Why do we need a Higgs factory?

Matej Haviernik

Future Colliders for Early-Career Researchers

Prague 2024

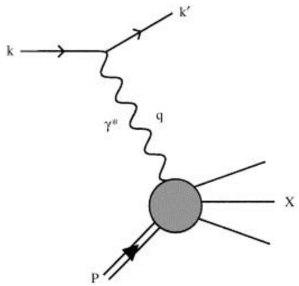
27.09.2024

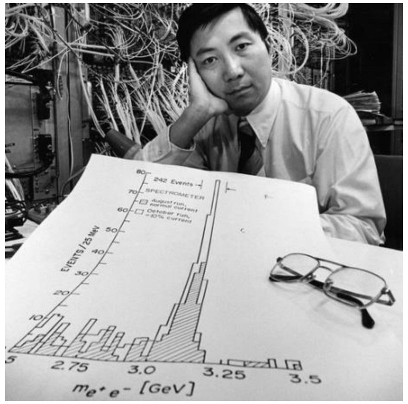
Disclaimer

I'm not a theoretical physicist

Working on ATLAS

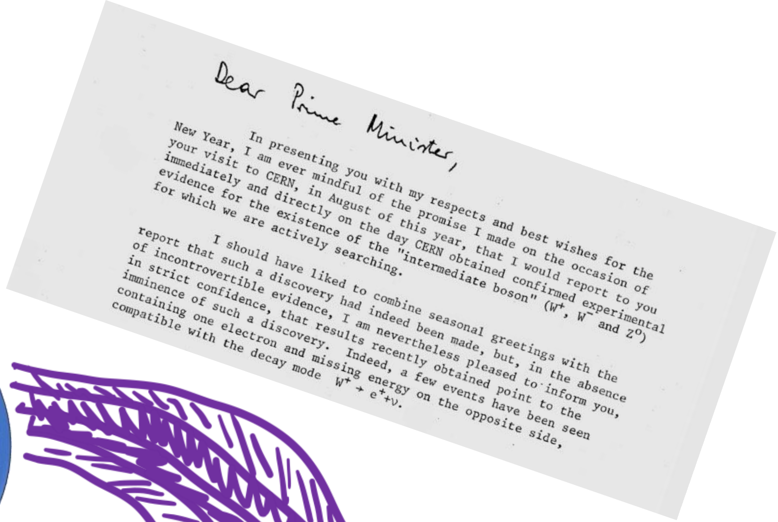
1968





1974

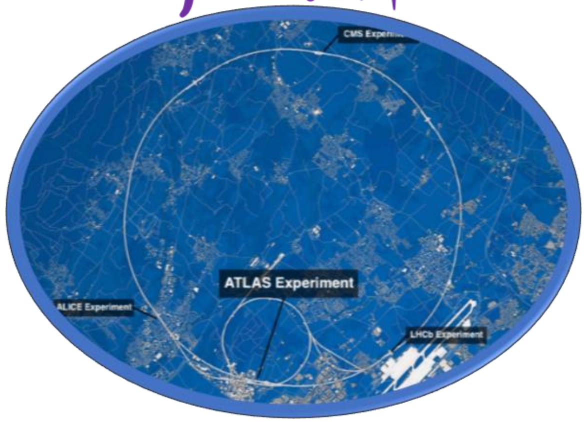
1983



Dear Prime Minister,

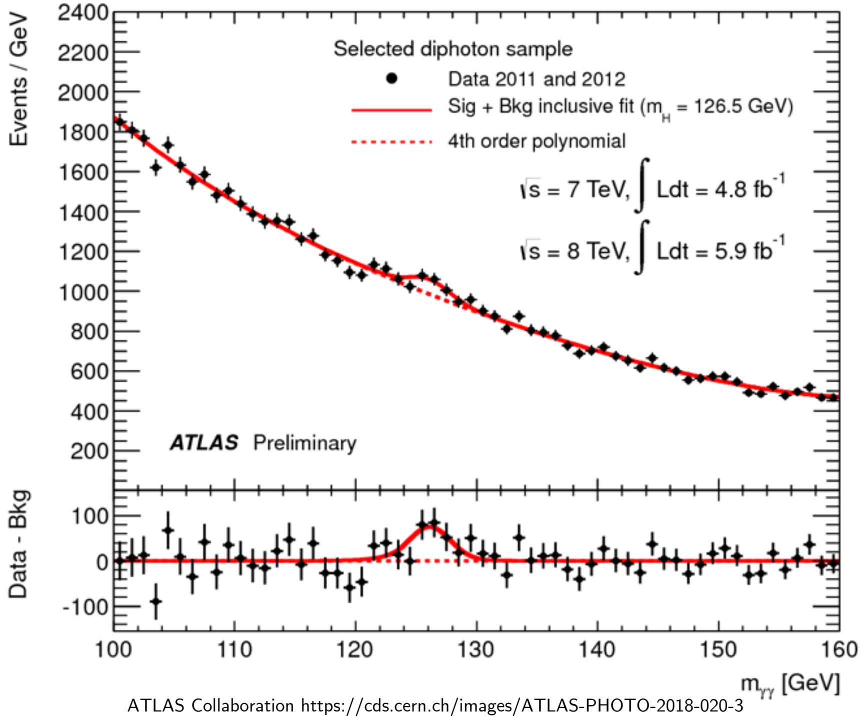
In presenting you with my respects and best wishes for the New Year, I am ever mindful of the promise I made on the occasion of your visit to CERN, in August of this year, that I would report to you immediately and directly on the day CERN obtained confirmed experimental evidence for the existence of the "intermediate boson" (W^+, W^- and Z^o) for which we are actively searching.

I should have liked to combine seasonal greetings with the report that such a discovery had indeed been made, but, in the absence of incontrovertible evidence, I am nevertheless pleased to inform you, in strict confidence, that results recently obtained point to the imminence of such a discovery. Indeed, a few events have been seen containing one electron and missing energy on the opposite side, compatible with the decay mode $W^+ \rightarrow e^+ + \nu$.



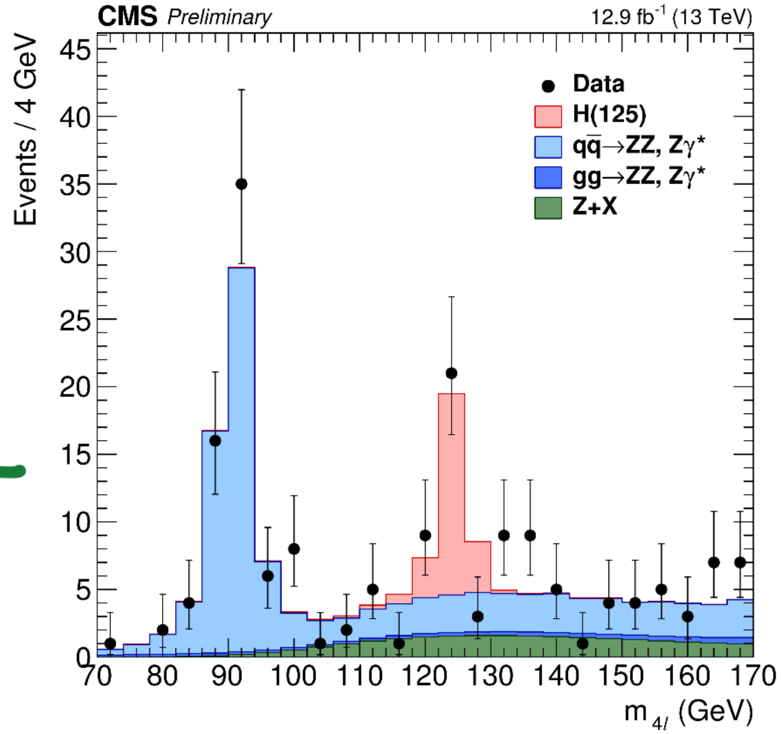
2012

Discovery of Higgs



ATLAS Collaboration https://cds.cern.ch/images/ATLAS-PHOTO-2018-020-3

$m_H = 125.22 \pm 0.11$ (stat.) $\pm$ 0.09(syst.) GeV

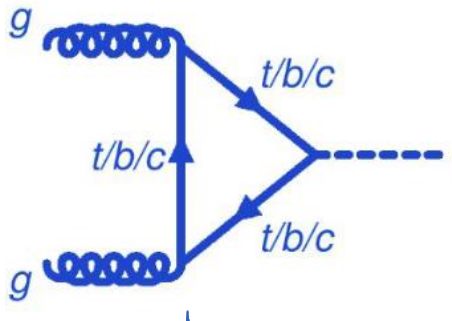


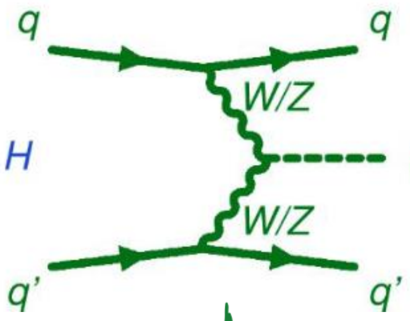
ATLAS Collaboration https://cds.cern.ch/images/ATLAS-PHOTO-2018-020-3

$m_H = 125.08 \pm 0.12$ GeV

LHC as a "Higgs factory"

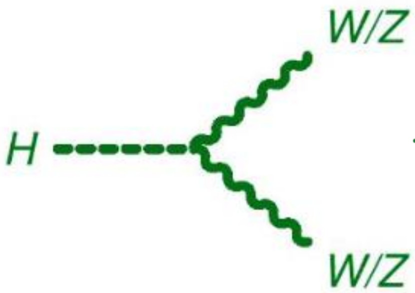
Production and decay channels at LHC





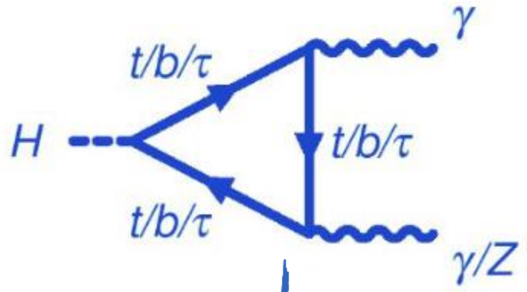
Gluon-gluon fusion (ggF)
~87%

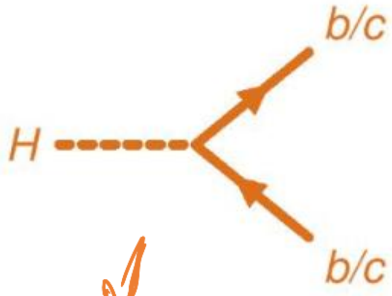
Vector boson fusion (VBF)
~7%



$H \rightarrow WW$
$\Gamma \sim 22\%$

$H \rightarrow ZZ$
$\Gamma \sim 3\%$



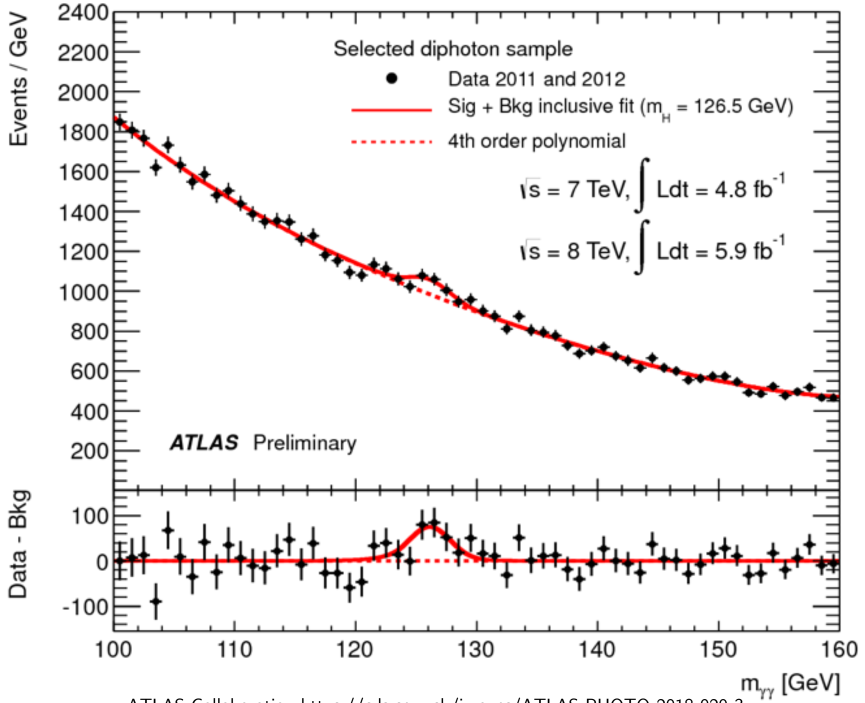


$H \rightarrow \gamma\gamma$
$\Gamma \sim 0.2\%$

$H \rightarrow bb$
$\Gamma \sim 58\%$

ATLAS Collaboration (2022). A detailed map of Higgs boson interactions by the ATLAS experiment ten years after the discovery. *Nature, 607(7917)*, 52–59. arXiv:2207.00092v2

Discovery of Higgs



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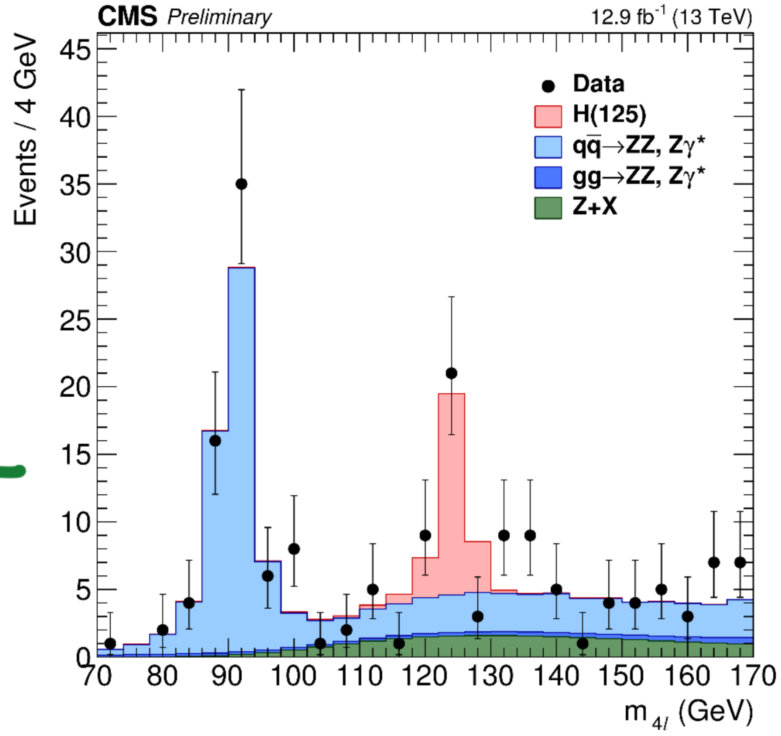
m_H= 125.22 ± 0.11 (stat.) ± 0.09(syst.) GeV



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m_H= 125.08 ± 0.12 GeV

LHC as a "Higgs factory" – what will future Higgs factories bring to the table?

Higgs as a (B)SM probe

- Invisible decay width – search for new particles
- Tension with SM in measurements of Higgs EW couplings and self-couplings (nature of Higgs potential, EWPT)

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BUT ALSO:

Electroweak factory

precision in Γ_Z, m_Z, Γ_W, $m_W \ldots$

weakly coupled BSM particles

flavour puzzle (CKM matrix, suppressed decay modes, lepton universality)

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Electroweak factory

precision in $\Gamma_Z,\ m_Z,\ \Gamma_W,\ m_W \ldots$

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flavour puzzle (CKM matrix, suppressed decay modes, lepton universality)

Top factory

precision in $\Gamma_t,\ m_t$

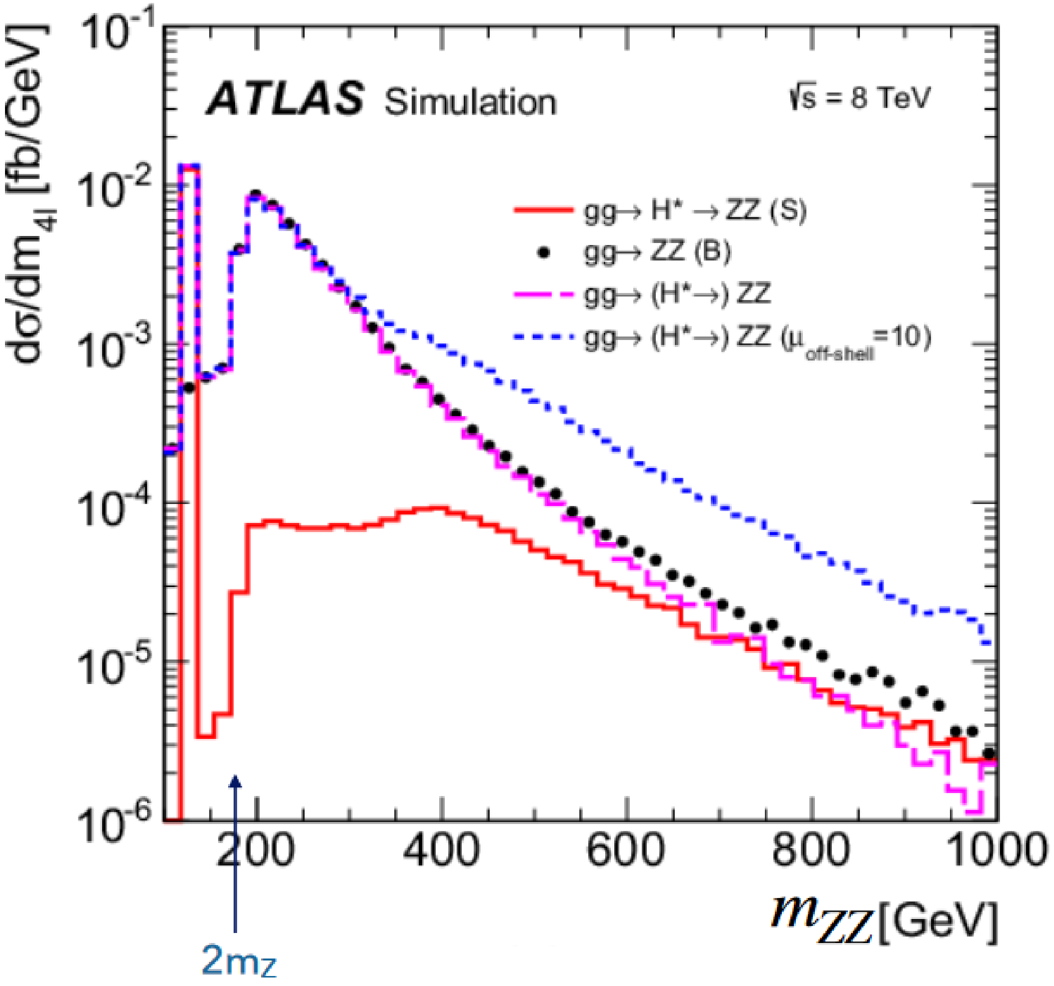
top couplings in EW sector

upper bounds on FCNC branching ratios

Invisible decay width

- SM prediction -> $\Gamma_H^{SM} = 4.1$ MeV
  - Too small for detector resolution at LHC
- Off-shell measurements

$$gg \to H^* \rightarrow H^* \to ZZ \to 4\ell$$



ATLAS Collaboration. Constraints on the off-shell Higgs boson signal strength in the high-mass *ZZ* and *WW* final states with the ATLAS detector. *Eur. Phys. J. C* **75**, 335 (2015)

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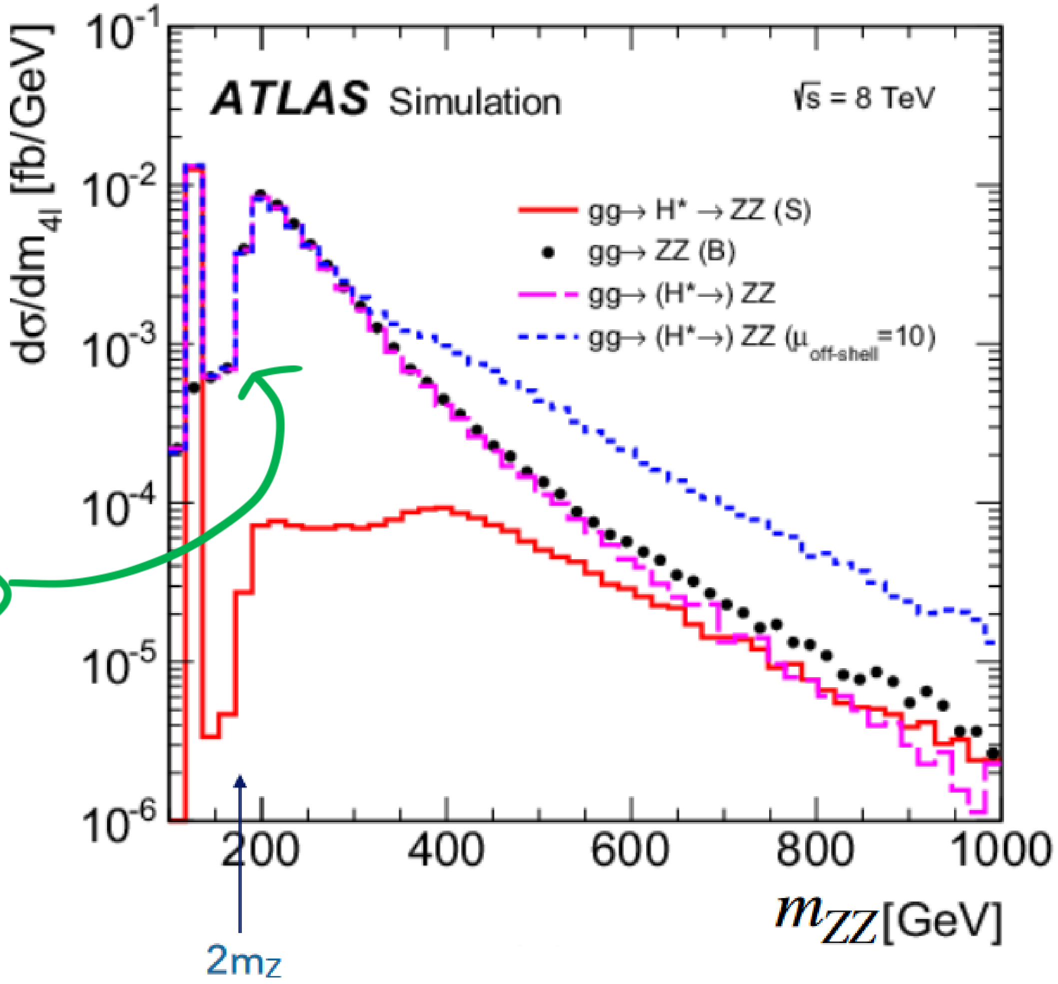
Enhanced production at around $2m_Z$



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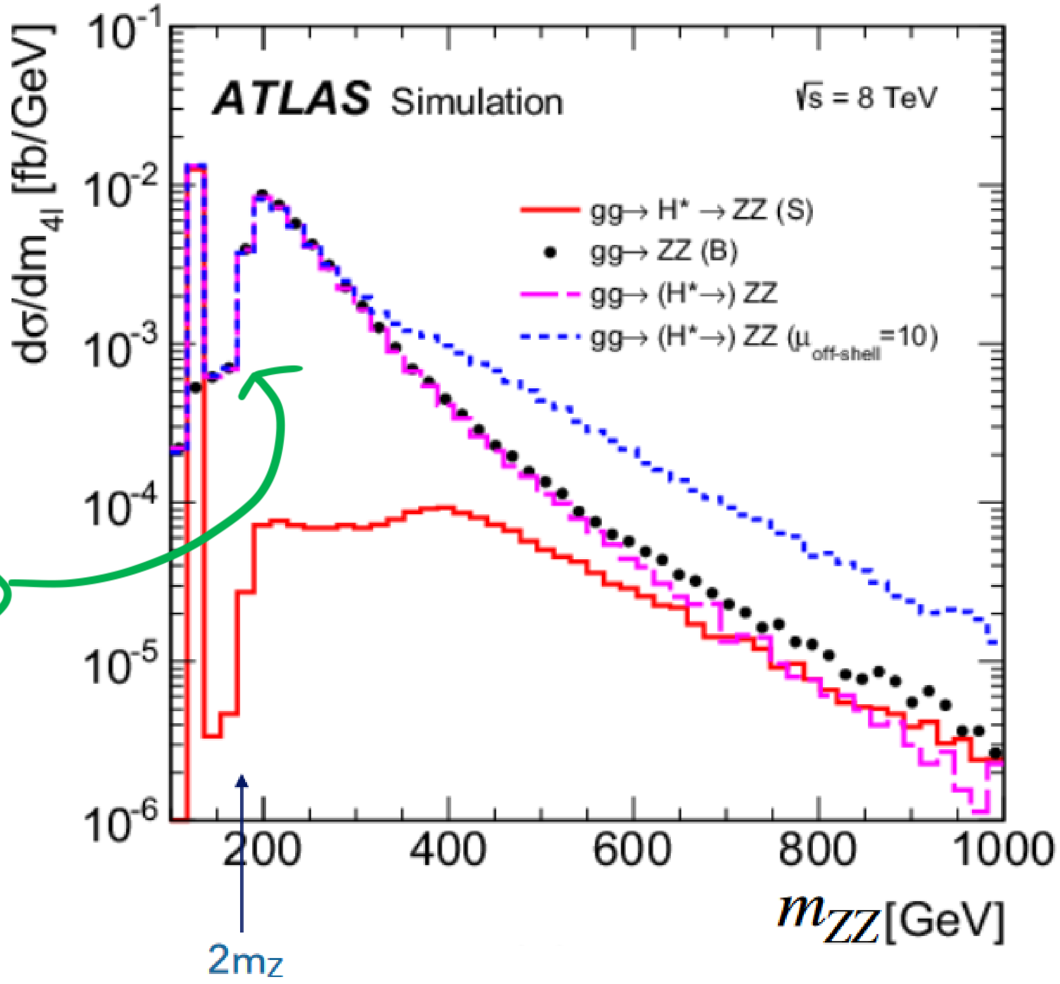
↓

$$\frac{\sigma_{\text{off-shell}}}{\sigma_{\text{on-shell}}} \propto \Gamma_H$$



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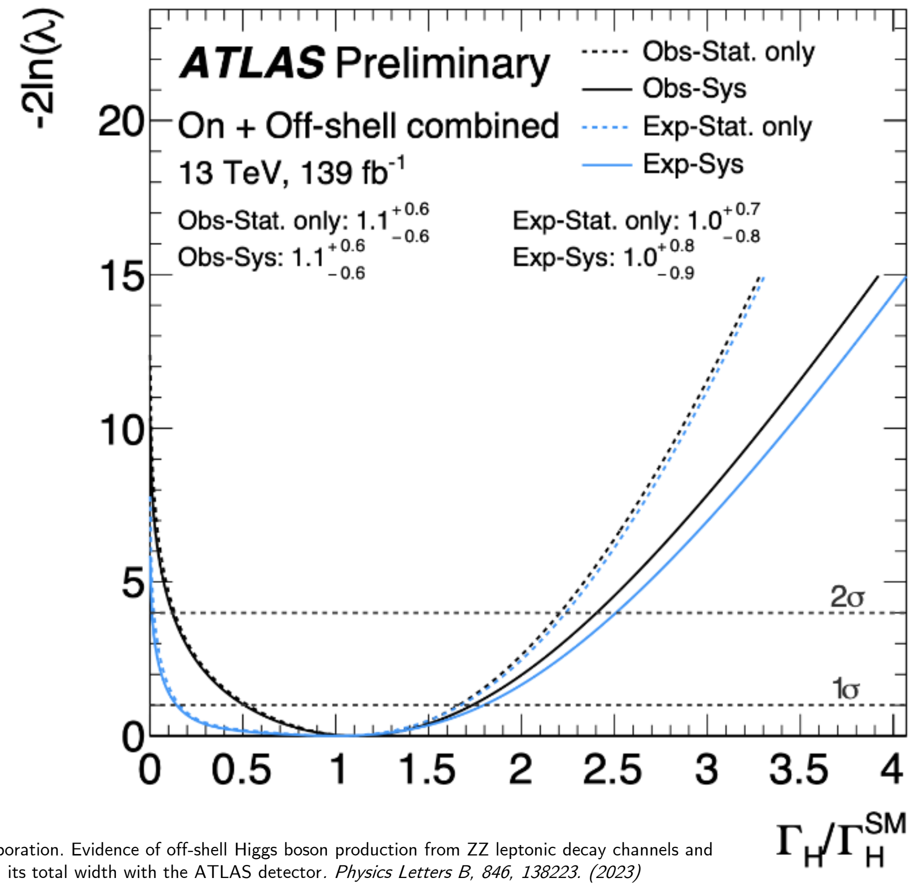
SM prediction: $\Gamma_H^{SM} = 4.1$ MeV ⟷ Measurements at ATLAS (2022): $\Gamma_H = 4.6^{+2.6}_{-2.5}$ MeV

↓

$$\Gamma_H / \Gamma_H^{SM} = 1.11^{+0.63}_{-0.60}$$



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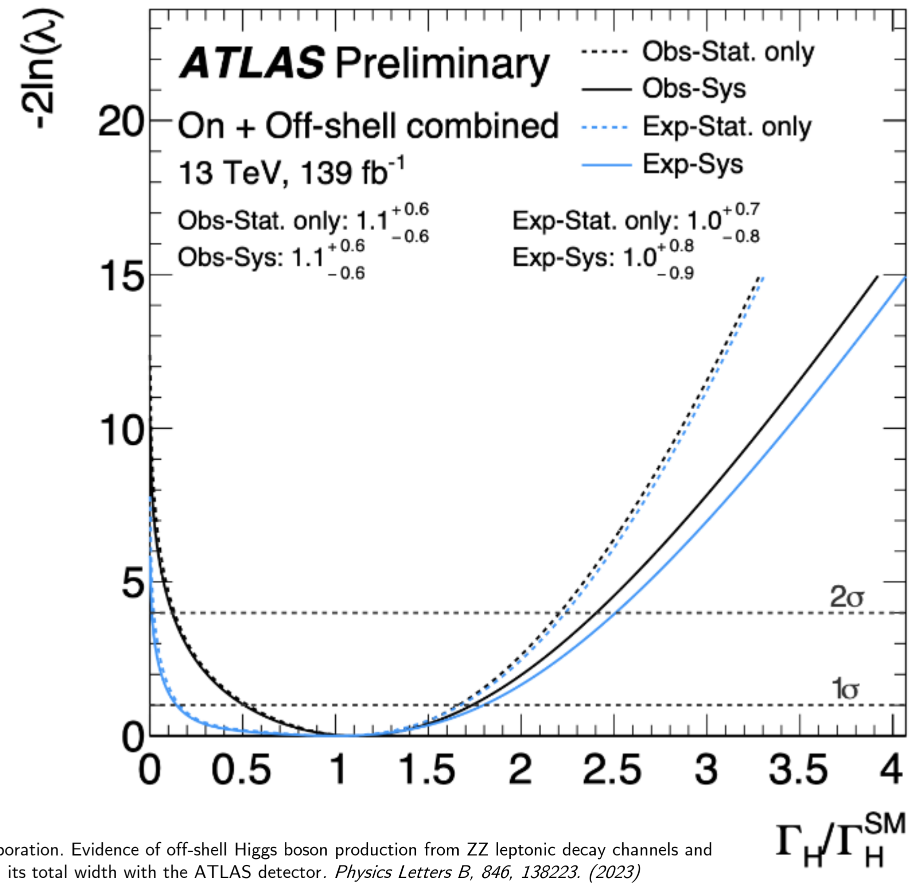
$$\Gamma_H / \Gamma_H^{SM} = 1.11^{+0.63}_{-0.60}$$

- Motivation: BR($H \rightarrow ZZ \rightarrow 4\nu$) ~ 0.1%, is there more?
  - Invisible decays would increase Γ_H^{meas} by a factor of $\frac{1}{1-\text{BR(BSM)}}$
  - Need for precise and model-independent measurements of Γ_H



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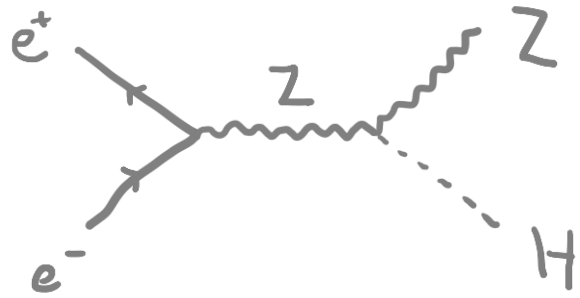
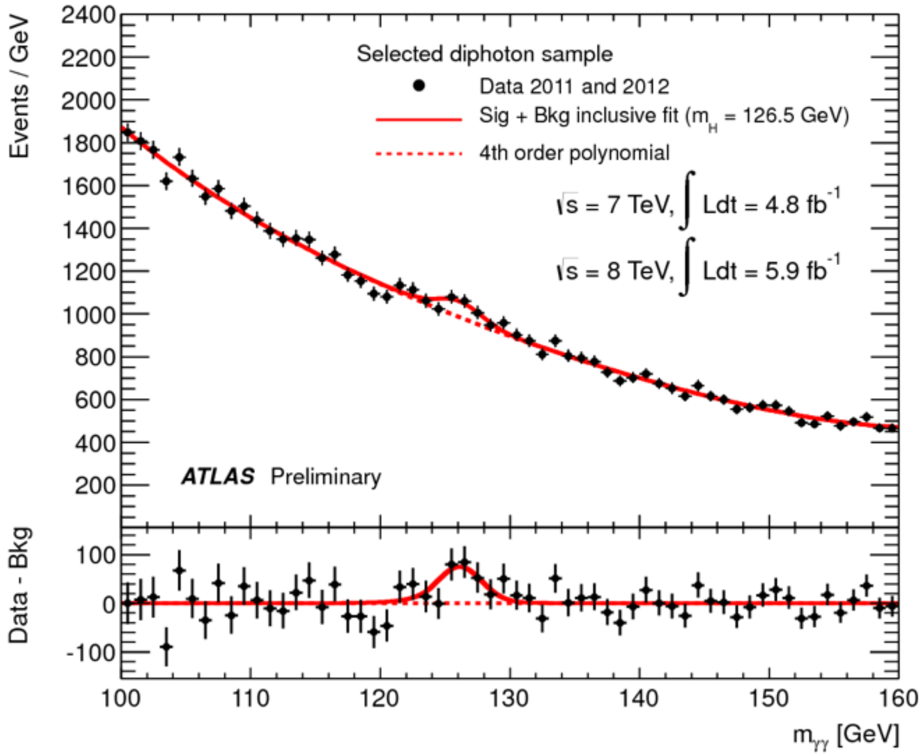
Measuring total decay width

- Hadron colliders
  - Diphoton spectrum peak shape – interference effects between S and B (low sensitivity)
  - Global fit of H couplings
  - $H \to ZZ^*/H^* \to ZZ$ decay (model-dependent)
- Lepton colliders
  - $e^+e^- \to ZH$ cross section
    - Recoil mass with $Z \to \ell^+\ell^-$ - removes need to directly tag H decay
  - Small systematic uncertainties



$$M^2_{recoil} = (\sqrt{s} - E_{l\bar{l}})^2 - p^2_{l\bar{l}}$$



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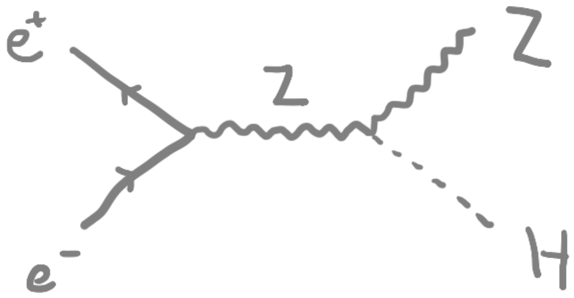

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Collider	$\delta\Gamma_H$ [%] [1]
HL-LHC	20
CEPC	2.8
$CLIC_{380}$	4.7
$CLIC_{1500}$	2.6
$CLIC_{3000}$	2.5
FCC-ee_{240}	2.7
FCC-ee_{365}	1.3
ILC_{250}	2.3
ILC_{500}	1.6
ILC_{1000}	1.4

Precision in Higgs coupling

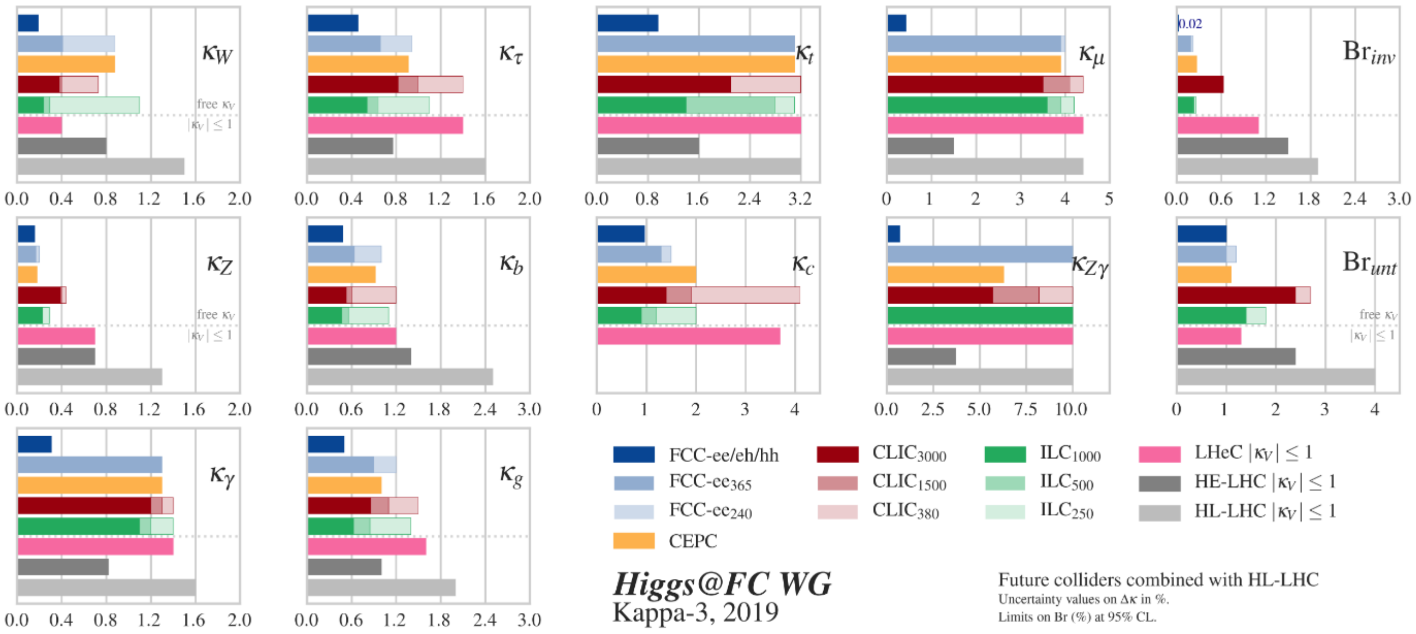
- Expressed in κ-framework
  - $\frac{\Gamma_{H\to VV}}{\Gamma^{SM}_{H\to VV}} = \kappa_V{}^2, \frac{\sigma_{ggH}}{\sigma^{SM}_{ggH}} = \kappa_g{}^2, \ldots$

- Motivation:

  Increase precision where κ_i serves as an input

  Search for deviations from SM predictions

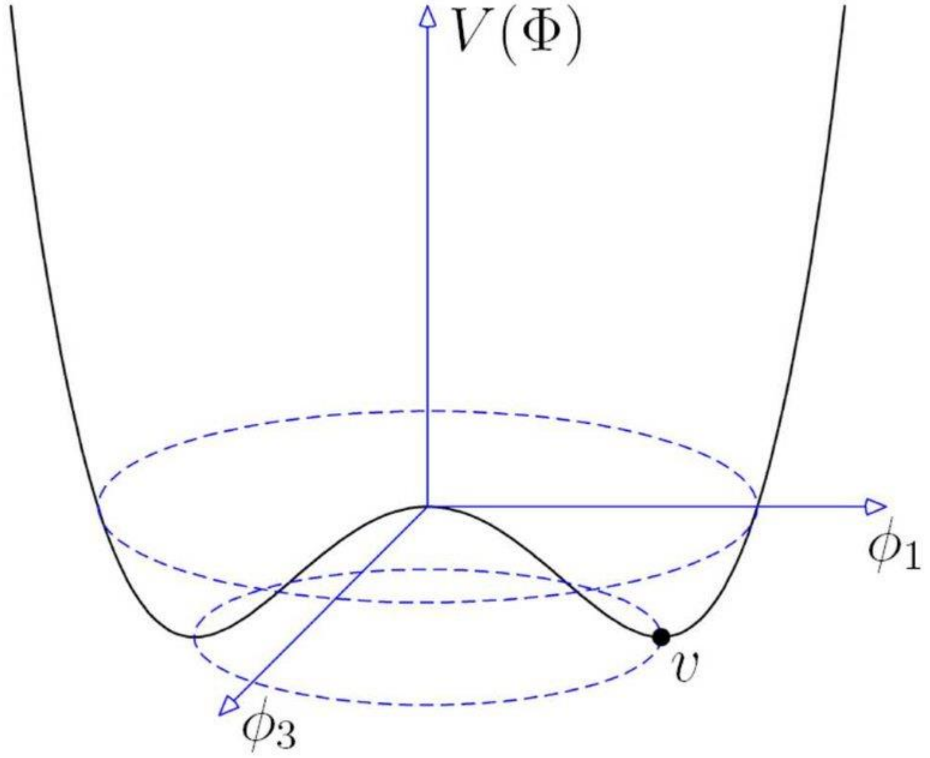
  Higgs potential - EW phase transition



Higgs Boson studies at future particle colliders. Journal of High Energy Physics, 2020(1). arXiv:1905.03764

Higgs self-coupling

- Terms responsible for Higgs self-interaction in the SM lagrangian:
  - $V(H) = \frac{m_H^2}{2} H^2 + \lambda_3 v H^3 + \lambda_4 H^4$
  - In SM: $m_H = \sqrt{2\lambda v^2},\ \lambda_3 = \lambda, \lambda_4 = \frac{1}{4}\lambda$ $\quad \kappa_3 = \frac{\lambda_3}{\lambda}$



Czodrowski, P., Kobel, M., & Cowan, T. Improvement of a Data-Driven Method for the Simulation of the ττ-Mass Shape in Z → ττ → ee + 4ν for ATLAS at the LHC (2009)

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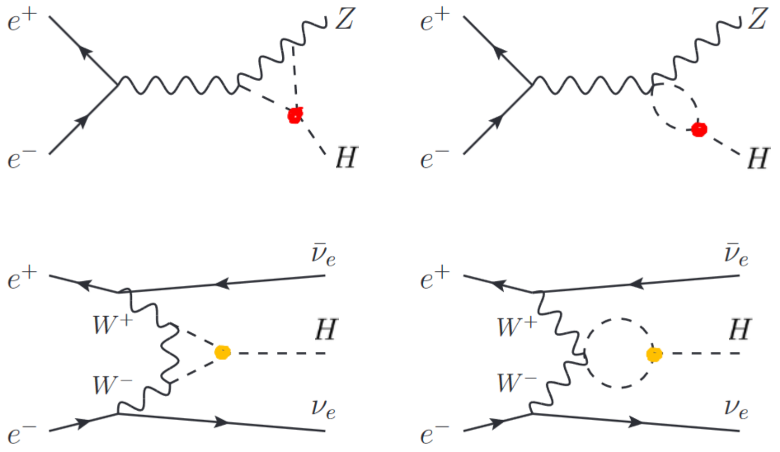
- Low $\sqrt{s}$ ($<$ 500 GeV) -> indirect measurement
  - *ZH* "Higgsstrahlung"
  - *VBF* Vector boson fusion



Di Vita et al. (2018). A global view on the Higgs self-coupling at lepton colliders. *Journal of High Energy Physics, 2018(2).* arXiv: 1711.03978

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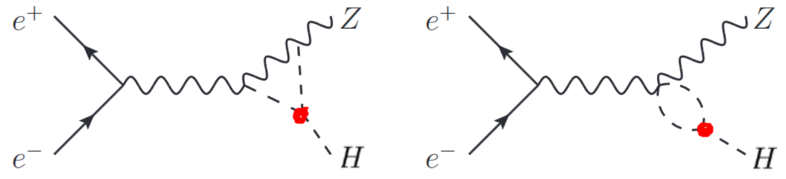
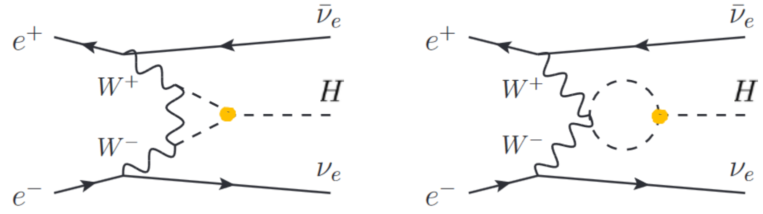
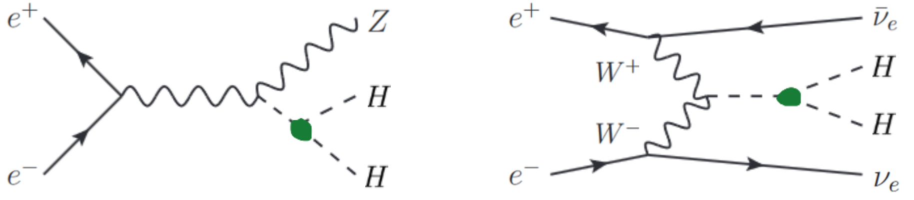


- Low $\sqrt{s}$ (< 500 GeV) -> indirect measurement
  - *ZH* "Higgsstrahlung"
  - *VBF* Vector boson fusion



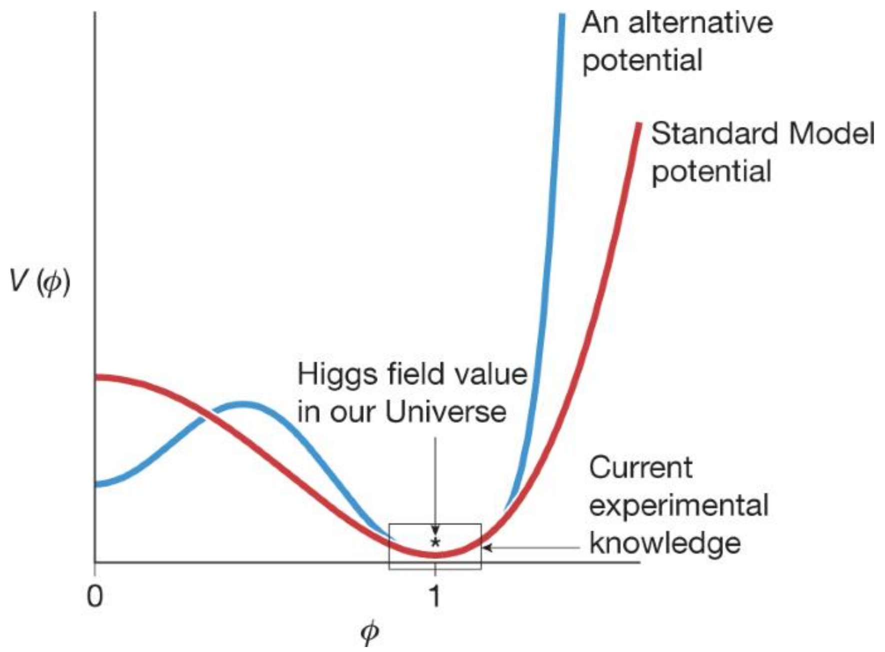
- Higher $\sqrt{s}$ -> possibility of direct measurements
  - Double Higgs production



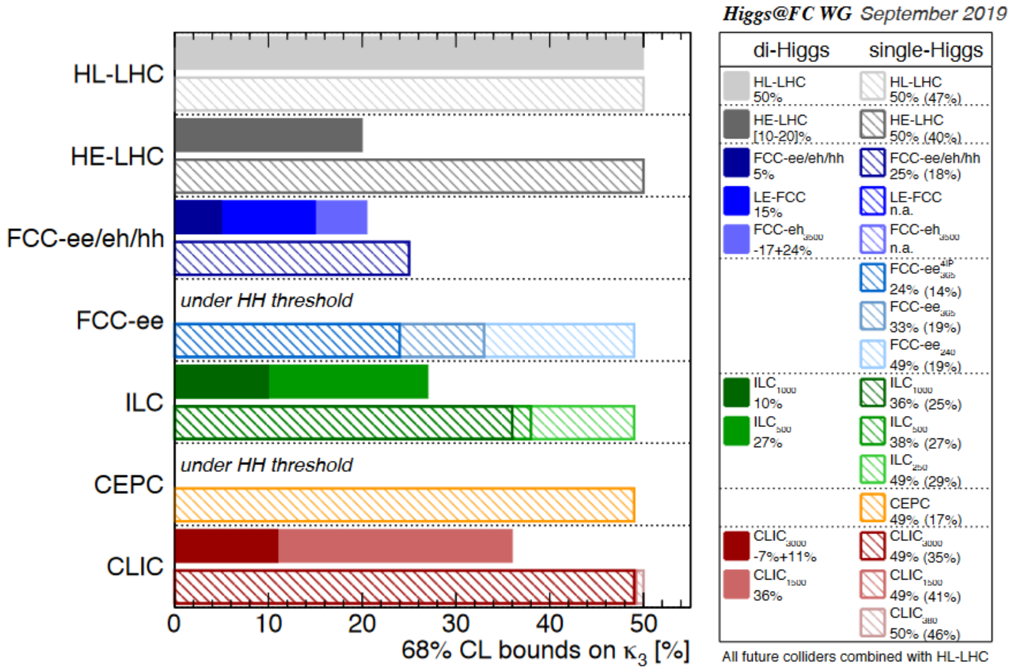
Di Vita et al. (2018). A global view on the Higgs self-coupling at lepton colliders. *Journal of High Energy Physics, 2018(2).* arXiv: 1711.03978

Higgs self-coupling

- Motivation: Higgs potential responsible for mass acquisition through EWSB
  - Precise measurements necessary to show potential deviations/departures from SM form
  - Behavior of Higgs potential during cooling after Big Bang

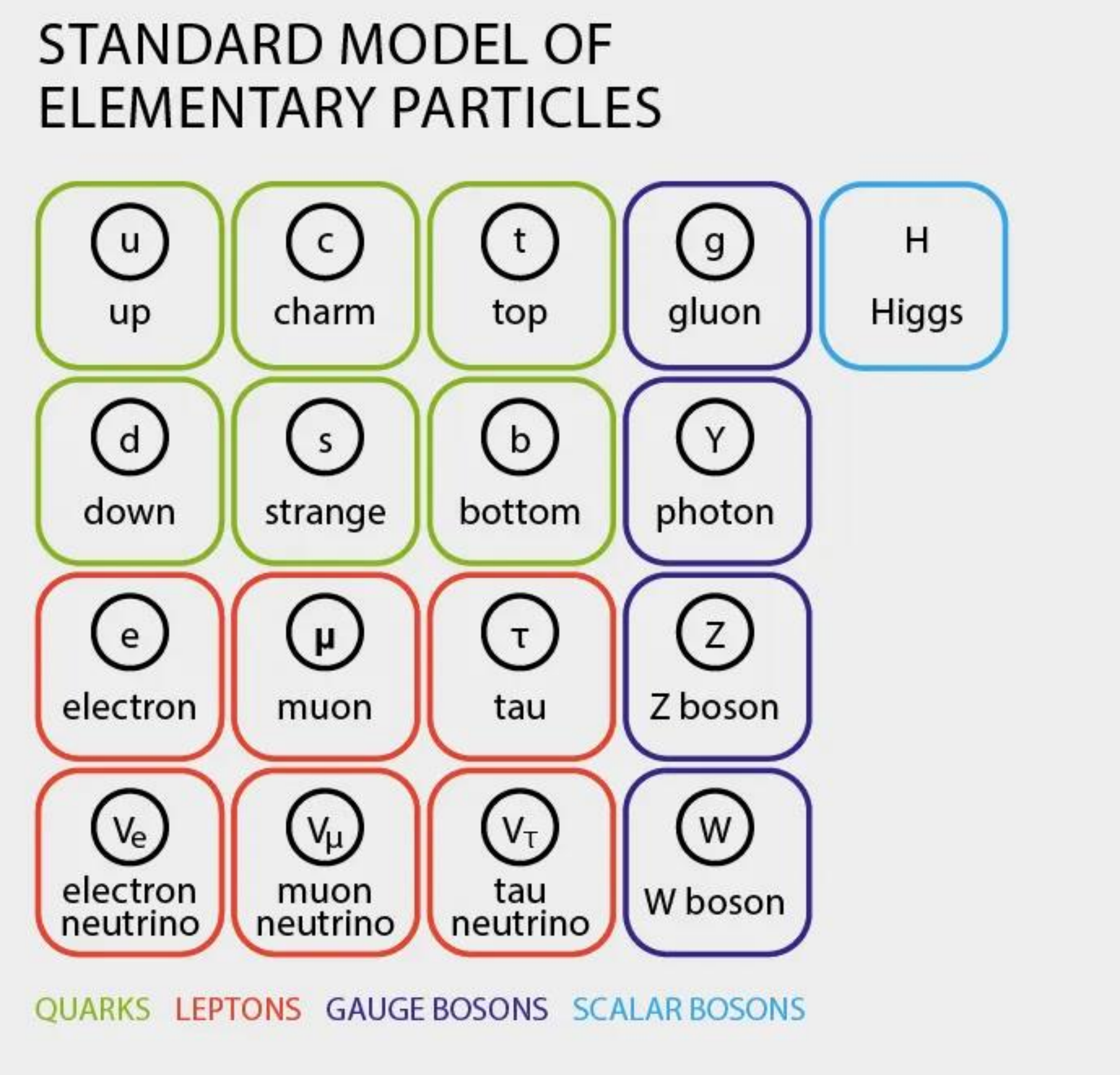


Salam, G.P., Wang, LT. & Zanderighi, G. The Higgs boson turns ten. *Nature* **607**, 41–47 (2022)



European Strategy for Particle Physics Preparatory Group. (2020). Physics Briefing Book. arXiv:1910.11775

Higgs rare decays



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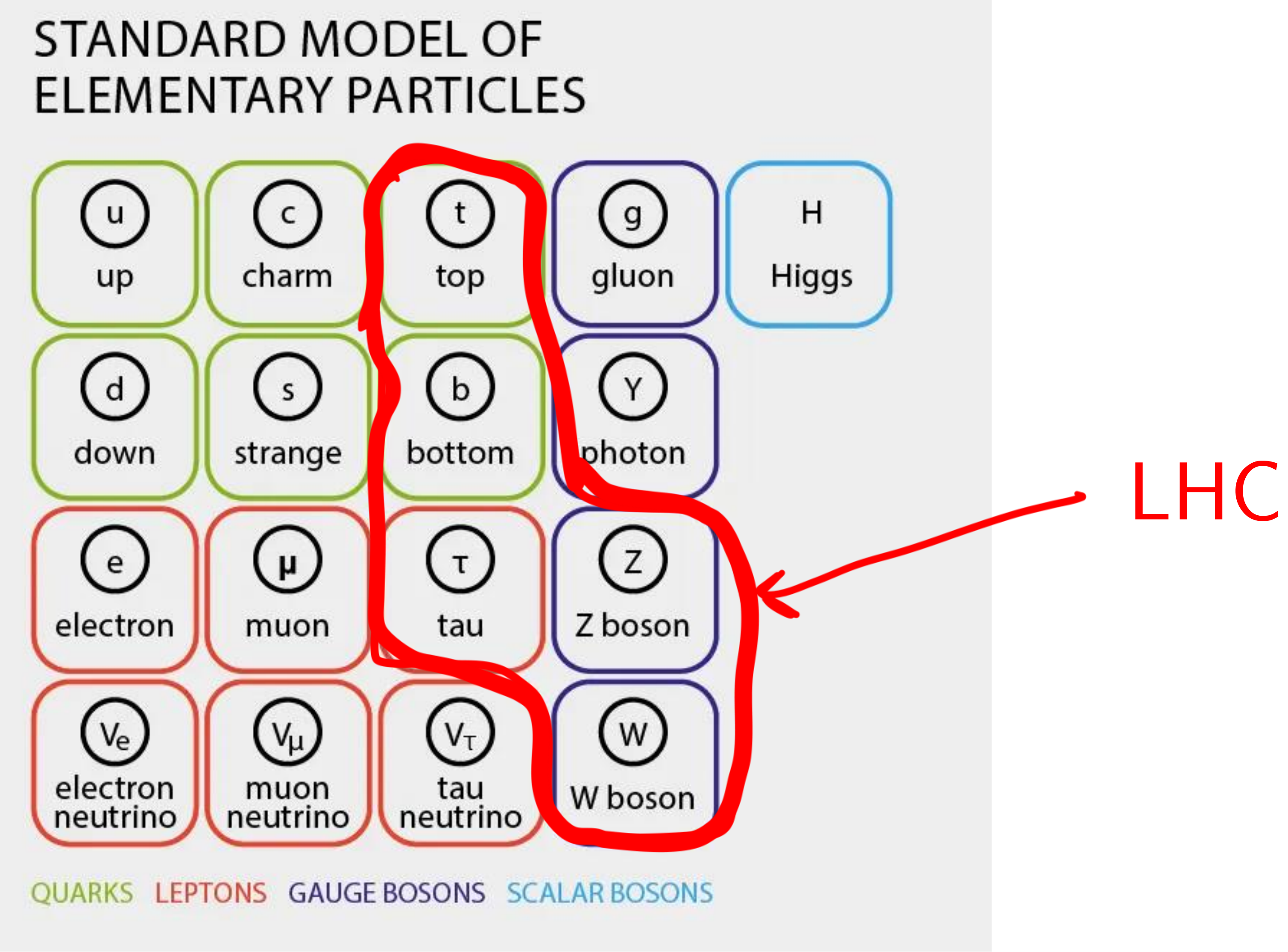

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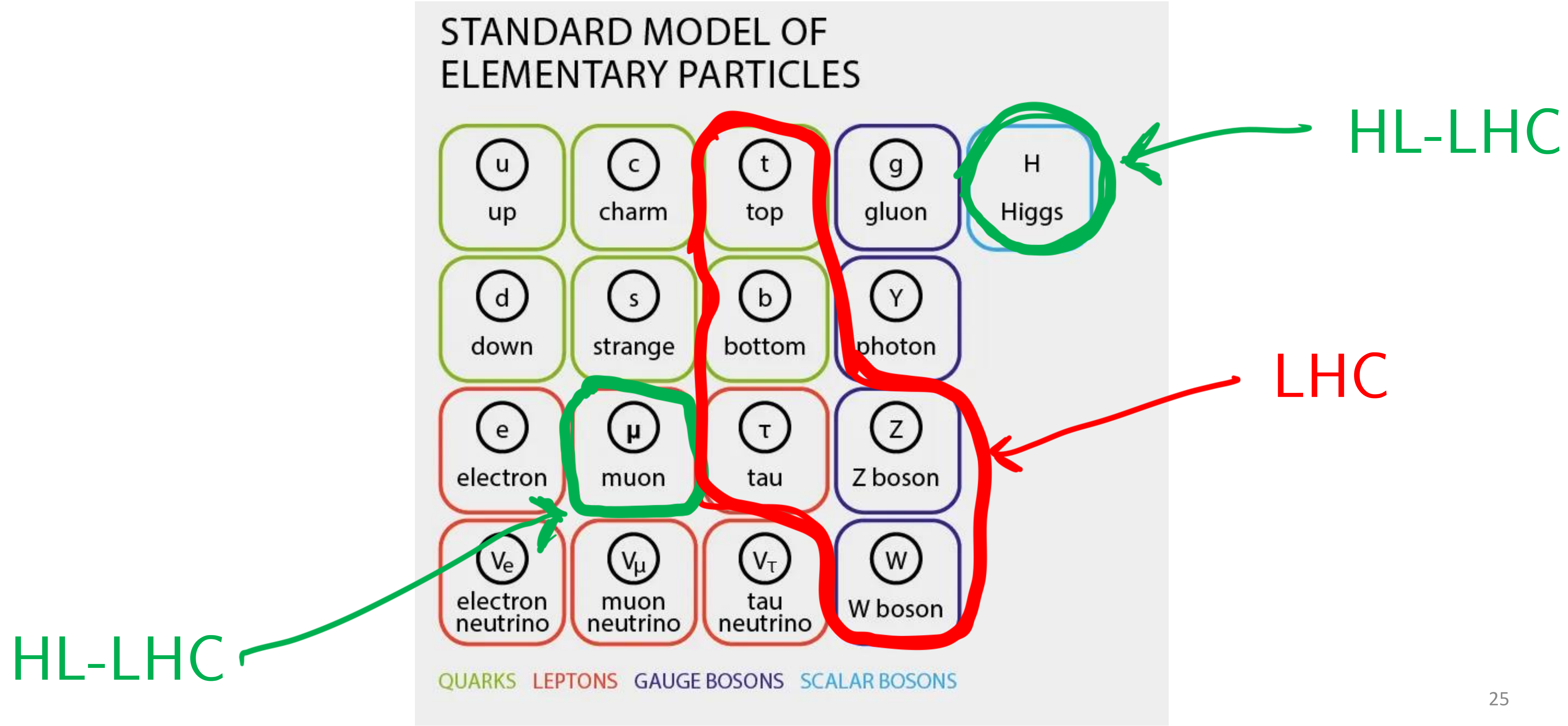

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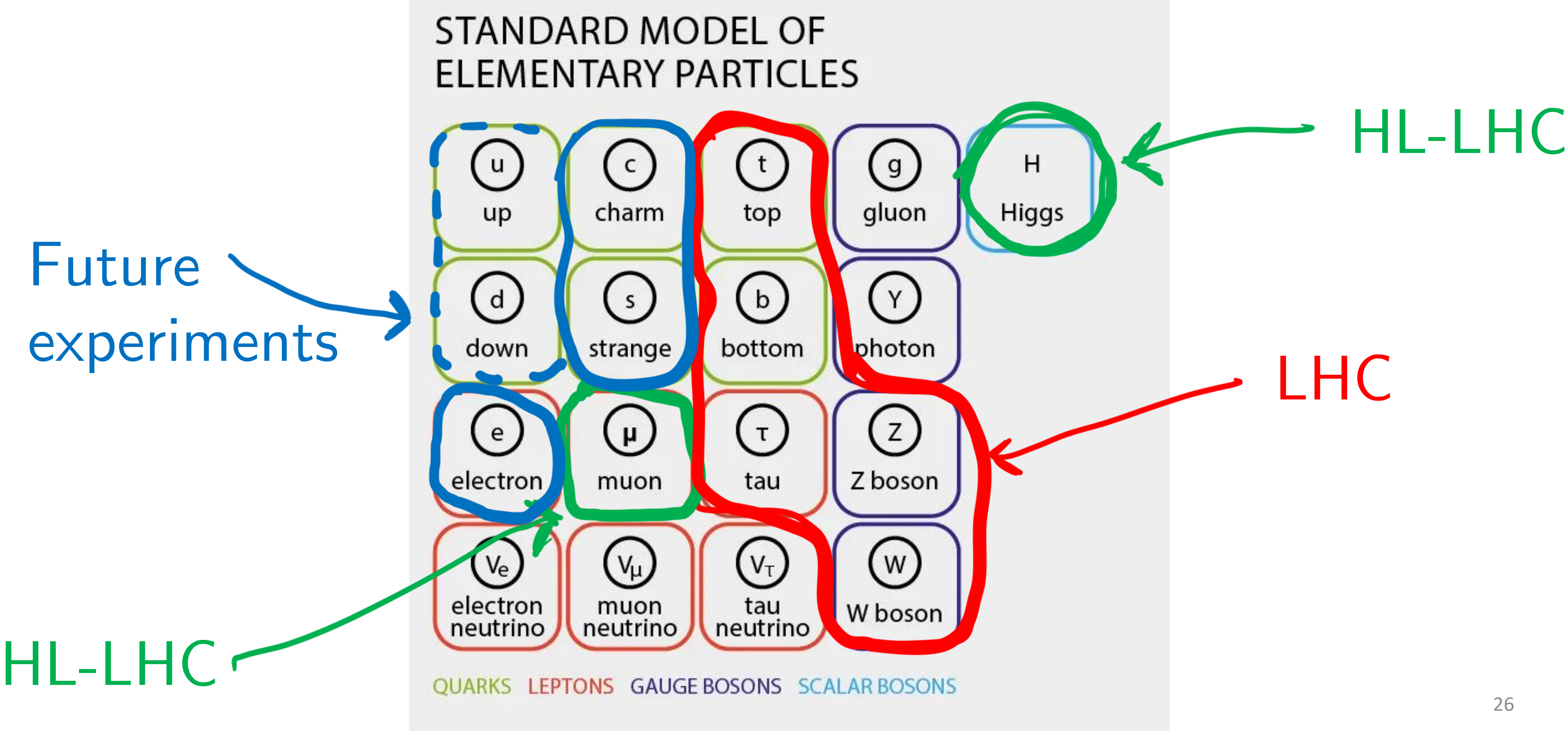
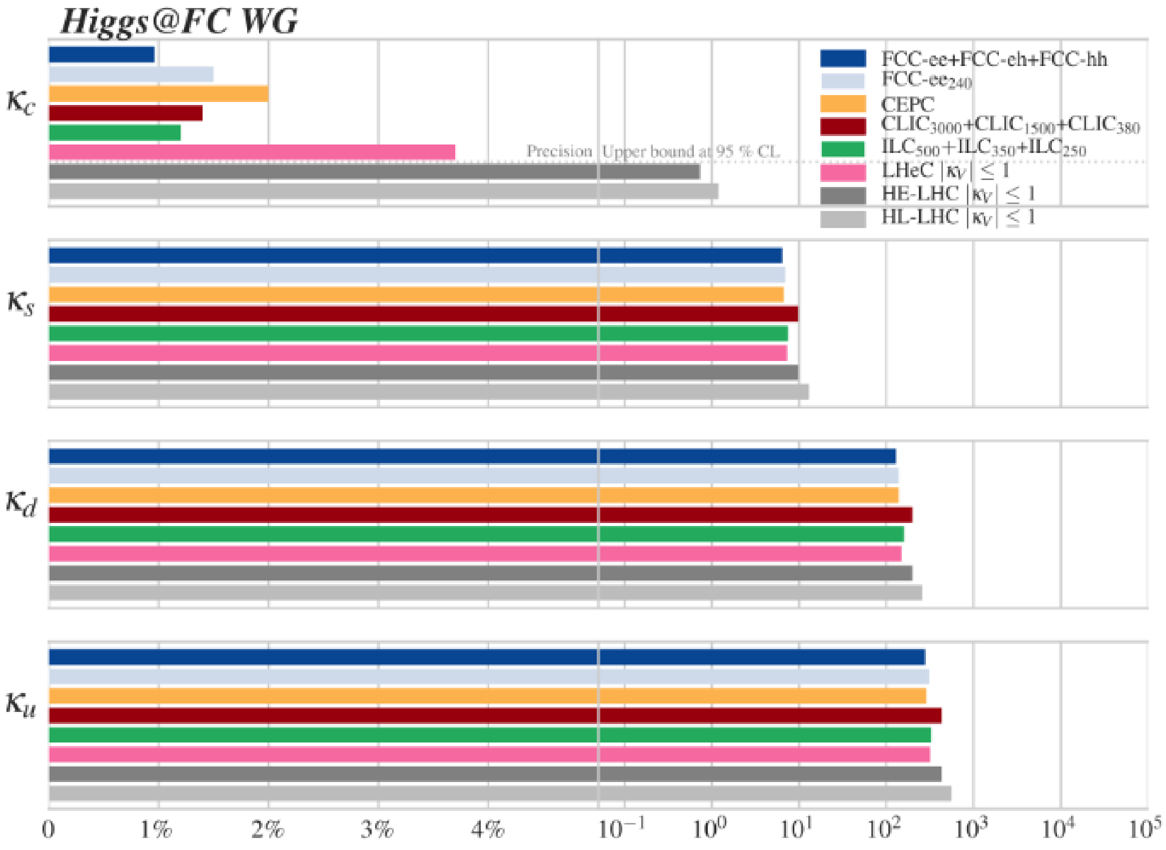


Higgs rare decays

- Motivation: Higgs couplings to light fermions out of reach for current colliders
- Light quarks: $H \to (\rho\varphi\omega)\gamma$
- Electron resonance: $e^+e^- \to H$



Blas, J. et al. (2020). Higgs Boson studies at future particle colliders. *Journal of High Energy Physics, 2020(1). arXiv: 1905.03764*

Conclusion

- Higgs factory will serve as a EW/top factory as well
  - Large statistic of W, Z bosons, t quarks
- Increased precision in the Higgs sector -> test of the Standard Model
  - Precise measurements of particle properties, upper bounds on suppressed/SM-violating processes
- Increased statistic -> searches for unknown particles

Thank you for your attention!

Backup

References

- [1]: Blas, J et al. Higgs Boson studies at future particle colliders. *Journal of High Energy Physics, 2020(1).* arXiv: 1905.03764