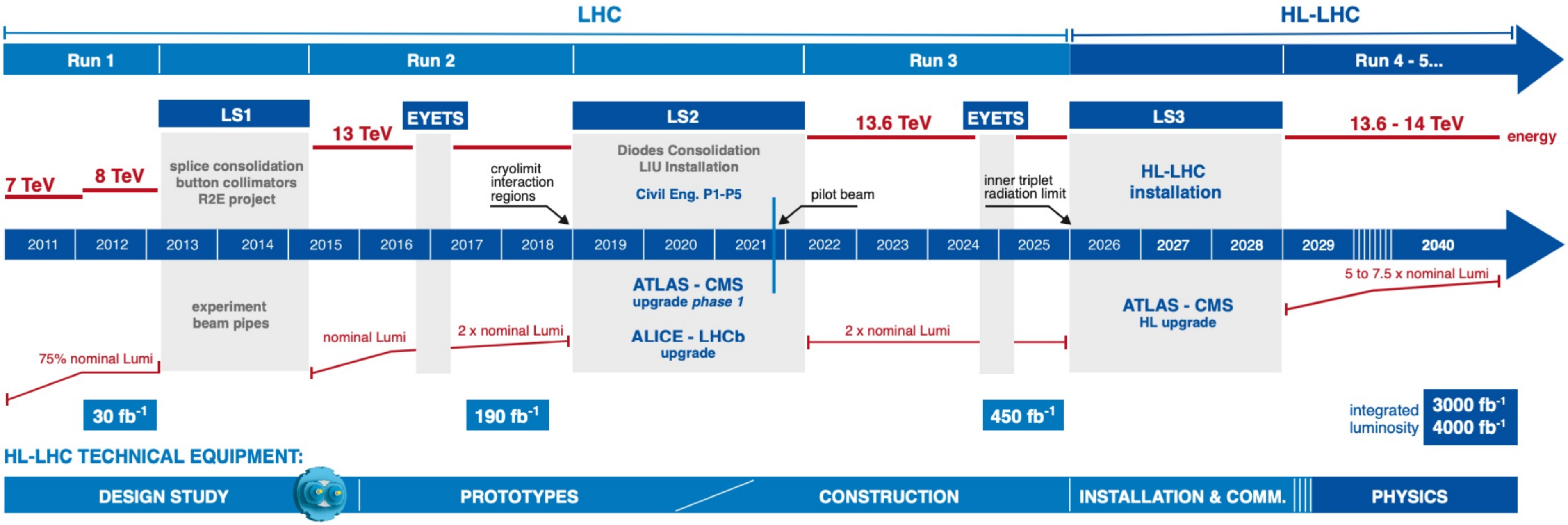
Standard Model Precision Tests in ATLAS and CMS experiments:

Higgs, Electroweak and Top physics

Tongguang Cheng (Beihang University)

北京航空航天大學
BEIHANG UNIVERSITY

LHC data taking plan : overview



Data taking : plan for Run-3

Run 3 luminosity targets

Indicative!

Mode	GPDs	LHCb	ALICE
p-p	250/fb	25 - 30/fb (~50/fb by LS4)	200/pb
Pb-Pb	7/nb (13/nb by LS4)	1/nb (2/nb by LS4)	7/nb (13/nb by LS4)
p-Pb	0.5/pb (~1/pb by LS4)	0.1/pb (~0.2/pb by LS4)	0.25/pb (~0.5/pb by LS4)
O-O	0.5/nb	0.5/nb	0.5/nb
p-O	LHCf 1.5/nb	2/nb	

Experiments also require HI reference pp data at 5.x TeV

Updated January 2022 (Run 3: 2022 - 2025)

Data taking : status and plan for Run-3

Option 1:

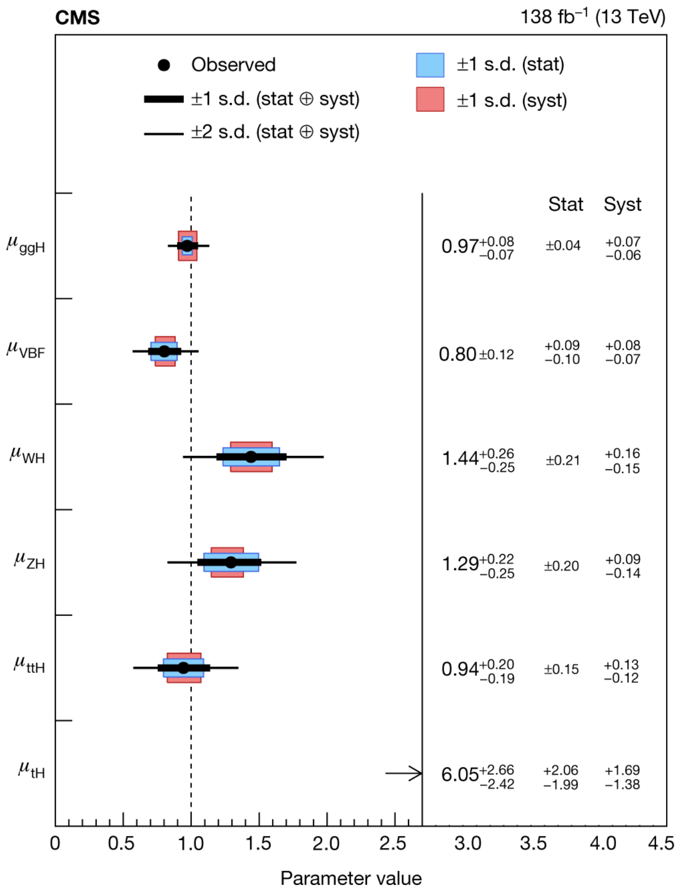
2024:	pp (115d):	83 fb^{-1}
	ion (18d):	1.9 nb^{-1}
2025:	pp (145d):	107 fb^{-1}
	ion (15d):	1.45 nb^{-1}
Total 24+25:	pp (260d):	190 fb^{-1}
	ion (33d):	3.35 nb^{-1}
[2022+2023:	pp (119d):	72 fb^{-1}]
	ion (32d):	2 nb^{-1}]
Total Run 3:	pp (379d) :	262 fb^{-1}
	ion (75d):	5.35 nb^{-1}

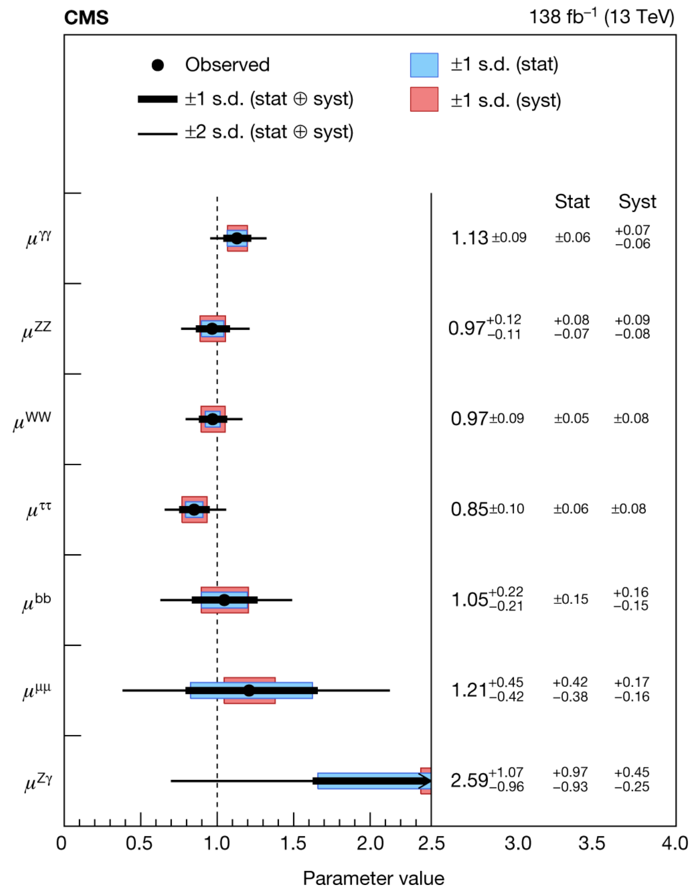
Outlines

- ❑ Higgs :
  - ❑ (Anomalous) Higgs couplings and CP structures
  - ❑ Higgs potential
- ❑ Electroweak :

  di-boson and tri-boson processes
- ❑ Top physics :
  - ❑ Top cross sections and EFT
  - ❑ Entanglement in ttbar

Higgs turns more than 10

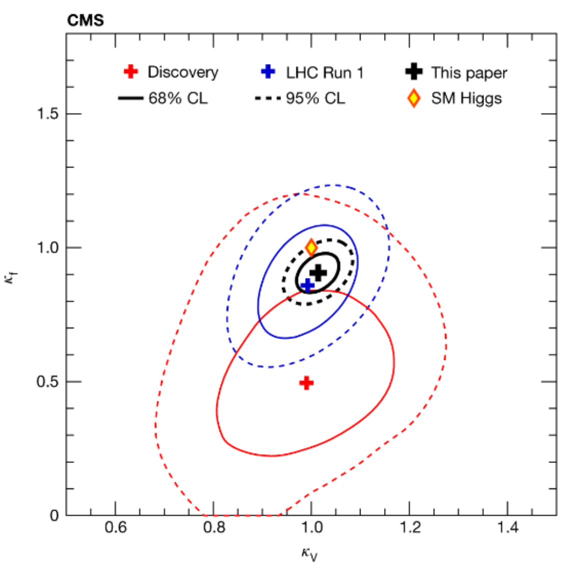


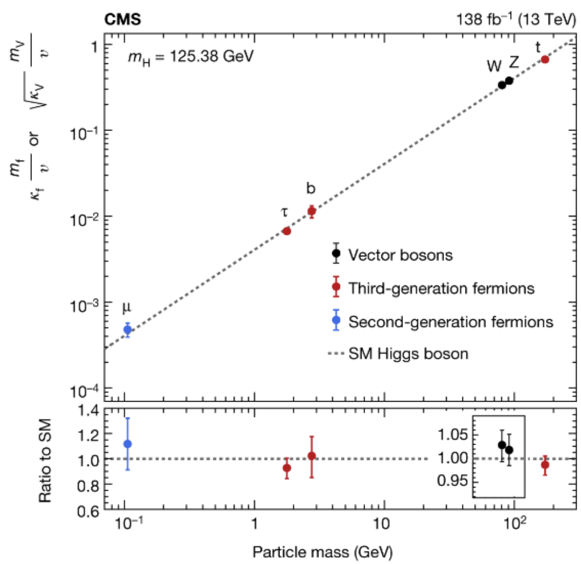


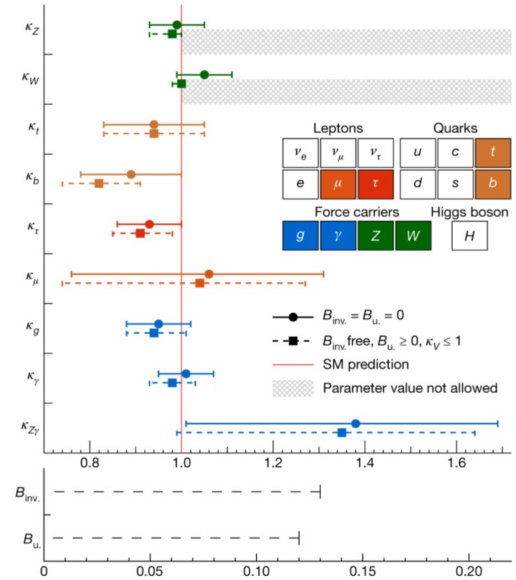
ATLAS: Nature 607, pages 52-59 (2022)
CMS: Nature 607 (2022) 60

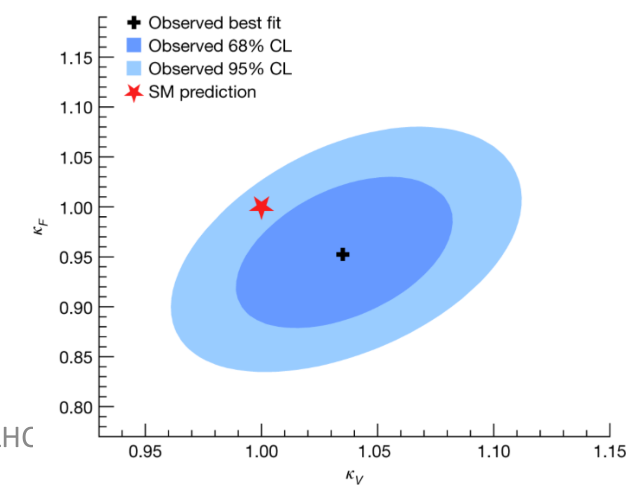
From signal strengths to κ-framework

Now we are able to study detailed structures on the Higgs couplings (not only the rate/signal strength)





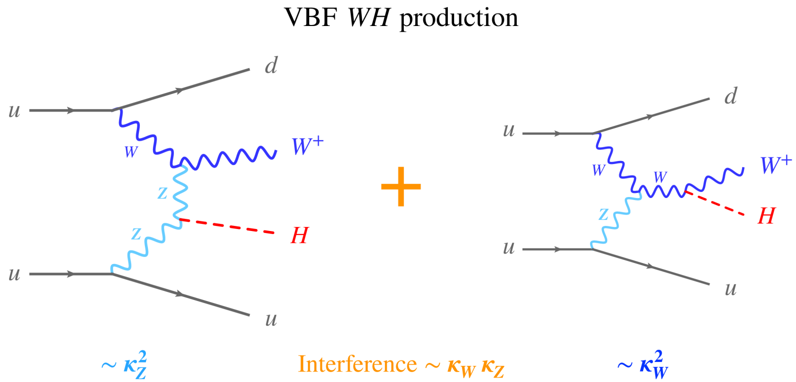




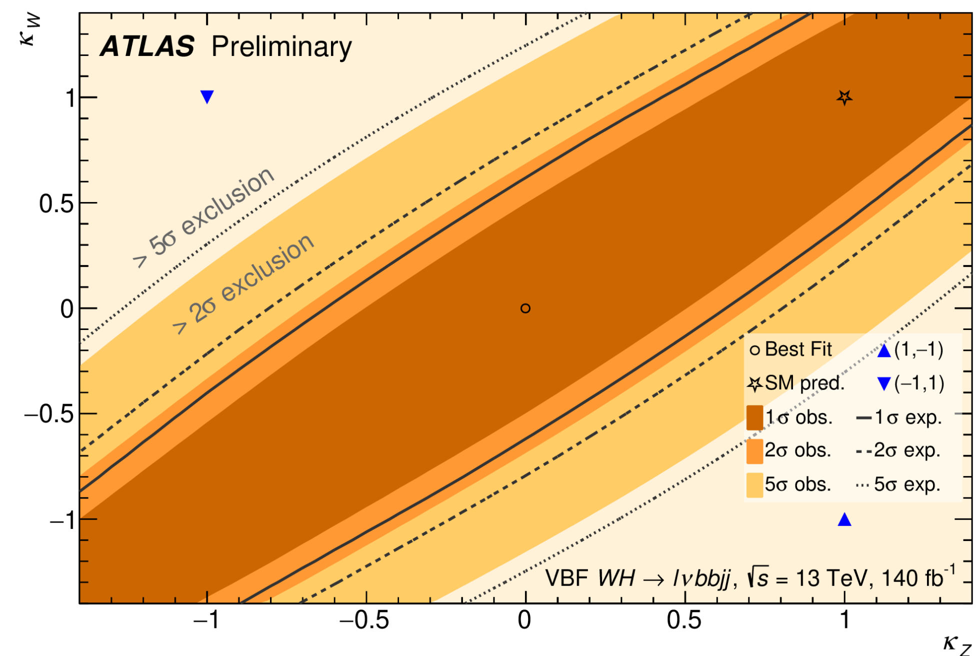
ATLAS: Nature 607, pages 52-59 (2022)
CMS: Nature 607 (2022) 60

From signal strengths to κ-framework

- κ-framework is not naively sqrt of signal strength
  - Interference can be used to determine their relative signs
  - Ratio between κs can probe new physics



$$\sigma_{\mathrm{VBF},WH} \propto \kappa_Z^2 |\mathcal{M}_Z|^2 + \kappa_W^2 |\mathcal{M}_W|^2 - 2\,\kappa_Z \kappa_W \,\Re[\mathcal{M}_Z^\dagger \mathcal{M}_W]$$
$$= \kappa_Z^2 |\mathcal{M}_Z|^2 + \kappa_W^2 |\mathcal{M}_W|^2 - 2\,\kappa_Z^2 \lambda_{WZ} \,\Re[\mathcal{M}_Z^\dagger \mathcal{M}_W]$$

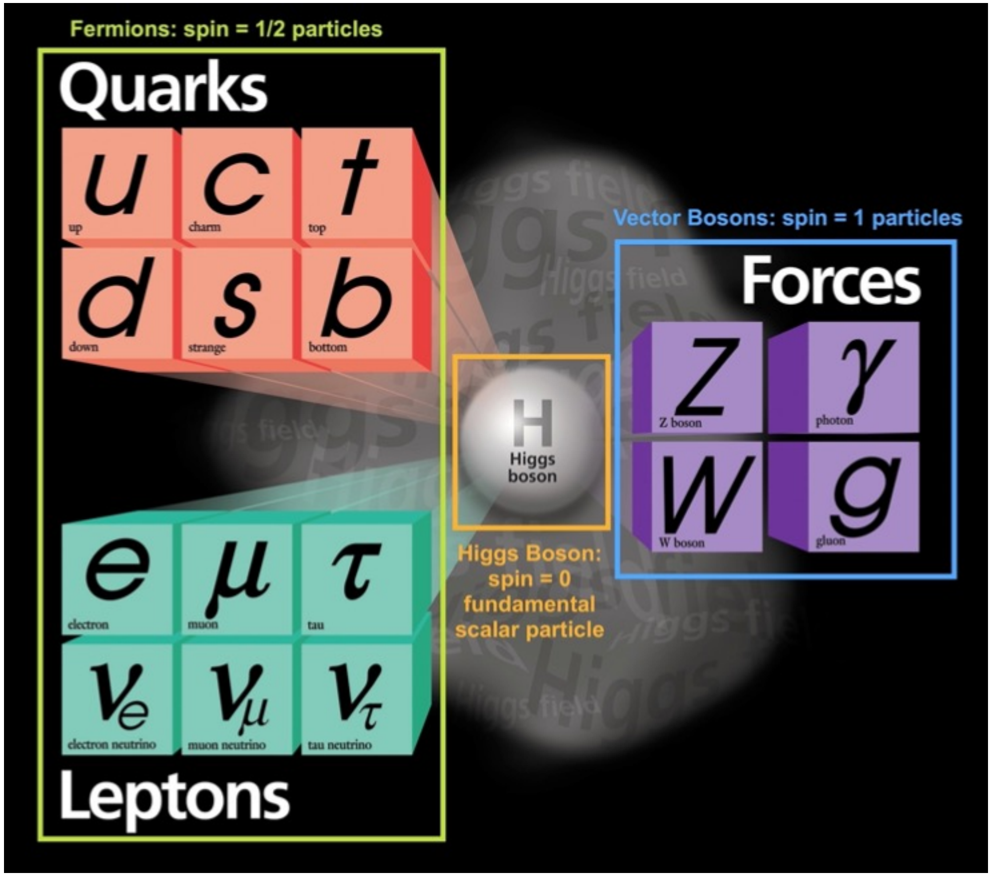


ATLAS-CONF-2023-057

Beyond κ-framework

Higgs coupling structures :

- ❑ **κ-framework** :
  based on inclusive production and decay rates, blind to tension in differential distributions
- ❑ **anomalous couplings/ EFT and CP structures**

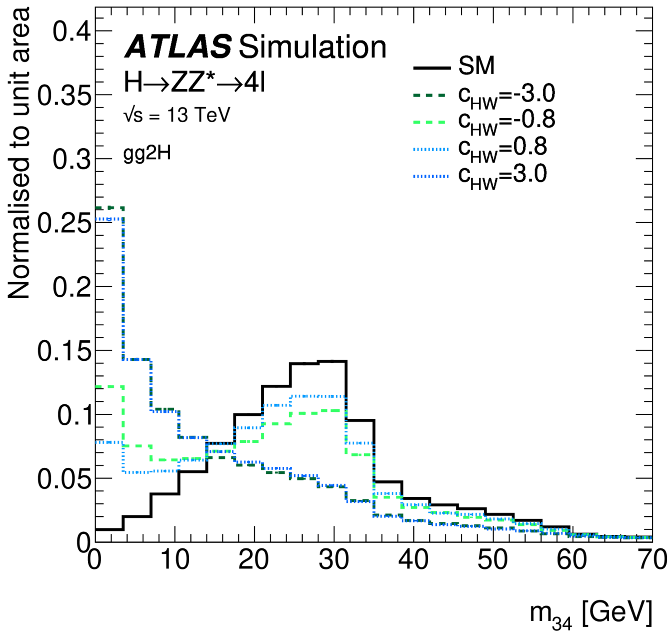


SMEFT parameterization

$$\sigma \propto \left| \mathcal{M}_{\rm SM} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} \mathcal{M}_i^{(6)} + \sum_i \frac{c_i^{(8)}}{\Lambda^4} \mathcal{M}_i^{(8)} \right|^2$$

$$= |\mathcal{M}_{\rm SM}|^2 + \sum_i 2Re\left(\mathcal{M}_{\rm SM}^* \mathcal{M}_i^{(6)}\right) \frac{c_i^{(6)}}{\Lambda^2}$$

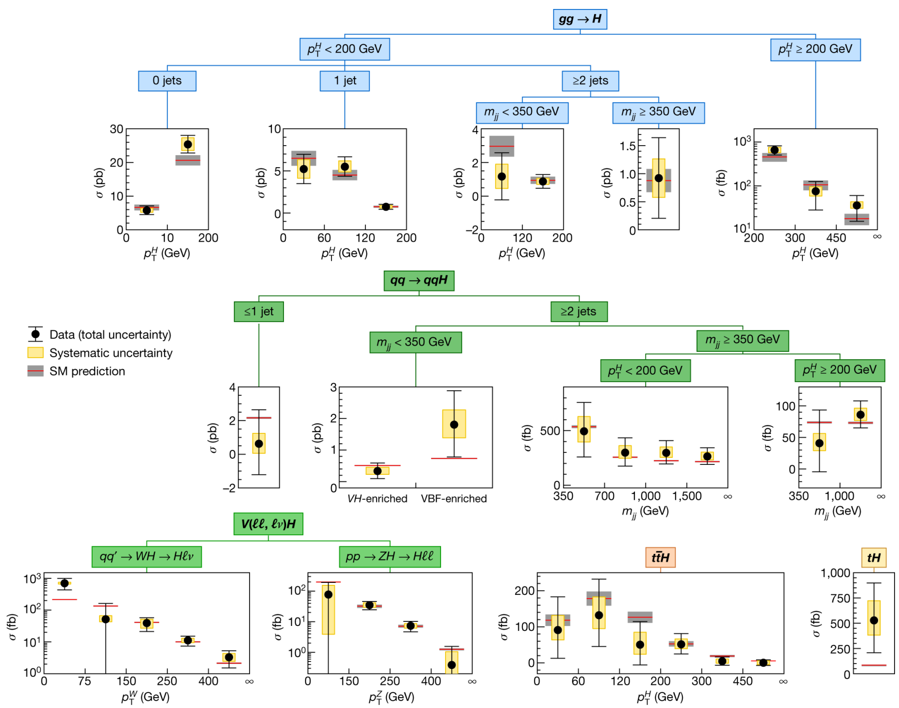
$$\mu^p(\vec{c}) = \frac{\sigma^p(\vec{c})}{\sigma_{\rm SM}} \cdot \frac{\mathcal{B}^{4\ell}(\vec{c})}{\mathcal{B}^{4\ell}_{\rm SM}} \cdot \frac{A(\vec{c})}{A_{\rm SM}}$$



Eur. Phys. J. C 80 (2020) 957

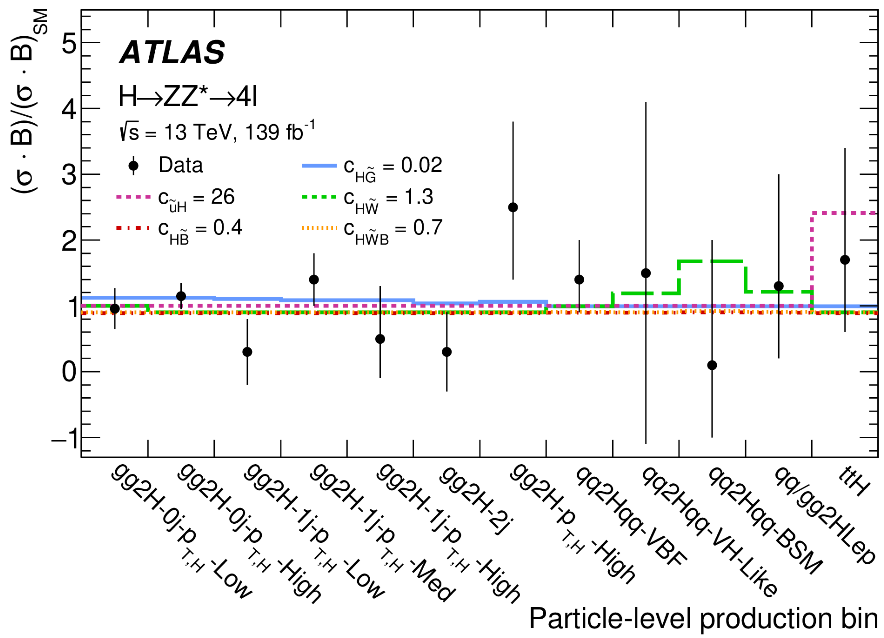
CP-even			CP-odd			Impact on	
Operator	Structure	Coeff.	Operator	Structure	Coeff.	production	decay
O_{uH}	$HH^\dagger \bar{q}_p u_r \tilde{H}$	c_{uH}	O_{uH}	$HH^\dagger \bar{q}_p u_r \tilde{H}$	$c_{\tilde{u}H}$	ttH	-
O_{HG}	$HH^\dagger G^A_{\mu\nu} G^{\mu\nu A}$	c_{HG}	$O_{H\tilde{G}}$	$HH^\dagger \tilde{G}^A_{\mu\nu} G^{\mu\nu A}$	$c_{H\tilde{G}}$	ggF	Yes
O_{HW}	$HH^\dagger W^l_{\mu\nu} W^{\mu\nu l}$	c_{HW}	$O_{H\widetilde{W}}$	$HH^\dagger \widetilde{W}^l_{\mu\nu} W^{\mu\nu l}$	$c_{H\widetilde{W}}$	VBF, VH	Yes
O_{HB}	$HH^\dagger B_{\mu\nu} B^{\mu\nu}$	c_{HB}	$O_{H\widetilde{B}}$	$HH^\dagger \widetilde{B}_{\mu\nu} B^{\mu\nu}$	$c_{H\widetilde{B}}$	VBF, VH	Yes
O_{HWB}	$HH^\dagger \tau^l W^l_{\mu\nu} B^{\mu\nu}$	c_{HWB}	$O_{H\widetilde{W}B}$	$HH^\dagger \tau^l \widetilde{W}^l_{\mu\nu} B^{\mu\nu}$	$c_{H\widetilde{W}B}$	VBF, VH	Yes

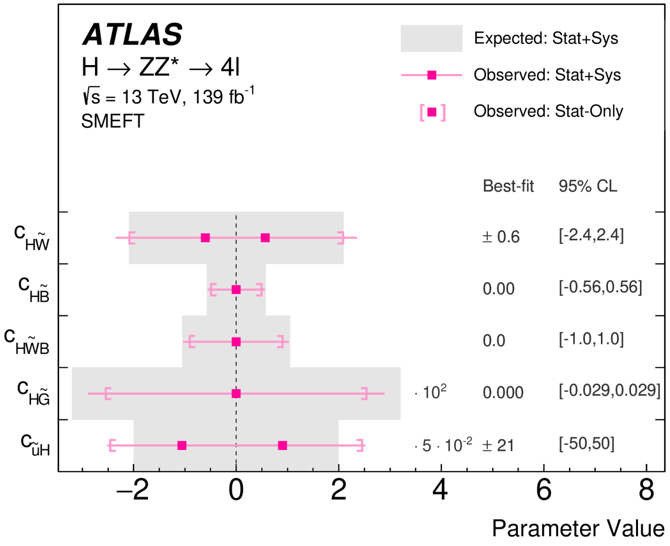
STXS framework



- ❑ Split phase space of Higgs production processes
- ❑ Defined by kinematics of Higgs boson and associated W/Z
- ❑ Provide differential cross-section measurements while easy to combine multiple production/decay channels

SMEFT from STXS





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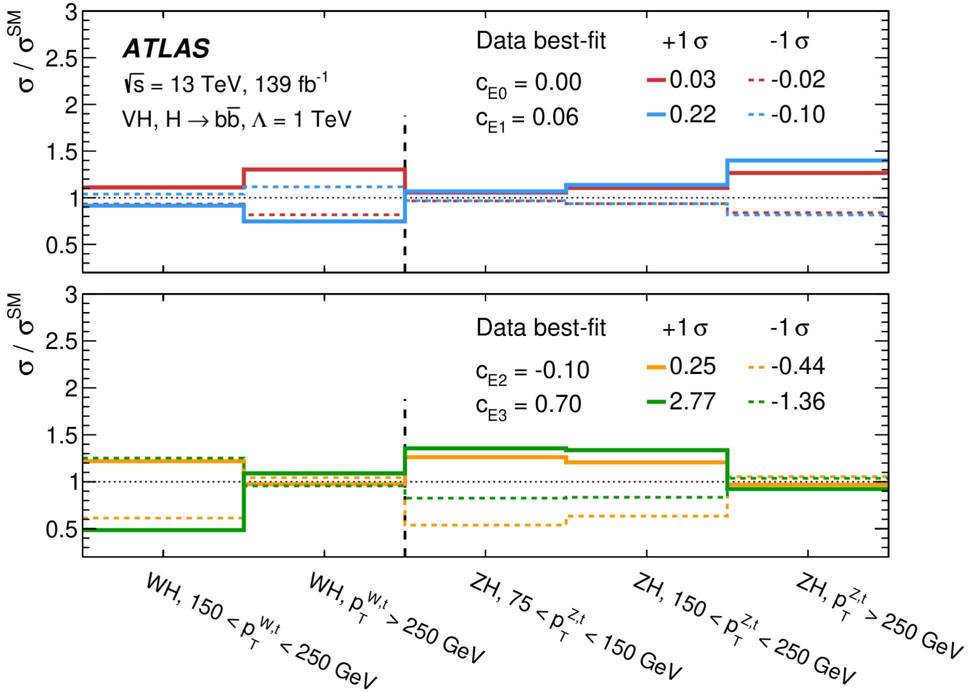
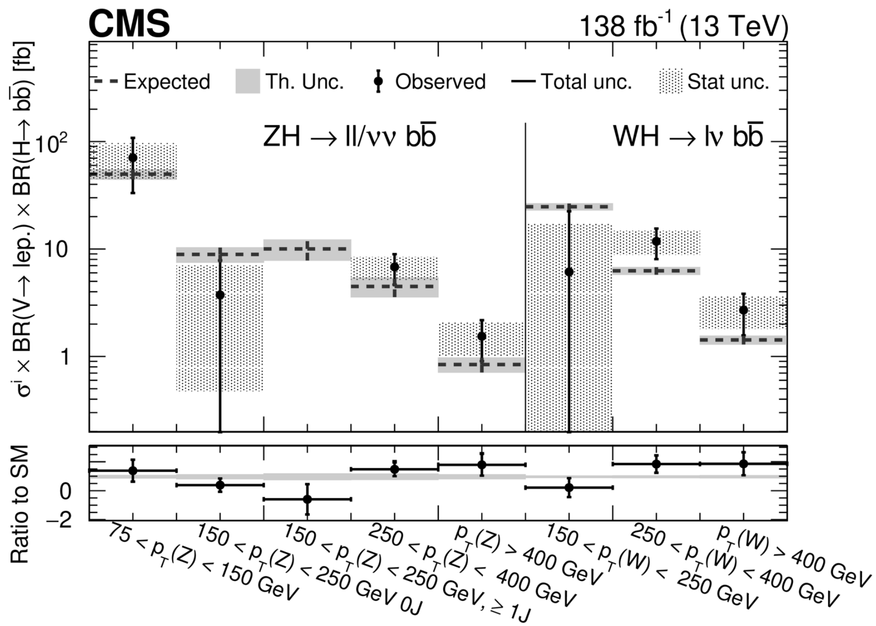
SMEFT from STXS in VHbb





Eur. Phys. J. C 81 (2021) 178

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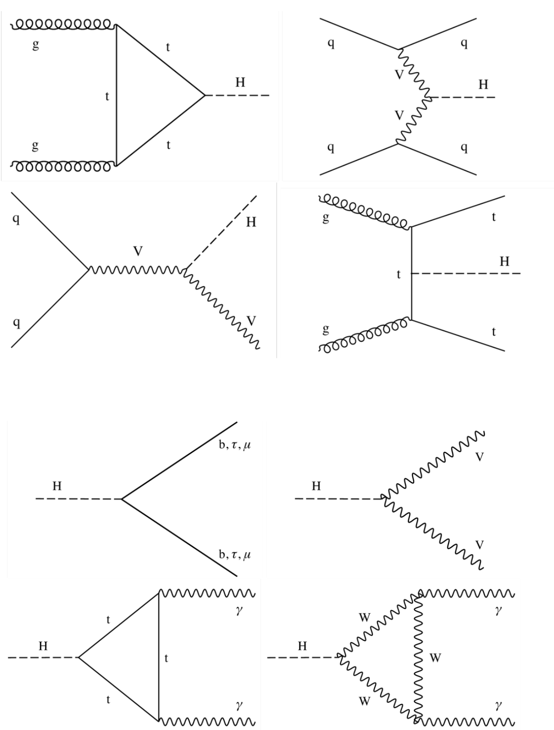
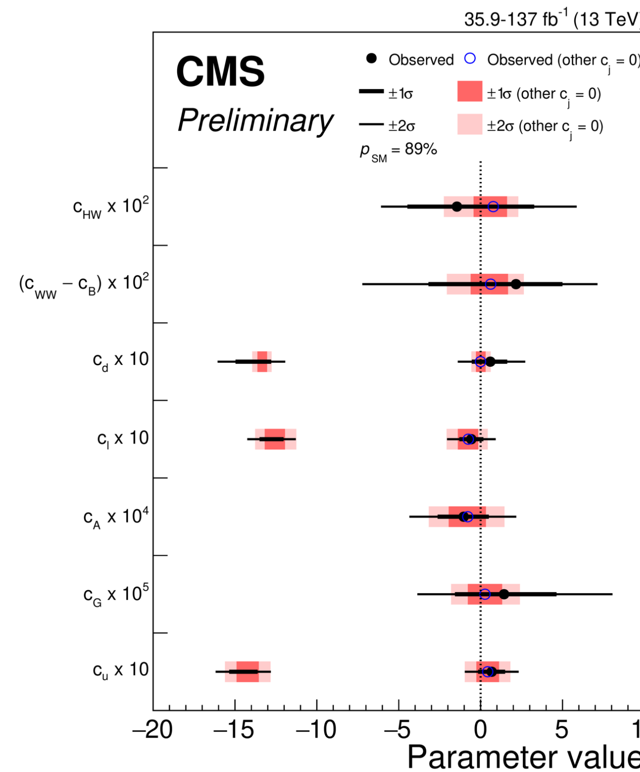
Combined fit from combined STXS



Wilson coefficient	Operator
c_H	$(H^\dagger H)^3$
$c_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
c_G	$f^{abc}G_\mu^{a\nu}G_\nu^{b\rho}G_\rho^{c\mu}$
c_W	$\epsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$
c_{HDD}	$\left(H^\dagger D^\mu H\right)^*\left(H^\dagger D_\mu H\right)$
c_{HG}	$H^\dagger H\, G^A_{\mu\nu}G^{A\mu\nu}$
c_{HB}	$H^\dagger H\, B_{\mu\nu}B^{\mu\nu}$
c_{HW}	$H^\dagger H\, W^I_{\mu\nu}W^{I\mu\nu}$
c_{HWB}	$H^\dagger\tau^I H\, W^I_{\mu\nu}B^{\mu\nu}$
$c^{(1)}_{Hl,11}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_1\gamma^\mu l_1)$
$c^{(1)}_{Hl,22}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_2\gamma^\mu l_2)$
$c^{(1)}_{Hl,33}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_3\gamma^\mu l_3)$
$c^{(3)}_{Hl,11}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{l}_1\tau^I\gamma^\mu l_1)$
$c^{(3)}_{Hl,22}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{l}_2\tau^I\gamma^\mu l_2)$
$c^{(3)}_{Hl,33}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{l}_3\tau^I\gamma^\mu l_3)$
$c_{He,11}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_1\gamma^\mu e_1)$
$c_{He,22}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_2\gamma^\mu e_2)$
$c_{He,33}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_3\gamma^\mu e_3)$
$c^{(1)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}\gamma^\mu q)$
$c^{(3)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{q}\tau^I\gamma^\mu q)$
c_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p\gamma^\mu u_r)$
c_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p\gamma^\mu d_r)$
$c^{(1)}_{HQ}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{Q}\gamma^\mu Q)$
$c^{(3)}_{HQ}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{Q}\tau^I\gamma^\mu Q)$
c_{Ht}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{t}\gamma^\mu t)$
c_{Hb}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{b}\gamma^\mu b)$

Wilson coefficient	Operator
$c^{(1,1)}_{Qq}$	$(\bar{Q}\gamma_\mu Q)(\bar{q}\gamma^\mu q)$
$c^{(1,8)}_{Qq}$	$(\bar{Q}T^a\gamma_\mu Q)(\bar{q}T^a\gamma^\mu q)$
$c^{(3,1)}_{Qq}$	$(\bar{Q}\sigma^i\gamma_\mu Q)(\bar{q}\sigma^i\gamma^\mu q)$
$c^{(3,8)}_{Qq}$	$(\bar{Q}\sigma^i T^a\gamma_\mu Q)(\bar{q}\sigma^i T^a\gamma^\mu q)$
$c^{(3,1)}_{qq}$	$(\bar{q}\sigma^i\gamma_\mu q)(\bar{q}\sigma^i\gamma^\mu q)$
$c^{(1)}_{tu}$	$(\bar{t}\gamma_\mu t)(\bar{u}\gamma^\mu u)$
$c^{(8)}_{tu}$	$(\bar{t}T^a\gamma_\mu t)(\bar{u}T^a\gamma^\mu u)$
$c^{(1)}_{td}$	$(\bar{t}\gamma_\mu t)(\bar{d}\gamma^\mu d)$
$c^{(8)}_{td}$	$(\bar{t}T^a\gamma_\mu t)(\bar{d}T^a\gamma^\mu d)$
$c^{(1)}_{Qu}$	$(\bar{Q}\gamma_\mu Q)(\bar{u}\gamma^\mu u)$
$c^{(8)}_{Qu}$	$(\bar{Q}T^a\gamma_\mu Q)(\bar{u}T^a\gamma^\mu u)$
$c^{(1)}_{Qd}$	$(\bar{Q}\gamma_\mu Q)(\bar{d}\gamma^\mu d)$
$c^{(8)}_{Qd}$	$(\bar{Q}T^a\gamma_\mu Q)(\bar{d}T^a\gamma^\mu d)$
$c^{(1)}_{tq}$	$(\bar{q}\gamma_\mu q)(\bar{t}\gamma^\mu t)$
$c^{(8)}_{tq}$	$(\bar{q}T^a\gamma_\mu q)(\bar{t}T^a\gamma^\mu t)$
$c_{eH,22}$	$(H^\dagger H)(\bar{l}_2 e_2 H)$
$c_{eH,33}$	$(H^\dagger H)(\bar{l}_3 e_3 H)$
c_{uH}	$(H^\dagger H)(\bar{q}Y_u^\dagger u\widetilde{H})$
c_{tH}	$(H^\dagger H)(\bar{Q}\widetilde{H}t)$
c_{bH}	$(H^\dagger H)(\bar{Q}Hb)$
c_{tG}	$(\bar{Q}\sigma^{\mu\nu}T^A t)\widetilde{H}\,G^A_{\mu\nu}$
c_{tW}	$(\bar{Q}\sigma^{\mu\nu}t)\tau^I\widetilde{H}\,W^I_{\mu\nu}$
c_{tB}	$(\bar{Q}\sigma^{\mu\nu}t)\widetilde{H}\,B_{\mu\nu}$
$c_{ll,1221}$	$(\bar{l}_1\gamma_\mu l_2)(\bar{l}_2\gamma^\mu l_1)$



ATLAS-CONF-2023-052

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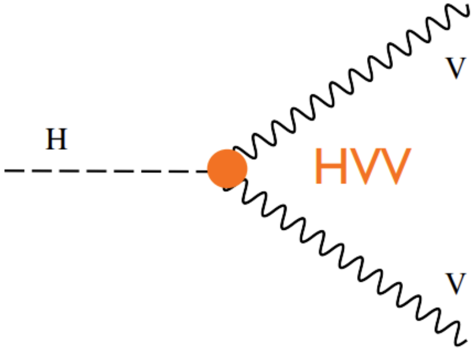
CP structures in Higgs-gauge boson

- Higgs-VV couplings measured based on the Effective Field Theory approach
- CP structure is explored with the Optimal Observable (OO)

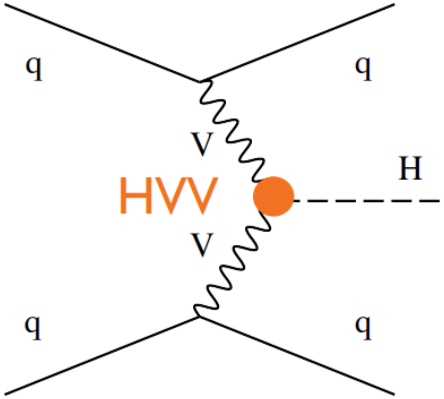


$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} O_i^{(6)}$$

Three independent dim-6 operators for CP-odd in SMEFT

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

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	
$O_{hZ\tilde{Z}}$	$hZ_{\mu\nu}\tilde{Z}^{\mu\nu}$	$\tilde{c}_{zz}$
$O_{hZ\tilde{A}}$	$hZ_{\mu\nu}\tilde{A}^{\mu\nu}$	$\tilde{c}_{z\gamma}$
$O_{hA\tilde{A}}$	$hA_{\mu\nu}\tilde{A}^{\mu\nu}$	$\tilde{c}_{\gamma\gamma}$



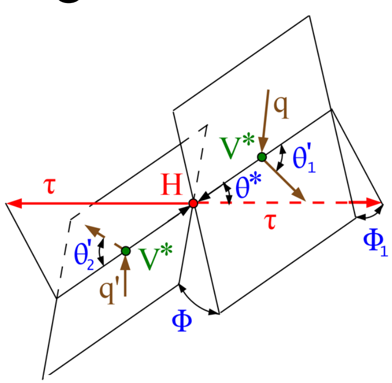
Anomalous couplings and CP structures in CMS

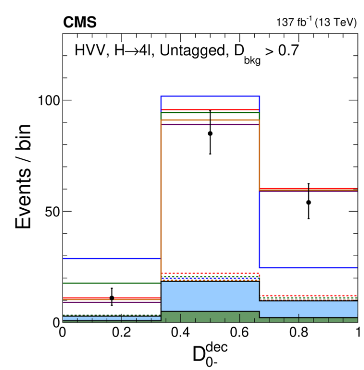
- Amplitude of HVV(ZZ, WW, $Z\gamma$, $\gamma\gamma$ and gg) are parameterized as (a and **κ** can be translated into EFT coefficients)

$$\mathcal{A}(\mathrm{HVV}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_1^2 + \kappa_2^{\mathrm{VV}} q_2^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2} \right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2)\mu\nu} + \boxed{a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2)\mu\nu}}$$

CP-odd

- Build matrix-element based discriminants to tag different anomalous couplings





Coupling	Discriminant
a_3^{gg}	$\mathcal{D}_{0-}^{ggH}$
a_3	$\mathcal{D}_{0-}$
a_2	$\mathcal{D}_{0h+}$
κ_1	$\mathcal{D}_{\Lambda 1}$
$\kappa_2^{Z\gamma}$	$\mathcal{D}_{\Lambda 1}^{Z\gamma}$

$$\delta c_z = \frac{1}{2} a_1 - 1,$$

$$c_{z\Box} = \frac{m_Z^2 s_W^2}{4\pi\alpha} \frac{\kappa_1}{(\Lambda_1)^2},$$

$$c_{zz} = -\frac{s_W^2 c_W^2}{2\pi\alpha} a_2,$$

$$\tilde{c}_{zz} = -\frac{s_W^2 c_W^2}{2\pi\alpha} a_3.$$

CMS: Phys. Rev. D 104, 052004 (2021)

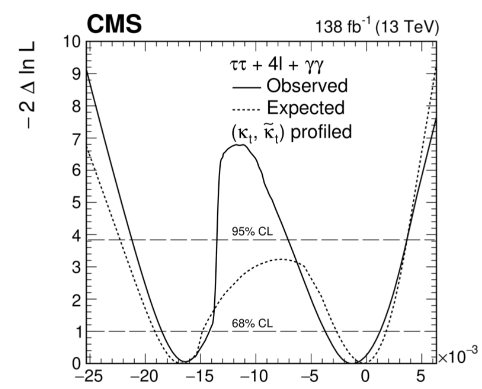
Anomalous couplings and CP structures in CMS

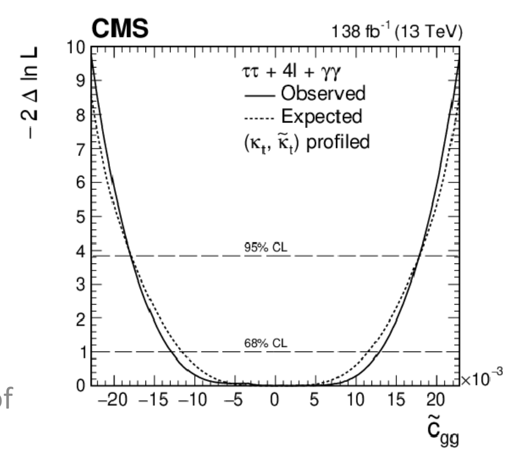
H4l+ H$\tau^+\tau^-$ are combined to constrain Higgs-gluon/HVV interactions

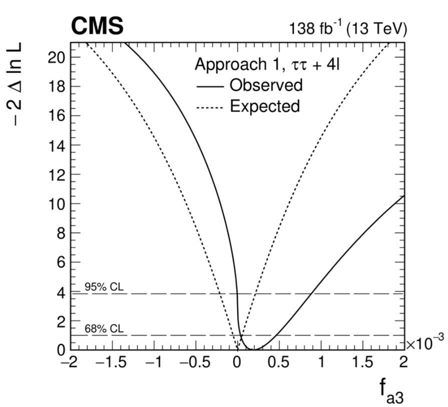
- CP-odd Higgs-gluon interaction $\tilde{c}_{gg}$ is consistent with zero
- Two approaches to interpret CP mixing in Higgs-VV interactions
  - Approach-1 $a_3^{WW} = a_3^{ZZ}$
  - Approach-2 $a_3^{WW} = cos^2(\theta_w) a_3^{ZZ}$

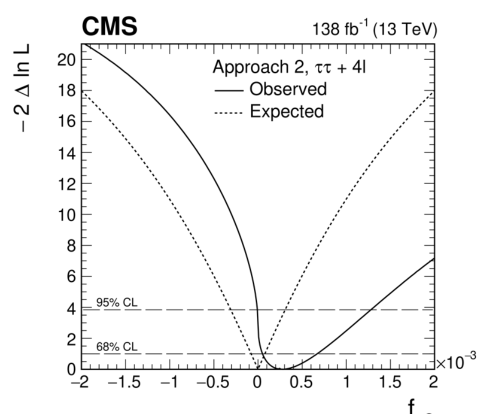
CP-even : $$c_{gg} = -\frac{1}{2\pi\alpha_S} a_2^{gg},$$

CP-odd : $$\tilde{c}_{gg} = -\frac{1}{2\pi\alpha_S} a_3^{gg},$$







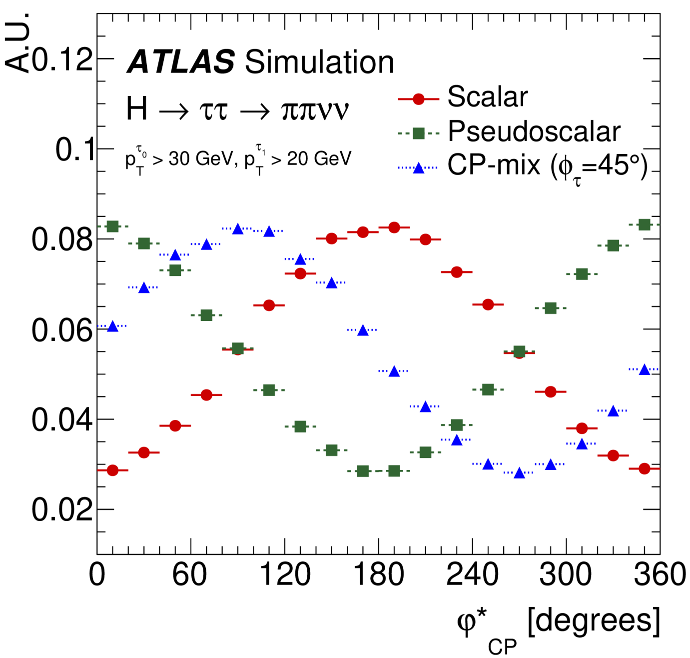


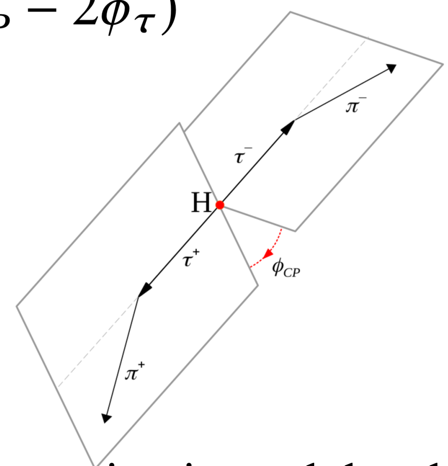
CMS: Phys. Rev. D 108 (2023) 032013

CP structure in H decays to τ-leptons

$$\mathcal{L}_Y = -\frac{m_\tau}{v} H(\kappa_\tau \bar{\tau}\tau + \tilde{\kappa}_\tau \bar{\tau} i\gamma_5 \tau) \quad \tan(\alpha^{H\tau\tau}) = \frac{\tilde{\kappa}_\tau}{\kappa_\tau}$$

$$d\Gamma_{H\to\tau^+\tau^-} \approx 1 - b(E_+)b(E_-)\frac{\pi^2}{16}\cos(\varphi^*_{CP} - 2\phi_\tau)$$



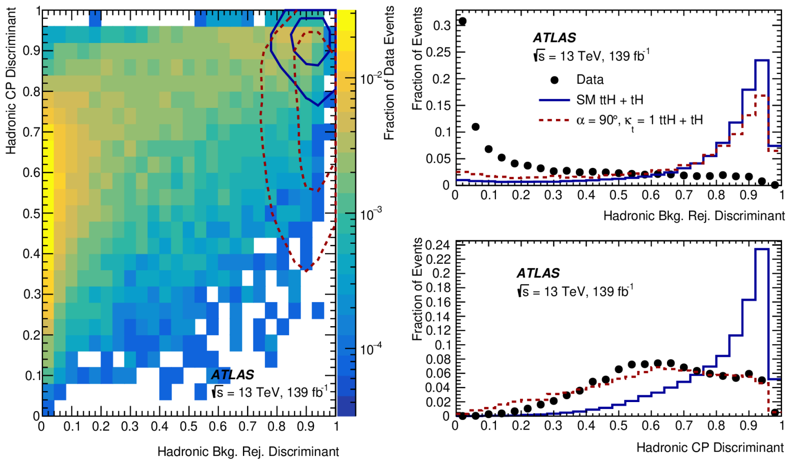


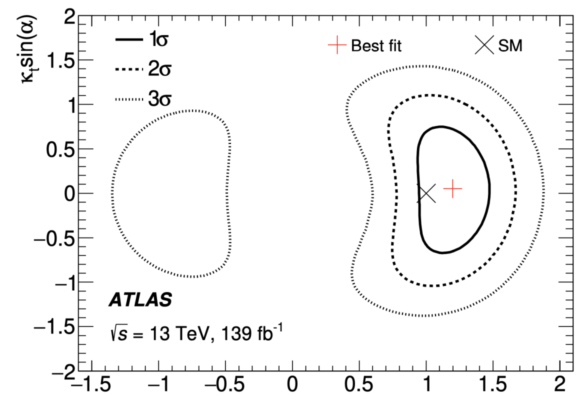
The cross section is modulated by the angular of two tau decay planes in the Higgs rest frame and the CP mixing angle ϕ_τ

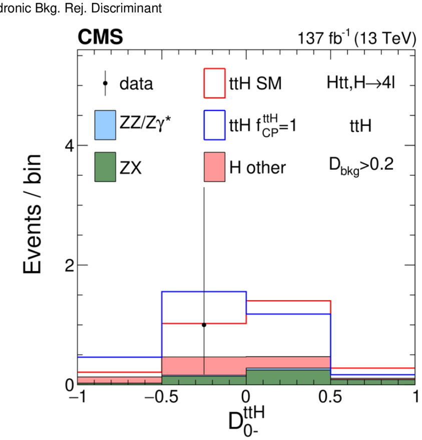
ATLAS: Eur. Phys. J. C 83 (2023) 563
CMS: JHEP 06 (2022) 012

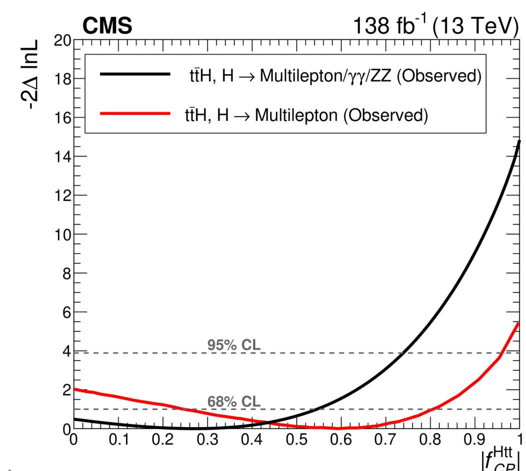
CP structures in ttH+tH

$$\mathcal{L} = -\frac{m_t}{v}\{\bar{\psi}_t \kappa_t [\cos(\alpha) + \mathrm{i}\sin(\alpha)\gamma_5]\psi_t\}H$$



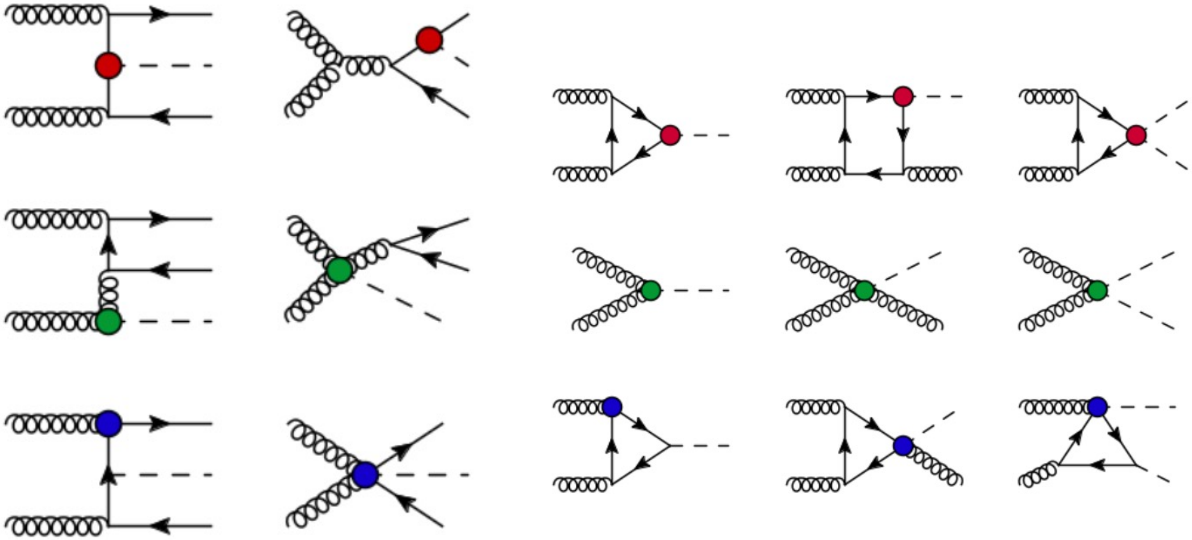


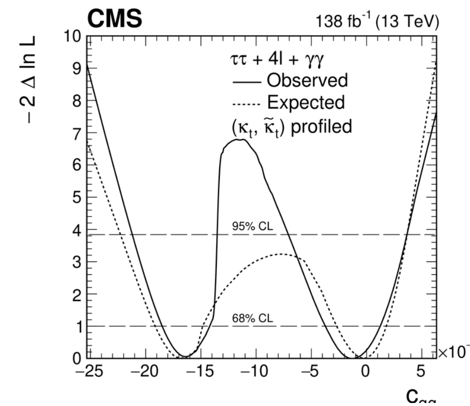


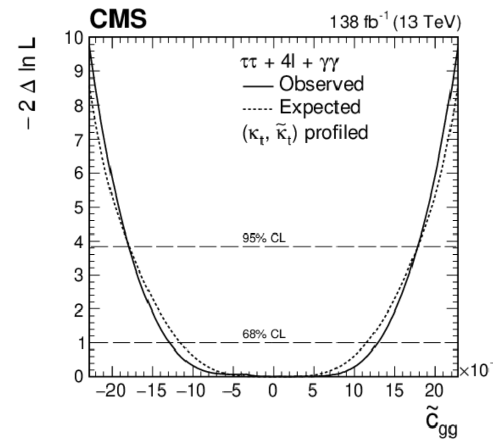


New Possibilities for H-top CP structures

Combine H-top results with ggH coupling measurements







$$O_{t\phi} = y_t^3 \left(\phi^\dagger\phi\right) \left(\bar{Q}t\right) \tilde{\phi}\,,$$

$$O_{\phi G} = y_t^2 \left(\phi^\dagger\phi\right) G^A_{\mu\nu} G^{A\mu\nu}\,,$$

$$O_{tG} = y_t g_s (\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{\phi} G^A_{\mu\nu}\,.$$

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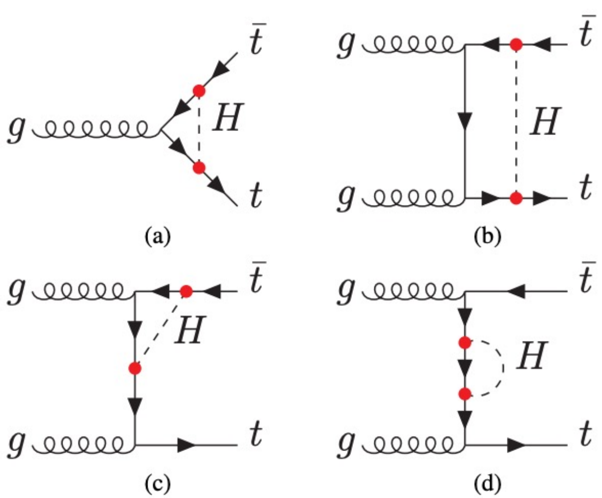
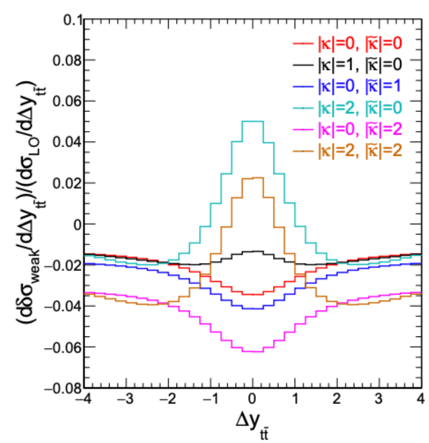
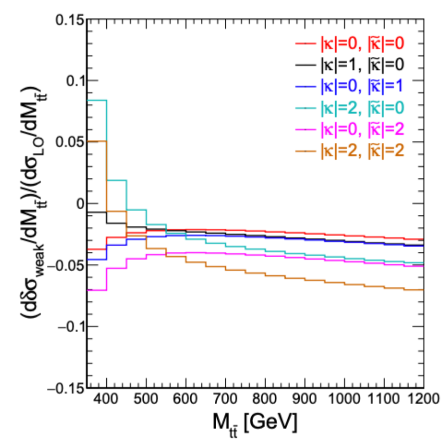
New Possibilities for H-top CP structures

CP dependence via EW NLO corrections

- ❑ Bkg becomes signal :
  with increased precision, electroweak NLO corrections become important.
- ❑ EW NLO corrections can depend on Higgs CP

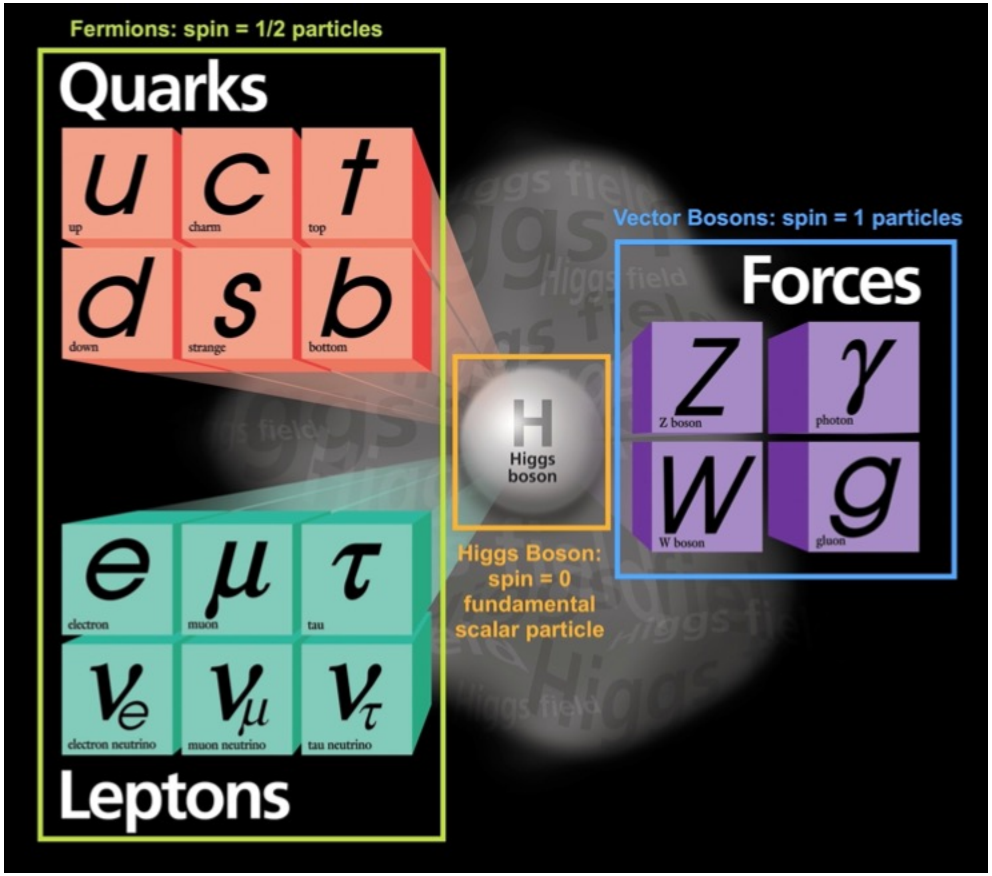




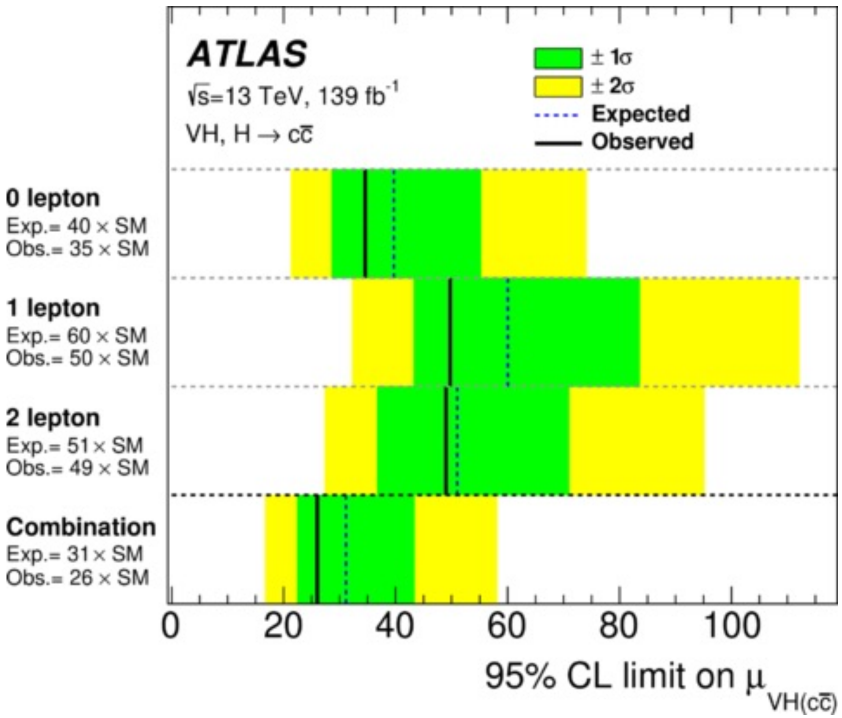


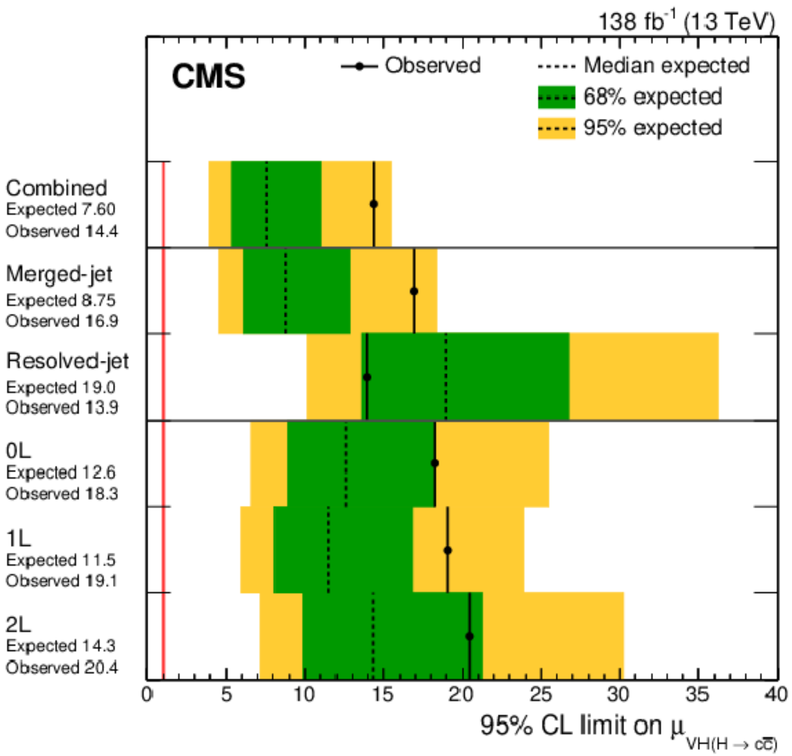
Phys. Rev. D 104, 055045 (2021)

Higgs couplings to 2nd fermions



Higgs decay to charm quarks





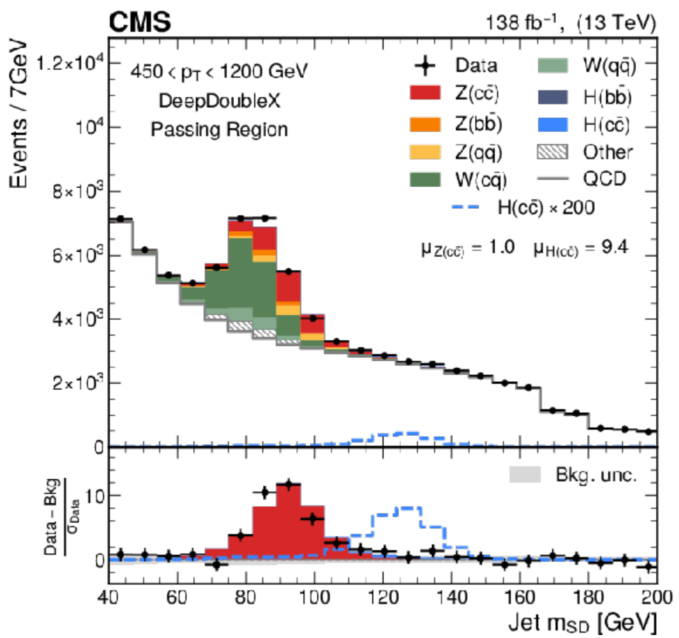
- $|\kappa_c| < 8.5$ (12.4) at 95% CL

  Eur. Phys. J. C 82 (2022) 717

- $1.1 < |\kappa_c| < 5.5$ at 95% CL

  Phys. Rev. Lett. 131 (2023) 061801

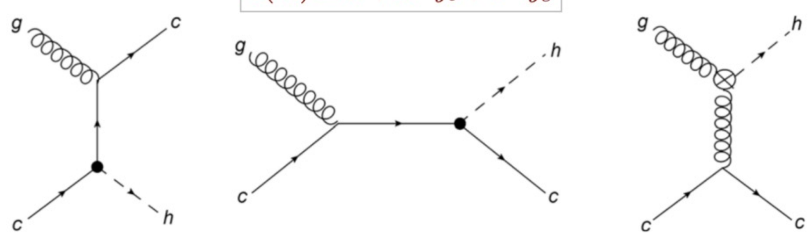
Higgs decay to charm quarks



- More boost regime:
  pT > 450GeV
  - Observed (expected) upper limit corresponds to 47 (39) × SM
  - Observed Z→cc signal strength is $1.00 \pm^{0.17}_{-0.14}\,(syst.) \pm 0.08(theo.) \pm 0.06(stat.)$

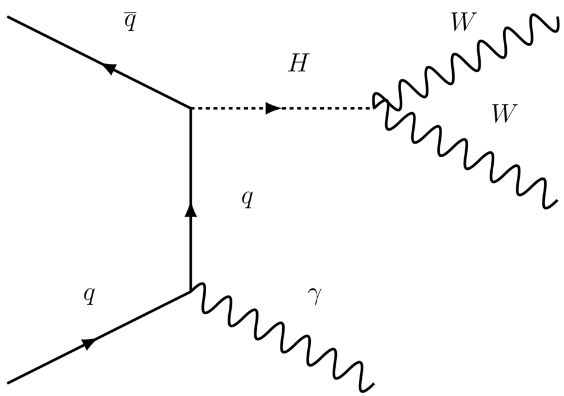
  [Phys. Rev. Lett. 131 (2023) 041801]

$$\sigma(hc) = A + B \cdot y_c + C \cdot y_c^2$$

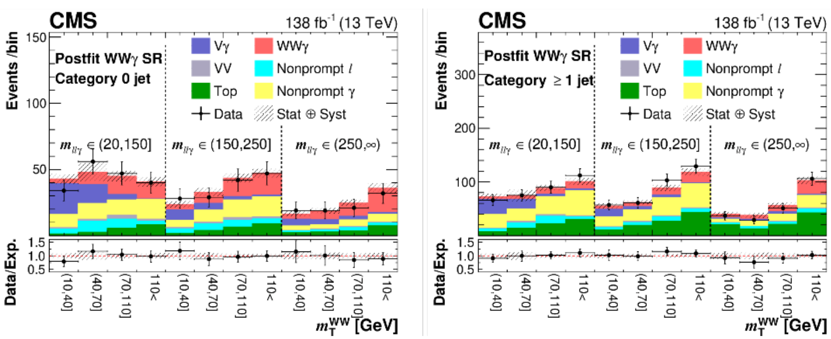


- Another possibility on-going is to search for H+c associated production

Higgs decay to charm quarks: Higgs+γ production



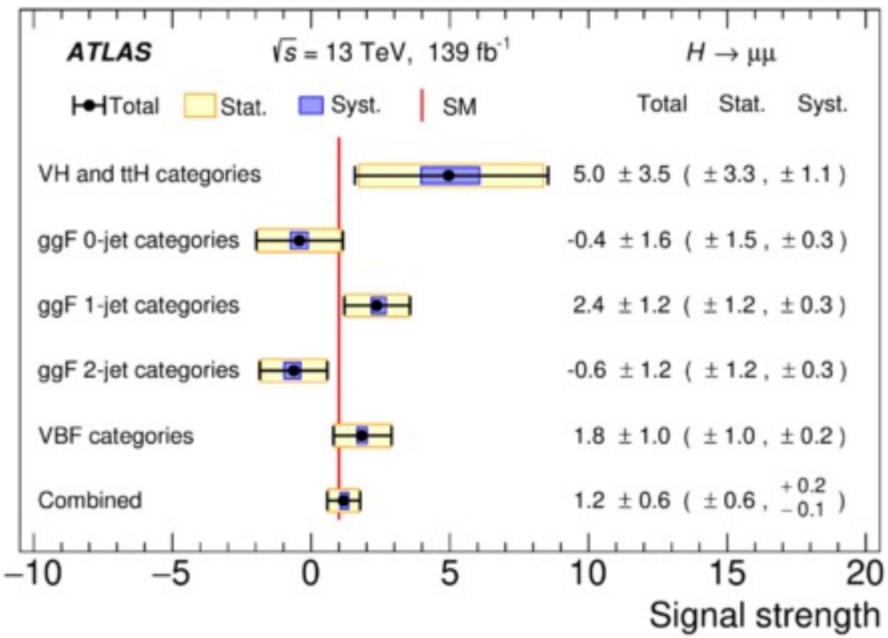
Higgs couplings to light quarks are also investigated in Higgs+γ production

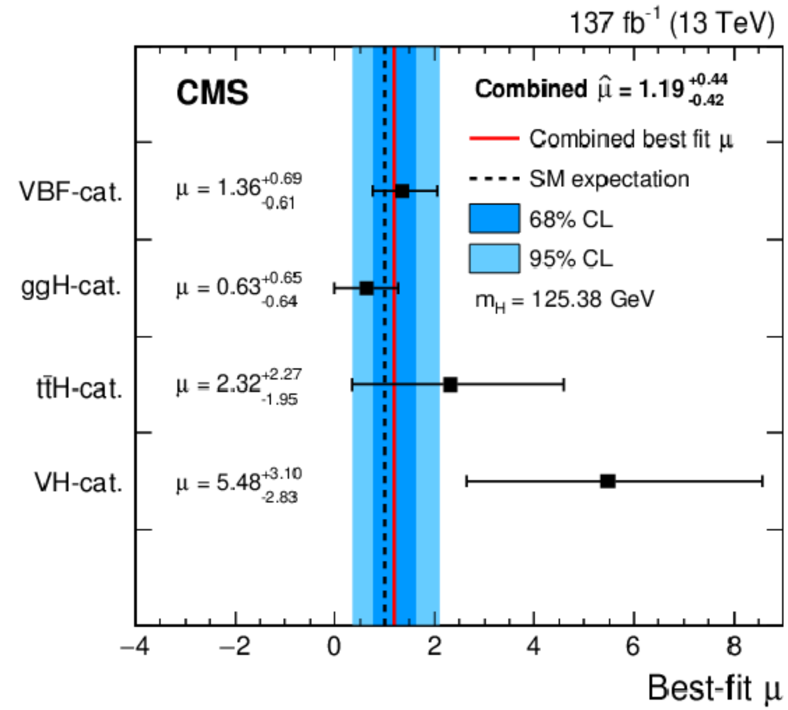


Process	σ upper limits obs. (exp.) [fb]	κ_q limits obs. (exp.) at 95% CL	$\bar{\kappa}_q$ limits obs. (exp.) at 95% CL
$u\bar{u} \to H+\gamma \to e\mu\nu_e\nu_\mu\gamma$	85 (67)	$\lvert\kappa_u\rvert \leq 16000$ (13000)	$\lvert\bar{\kappa}_u\rvert \leq 7.5$ (6.1)
$d\bar{d} \to H+\gamma \to e\mu\nu_e\nu_\mu\gamma$	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)

arXiv:2310.05164

Higgs decay to muons



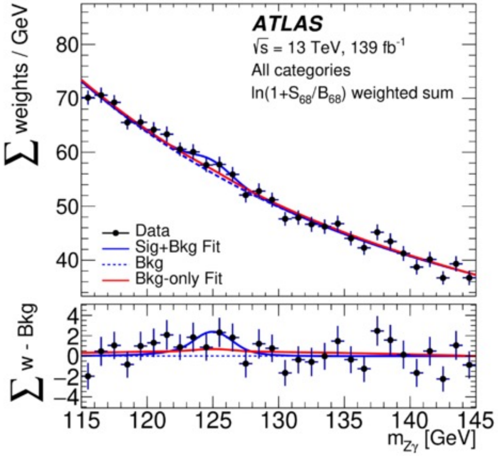


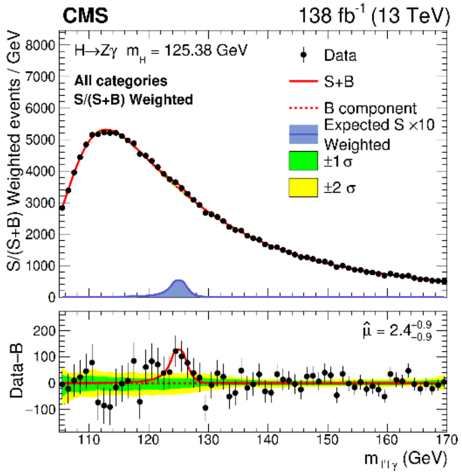
- Expected BR: 2.17×10^{-4}
- **One can expect the discovery of $H\mu^+\mu^-$ with Run2+Run3 data**

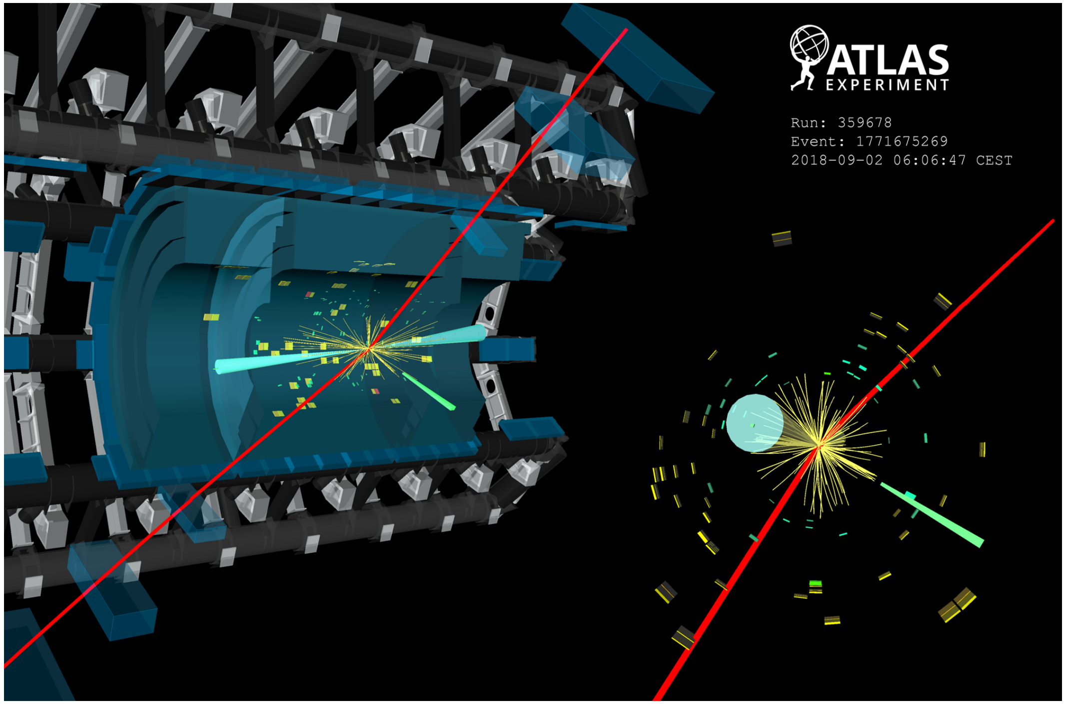
ATLAS : observed (expected) significance: 2.0σ(1.7σ)
CMS : claimed first evidence : 3.0σ(2.5σ) observed (expected)

ATLAS: Phys. Lett. B 812 (2021) 135980
CMS: JHEP 01 (2021) 148

Higgs decay to Zγ



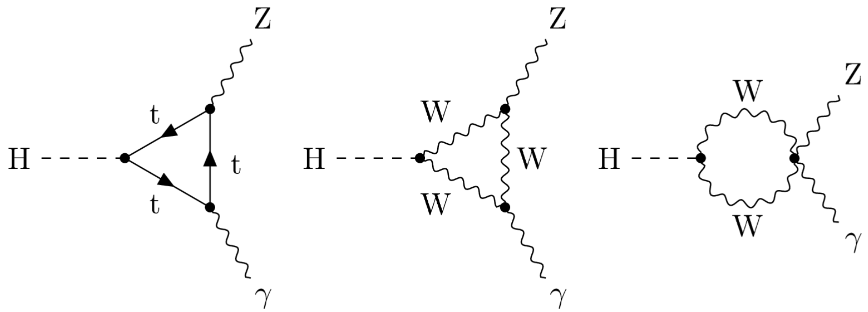


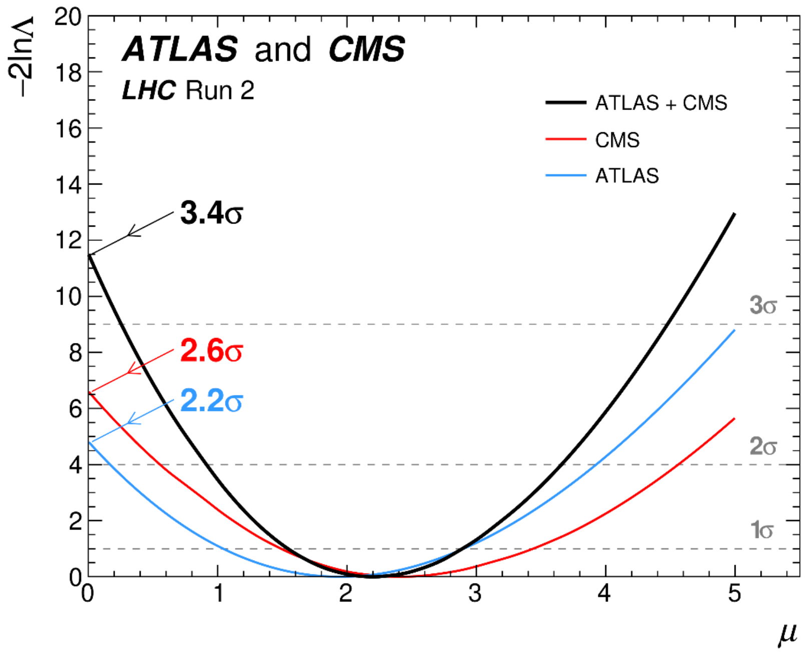


ATLAS-CONF-2023-025 + CMS HIG-23-002

Phys. Rev. Lett. 125 (2020) 221802

Higgs decay to Zγ





First evidence for H→Zγ (3.4σ)

(Surprisingly best-fit at ~2 for both experiments)

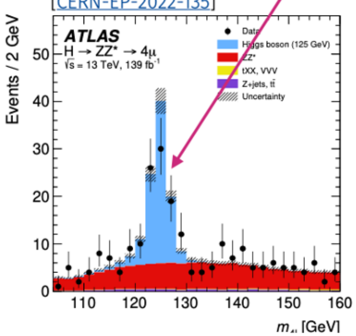
ATLAS-CONF-2023-025 + CMS HIG-23-002

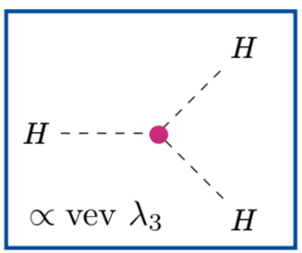
Phys. Rev. Lett. 125 (2020) 221802

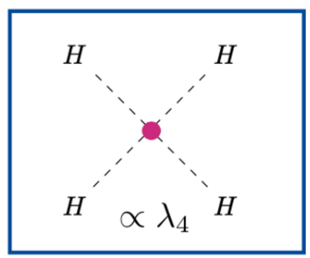
Higgs potential

$$V(H) = \frac{1}{2} m_H^2 H^2 + \lambda_3 \text{ vev } H^3 + \frac{1}{4} \lambda_4 H^4$$

[CERN-EP-2022-135]





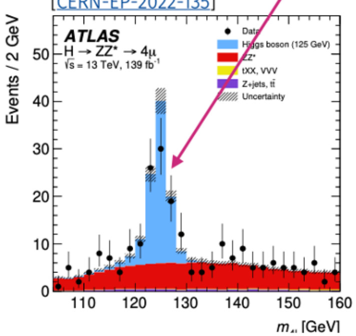


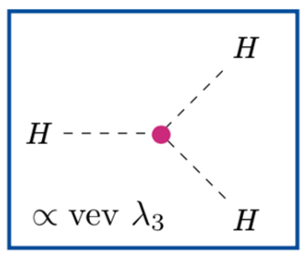
Plot borrowed from talk in HHH workshop 2023

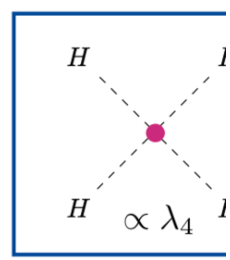
Higgs potential

$$V(H) = \frac{1}{2}m_H^2 H^2 + \lambda_3 \text{ vev } H^3 + \frac{1}{4}\lambda_4 H^4$$

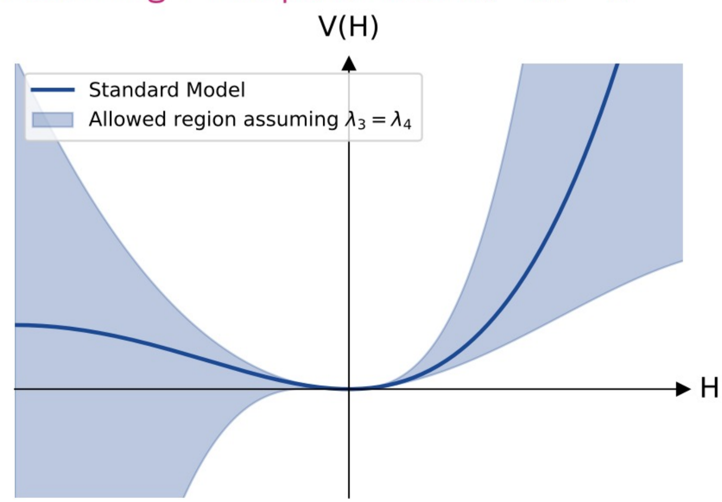
[CERN-EP-2022-135]







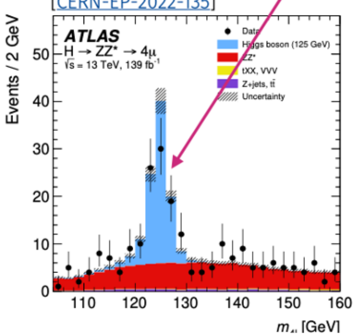
Assuming 1 free parameter $\lambda_3 = \lambda_4 = \lambda$

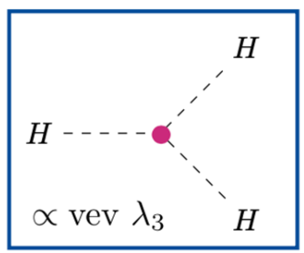


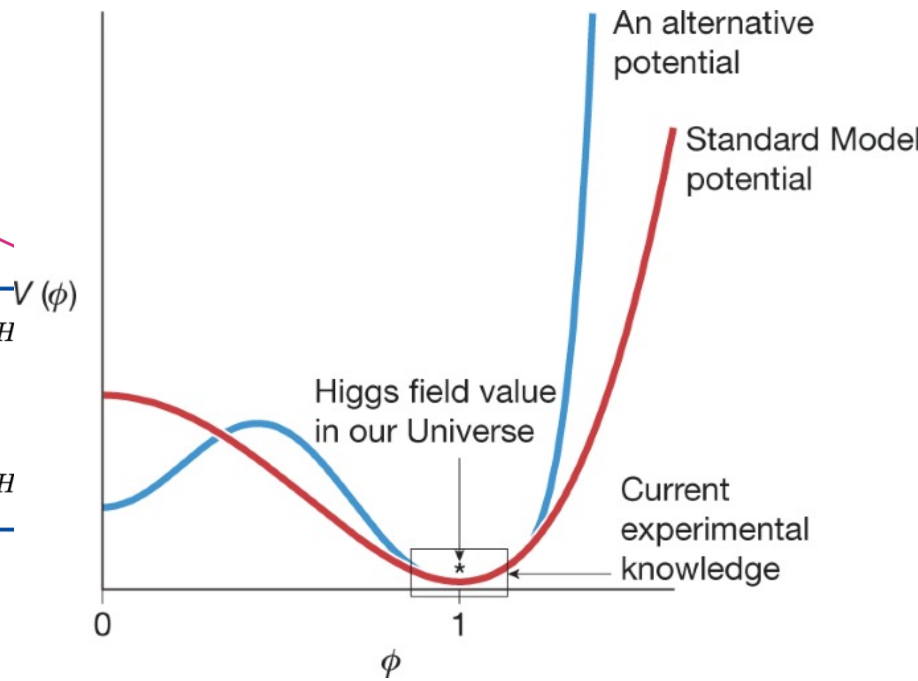
Higgs potential

$$V(H) = \frac{1}{2} m_H^2 H^2 + \lambda_3 \text{ vev } H^3 + \frac{1}{4}\lambda_4 H^4$$

[CERN-EP-2022-135]

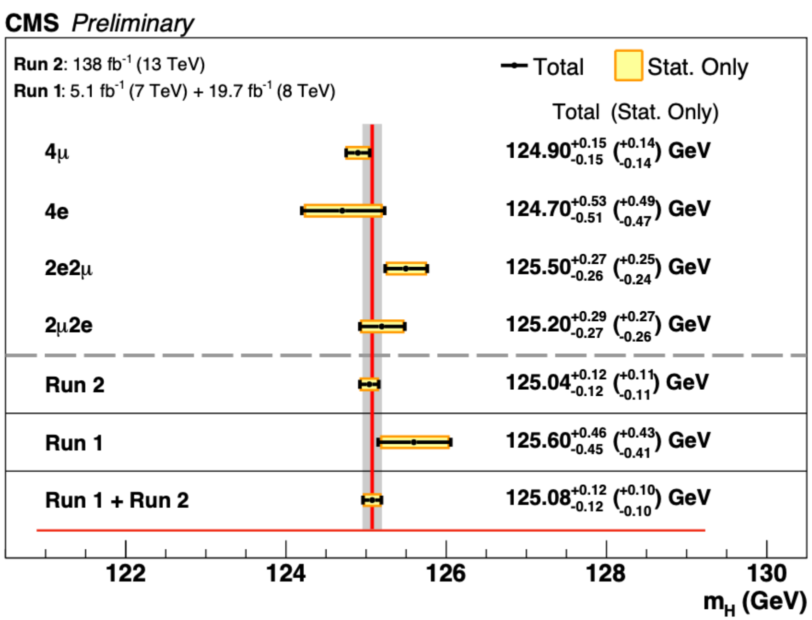


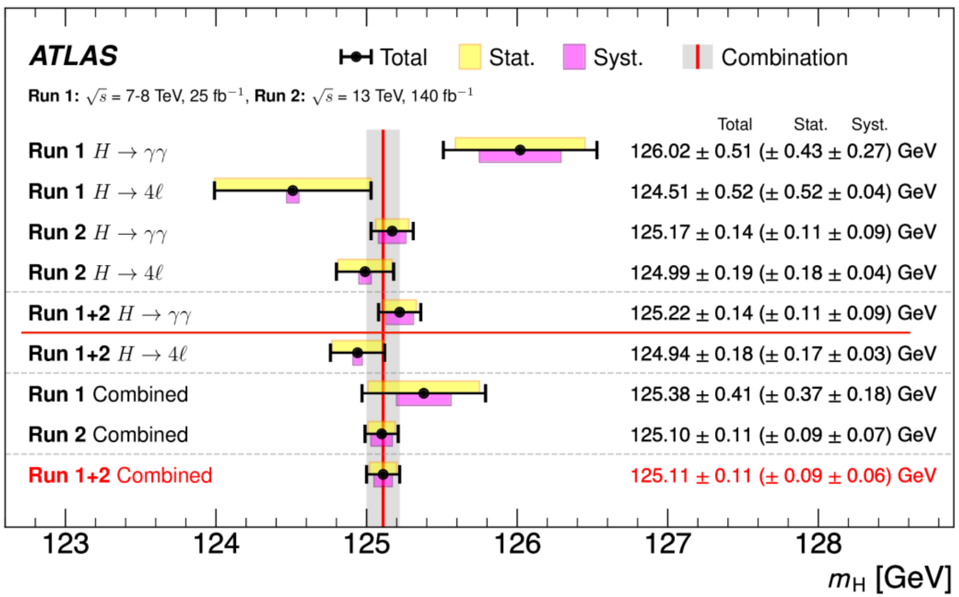




[The Higgs boson turns ten](#)

Higgs mass





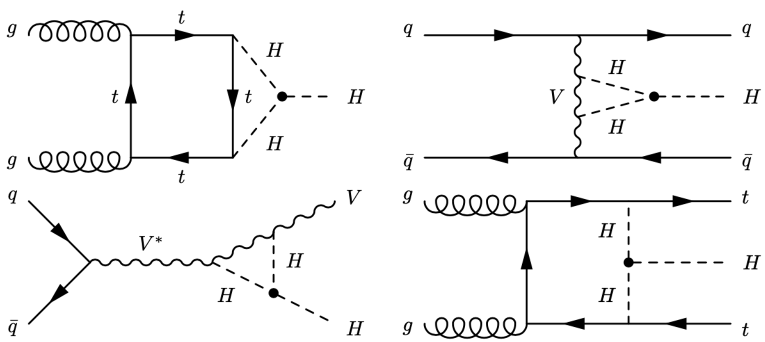
Detailed studies of the calibration of the muons, electrons and photons with the very large HL-LHC sample have not been done yet, however it is plausible that the mass of the Higgs boson will be measured with a precision of 10-20 MeV, assuming that with the higher statistics the analysis will be further optimised to gain in statistical precision and that systematic uncertainties on the muon transverse momentum scale will significantly improve with the higher statistics.

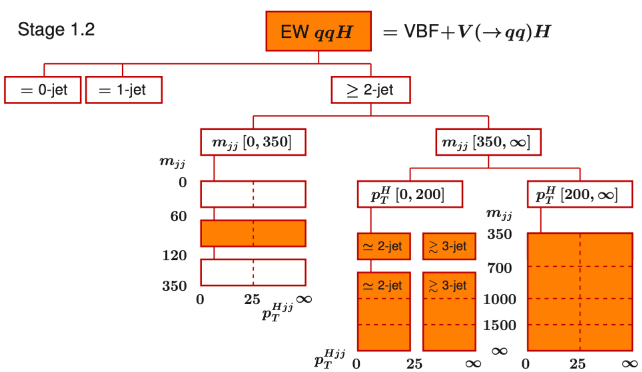
Trilinear-Higgs coupling : single Higgs

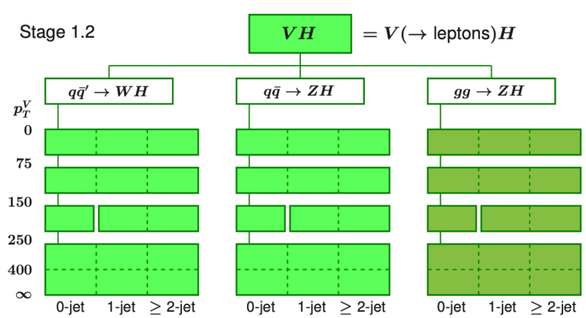
LHC Higgs Working Group*

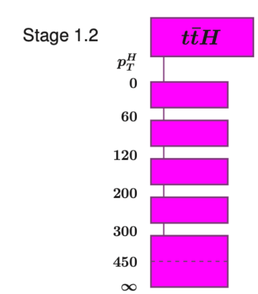
Public Note

Modeling of the single-Higgs simplified template cross-sections (STXS 1.2) for the determination of the Higgs boson trilinear self-coupling



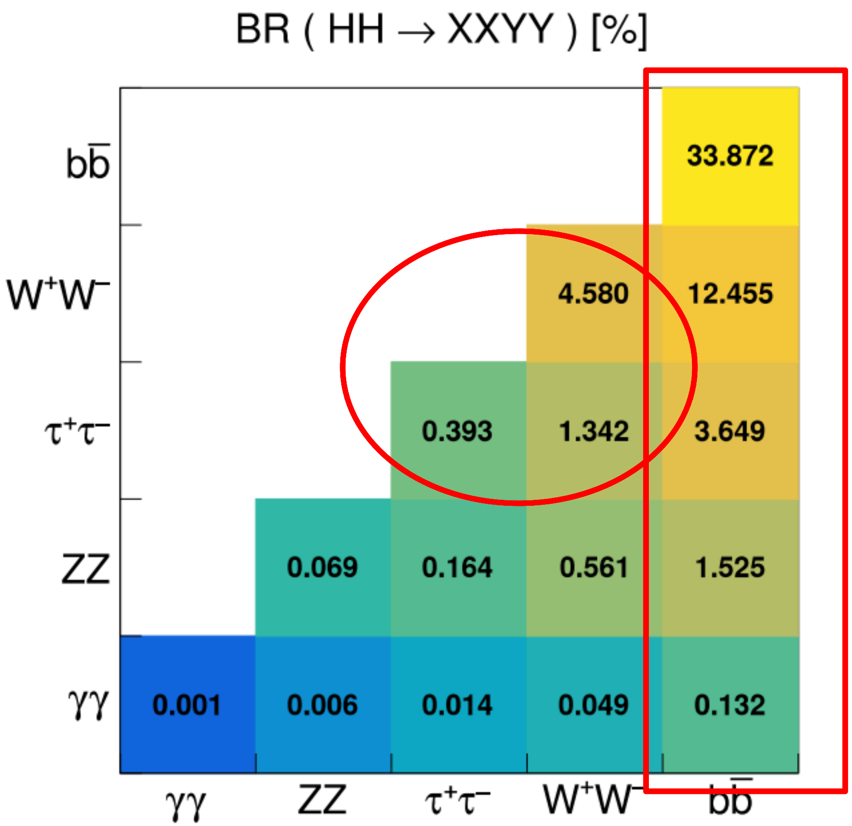


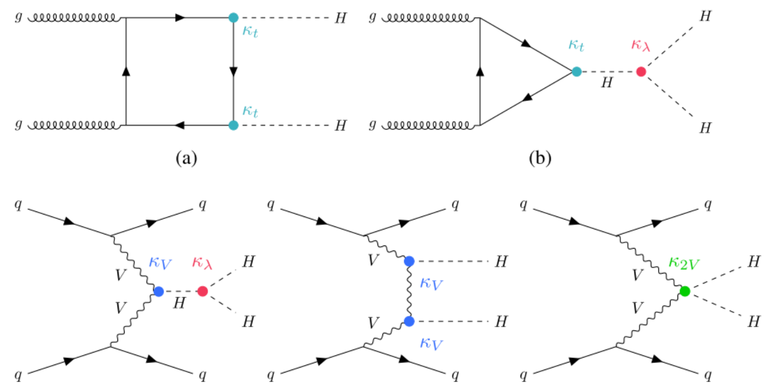


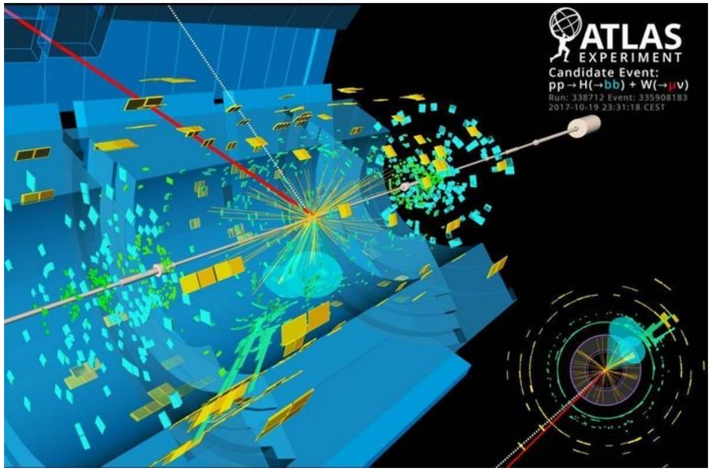


Modelling of the single-Higgs simplified template cross-sections STXS 1.2 for the determination of the Higgs boson trilinear self-coupling

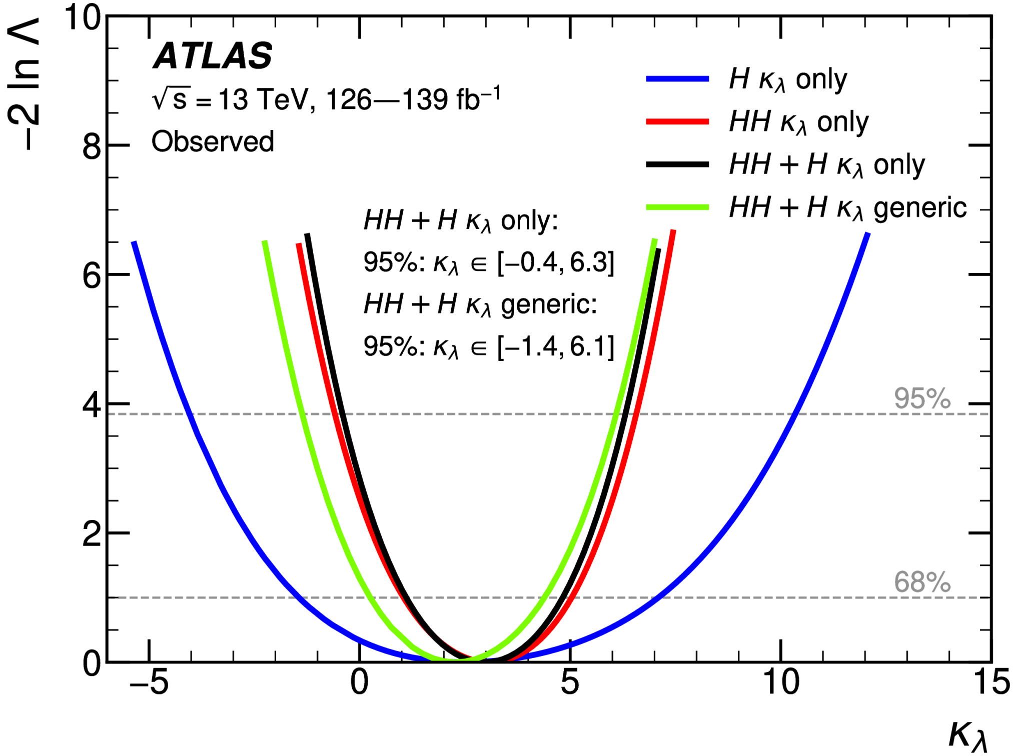
Trilinear-Higgs coupling : di-Higgs

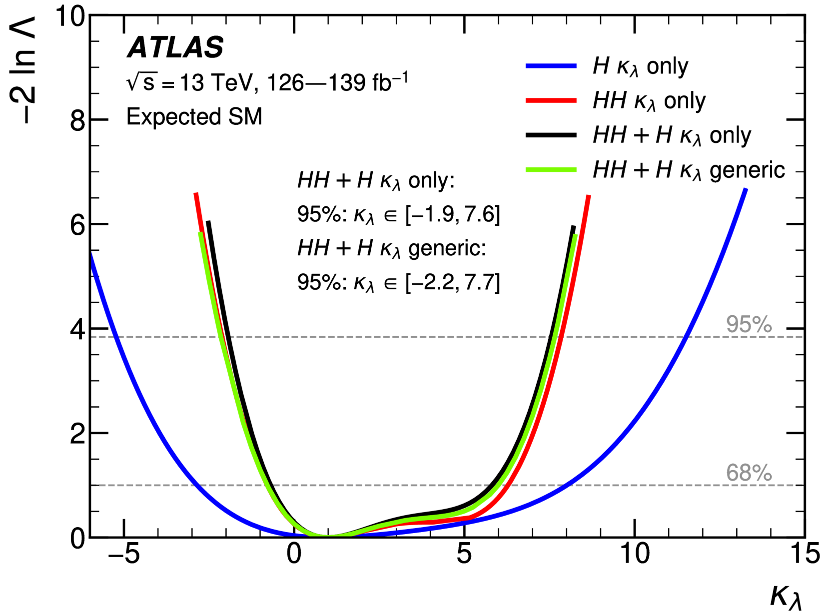






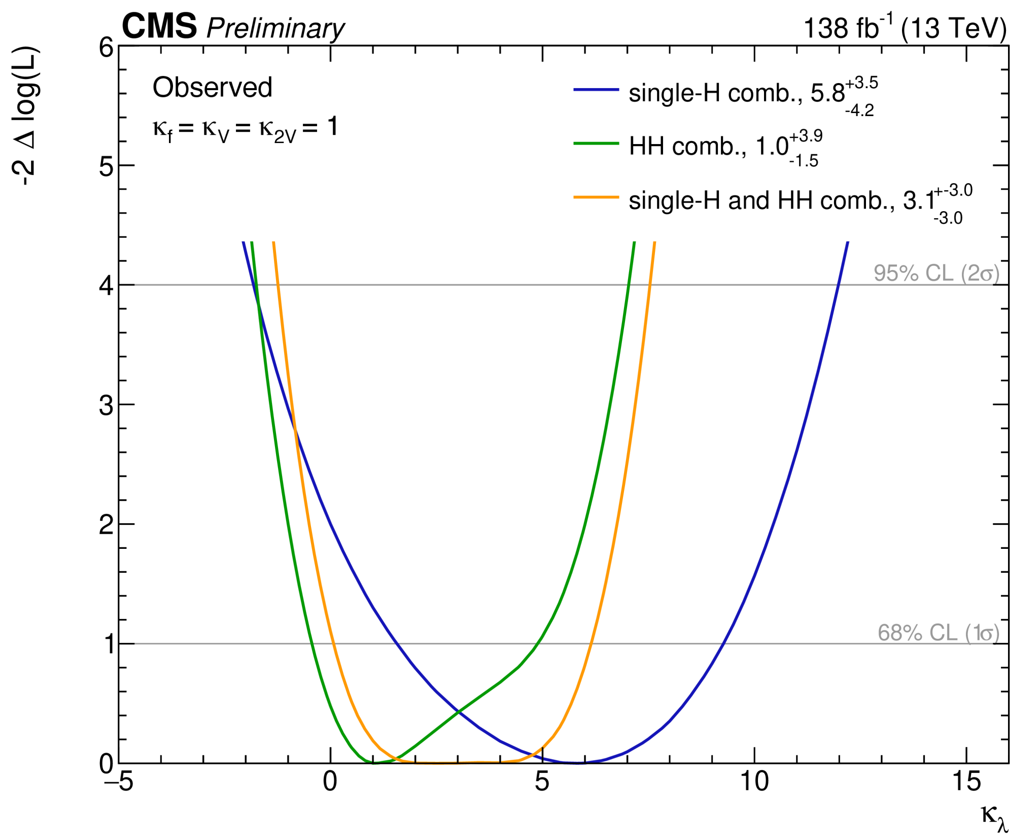
Trilinear-Higgs coupling : H+HH combination





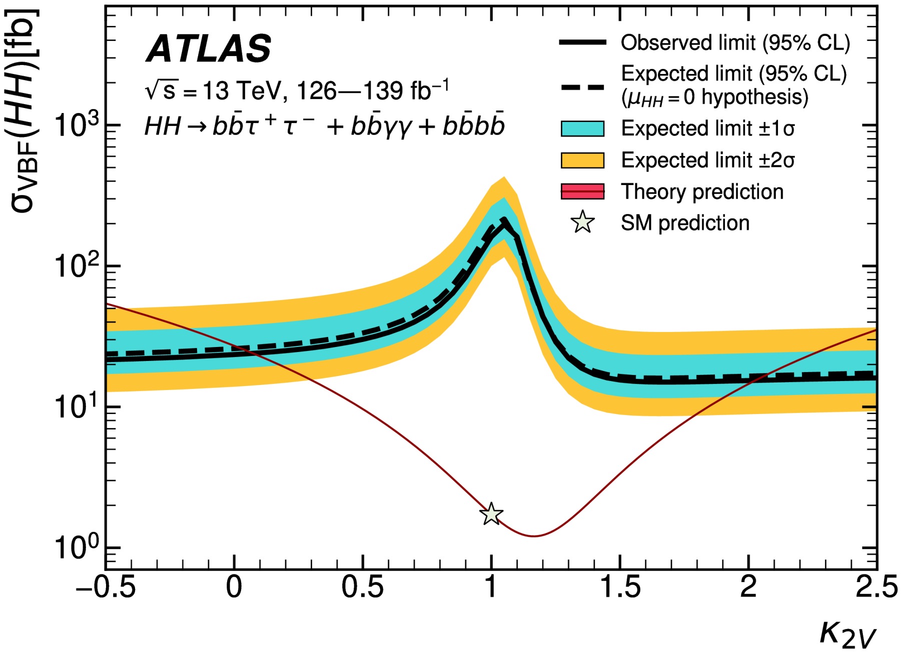
Phys. Rev. D 108 (2023) 052003

Trilinear-Higgs coupling : H+HH combination



[HIG-23-006]

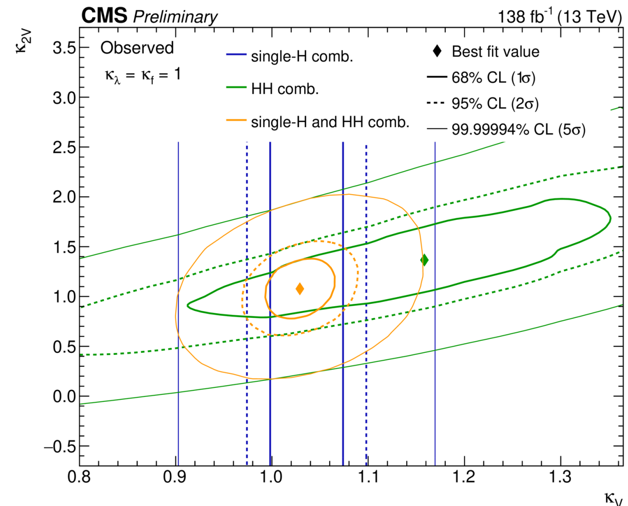
VHH coupling : di-Higgs

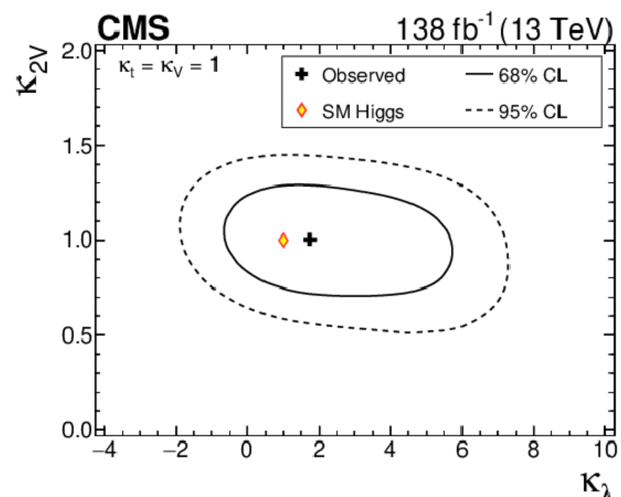


ATLAS: [Phys. Lett. B 843 (2023) 137745]

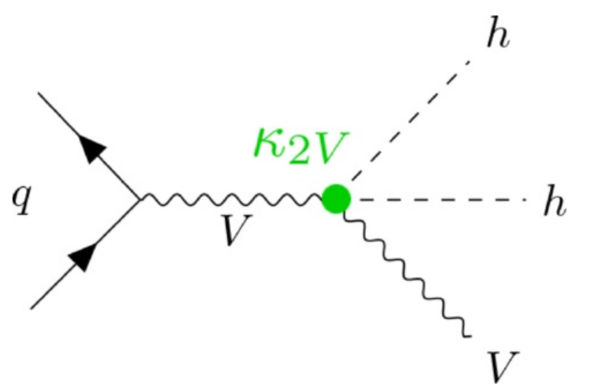
CMS: [Nature 607 (2022) 60]

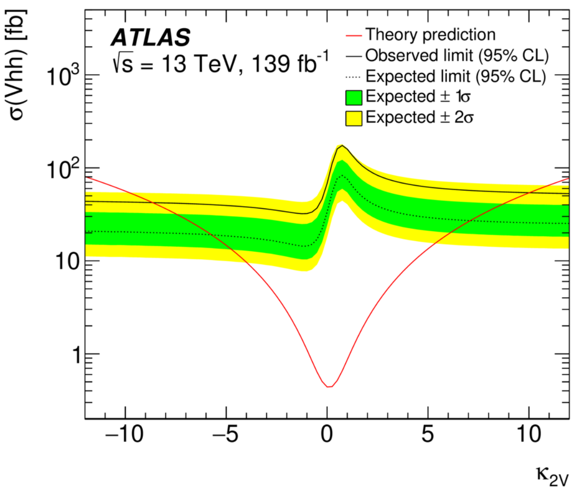
[HIG-23-006]



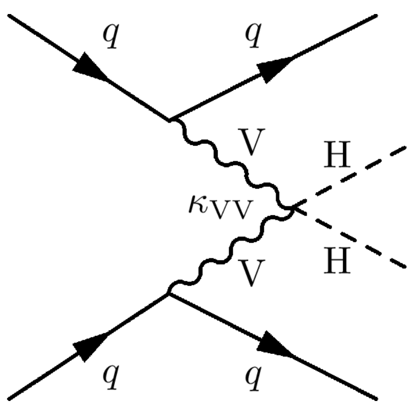


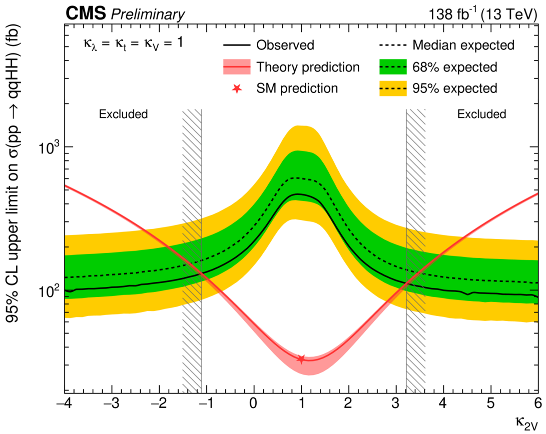
VHH coupling : dedicated analyses





[Eur. Phys. J. C 83 (2023) 519]

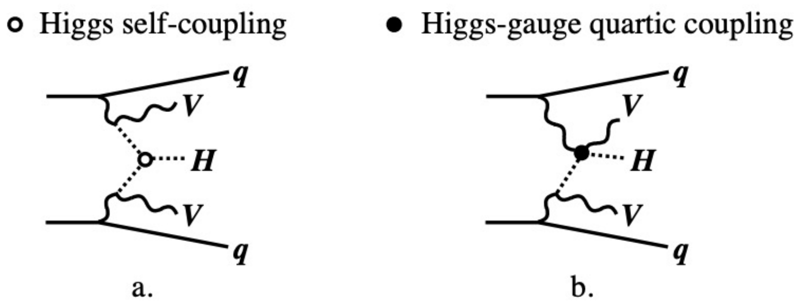




 [HIG-21-005]

Self-coupling from single Higgs

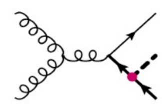
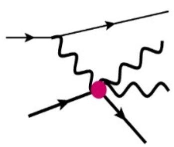
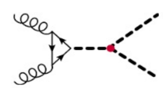
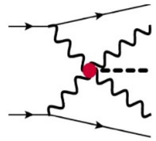
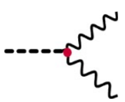
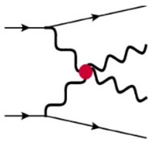
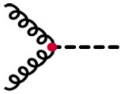
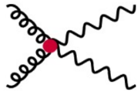
Higgs coupling without Higgs



- ❑ EFT could induce energy-growing effects involving longitudinally polarized W/Z bosons
- ❑ study these effects offshell and at high energy

$$\mathcal{O}_r = |H|^2 \partial_\mu H^\dagger \partial^\mu H, \qquad \mathcal{O}_{y_\psi} = Y_\psi |H|^2 \psi_L H \psi_R,$$
$$\mathcal{O}_{BB} = g'^2 |H|^2 B_{\mu\nu} B^{\mu\nu}, \qquad \mathcal{O}_{WW} = g^2 |H|^2 W^a_{\mu\nu} W^{a\mu\nu},$$
$$\mathcal{O}_{GG} = g_s^2 |H|^2 G^a_{\mu\nu} G^{a\mu\nu}, \qquad \mathcal{O}_6 = |H|^6,$$

PRL 123, 181801 (2019)

		HC	HwH	Growth
κ_t	$\mathcal{O}_{y_t}$			$\sim(E^2/\Lambda^2)$
κ_λ	$\mathcal{O}_6$			$\sim(vE/\Lambda^2)$
$\kappa_{Z\gamma}$ $\kappa_{\gamma\gamma}$ κ_V	$\mathcal{O}_{WW}$ $\mathcal{O}_{BB}$ $\mathcal{O}_r$			$\sim(E^2/\Lambda^2)$
κ_g	$\mathcal{O}_{gg}$			$\sim(E^2/\Lambda^2)$

Coupling structures in off-shell HVV

Higgs production rate: $d\sigma \propto \frac{g_{prod}^2 g_{dec}^2}{(q_H^2 - m_H^2)^2 + m_H^2\Gamma_H^2} dq_H^2$

$$\sigma^{on-shell} \propto \frac{g_{prod}^2 g_{dec}^2}{\Gamma_H} \propto \boxed{\mu_{on-shell}}$$

$$\sigma^{off-shell} \propto \int \frac{g_{prod}^2 g_{dec}^2}{(q_H^2 - m_H^2)^2} dq_H^2 \propto \mu_{off-shell} \propto \boxed{\mu_{on-shell} \times \Gamma_H/\Gamma_{SM}}$$

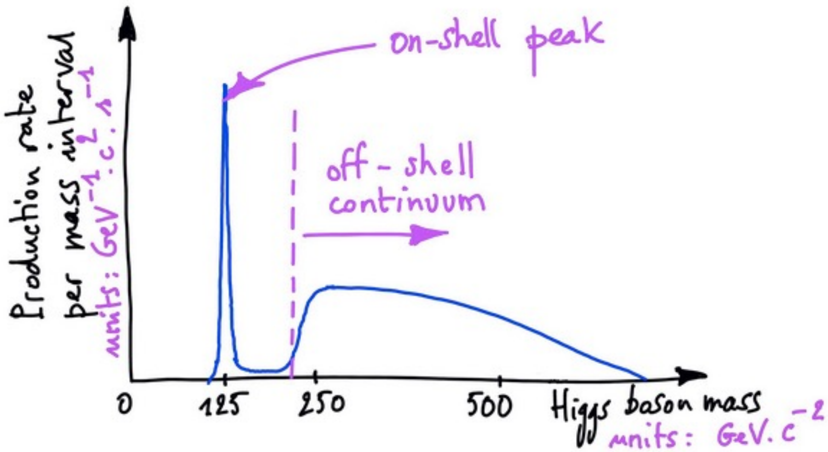
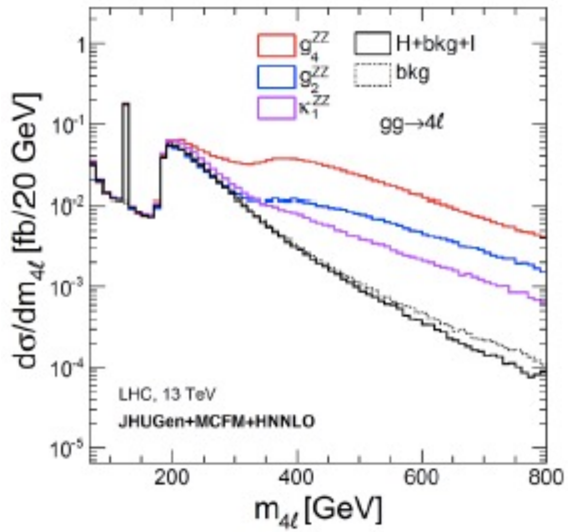
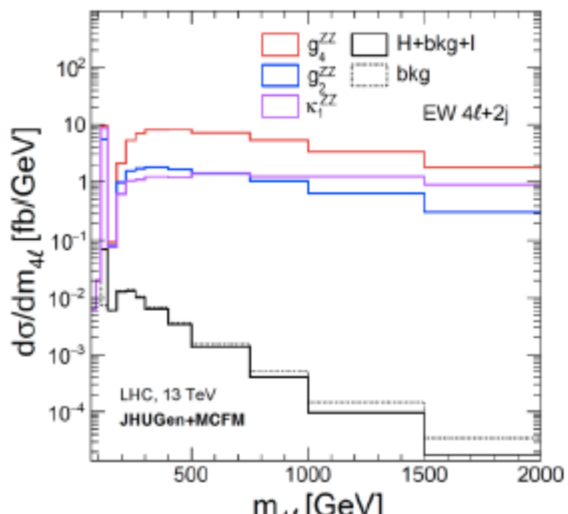


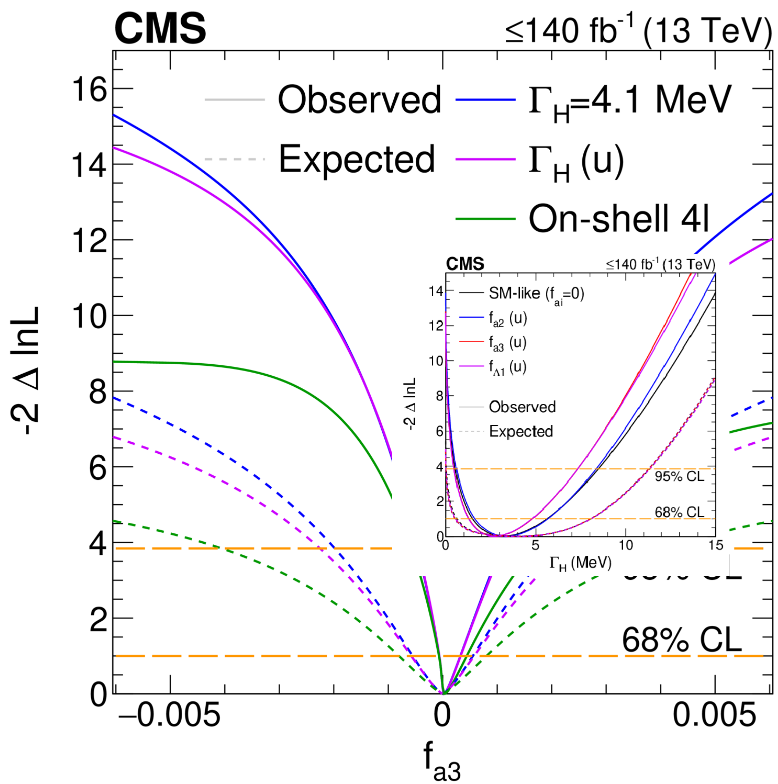
Fig. from https://cms.cern/news/life-higgs-boson



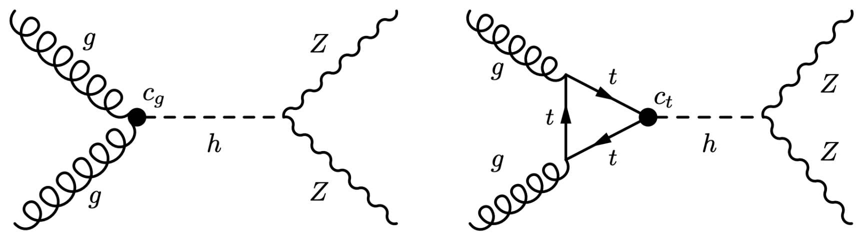
Phys. Rev. D 102, 056022 (2020)



Anomalous coupling/EFT in off-shell HVV

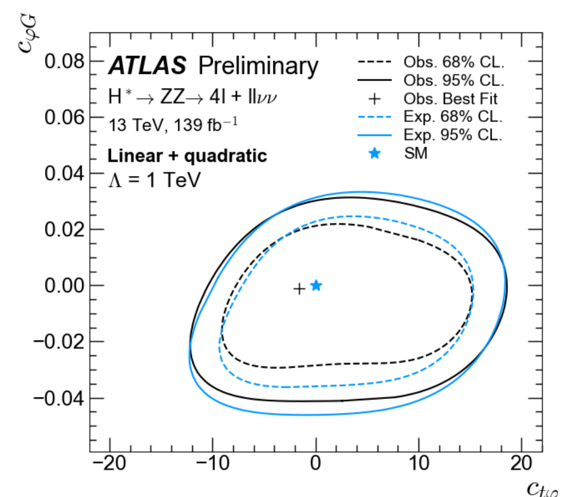


[Nat. Phys. 18 (2022) 1329]



$$\frac{\sigma^{\mathrm{SMEFT}}(c_t, c_g)}{\sigma^{\mathrm{SM}}} \simeq (c_t + c_g)^2 \left(1 - \frac{7}{15}\frac{c_g}{c_t + c_g}\frac{m_h^2}{4m_t^2}\right)$$

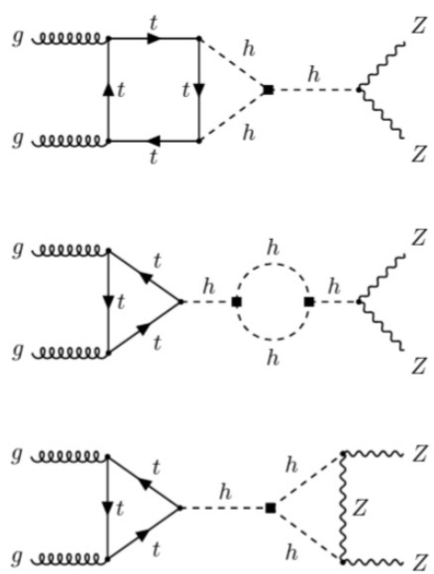
$$c_{\varphi G} = \frac{g_s^2 \Lambda^2}{48\pi^2 v^2} c_g$$



$$c_{t\varphi} = -\frac{y_t \Lambda^2}{v^2}(c_t - 1)$$

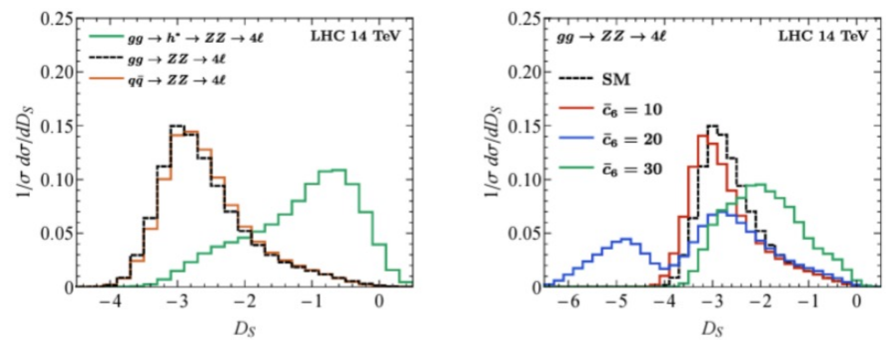
Trilinear-Higgs coupling from single Higgs off-shell

New off-shell effects can also be induced by modifications in the Higgs trilinear coupling ([JHEP 02 (2022) 030](#))

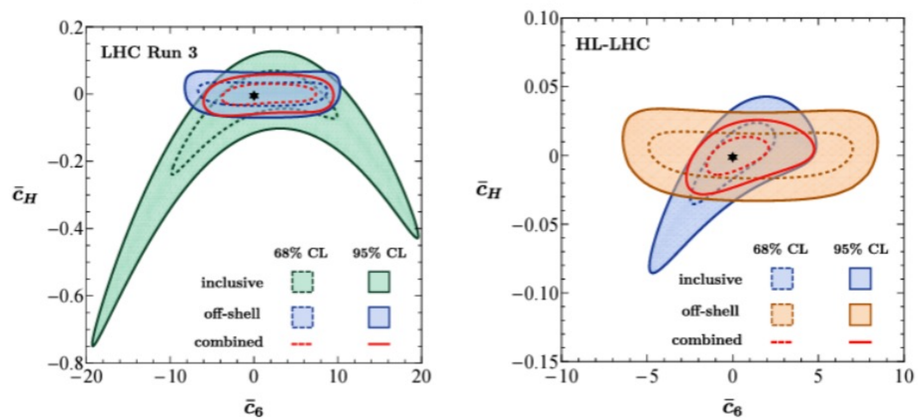


$$\mathcal{O}_6 = -\lambda |H|^6 \,, \qquad \mathcal{O}_H = \frac{1}{2}\left(\partial_\mu |H|^2\right)^2$$

$$c_3 = 1 + \bar{c}_6 - \frac{3}{2}\bar{c}_H$$

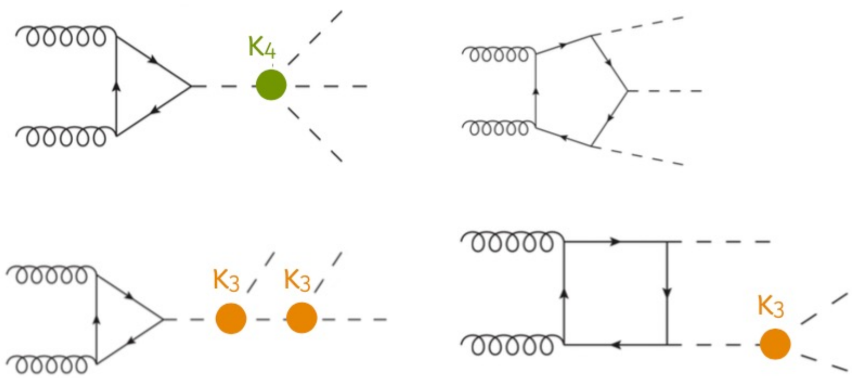


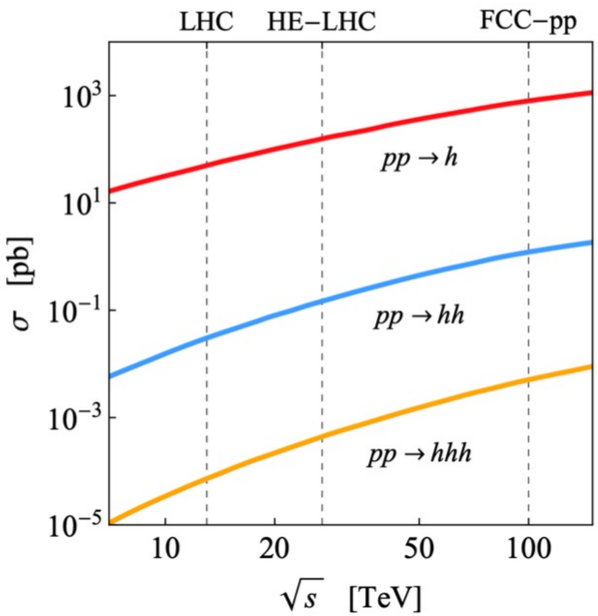
$$D_S = \log_{10}\left(\frac{P_h}{P_{gg} + c \cdot P_{q\bar{q}}}\right)$$



Quartic-Higgs interaction : HHH

pp→HHH:





Efforts on-going on ATLAS/CMS to challenge HHH->4b+X!

Machine learning technics widely investigated in

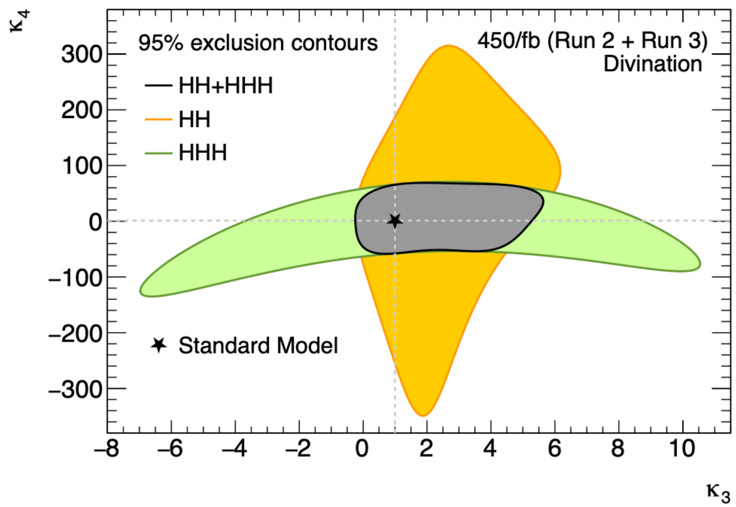
- ❑ (boosted) b jet tagging
- ❑ improve combinatorials in multi b-jet final state

Run 2 expected yields:

pp→HH: ~ 4500 events

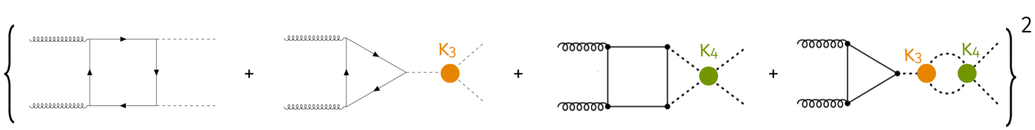
pp→HHH: ~ 13 events

Trilinear v.s. Quartic-Higgs interaction



See talk in HHH workshop 2023

$\sigma(pp \to HH) \sim$



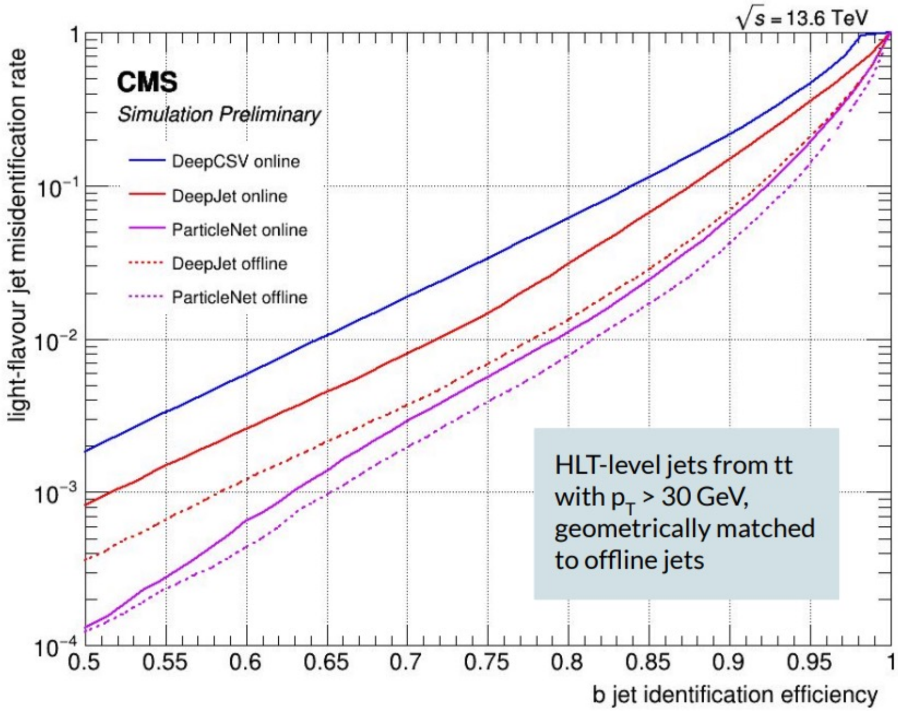
CERN-TH-2018-218

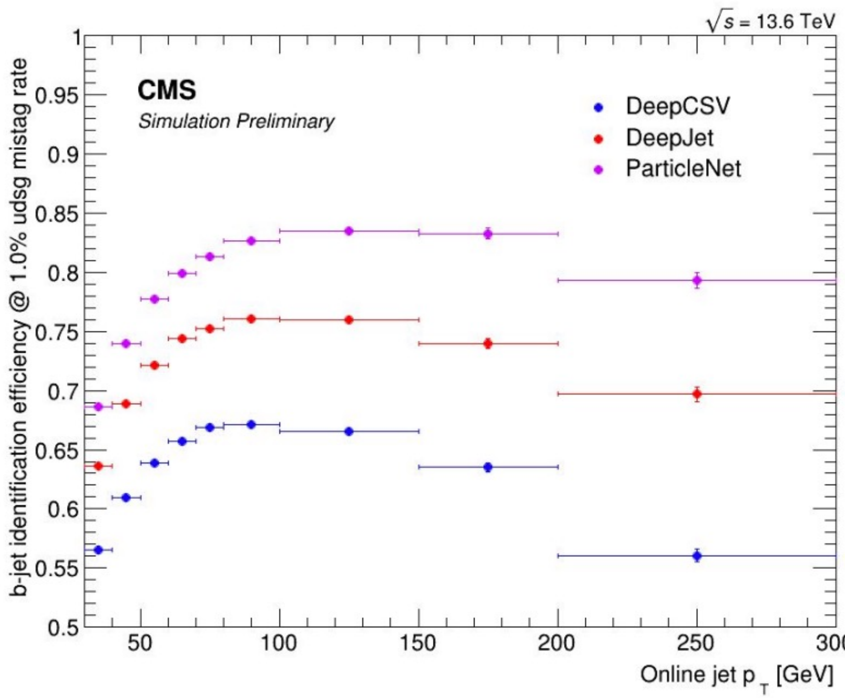
$\sim p_0 + p_1\ \kappa_3 + p_2\ \kappa_4 + p_3\ \kappa_3^2 + p_4\ \kappa_3\kappa_4 + p_5\ \kappa_4^2 + p_6\ \kappa_3^2\kappa_4 + p_7\ \kappa_3\kappa_4^2 + p_8\ \kappa_3^2\kappa_4^2$

With the combined Run 2 and Run 3 dataset we might already be getting close to the unitarity threshold for κ_4

Triggers in Run-3 for HH and HHH

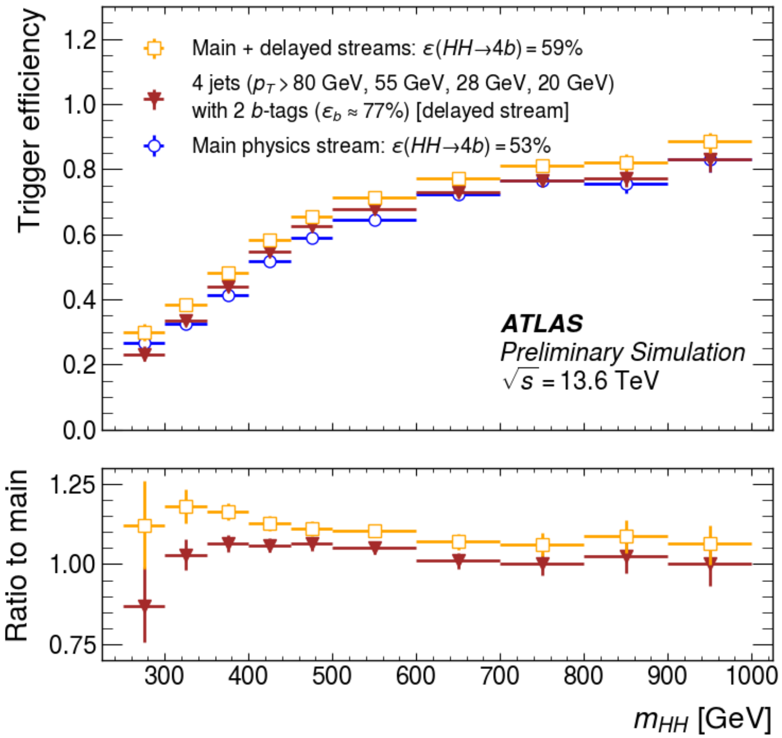
- Lighter version of ParticleNet tagger deployed online (HLT) since the beginning of Run 3
- 5-10% improvement w.r.t. DeepJet



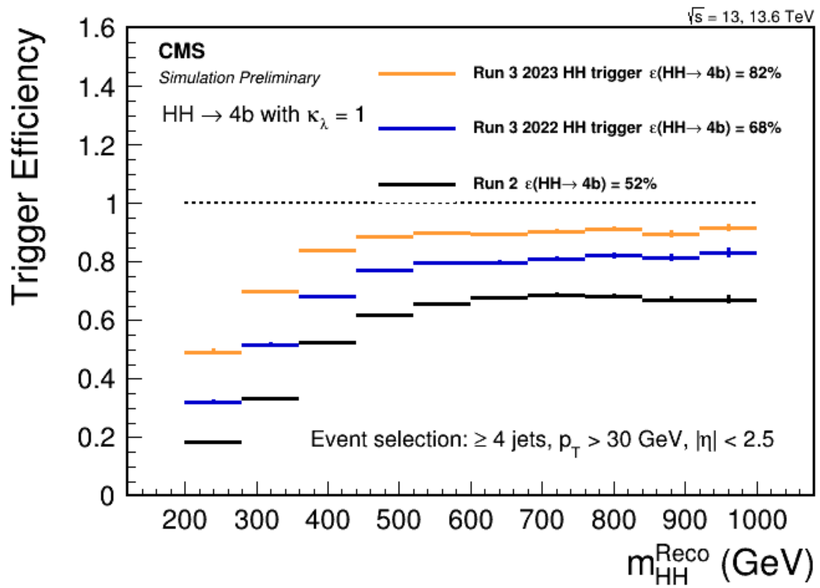


https://cds.cern.ch/record/2857440

Triggers in Run-3 for HH and HHH



[ATLAS trigger efficiency]

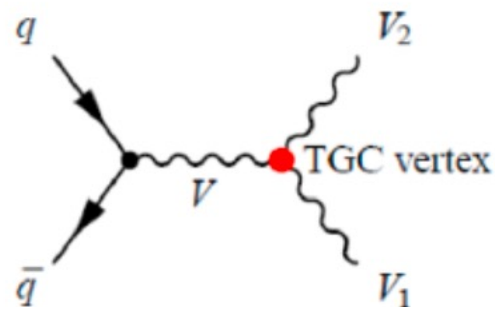


[CMS trigger efficiency]

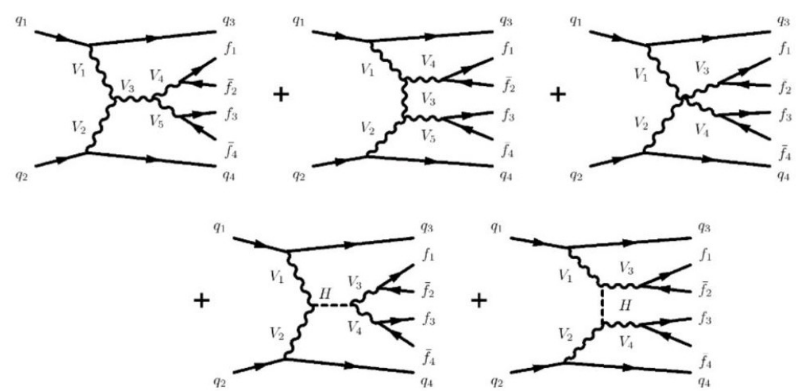
Delayed physics stream/data parking increase the trigger rate to 150/180Hz for ATLAS/CMS

Electroweak physics : multi-boson

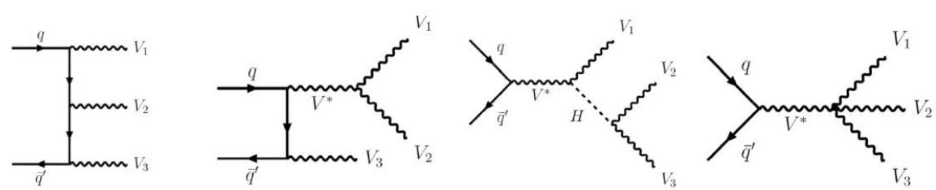
- ❑ Vector boson scattering/fusion processes probe the mechanism of electroweak symmetry breaking



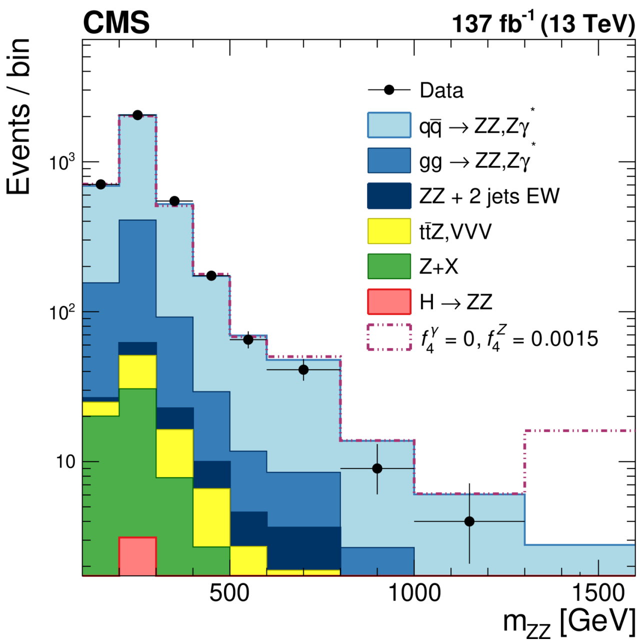
- ❑ Triple/Quartic Gauge Couplings:
  - ❑ search for anomalous couplings
  - ❑ EFT interpretation



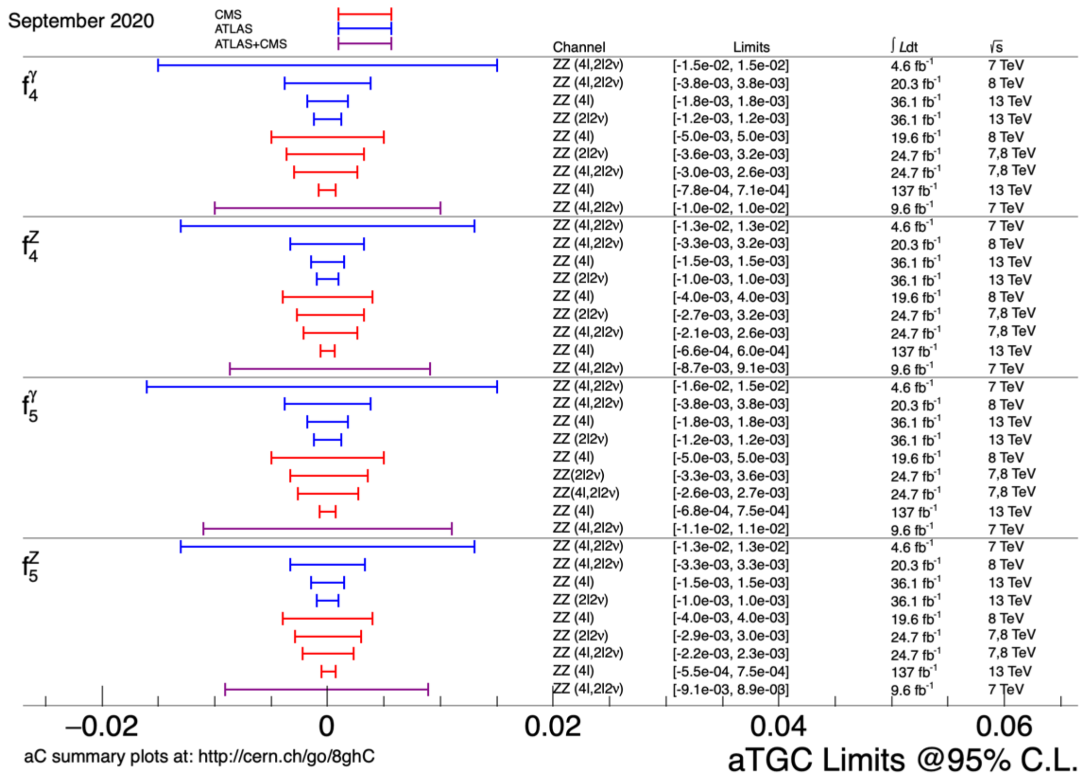
$$\mathcal{L}_{\mathrm{SMEFT}} \approx \mathcal{L}_{\mathrm{SM}}^{(4)} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)} + \sum_j \frac{c_j^{(8)}}{\Lambda^4} \mathcal{O}_j^{(8)}$$



EWK physics : aTGC in di-boson

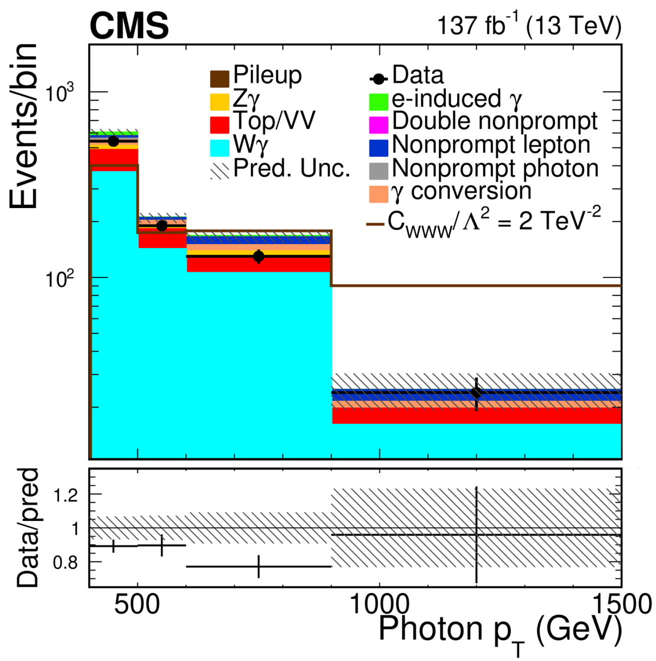


EPJC 81 (2021) 200



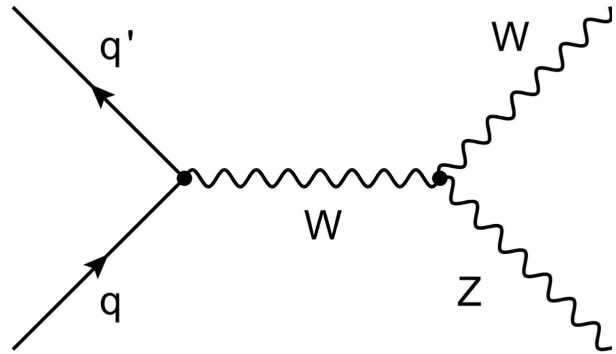
link to summary twiki

EWK physics : aTGC in di-boson

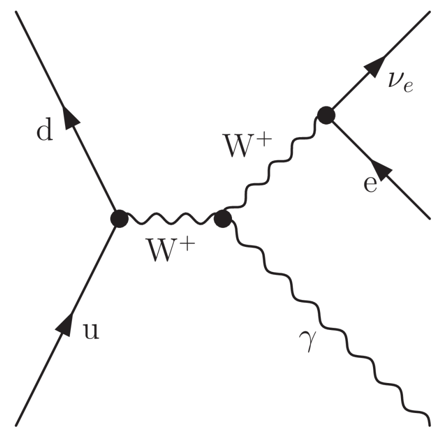


Coefficient	Exp. lower	Exp. upper	Obs. lower	Obs. upper
c_{WWW}/Λ^2	−0.85	0.87	−0.90	0.91
c_B/Λ^2	−46	45	−40	41
$c_{\widetilde{W}WW}/\Lambda^2$	−0.43	0.43	−0.45	0.45
$c_{\widetilde{W}}/\Lambda^2$	−23	22	−20	20

More charged aTGC results are at here

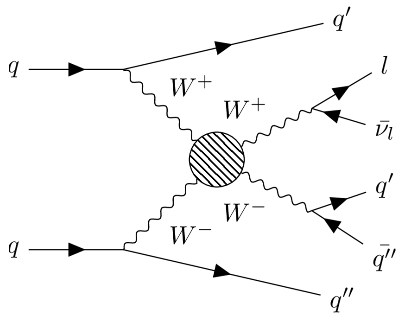


JHEP 07 (2022) 032

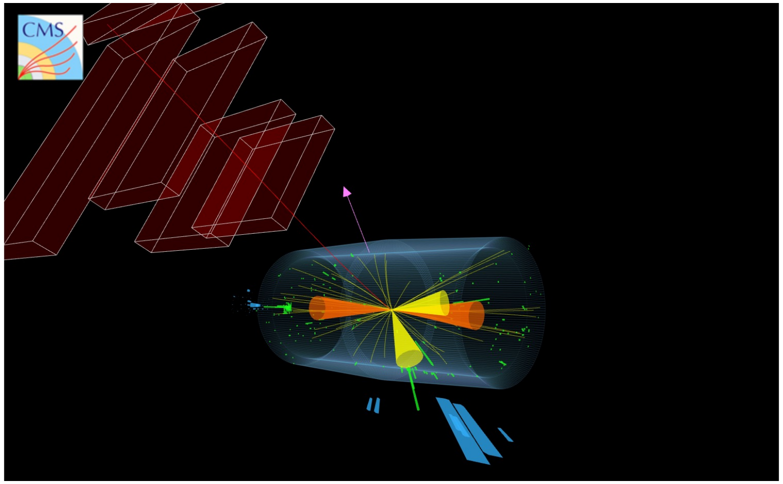


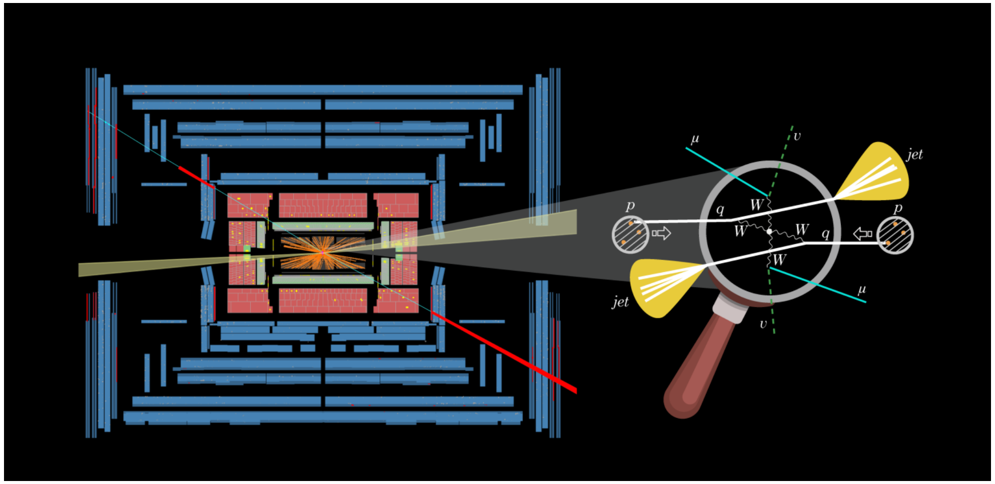
Phys. Rev. Lett. 126 (2021) 252002

VBS : LHC as the vector boson collider



[Phys. Lett. B 834 (2022) 137438]



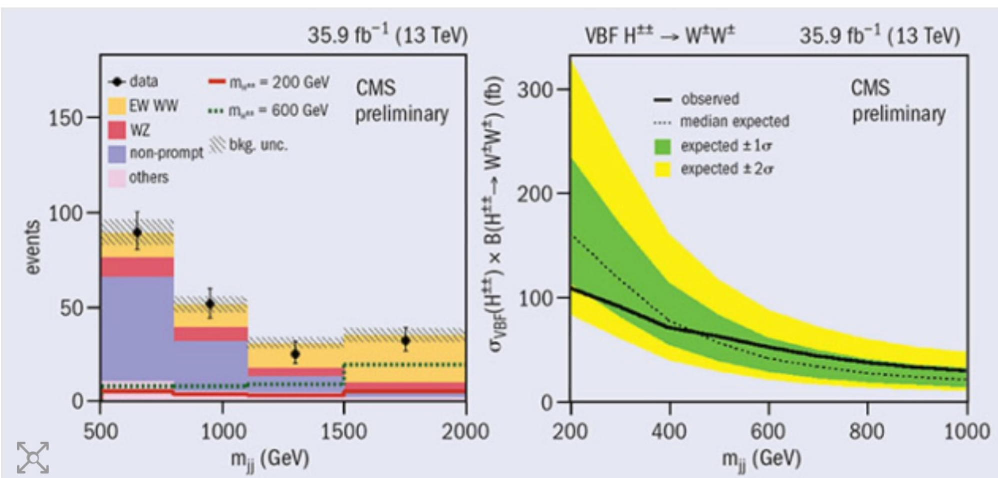


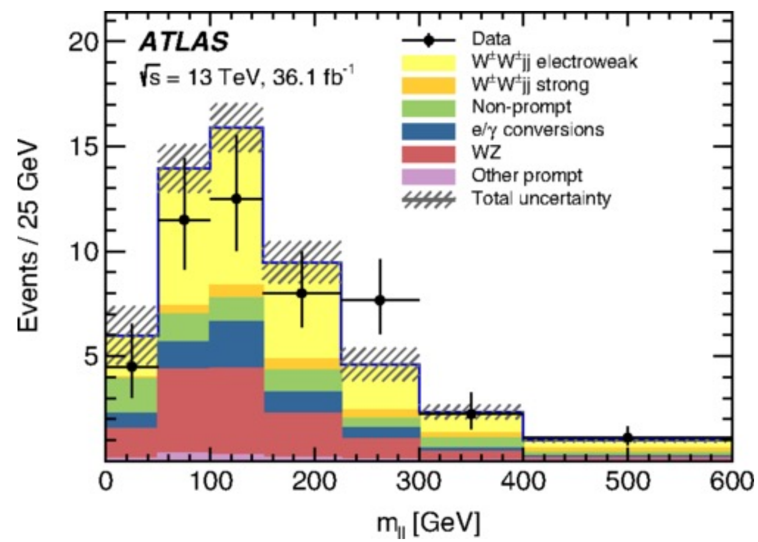
VBS : LHC as the vector boson collider

HIGGS AND ELECTROWEAK | NEWS

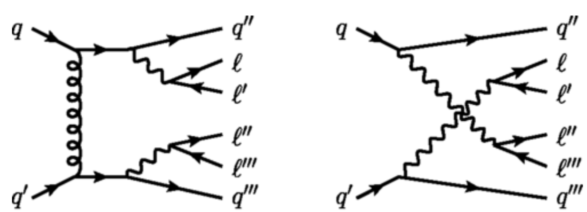
CMS observes production of same-sign W-boson pairs

10 July 2017





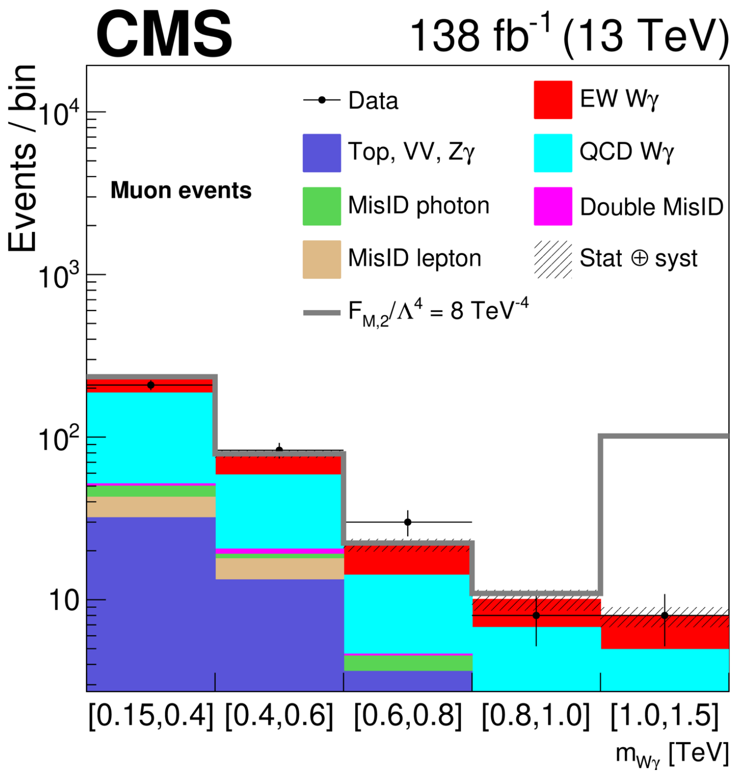
PhysRevLett.120.081801

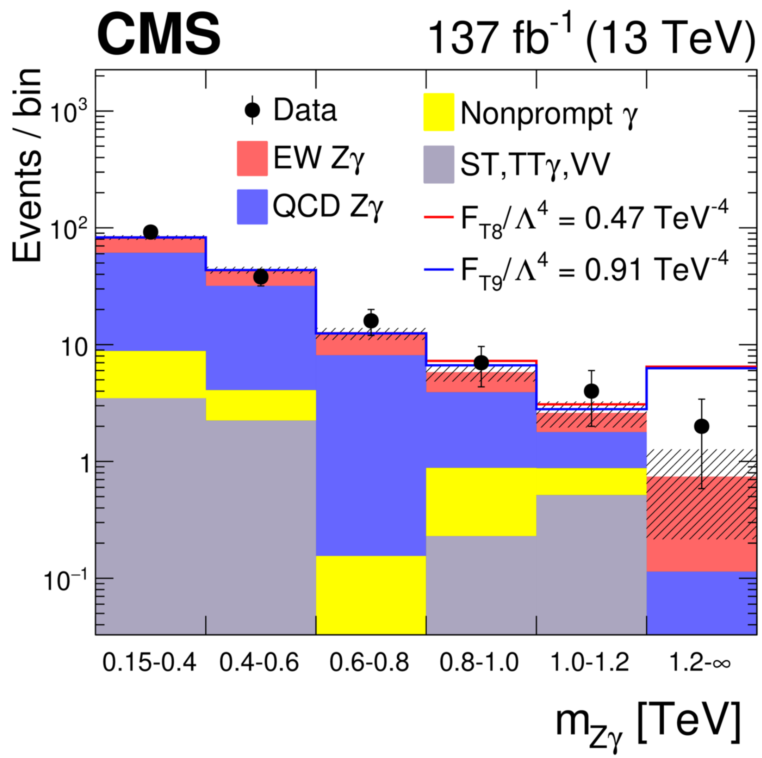


(a) (b)

PhysRevLett.120.081801

Electroweak physics : VBS Wγ/ Zγ

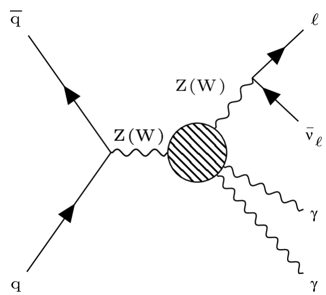


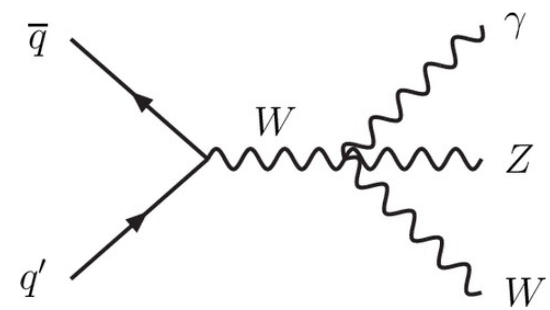


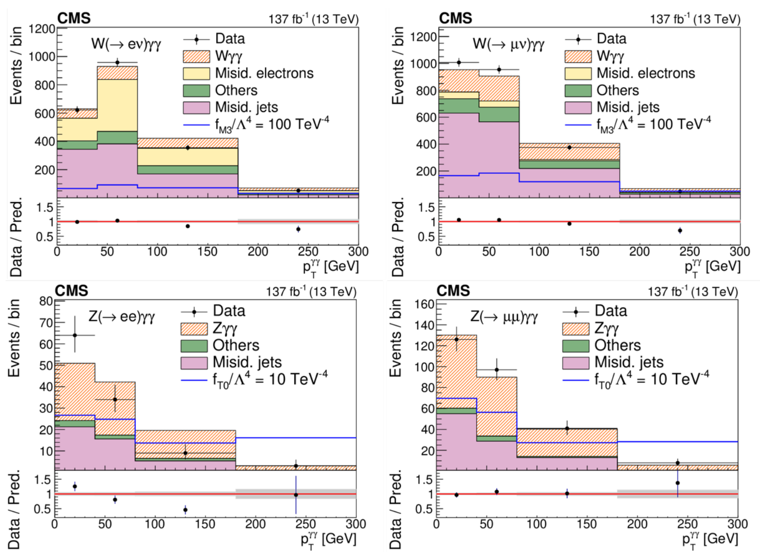
Phys. Rev. D 108 (2023) 032017

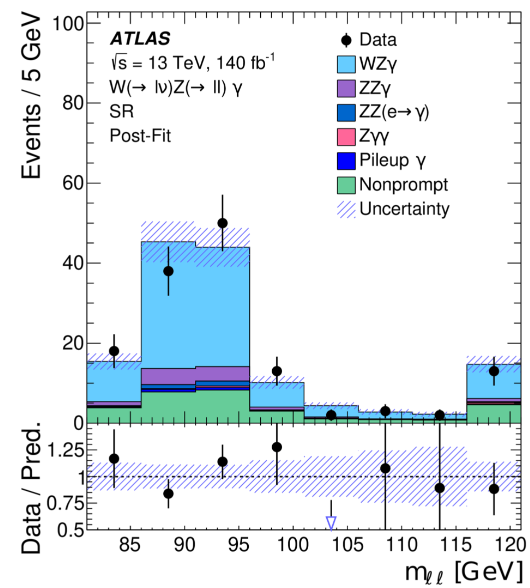
Phys. Rev. D 104 (2021) 072001

Electroweak physics : tri-boson





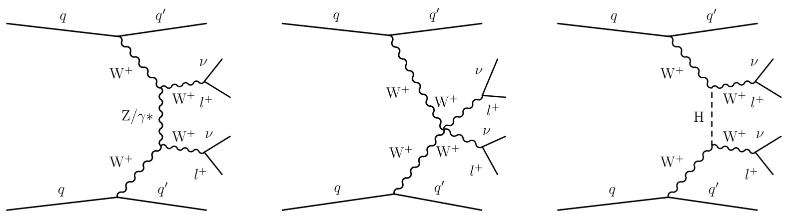


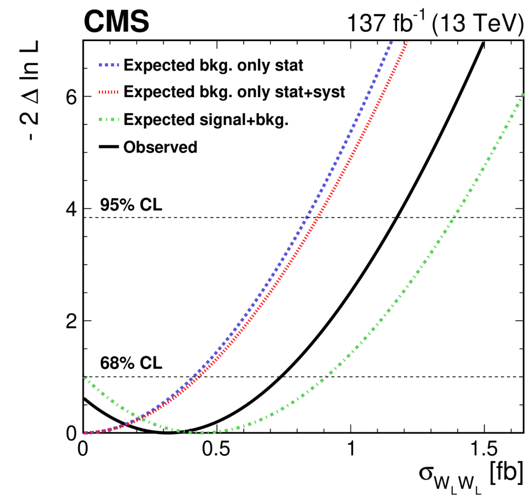


[JHEP 10 (2021) 174](#)
[Eur. Phys. J. C 83 (2023) 539](#)
[Phys. Lett. B 848 (2024) 138400](#)

[Phys. Rev. Lett. 132 (2024) 021802](#)

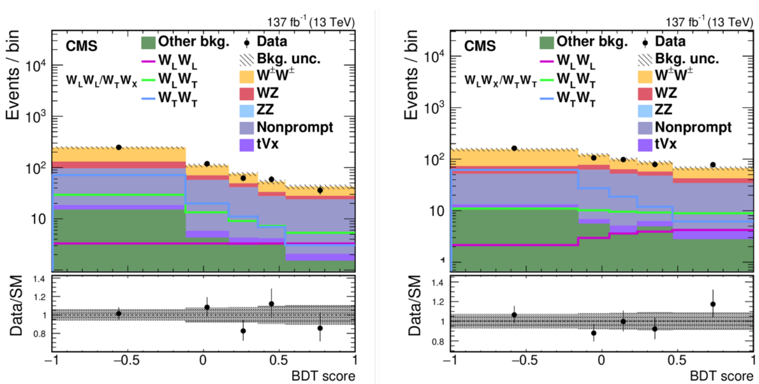
EWK physics : VBS polarization





$V_L V_L$ scattering is related to the scattering of Goldstone bosons, which probes the mechanism of electroweak symmetry breaking

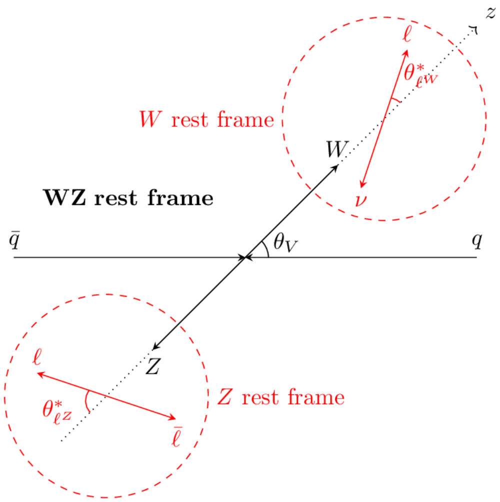
[Phys.Rev.Lett. 69(1992) 2619]

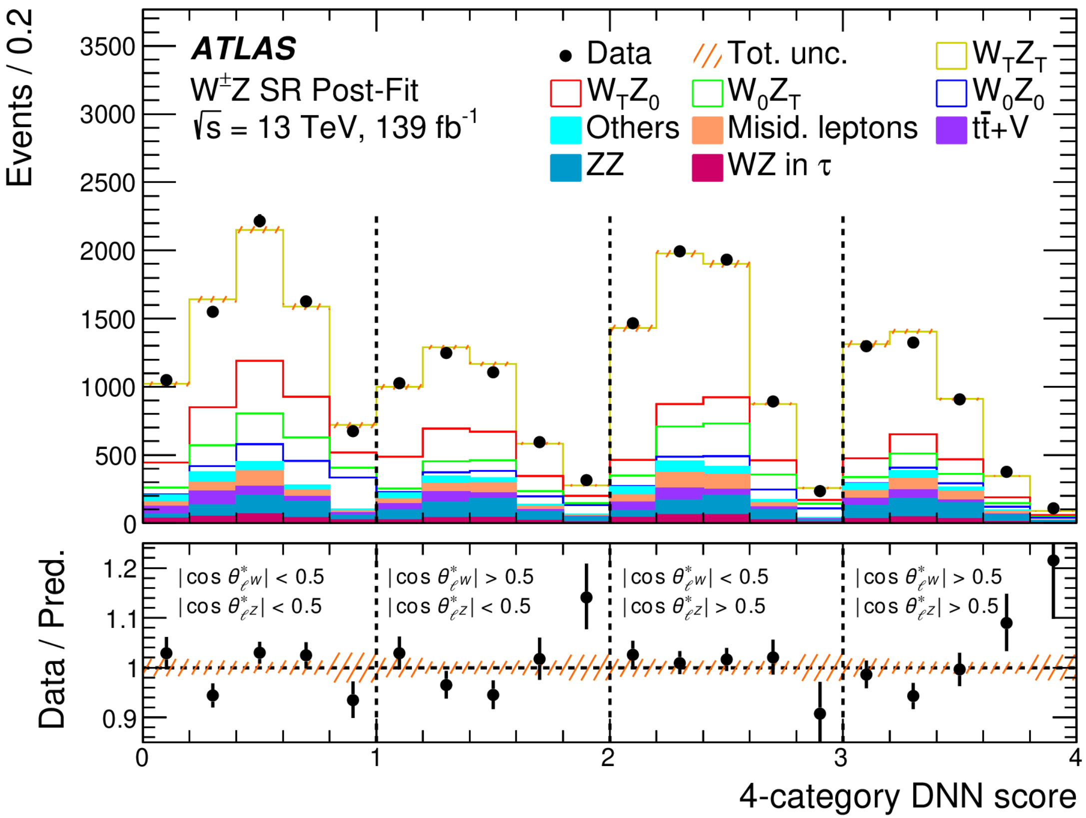


[Phys. Lett. B 812 (2020) 136018]

- ❑ Simultaneous fit on two BDT discriminants to separate polarization
- ❑ LL and LT+LL:
  0.88 (1.17)σ 2.3 (3.1)σ

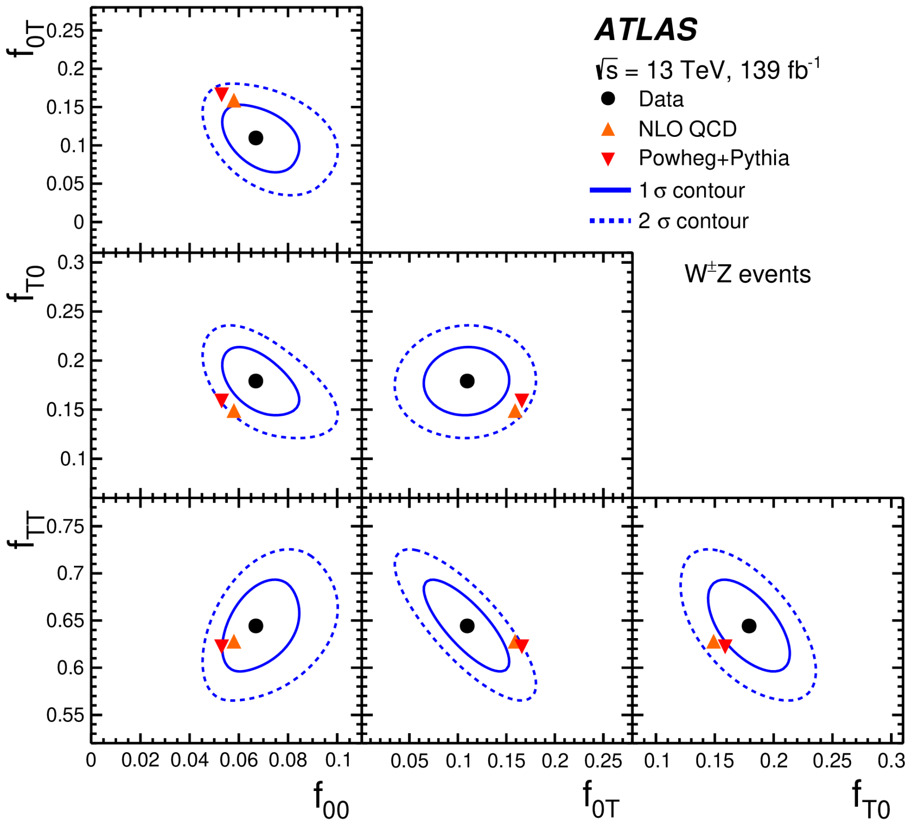
EWK physics : VBS polarization





Phys. Lett. B 843 (2023) 137895

EWK physics : VBS polarization

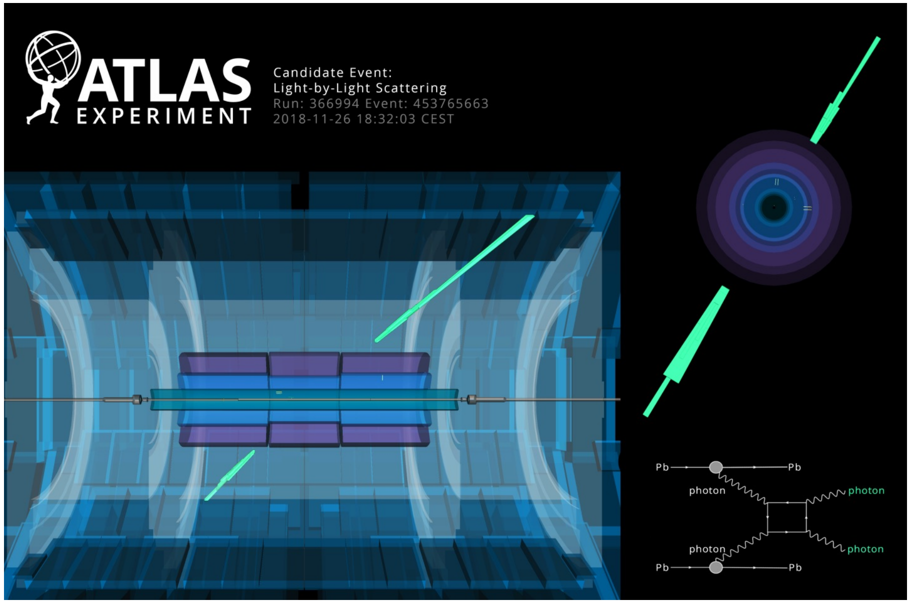


Also see CMS at JHEP 07 (2022) 032

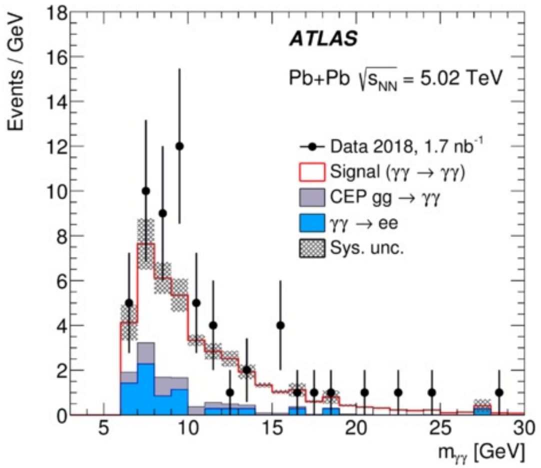
	Data	POWHEG+PYTHIA	NLO QCD
	$W^{\pm}Z$		
f_{00}	0.067 ± 0.010	0.0590 ± 0.0009	0.058 ± 0.002
f_{0T}	0.110 ± 0.029	0.1515 ± 0.0017	0.159 ± 0.003
f_{T0}	0.179 ± 0.023	0.1465 ± 0.0017	0.149 ± 0.003
f_{TT}	0.644 ± 0.032	0.6431 ± 0.0021	0.628 ± 0.004
	$W^{+}Z$		
f_{00}	0.072 ± 0.016	0.0583 ± 0.0012	0.057 ± 0.002
f_{0T}	0.119 ± 0.034	0.1484 ± 0.0022	0.155 ± 0.003
f_{T0}	0.152 ± 0.033	0.1461 ± 0.0022	0.147 ± 0.003
f_{TT}	0.66 ± 0.04	0.6472 ± 0.0026	0.635 ± 0.004
	$W^{-}Z$		
f_{00}	0.063 ± 0.016	0.0600 ± 0.0014	0.059 ± 0.002
f_{0T}	0.11 ± 0.04	0.1560 ± 0.0027	0.166 ± 0.003
f_{T0}	0.21 ± 0.04	0.1470 ± 0.0027	0.152 ± 0.003
f_{TT}	0.62 ± 0.05	0.6370 ± 0.0033	0.618 ± 0.004

First observation of WZ state: 7.1 (6.2)σ in observation

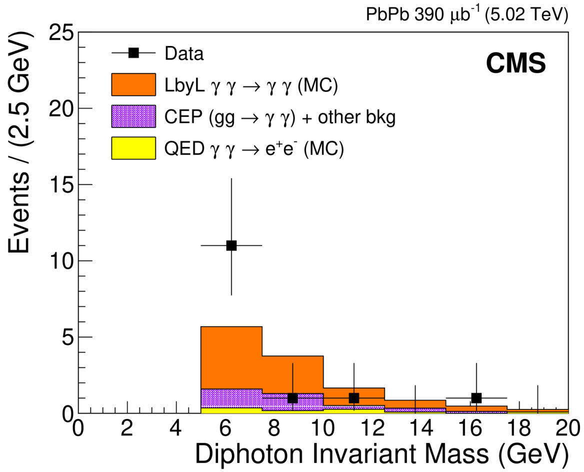
LHC as a photon collider



ultraperipheral Pb+Pb collisions

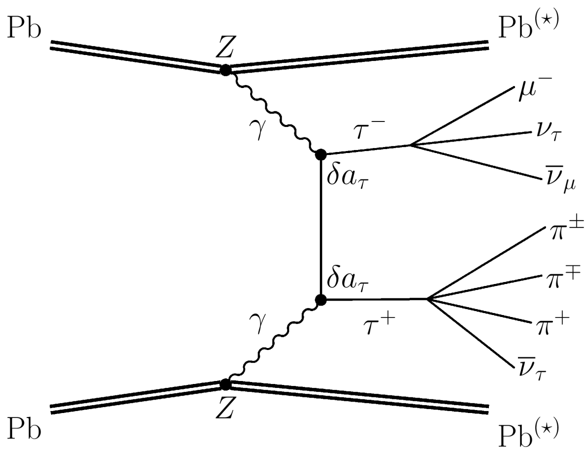


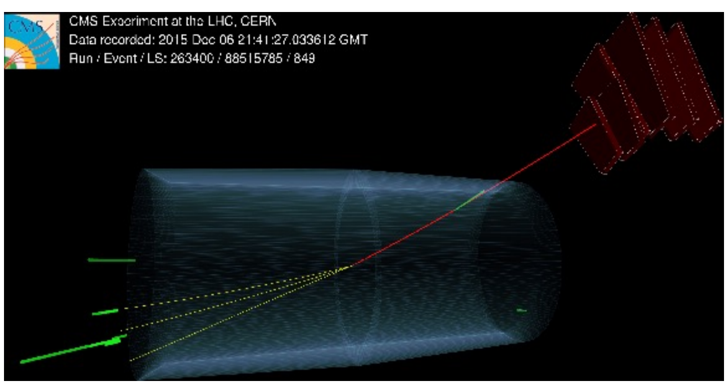
Phys. Rev. Lett. 123 (2019) 052001

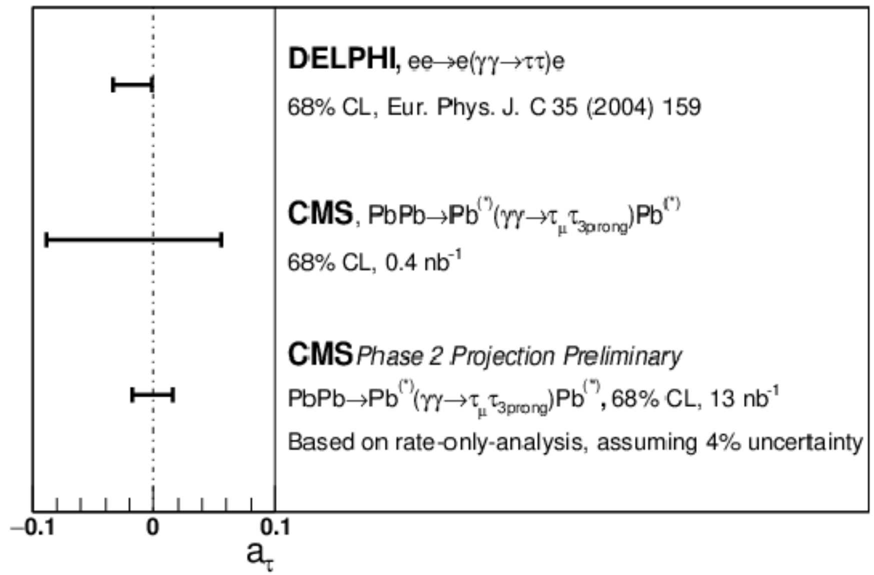


Phys. Lett. B 797 (2019) 134826

LHC as a photon collider : anomalous magnetic moment

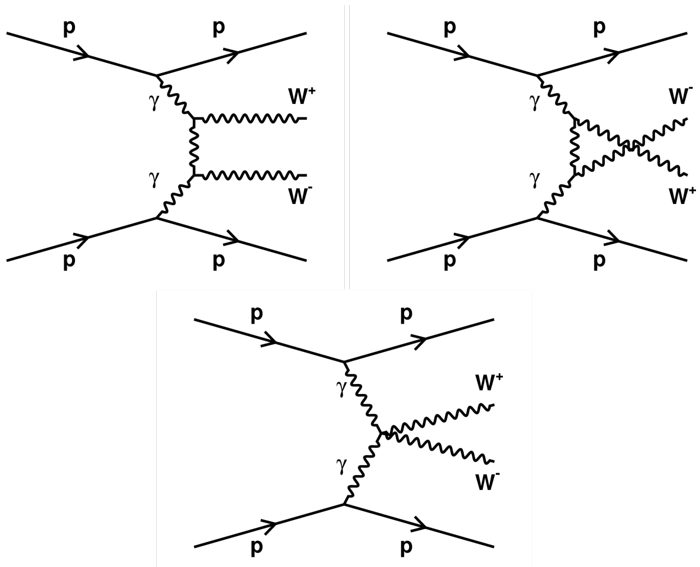


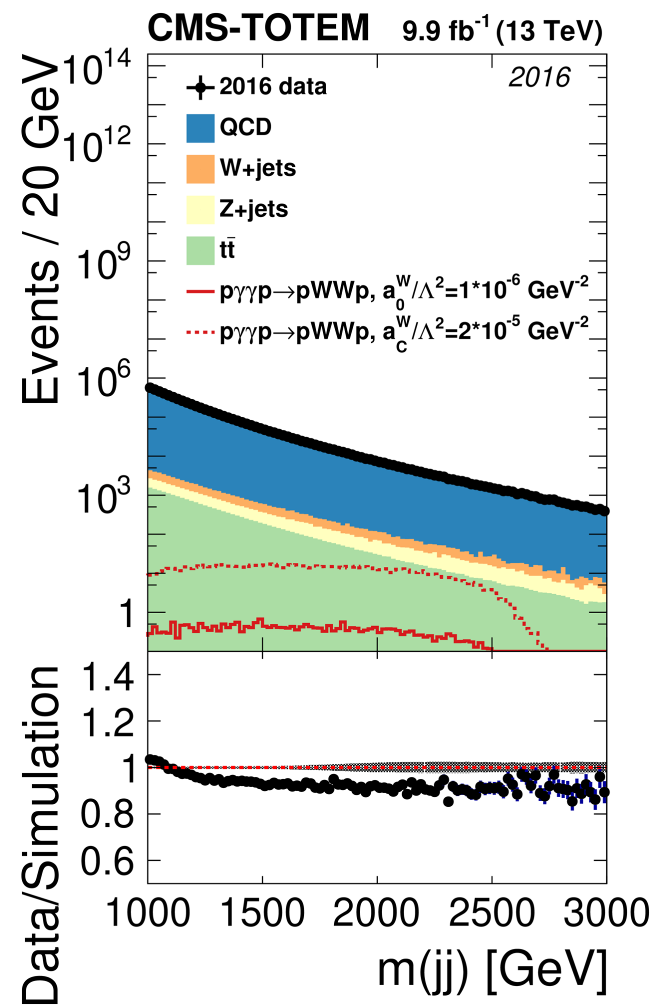




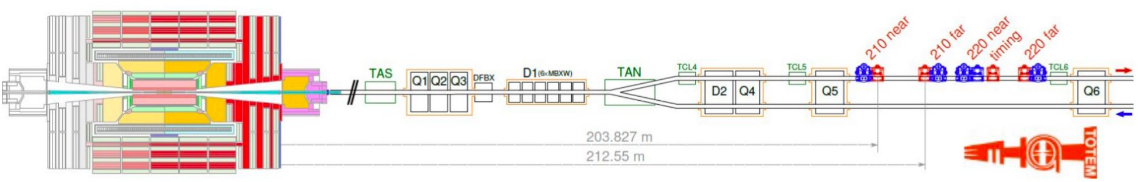
Phys. Rev. Lett. 131 (2023) 151803

LHC as a photon collider



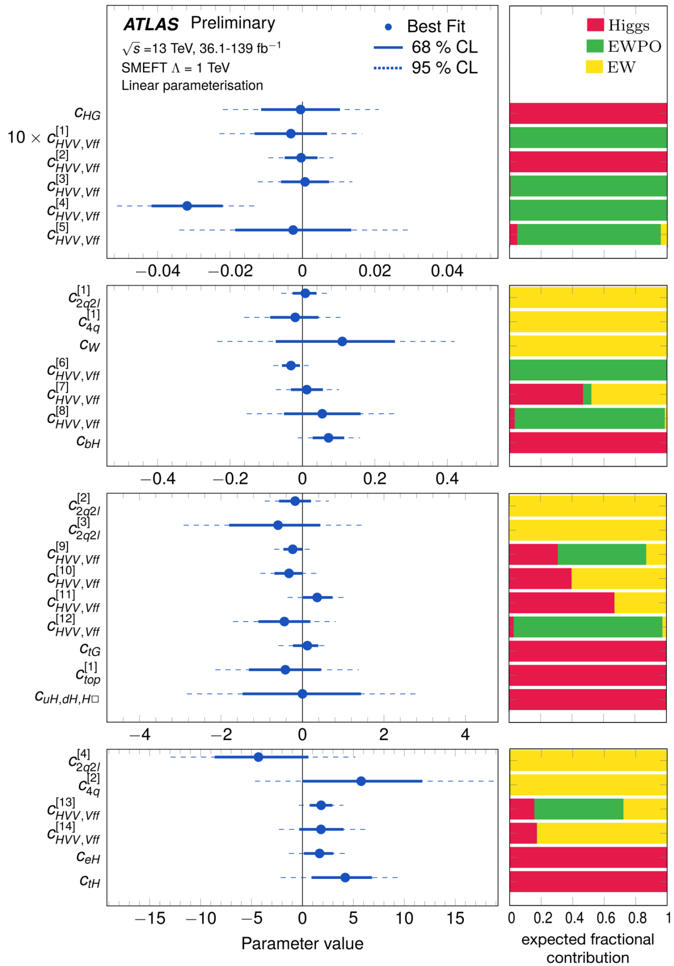


CMS-TOTEM Precision Proton Spectrometer (CTPPS)
is used to tag light-by-light interactions in proton collisions



https://cms.cern/news/lhc-photon-collider

EWK physics : global EFT

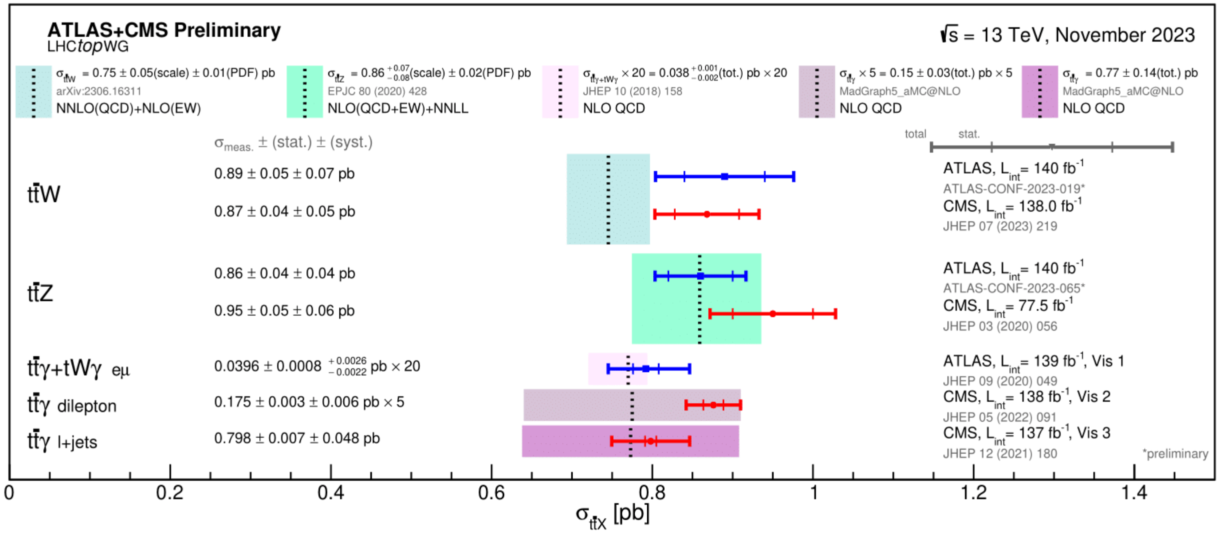


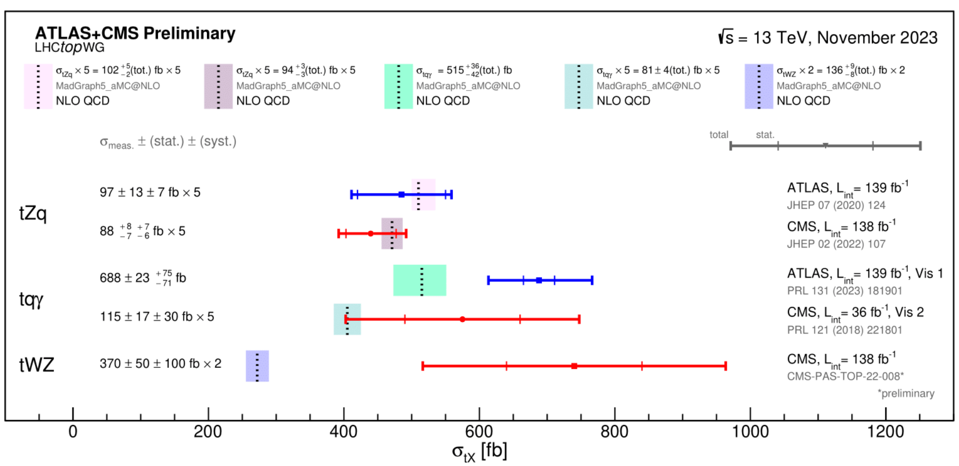
Decay channel	Target Production Modes	$\mathcal{L}$ [fb^{-1}]	Ref.
$H \to \gamma\gamma$	ggF, VBF, $WH, ZH, t\bar{t}H, tH$	139	[10]
$H \to ZZ^*$	ggF, VBF, $WH, ZH, t\bar{t}H(4\ell)$	139	[11]
$H \to WW^*$	ggF, VBF	139	[12]
$H \to \tau\tau$	ggF, VBF, $WH, ZH, t\bar{t}H(\tau_{\text{had}}\tau_{\text{had}})$	139	[13]
$H \to b\bar{b}$	WH, ZH	139	[14,15,16]
	VBF	126	[17]
	$t\bar{t}H$	139	[18]

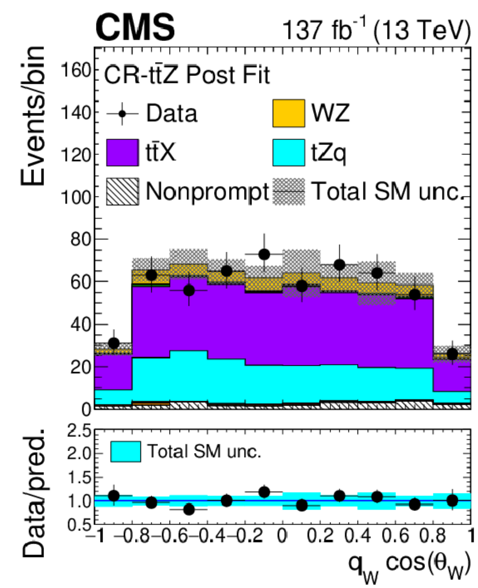
Process	Important phase space requirements	Observable	$\mathcal{L}$ [fb^{-1}]	Ref.
$pp \to e^{\pm}\nu\mu^{\mp}\nu$	$m_{\ell\ell} > 55\,GeV$, $p_{\text{T}}^{\text{jet}} < 35\,GeV$	$p_{\text{T}}^{\text{lead. lep.}}$	36	[19]
$pp \to \ell^{\pm}\nu\ell^{+}\ell^{-}$	$m_{\ell\ell} \in (81, 101)\,GeV$	m_{T}^{WZ}	36	[20]
$pp \to \ell^{+}\ell^{-}\ell^{+}\ell^{-}$	$m_{4\ell} > 180\,GeV$	m_{Z2}	139	[21]
$pp \to \ell^{+}\ell^{-}jj$	$m_{jj} > 1000\,GeV$, $m_{\ell\ell} \in (81, 101)\,GeV$	$\Delta\phi_{jj}$	139	[22]

ATL-PHYS-PUB-2022-037

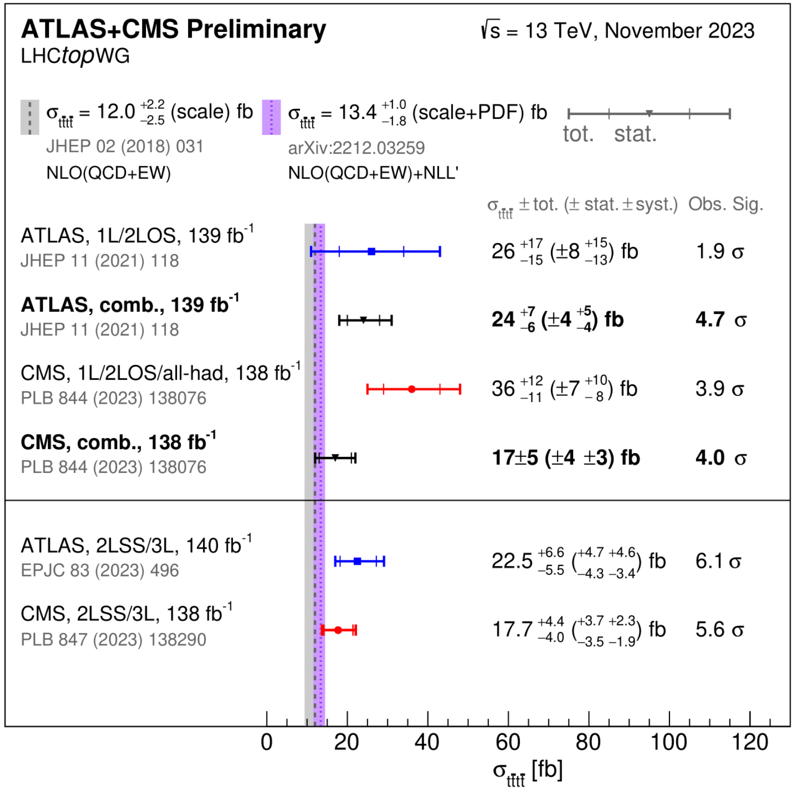
Top physics : cross sections





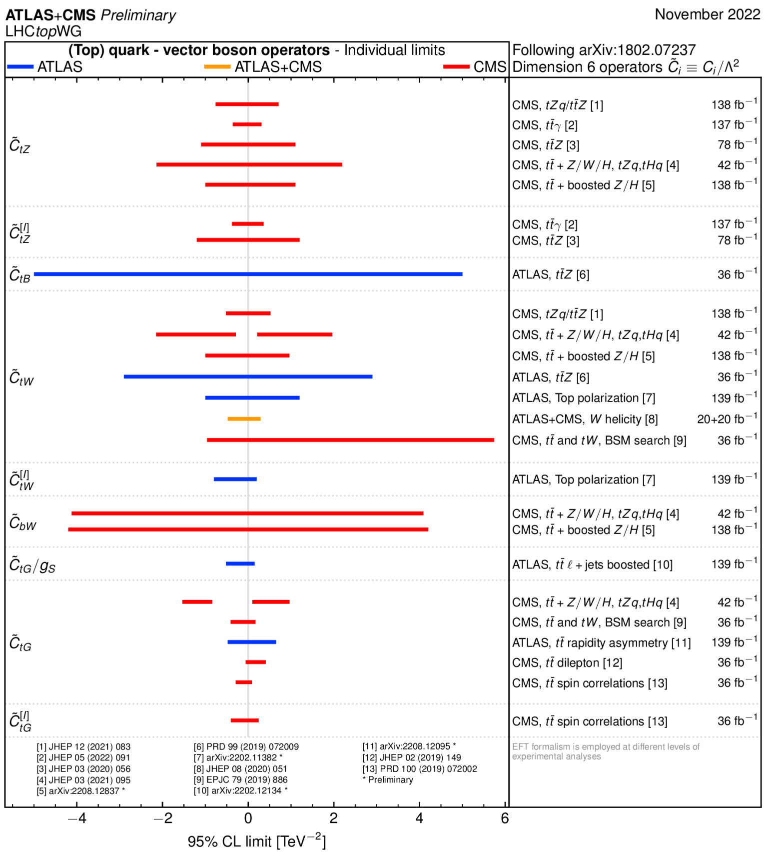


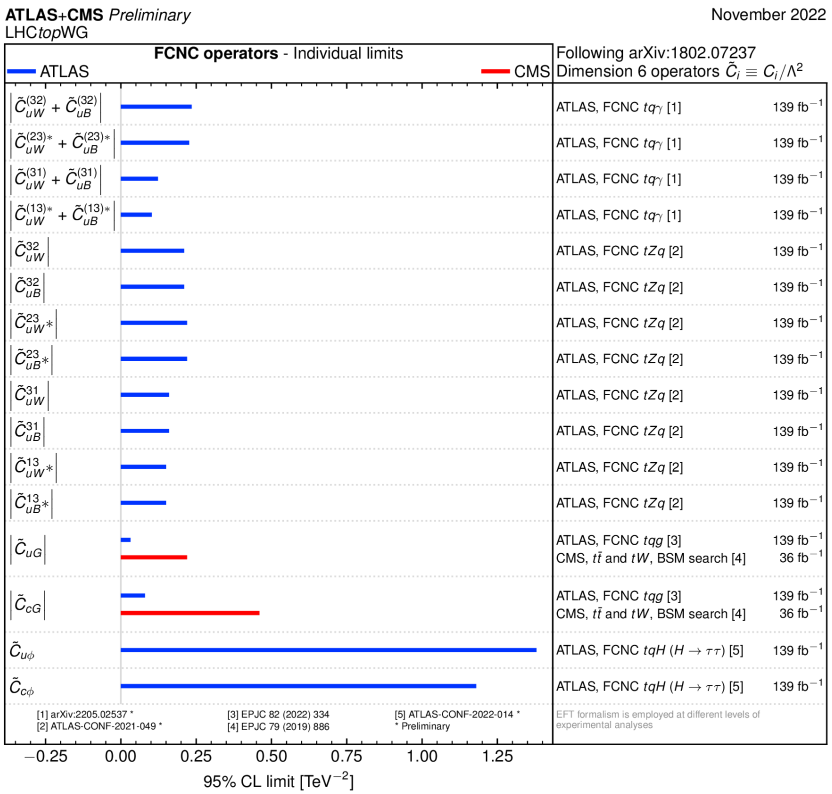
Top physics : four-top process



- sensitive to EFT operators
  - cross section is ~20% more at 13.6 TeV while backgrounds don't scale that much
  - observation in 2lSS/3l channels, opportunity to revisit other channels

Top EFT : t+X, ttbar+X, four-top, FCNC

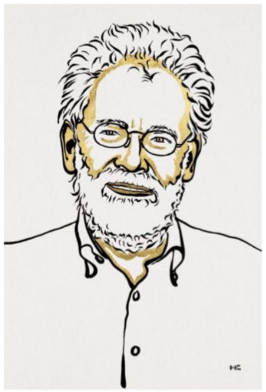




Test quantum mechanics at the LHC

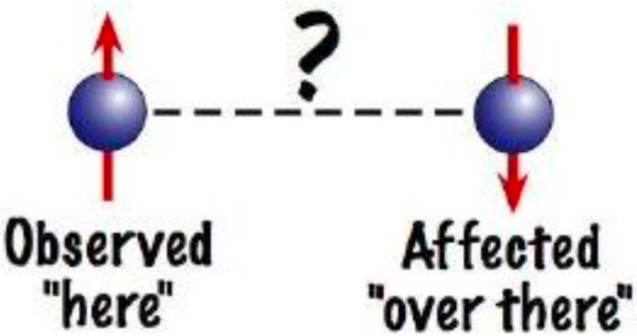
Ill. Niklas Elmehed © Nobel Prize Outreach
Alain Aspect
Prize share: 1/3

Ill. Niklas Elmehed © Nobel Prize Outreach
John F. Clauser
Prize share: 1/3



Ill. Niklas Elmehed © Nobel Prize Outreach
Anton Zeilinger
Prize share: 1/3

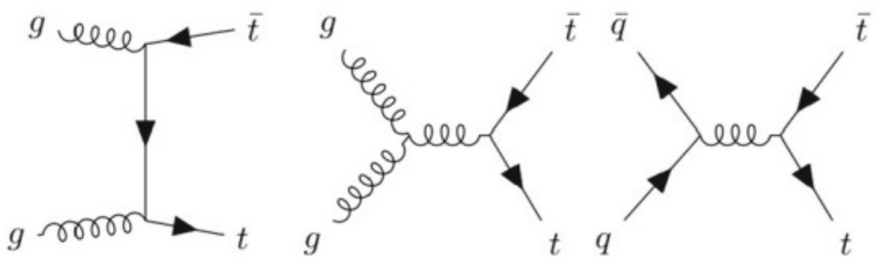
The Nobel Prize in Physics 2022 was awarded jointly to Alain Aspect, John F. Clauser and Anton Zeilinger "for experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science"



$$|\Phi^{\pm}\rangle = \frac{1}{\sqrt{2}}\big(\,|\uparrow\uparrow\rangle \pm |\downarrow\downarrow\rangle\,\big),$$

$$|\Psi^{\pm}\rangle = \frac{1}{\sqrt{2}}\big(\,|\uparrow\downarrow\rangle \pm |\downarrow\uparrow\rangle\,\big).$$

Quantum tomograph



$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega_1\Omega_2} = \frac{1}{4\pi^2}\left(1 + \alpha_1\,\mathbf{B}_1\cdot\hat{\ell}_1 + \alpha_2\,\mathbf{B}_2\cdot\hat{\ell}_2 + \alpha_1\alpha_2\,\hat{\ell}_1\cdot\mathbb{C}\cdot\hat{\ell}_2\right)$$

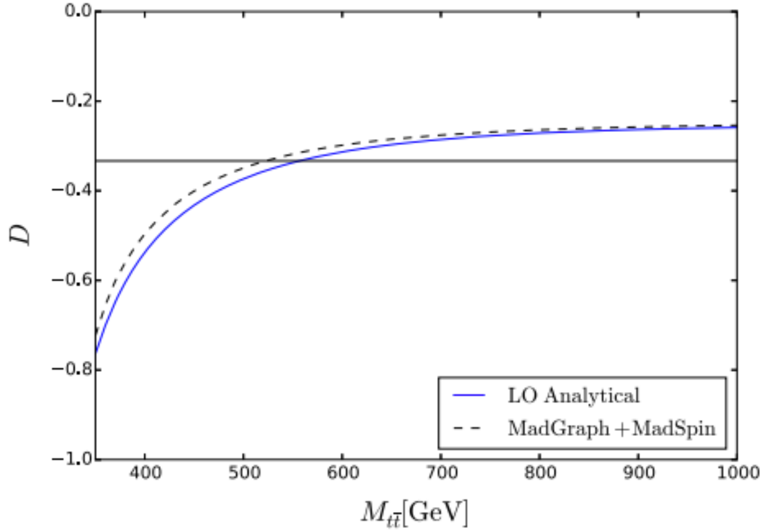
top polarisations ✚ spin correlations

= full spin density matrix

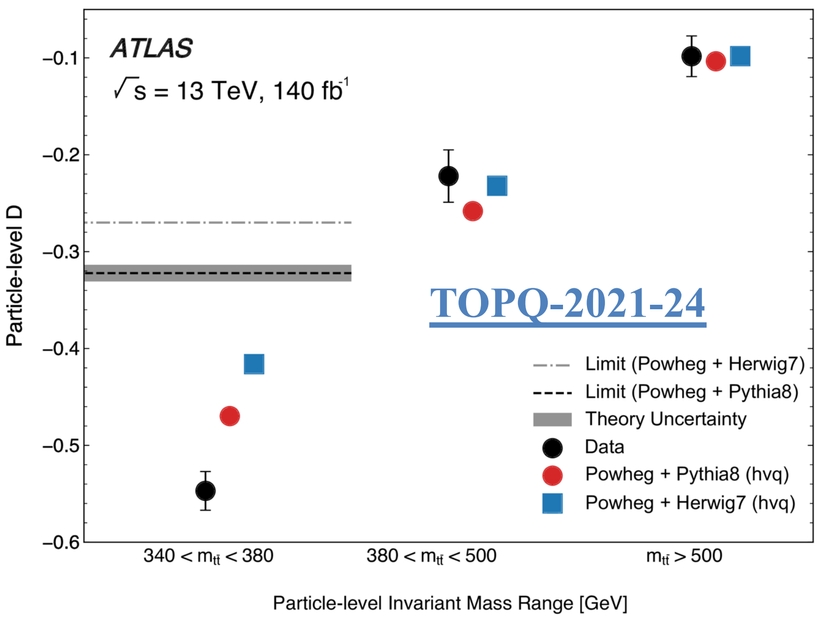
- ❑ Quantum tomograph : measure Bs and Cs
- ❑ P and CP invariance under ttbar production : $B_1 = B_2 = 0$ and $C_{ij} = C_{ji}$

Entanglement in ttbar

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\varphi} = \frac{1}{2}(1 - D\cos\varphi)$$



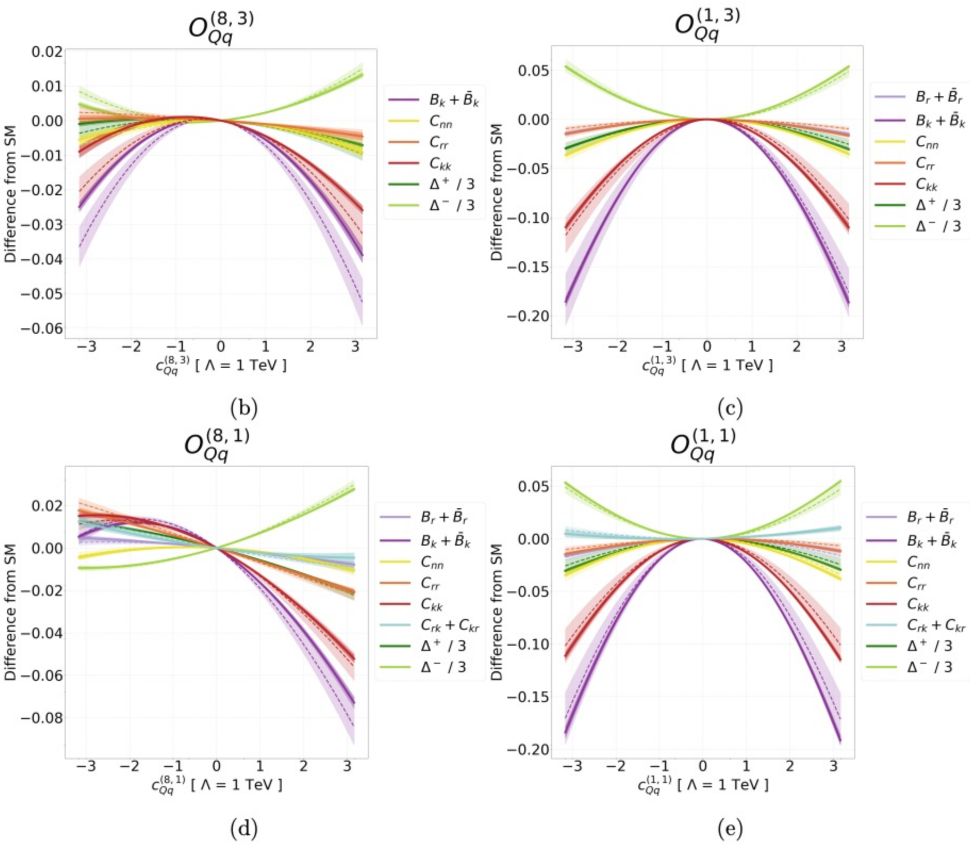
Eur. Phys. J. Plus (2021) 136:907



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

D < 1/3 : a quantum entanglement marker

Quantum entanglement and SMEFT



Four fermion operators

$$\mathcal{O}_{tu}^{8} = \sum_{\mathrm{f}=1}^{2}(\bar{t}\gamma_\mu T^A t)(\bar{u}_\mathrm{f}\gamma^\mu T_A u_\mathrm{f}) = \sum_{\mathrm{f}=1}^{2} -\tfrac{1}{6}\mathcal{Q}_{uu,\mathrm{ff33}} + \tfrac{1}{2}\mathcal{Q}_{uu,\mathrm{3ff3}}, \quad (2.13)$$

$$\mathcal{O}_{td}^{8} = \sum_{\mathrm{f}=1}^{3}(\bar{t}\gamma_\mu T_A t)(\bar{d}_\mathrm{f}\gamma^\mu T^A d_\mathrm{f}) = \sum_{\mathrm{f}=1}^{3} \mathcal{Q}_{ud,\mathrm{33ff}}^{(8)}, \quad (2.14)$$

$$\mathcal{O}_{tq}^{8} = \sum_{\mathrm{f}=1}^{2}(\bar{q}_\mathrm{f}\gamma_\mu T_A q_\mathrm{f})(\bar{t}\gamma^\mu T^A t) = \sum_{\mathrm{f}=1}^{2} \mathcal{Q}_{qu,\mathrm{ff33}}^{(8)}, \quad (2.15)$$

$$\mathcal{O}_{Qu}^{8} = \sum_{\mathrm{f}=1}^{2}(\bar{Q}\gamma_\mu T_A Q)(\bar{u}_\mathrm{f}\gamma^\mu T^A u_\mathrm{f}) = \sum_{\mathrm{f}=1}^{2} \mathcal{Q}_{qu,\mathrm{33ff}}^{(8)}, \quad (2.16)$$

$$\mathcal{O}_{Qd}^{8} = \sum_{\mathrm{f}=1}^{3}(\bar{Q}\gamma_\mu T_A Q)(\bar{d}_\mathrm{f}\gamma^\mu T^A d_\mathrm{f}) = \sum_{\mathrm{f}=1}^{3} \mathcal{Q}_{qd,\mathrm{33ff}}^{(8)}, \quad (2.17)$$

$$\mathcal{O}_{Qq}^{1,8} = \sum_{\mathrm{f}=1}^{2}(\bar{Q}\gamma_\mu T^A Q)(\bar{q}_\mathrm{f}\gamma^\mu T_A q_\mathrm{f}) = \sum_{\mathrm{f}=1}^{2} \tfrac{1}{4}\mathcal{Q}_{qq,\mathrm{3ff3}}^{(1)} - \tfrac{1}{6}\mathcal{Q}_{qq,\mathrm{33ff}}^{(1)} + \tfrac{1}{4}\mathcal{Q}_{qq,\mathrm{3ff3}}^{(3)}, \quad (2.18)$$

$$\mathcal{O}_{Qq}^{3,8} = \sum_{\mathrm{f}=1}^{2}(\bar{Q}\gamma_\mu T^A \sigma_I Q)(\bar{q}_\mathrm{f}\gamma^\mu T_A \sigma^I q_\mathrm{f}) = \sum_{\mathrm{f}=1}^{2} \tfrac{3}{4}\mathcal{Q}_{qq,\mathrm{3ff3}}^{(1)} - \tfrac{1}{6}\mathcal{Q}_{qq,\mathrm{33ff}}^{(3)} - \tfrac{1}{4}\mathcal{Q}_{qq,\mathrm{3ff3}}^{(3)}. \quad (2.19)$$

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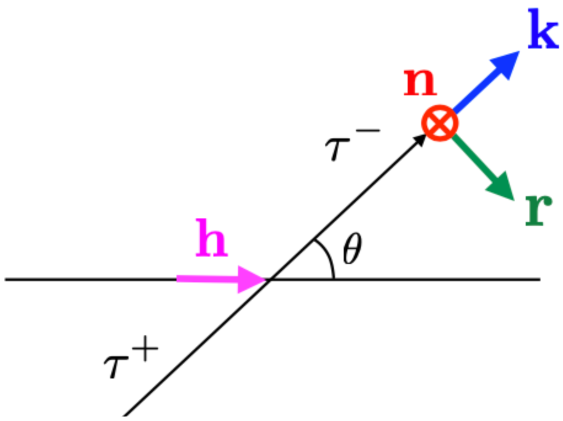
Entanglement in Higgs decays?



$$\rho_{mn,\bar{m}\bar{n}} = \frac{1}{2}\begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & e^{-i2\delta} & 0 \\ 0 & e^{i2\delta} & 1 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

$$|\Psi_{H\to\tau\tau}(\delta)\rangle = \frac{1}{\sqrt{2}}\left(|+,-\rangle + e^{i2\delta}|-,+\rangle\right)$$

[Phys. Rev. D 107, 093002 (2023)]

JHEP

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Stringent bounds on HWW and HZZ anomalous couplings with quantum tomography at the LHC

$$|\psi_{ZZ}\rangle = \frac{1}{\sqrt{2+\beta^2}}\left(|+-\rangle - \beta\,|00\rangle + |-+\rangle\right)$$

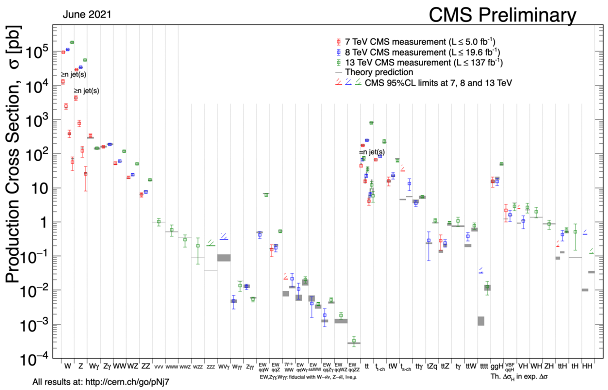
$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega_1 d\Omega_2} = \frac{1}{(4\pi)^2}\Big[1 + A^1_{LM}B_L Y^M_L(\theta_1,\varphi_1) + A^2_{LM}B_L Y^M_L(\theta_2,\varphi_2) + C_{L_1M_1L_2M_2}B_{L_1}B_{L_2}Y^{M_1}_{L_1}(\theta_1,\varphi_1)Y^{M_2}_{L_2}(\theta_2,\varphi_2)\Big],$$

[JHEP 09 (2023)195]

[Phys. Rev D 107, 016012 (2023)]

Summary

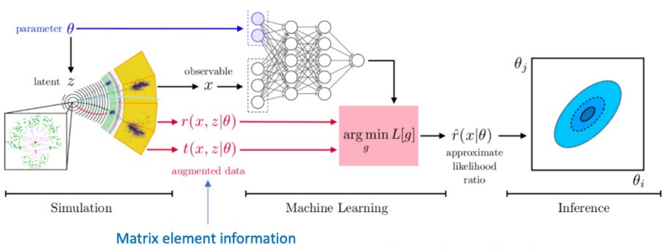
- ATLAS and CMS experiments are able to tag processes with cross sections over ~9 orders of magnitude



- EFT interpretation is used to measure the possible deviation from Standard Model in terms of STXS, differential cross sections

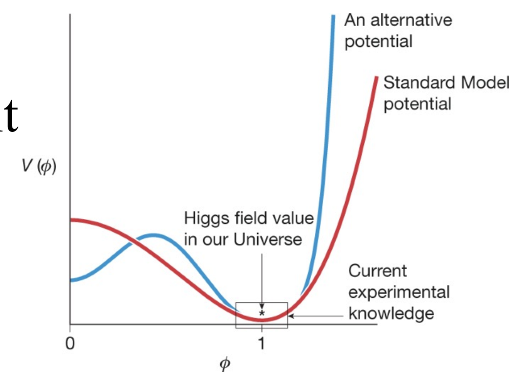
  - Everything could be signal : combination between Higgs, EWK multi-boson and top is crucial

  - ML technic may help build the tool to improve EFT/CP sensitivity



Summary

- Higgs self-coupling is crucial and attractive topic
  - Combination between single Higgs and multi Higgs result improves sensitivity
  - HHH is also important and worth trying
  - Improvements heavily rely on online/offline jet tagging and (deep learning based) jet pairing
- Can expect to discover $H\mu^+\mu^-$ and enforce sensitivity for $Z\gamma$
- Quantum entanglement may be a new way to new physics



Summary

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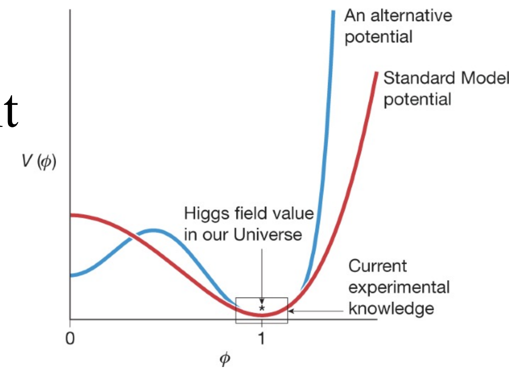
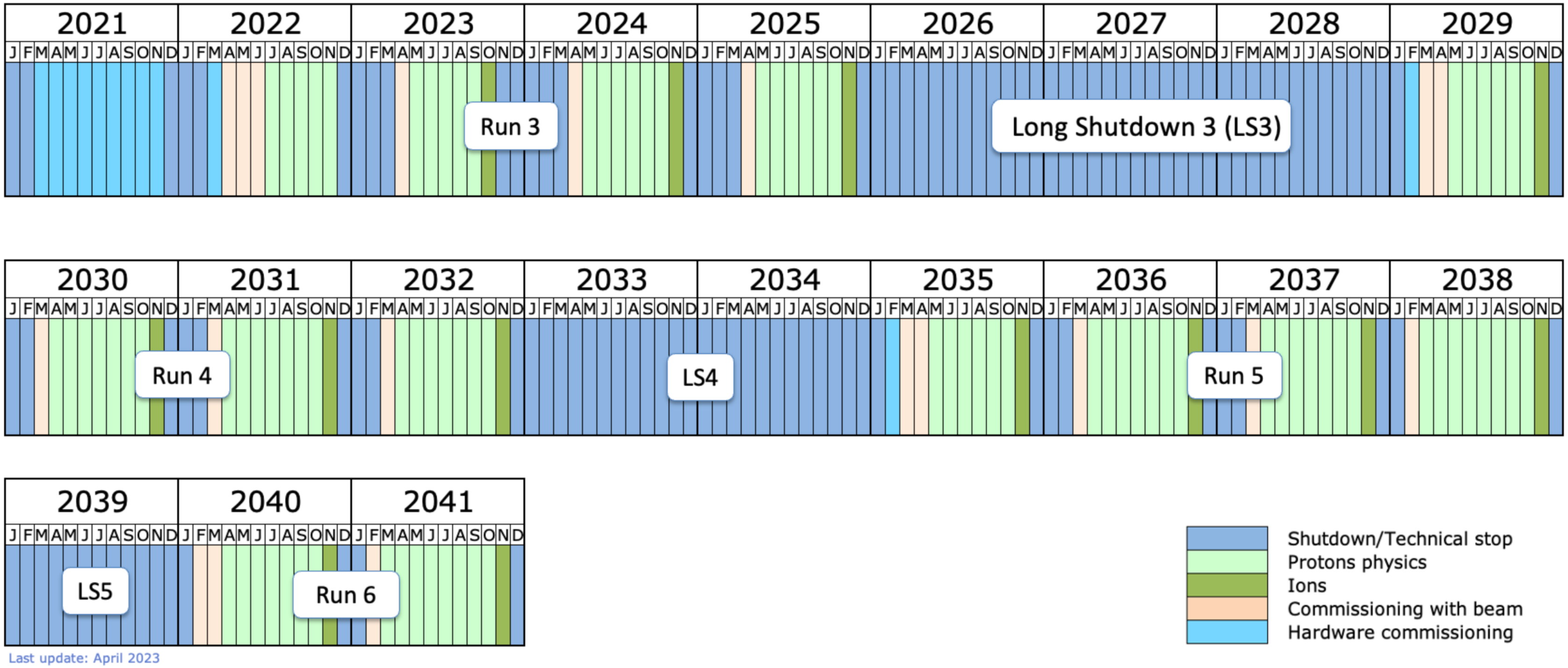


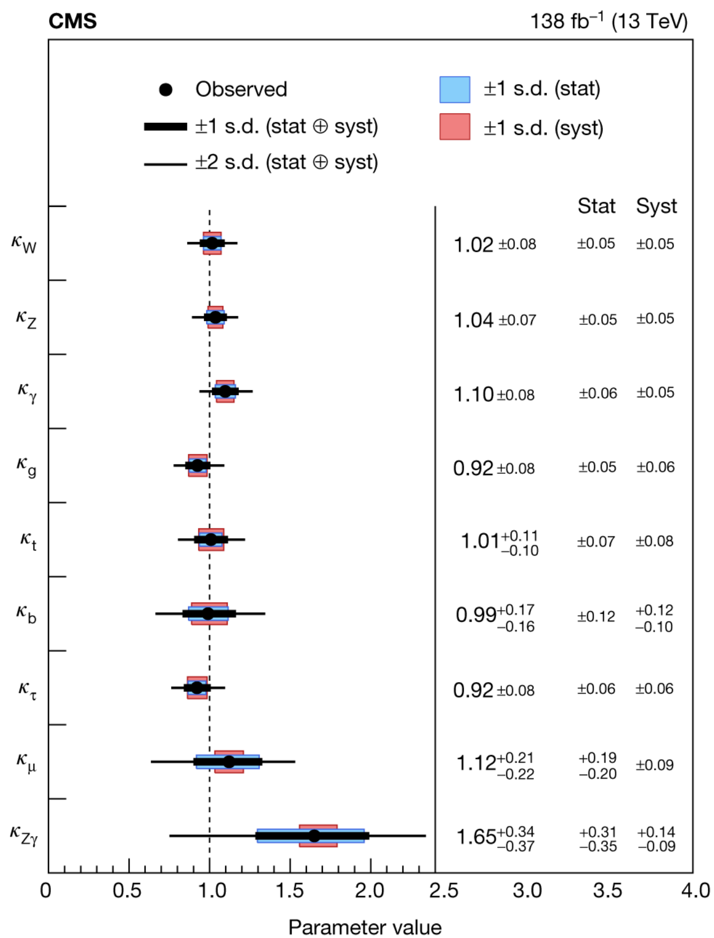
Backup

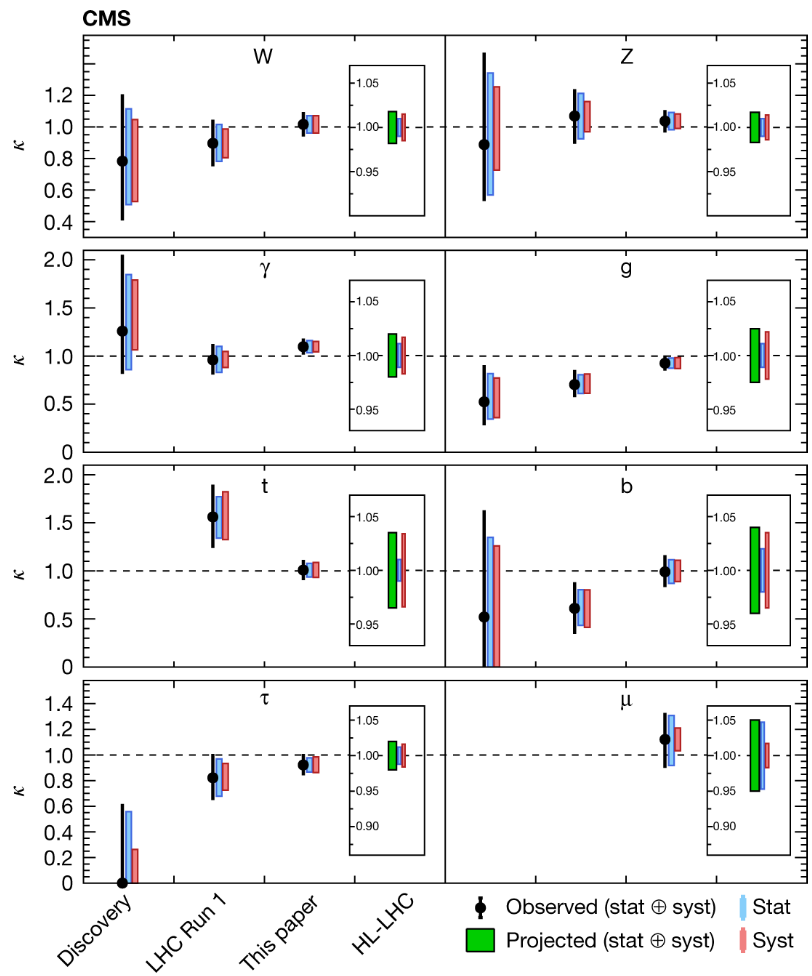
Longer term LHC schedule

In January 2022, the schedule was updated with long shutdown 3 (LS3) to start in 2026 and to last for 3 years. HL-LHC operations now foreseen out to end 2041.

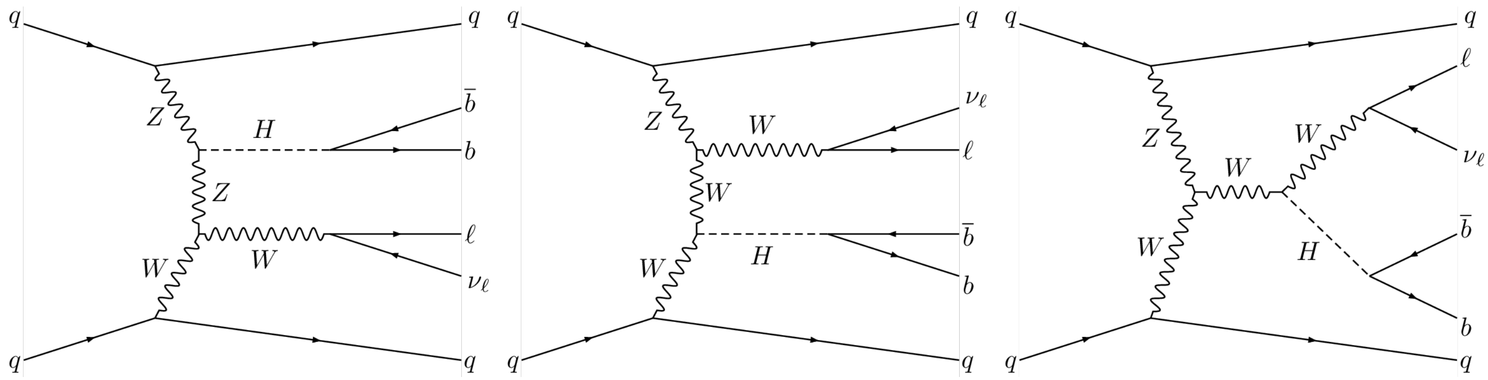


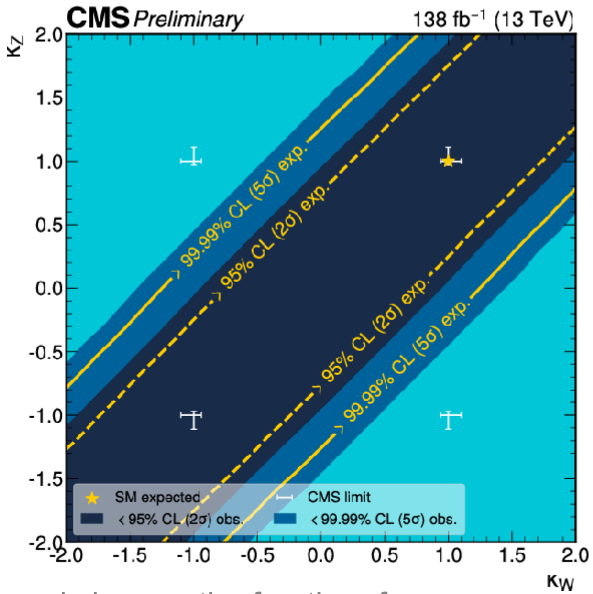
From signal strengths to κ-framework





From signal strengths to κ-framework





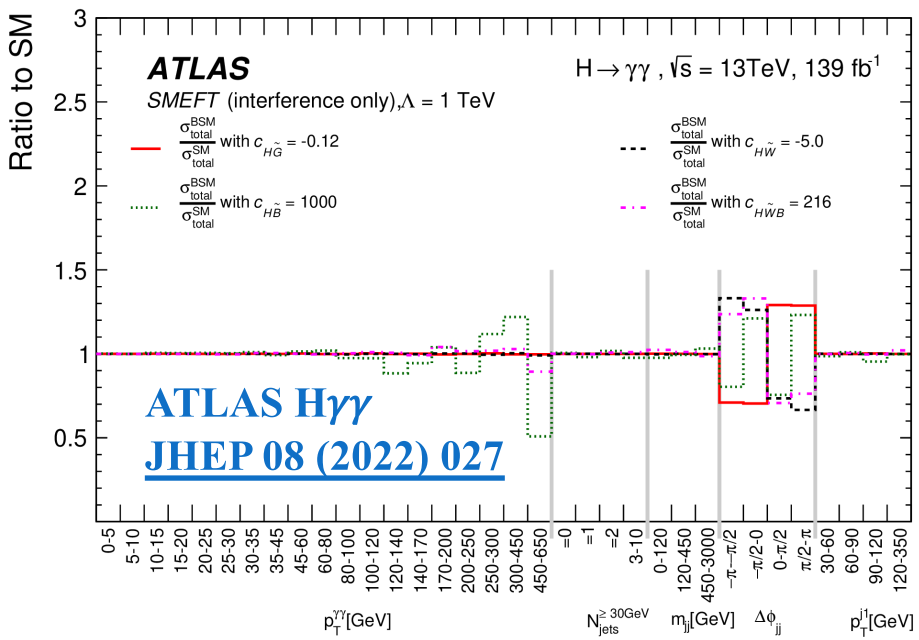
CMS-PAS-HIG-23-007

Global fit from combined STXS

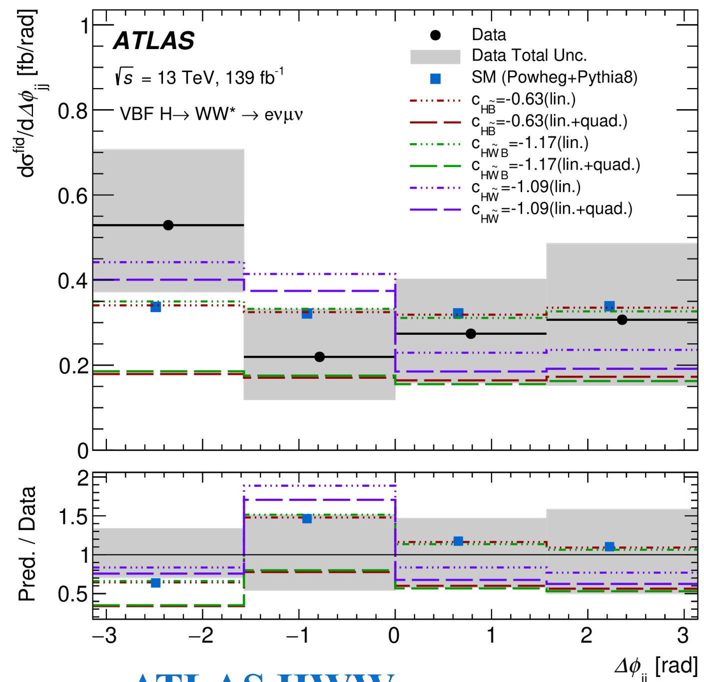
HEL Parameters	Definition	Others profiled	Fix others to SM
$c_A \times 10^4$	$c_A = \frac{m_W^2}{g'^2}\frac{f_A}{\Lambda^2}$	$-1.03^{+1.53}_{-1.59}$ $\left(^{+1.59}_{-1.56}\right)$	$-0.78^{+1.11}_{-1.16}$ $\left(^{+1.10}_{-1.11}\right)$
$c_G \times 10^5$	$c_G = \frac{m_W^2}{g_s^2}\frac{f_G}{\Lambda^2}$	$1.43^{+3.20}_{-3.00}$ $\left(^{+3.13}_{-2.74}\right)$	$0.27^{+1.05}_{-1.05}$ $\left(^{+1.03}_{-1.01}\right)$
$c_u \times 10$	$c_u = -v^2\frac{f_u}{\Lambda^2}$	$0.68^{+0.82}_{-0.83}$ $\left(^{+0.83}_{-0.79}\right)$	$0.43^{+0.69}_{-0.69}$ $\left(^{+0.68}_{-0.67}\right)$
$c_d \times 10$	$c_d = -v^2\frac{f_d}{\Lambda^2}$	$0.59^{+1.03}_{-1.13}$ $\left(^{+1.08}_{-1.05}\right)$	$-0.01^{+0.31}_{-0.28}$ $\left(^{+0.30}_{-0.28}\right)$
$c_\ell \times 10$	$c_\ell = -v^2\frac{f_\ell}{\Lambda^2}$	$-0.57^{+0.74}_{-0.73}$ $\left(^{+0.72}_{-0.77}\right)$	$-0.75^{+0.60}_{-0.64}$ $\left(^{+0.58}_{-0.60}\right)$
$c_{HW} \times 10^2$	$c_{HW} = \frac{m_W^2}{2g}\frac{f_{HW}}{\Lambda^2}$	$-1.45^{+4.72}_{-3.03}$ $\left(^{+3.93}_{-3.27}\right)$	$0.77^{+0.84}_{-1.20}$ $\left(^{+1.04}_{-1.38}\right)$
$(c_{WW} - c_B) \times 10^2$	$c_{WW} = \frac{m_W^2}{g}\frac{f_{WW}}{\Lambda^2}$, $c_B = \frac{2m_W^2}{g'}\frac{f_B}{\Lambda^2}$	$2.16^{+2.84}_{-5.35}$ $\left(^{+3.46}_{-5.00}\right)$	$0.62^{+1.06}_{-1.22}$ $\left(^{+1.09}_{-1.23}\right)$

HIG-19-005

CP structures from differential measurements



[ATLAS Hγγ JHEP 08 (2022) 027]

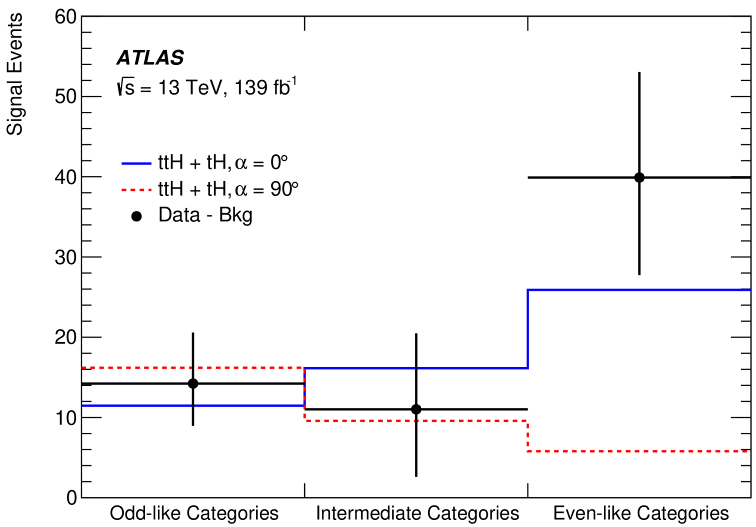


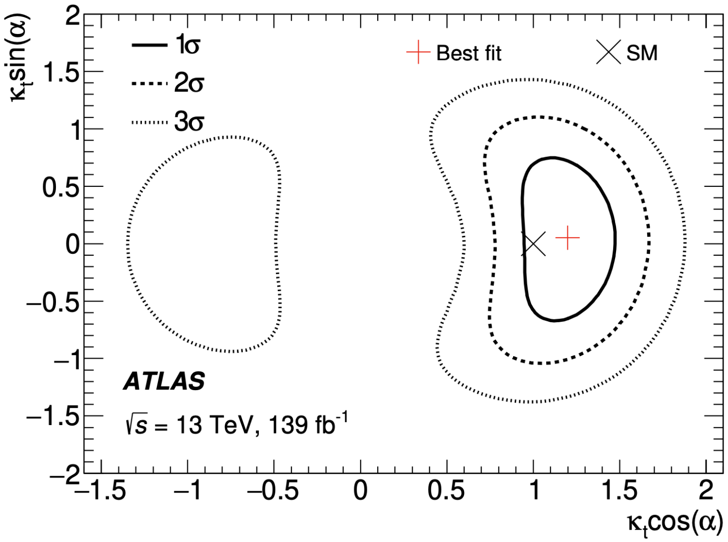
[ATLAS HWW Phys. Rev. D 108, 072003 (2023)]

- ❑ Differential observables related to Higgs production/decay can be used constrain SMEFT and CP structures

CP structures in ttH+tH(Hγγ)

$$\mathcal{L} = -\frac{m_t}{v}\{\bar{\psi}_t\kappa_t[\cos(\alpha) + i\sin(\alpha)\gamma_5]\psi_t\}H$$

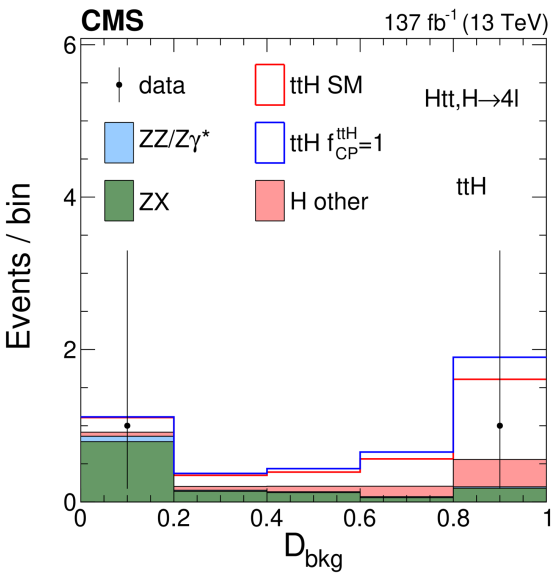


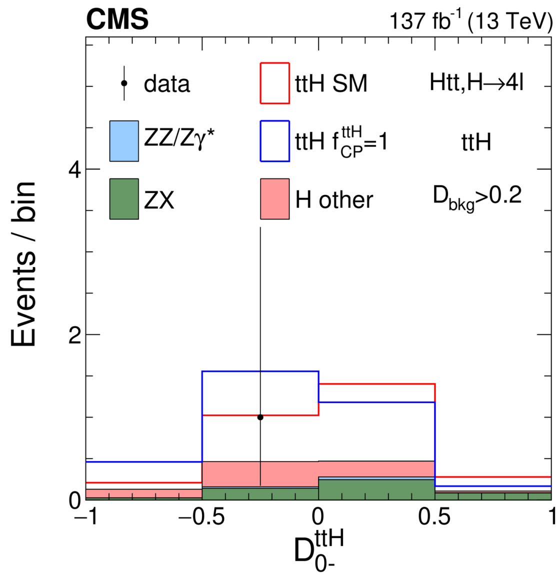


- Data with background subtracted are compared with CP-even and CP-odd signals in three categories
  - categorization based on events' CP BDT ranges
- CP mixing angle $|\alpha|<43^\circ$ @95% CL

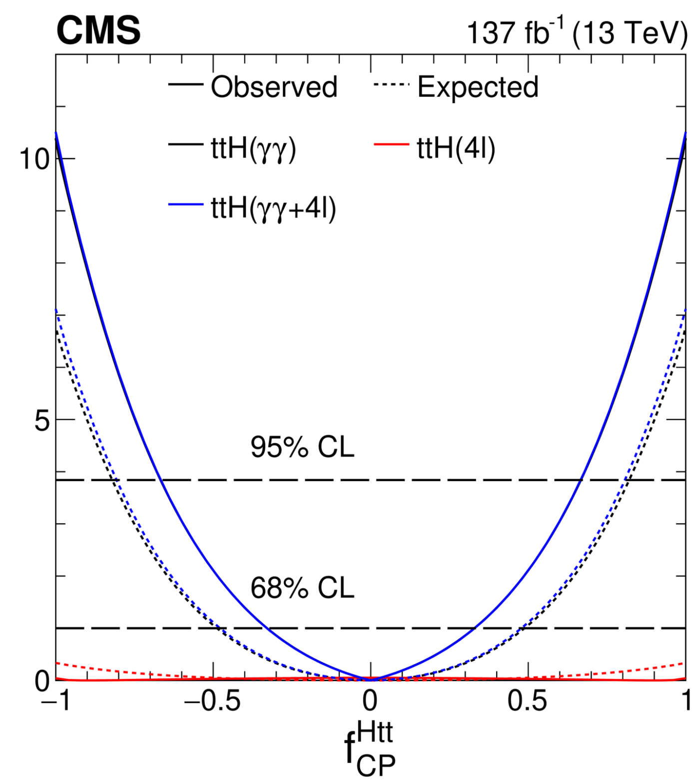
ATLAS Hγγ : [Phys. Rev. Lett. 125 (2020) 061802]

CP structures in ttH+tH(HZZ4l)





$$f_{CP}^{Htt} = \frac{|\tilde{\kappa}_t|^2}{|\kappa_t|^2 + |\tilde{\kappa}_t|^2} \, \mathrm{sign}(\tilde{\kappa}_t/\kappa_t)$$

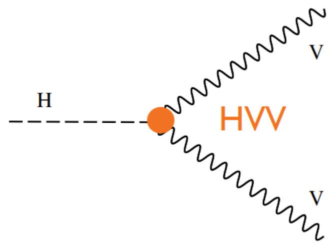


- MELA discriminant D_{bkg} and D_{0-} to separate sig/bkg and CP-even/odd
- f_{CP}^{Htt} is weakly constrained by H-to-4l

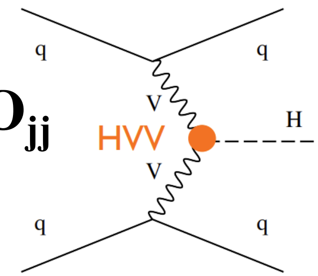
CMS HZZ4l : Phys. Rev. D 104 (2021) 052004

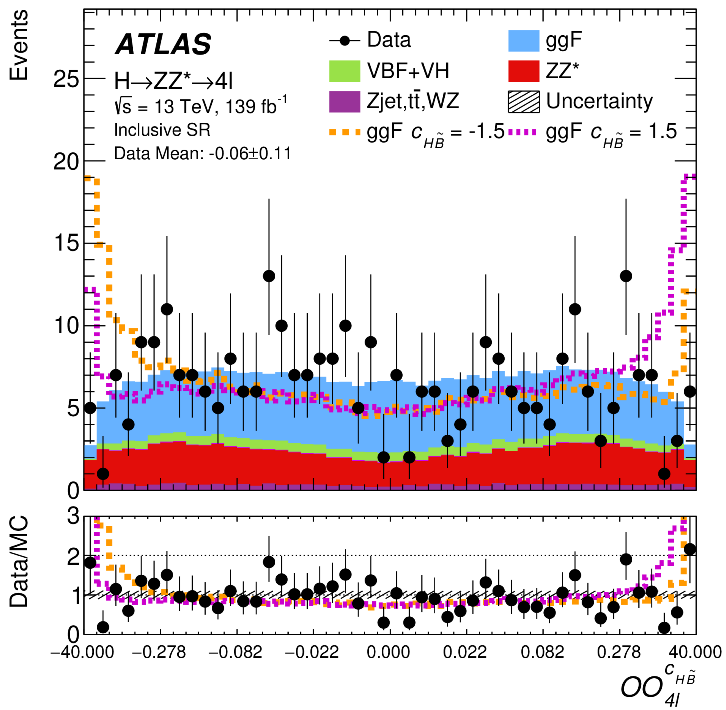
CP structures in HVV(Higgs-to-4l)

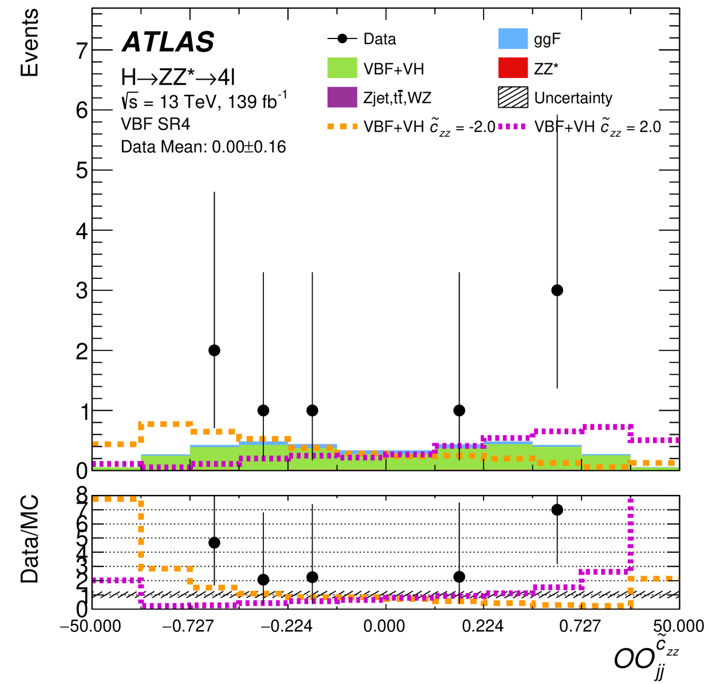
Decay OO_{4l}



Production OO_{jj}

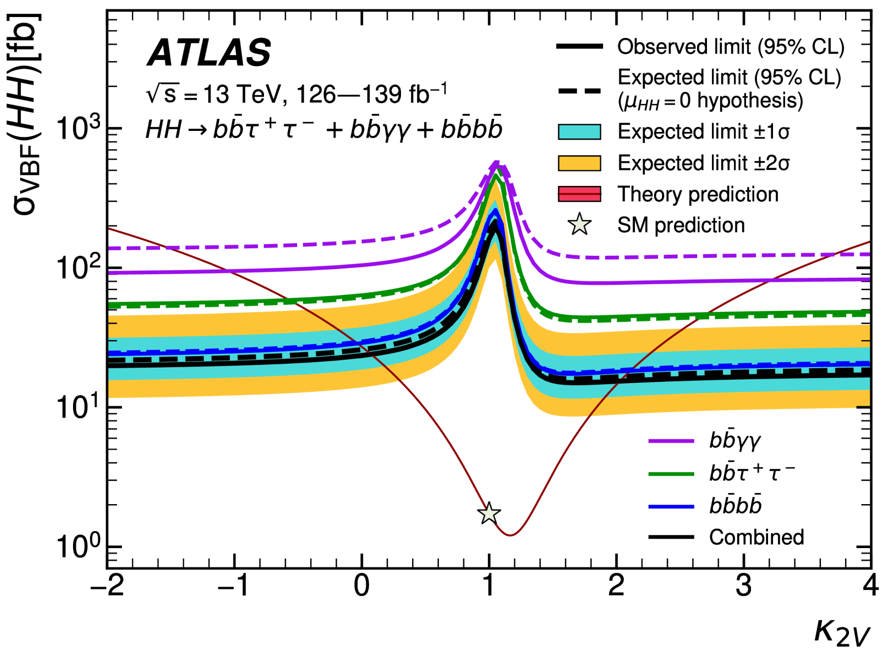


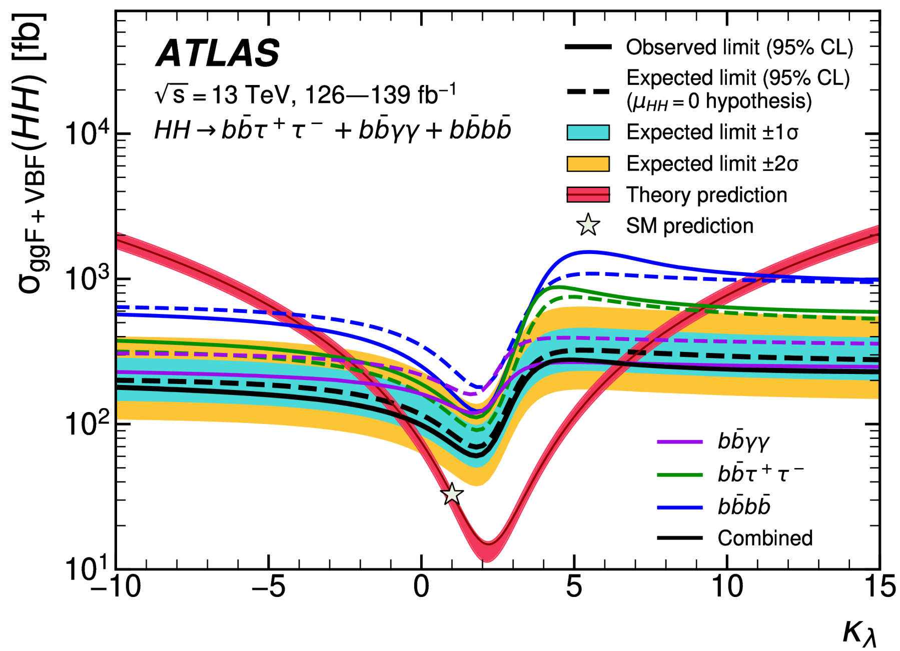




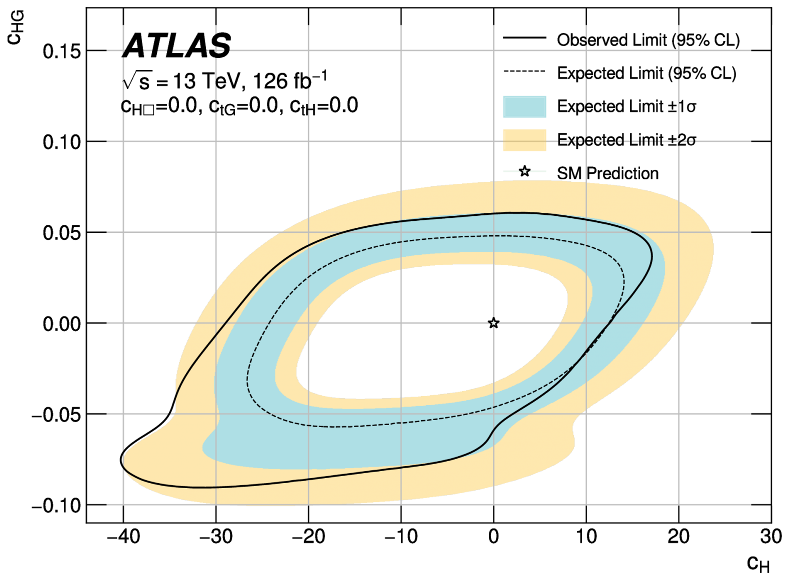
ATLAS Higgs-to-4l: arXiv:2304.09612(submitted to JHEP)

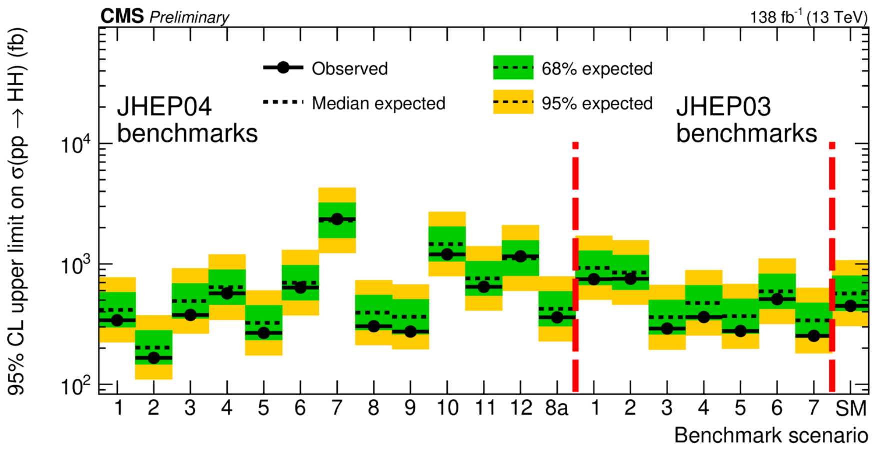
Triple-Higgs coupling : di-Higgs





Triple-Higgs coupling : di-Higgs

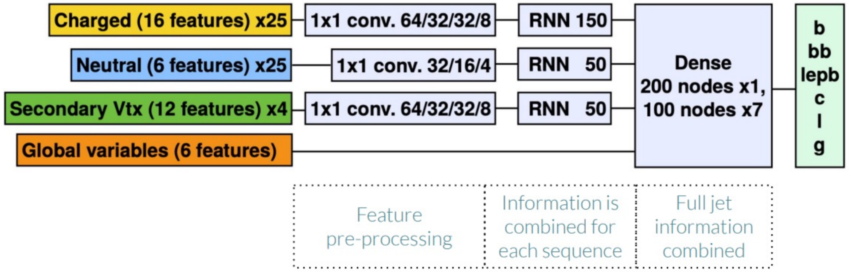


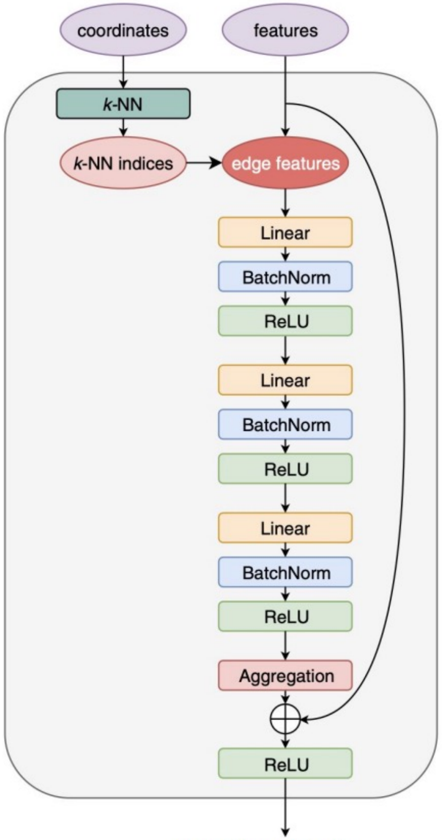


Phys. Rev. D 108 (2023) 052003

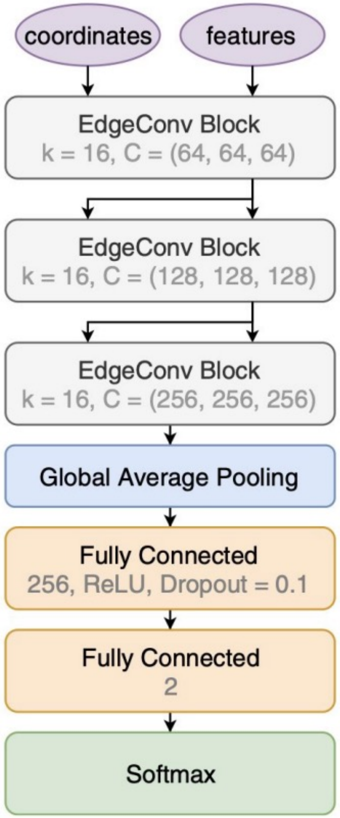
HIG-21-005

From DeepJet to ParticleNet





EdgeConv block

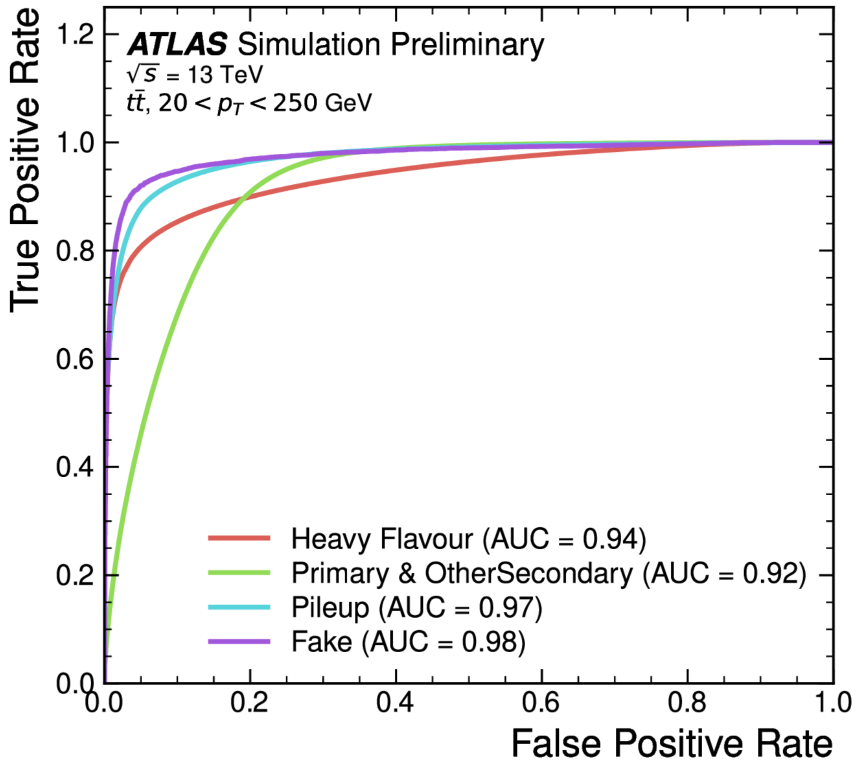


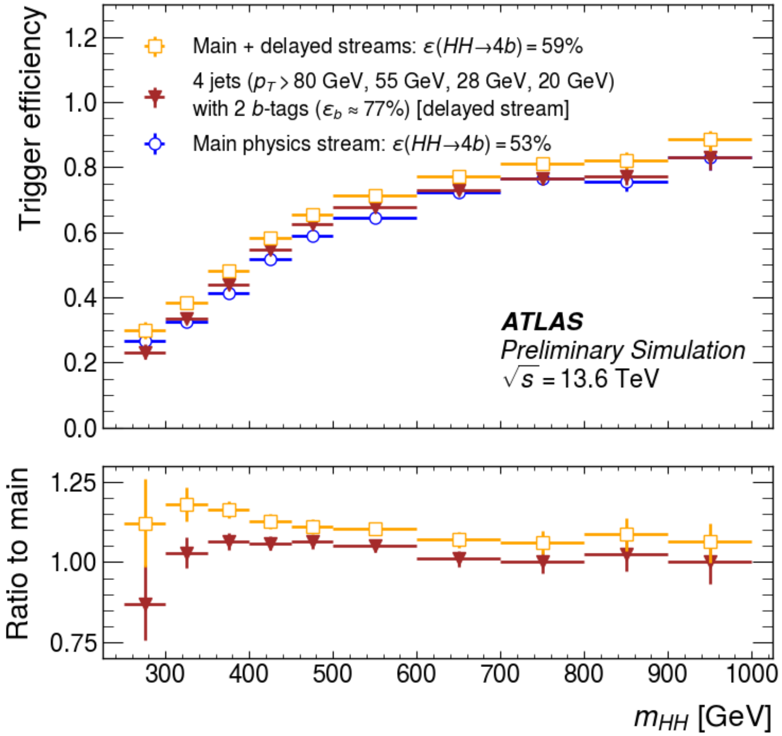
ParticleNet architecture

Jet tagging via particle clouds

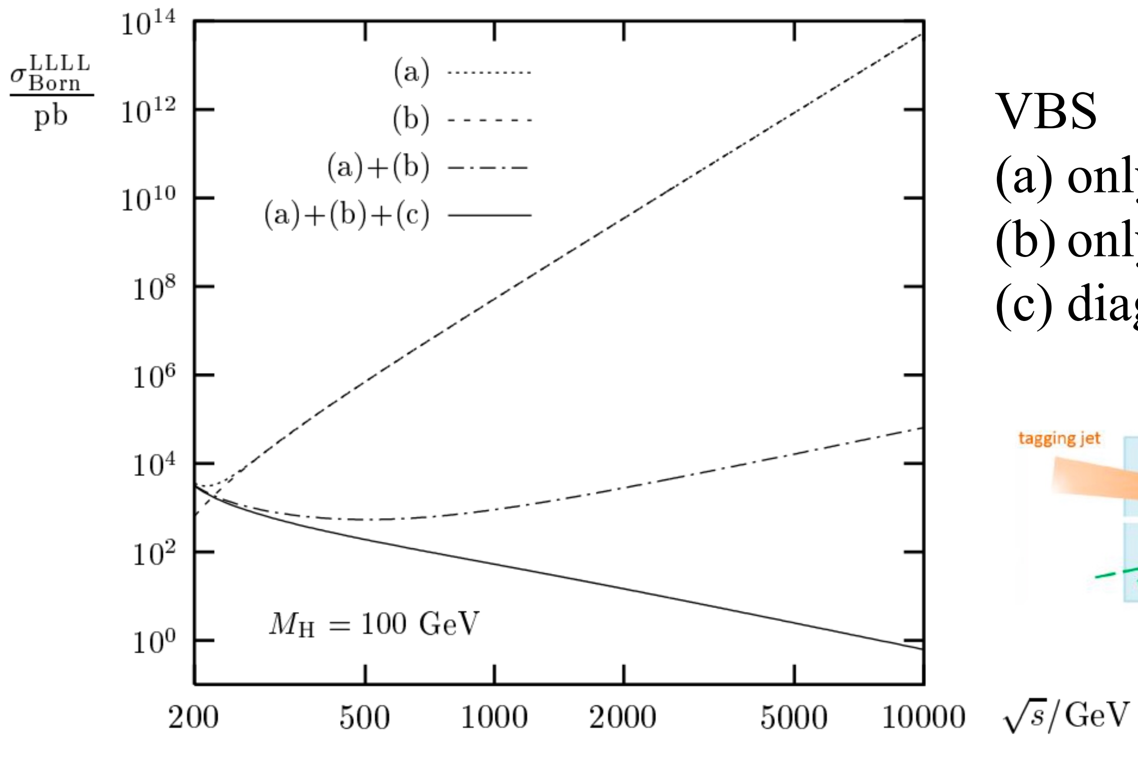
Triggers in Run-3 for HH and HHH

ATLAS trigger efficiency

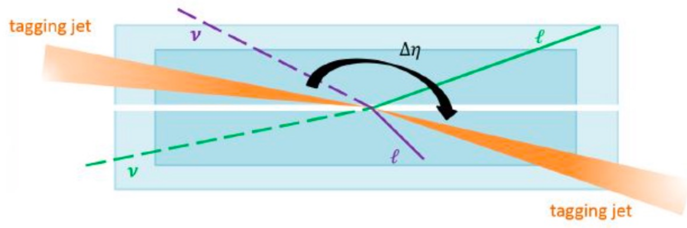




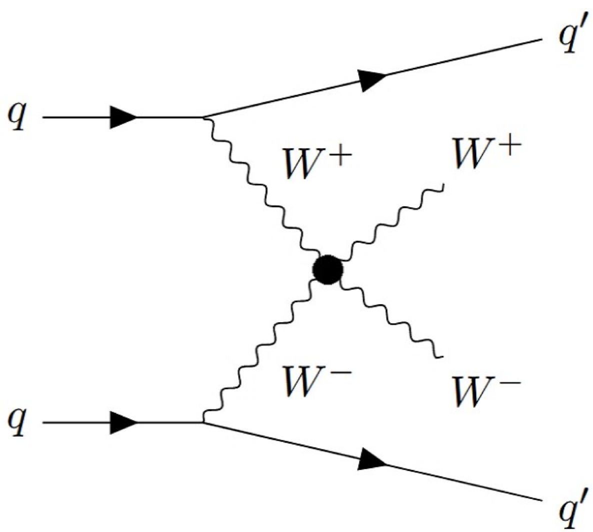
EWK physics : VBS

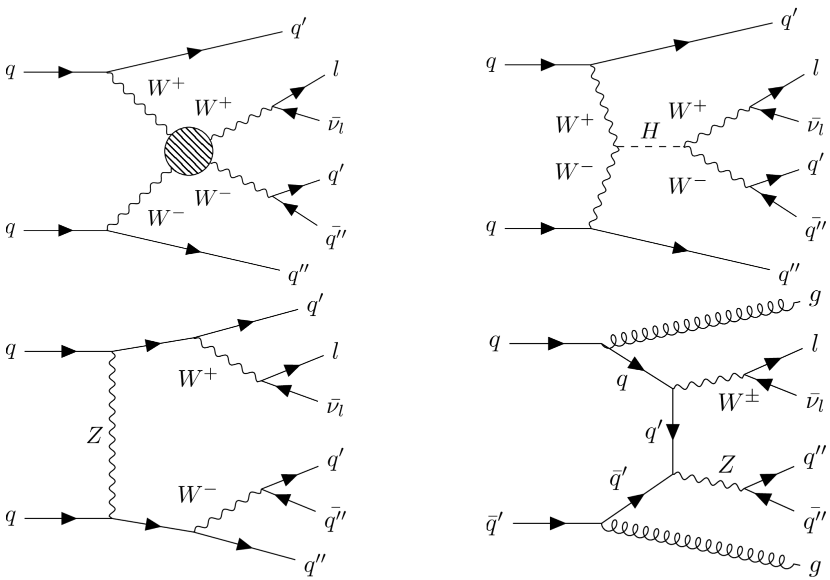


VBS
(a) only triple-gauge couplings
(b) only quartic-gauge couplings,
(c) diagrams involving Higgs bosons.



EWK physics : VBS WZ/W$^+$W$^-$

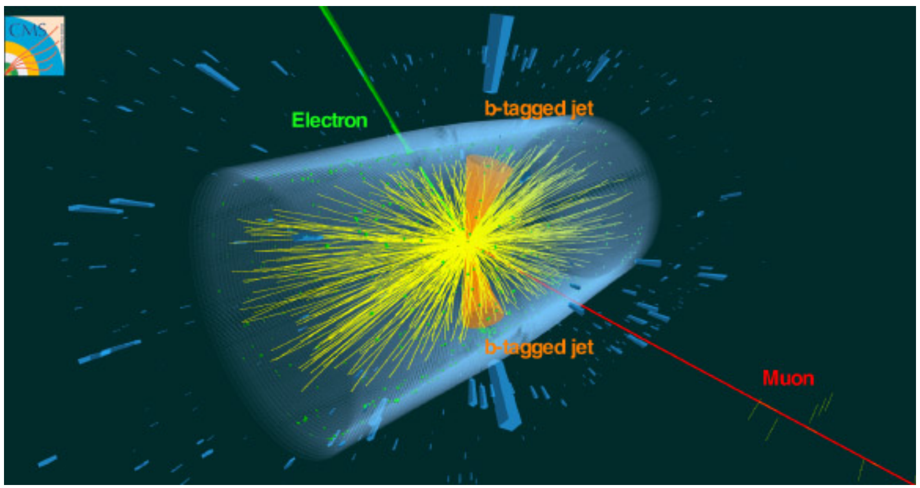


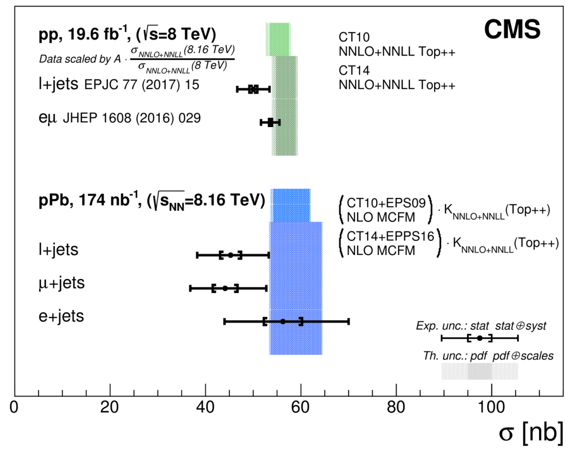


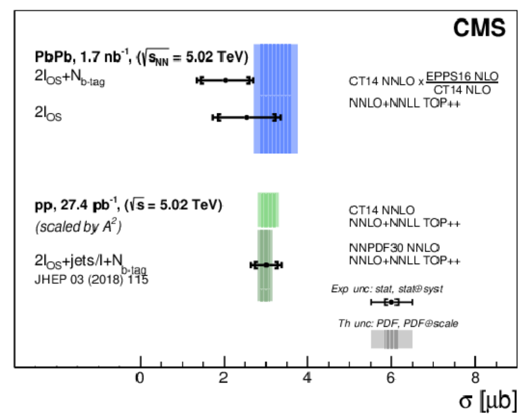
Observation : PLB 841 (2023) 137495

Evidence WV->lvqq
Phys. Lett. B 834 (2022) 137438

Find First Evidence for Production of Top Quarks in Nucleus-Nucleus Collisions







Probes of nuclear-PDFs
and the properties of the quark-gluon plasma

PhysRevLett. 119 (2017) 242001

Phys. Rev. Lett. 125 (2020) 222001

ATLAS-CONF-2023-063

Test quantum mechanics at the LHC

Ill. Niklas Elmehed © Nobel Prize Outreach

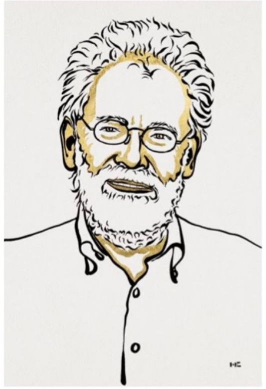
Alain Aspect

Prize share: 1/3

Ill. Niklas Elmehed © Nobel Prize Outreach

John F. Clauser

Prize share: 1/3

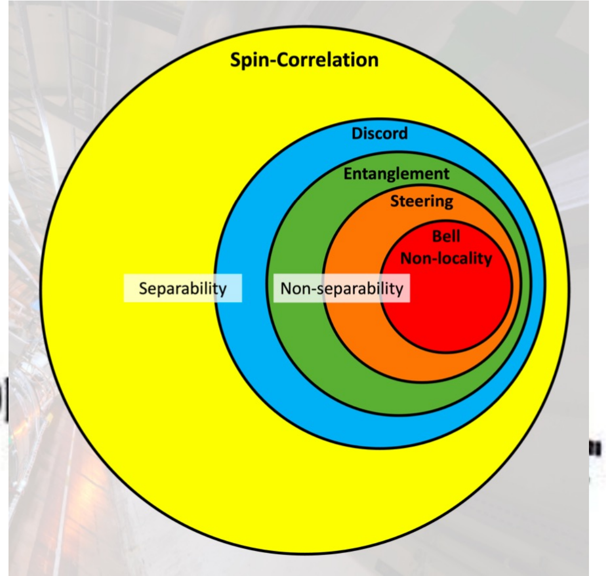


Ill. Niklas Elmehed © Nobel Prize Outreach

Anton Zeilinger

Prize share: 1/3

The Nobel Prize in Physics 2022 was awarded jointly to Alain Aspect, John F. Clauser and Anton Zeilinger "for experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science"



$$|\Phi^{\pm}\rangle = \frac{1}{\sqrt{2}}\left(|\uparrow\uparrow\rangle \pm |\downarrow\downarrow\rangle \right),$$

$$|\Psi^{\pm}\rangle = \frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle \pm |\downarrow\uparrow\rangle \right).$$

Phys. Rev. Lett. 130(2023) 221801

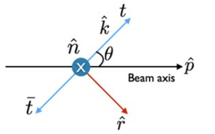
Bell inequalities at the LHC

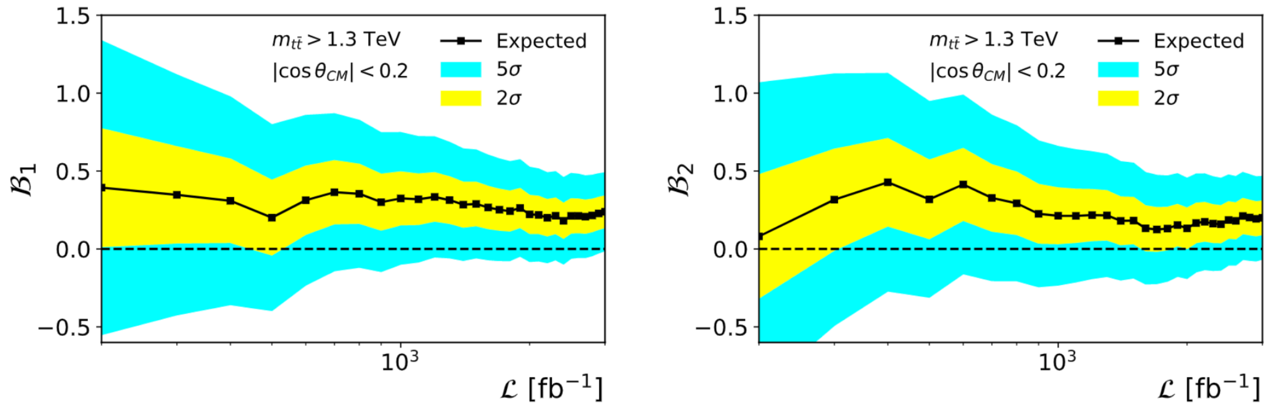
When the Machine Chimes the Bell:
Entanglement and Bell Inequalities with Boosted ttbar
https://arxiv.org/abs/2305.07075

LHC Projections

- Bell/CHSH inequalities: $\mathcal{B}_1 \equiv |C_{rr} - C_{nn}| - \sqrt{2} > 0$
  $\mathcal{B}_2 \equiv |C_{kk} + C_{rr}| - \sqrt{2} > 0$

Helicity basis
$\hat{k}$ = top quark direction
$\hat{r} = \mathrm{sign}(\cos\theta)(\hat{p} - \cos\theta\hat{k})/\sin\theta$
$\hat{n} = \hat{k} \times \hat{r}$



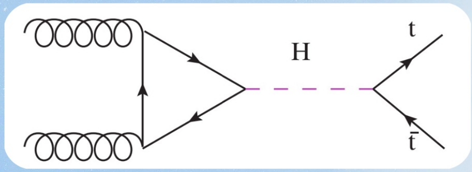


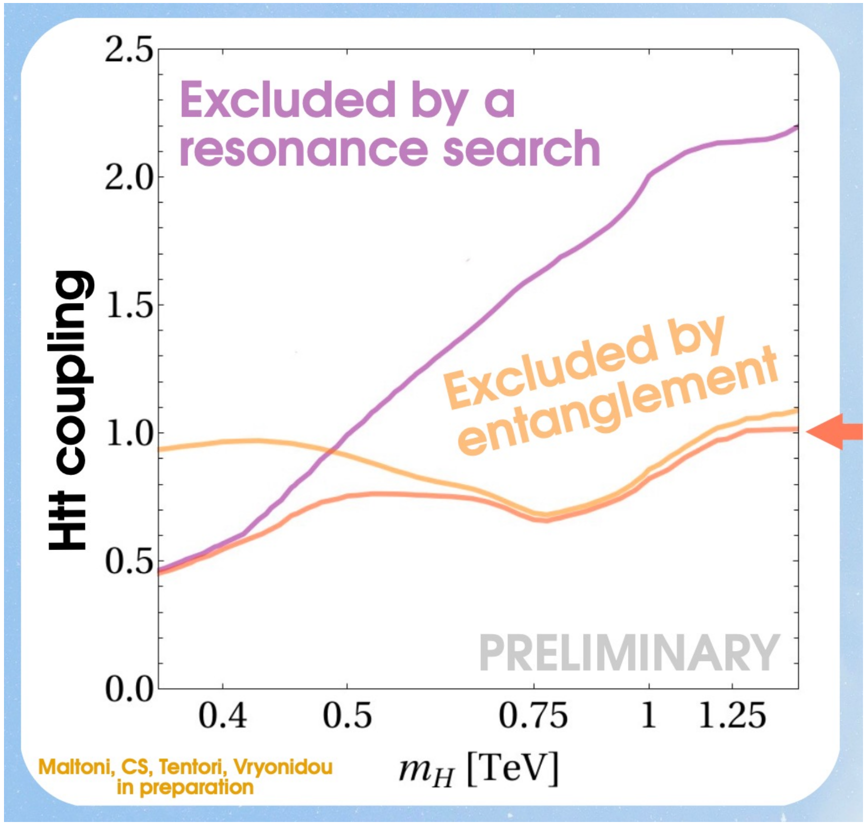
Quantum entanglement and new physics

Resonant new physics

There is still room for resonant new physics in the top sector.

A (pseudo)scalar heavier than $2m_t$ is particularly interesting, and challenging to detect in $m_{t\bar{t}}$ resonance searches.





talk from TOP2023

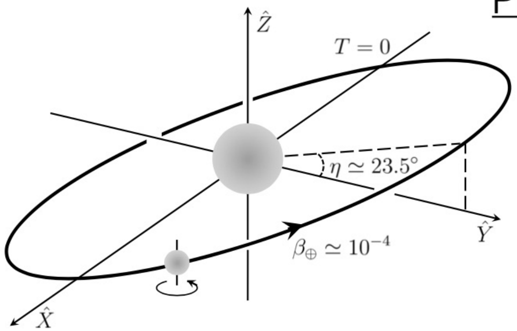
LV/NC at the LHC

Lorentz transformation:

$x^\mu \mapsto x'^\mu = \Lambda^\mu{}_\nu x^\nu$

- Rotations

- Lorentz boosts



Lorentz-violating Standard Model Extension (SME):

- Motivated by String theory or Loop quantum gravity
- Add all **Lorentz-violating operators** to the SM Lagrangian
- Tested in many sectors, but only once with top quarks (D0, PRL 108 (2012) 261603)): precision O(10%)

$$L_{\rm SME} = \frac{1}{2} i \bar{\psi} (\gamma^\nu + c^{\mu\nu}\gamma_\mu + d^{\mu\nu}\gamma_5\gamma_\mu) \overleftrightarrow{\partial_\nu} \psi - m_t \bar{\psi}\psi.$$

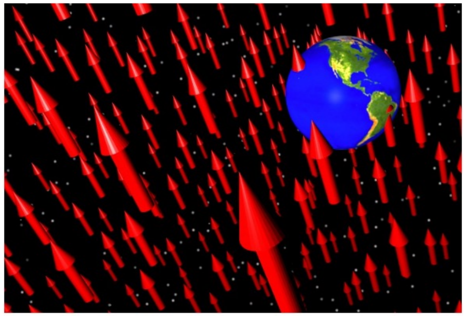
- SME coefficients: constant matrices (Lorentz-violating)
- Indicate **preferential directions in spacetime**

Report the measurement in the **Sun-centered frame**:

- CMS frame is rotating daily around the earth Z-axis,

=> modulation of the top-antitop cross section with sidereal time

Rotation period of the earth lasts ~23h 56min 4s (UTC time ~UNIX time), or 24h, 86400 s (sidereal time)



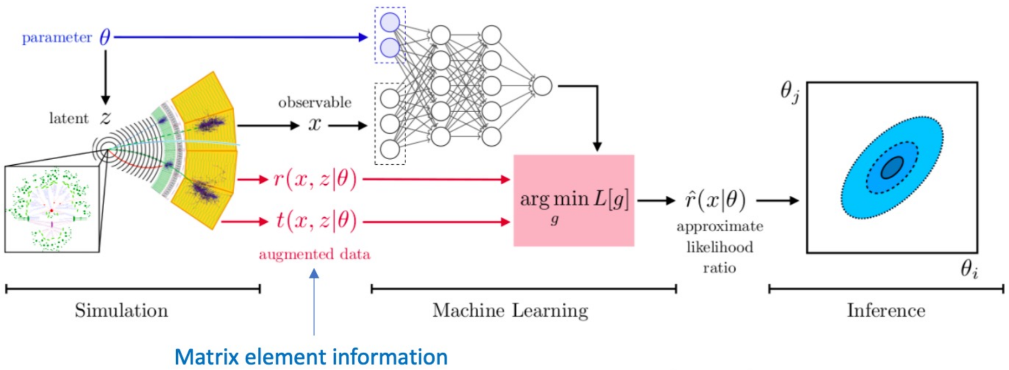
from talk at Probing space-time properties (LIV/NC) at HEP experiments

ML in EFT

Simulation-based inference

[Brehmer et al.,1906.01578,1805.12244,1805.00013,1805.00020,1808.00973,1907.10621]

[Brehmer et al.,1805.00013]



- Allows to extract the full available information (maximal sensitivity).
- No information loss due to binning (as for BDT analysis).
- No approximation of shower and detector effects

Example applications:

- $t\bar{t}H \rightarrow \sim$ 35% better limits on CP phase than from 2D histogram. [Barman et al.,2110.07635;HB & Brass 2110.10177]
- $WH \rightarrow$ ~25% better limits on $c_{\tilde{H}W}$ than from 2D histogram [Barrue et al., 2308.02882]

from talk at The 20th Workshop of the LHC Higgs Working Group