A theory view on seeing two Higgs bosons together at the LHC

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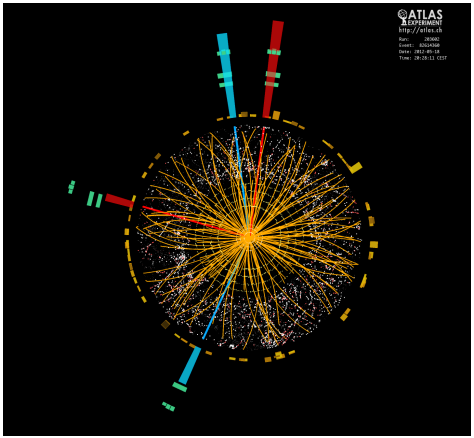
Outlook

- **Introduction**
  $\rightarrow$ Thoughts about interplay between theory and experiment
- **Di-Higgs production at the LHC**
  $\rightarrow$ Theory overview in the Standard Model
- **Beyond the Standard Model**
  $\rightarrow$ Coupling extractions

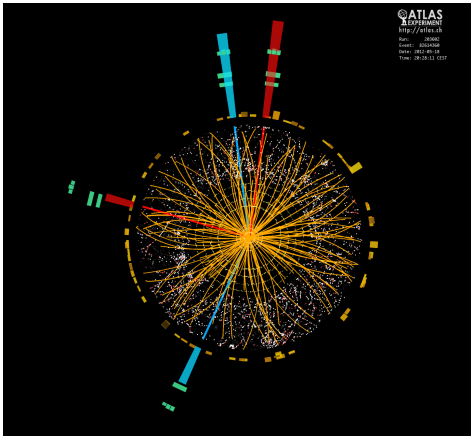
Outlook

- **Introduction**
  $\rightarrow$ Thoughts about interplay between theory and experiment

→ Common point between these pictures?



→ Display **known** and **unknown**!



→ Observing fragments of reality and looking for the truth

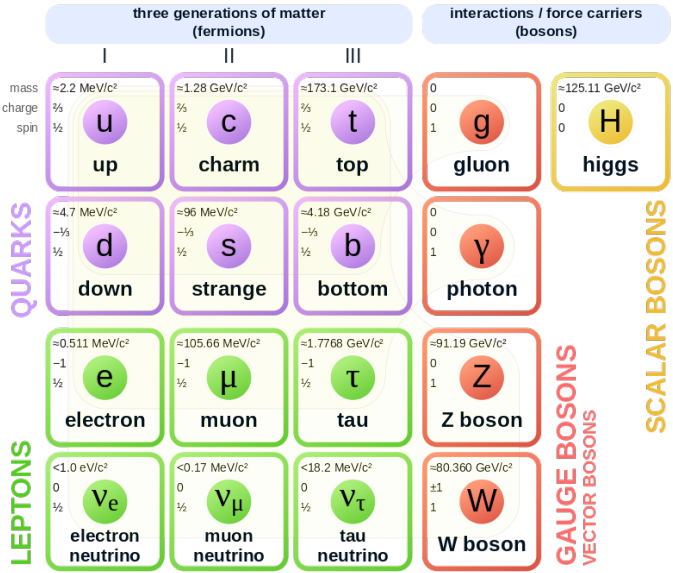
Allegory of the Cave - Plato

[source: MatiasEnElMundo/Getty Images]

→ Same in particles physics!
... but with some differences

Fragments of reality:

The particles of the
Standard Model
and their interactions



→ Same in particles physics! ... but with some differences...

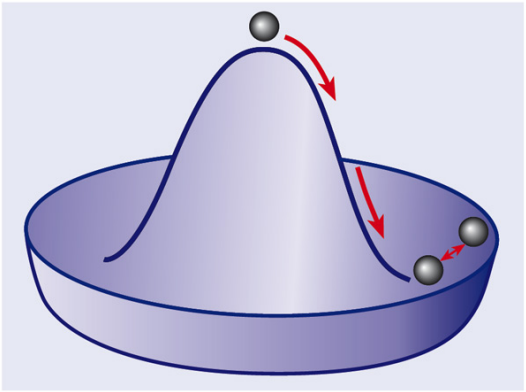
The truth about ...

- Dark Matter
- Matter-antimatter asymmetry
- Neutrino nature/masses
- Electroweak Symmetry Breaking
- How W and Z boson get their masses
- Higgs-boson properties
- ...

[source: bing image creator]

Electroweak symmetry breaking

The Higgs mechanism converts Goldstone modes into the longitudinal polarisation states of massive weak bosons
$\rightarrow$ W and Z get their mass from Higgs mechanism



[source: CERN]

→ Higgs potential

$$\mathscr{L} = y\,H\,\psi\,\bar{\psi} + \mu^2\,|H|^2 - \lambda\,|H|^4 - V_0$$

flavour — *naturalness* — *stability* — *cosmological constant*

[source: Salam, Giudice, Gianotti]

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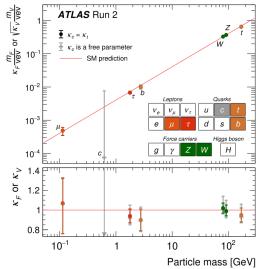
→ Next targets at the LHC

- Coupling of Higgs to muon/charm quark



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- Coupling of Higgs to muon/charm quark
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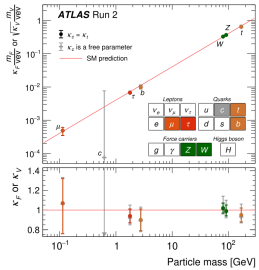
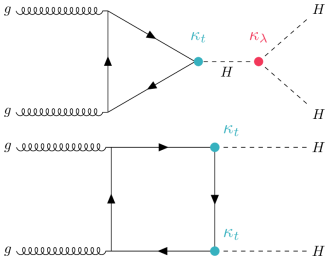
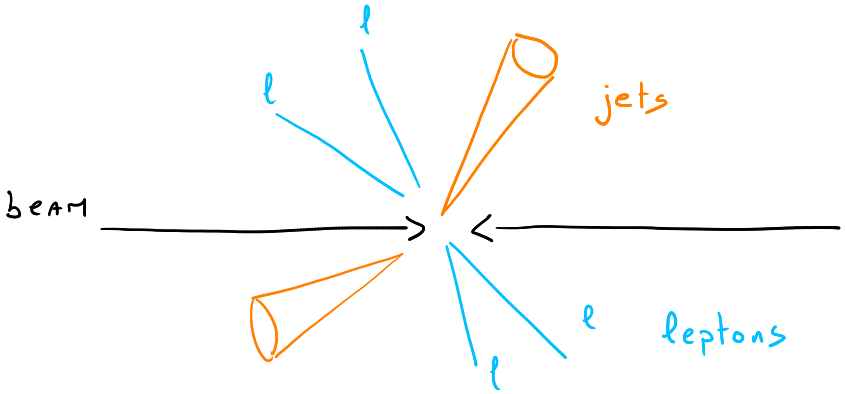
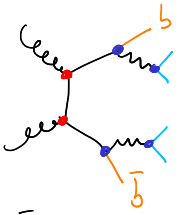




Some interesting LHC final state... (simplified view)

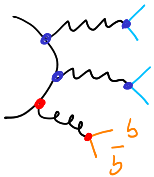


→ For example: $\{4\ell\} = \{e^+\nu_e\mu^-\bar{\nu}_\mu\}$ and $\{2j\} = \{b\bar{b}\}$



$t\bar{t}$ - prod.

$\mathcal{O}(\alpha_s^2 \alpha^4)$



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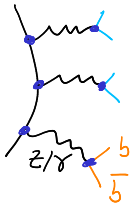
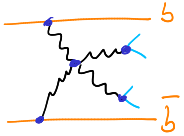


Tri-boson prod.

$\mathcal{O}(\alpha^6)$



VBS

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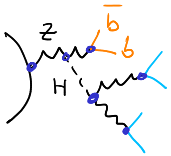

ZH prod.

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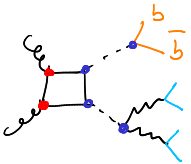

Di-Higgs prod.

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- **All contributing to measurement**
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  $\rightarrow$ only access to physical observables
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→ **Example of cuts**

• $t\bar{t}$: $m_{\ell\nu b} \sim m_t$ • Di-boson: $m_{\ell\nu} \sim m_W$ (twice) • ZH: $m_{b\bar{b}} \sim m_Z + m_{2\ell 2\nu} \sim m_H$
• VBS: $m_{jj} \gg 1$ • Tri-boson: $m_{b\bar{b}} \sim m_Z$ • Di-Higgs: $m_{b\bar{b}} \sim m_H + m_{2\ell 2\nu} \sim m_H$

→ altered by higher-order effects and exp. constraints

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Difficult interpretation

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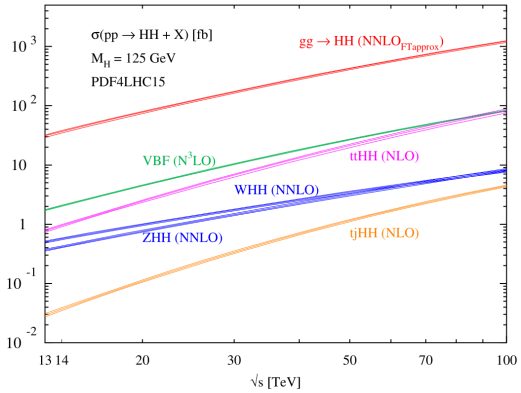
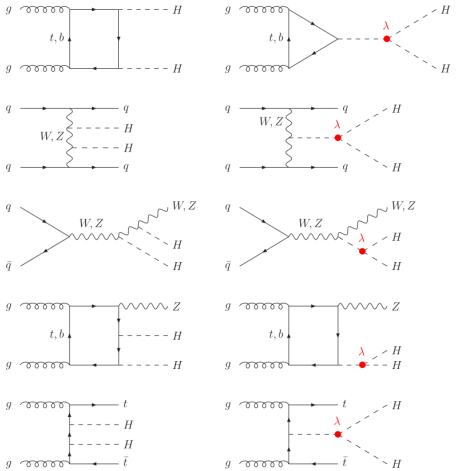
Crucial interplay between theory and experiment!

- **Di-Higgs production at the LHC**
  $\rightarrow$ Theory overview in the Standard Model

Di-Higgs production at the LHC

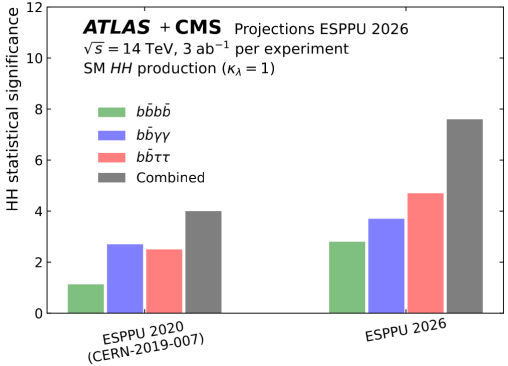


[1910.00012; Di Micco et al.]

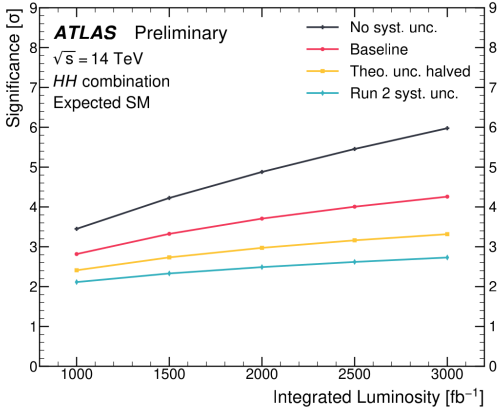


→ Focus on gg → HH and VBF production

HL-LHC expectations



[ATLAS+CMS; 2504.00672]



[ATLAS; ATL-PHYS-PUB-2025-006]

→ Projections are becoming increasingly optimistic / theory uncertainty critical

→ Conclusion slide from Joshua Davis at *Loops and Legs in Quantum Field Theory 26*

Conclusions

Lots of theory progress on HH over the last few years:

NLO QCD:
- analytic descriptions via kinematic expansions → fast and flexible NLO
- understanding of leading logarithmic structure → resummation in HE region

NLO EW:
- full numerical result, + cross checks for diagram subsets
- analytic progress: LME and HE (all t-quark diagrams), full result (light quark diagrams + $q\bar{q}$ ch.)

NNLO+ QCD:
- N3LO+N3LL HTL in SV approximation: sub-percent ren. scale uncertainty
- first results and ongoing work on NNLO m_t dependence

Outlook: optimistic that we can significantly reduce theory uncertainties for HL-LHC analyses!

22/22

→ Link: `https://indico.desy.de/event/48474/contributions/198780/`

HH production via gluon fusion

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  → Recommendation for inclusive cross sections
  → Recommendation for uncertainty (not only scale variation)
  ⚠ Large uncertainty due to scheme and scale choice for mt
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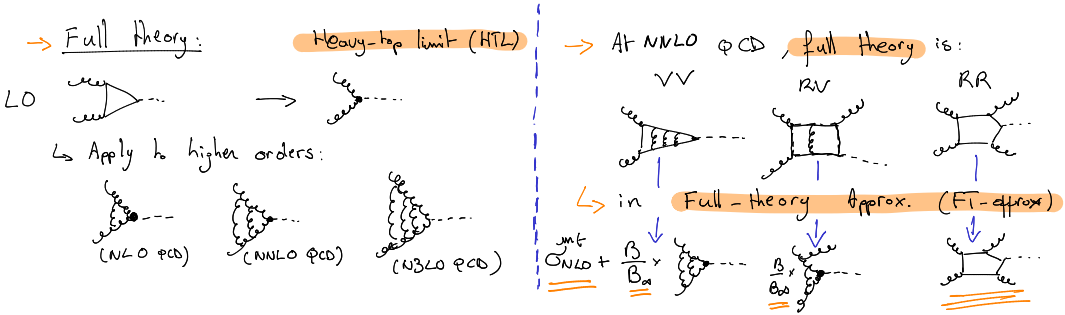
- Focus on three highlights:
  → N3LO QCD corrections [Chen et al.; 2601.19990]
  → NNLO QCD corrections matched to parton shower [Garosi, Wiesemann, Zanderighi; 2606.05300]
  → NLO EW corrections [Bi et al.; 2311.16963]

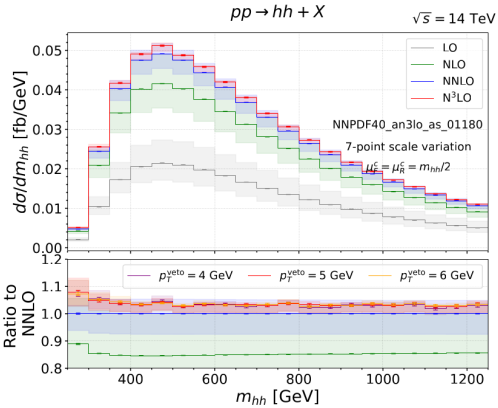
→ Complicated computations... many approximations...

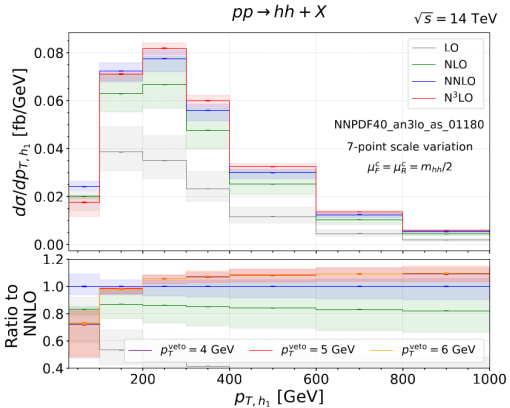


→ Other approximations: $\sigma^{\text{NNLO}}_{\text{NLO}-\text{I}} = \sigma^{\text{NLO}}_{\text{FT}} \frac{\sigma^{\text{NNLO}}_{\text{HTL}}}{\sigma^{\text{NLO}}_{\text{HTL}}}$ and $\sigma^{\text{NNLO}}_{\text{Born}-\text{I}} = \sigma^{\text{NNLO}}_{\text{HTL}} \frac{\sigma^{\text{LO}}_{\text{FT}}}{\sigma^{\text{LO}}_{\text{HTL}}}$

NB: Example for single Higgs but same for double-Higgs production

N3LO QCD corrections (in HTL)



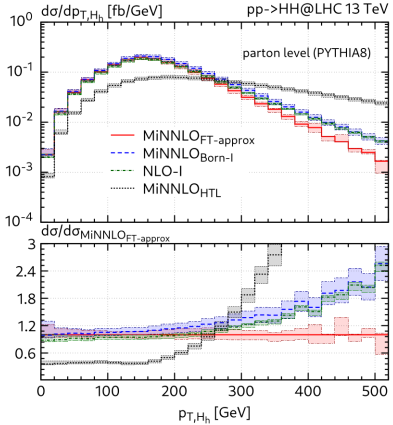


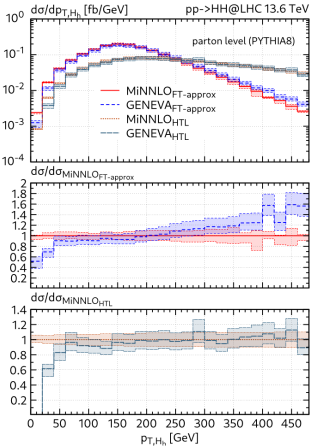
[Chen et al.; 2601.19990]

→ Moderate N3LO corrections but sizeable reduction of scale uncertainty

MiNNLO implementation of NNLO QCD mathed to PS

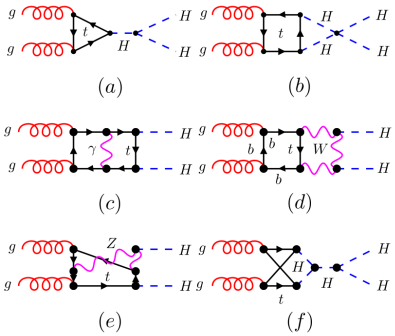
- MiNNLO framework [Garosi, Wiesemann, Zanderighi; 2606.05300]
- Based on ggxy library [Davies, Schönwald, Steinhauser, Stremmer; 2506.04323]



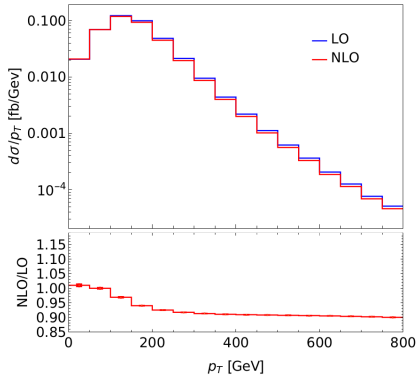


NLO EW to pp → HH

- Loop induced process
  → LO is one-loop
  → NLO is two-loop for the virtual part
- No real QED correction (Furry's theorem)
  → Weak radiation (W,Z) not needed for IR finiteness and rejected experimentally
- NLO EW is "only" the two-loop virtual contribution
- Exact calculation: [Bi et al.; 2311.16963]
  Large m_t-limit: [Davies, Schönwald, Steinhauser, Zhang; 2308.01355, 2603.08789]
  + partial results by [Heinrich et al.; 2407.04653], [Bhattacharya et al.; 2512.14823], [Bonetti et al.; 2503.16620, 2601.16924]



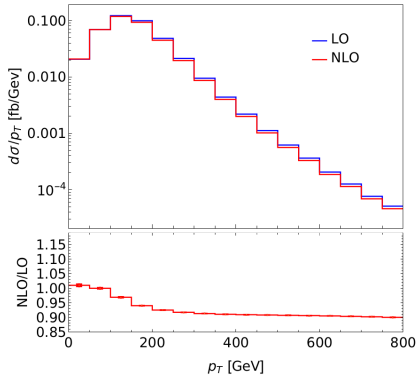
NLO EW to pp $\rightarrow$ HH [Bi et al.; 2311.16963]

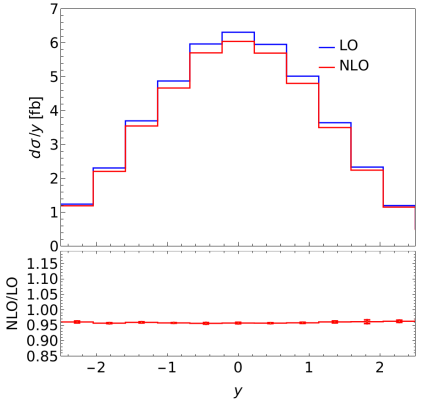


Typical behaviour for EW corrections at the LHC

- EW corrections larger in high-energy limit (Sudakov logarithms)

NLO EW to pp $\longrightarrow$ HH [Bi et al.; 2311.16963]





Typical behaviour for EW corrections at the LHC

- EW corrections larger in high-energy limit (Sudakov logarithms)
- Flat corrections for inclusive observables ($\sim$ per cent)

VBF HH

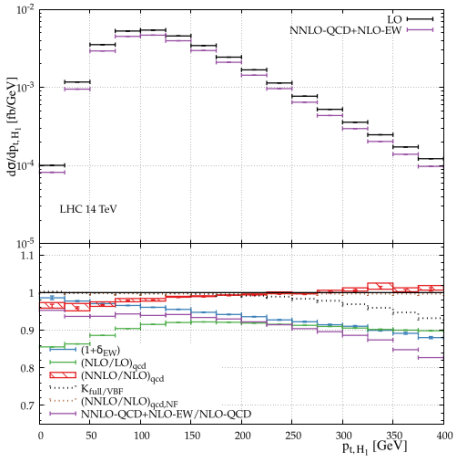
State of the art

- Inclusive cross section: N3LO QCD + NLO EW
  $\rightarrow$ YR5 recommendation [Gröber, Karlberg, MP, Sacchi, Spira; 2603.02764]
- Differentially: NNLO QCD + NLO EW [Dreyer, Karlberg, MP, Lang; 2005.13341]
- Public tools: `proVBFHH` [Dreyer, Karlberg, et al.; 1811.07906, 1811.07918,1506.02660,1606.00840]

  + `MoCaNLO` [Denner, Lombardi, Lopez Portillo Chavez, MP, Pelliccioli; 2602.19842] MoCaNLO

Event generators

- Accuracy: NLO QCD matched to parton shower
- YR5 contribution [Braun et al.; 2511.02488]
  + recommendations for parton showerv in VBF [Barone, MP, et al.; 2507.22574]
- Tools: `GoSam` [Braun et al.; 2507.23549]+ `Whizard` [Kilian, Ohl, Reuter; 0708.4233]
  or `POWHEG-BOX` [Jäger, Karlberg, Reinhard; 2502.09112] (or MadGraph5_aMC@NLO/`Sherpa`)



[Dreyer, Karlberg, MP, Lang; 2005.13341]

→ Typical behaviour of EW corrections
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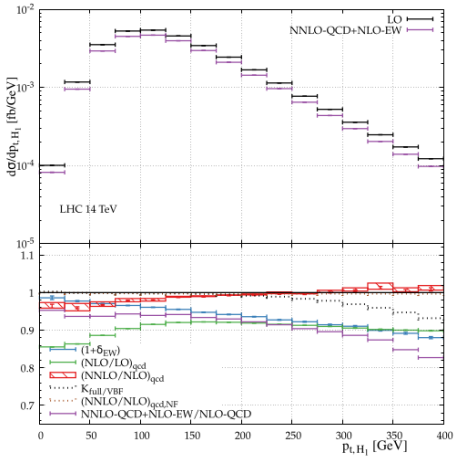

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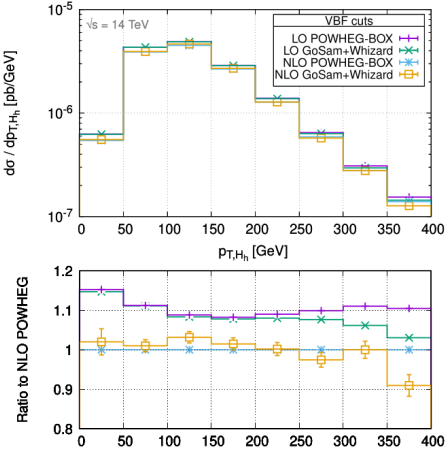
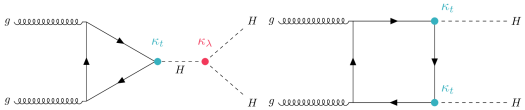


[Braun et al.; 2511.02488]

→ Differences between full EW process and VBF approximation

- **Beyond the Standard Model**
  $\rightarrow$ Coupling extractions ... aka the dangerous zone...

Principle



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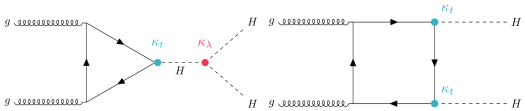

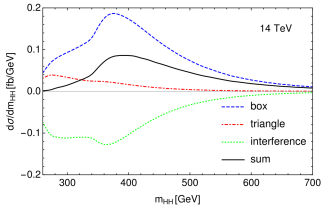

[1910.00012; Di Micco et al.]

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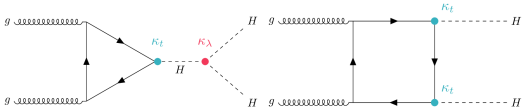
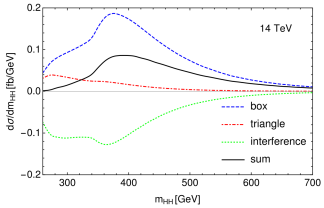


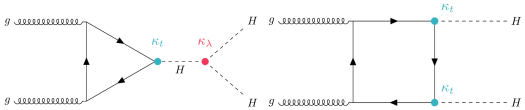


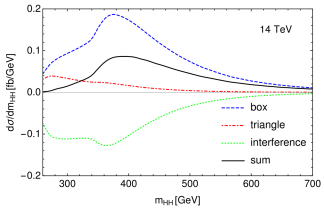
[1910.00012; Di Micco et al.]

$$\sigma = \left(\sigma_{\mathrm{Box}}\kappa_{\mathrm{t}}^4 + \sigma_{\mathrm{Tri.}}\kappa_{\mathrm{t}}^2\kappa_\lambda^2 - |\sigma_{\mathrm{Int}}|\kappa_{\mathrm{t}}^3\kappa_\lambda\right)\sigma_{\mathrm{SM}}$$

with $\kappa_f = Y_f/Y_{\mathrm{SM}}$

Principle





[1910.00012; Di Micco et al.]

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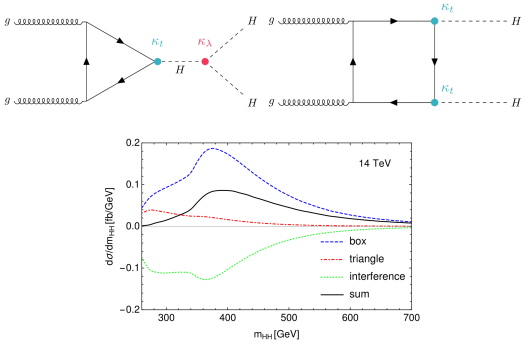

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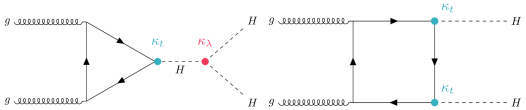

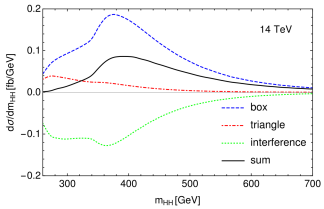

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Legacy measurements

- Measurements are always physical
- Interpretation are not always!

→ All information should be made available...

... reinterpretation, reproducibility, ...

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Conclusion

Seeing two Higgs boson at the same time at the LHC

Unique window into Electroweak Symmetry Breaking Mechanism
and fundamental properties of the Higgs boson

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- **Exciting physics at the LHC!**
- **Probing fundamental aspect of particle physics!**

BACK-UP