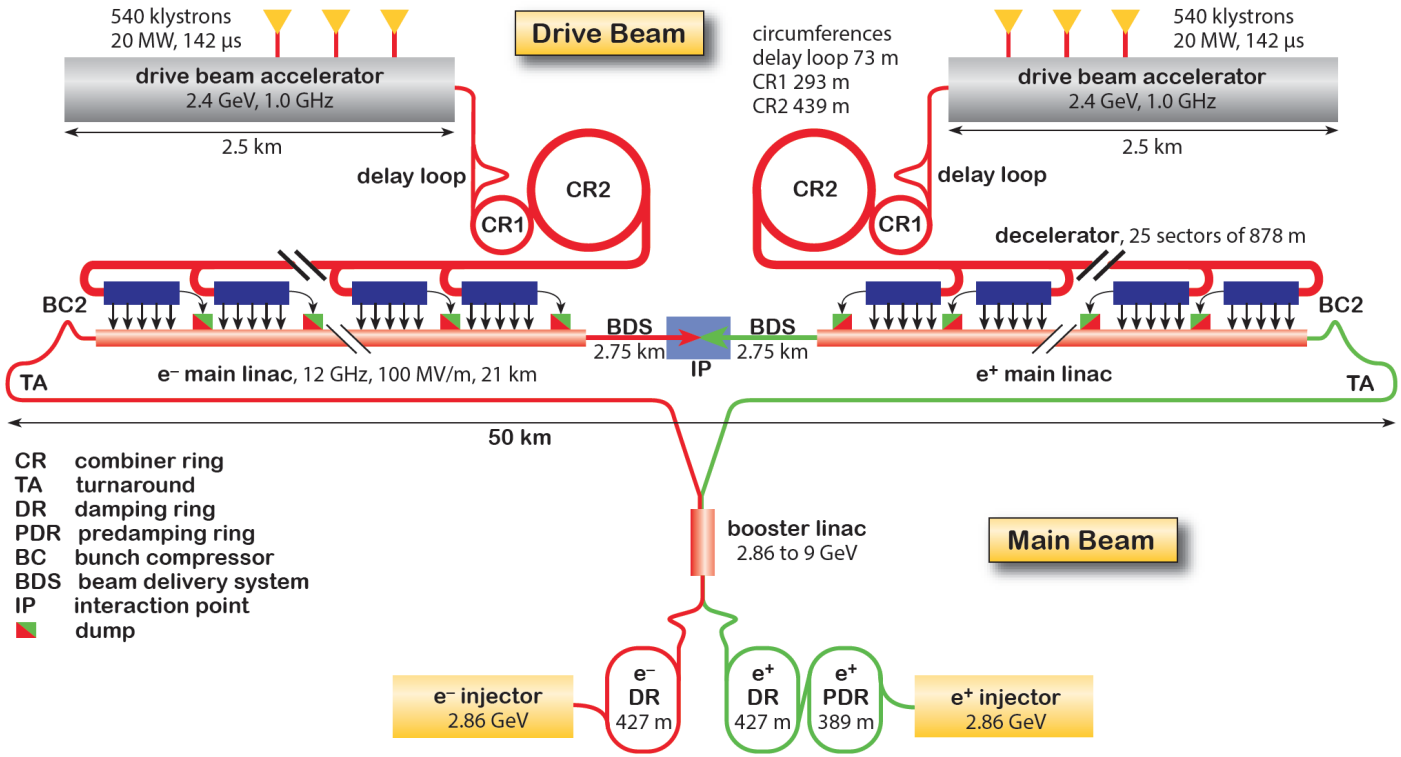
https://cds.cern.ch/record/1975962

Options for after the HL-LHC:

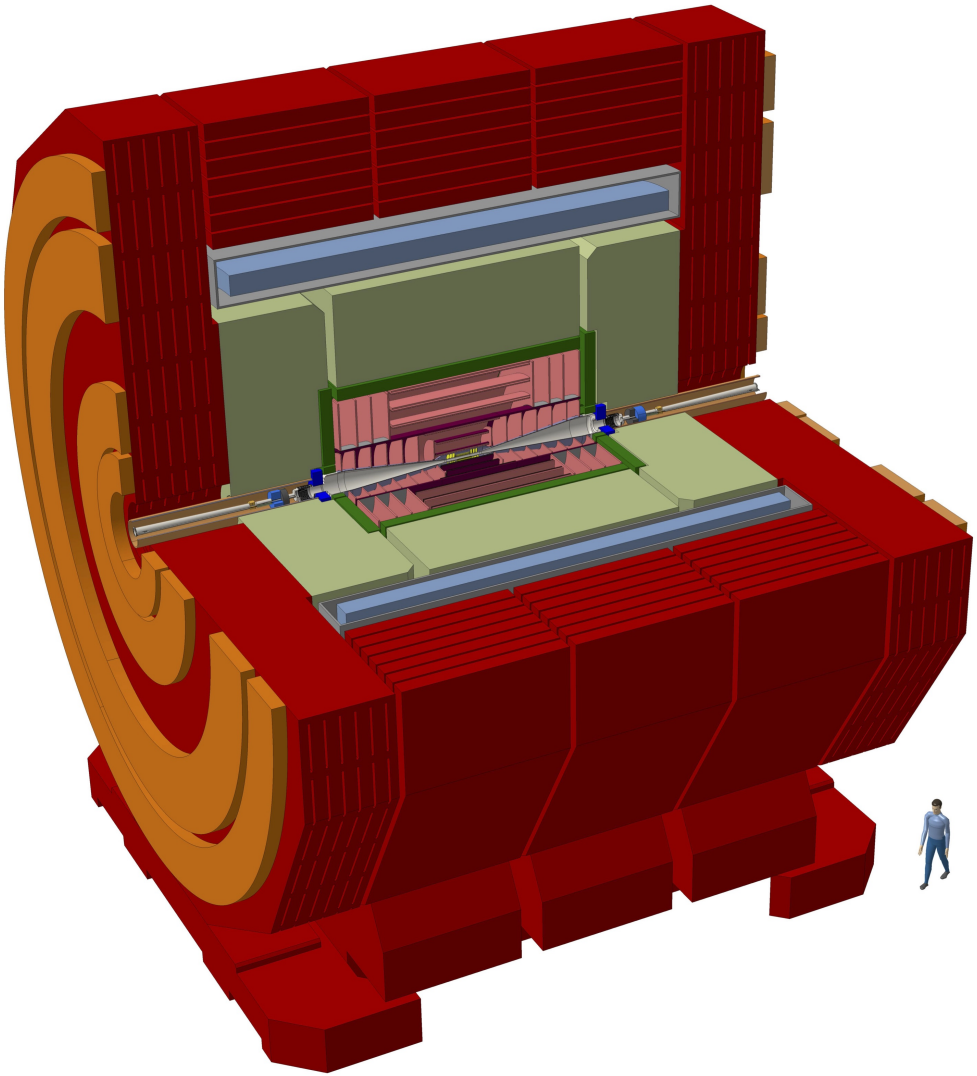
- At CERN :
  - Compact Linear Collider CLIC
  - Future Circular Collider FCC
- International Linear Collider ILC
- ...

Compact Linear Collider CLIC

Novel accelerator technique based on radio-frequency devices and a two-beam acceleration scheme for e^+e^- collisions



CLIC Detector



Designed for Particle Flow Analysis

- 4 T B-field
- Vertex detector (3 double layers)
- Silicon tracker
- ECAL 40 layers (22 X_0)
- HCAL 60 layers (7.5 λ)

Precise timing for background suppression

CLIC timeline

2013 - 2019 Development Phase

Development of a Project Plan for a staged CLIC implementation in line with LHC results; technical developments with industry, performance studies for accelerator parts and systems, detector technology demonstrators

2020 - 2025 Preparation Phase

Finalisation of implementation parameters, preparation for industrial procurement, Drive Beam Facility and other system verifications, Technical Proposal of the experiment, site authorisation

2026 - 2034 Construction Phase

Construction of the first CLIC accelerator stage compatible with implementation of further stages; construction of the experiment; hardware commissioning

2019 - 2020 Decisions

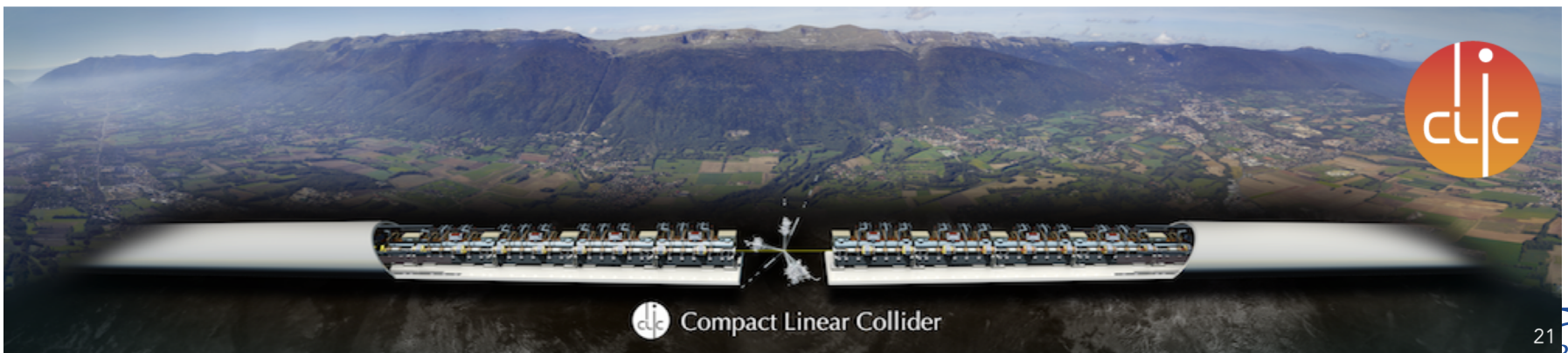
Update of the European Strategy for Particle Physics; decision towards a next CERN project at the energy frontier (e.g. CLIC, FCC)

2025 Construction Start

Ready for construction; start of excavations

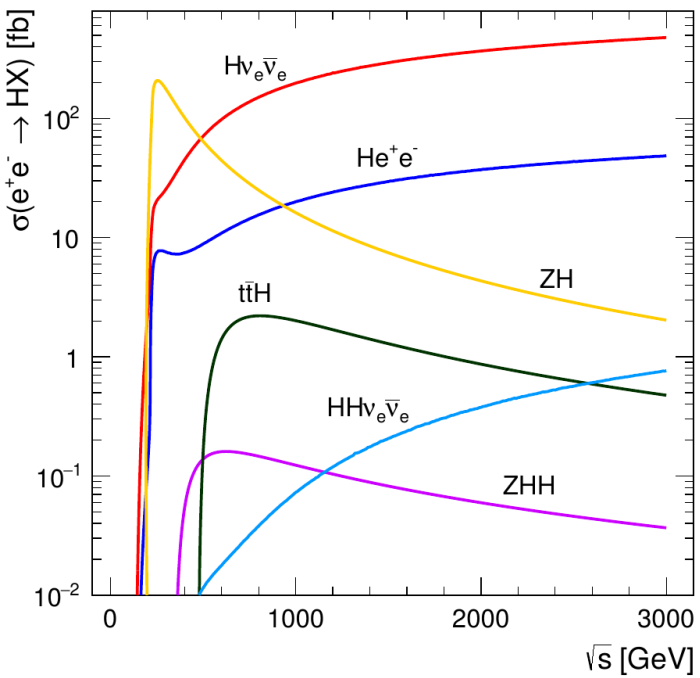
2035 First Beams

Getting ready for data taking by the time the LHC programme reaches completion



Higgs physics at CLIC

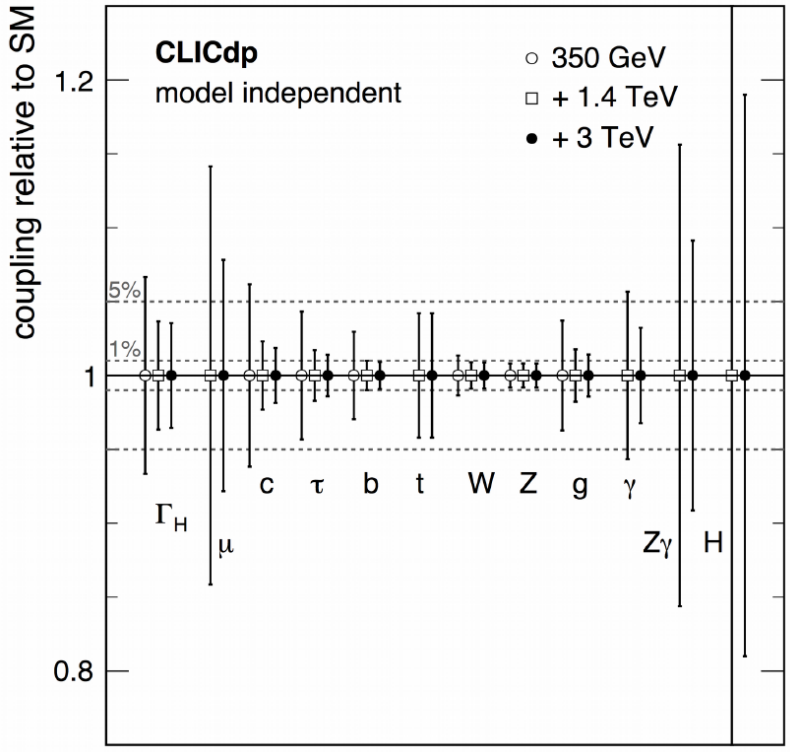
$\sqrt{s}$	Luminosity	N(Higgs) in 4y
380 GeV	$1.5\times10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$	90k
1.5 TeV	$3.7\times10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$	430k
3 TeV	$5.9\times10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$	920k



- Multiple production modes already at first stage
- Recoil mass in HZ production $\Rightarrow$ model-independent g_{HZZ} measurement
- Model-independent measurement of invisible Higgs decays
- Higgs self-coupling $\Delta\lambda \approx 10\,\%$

Higgs properties at CLIC

Couplings to SM particles and self-couplings

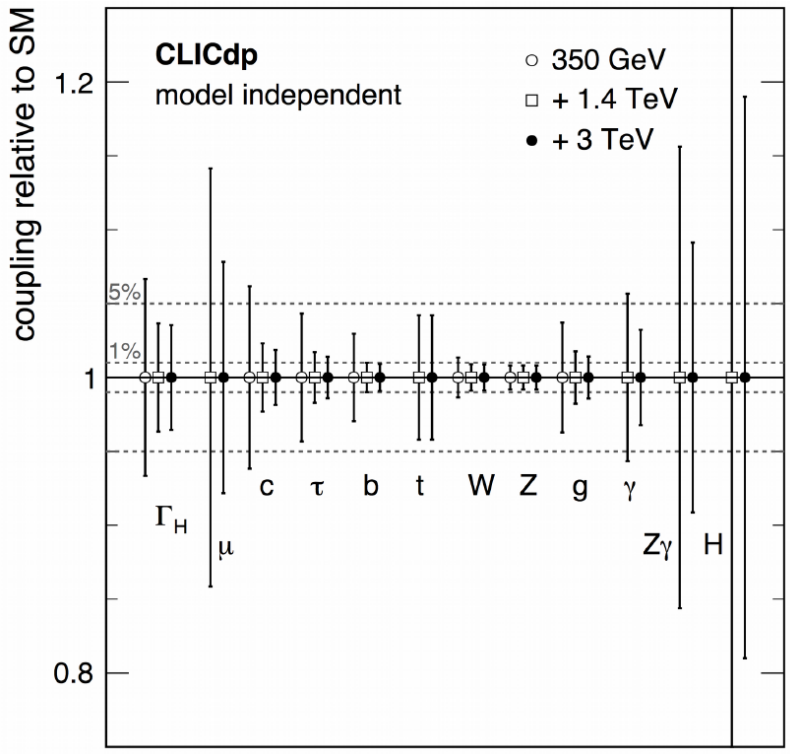


Summary of full analyses including beam-induced backgrounds

Eur. Phys. J. C 77, 475 (2017)

Higgs properties at CLIC

Couplings to SM particles and self-couplings



Summary of full analyses including beam-induced backgrounds

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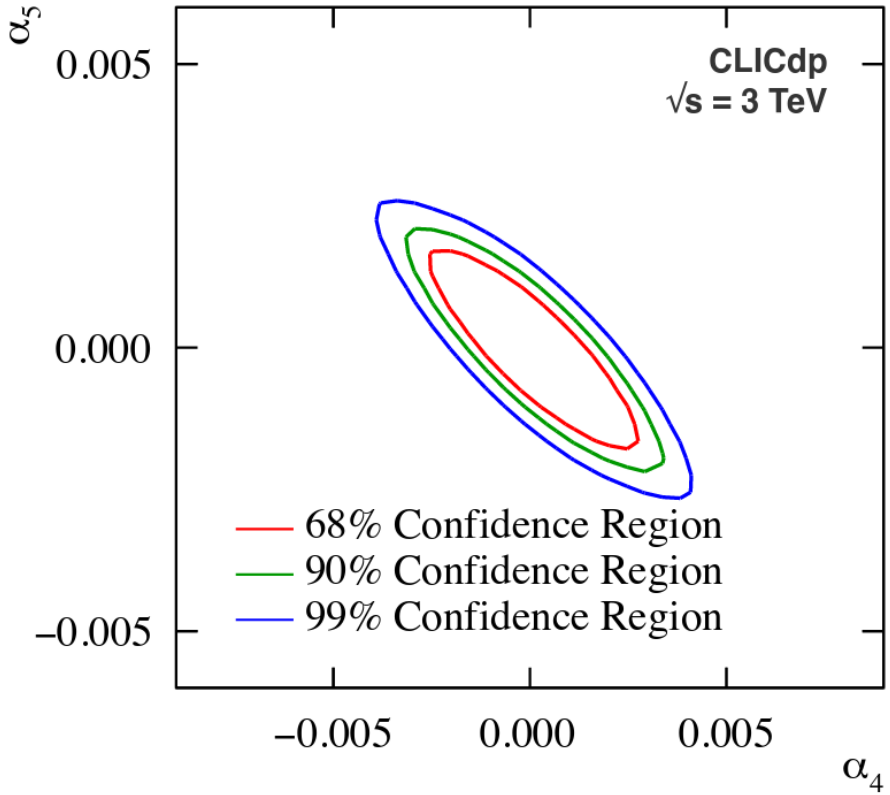
Anomalous gauge couplings in vector boson scattering



Fully hadronic *WW* and *ZZ*

CLICdp-Conf-2017-018

Conclusions

Open questions beyond the Standard Model:

- the origin of mass
- the origin of flavour
- the origin of CP violation
- the connection between the electroweak, strong and gravitational forces.

$\Rightarrow$ still work in progress