

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

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- **Introduction**

- Thoughts about interplay between theory and experiment

- **Di-Higgs production at the LHC**

- Theory overview in the Standard Model

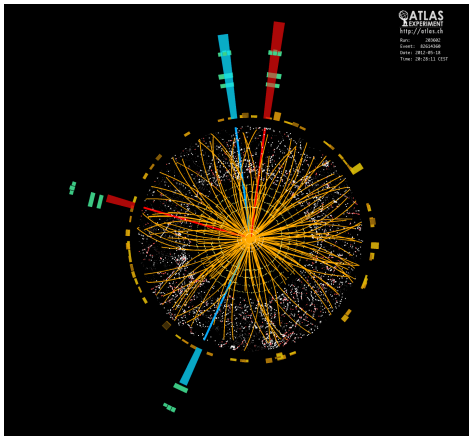
- **Beyond the Standard Model**

- Coupling extractions

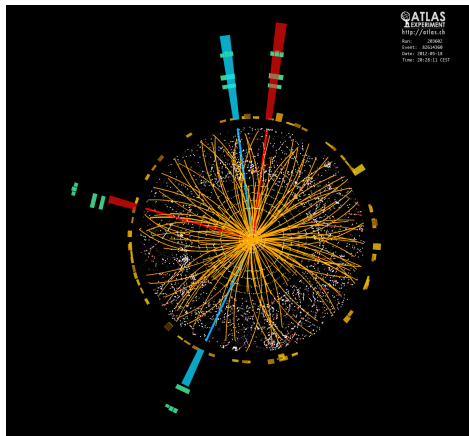
- **Introduction**

- 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



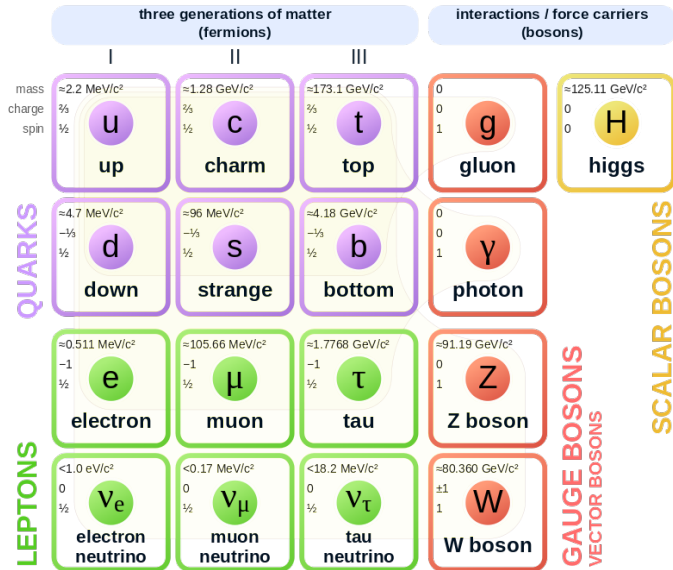
[source: MatiasEnElMundo/Getty Images]

Standard Model of Elementary Particles

→ Same in particles physics!

Fragments of reality ...

The particles of the
Standard Model
and their interactions



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
- ...

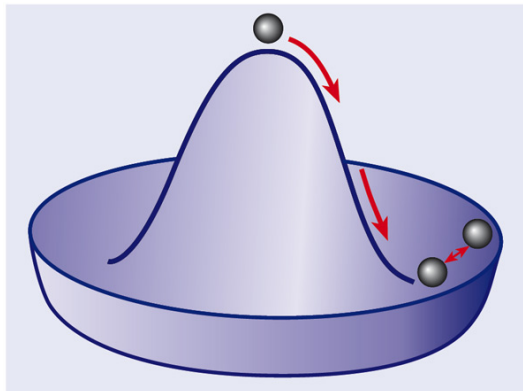


[source: bing image creator]

Electroweak symmetry breaking

The Higgs mechanism converts Goldstone modes into the longitudinal polarisation states of massive weak bosons

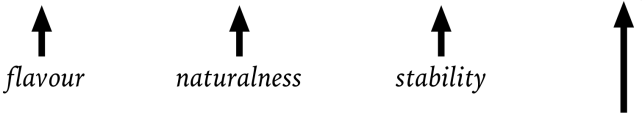
→ W and Z get their mass from Higgs mechanism



[source: CERN]

→ Higgs potential

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


flavour naturalness stability
cosmological constant

[source: Salam, Giudice, Gianotti]

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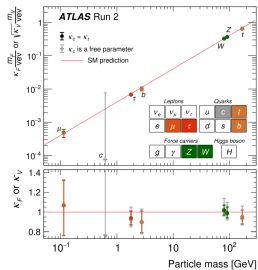
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$\uparrow$ flavour $\uparrow$ naturalness $\uparrow$ stability $\uparrow$ cosmological constant

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→ Next targets at the LHC

- Coupling of Higgs to muon/charm quark



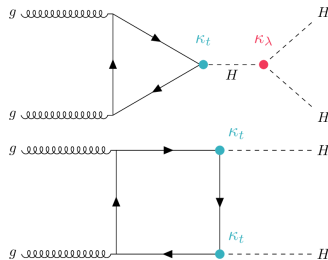
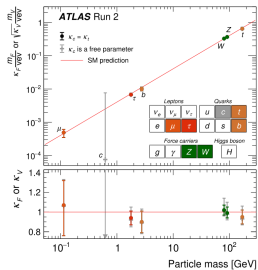
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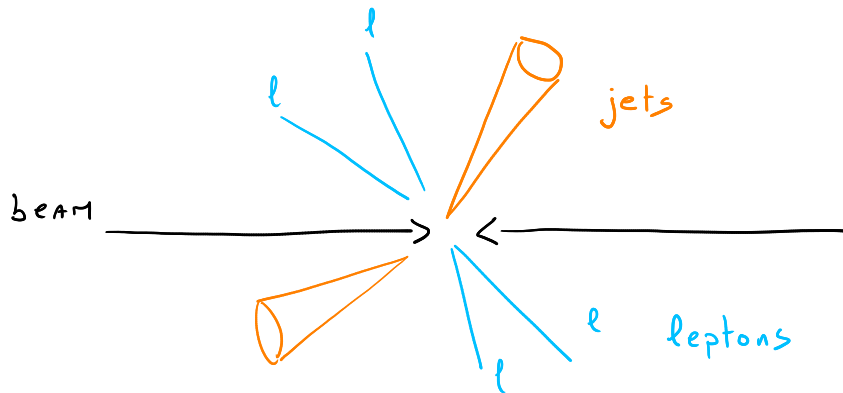
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→ Next targets at the LHC

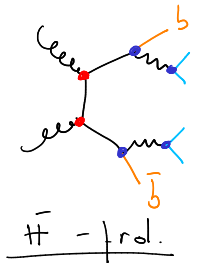
- Coupling of Higgs to muon/charm quark
- Di-Higgs production



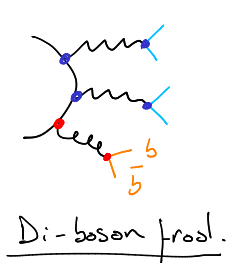
Some interesting LHC final state... (simplified view)



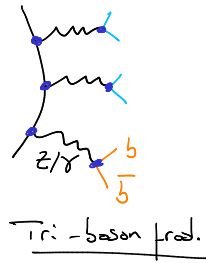
→ For example: $\{4\ell\} = \{e^+ \nu_e \mu^- \bar{\nu}_\mu\}$ and $\{2j\} = \{b\bar{b}\}$



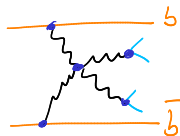
$$\mathcal{O}(\alpha_s^2 \alpha^4)$$



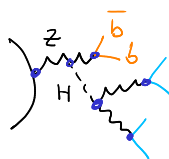
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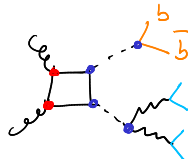
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- **Solutions for isolation of single contributions:**

- **Event selection (exp.)**

- ⚠ Assumption:

- no overlap between $\neq$ proc.

- only access to physical observables

- **Approximations (th.)**

- e.g. on-shell approx.

- easier to compute

- good enough? ... interplay with cuts

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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

More physical -
Difficult interpretation



Less physical -
Easy interpretation

- ① Full measurement vs. Full calculation (all contr.)
→ [Measurement of leptons and jets]

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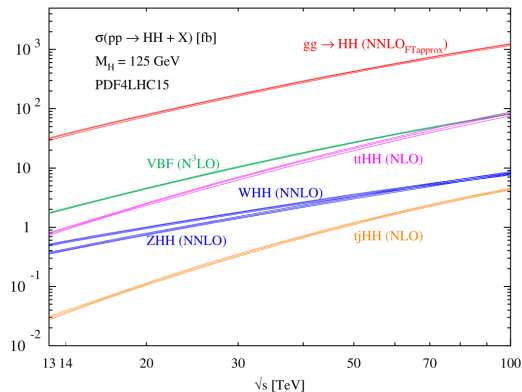
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Crucial interplay between theory and experiment!



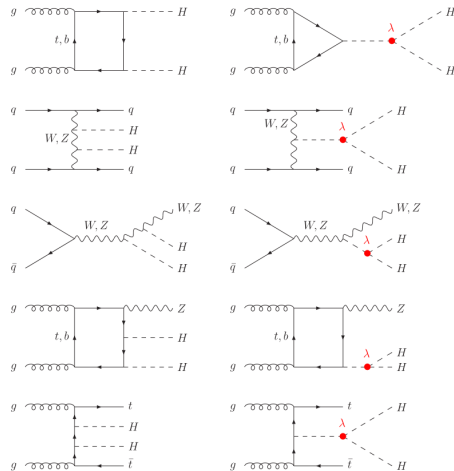
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Di-Higgs production at the LHC

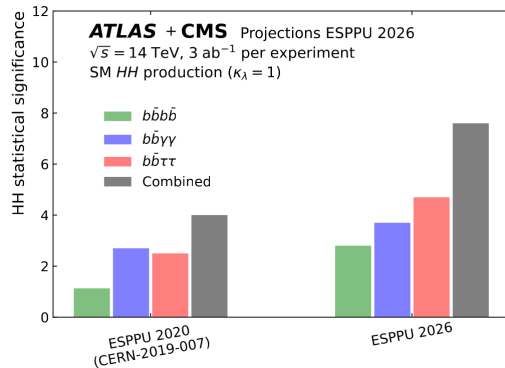


[1910.00012; Di Micco et al.]

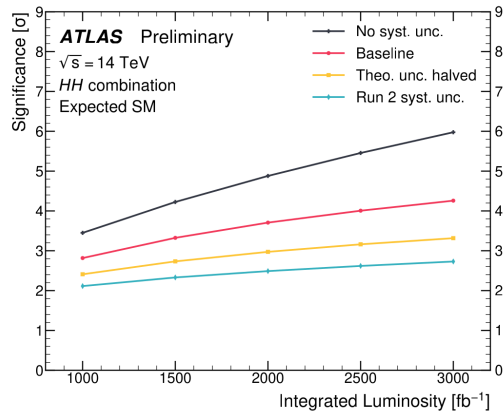
→ Focus on $gg \rightarrow HH$ and VBF production



HL-LHC expectations



[ATLAS+CMS; 2504.00672]



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

→ Projections are becoming increasingly optimistic / theory uncertainty critical

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

HH production via gluon fusion

- Lots of developments recently
 - full review, see presentation by Joshua Davies:
<https://indico.desy.de/event/48474/contributions/198780/>

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- No official recommendations yet from the Higgs cross section working group (expected this week or next week)

→ Recommendation for inclusive cross sections

→ Recommendation for uncertainty (not only scale variation)

⚠ Large uncertainty due to scheme and scale choice for m_t

⚠ Several approximations used

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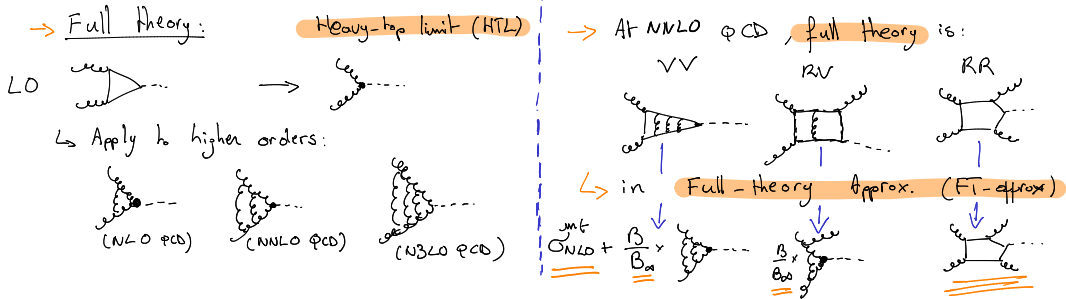
- Focus on three highlights:

→ N3LO QCD corrections [Chen et al.; 2601.19990]

→ NNLO QCD corrections matched to parton shower [Garosi, Wiesenmann, Zanderighi; 2606.05300]

→ NLO EW corrections [Bi et al.; 2311.16963]

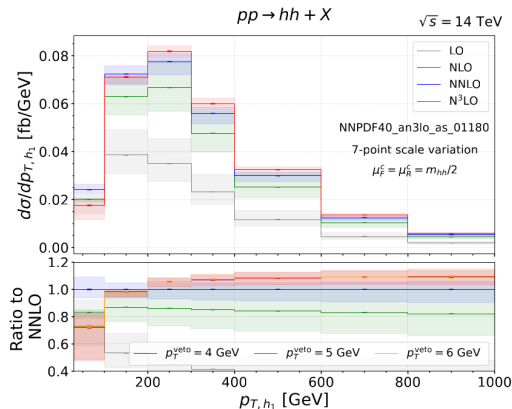
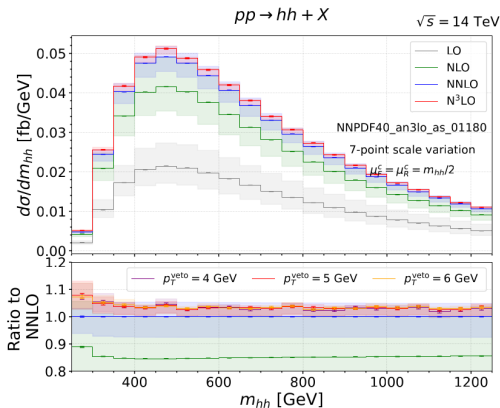
→ Complicated computations... many approximations...



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

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

N3LO QCD corrections (in HTL)

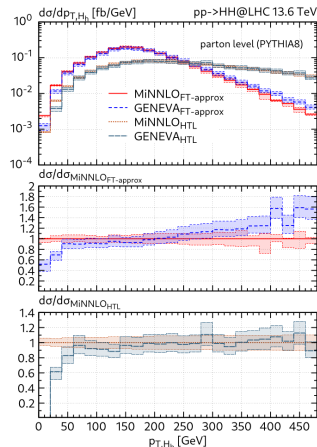
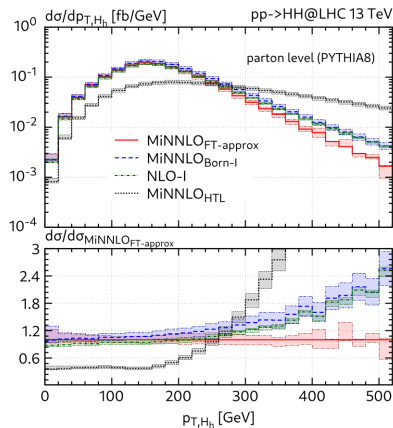


[Chen et al.; 2601.19990]

→ Moderate N3LO corrections but sizeable reduction of scale uncertainty

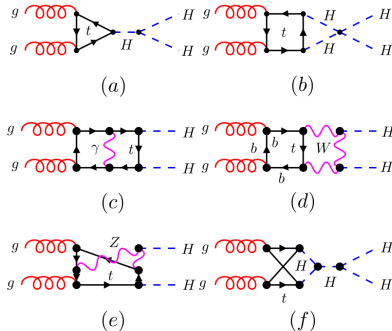
MiNNLO implementation of NNLO QCD matched to PS

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

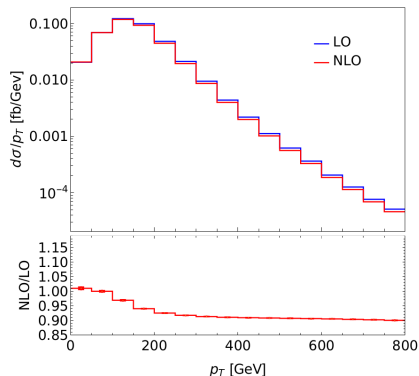


NLO EW to $pp \rightarrow HH$

- 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]



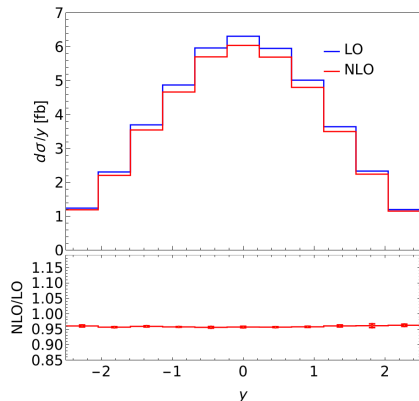
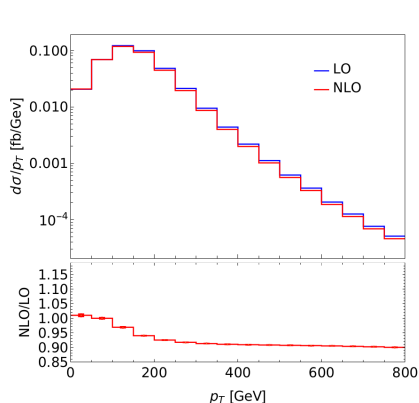
NLO EW to $pp \rightarrow HH$ [Bi et al.; 2311.16963]



Typical behaviour for EW corrections at the LHC

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

NLO EW to $pp \rightarrow HH$ [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)

State of the art

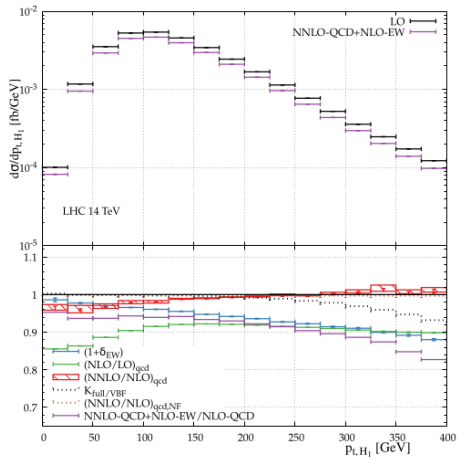
- Inclusive cross section: N3LO QCD + NLO EW
→ YR5 recommendation [Gröber, Karlberg, MP, Sacchi, Spira; 2603.02764]
- Differentially: NNLO QCD + NLO EW [Dreyer, Karlberg, MP, Lang; 2005.13341]
- Public tools: proVBFHH [Dreyer, Karlberg, et al.; 1811.07906, 1811.07918, 1506.02660, 1606.00840]

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



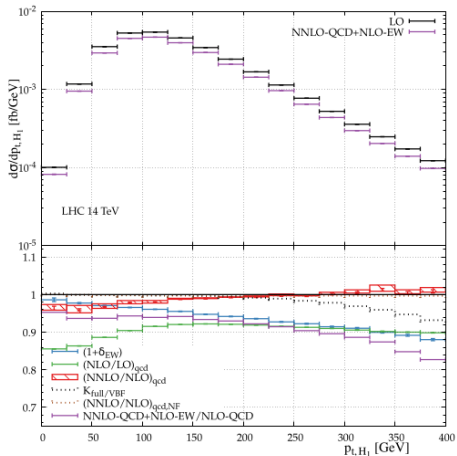
Event generators

- Accuracy: NLO QCD matched to parton shower
- YR5 contribution [Braun et al.; 2511.02488]
+ recommendations for parton shower 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)



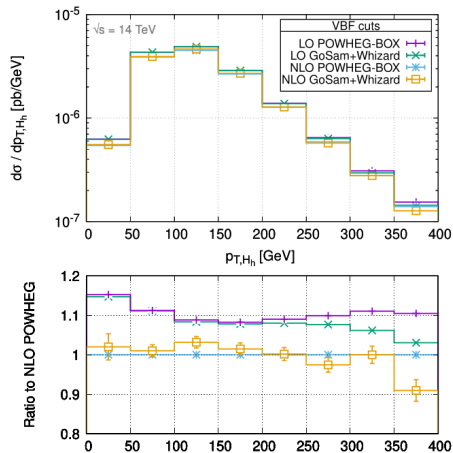
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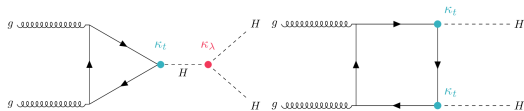
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→ Differences between full EW process
and VBF approximation

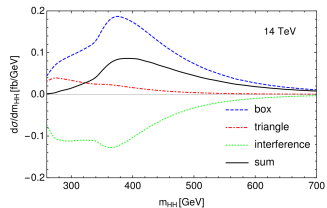
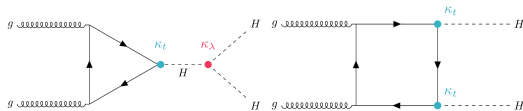
- **Beyond the Standard Model**

→ Coupling extractions ... aka the dangerous zone...

Principle

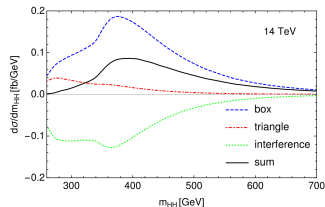
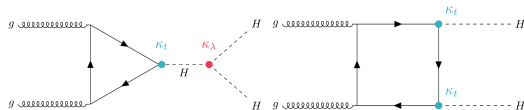


Principle



[1910.00012; Di Micco et al.]

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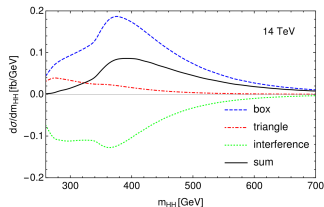
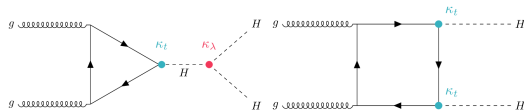


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$$\sigma = \left(\sigma_{\text{Box}} \kappa_t^4 + \sigma_{\text{Tri.}} \kappa_t^2 \kappa_\lambda^2 - |\sigma_{\text{Int}}| \kappa_t^3 \kappa_\lambda \right) \sigma_{\text{SM}}$$

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

Principle



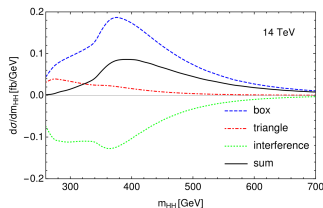
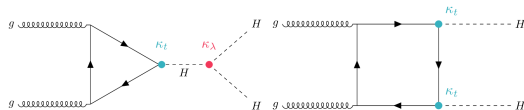
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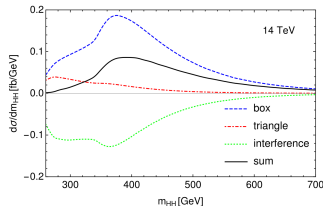
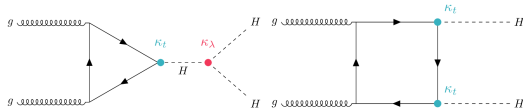
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- ⚠ Gauge invariance, potentially meaningless results!
- Better use EFT frameworks
 - Theoretically consistent
 - Typically limited accuracy

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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

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



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Discovery mode activated

High-luminosity programme of LHC upcoming

- Lot of work on both th. and exp. side
- Lot of work at the interface



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



BACK-UP