Status of the LHC
and
Standard Model physics

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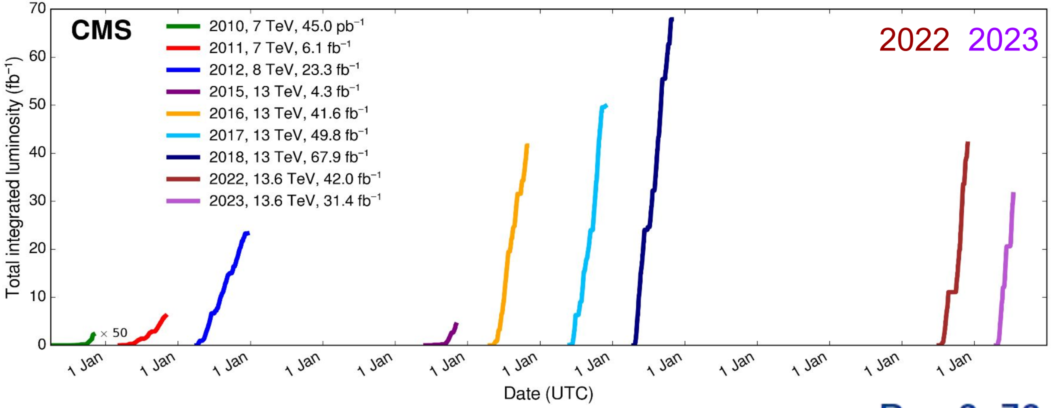
Performance of the LHC machine

- Demonstrated reliable operation with upto 6.8 TeV proton beams ($\sqrt{s}$ = 13.6 TeV)
- Reached fast the design value of instantaneous luminosity $L = 10^{34}\ \mathrm{cm^{-2}s^{-1}}$ (at ATLAS and CMS interaction points) … *and delivered collisions at a much higher rate* [eg., 2023: 3452 bunches, 1.6 $\times 10^{11}$ protons/bunch]

- 2 serious problems shortened the pp operation in 2023; data corr. to integrated lumi ($\mathcal{L}$)~ 31 $\mathrm{fb^{-1}}$.

Integrated luminosity in CMS so far



Run 1: 29 $\mathrm{fb^{-1}}$

Run 2: 164 $\mathrm{fb^{-1}}$

Run 3: 73 $\mathrm{fb^{-1}}$

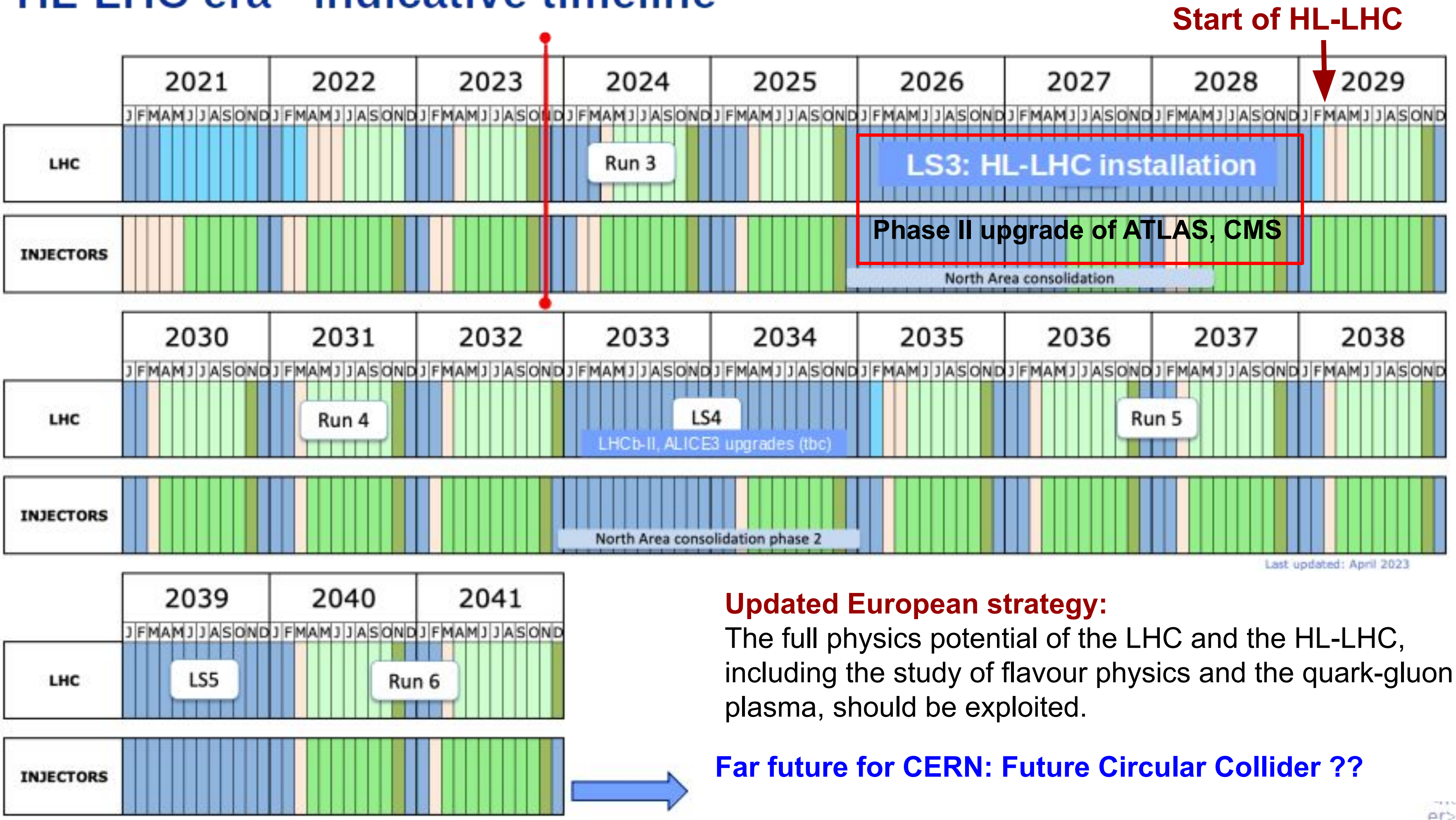
+ 2 more full years to go
Expected total ~ 200 $\mathrm{fb^{-1}}$

Heavy ion operation in 2023: $L = 10^{27}\ \mathrm{cm^{-2}s^{-1}}$
data: $\mathcal{L}$~ 2/nb

High Luminosity (HL) LHC ⇒

- Nominal $L = 5\times10^{34}\ \mathrm{cm^{-2}s^{-1}}$ ⇒ ~130 events/crossing (pile up)
- Ultimate inst. lumi: $7.5\times10^{34}\ \mathrm{cm^{-2}s^{-1}}$ (PU ~200)
- Expected total data vol. $\mathcal{L}$~ 3000 $\mathrm{fb^{-1}}$
- In preparation, experiments are being upgraded in significant way.
- *India playing significant role in the upgrade of several subsystems of CMS detector.*

HL-LHC era - indicative timeline



Updated European strategy:
The full physics potential of the LHC and the HL-LHC, including the study of flavour physics and the quark-gluon plasma, should be exploited.

Far future for CERN: Future Circular Collider ??

Next generation colliders on the plate

JHEP 01 (2020) 139

Data ⇒ significant gap between electroweak (EW) scale and the scale of New Physics (NP)
→ use precision Higgs measurements as a tool to probe NP indirectly.

1% uncertainty in Higgs properties ⇒ 1 TeV scale of NP causing such a deviation ⇒ probe 10 TeV region
→ go for exploratory hadron collider: 100 TeV FCC-hh!

- *European Strategy Group, Jan.,2020:* strengthen R&D in high-field superconducting magnets at high temp.
  → strong inclination for supporting FCC; decision in 2026.

- However in not very far future: mass-produce Higgs bosons in clean collisions (e+e- collider) ⇒ need a linear collider

Note:Higgs factory is limited by lumi: can't probe rare H decays. (Branching fractions vary over many orders of magnitude unlike for Z)

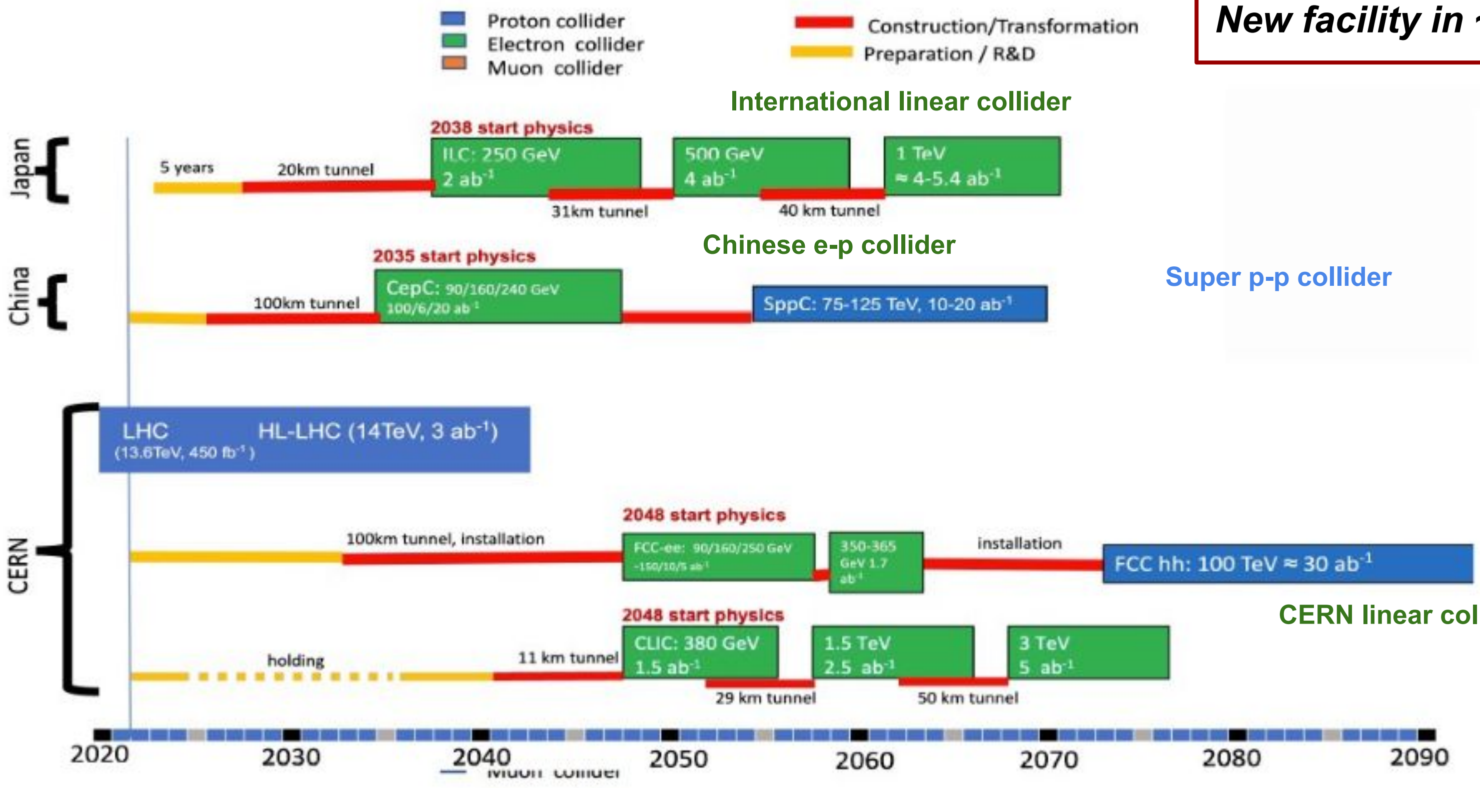
- *Japan, 2023:* increased support for addressing International Linear Collider technical issues.

- *US HEPAP recommendations ,8.12.23*: HL-LHC + off-shore Higgs factory + …

Timelines in Snowmass Energy Frontier summary

arXiv:2301.06581

New facility in ~ 1.5 decade?



International linear collider

Chinese e-p collider

Super p-p collider

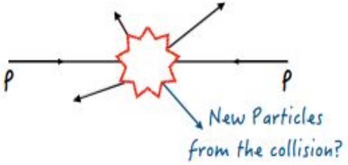
CERN linear collider

Back to present: physics performance at the LHC

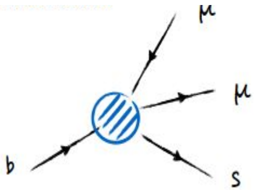
Huge amount pp collision data (~100 PB) already collected by each of the LHC experiments [ATLAS, CMS : ~ 100 paper/year]
This talk: only an effort to exemplify the span of interesting physics at the LHC under the aegis of ***Standard physics***

- Physics program encompasses searches, measurements, rare decays, and more.
- No direct evidence for physics beyond SM.
- Precision era of LHC reached very fast.

Direct search



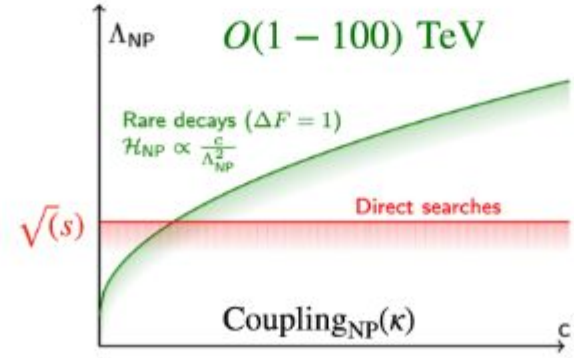
Indirect search



Strategy:

- Study processes which are suppressed / forbidden in SM.
  New Physics interactions potentially enhance the rate.
- Access higher mass scales in terms of virtual contribution.
- New physics, unreachable directly, ⇒ can effectively modify the couplings in various types of interactions

  ⇒ effective field theory (EFT) interpretation.



- Direct & indirect searches continue (including novelties)→ ***Talk by A.Nayak***

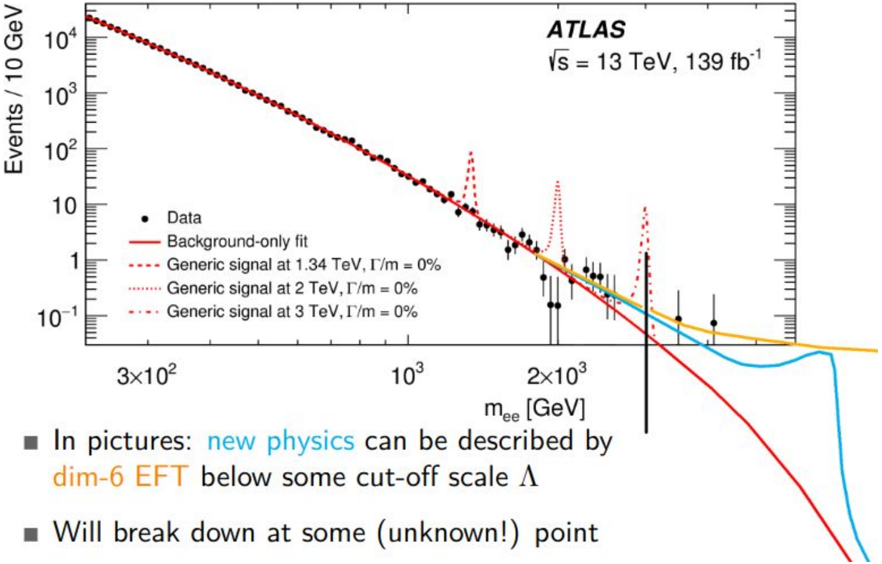
Effective field theories

- EFT describes possible pattern of deviations introduced by new physics & also constrain the deviations.
- Does not assume the SM structure of the couplings.

- Using global fit construct a sensitive but theoretically consistent framework.
- Put constraints simultaneously as many parameters as possible.

$$\mathcal{L}_{\rm Eff} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \frac{1}{\Lambda^3}\mathcal{L}_7 + \frac{1}{\Lambda^4}\mathcal{L}_8 + \cdots , \qquad \mathcal{L}_d = \sum_i c_i^{(d)} \mathcal{O}_i^{(d)}$$

$\mathcal{O}_i$: operators invariant under SM
c_i: real, dimensionless Wilson coefficients (parameters)



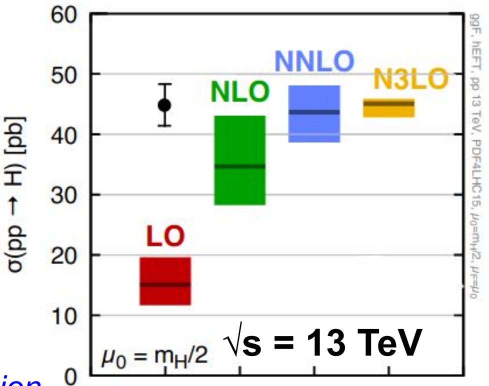
- In pictures: new physics can be described by dim-6 EFT below some cut-off scale Λ
- Will break down at some (unknown!) point

Some of the challenges at present:

- Integration of Higgs measurements in the global fit along with EW observables.
- Large no of parameters.
- Expand the range of parameter space after taking into account correlations.
- Precise predictions in SMEFT.
- Matching between different EFT models.

Collectively achieve more than anticipated!

- Diversity of efforts, based on diversity of data taking strategies ⇒ operating the ultimate multipurpose detectors performing over the expectations.
- Enormous progress in computing capabilities combined with advances in machine learning techniques.
- Precision theoretical description of the dominant SM processes.
- Extensive understanding of the performance of the experiments.

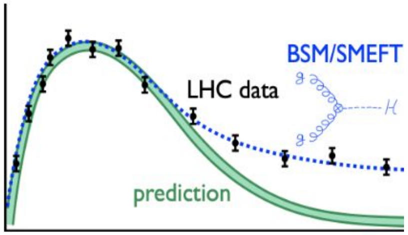


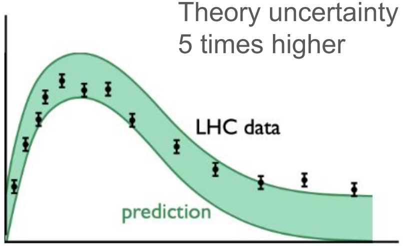
Precision in the prediction for Higgs boson production cross section

σ_{ggF} (theory) = 48.68 ± 3.9 (scales) ± 1.9 (PDF) ± 2.6(α_S) pb

- higher order quantum corrections in perturbative calc.
  i) upto next-to-next-to-next-to leading order (N3LO) of QCD coupling (α_S)
  ii) Electroweak corrections
  iii) finite quark mass effects
- PDF uncertainty
- Uncertainty due to α_S

We cannot afford to miss a discovery!



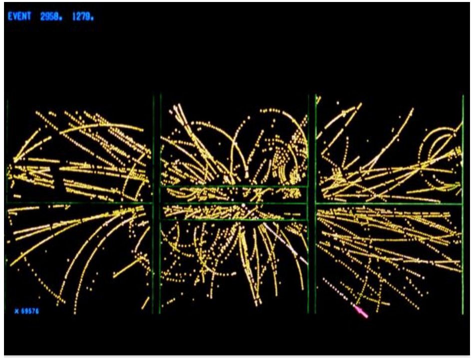


Theory uncertainty
5 times higher

Electroweak physics

Milestones reached by 2023

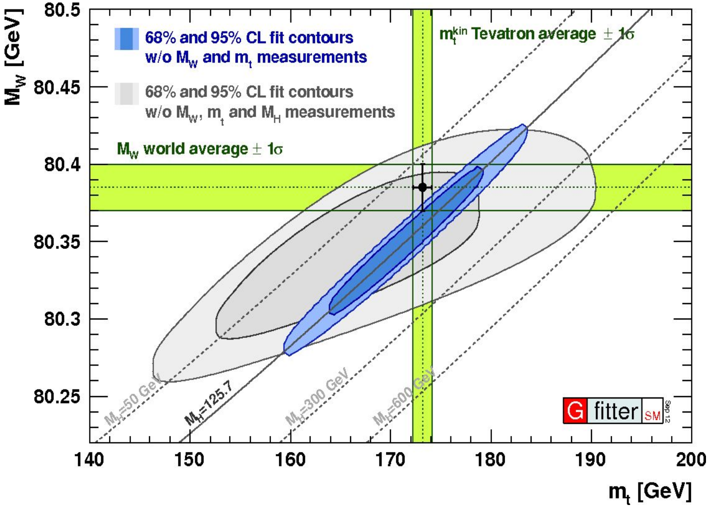
- Neutral currents: 50 yrs
- W, Z turn 40
- Top: 28
- Higgs: 11

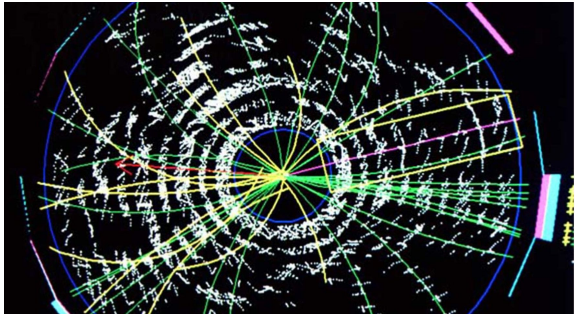


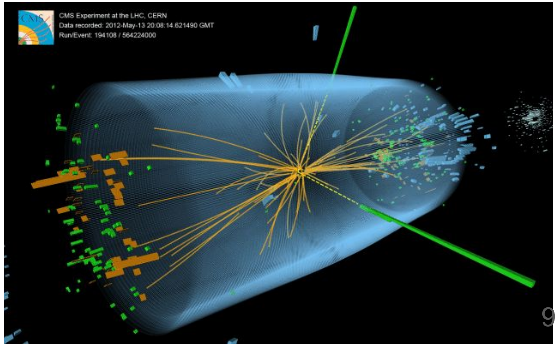
SM input parameters

- W Mass
- Top Mass
- Higgs Mass
- …

⇒ LHC measurements crucial





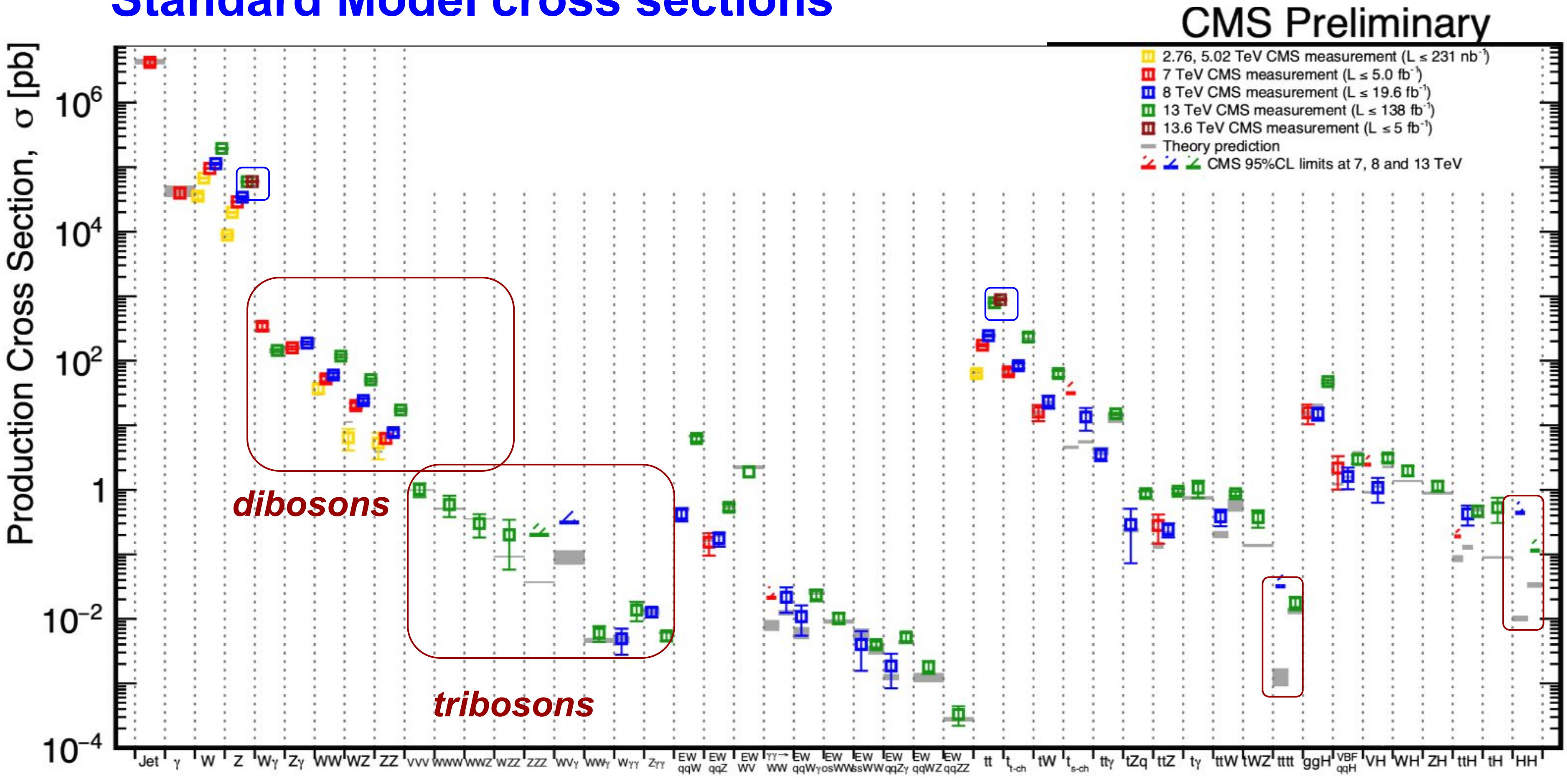


LHC unraveling in productions of

- Multi-bosons
- Four Top quarks
-

Note: more than 80 years back, D.M.Bose and Bibha Choudhary first used track counting in emulsion plates to analyse nature of cosmic ray interactions.

Standard Model cross sections

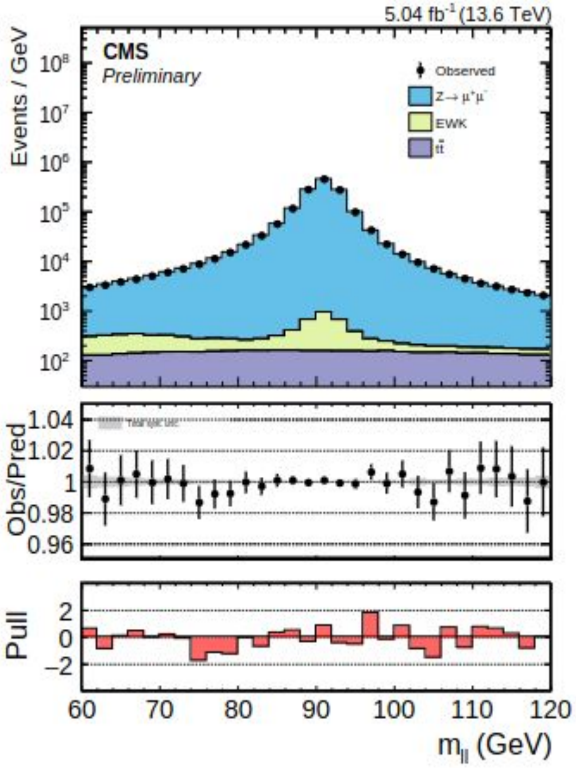


dibosons

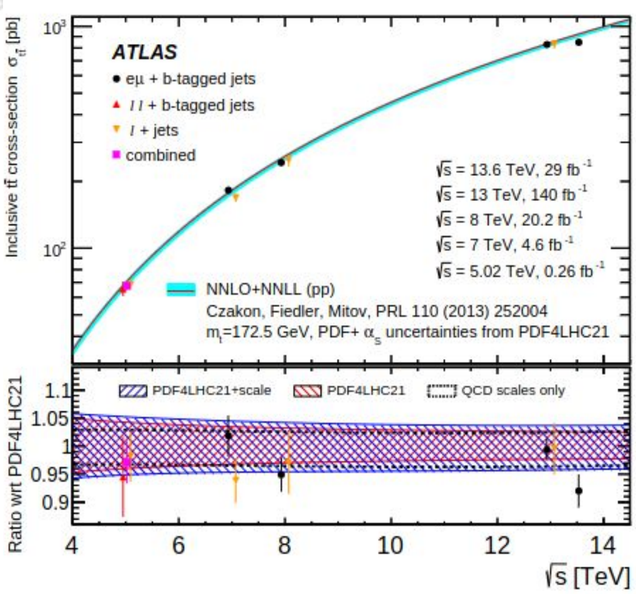
tribosons

All results at: http://cern.ch/go/pNj7

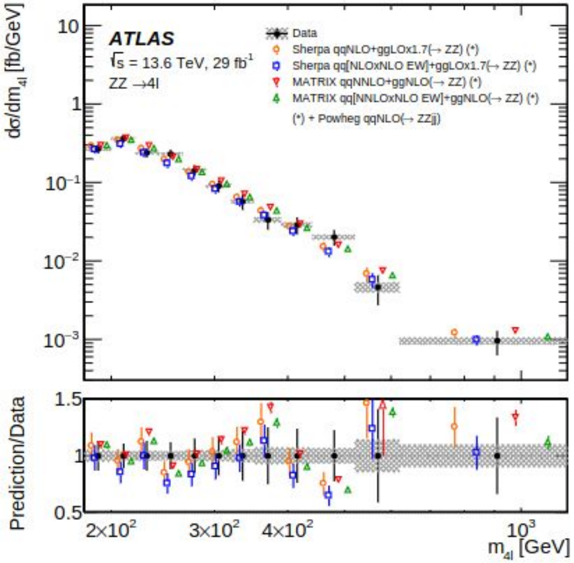
SM cross sections with Run 3 data, √s = 13.6 TeV



PAS-SMP-22-017



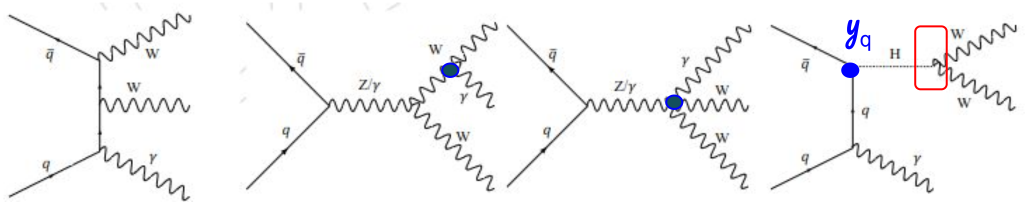
arXiv:2308.09529

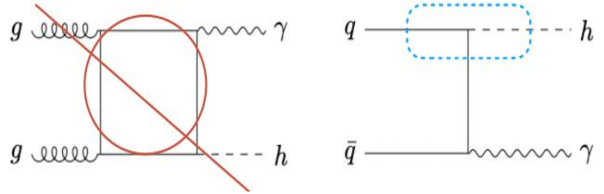


arXiv:2311.09715

Observation of WWγ and search for Hγ process

arXiv:2310.05164

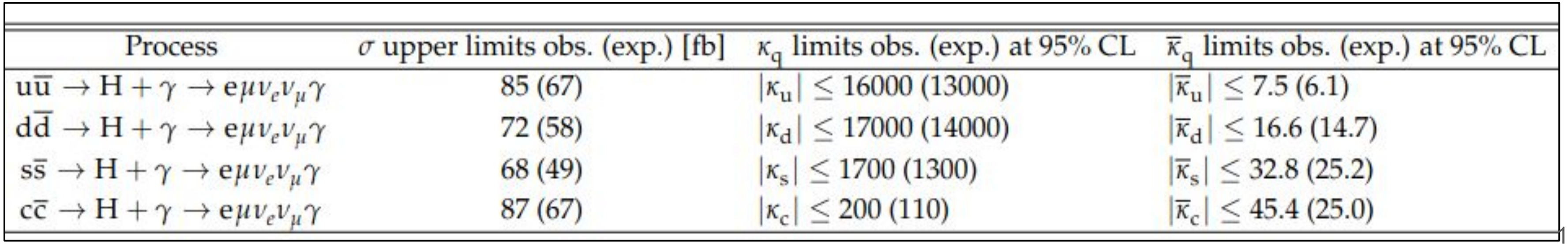




- Direct measurement of gauge boson self-couplings→ probes the non-abelian gauge structure of SM.
- Anomalous coupling between the Higgs boson and the quarks can increase the cross section at high energies.

CMS result: first observation

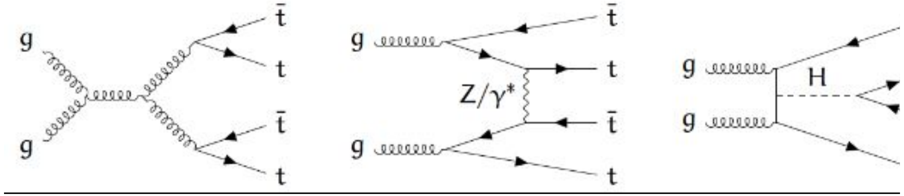
- Measured fiducial cross section for WWγ process: 6.0 ± 1.2 fb
- Upper limits for H production and derived limits on Yukawa couplings of the light quarks.
- Note recent constraint on anomalous Hcc coupling $1.1|\kappa_c|<5.5$ PRL 131 (2023) 061801



Process	σ upper limits obs. (exp.) [fb]	κ_q limits obs. (exp.) at 95% CL	$\bar{\kappa}_q$ limits obs. (exp.) at 95% CL
$u\bar{u} \to H+\gamma \to e\mu\nu_e\nu_\mu\gamma$	85 (67)	$\lvert\kappa_u\rvert \leq 16000\ (13000)$	$\lvert\bar{\kappa}_u\rvert \leq 7.5\ (6.1)$
$d\bar{d} \to H+\gamma \to e\mu\nu_e\nu_\mu\gamma$	72 (58)	$\lvert\kappa_d\rvert \leq 17000\ (14000)$	$\lvert\bar{\kappa}_d\rvert \leq 16.6\ (14.7)$
$s\bar{s} \to H+\gamma \to e\mu\nu_e\nu_\mu\gamma$	68 (49)	$\lvert\kappa_s\rvert \leq 1700\ (1300)$	$\lvert\bar{\kappa}_s\rvert \leq 32.8\ (25.2)$
$c\bar{c} \to H+\gamma \to e\mu\nu_e\nu_\mu\gamma$	87 (67)	$\lvert\kappa_c\rvert \leq 200\ (110)$	$\lvert\bar{\kappa}_c\rvert \leq 45.4\ (25.0)$

Four top quarks

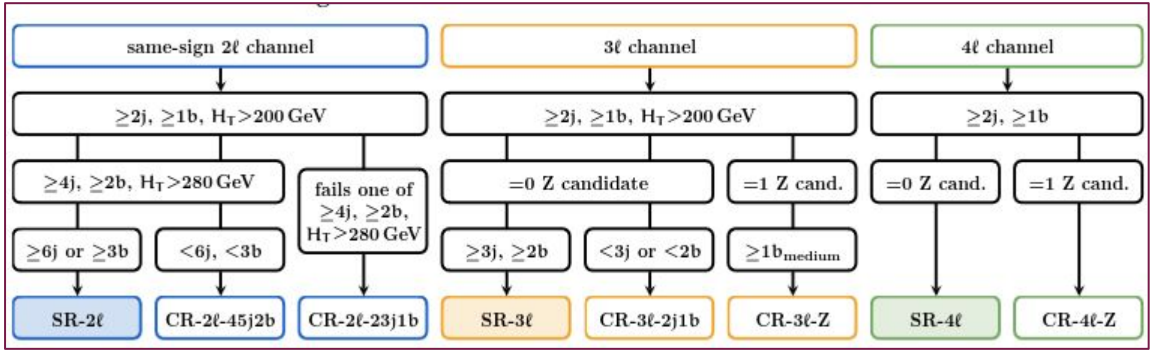
EPJC 83 (2023) 496
PLB 847 (2023) 138290



- Heaviest final state at the LHC
- Rare process: σ_{SM}~ 12 fb
- Expect about 2k events @13 TeV

- Cross section sensitive to top Yukawa coupling, its CP properties.
- Many possible BSM physics predicts enhancement: eg.,Gluino pair, scalar gluon, associated production of a heavy scalar, heavy pseudo scalar in 2HDM, compositeness, ….
- EFT: constrain on 4-fermion interactions, oblique parameters, etc.

Example of typical analysis strategy:
i) categorize events to increase signal sensitivity!
ii) Define signal and control regions (SR, CR).



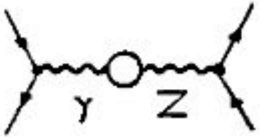
Observed (expected) significance

6.1(4.7)σ :ATLAS

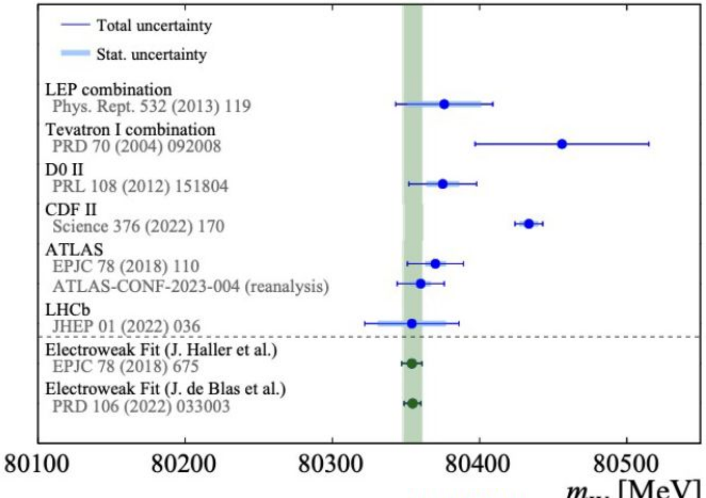
5.6 (4.9)σ: CMS

Measurement of W mass

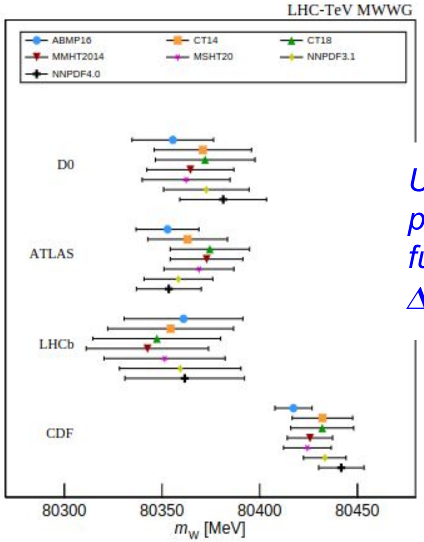
- M_W important input parameter of SM → provides sensitive test for the consistency of the model.
- Precision prediction for electroweak observables ⇒ unending efforts to reduce ΔM_W



$$\Delta r = 1 - \frac{\pi\alpha}{\sqrt{2}G_\mu}\frac{1}{M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right)}$$



- 80376 ± 33 MeV :LEP [Phys. Rep 532 (2013) 119]
- 80370 ± 19 MeV :ATLAS [EPJC 78 (2018) 110]
- 80354 ± 32 MeV : LHCb [JHEP 01 (2022) 036]
- 80443.5 ± 9.4 MeV :CDF II [Science 378 (2022) 170]



Uncertainty in parton density function:
ΔM_W ~ 5 MeV

- Average of all measurements except CDF II = 80369.2 ± 13.3 MeV
- **LHC EW WG: This average and the published CDF result considered on equal footing but statistically incompatible.**
- Future: ~ 3-4 MeV

Top quark mass

The most massive fundamental particle in SM.

Mass/Yukawa coupling is free parameter to be measured.

Abundant production at the LHC (in Run 2 ~10^8) with unique experimental signatures.

ATLAS & CMS combination using Run1 data (√s =7 and 8 TeV) uses top pair and single top productions:

m_t = 172.52 ± 0.33 [0.14 (stat), 0.33(syst)] GeV → precision of 0.18% !

ATLAS-CONF-023-066, CMS-PAS-TOP-022-001

EPJC 83 (2023) 963

Currently, **the best measurement in a single channel: m_t = 171.77 ± 0.37 GeV**

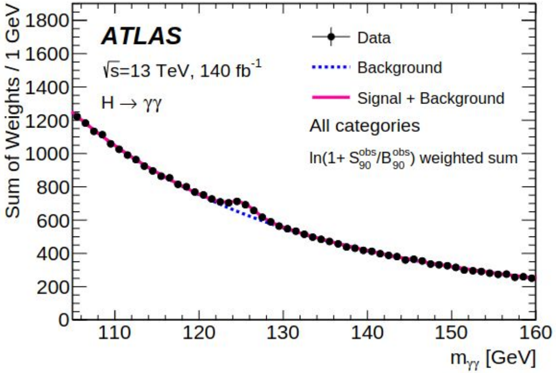
Issue: difference of ~ 0.5 GeV between direct measurement of m_t^{MC} (parameter in event generation tool) and indirect measurement from cross section corr. to m_t^{pole} (top-mass renormalization scheme in field-theory).

arXiv: 2004.01915

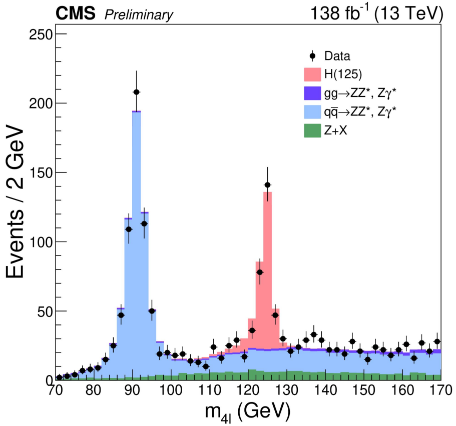
Higgs boson mass

- A free parameter in SM.
- Important ingredient for predictions of SM eg.,couplings → production and decay rates of Higgs.
- Mass best measured in high resolution channels: H → $\gamma\gamma$ and H→ ZZ* → 4ℓ.

arXiv 2308.07216, 2308.04775



CMS PAS-HIG-21-019



ATLAS

Combined Run 1 + Run 2 (4ℓ+ $\gamma\gamma$):

125.11 ± 0.11 (stat.: ± 0.09) GeV

Best to-date precision of m_H: 0.09%

CMS

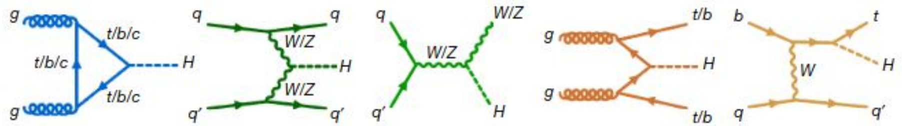
Run 2: H→4ℓ : 125.04 ± 0.12 (stat.) ± 0.05 (syst.) GeV

Best single channel measurement

Combined Run 1 + Run 2 (4ℓ+ $\gamma\gamma$): 125.08 ± 0.12 GeV (stat.: ± 0.09)

- Combination of Run1 + Run2 results still statistically limited.
- Future of Δm_H:
  HL-LHC: ~ 20 MeV arXiv:1902.00134
  ILC: ~ 14 MeV PRD103 (2021) 099903
  Fcc-ee ~ 10 MeV

Standard Model Higgs Physics



- Total no. of Higgs bosons already produced at each interaction point ~10^7
- Higgs signal strength measured with ~ 6% precision, uncertainty still dominated by statistics.

Evolution in interpretation of data for Higgs physics


Model dependence

Statistically limited

Inclusive xsec
Signal strenghts

Simplified Template Cross Sections

Fiducial Cross Sections

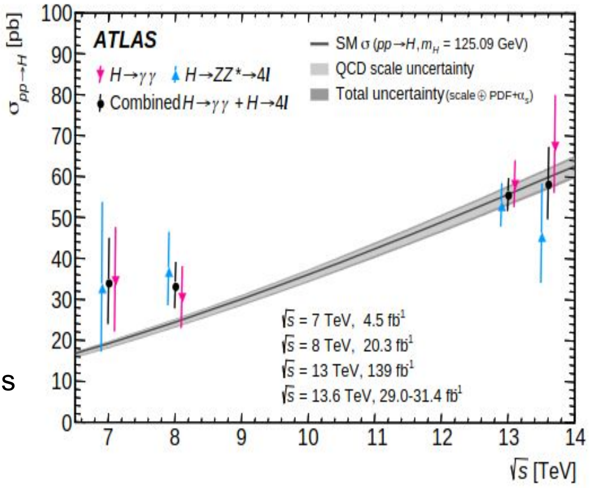
detector effects unfolded for the fiducial phase space defined at the generator level.

- Essential to establish a channel.
- But only the Higgs boson production times decay branching fraction can be studied.

more information than inclusive cross sections
→ more powerful to validate or falsify models

First round of Run 3 Higgs measurements are out!

ATLAS HIGG-2022-012



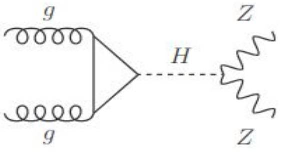
Decay width of the Higgs boson

- $\tau_H \approx 1.6 \times 10^{-22}$ sec ⇒ the natural width, $\Gamma_H = 4.14 \pm 0.02$ MeV in SM.
- Indirect estimate of Γ_H: compare on-shell and off-shell productions, assuming SM couplings and no new signal, other than possible enhancement of off-shell H contribution .

Direct measurement using the on-shell width or lifetime.

But experimental resolution: ~ 1 GeV

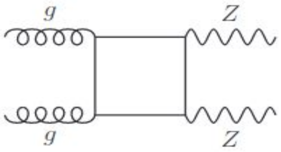
$gg \to H \to ZZ$:



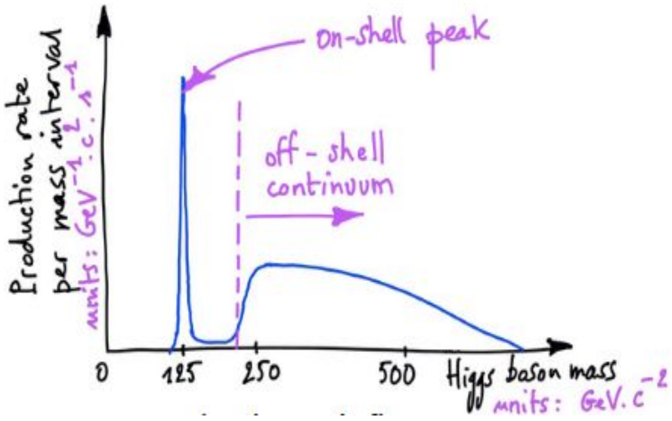
$$\sigma^{pp\to H\to ZZ}_{onshell} \sim \frac{g^2_{Hgg}\, g^2_{HZZ}}{m_H \Gamma_H} \qquad \rightarrow \qquad \frac{\sigma_{offshell}}{\sigma_{onshell}} \propto \Gamma_H$$

$$\sigma^{pp\to H\to ZZ}_{offshell} \sim \frac{g^2_{Hgg}\, g^2_{HZZ}}{M_{ZZ} - m_H}$$

$gg \to ZZ$:



- 15% of Higgs production x-sec. in HZZ is for large off-shell masses.
- Negative interference



$\Delta\Gamma_H$: ~ 20% @ HL-LHC

: 1-5% at future colliders arXiv 2209.07510

CMS: $\Gamma_H = 2.9^{+2.3}_{-1.7}$ MeV

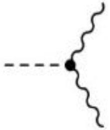
ATLAS: $\Gamma_H = 4.5^{+3.3}_{-2.5}$ MeV

CMS PAS-HIG-21-019

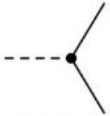
arXiv:2304.01532

Extracted value of H width consistent with SM.

Couplings of H

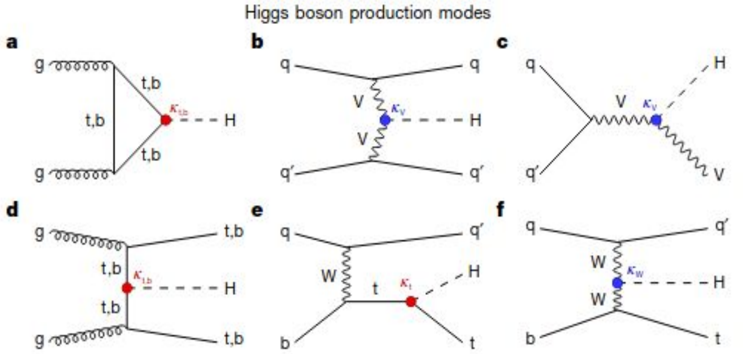


$g_V = 2\frac{m_V^2}{v}$



$g_F = \sqrt{2}\frac{m_f}{v}$

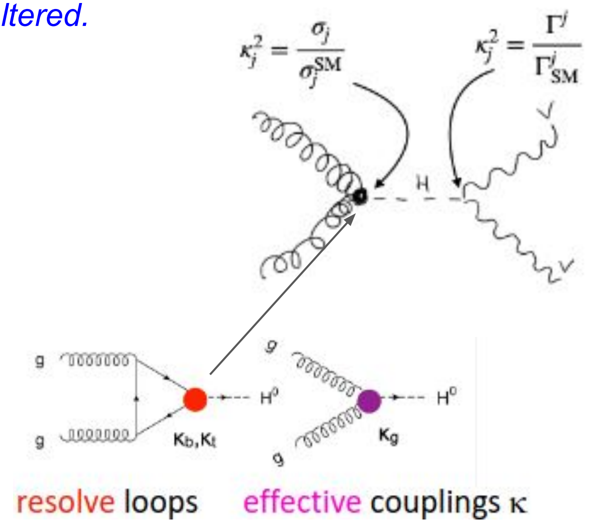
Yukawa couplings of fermions →
a new interaction of Nature

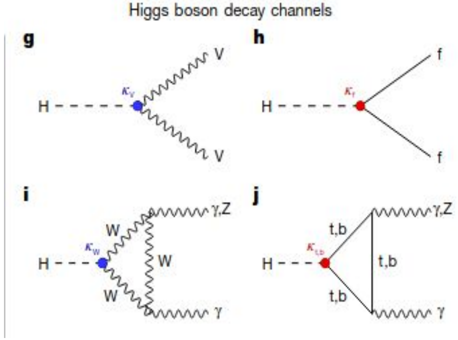


- *Current precision in measurements allows for anomalous couplings.*
- Describe possible deviations with the scale factors $\boldsymbol{\kappa}_i$
→ the cross section or the partial decay width scales with $\boldsymbol{\kappa}_i^2$ when compared to the SM prediction.
- *Assume event kinematics to be unaltered.*
- **$\boldsymbol{\kappa}$- f**ramework can accommodate any non-SM invisible or undetected component.

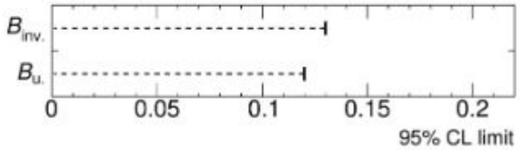
$$(\sigma_i \times B_f) = k_i^2 \sigma_i^{SM} \frac{k_f^2 \Gamma_f^{SM}}{k_H^2 \Gamma_H^{SM}}$$

- κ_i =1 → SM
- κ_i ≠1 → BSM





When upper limits on B_{inv} considered as free, $B_u \geq 0$ with $\kappa_{W,Z} \leq 1$



Reduced coupling modifiers of H to bosons and fermions

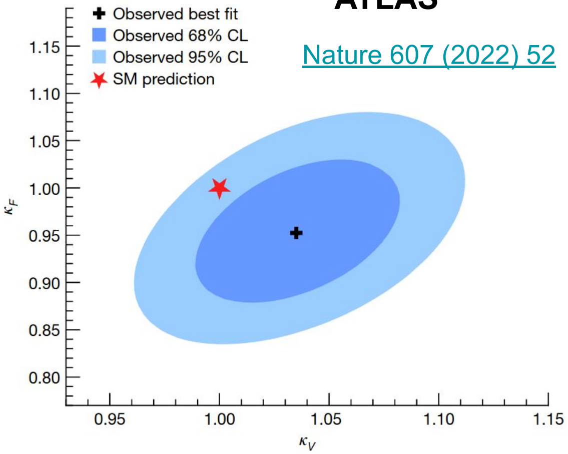
- m_H value allows variety of decays to be measured!

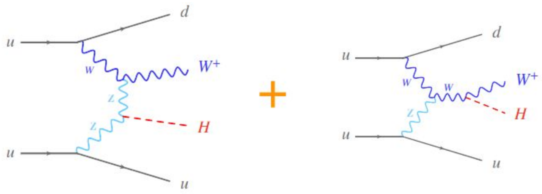
- The coupling modifier framework parametrizes the production and decay modes inclusively.

Assuming no invisible or decays to BSM particles contributing to total width.

ATLAS

Nature 607 (2022) 52

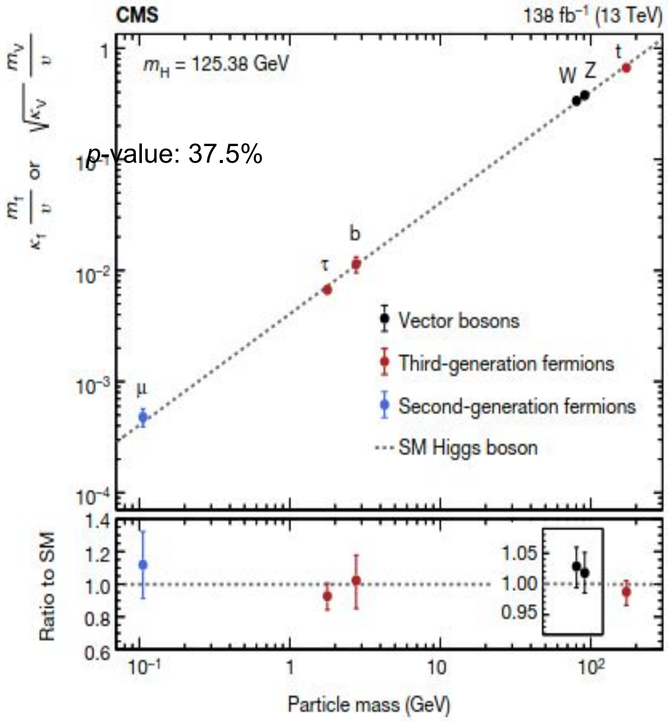




Same sign coupling of H with W and Z (κ_W and κ_Z) established with significance > 8σ

ATLAS-CONF-2023-057

Nature 607 (2022) 7917



p-value: 37.5%

Similar plot by ATLAS Collaboration

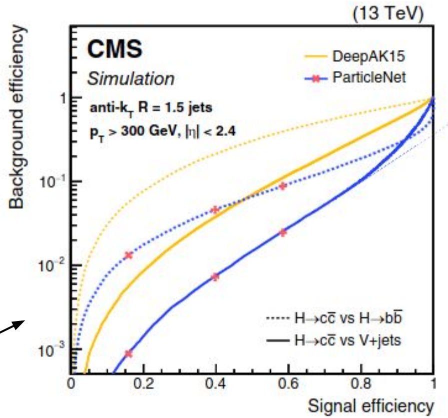
Data follows the pattern expected in SM.

H decays to 2nd generation fermions

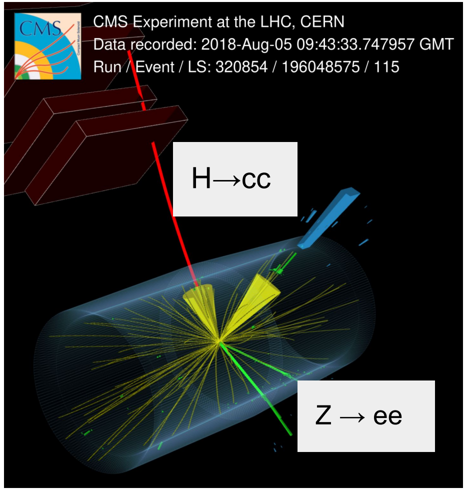
- Br(H→$\mu\mu$): ~ 0.02%
- **CMS: evidence in Run 2** JHEP 01 (2021) 148
- CMS/ATLAS observation with Run 3 data expected

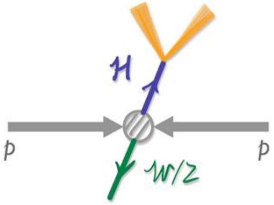
- Br(H→cc): ~ 2.9%
- CMS upper limit: gain from particle net methodology of identification of charm jets.
  Obsd. σ(VH) *Br(H→ cc) < 0.94 pb = 14.4 * SM
  PRL 131 (2023) 061801
- ILC, FCC: expect coupling uncertainty ~ 1%

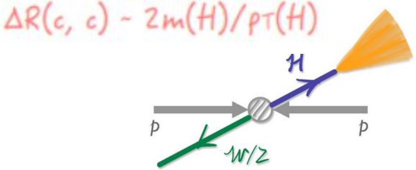
- Br(H→ss) < 10^{-3} → out of reach at (HL-)LHC.
- Best expectation from CEPC: < 3 X SM arXiv:2310.03440

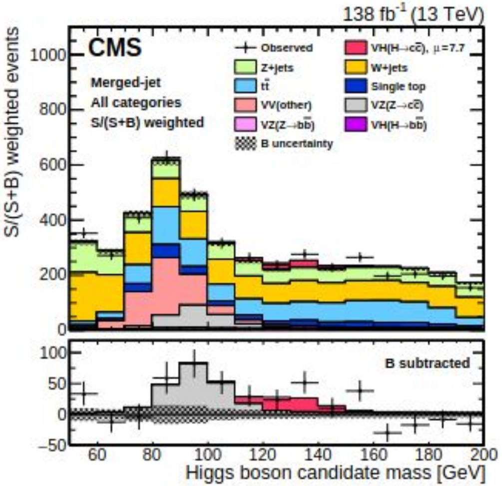


PRD 101 (2020) 056019

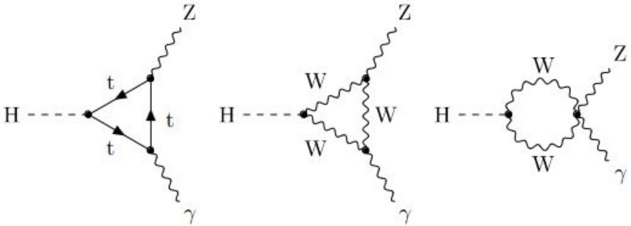








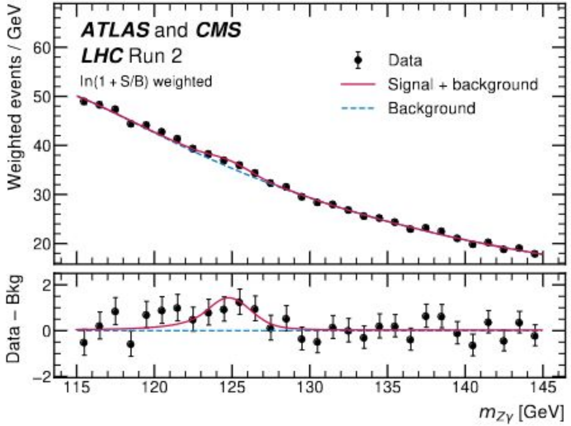
H→ Zγ

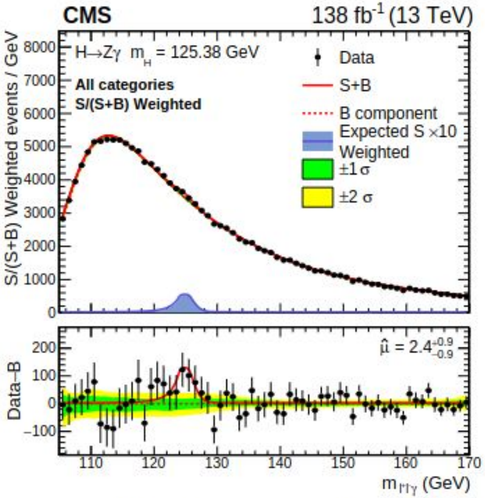


SM :
Br(H→ Zγ) = (1.54(7) ± 0.09)X 10^{-3} for m_H = 125.09 (38) GeV

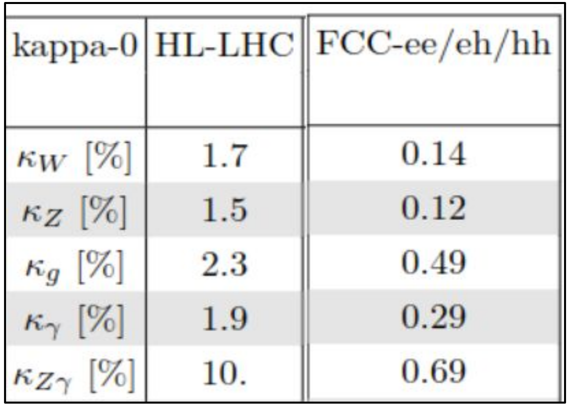
BSM particles and couplings can be present in the quantum loops.

Difference between H→Zγ and H→ $\gamma\gamma$/ZZ decay sensitive to NP.





H→ Zγ process observed:
Signal significance: 3.4σ
Signal strength: 2.2 ± 0.7,
Result within 1.9σ of SM.



kappa-0	HL-LHC	FCC-ee/eh/hh
κ_W [%]	1.7	0.14
κ_Z [%]	1.5	0.12
κ_g [%]	2.3	0.49
κ_γ [%]	1.9	0.29
$\kappa_{Z\gamma}$ [%]	10.	0.69

ATLAS+ CMS combination:arXiv:2309.03501

Self-coupling of the Higgs boson

H-potential:

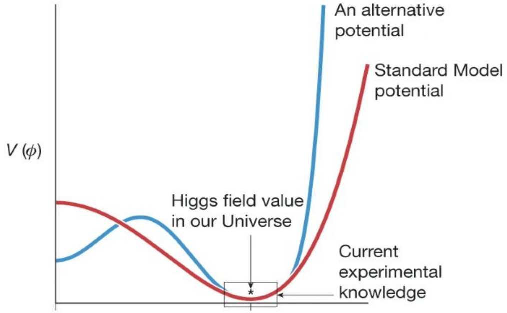
before electroweak sym. breaking: $V(\phi) = \mu^2|\phi|^2 + \lambda|\phi|^4$

$\Phi = v + h$

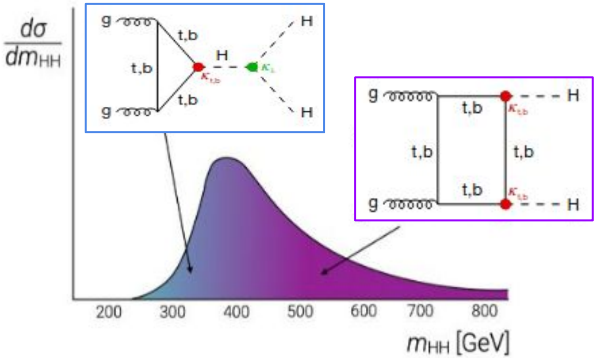
after EWSB:

$$\boxed{V(h) = \frac{1}{2}m_H^2 h^2 + \lambda_3 v h^3 + \frac{1}{4}\lambda_4 h^4, \qquad \text{with} \quad \lambda_3^{\rm SM} = \lambda_4^{\rm SM} = \frac{m_H^2}{2v^2}}$$

$\boldsymbol{\lambda}_3$ and $\boldsymbol{\lambda}_4$ *may be different in BSM*

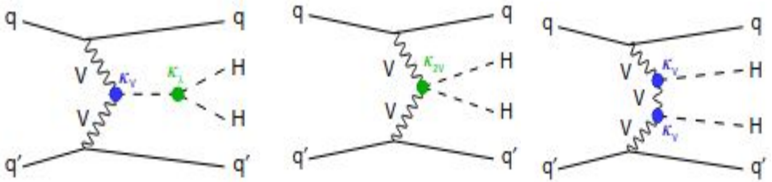


- Determination of Higgs self-coupling $\boldsymbol{\lambda}$: presently THE most important mandate to understand the nature or shape of the potential near the minimum
  → related to the evolution of the universe at the EW scale.



- Inclusive Higgs pair production at the LHC (ggF and VBF)
  → direct access to HHH and VVHH vertices → $\boldsymbol{\kappa}_{\boldsymbol{\lambda}}$, $\boldsymbol{\kappa}_{2V}$

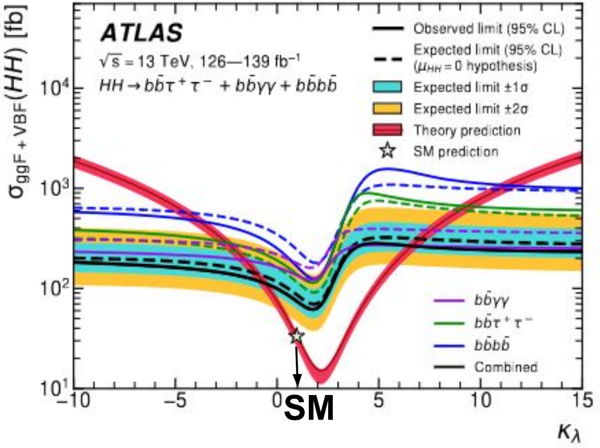
σ(pp→HH+X) ~ 31 fb ~ $1/10^3$ * σ(pp→H+X)



- Interference among relevant diagrams →cross section dependency on $\boldsymbol{\kappa}$s.

ATLAS-CONF-2022-050
Nature 607 (2022) 60-68

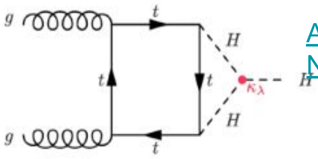
Limits on trilinear self-coupling and quartic couplings

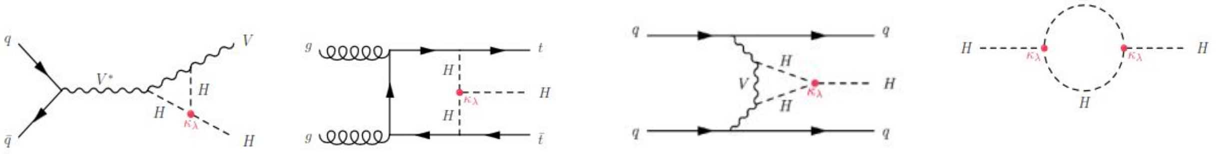


PLB 843 (2023) 137745

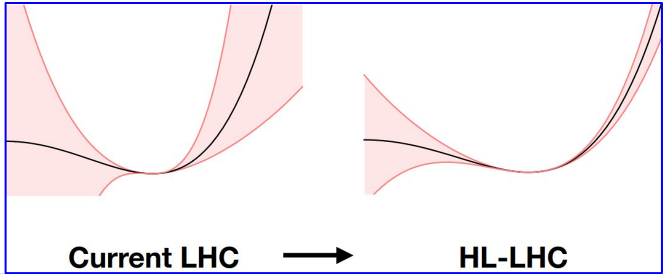
ATLAS-CONF-2022-050
Nature 607 (2022) 60-68

One-loop single Higgs production also involves κ_λ at higher orders, ⇒ better constraints on κ_λ and other couplings.



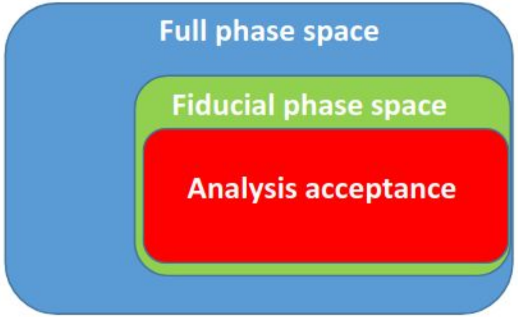


- **Observed (expected) best limit on HH cross section by ATLAS: μ_{HH} < 2.4 (2.9) * SM and $-0.4 < \kappa_\lambda < 6.3$ @95% CL**
- **κ_{2V} = 0 excluded by CMS with a 6.6σ significance.**
- **Allowed range of κ_{2V} by ATLAS: [0.1, 2.0]**



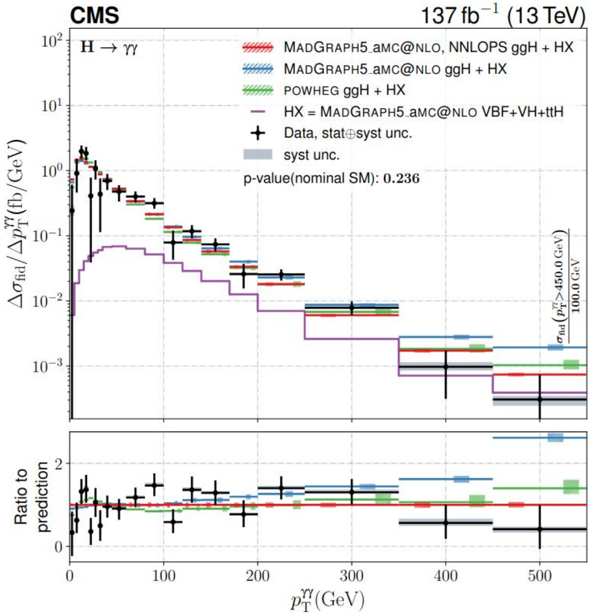
HL-LHC (Snowmass 2022) projections for SM HH:
- ATLAS γγbb & bbττ combination: 3.2σ
- CMS simple-minded combination of γγbb, γγWW, γγττ & ttHH(bbbb) assures 5σ significance observation.

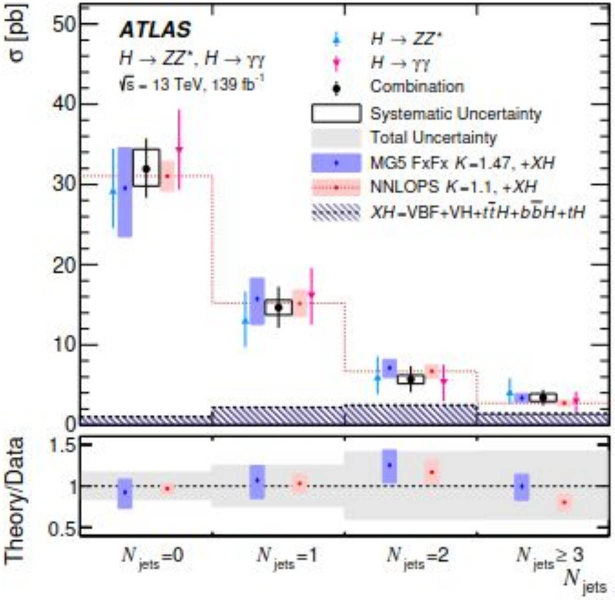
Fiducial cross section in dedicated regions of phase space


Full phase space

Fiducial phase space

Analysis acceptance





Shape of $p_T^{\gamma\gamma}$ spectrum:

i) low p_T region sensitive to light quark Yukawa couplings.

ii) high p_T region sensitive to effective coupling to gluon.

No sensitivity of p_T to HVV couplings in SM.

CMS (H →γγ)

$$\sigma_{\text{fid}} = 73.4^{+5.4}_{-5.3}\,(\text{stat})^{+2.4}_{-2.2}\,(\text{syst})\ \text{fb} = 73.4^{+6.1}_{-5.9}\ \text{fb}$$

SM prediction: 75.4 ± 4.1 fb

JHEP 05 (2023) 058
JHEP 03 (2023) 091

CP properties of the Higgs boson & effective field theory

- Higgs boson in SM is CP even: $J^{CP} = 0^{++}$
- CP-odd H complements other known sources → indication of BSM physics.
- Pure CP-odd Higgs excluded at > 99% CL by Run 1 data
- Strong theoretical motivation to search for CP-violating effects in the couplings of Higgs with fermions
- Search for CPV in the shapes of various optimal observables (rate measurement is not sensitive to CPV)
- Fermionic couplings (Hff) modelled as :

$$\boxed{\mathscr{L}_{ffH} = \kappa'_f y_f \phi \bar{\psi}_f (\cos\alpha + i\gamma_5 \sin\alpha)\psi_f}$$

→ tree-level effect prominent in 3rd generation; eg., ttH production, H→ $\tau\tau$ decay processes.

- Bosonic couplings (HVV): higher order operators suppressed by BSM scale Λ :

  → pure CPV effects in interference term

$$\boxed{\mathscr{L}_{VVH} = \mathscr{L}_{SM} + \frac{c_i}{\Lambda^2}\phi \tilde{V}_{\mu\nu} V^{\mu\nu} + \ldots}$$

PRD 108 (2023) 038013

- EFT⇒ look for "low energy" deviations of "high energy" BSM physics.

$$\mathcal{A}(\mathrm{HVV}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_1^2 + \kappa_2^{\mathrm{VV}} q_2^2}{(\Lambda_1^{\mathrm{VV}})^2}\right] m_{\mathrm{V}1}^2 \epsilon_{\mathrm{V}1}^* \epsilon_{\mathrm{V}2}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2)\mu\nu} + \boxed{a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2)\mu\nu},}$$

a_i,κ_i: to be determined from data

a_3 : CPV

f: gauge boson field strength tensors

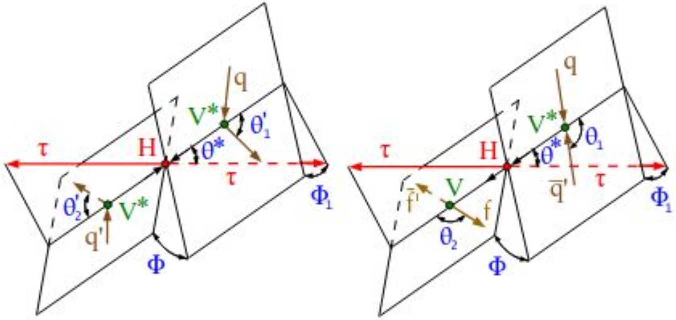
CP violation in HVV coupling using H →$\tau\tau$

PRD 28 (2023) 032013
JHEP 06 (2022) 012

- Effectively, estimate constraints on the fractional contribution of the anomalous couplings to the Higgs boson cross sections

- Effective cross sections measured in terms of ratios, like,

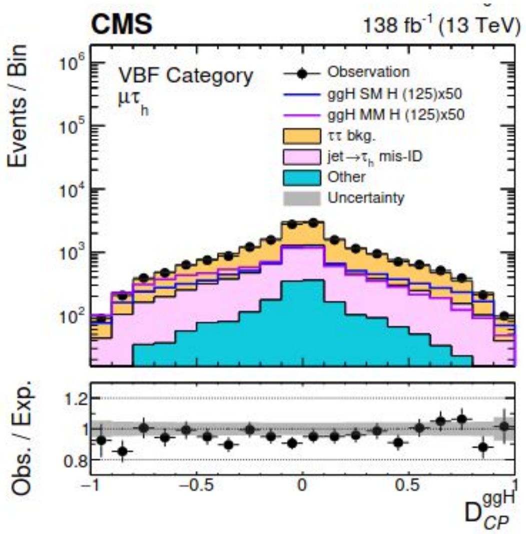
$$\boxed{f_{ai} = \frac{|a_i|^2\sigma_i}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + |\kappa_1|^2\sigma_{\Lambda 1} + |\kappa_1^{Z\gamma}|^2\sigma_{\Lambda 1}^{Z\gamma}}\,\mathrm{sgn}\left(\frac{a_i}{a_1}\right)}$$



Matrix element calculations → discriminating variables

$$\mathcal{D}_{\mathrm{BSM}} = \frac{\mathcal{P}_{\mathrm{SM}}(\vec{\Omega})}{\mathcal{P}_{\mathrm{SM}}(\vec{\Omega}) + \mathcal{P}_{\mathrm{BSM}}(\vec{\Omega})}$$

$$\boldsymbol{\Omega}^{\mathrm{assoc}} = \{\theta_1^{\mathrm{VBF}}, \theta_2^{\mathrm{VBF}}, \theta^{*\mathrm{VBF}}, \Phi^{\mathrm{VBF}}, \Phi_1^{\mathrm{VBF}}, q_1^{2,\mathrm{VBF}}, q_2^{2,\mathrm{VBF}}\}$$



Combination of H → $\tau\tau$, H→ ZZ* →4l, H→$\gamma\gamma$ ⇒ higher sensitivity towards EFT parameters.

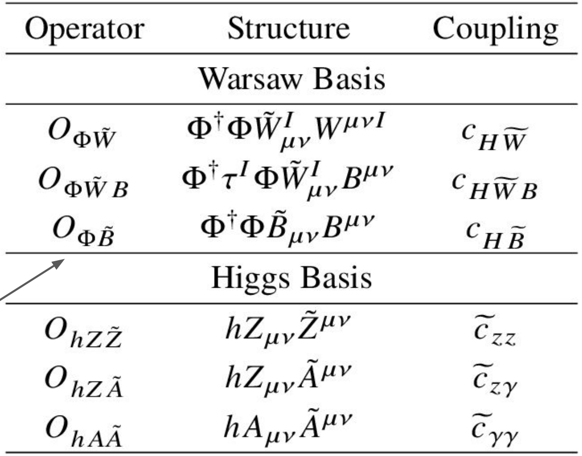
CP invariance in H→ ZZ* → 4l

SMEFT Lagrangian:

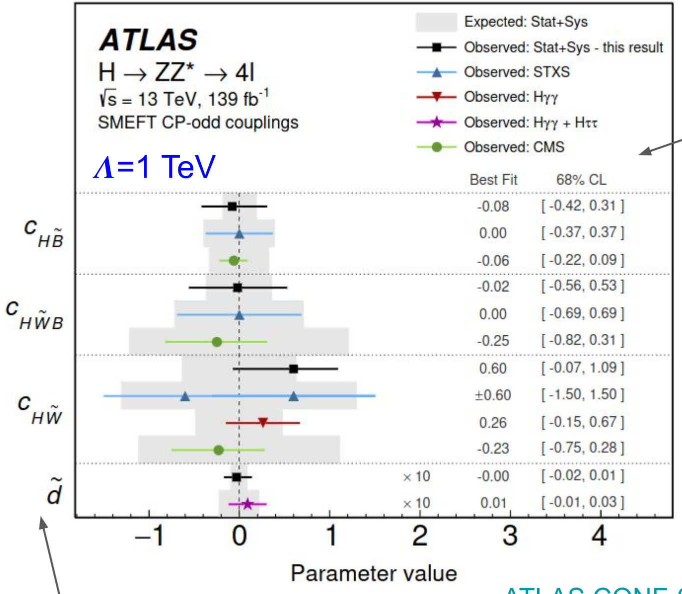
$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} O_i^{(6)}$$

$O_i^{(6)}$: CP-odd dimension-6 operators

c_i : constrain them assuming a single Higgs CP-odd BSM coupling under different assumptions.



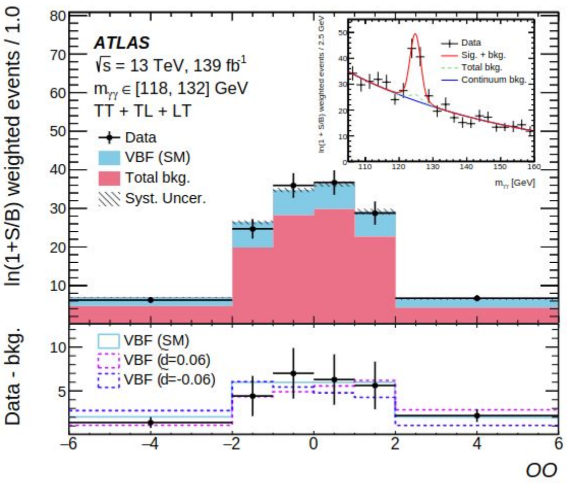
Operator	Structure	Coupling
	Warsaw Basis	
$O_{\Phi\tilde{W}}$	$\Phi^\dagger\Phi\tilde{W}^I_{\mu\nu}W^{\mu\nu I}$	$c_{H\widetilde{W}}$
$O_{\Phi\tilde{W}B}$	$\Phi^\dagger\tau^I\Phi\tilde{W}^I_{\mu\nu}B^{\mu\nu}$	$c_{H\widetilde{W}B}$
$O_{\Phi\tilde{B}}$	$\Phi^\dagger\Phi\tilde{B}_{\mu\nu}B^{\mu\nu}$	$c_{H\tilde{B}}$
	Higgs Basis	
$O_{hZ\tilde{Z}}$	$hZ_{\mu\nu}\tilde{Z}^{\mu\nu}$	$\tilde{c}_{zz}$
$O_{hZ\tilde{A}}$	$hZ_{\mu\nu}\tilde{A}^{\mu\nu}$	$\tilde{c}_{z\gamma}$
$O_{hA\tilde{A}}$	$hA_{\mu\nu}\tilde{A}^{\mu\nu}$	$\tilde{c}_{\gamma\gamma}$



- Couplings scale as $1/\Lambda^2$
- Some couplings relevant for production, some at decay, some for both.

Using H→γγ

- Optimum Observable depends on CP-odd interference term of SM and BSM amplitudes.



PRL 131 (2023) 061802

ATLAS CONF-023-057

CP-odd HVV coupling

Spin entanglement (observed at the highest energy so far)

- Spin correlation explored typically in low energy regime in various context.
- LHC: a pair of quarks available at relativistic energies.
- Top: the only “bare” quark, decays before hadronization
  ⇒ spin information transferred to decay products.

$$\underbrace{\frac{1}{m_t}}_{\substack{\text{production}\\ 10^{-27}\ \text{s}}} < \underbrace{\frac{1}{\Gamma_t}}_{\substack{\text{lifetime}\\ 10^{-25}\ \text{s}}} < \underbrace{\frac{1}{\Lambda_{\text{QCD}}}}_{\substack{\text{hadronization}\\ 10^{-24}\ \text{s}}} < \underbrace{\frac{m_t}{\Lambda^2}}_{\substack{\text{spin-flip}\\ 10^{-21}\ \text{s}}}$$

- Study two-qubit states of ttbar at production threshold (mostly singlet) with well-specified fiducial phase-space → correlated or entangled!

ATLAS-CONF-023-069

- observable dependent on the angle between the charged leptons in the rest frame of their parents.

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega_+ d\Omega_-} = \frac{1 + \mathbf{B}^+\cdot\hat{\mathbf{q}}_+ - \mathbf{B}^-\cdot\hat{\mathbf{q}}_- - \hat{\mathbf{q}}_+\cdot\mathbf{C}\cdot\hat{\mathbf{q}}_-}{(4\pi)^2}$$

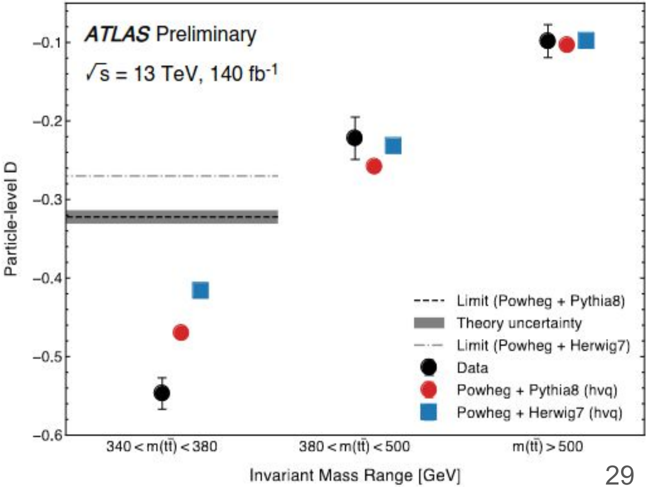
B : top polarization
$\mathbb{C}$: spin correlation matrix
Tr.[$\mathbb{C}$] < -1

$$D = \frac{\mathrm{Tr}\,[\mathbb{C}]}{3} \Rightarrow D < -\frac{1}{3}$$

Measured D= -0.547 ± 0.002 (stat) ± 0.020 (syst)

Significance more than 5σ compared to null hypothesis of no-entanglement

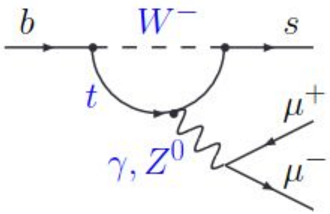
CMS: similar result PAS-TOP-23-001



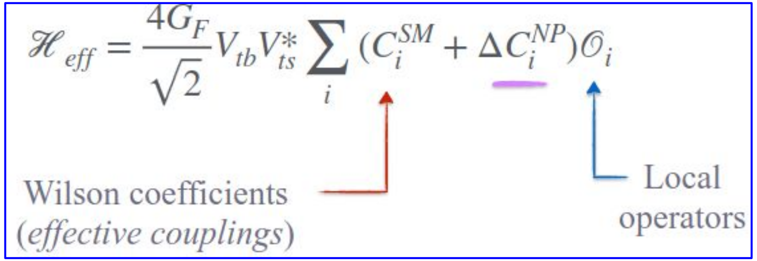
Amplitude analysis of $B^0 \to K^{*0}\mu^+\mu^-$ decays at LHCb

LHCb-2023-032

- Last few years: several anomalies in various measurements in heavy flavour sector (quark transitions observed in B hadron decays).
- Main issue: lower rate for $b \to s\,\mu^+\mu^-$ in decays of B_s, B^0, B^+



- Interpretation not straightforward due to hadronic uncertainties in SM predictions (form-factors, decay constant etc.).
- Also non-perturbative effects. Including long-distance charm loops.



$$\mathcal{H}_{eff} = \frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^{*} \sum_i (C_i^{SM} + \Delta C_i^{NP})\mathcal{O}_i$$

Wilson coefficients (*effective couplings*)

Local operators

$$\mathcal{O}_{7\gamma} = \frac{e}{16\pi^2} m_b \bar{b}_R^{\alpha} \sigma^{\mu\nu} F_{\mu\nu} s_L^{\alpha}\,, \qquad \textit{photon}$$

$$\mathcal{O}_{9V} = \frac{1}{2} \bar{b}_L^{\alpha} \gamma^{\mu} s_L^{\alpha} \bar{\ell} \gamma_{\mu} \ell\,, \qquad \textit{vector}$$

$$\mathcal{O}_{10A} = \frac{1}{2} \bar{b}_L^{\alpha} \gamma^{\mu} s_L^{\alpha} \bar{\ell} \gamma_{\mu} \gamma_5 \ell\,, \qquad \textit{axial-vector}$$

- First q^2-unbinned (model-dependent fit) amplitude analysis of $B^0 \to K^{*0}\mu^+\mu^-$
- Estimation of non-local hadronic contributions (incl.charm loop) from data (with certain assumptions).
- **Result consistent with anomalies observed in $b \to s\,\mu^+\mu^-$ studies:**

  1.8σ in C_9 and 1.4σ global deviation in data from SM.

Conclusion

- In the first 12 years since the start up, the LHC machine has operated beyond expectation.
- Though it has delivered only a few percent of the total data volume expected in the next 2 decades, a plethora of interesting physics results, beyond expectation has been derived already.
- The measurements, within uncertainties, indicate that the standard model is doing well in the TeV energy scale.
- There is no significant indication in data about physics of higher energy scale.
- Presented only a small (and with personal bias) sample of recent experimental results to showcase the vast expanse of extremely interesting *standard physics at the LHC*.

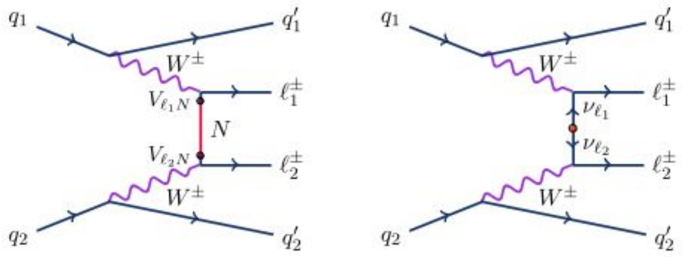
Stay tuned with LHC physics!

Thank you

Backup

Vector boson fusion process: novel tool for BSM search

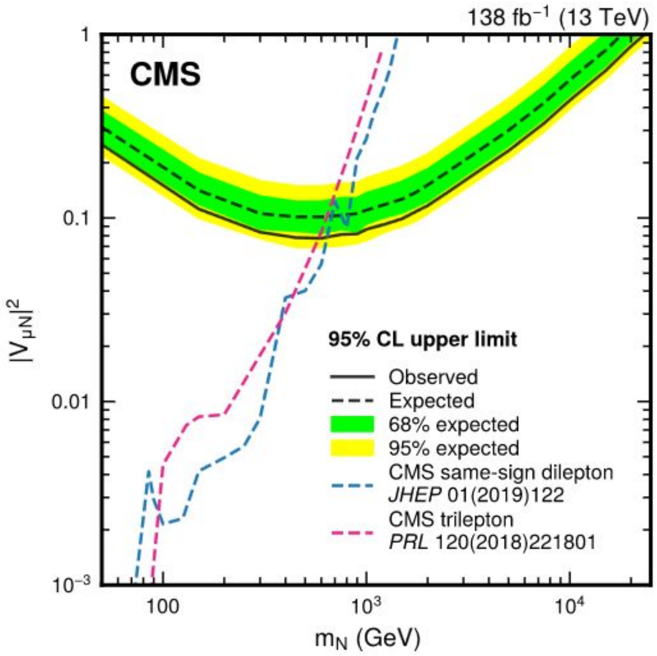
PRL 131 (2023) 011803



- Same sign dilepton in central region of detector in VBF-like event topology
  ==> lepton number violation

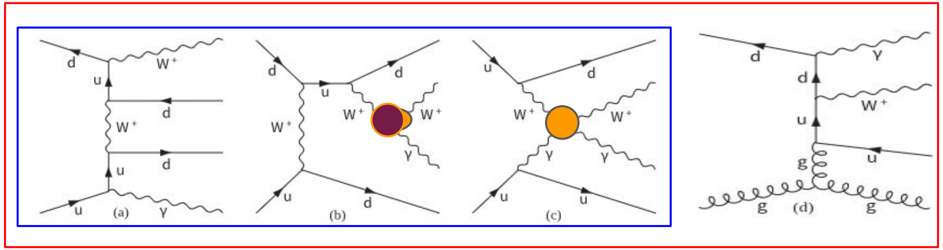
i) Heavy, Majorana neutrino (N) production

ii) Process mediated by Weinberg operator (dim-5) with flavour-dependent coefficients



- **Best limit on mixing element $|V_{mN}|^2$so far: m_N > 650 GeV**
- **Effective Majorana mass associated with W-operator excluded : 10.8 GeV**

Electroweak production of di/tribosons $W\gamma$, $W\gamma\gamma$

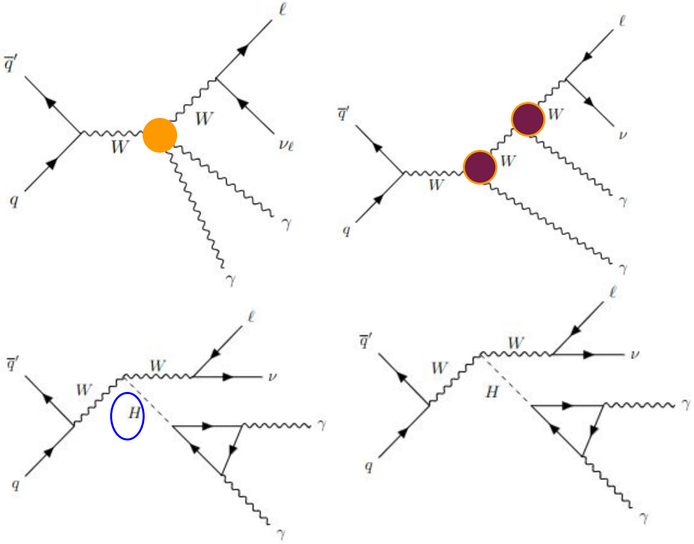


EW: 23.5 fb

total: 103 fb

- First observation of $W\gamma$ at 13 TeV
- Anomalous aTGC, aQGC couplings →access to dim-8 operators

PRD 108 (2023) 032017

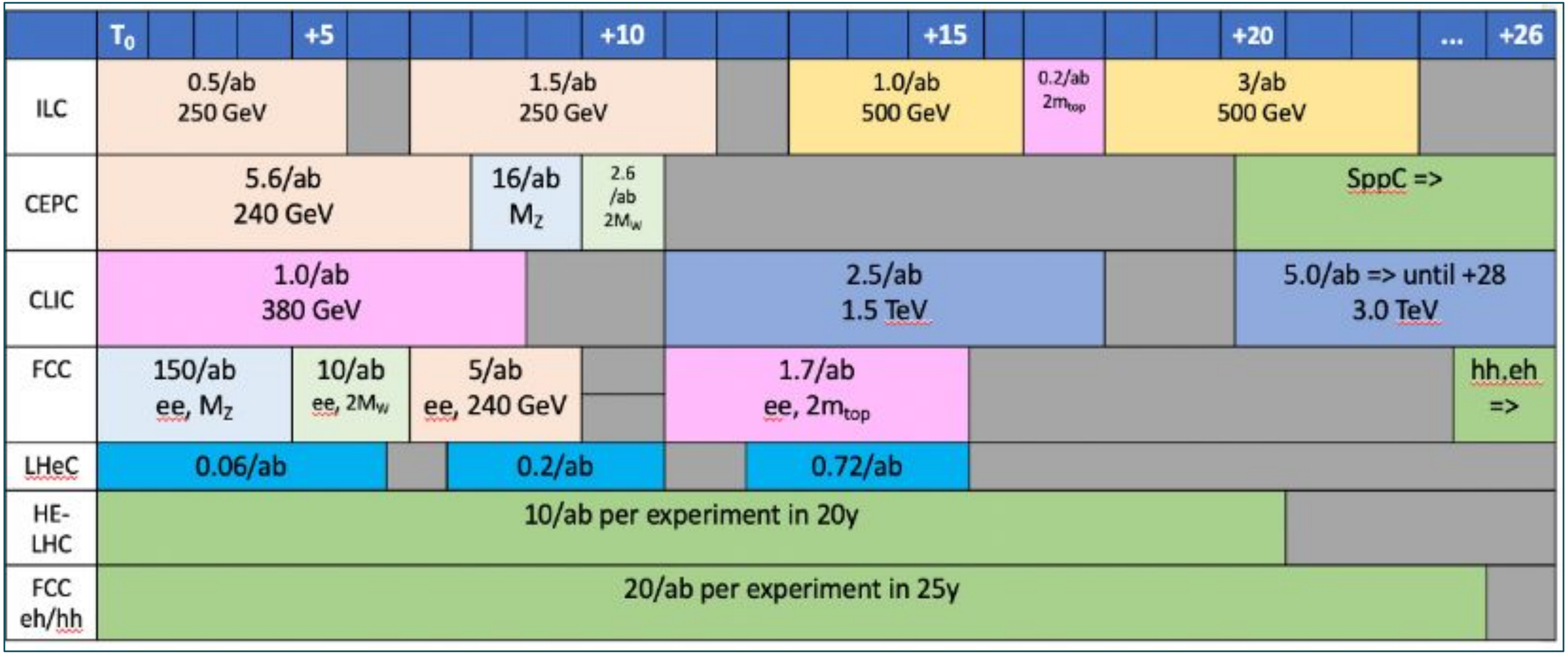


- $W\gamma\gamma$ process: 5.6 σ observation
- Muon channel rate: ~ 12.2 ± 2 fb

All measurements match SM

ATLAS-CONF-2023-005

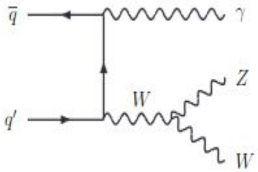
Projected data volume in future colliders

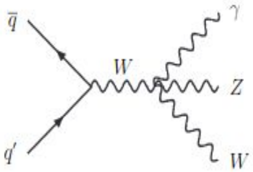


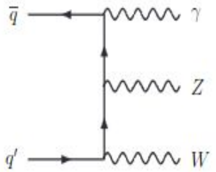
<table>
<tr><th></th><th>T_0</th><th></th><th></th><th></th><th>+5</th><th></th><th></th><th></th><th></th><th>+10</th><th></th><th></th><th></th><th></th><th>+15</th><th></th><th></th><th></th><th></th><th>+20</th><th></th><th></th><th>...</th><th>+26</th></tr>
<tr><td>ILC</td><td colspan="5">0.5/ab
250 GeV</td><td></td><td colspan="5">1.5/ab
250 GeV</td><td></td><td colspan="4">1.0/ab
500 GeV</td><td>0.2/ab
$2m_{top}$</td><td colspan="5">3/ab
500 GeV</td><td colspan="2"></td></tr>
<tr><td>CEPC</td><td colspan="7">5.6/ab
240 GeV</td><td colspan="2">16/ab
M_Z</td><td>2.6
/ab
$2M_W$</td><td colspan="9"></td><td colspan="5">SppC =></td></tr>
<tr><td>CLIC</td><td colspan="8">1.0/ab
380 GeV</td><td colspan="2"></td><td colspan="7">2.5/ab
1.5 TeV</td><td colspan="2"></td><td colspan="5">5.0/ab => until +28
3.0 TeV</td></tr>
<tr><td>FCC</td><td colspan="4">150/ab
ee, M_Z</td><td colspan="2">10/ab
ee, $2M_W$</td><td colspan="3">5/ab
ee, 240 GeV</td><td></td><td colspan="5">1.7/ab
ee, $2m_{top}$</td><td colspan="7"></td><td colspan="2">hh,eh
=></td></tr>
<tr><td>LHeC</td><td colspan="5">0.06/ab</td><td></td><td colspan="4">0.2/ab</td><td colspan="2"></td><td colspan="3">0.72/ab</td><td colspan="9"></td></tr>
<tr><td>HE-LHC</td><td colspan="20">10/ab per experiment in 20y</td><td colspan="4"></td></tr>
<tr><td>FCC eh/hh</td><td colspan="23">20/ab per experiment in 25y</td><td></td></tr>
</table>

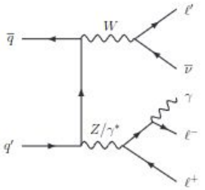
WZgamma observation

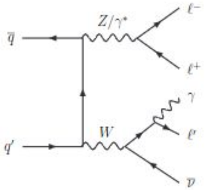
ATLAS:2305.16994











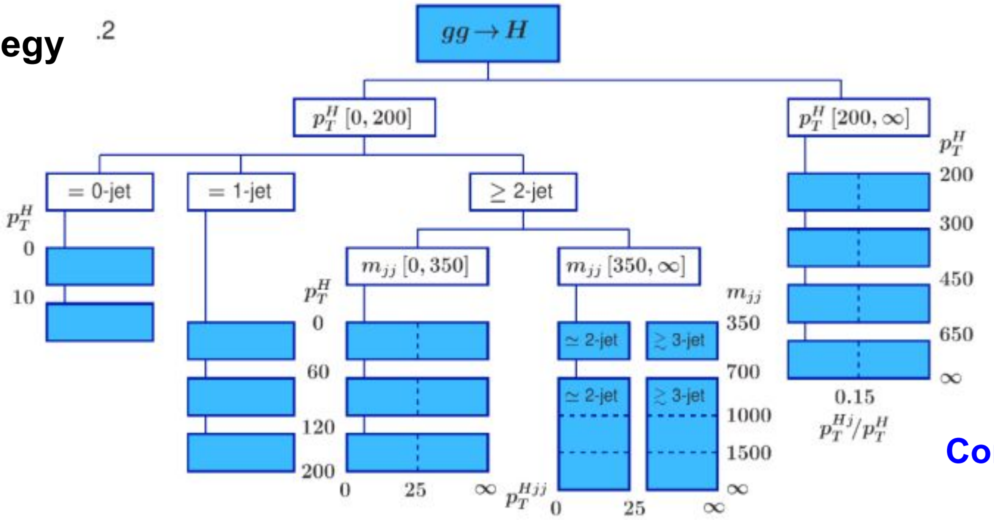
Triple, quartic gauge boson vertices

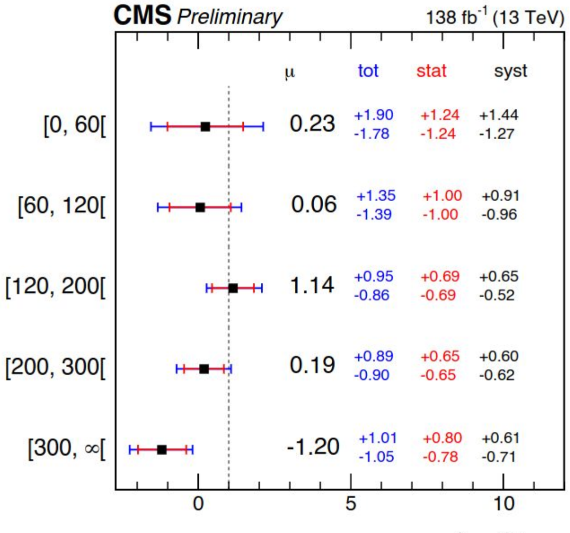
Fiducial cross section measured with 6 sd significance: 2 fb (SM expected ~ 1.5 fb, 5 sd)

Simplified template cross section: STXS

- Cross sections for each production mode with specific final states, in bins of kinematic variables (eg. p_T^H, N_{jets}, m_{jj}) in exclusive regions of phase space. Specific bins have increased sensitivity to BSM.
- Granular measurement of the cross section for each production mode → allows kinematics-dependent interpretations.
- Provide a common set of definitions for the combination of the measurements → inclusive over the Higgs decays
- Analyses presently most sensitive to ggH.

strategy .2





$\hat{\mu} = \hat{\sigma}/\sigma_{SM}$

Consistent with SM within 1.3σ

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Statistical treatment

The combined results are obtained from a likelihood function defined as the product of the likelihoods of each input measurement.

The observed yield in each category of reconstructed events follows a Poisson distribution the parameter of which is the sum of the expected signal and background contributions.

The number of signal events in any category *k* is split into the different production and decay modes:

$$n_k^{\text{signal}} = \mathcal{L}_k \sum_i \sum_f (\sigma_i B_f)(A\epsilon)_{if}^k$$

the sum indexed by *i* runs either over the production processes (ggF, VBF, *WH*, *ZH*, tt*H*, *tH*) or over the set of the measured production kinematic regions, and the sum indexed by *f* runs over the decay final states (*ZZ*, *WW*, $\gamma\gamma$, $Z\gamma$, bb, cc, $\tau^+\tau^-$, $\mu^+\mu^-$).

$\mathcal{L}_k$ *:* integrated luminosity of the dataset used in category *k.*

$(A\epsilon)^k_i$ *:* acceptance times selection efficiency factor for production process *i* and decay mode *f* in category *k*.