Higgs boson as a tool for discoveries at LHC and beyond

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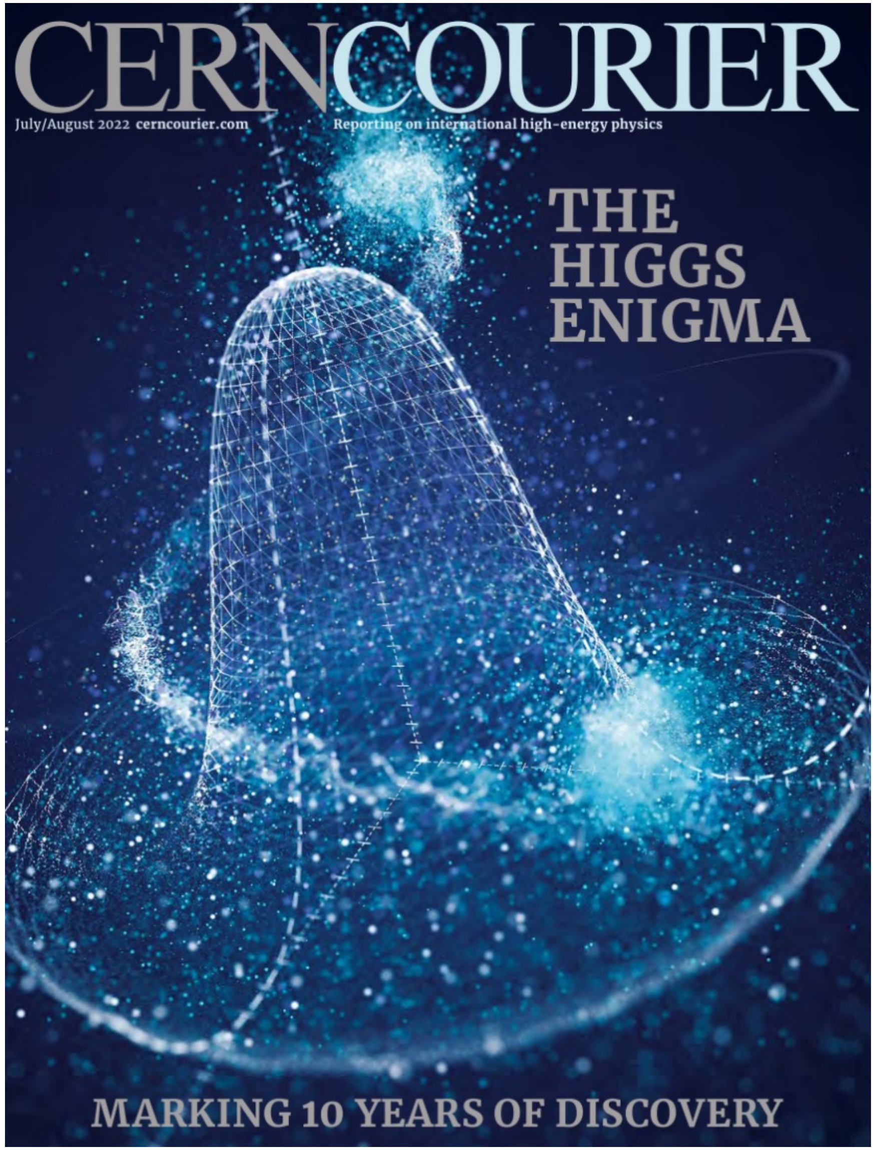
Outline

- Introduction
- Higgs boson and its role in our quest to “know thyself”
- How Higgs boson produced & identified at CMS
- What do we know about the Higgs now
  - Mass
  - Signal strengths
  - Couplings
  - Self-couplings
- Prospects for the future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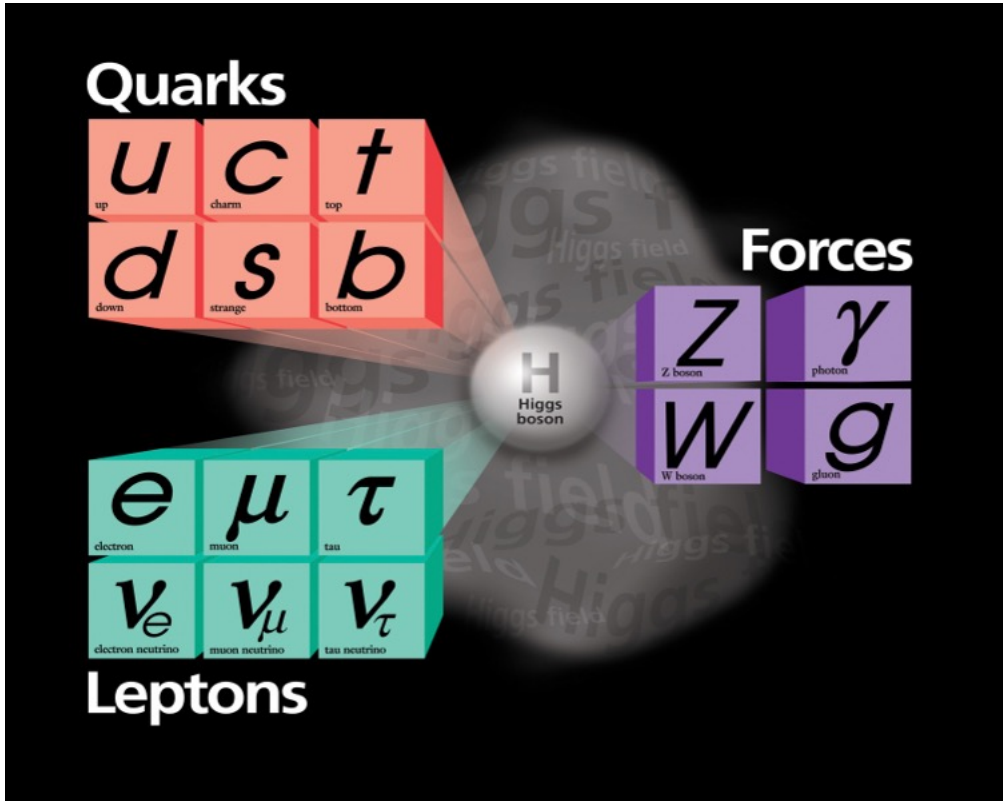
Reporting on international high-energy physics

THE HIGGS ENIGMA

MARKING 10 YEARS OF DISCOVERY

Standard model

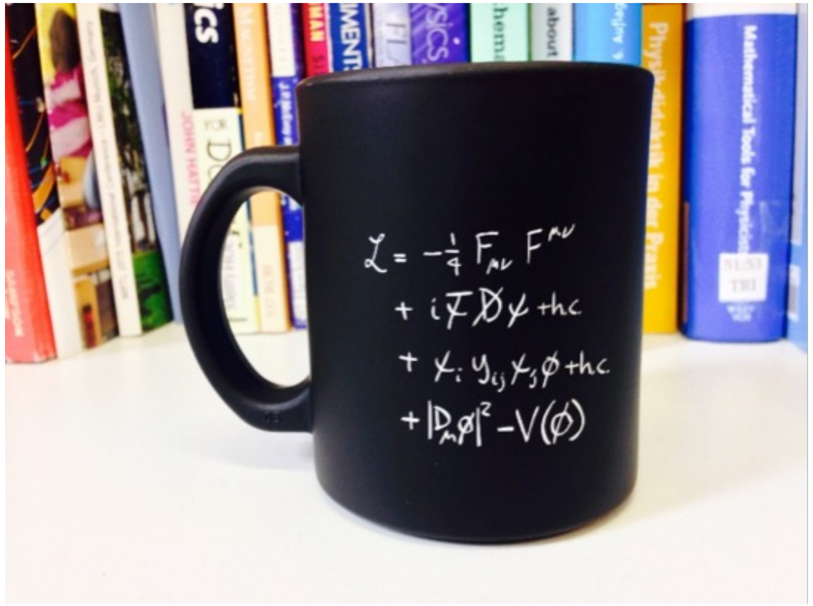
- Fundamental* constituents and forces
  - Quarks:
    - Matter particles
    - Electroweak and strong interactions
  - Leptons:
    - Matter particles
    - Electroweak interactions
  - Gauge bosons
    - Force carriers
    - Mediate electroweak and strong interactions
  - Higgs boson
    - Provides electroweak symmetry breaking
    - Simplest possible fundamental particle

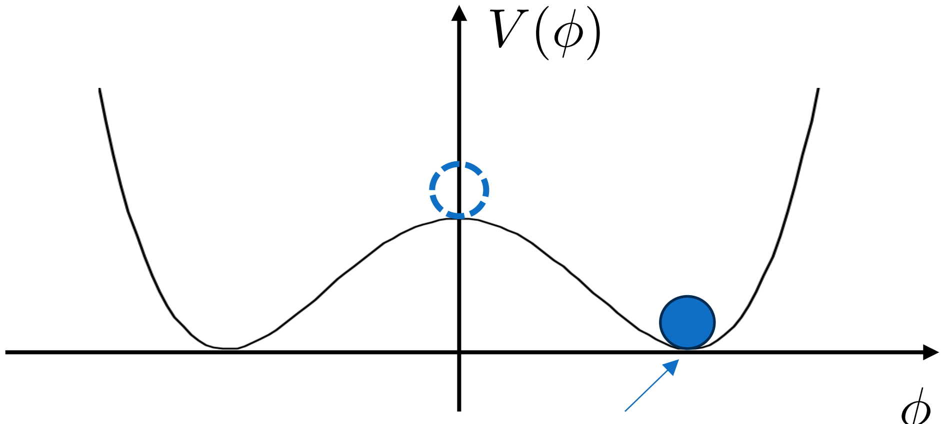


- Brout-Englert-Higgs mechanism was a “fix” to allow massive particles in the standard model

SM Lagrangian

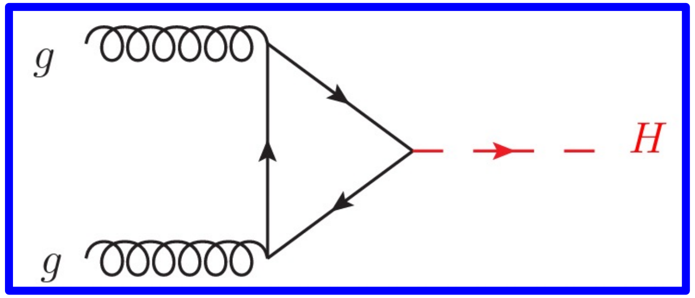
- Simple Lagrangian that describes particles and their interaction does not work if particles are massive
  - Violation of local gauge invariance
  - WW scattering breaks unitarity at high energies
- There must be something in 10-1000 GeV range to fix these problems
  - Case for LHC: “no-lose theorem”
- Mass is acquired by interaction with Higgs (ϕ)
- Higgs potential in SM: $V(\phi) = -\mu^2\phi^2 + \lambda\phi^4$
- Initially universe was in the symmetric state but as it cools down, it went into the lower-energy state, breaking symmetry
  - New interactions: “fifth force”
  - Electroweak symmetry breaking

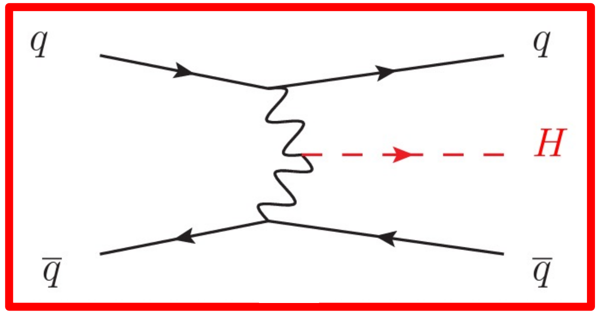


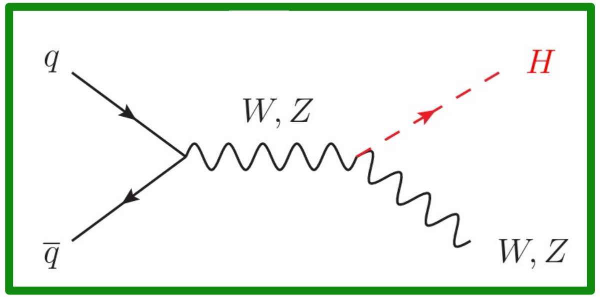


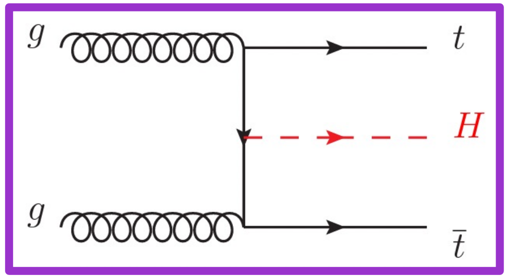
$$\frac{\mu}{\sqrt{\lambda}} = v = 246 \text{ GeV}$$

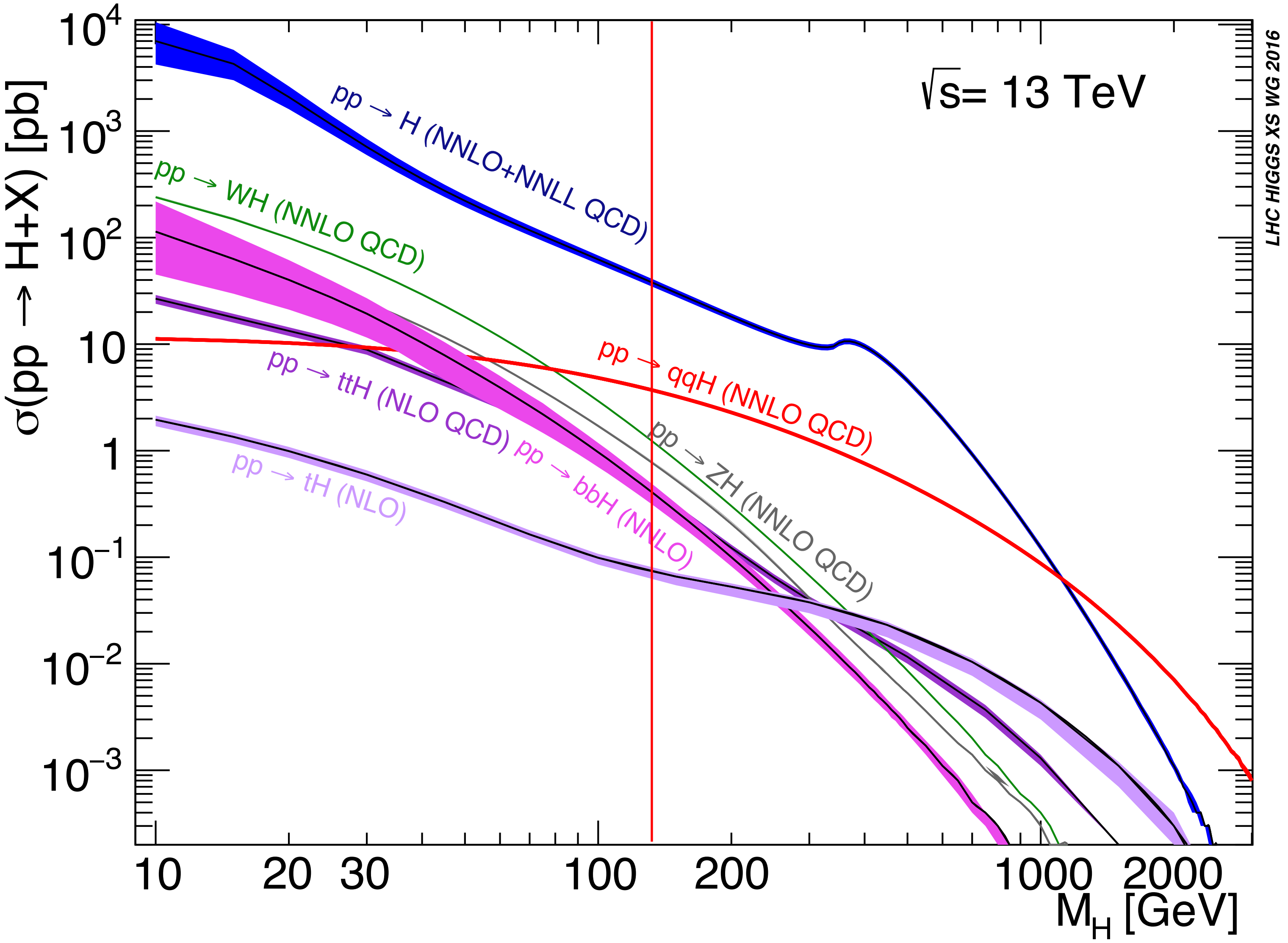
Production of the Higgs boson



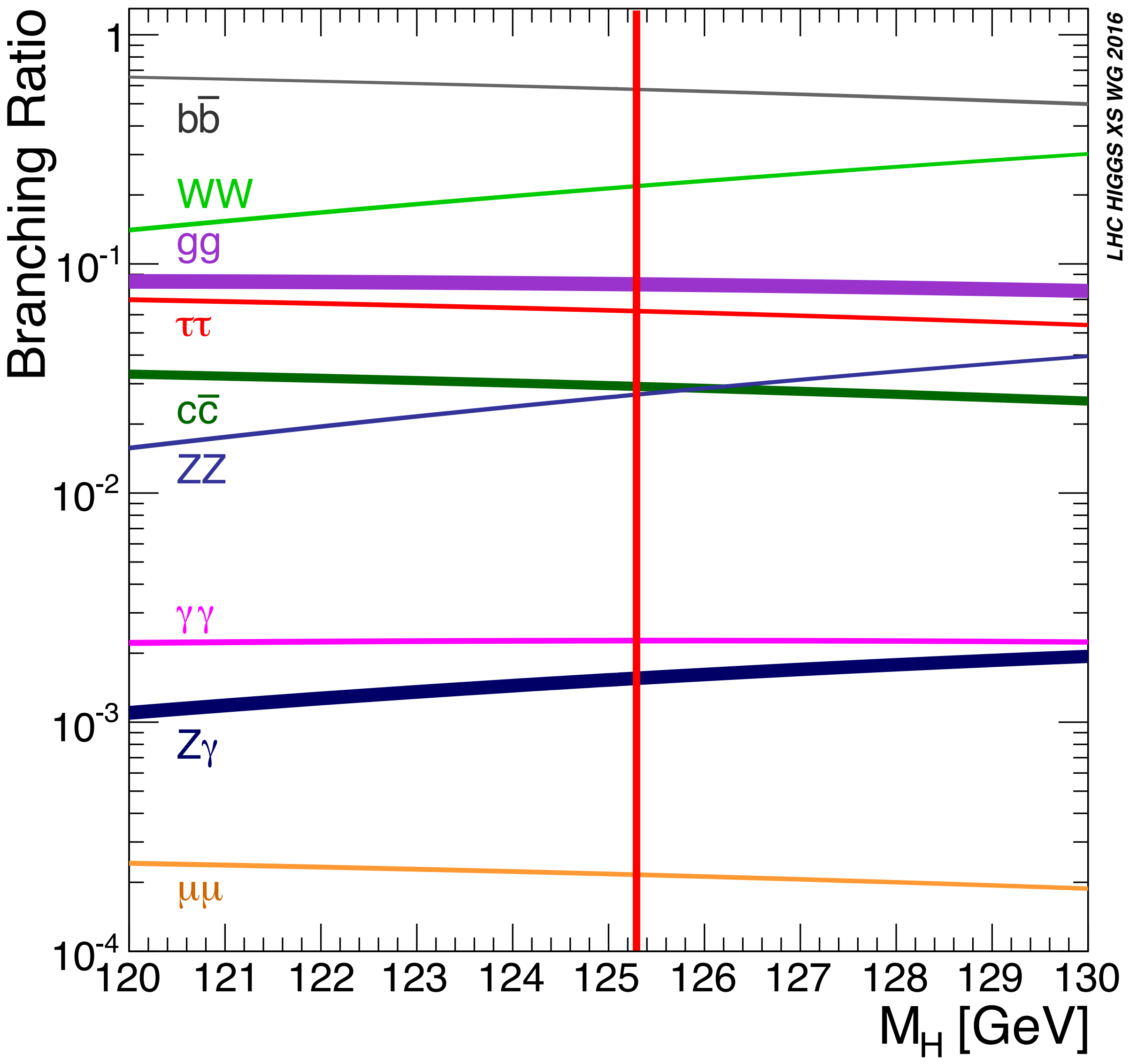


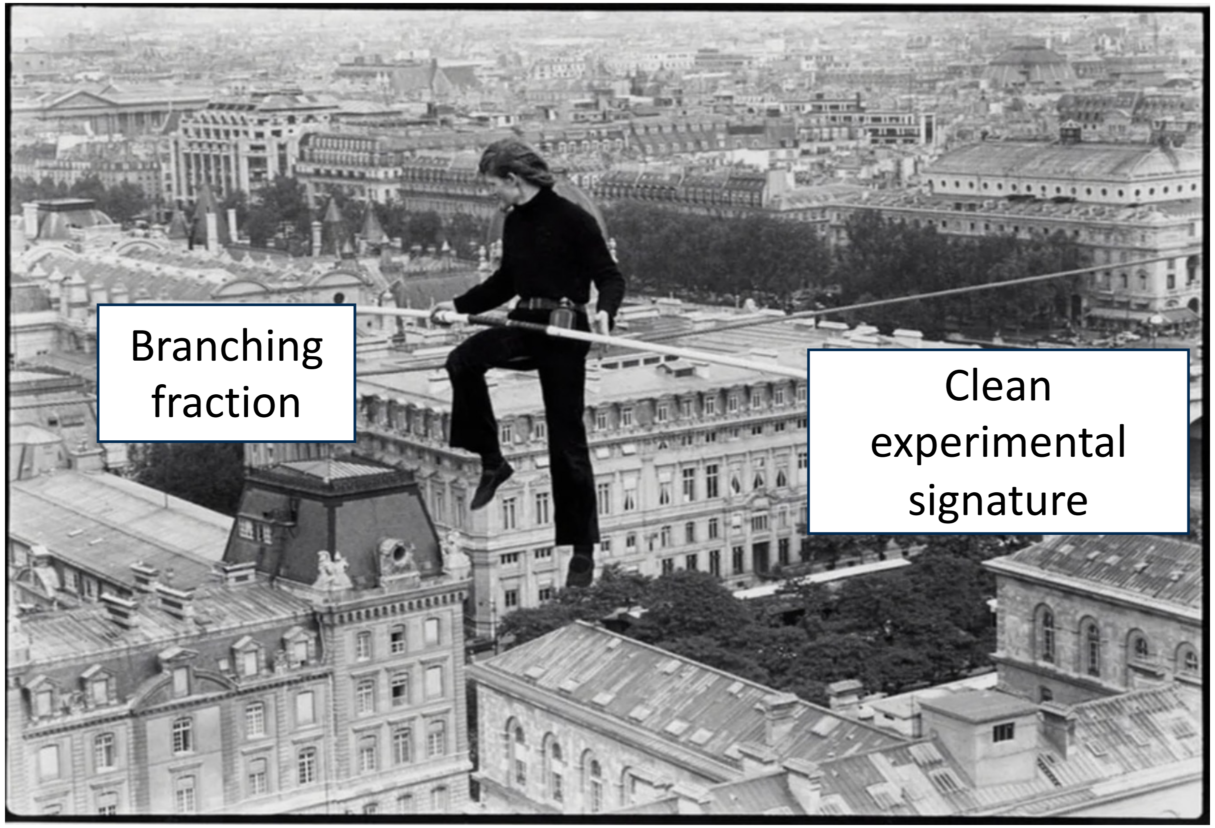






Decay of the Higgs boson





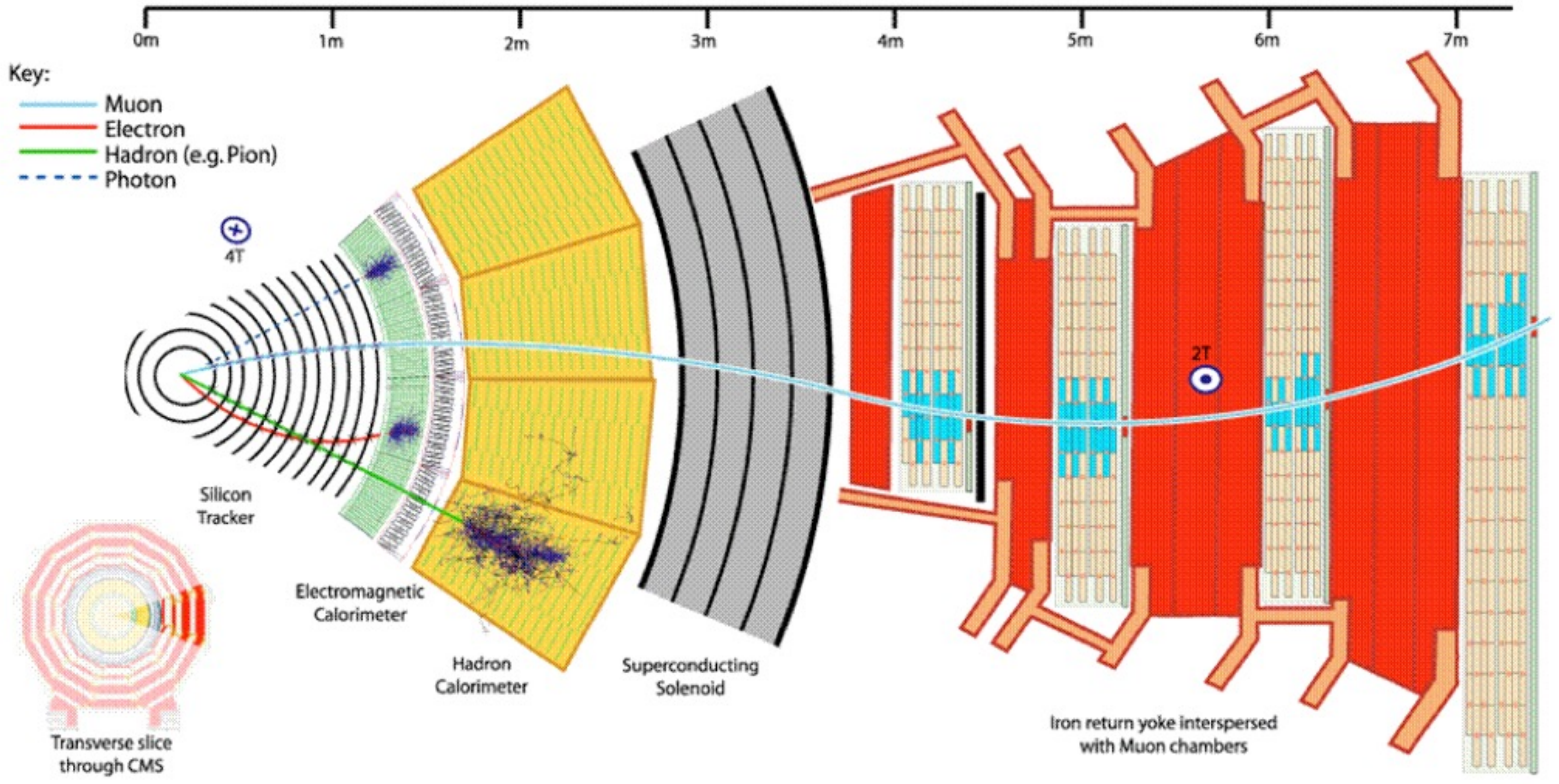
Branching fraction

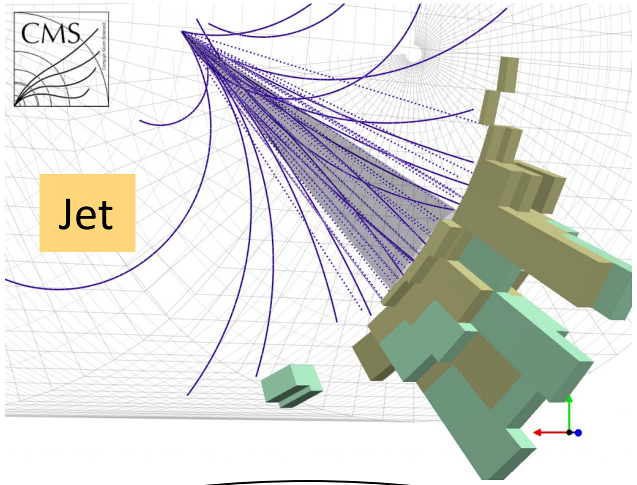
Clean experimental signature

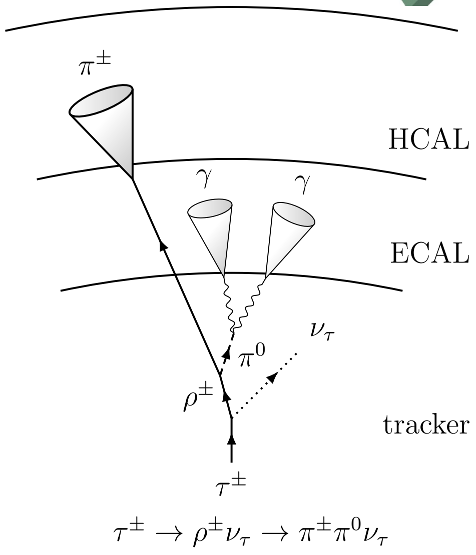
Man on wire

CMS Particle Reconstruction

- CMS uses Particle Flow algorithm to reconstruct stable particles combining the information from all sub-detectors
    - γ, e, μ, charged and neutral hadrons, imbalance in transverse energy: MET

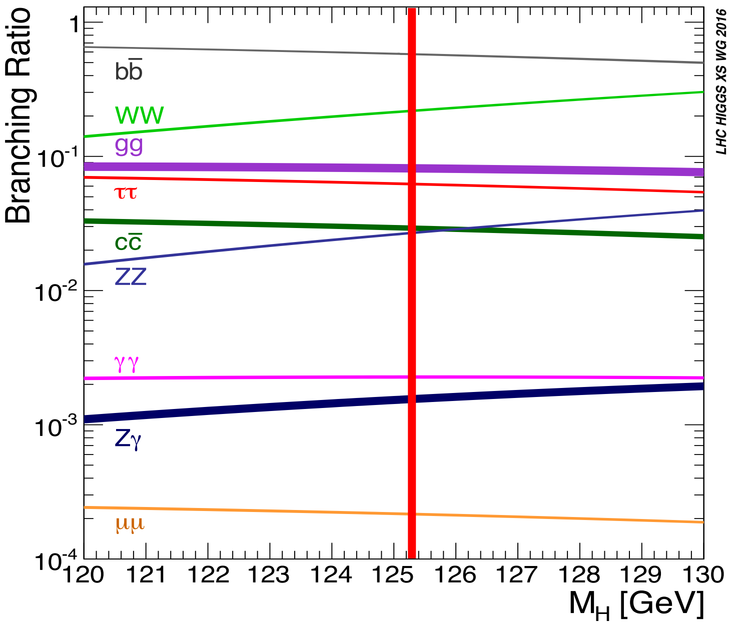




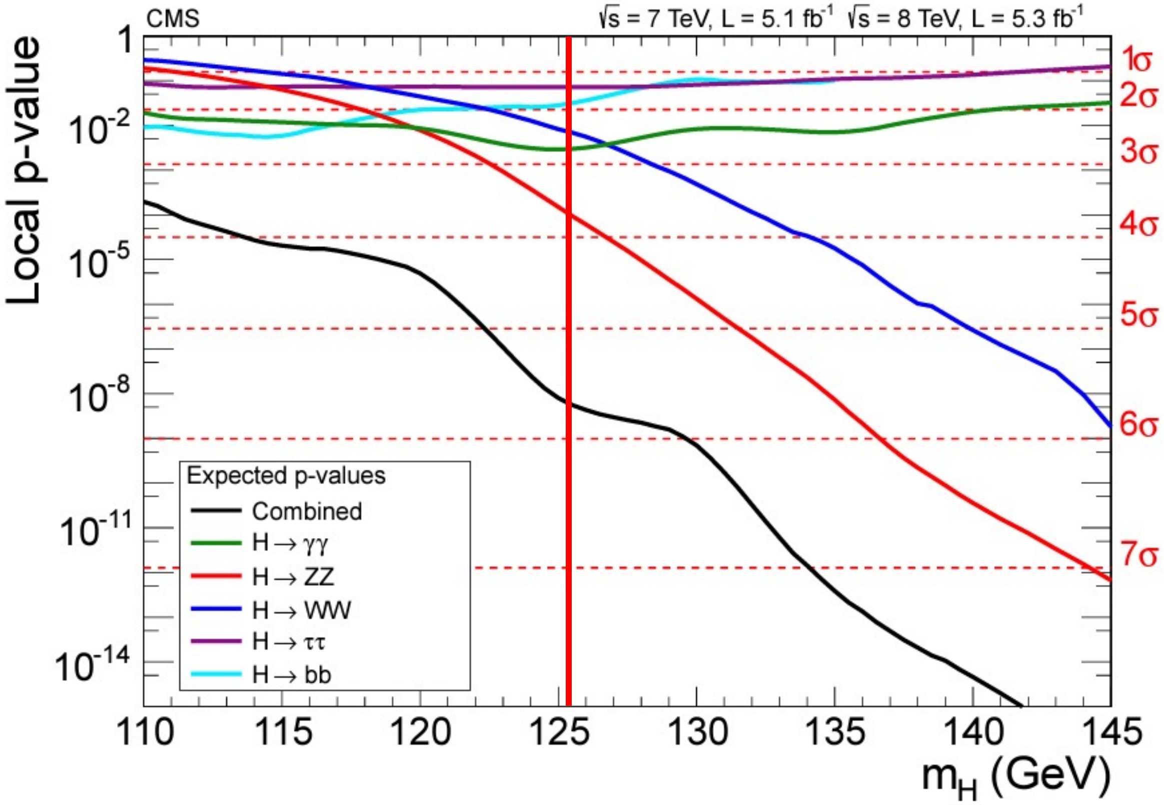


τ lepton reconstruction

Big five

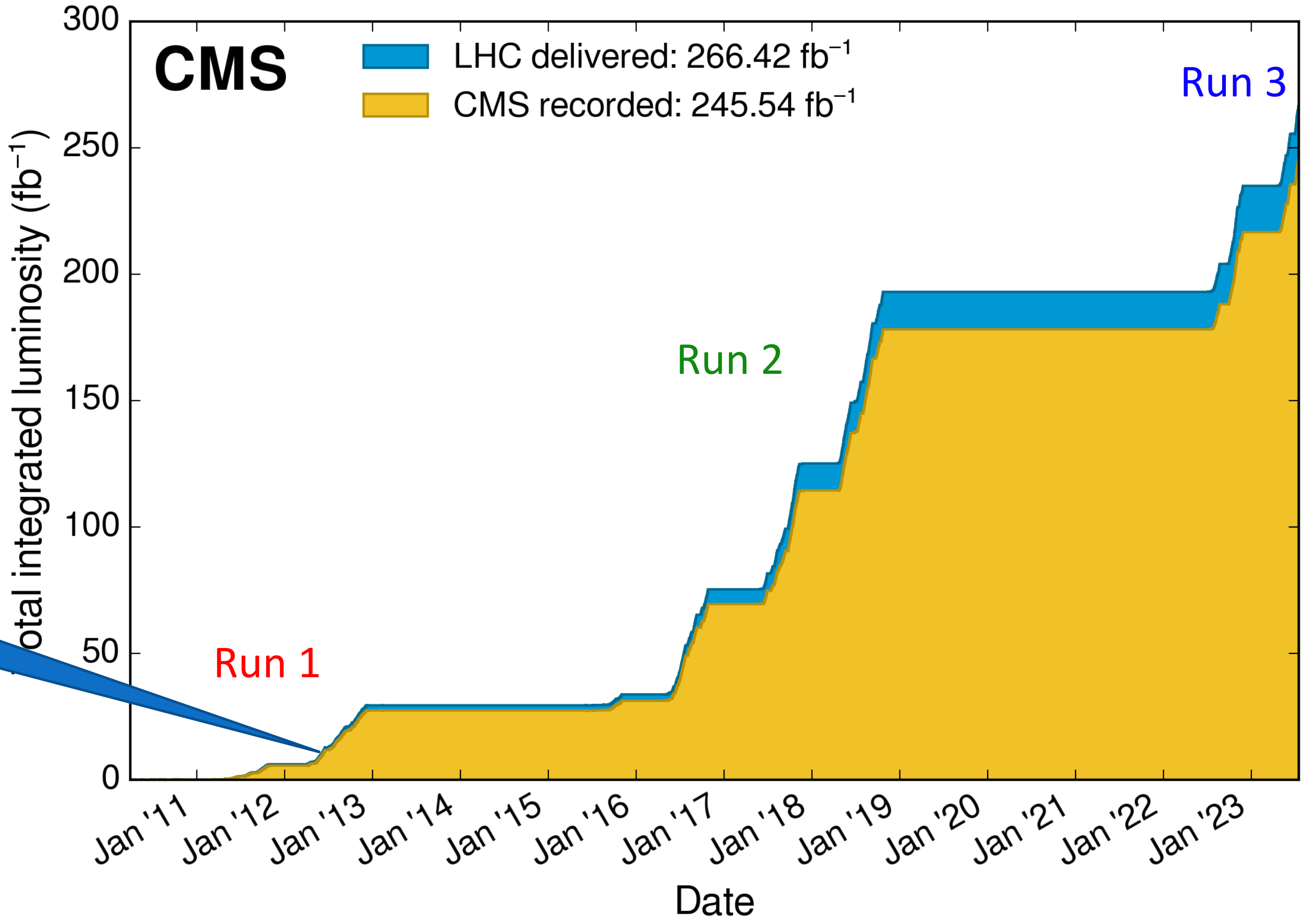


- Five decay channels are most promising
  - $\mathrm{H} \rightarrow \mathrm{ZZ} \rightarrow 4\ell$, 1-2% mass resolution
  - $\mathrm{H} \rightarrow \gamma\gamma$, 1-2% mass resolution
  - $\mathrm{H} \rightarrow \mathrm{WW} \rightarrow 2\ell 2\nu$, 20% mass resolution
  - $\mathrm{H} \rightarrow bb$, 15% mass resolution
  - $\mathrm{H} \rightarrow \tau\tau$, 15% mass resolution



LHC data

- Three distinct periods of data taking: Run 1, Run 2, Run 3
  - Cumulative CMS efficiency ~92%

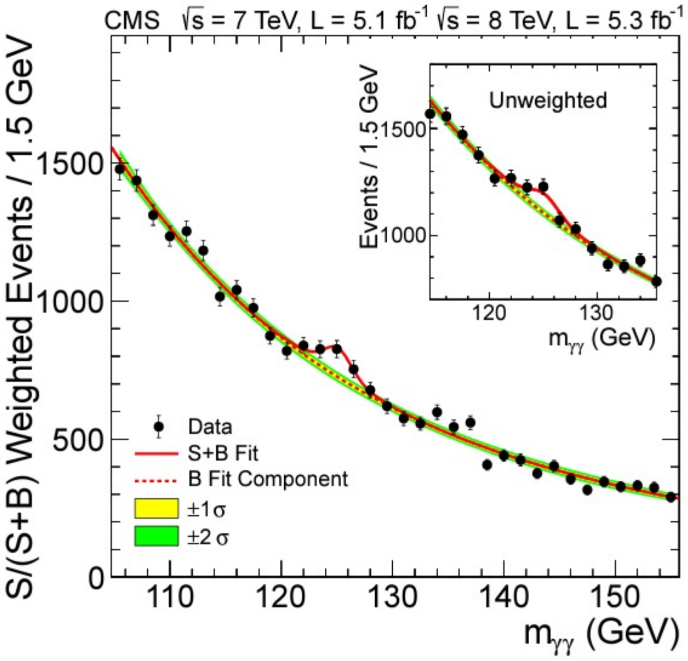


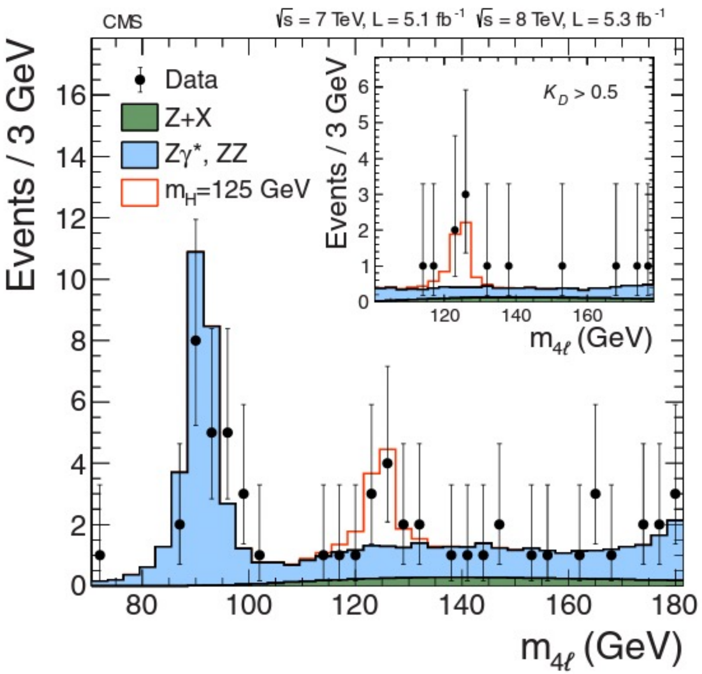
Discovery of narrow spin zero resonance

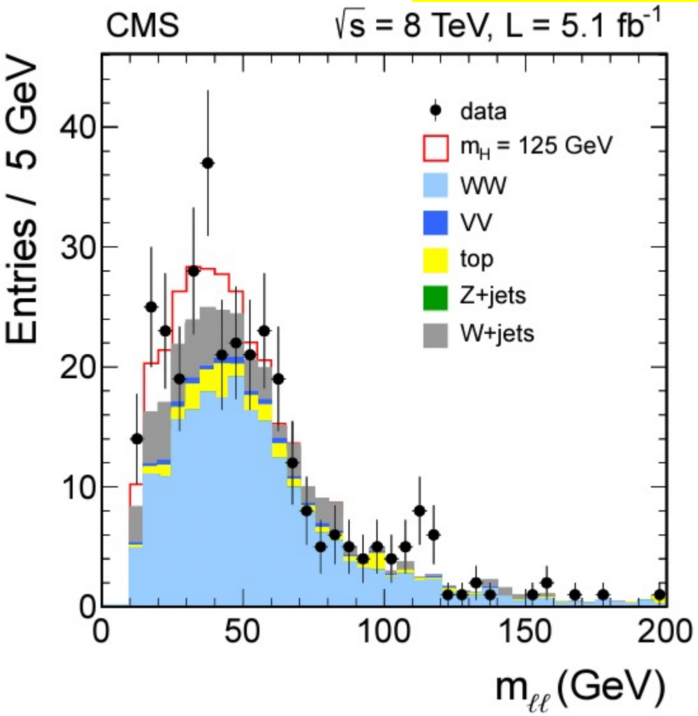
From narrow resonance to Higgs boson

- In the discovery paper new particle was referred to as narrow spin 0 (two photon decay) resonance

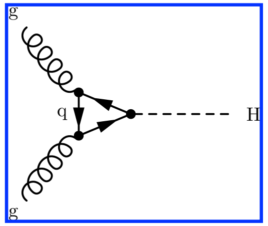
PLB 716 (2012) 30-61





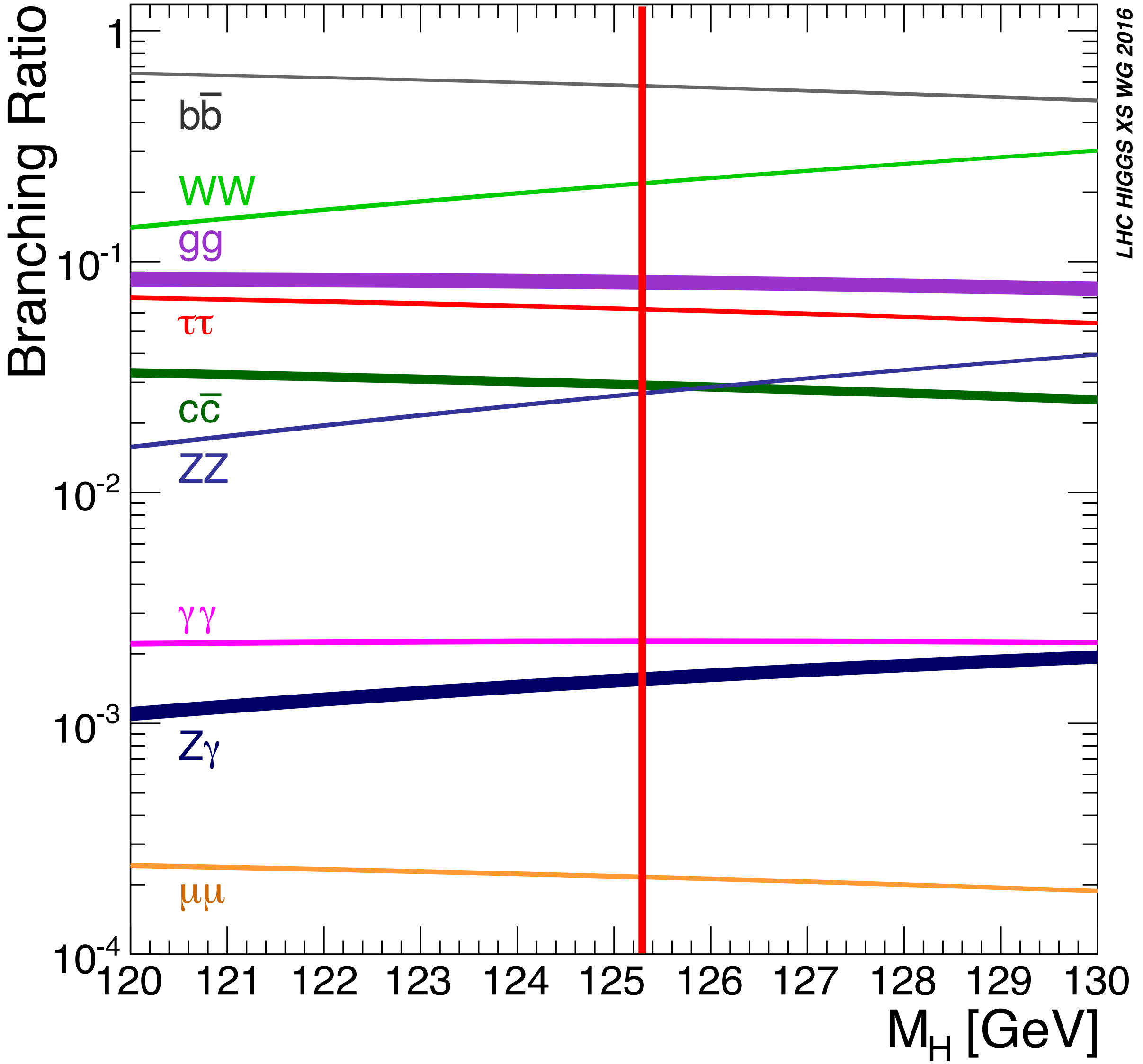


- Observed direct coupling to bosons only ($H \to \gamma\gamma$, $H \to ZZ$, $H \to WW$)
  - Beginning of massive undertaking to study the properties of the narrow resonance to see if it matches to that expected from the SM Higgs boson



Milestones: Yukawa couplings

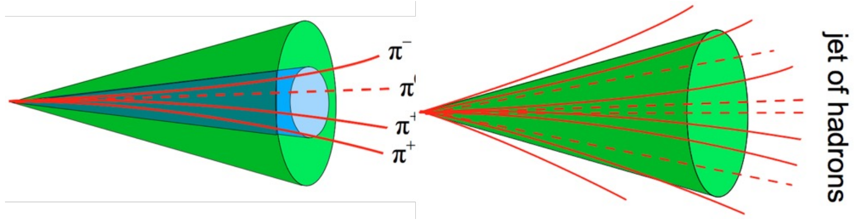
- Several processes
  - $\mathrm{H} \to \tau\tau$
  - $\mathrm{H} \to b\bar{b}$, perhaps $\mathrm{H} \to c\bar{c}$
  - $tt\mathrm{H}$
  - … and may be $\mathrm{H} \to \mu\mu$
- Very challenging but essential to test SM predictions
  - $\mathrm{H} \to \tau\tau$: significant irreducible background from $\mathrm{Z} \to \tau\tau$ and background from QCD multijet processes with jet $\to \tau$
  - $\mathrm{H} \to b\bar{b}$: overwhelming QCD multijet background, search in VH processes
  - $\mathrm{H} \to c\bar{c}$: similar to $\mathrm{H} \to b\bar{b}$, but more difficult due to smaller branching fraction and c quark identification
  - $\mathrm{H} \to \mu\mu$: small Yukawa coupling, rare process
- Yukawa matrix does not have to be diagonal
  - Important to look for flavor violating decays

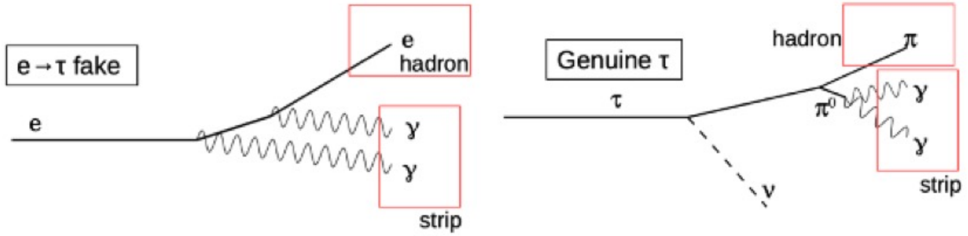


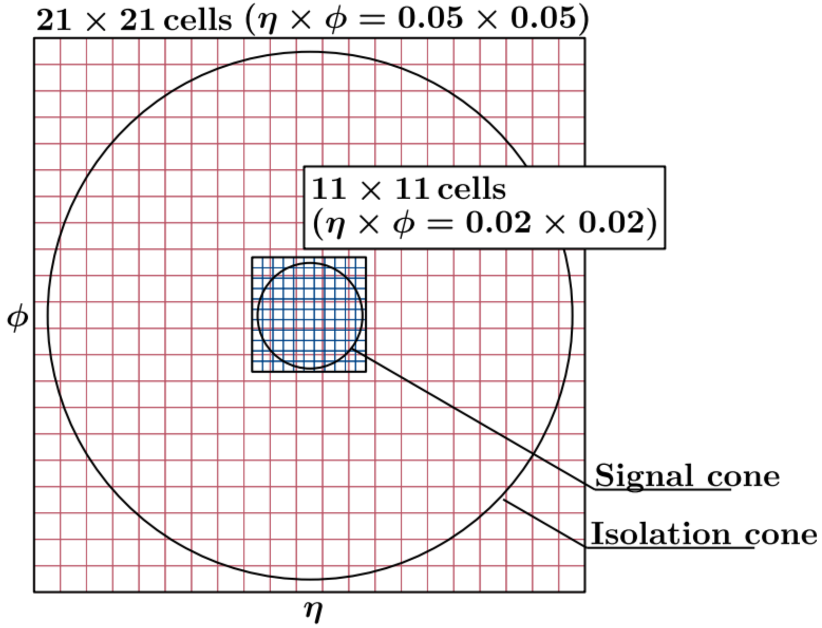
Machine learning tools: deep tau ID

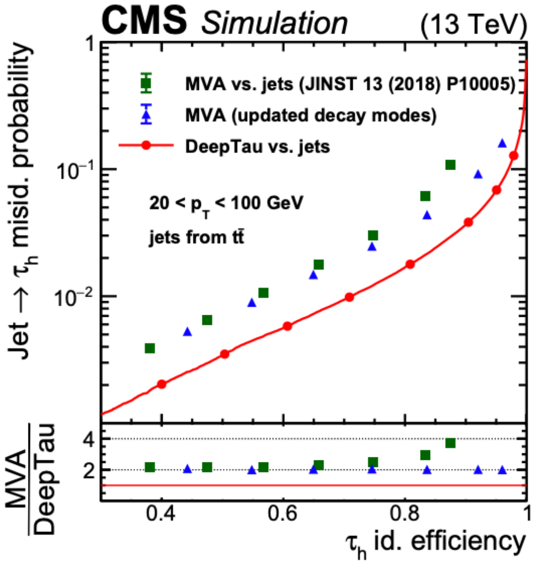
JINST 17 (2022) P07023

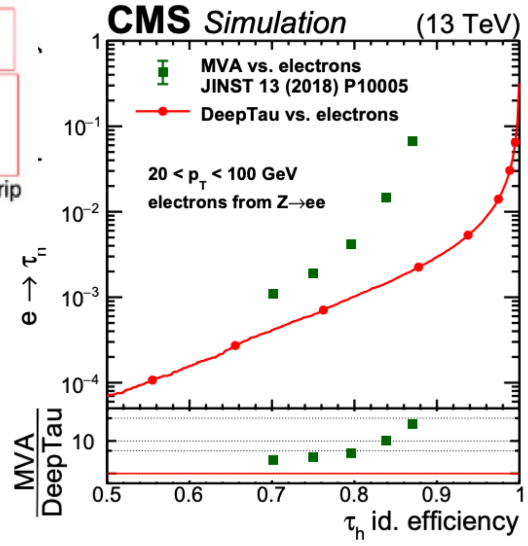
- Major background to tau lepton identification are jets

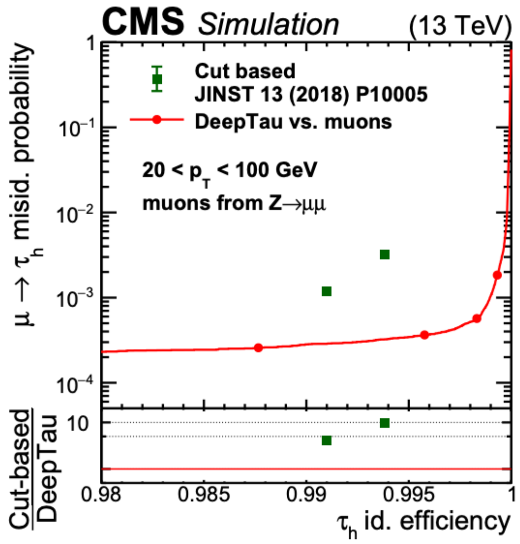










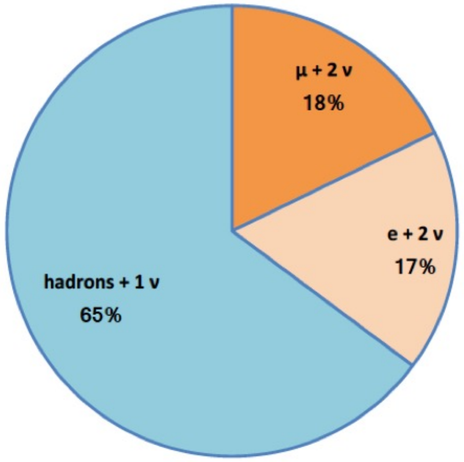


- Deep convolutional neural network for τ identification
  - About 100k input features used in training

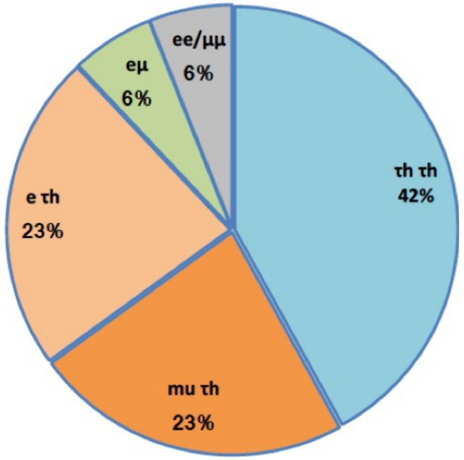
H → $\tau\tau$

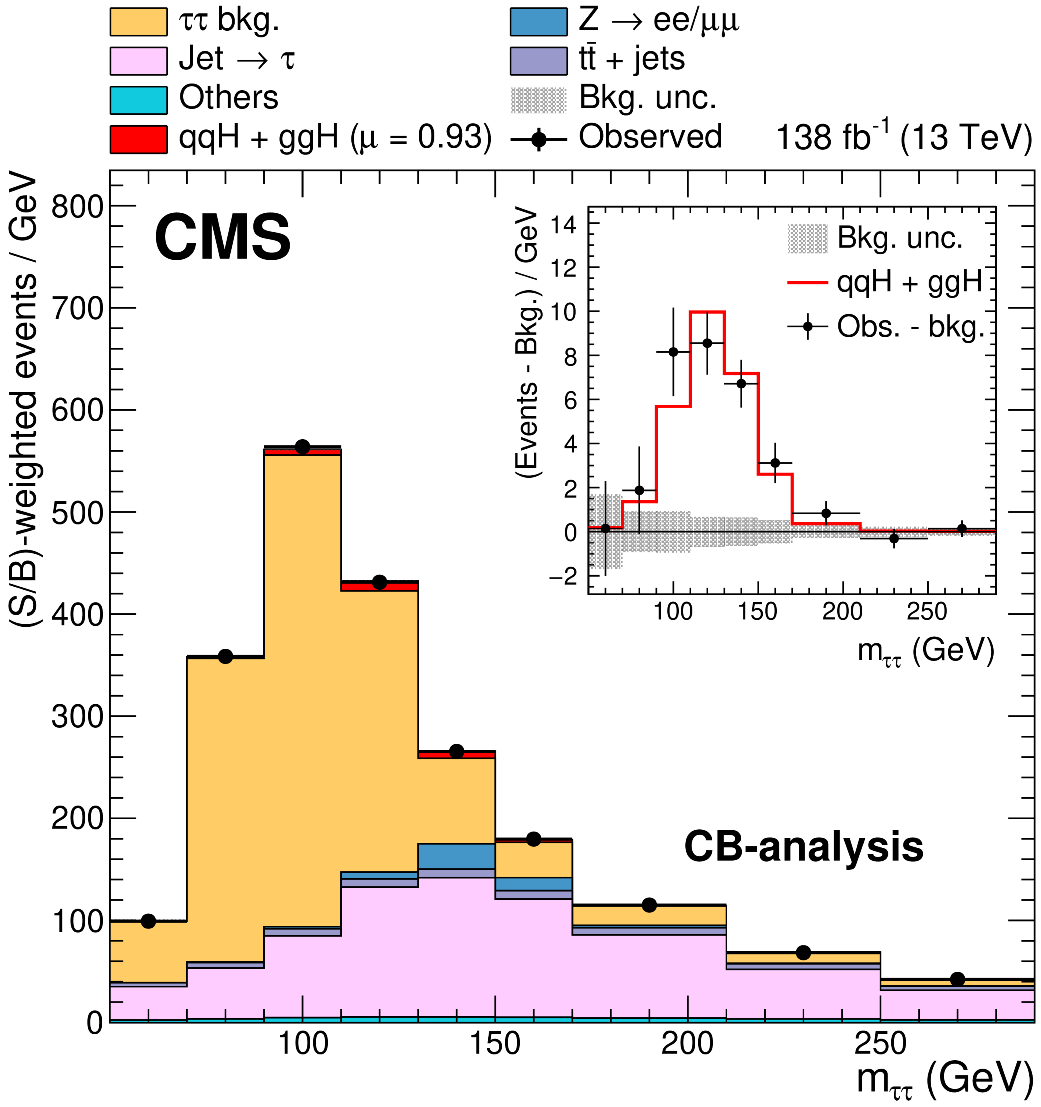
Eur. Phys. J. C 83 (2023) 562

TAU DECAYS



TT DECAYS





Drell Yan (Z → $\tau\tau$)

QCD

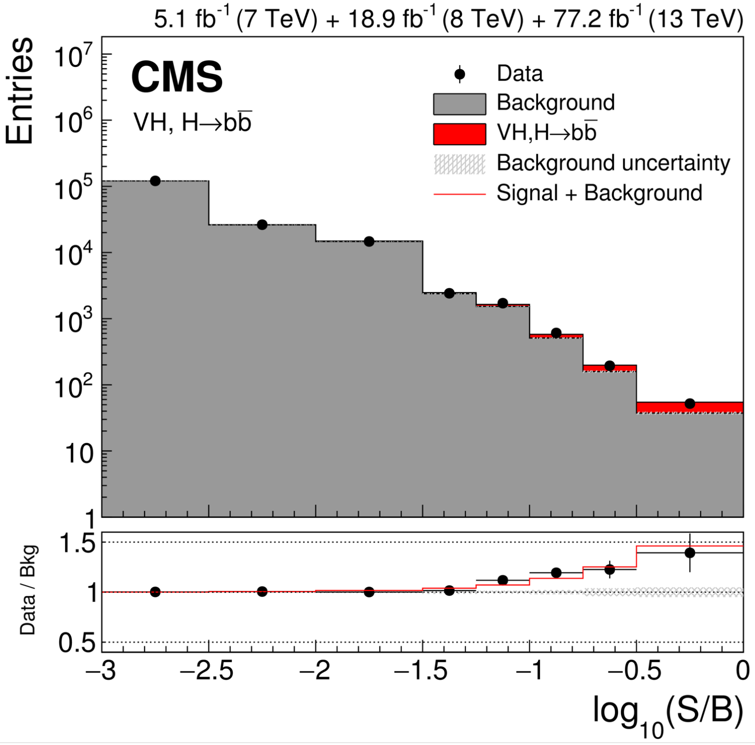
W+jets

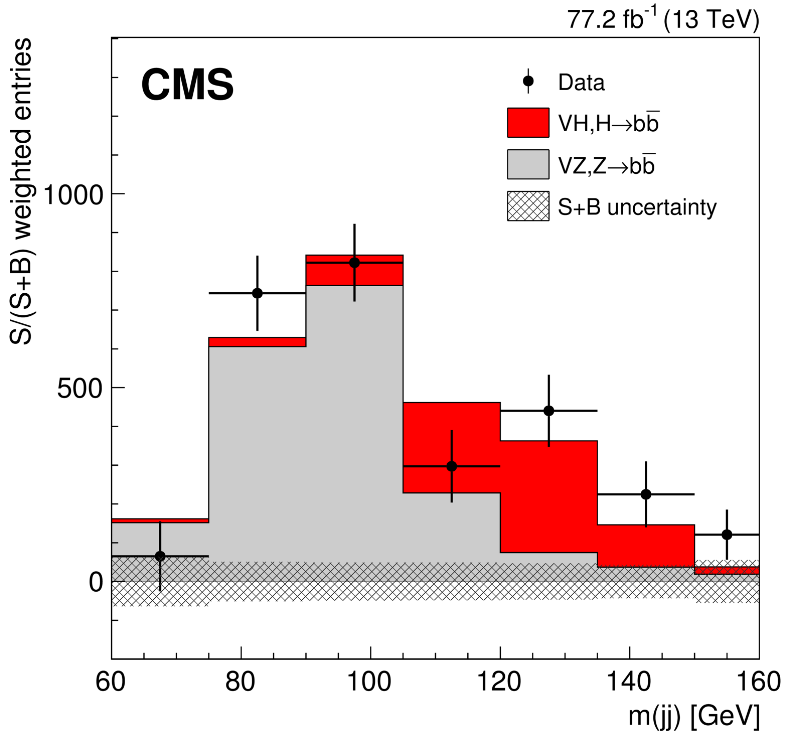
Using ML for particle identification and relying on human brains to do the analysis gave the same performance as the purely ML approach!

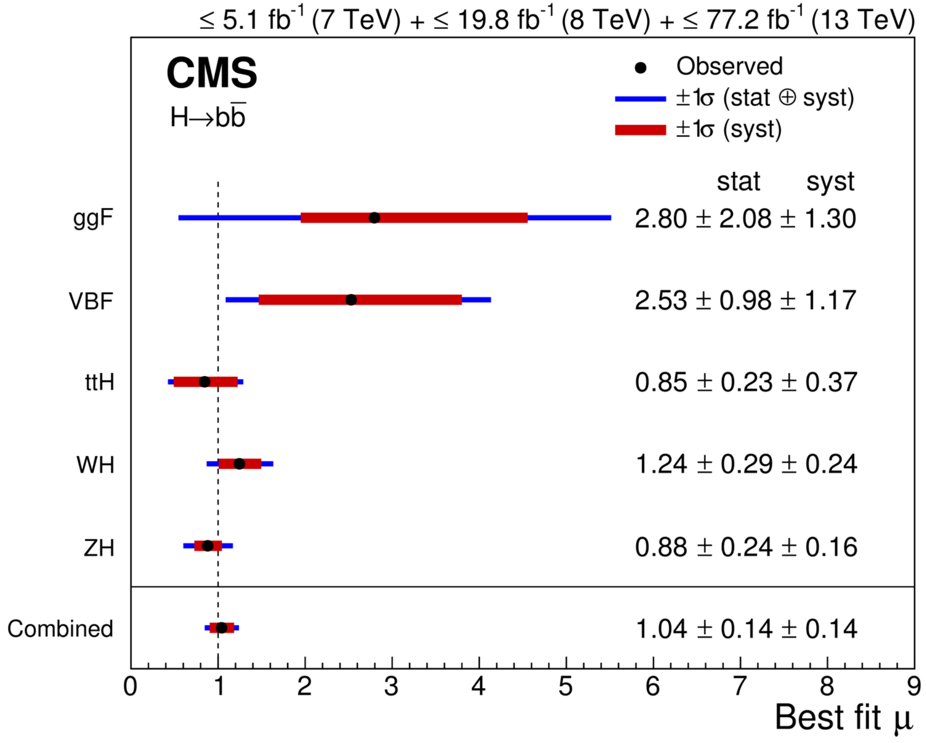
Milestones: Yukawa couplings in $\mathrm{H} \rightarrow b\bar{b}$

PRL 121 (2018) 121801

- Yukawa coupling to quarks
  - Multivariate networks made a crucial impact: deepCSV for b-tagging and DNN for signal to background separation
- Signal strength $\mu = \frac{\sigma_i}{\sigma_{SM}}$



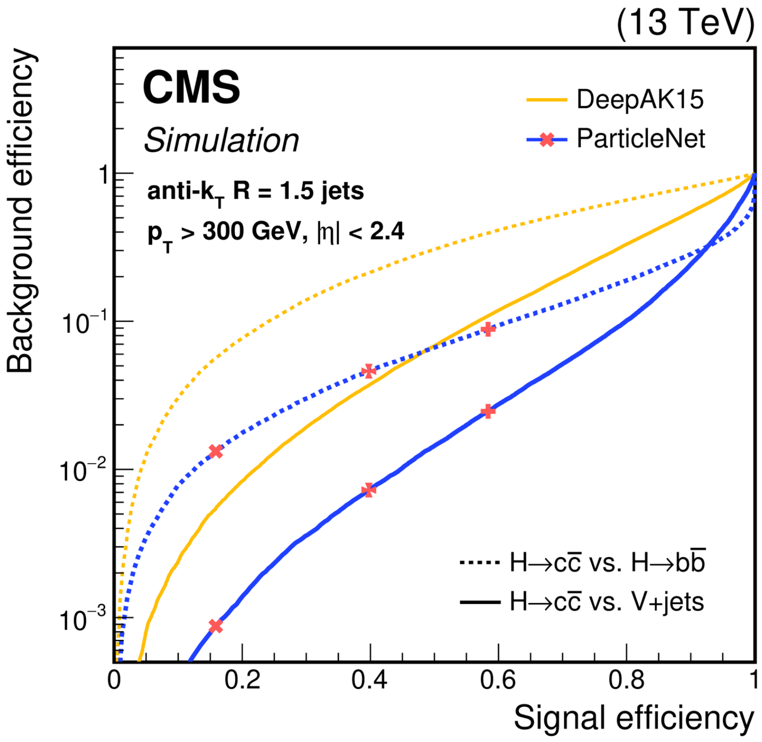


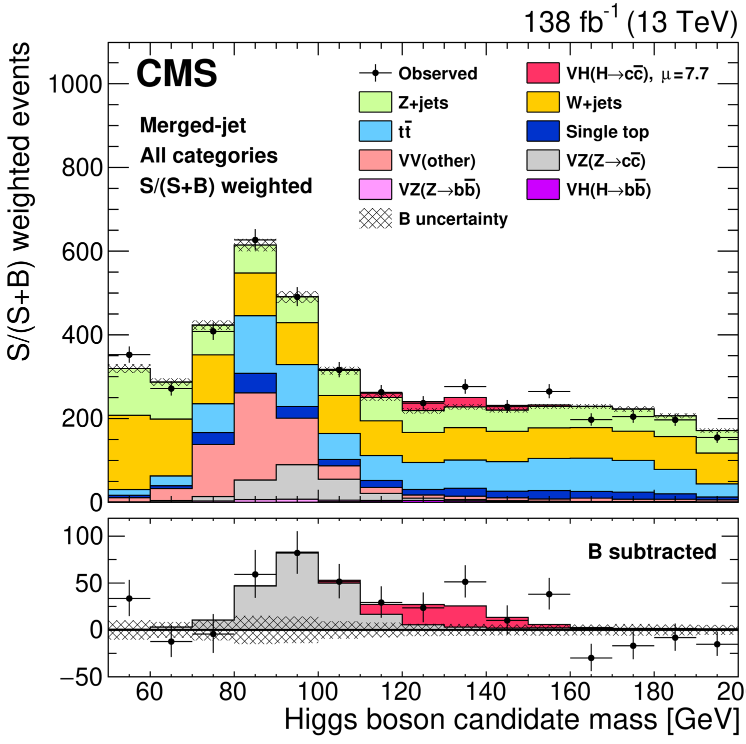


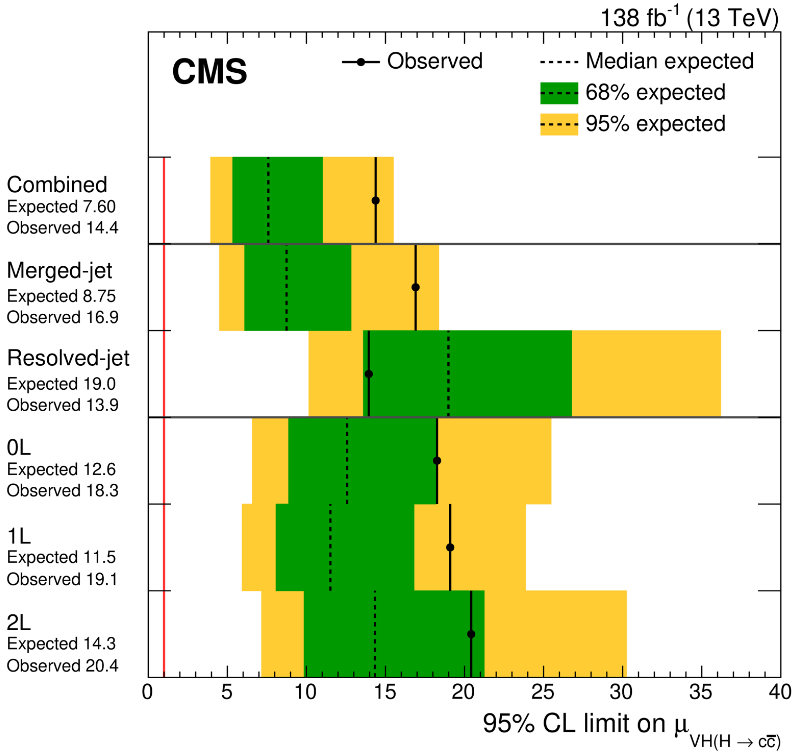
Search for $\mathrm{H} \rightarrow c\bar{c}$

PRL 131 (2023) 061801

- Fast progress on $\mathrm{H} \rightarrow c\bar{c}$
  - Sophisticated taggers to identify c-quark jets
- Current sensitivity is too low for observation: exploring Yukawa Hcc coupling using H+c processes



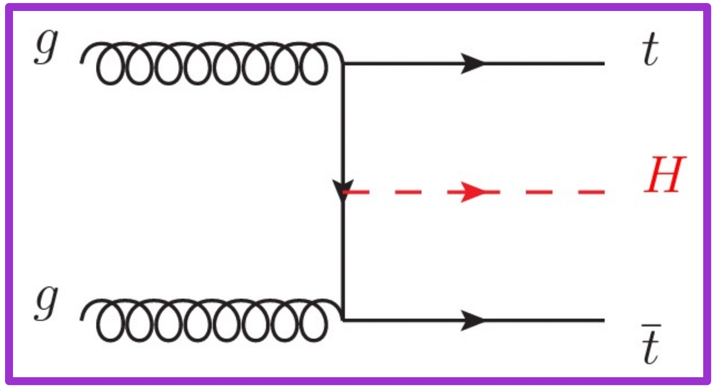


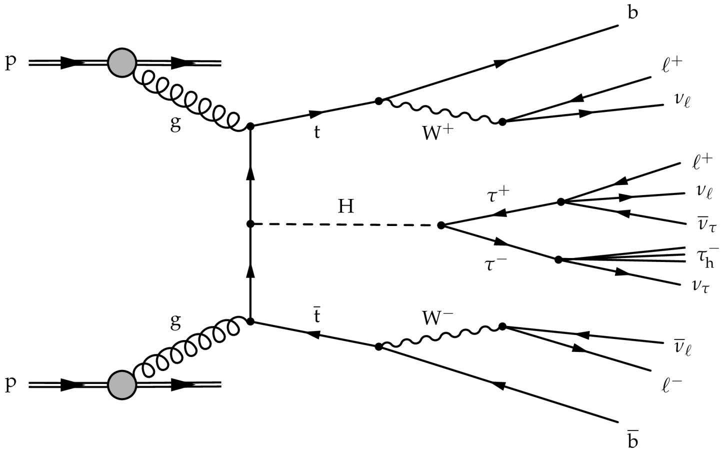


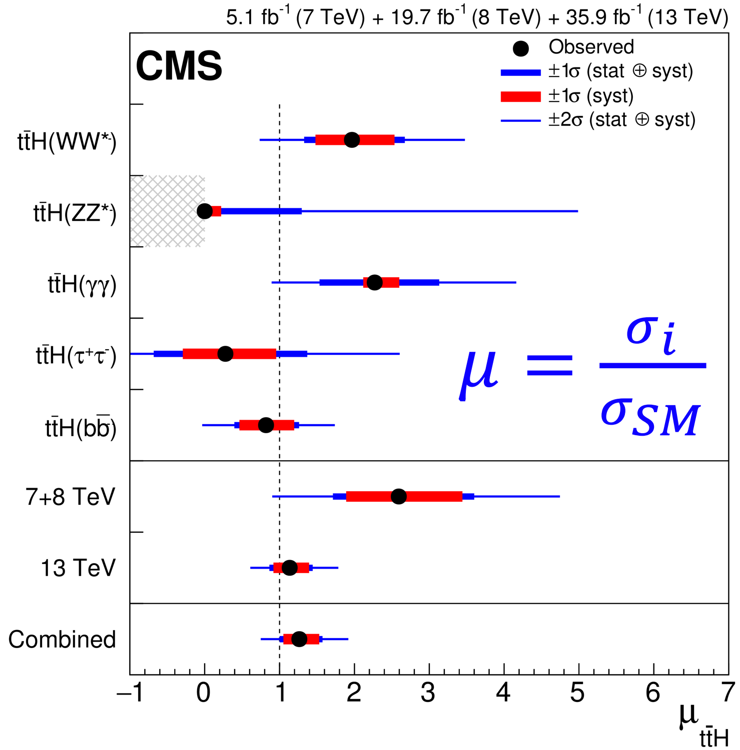
Rare process: ttH

PRL 120 (2018) 231801

- Rare process: almost two orders of magnitude below gluon fusion production
- Direct probe of the top quark to Higgs coupling
- Complex analysis due large number of final state objects and permutations
  - $t \rightarrow bW \rightarrow b\ell\nu$ or bjj
  - $H \rightarrow \gamma\gamma, bb, \tau\tau, WW, ZZ$



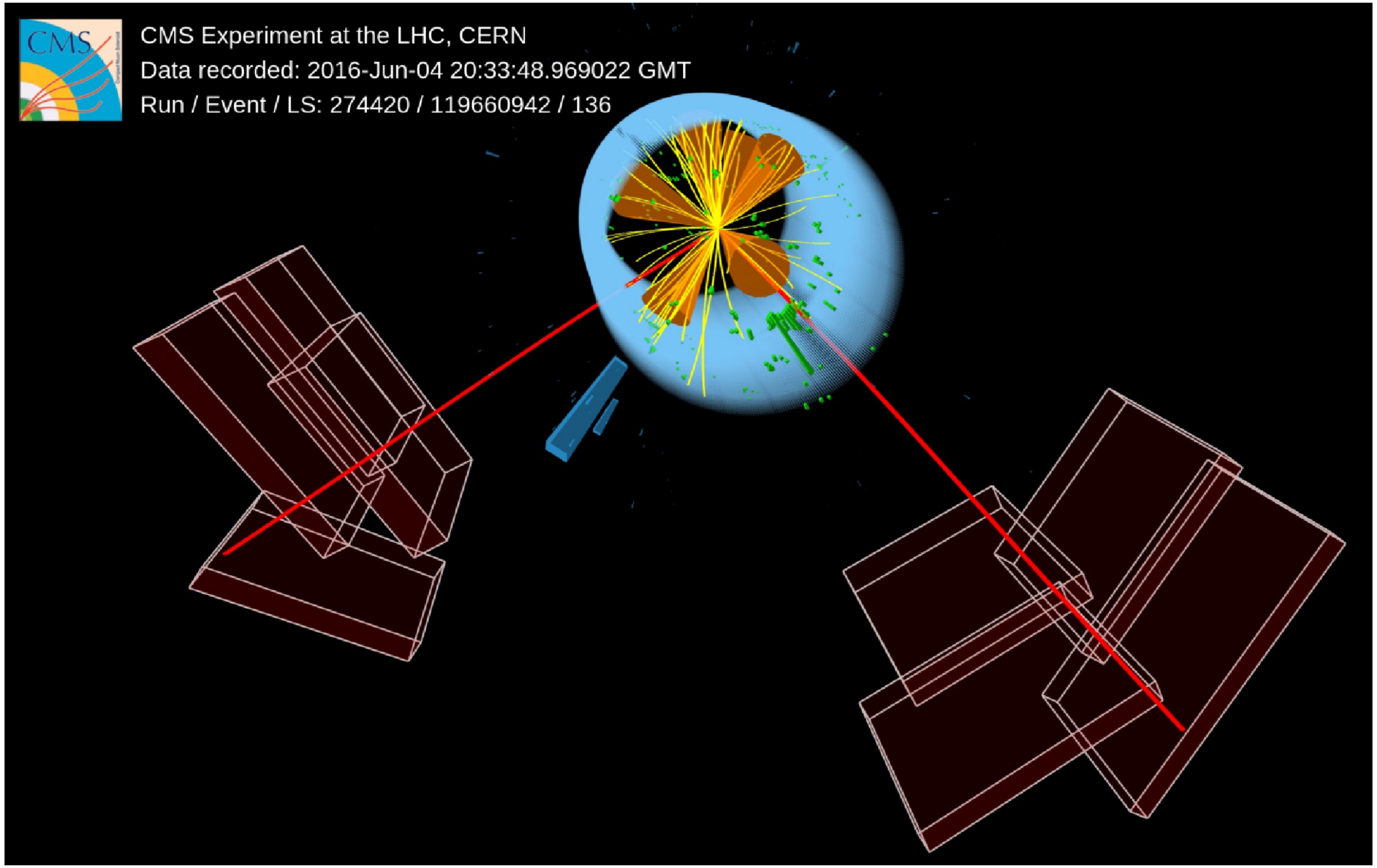




$$\mu = \frac{\sigma_i}{\sigma_{SM}}$$

Evidence for $\mathrm{H} \rightarrow \mu\mu$

JHEP 01 (2021) 148

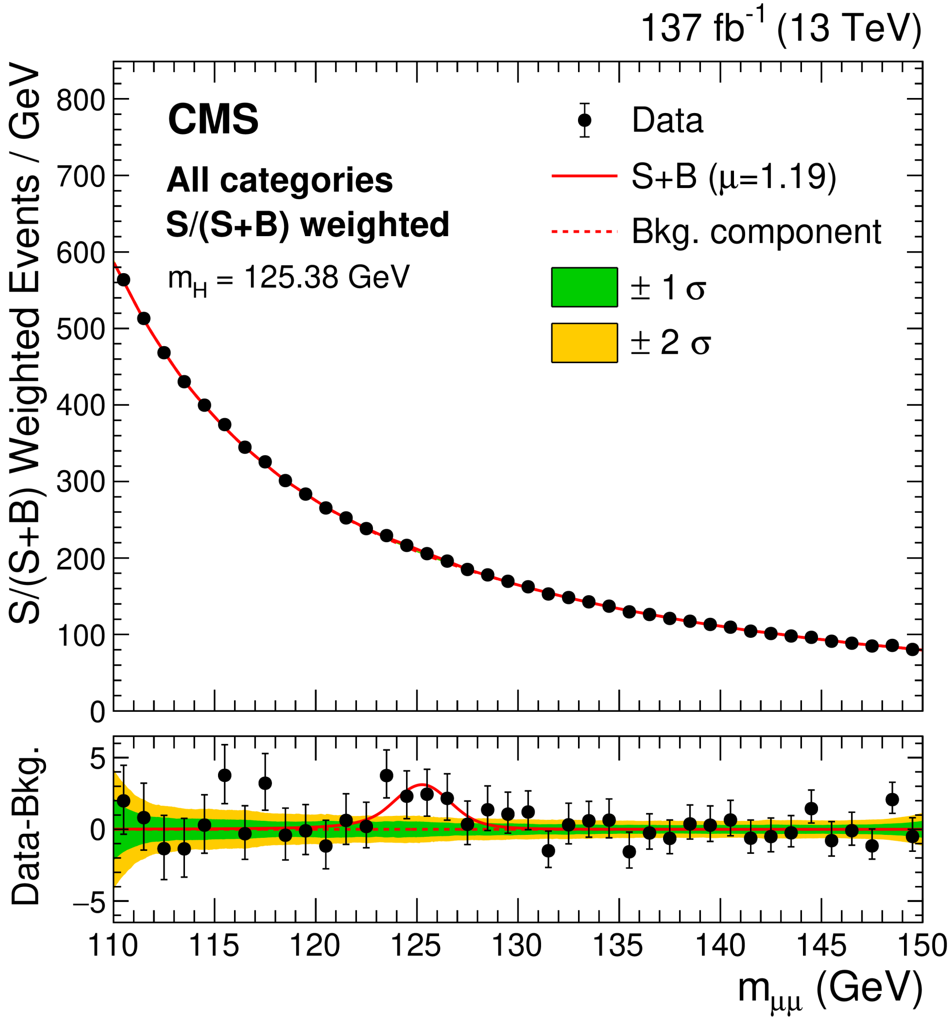


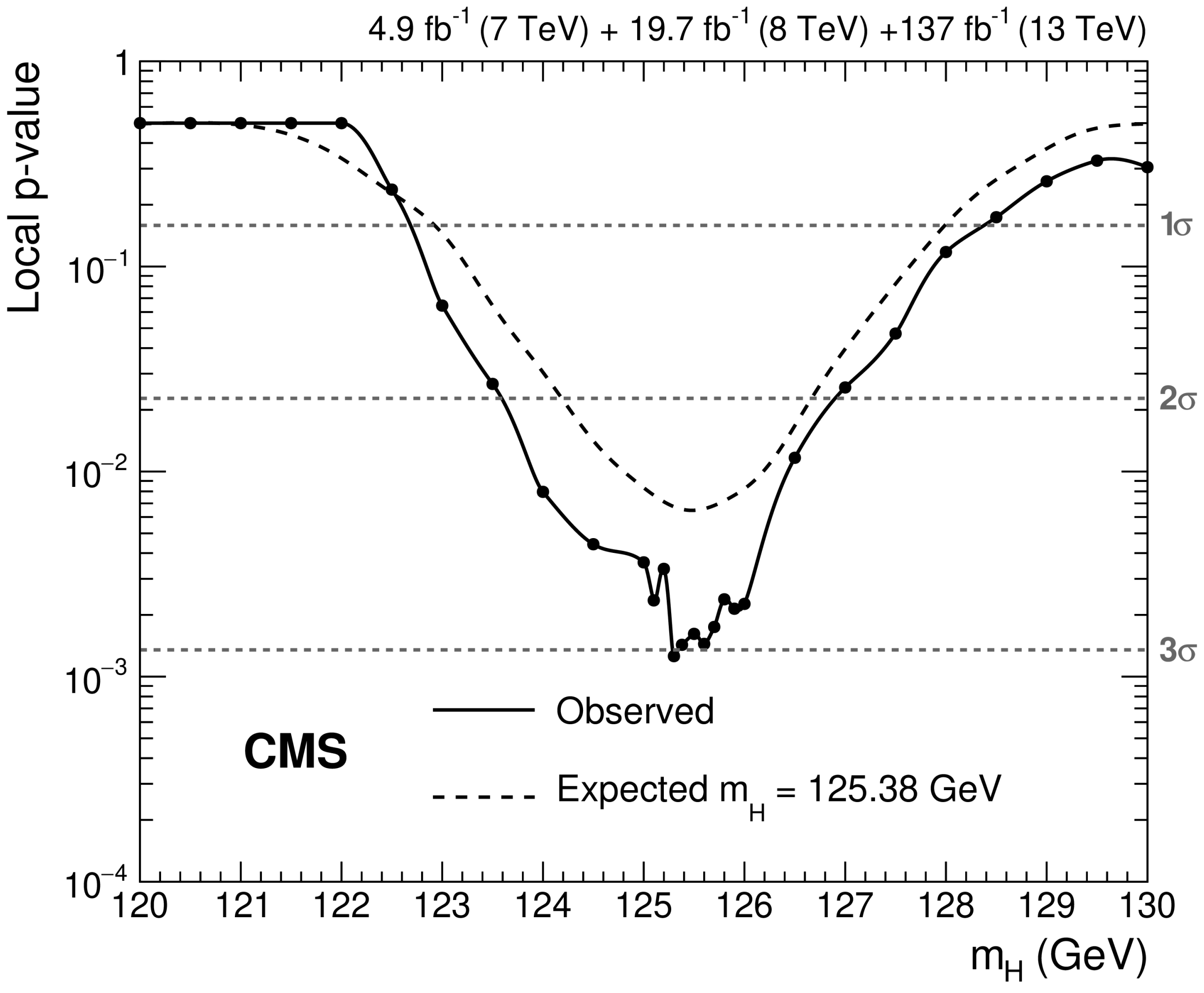
- Candidate event display of a Higgs boson decaying into two muons

Evidence for H → $\mu\mu$

JHEP 01 (2021) 148

- 3σ observed significance (2.5σ)

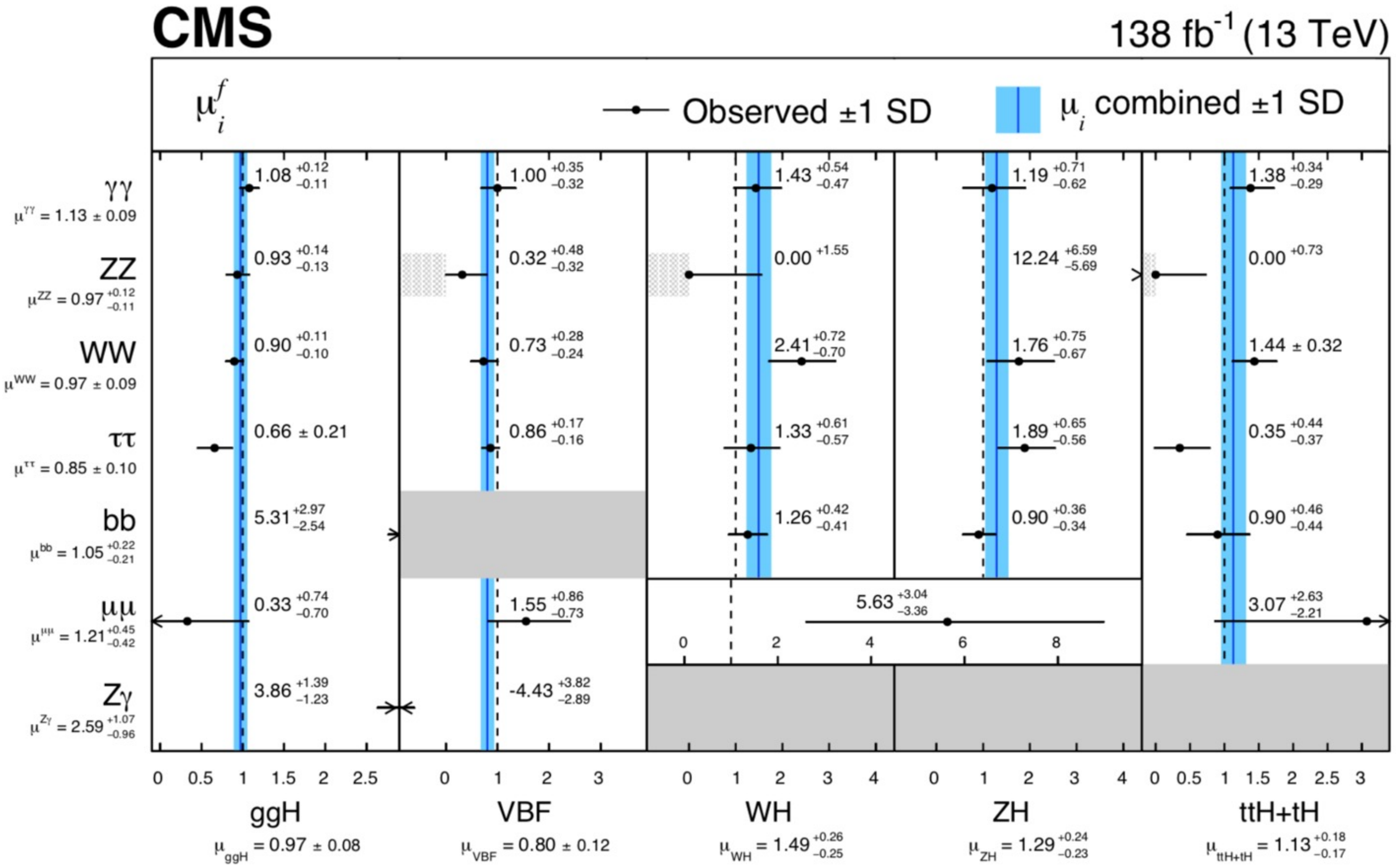




Current status

$$\mu = 1.002 \pm 0.057$$
$$= 1.002 \pm 0.036\ (\text{theo}) \pm 0.033\ (\text{syst}) \pm 0.029\ (\text{stat})$$

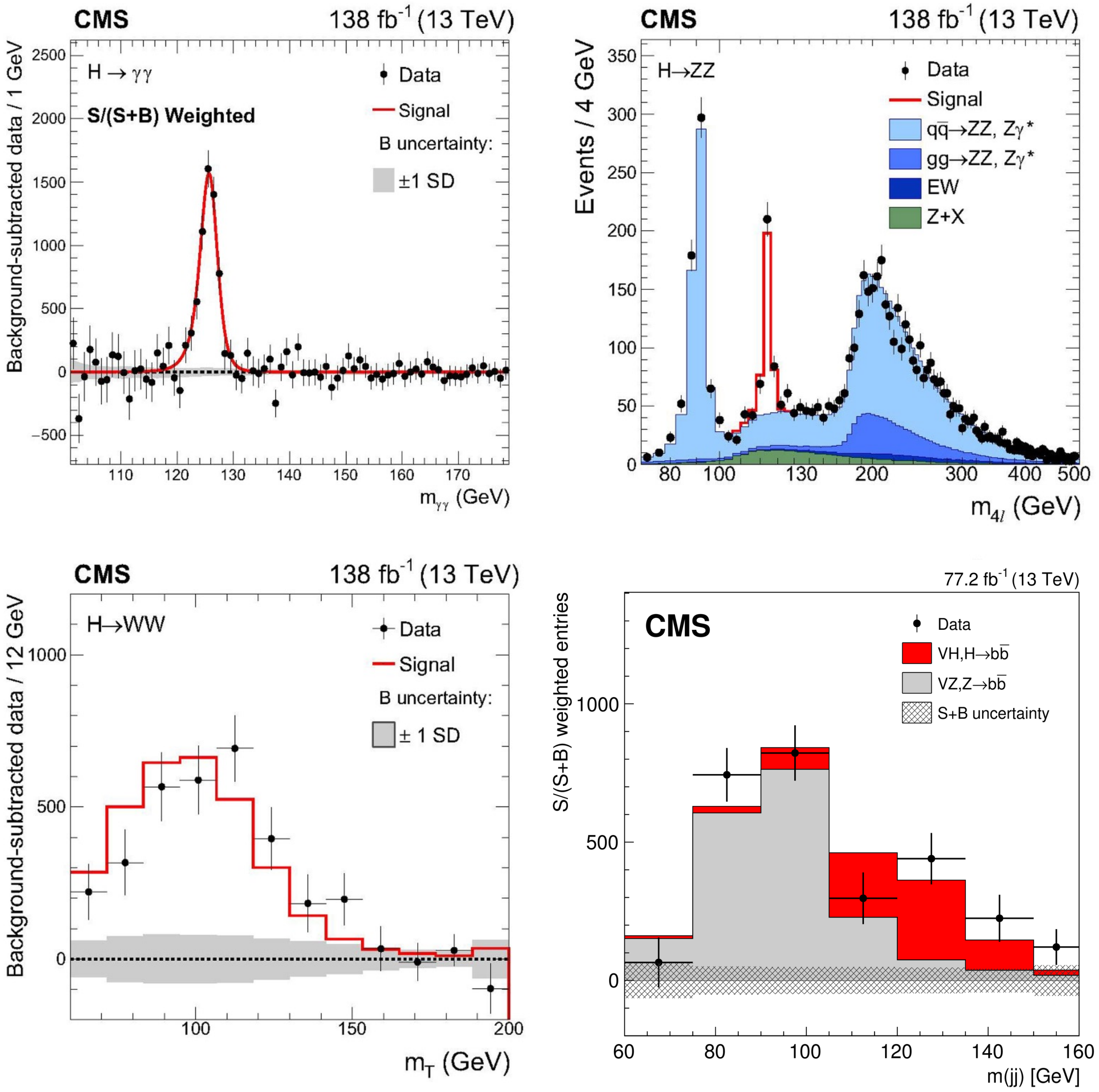
- Observed Higgs production in all main production and decay modes
  - So far, all predictions agree with the SM ones



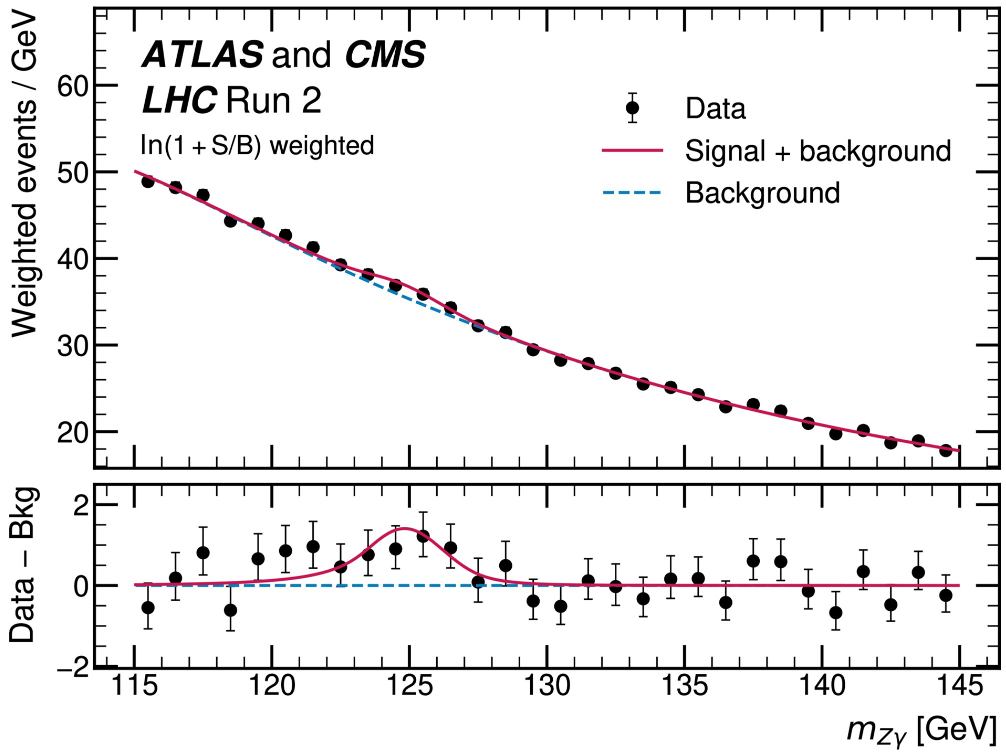
$$\mu = \frac{\sigma_i}{\sigma_{SM}}$$

Mass and width of the Higgs boson

Nature 607 (2022) 60-68

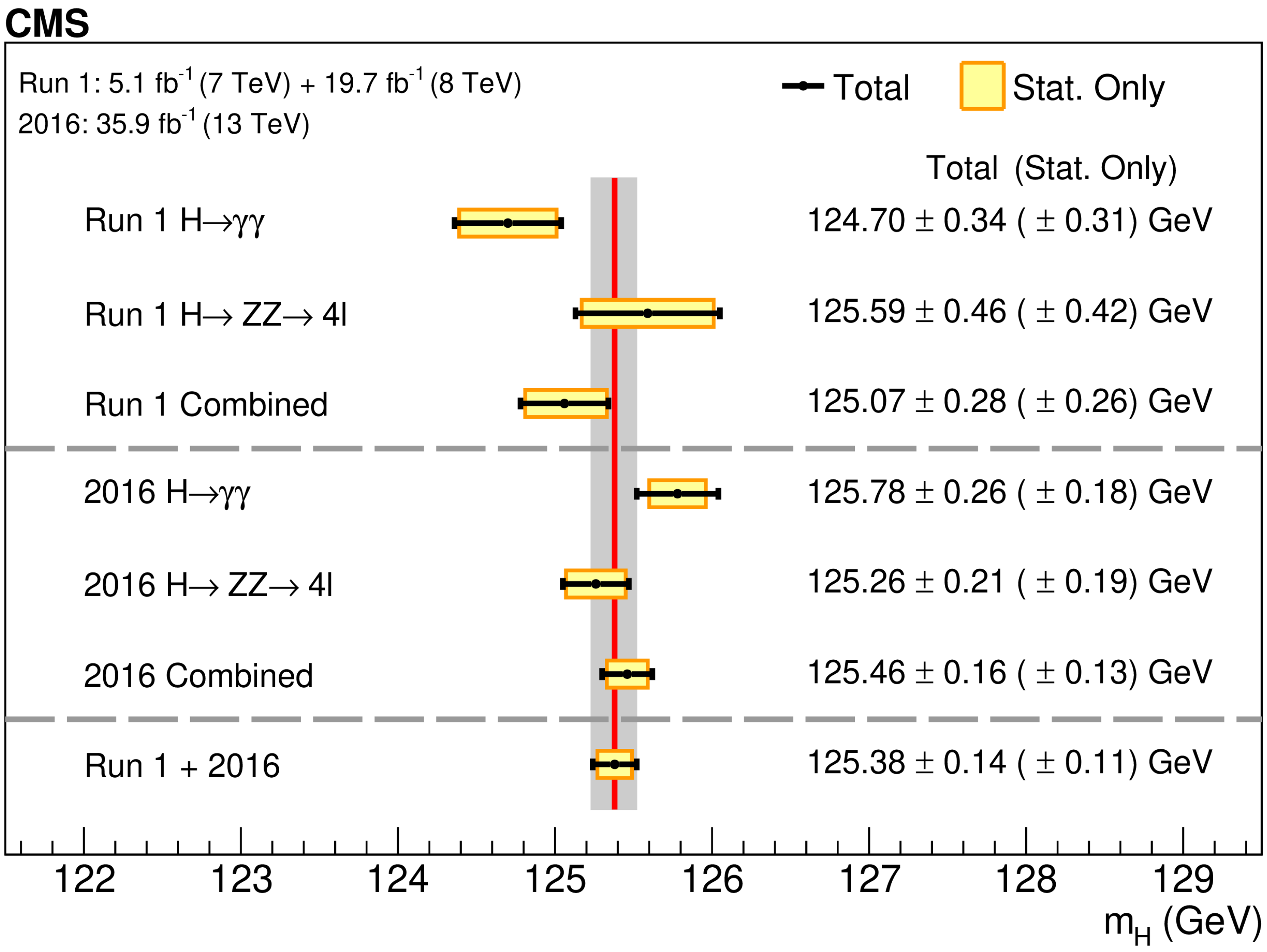


arXiv:2309.03501



Current status: mass of Higgs boson

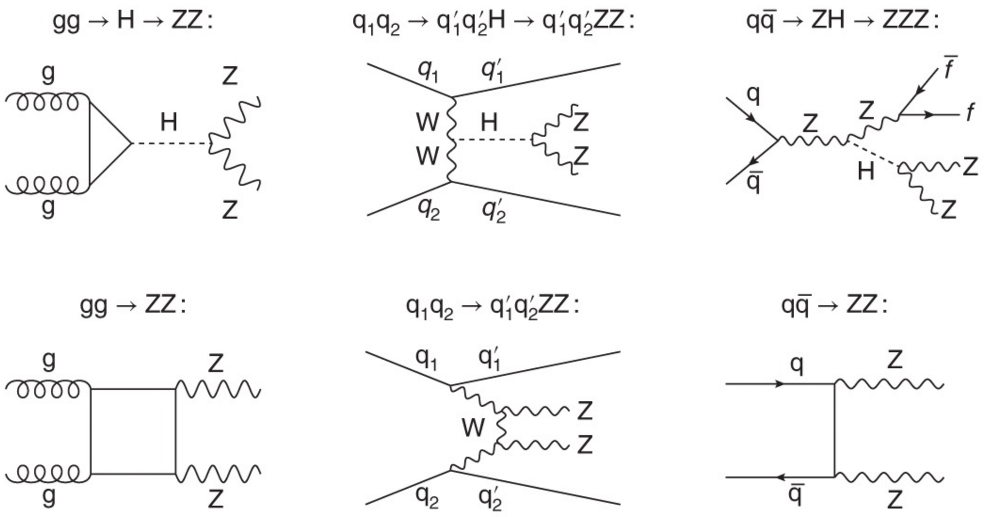
PLB 805 (2020) 135425

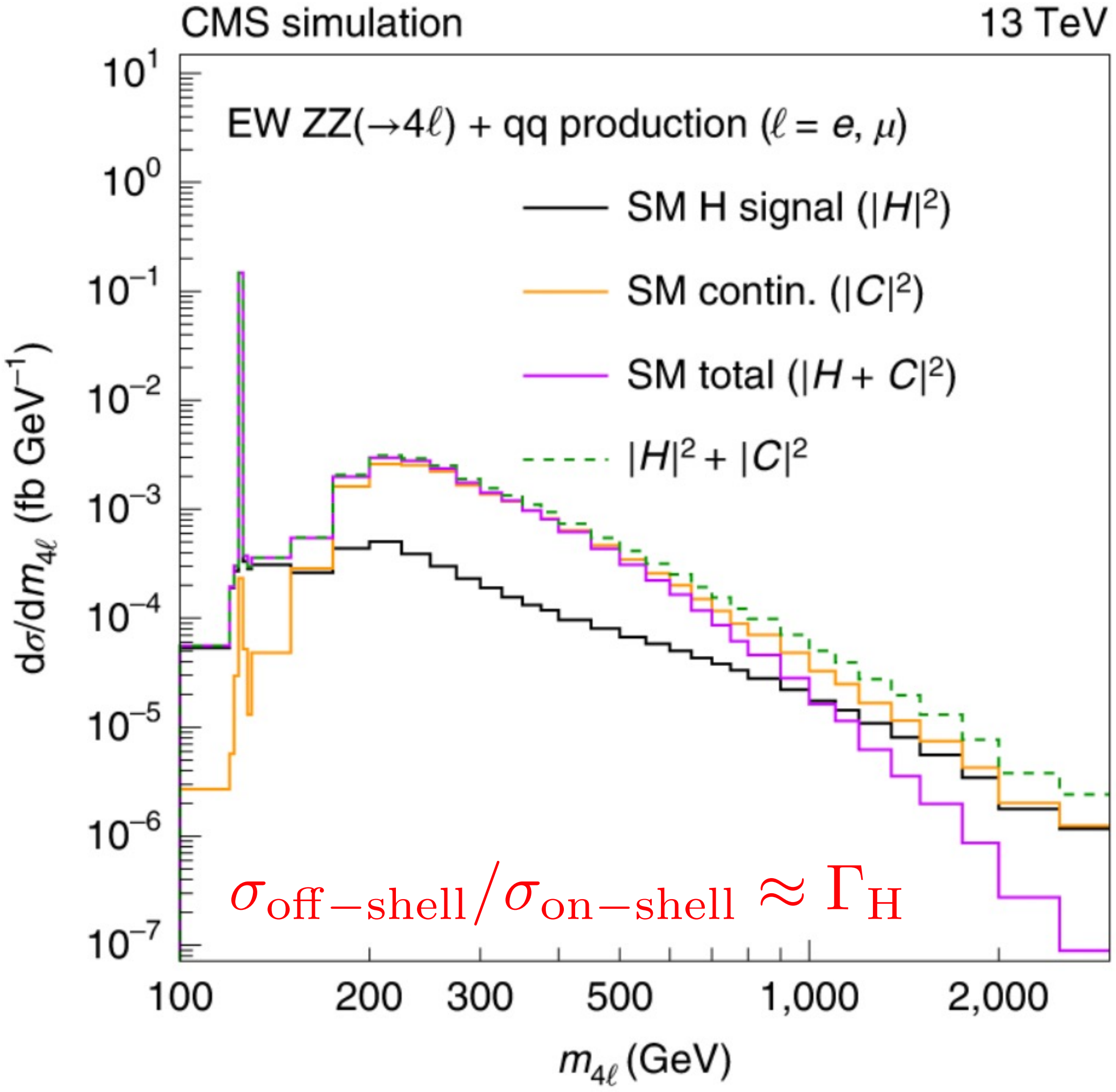


Current status: width of Higgs boson

Nature Physics 18 (2022) 1329-1334

- Width of Higgs boson is important
  - Access to invisible decays of the Higgs
  - Constrains many BSM scenarios
- Difficult to be done directly
  - SM predicts $\Gamma_H = 4.1$ MeV
- Study off-shell interference effects in ZZ decay mode

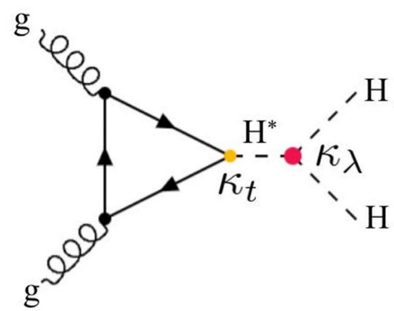




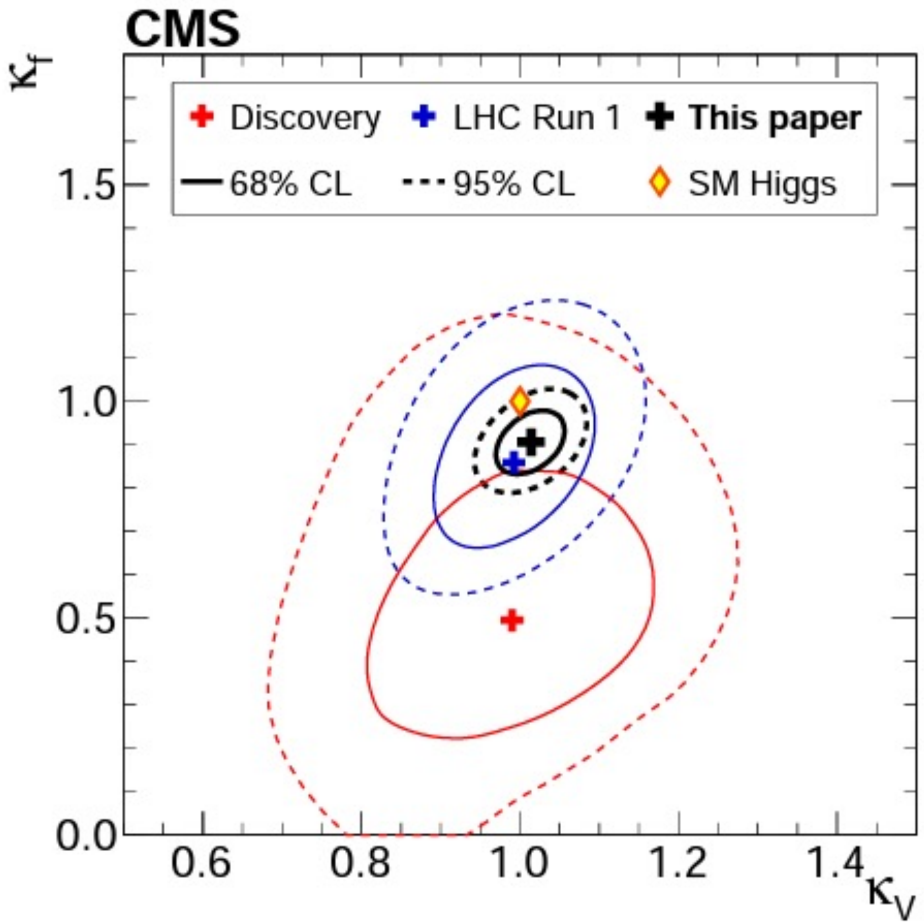
$$\sigma_{\mathrm{off-shell}}/\sigma_{\mathrm{on-shell}} \approx \Gamma_{\mathrm{H}}$$

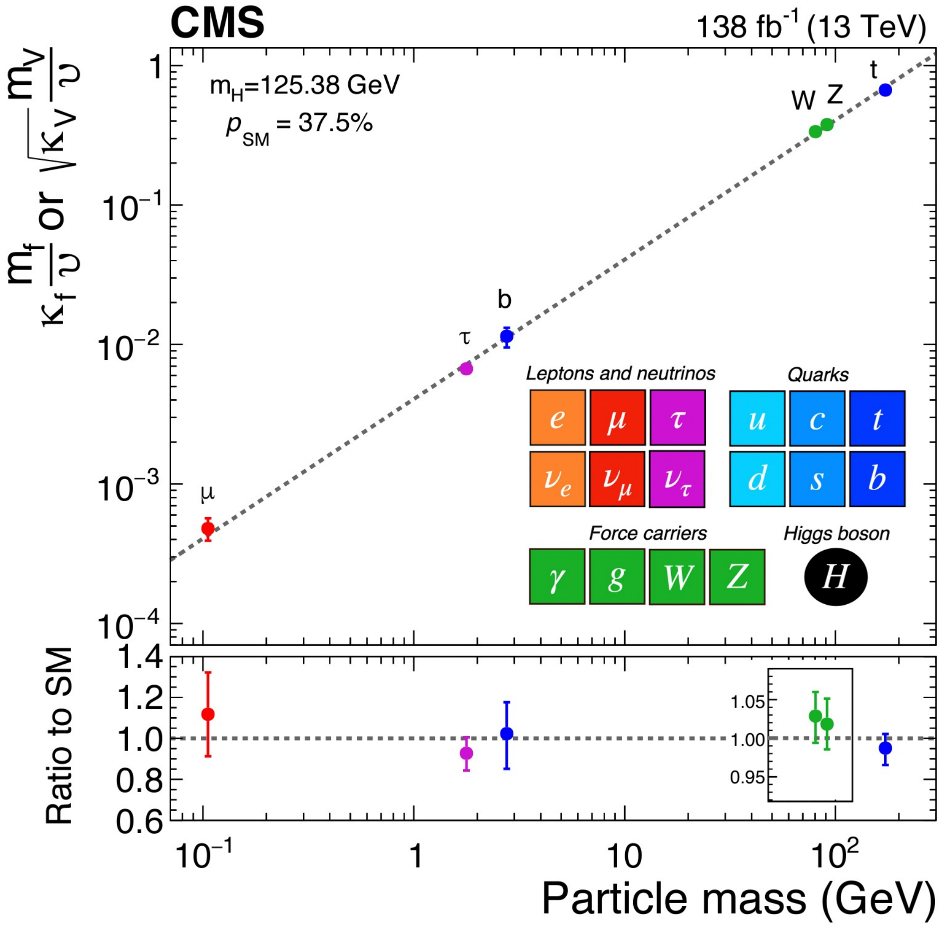
Current status: couplings

Nature 607 (2022) 60-68



- κ framework: modifiers to the standard couplings
  - Joined or decomposed loop couplings (tensor structure etc.)





Exploring tensor structure

PRD 108 (2023) 032013

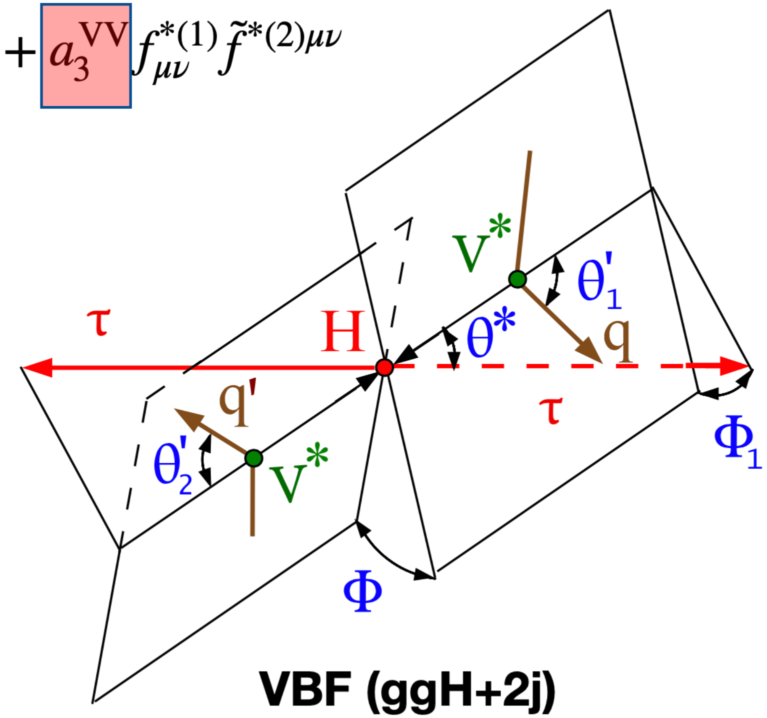
- Most generic amplitude

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

$a_1^{WW,ZZ}$ - CP even coupling (SM)

$a_2^{WW,ZZ}$, $\kappa_{1,2}^{WW,ZZ}/(\Lambda_1^{WW,ZZ})^2$- CP even coupling (SM)

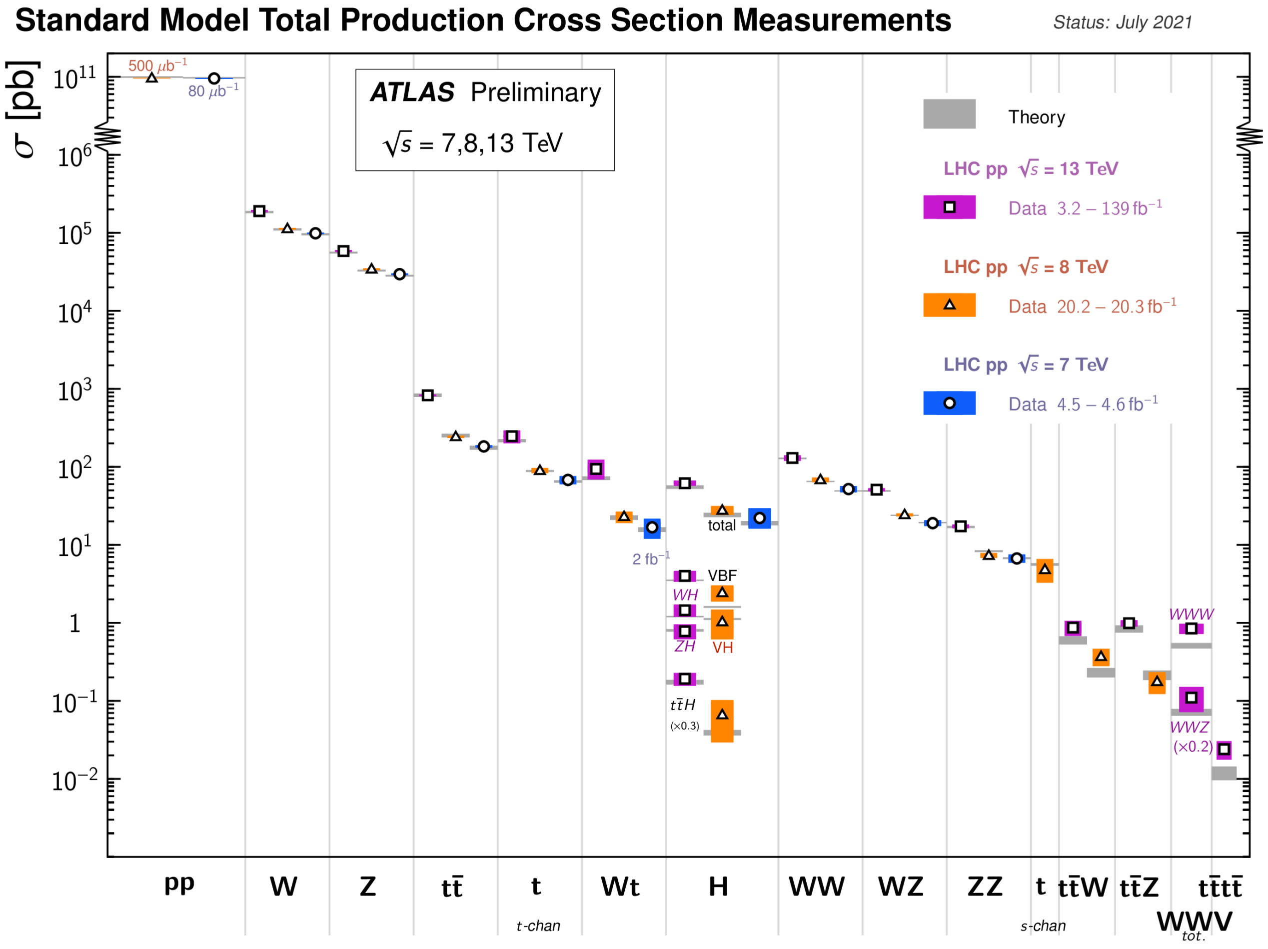
$a_3^{WW,ZZ}$ - CP odd coupling

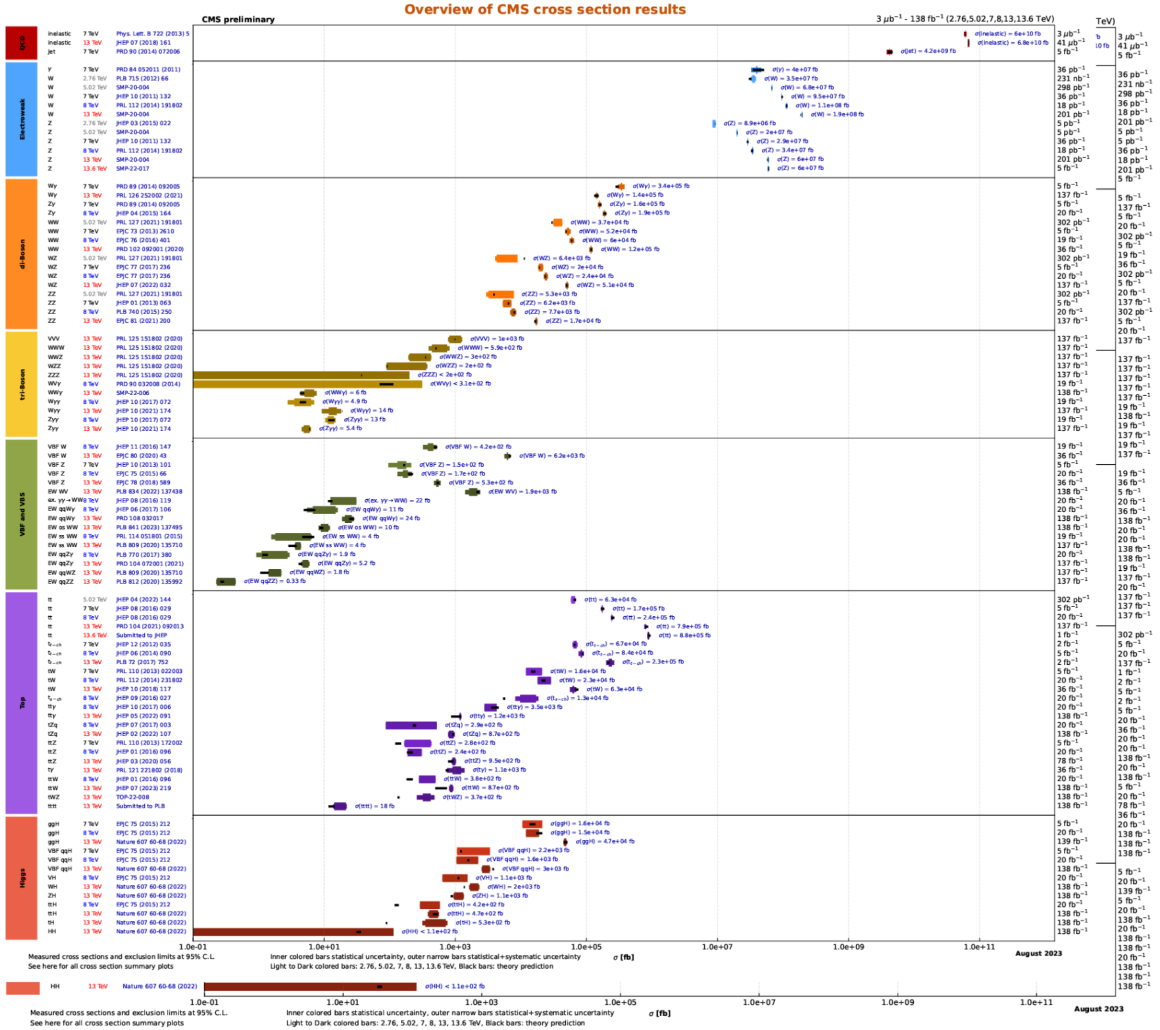


VBF (ggH+2j)

- Exploit kinematic correlations using Matrix Element Likelihood Analysis (MELA)
  - Sensitivity to large anomalous and CP-violating couplings: H → ZZ
  - Sensitivity to small values come from high statistics channels: $H \rightarrow \tau\tau$, $\gamma\gamma$, WW

Triumph of the standard model





Are we done yet?

``… The more important fundamental laws and facts of physical science have all been discovered, and these are now so firmly established that the possibility of their ever being supplanted in consequence of new discoveries is exceedingly remote…’’

1894, six years before the birth of Quantum Mechanics

Albert A. Michelson

Don’t Be Fooled by Bright Lights

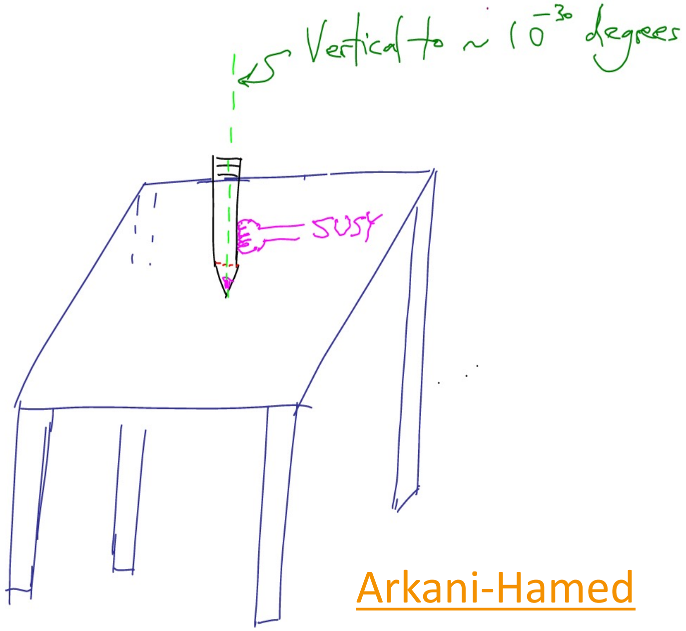
The Dark Side Rules The Universe

Dark Matter Binds It Together

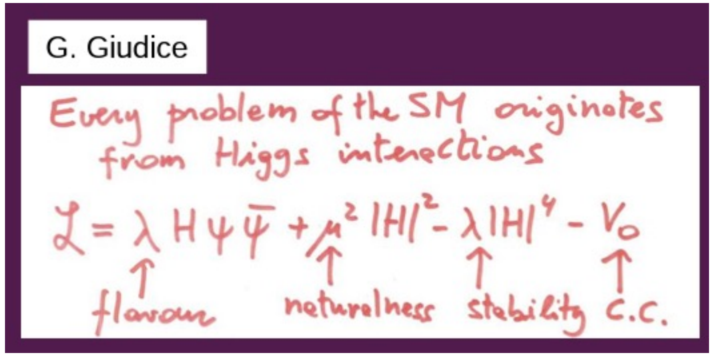
Dark Energy Controls Its Destiny

Higgs boson and the quest for ultimate theory

- The standard model is a low-energy approximation theory that leaves a lot of fundamental questions unanswered:
  - Dark matter candidate? Only one???
    - Higgs boson could be the only gateway to the dark sector
  - What makes Higgs boson light?
    - SUSY, Vector-like quarks
  - Origin of neutrino masses?
    - Heavy neutrinos? Does Higgs have anything to do with it?
  - Where is all anti-matter?
    - Higgs boson potential shape study is crucial
  - Why 3 generations of matter?
    - The only difference is in mass generated by the Higgs field
- Higgs boson is profoundly different from everything we have discovered previously and linked to some of the deepest structural questions



Arkani-Hamed



G. Giudice

Every problem of the SM originates from Higgs interactions

$$\mathcal{L} = \underset{\substack{\uparrow\\ \text{flavour}}}{\lambda H\psi\bar{\psi}} + \underset{\substack{\uparrow\\ \text{naturalness}}}{\mu^2|H|^2} - \underset{\substack{\uparrow\\ \text{stability}}}{\lambda|H|^4} - \underset{\substack{\uparrow\\ \text{C.C.}}}{V_0}$$

Higgs cannot be the end of the story…

- In SM there is no understanding of Higgs sector: Higgs potential and couplings put in by hand and unexplained: toy model?
  - It is remarkable that this toy model could be just right.

G. Giudice

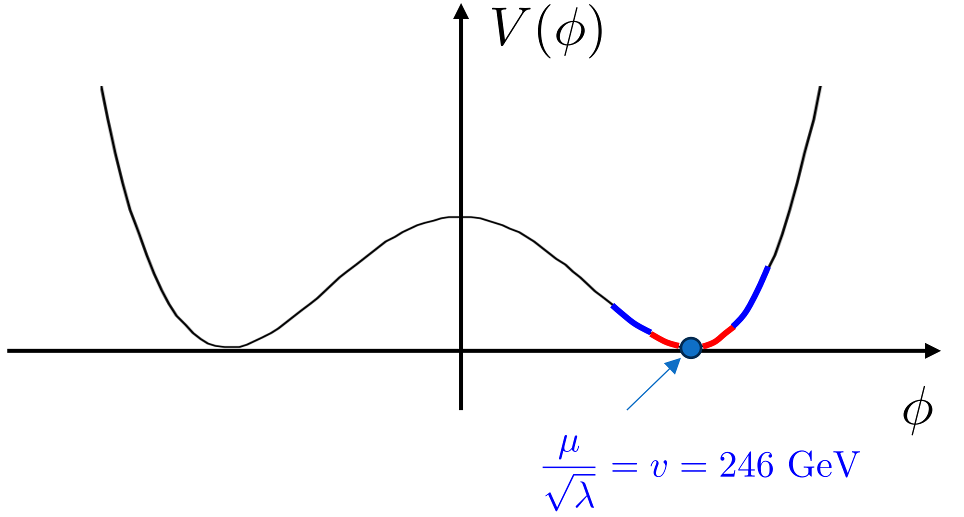
Scrutinizing Higgs boson with the LHC and beyond remain one of the most important undertaking in high energy physics

Is our universe stable? Aka Higgs potential

- What have we measured so far
  - SM Higgs potential: $V(\phi) = -\mu^2\phi^2 + \lambda\phi^4$
  - Expanding around minimum yields

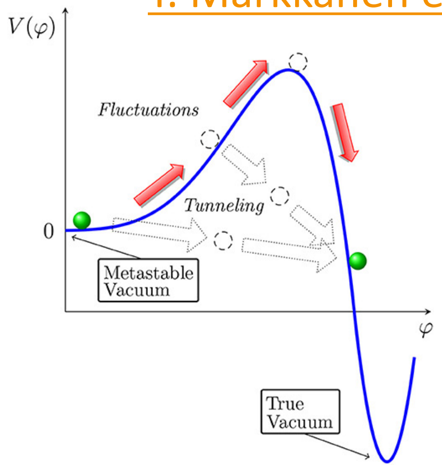
$$V = V_0 + \frac{1}{2}m_H^2 h^2 + \frac{m_H^2}{2v^2} v h^3 + \ldots$$

Mass term Self-interaction

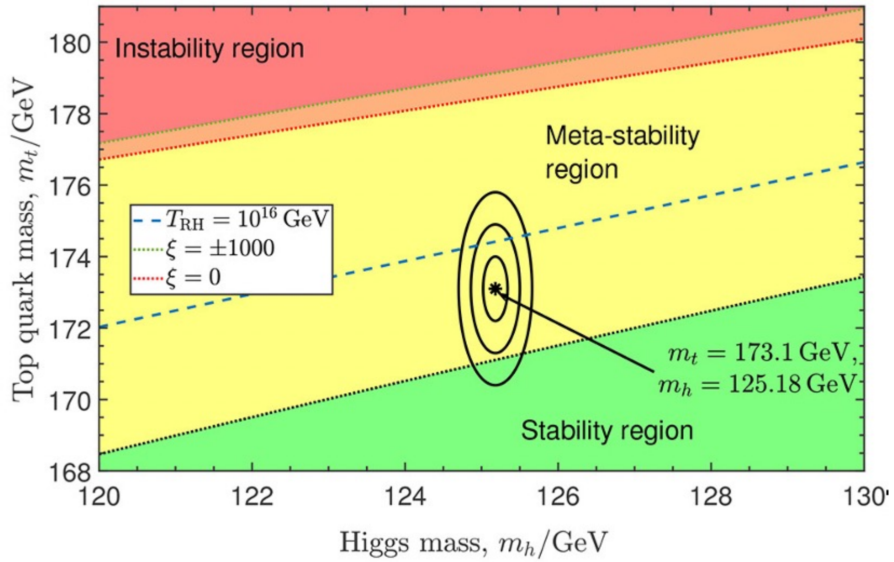


- Mapping the shape of the potential is important
  - New physics can move our universe between stability and instability
  - EWK baryogenesis requires non-SM $V(\phi)$

T. Markkanen et al.

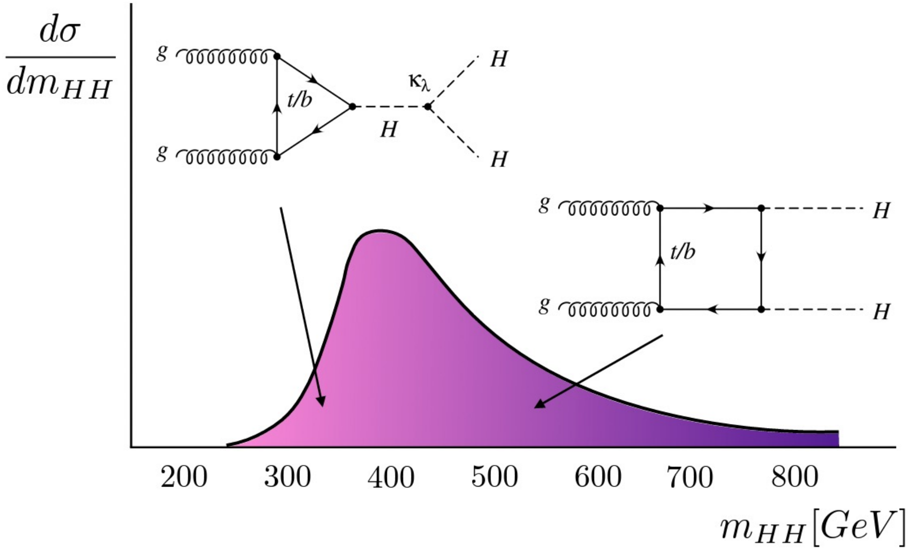


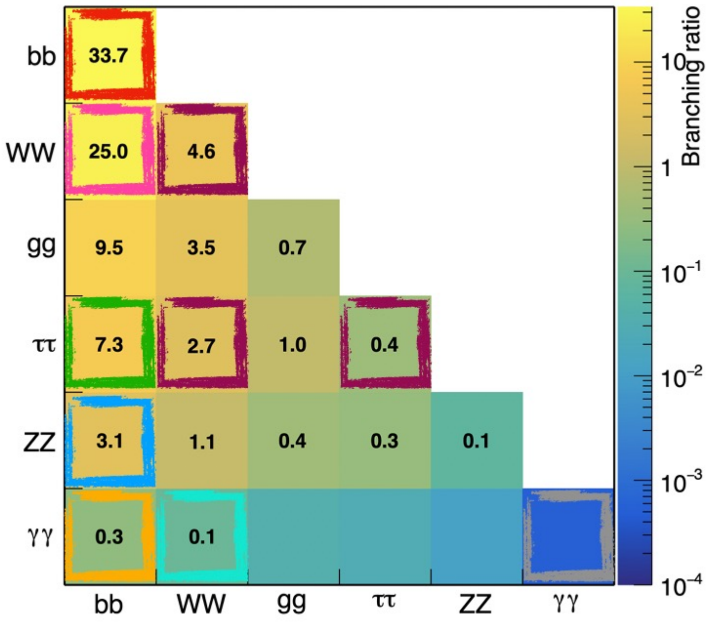
G. Degrassi *et al*



Di-Higgs production

- Measuring κ_λ is difficult
  - Two diagrams that destructively interfere: x500 lower cross section than the single Higgs boson production
  - Non-SM κ_λ makes triangular diagram to dominate: peak shifts to lower values of m_{HH}
- Many decay channels possible
  - Photon, tau lepton and b-jet decay channels seem to be most promising
  - Use ML tools to boost performance



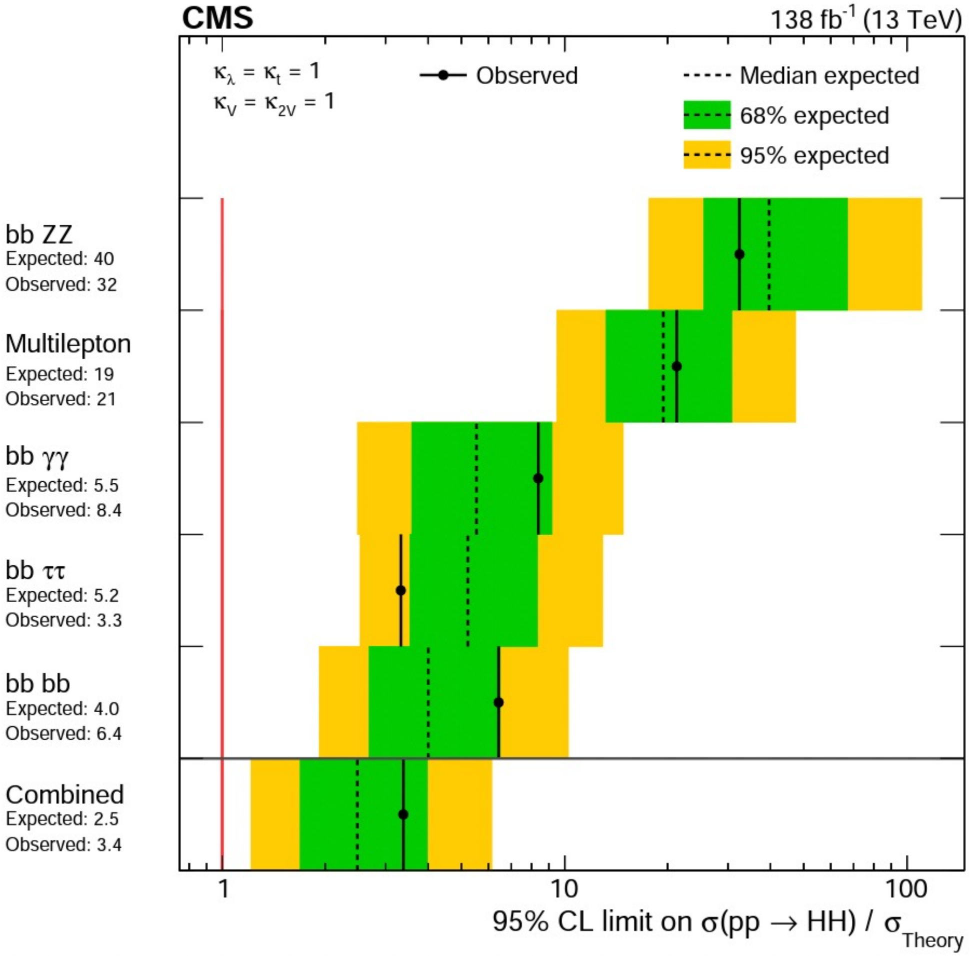


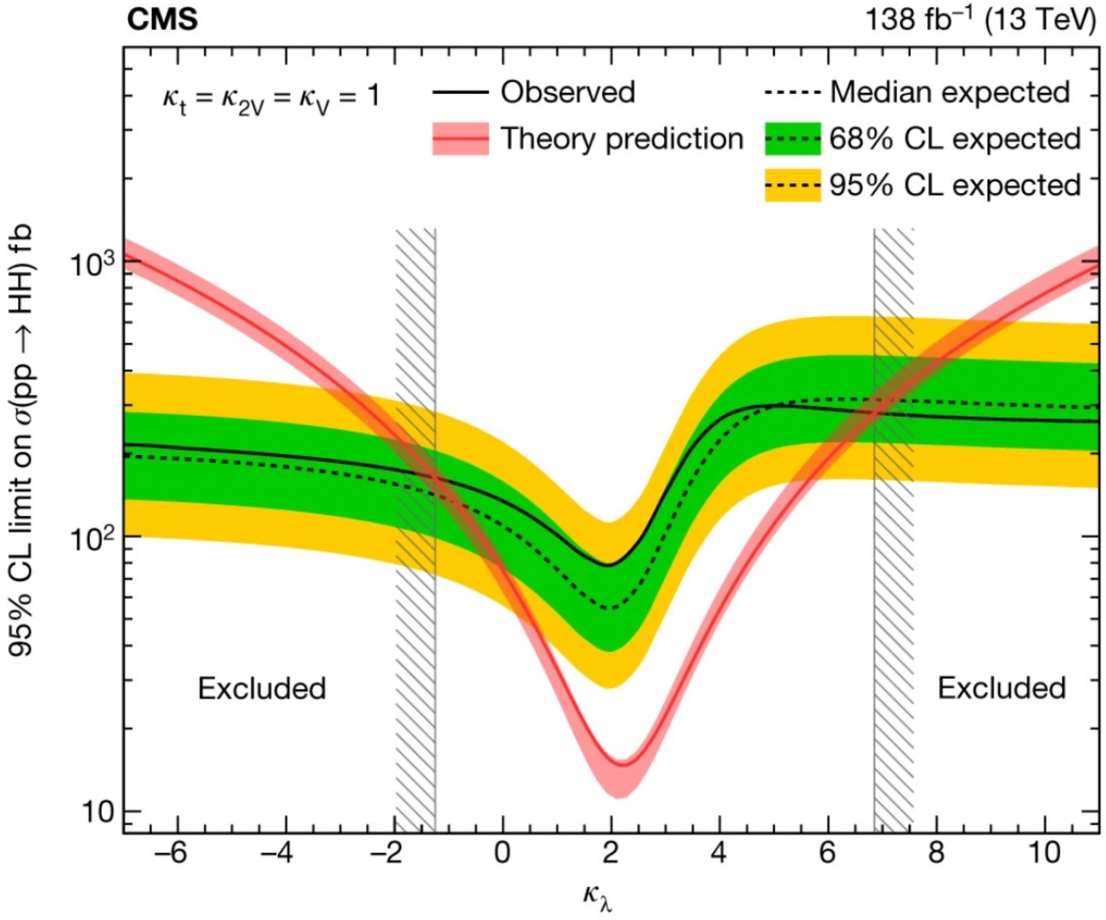
	bb	WW	gg	ττ	ZZ	γγ
bb	33.7					
WW	25.0	4.6				
gg	9.5	3.5	0.7			
ττ	7.3	2.7	1.0	0.4		
ZZ	3.1	1.1	0.4	0.3	0.1	
γγ	0.3	0.1				

Di-Higgs production

Nature 607 (2022) 60-68

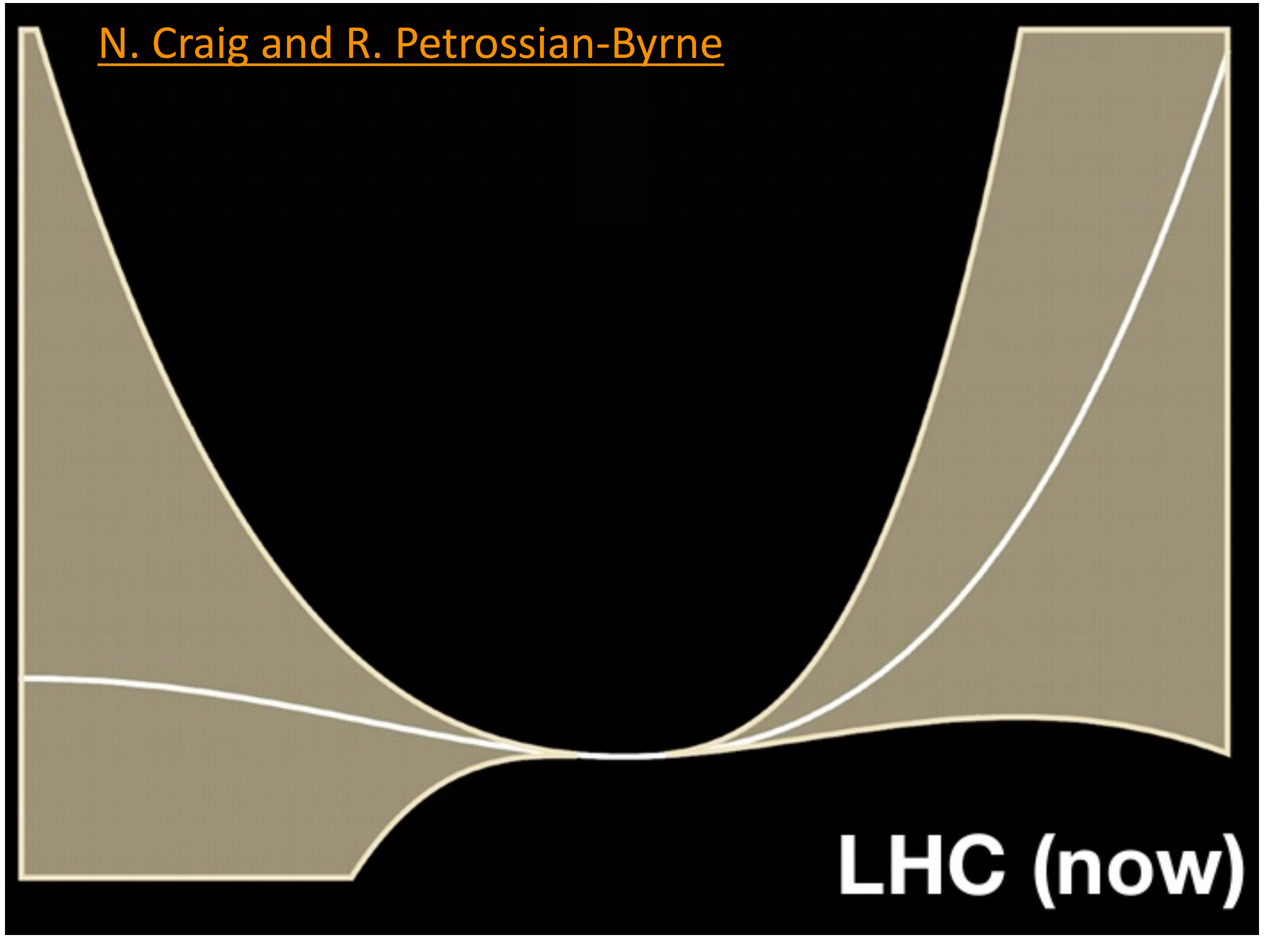
- For EWK baryogenesis κ_λ should be somewhere between 1 and 6
  - Already started to probe interesting region: $-1.24 < \kappa_\lambda < 6.49$ at 95% CL





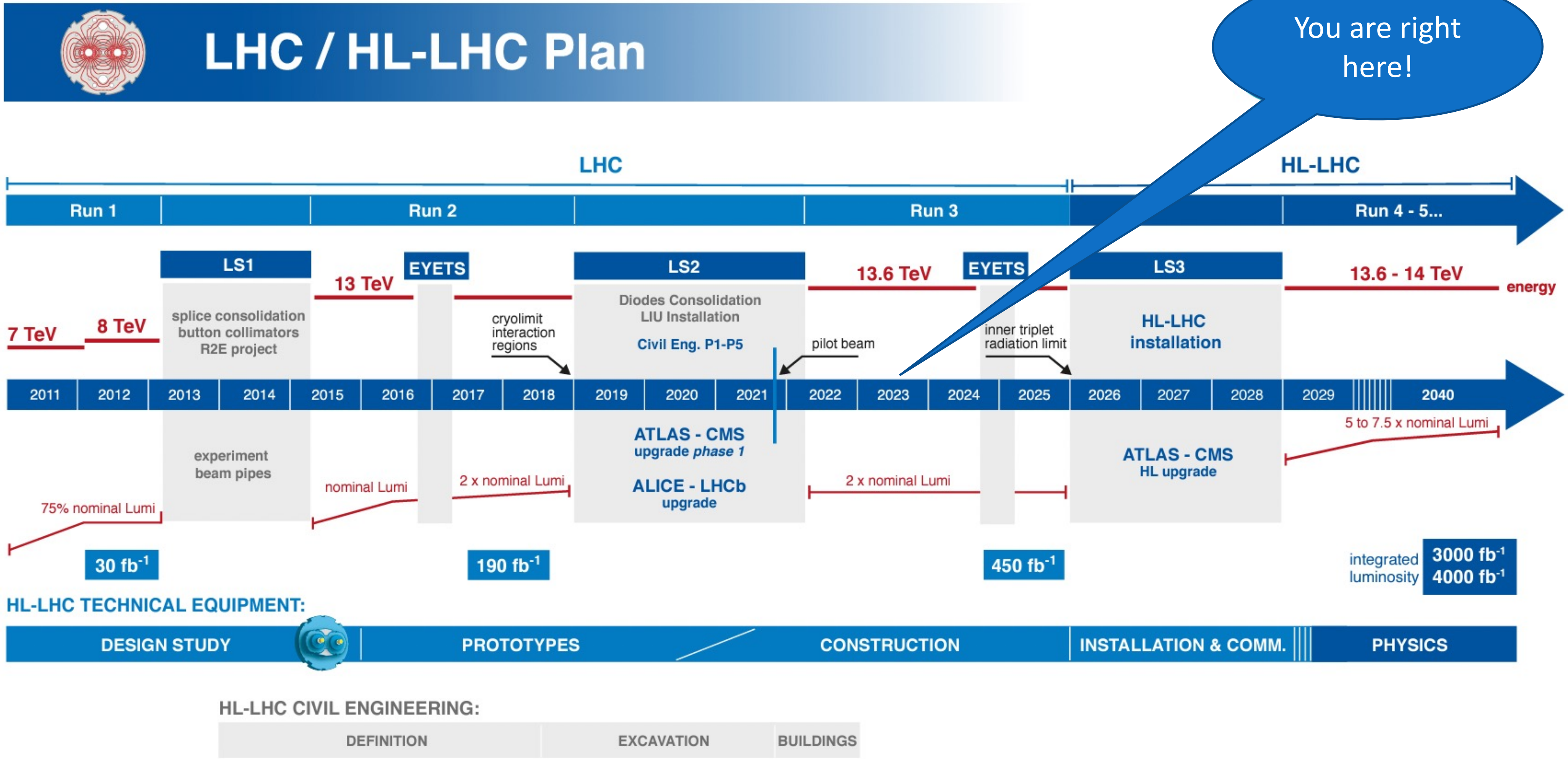
Higgs potential shape

- How well do we know the shape of the Higgs potential?
  - Not quite well
- Significant improvement in Run 2 utilizing neural networks with respect to projections
  - More to come in Run 3


N. Craig and R. Petrossian-Byrne

HL-LHC: LHC on steroids

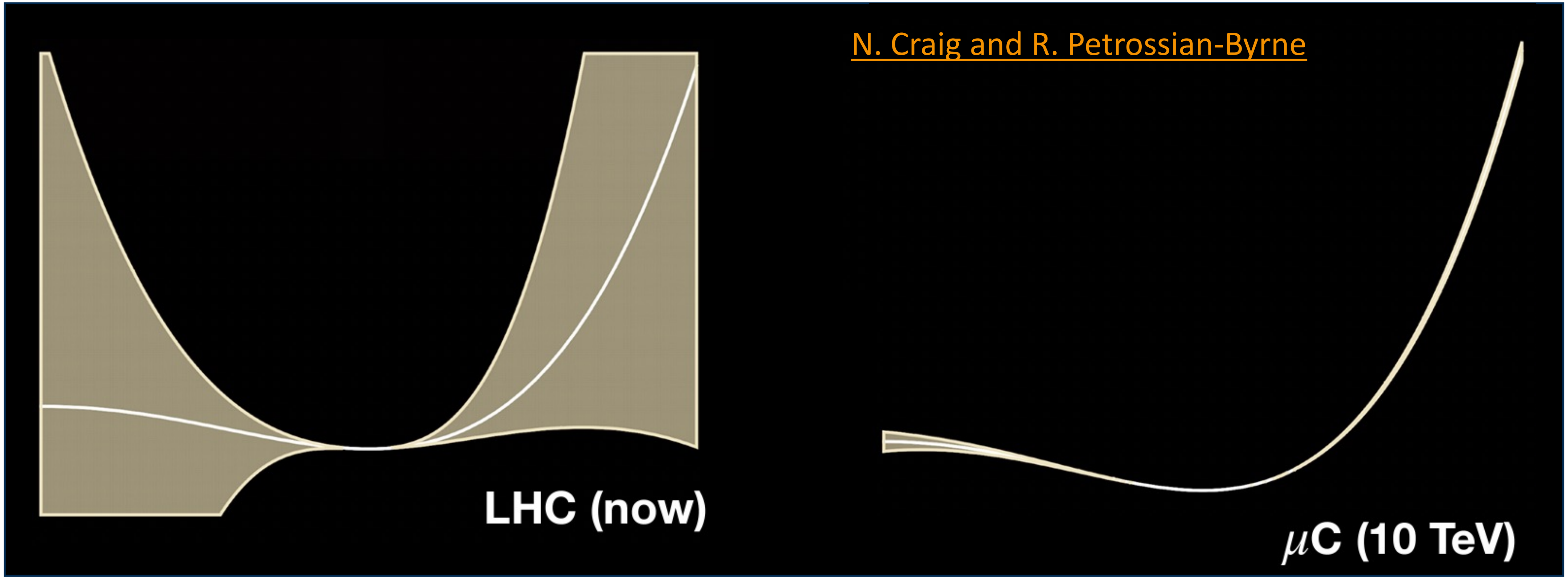
- Significant upgrade of the detector, 10x more data



You are right here!

HL-LHC: LHC on steroids

- Sensitivity to κ_λ to about 50%

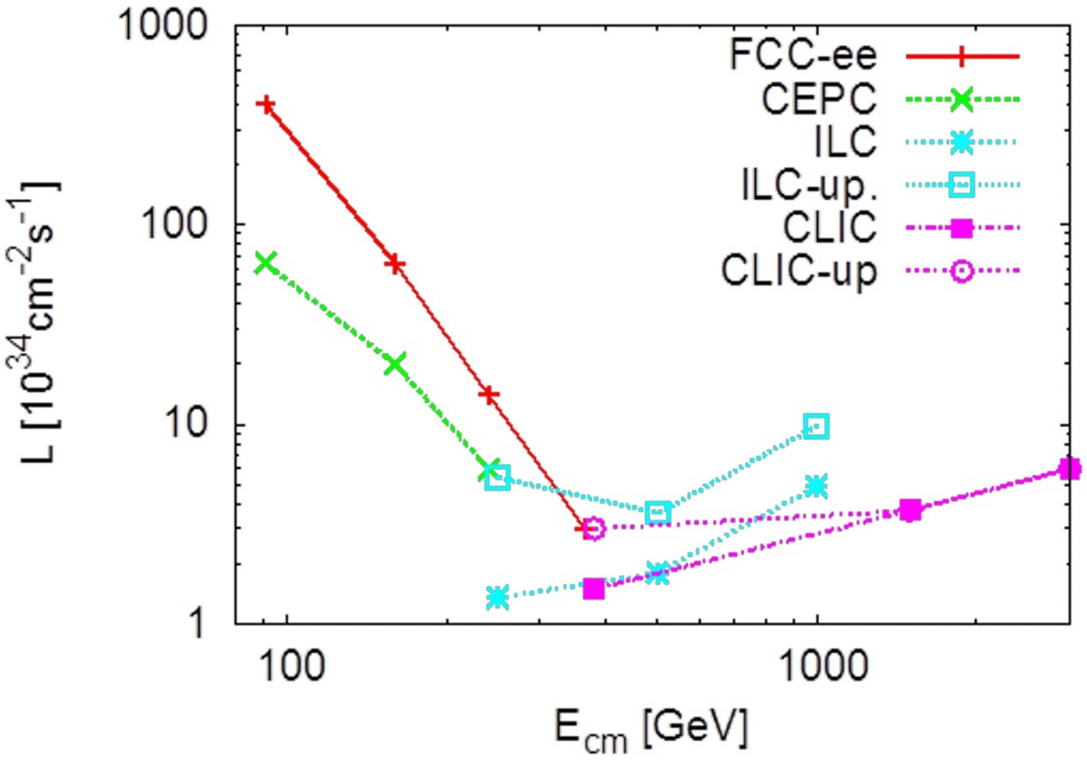

N. Craig and R. Petrossian-Byrne

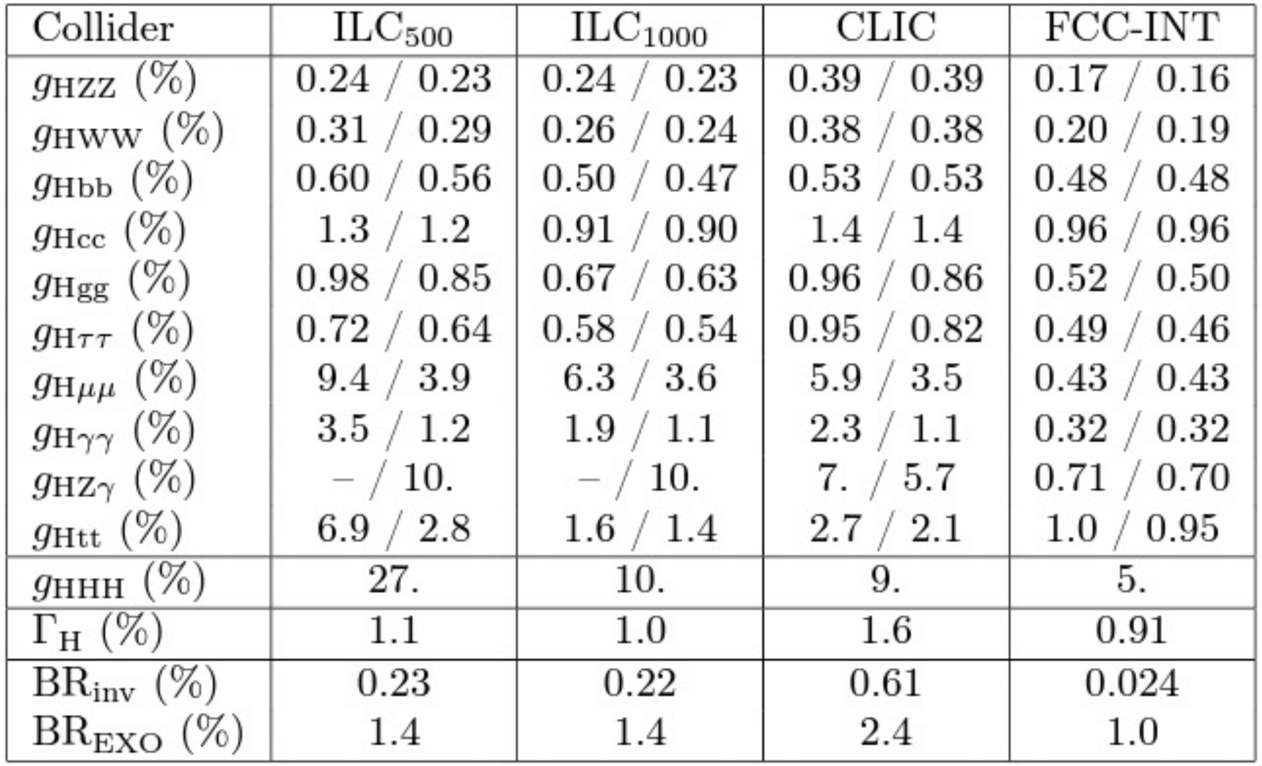
- The holy grail is however < 10%

Beyond HL-LHC

- Several e^+e^- projects: linear (CLIC, ICL) and circular (FCC and CEPC), also a $\mu^+\mu^-$ collider
  - Circular colliders can be turned to pp machines

A. Blondel and P. Janot





Collider	ILC_{500}	ILC_{1000}	CLIC	FCC-INT
g_{HZZ} (%)	0.24 / 0.23	0.24 / 0.23	0.39 / 0.39	0.17 / 0.16
g_{HWW} (%)	0.31 / 0.29	0.26 / 0.24	0.38 / 0.38	0.20 / 0.19
g_{Hbb} (%)	0.60 / 0.56	0.50 / 0.47	0.53 / 0.53	0.48 / 0.48
g_{Hcc} (%)	1.3 / 1.2	0.91 / 0.90	1.4 / 1.4	0.96 / 0.96
g_{Hgg} (%)	0.98 / 0.85	0.67 / 0.63	0.96 / 0.86	0.52 / 0.50
$g_{\mathrm{H}\tau\tau}$ (%)	0.72 / 0.64	0.58 / 0.54	0.95 / 0.82	0.49 / 0.46
$g_{\mathrm{H}\mu\mu}$ (%)	9.4 / 3.9	6.3 / 3.6	5.9 / 3.5	0.43 / 0.43
$g_{\mathrm{H}\gamma\gamma}$ (%)	3.5 / 1.2	1.9 / 1.1	2.3 / 1.1	0.32 / 0.32
$g_{\mathrm{HZ}\gamma}$ (%)	– / 10.	– / 10.	7. / 5.7	0.71 / 0.70
g_{Htt} (%)	6.9 / 2.8	1.6 / 1.4	2.7 / 2.1	1.0 / 0.95
g_{HHH} (%)	27.	10.	9.	5.
Γ_{H} (%)	1.1	1.0	1.6	0.91
$\mathrm{BR}_{\mathrm{inv}}$ (%)	0.23	0.22	0.61	0.024
$\mathrm{BR}_{\mathrm{EXO}}$ (%)	1.4	1.4	2.4	1.0

Closing remarks

- "…Essentially all problems or unsatisfactory aspects of the standard model are ultimately related to the structure of Higgs interactions…"

  Phyiscs Briefing Book, 2020

  - Higgs sector remains poorly known
  - Higgs is truly unlike anything we have discovered before
- Discovery of the Higgs boson is just a beginning of a massive undertaking to study its properties, the next 20 years will be very interesting!
  - Discovery of W and Z bosons that were part of the motivation to build LEP: similar to the situation we are in now
- Future colliders are ultimate precision tools to explore Higgs sector
  - Vital to dedicate sufficient effort to make the future colliders a reality

Backup

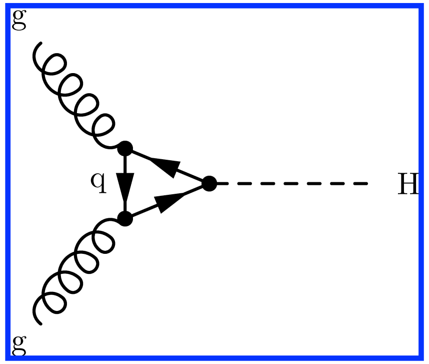
Tensor structure of Higgs boson coupling

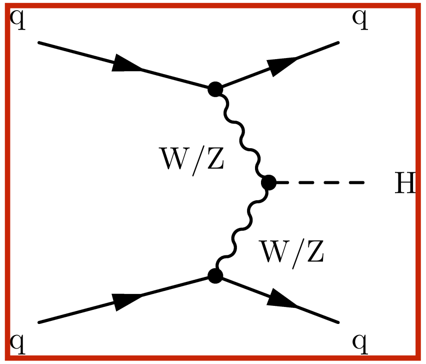
- Look for surprises in ggH and VVH (and VH) couplings
  - No luck* in finding new particles directly? Look for anomalous contributions from heavy particles contributing in loops!
- Generic HVV amplitude (V = g, W, Z, γ)

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

- Consideration of symmetry and gauge invariance require

$$a_1^{Z\gamma} = a_1^{\gamma\gamma} = a_1^{gg} = 0,\ \kappa_1^{ZZ} = \kappa_2^{ZZ},\ \kappa_1^{\gamma\gamma} = \kappa_2^{\gamma\gamma} = 0,\ \kappa_1^{gg} = \kappa_2^{gg} = 0$$





Study of the Higgs boson production

- Look for surprises in ggH and VVH (and VH) couplings
  - No luck* in finding new particles directly? Look for anomalous contributions from heavy particles contributing in loops!
- Generic HVV amplitude (V = g, W, Z, γ)

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

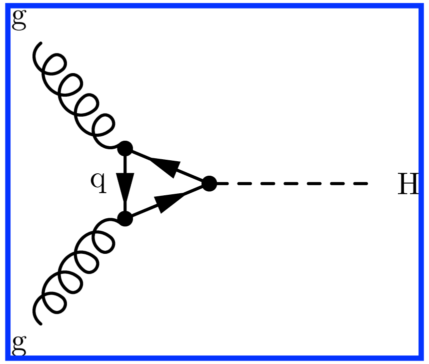
- Consideration of symmetry and gauge invariance require

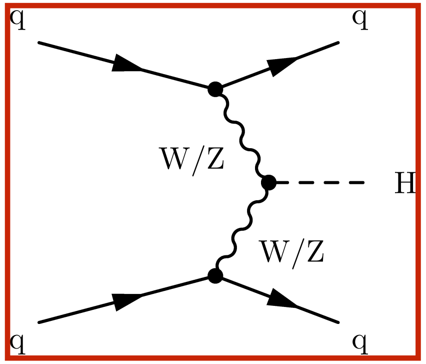
$$a_1^{Z\gamma} = a_1^{\gamma\gamma} = a_1^{gg} = 0,\ \kappa_1^{ZZ} = \kappa_2^{ZZ},\ \kappa_1^{\gamma\gamma} = \kappa_2^{\gamma\gamma} = 0,\ \kappa_1^{gg} = \kappa_2^{gg} = 0$$

- For ggH production (V = g) we are left with 2 terms

a_2^{gg} - CP even coupling (SM)

a_3^{gg} - CP odd coupling





Generic HVV production

- For the case of HVV coupling (V = W, Z) we have a more complicated case

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

$a_1^{WW,ZZ}$ - CP even coupling (SM)

$a_2^{WW,ZZ}$, $\kappa_{1,2}^{WW,ZZ}/(\Lambda_1^{WW,ZZ})^2$- CP even coupling (SM)

$a_3^{WW,ZZ}$ - CP odd coupling

- Custodial symmetry: $a_1^{WW} = a_1^{ZZ}$
- Two approaches are used to relate anomalous WW and ZZ couplings
  - Approach 1: assume that they are equal, i.e., $a_3^{WW} = a_3^{ZZ}$
  - Approach 2: $a_3^{WW} = \cos^2\theta_W \, a_3^{ZZ}$

Parameters of interest

- Convenient to parameterize anomalous couplings in terms of fractions

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

Fraction	σ_i/σ_1
f_{a3}	0.153
f_{a2}	0.361
$f_{\Lambda 1}$	0.682
$f_{\Lambda 1}^{Z\gamma}$	1.746

- Four fractions of interest for HVV: $f_{a3}, f_{a2}, f_{\Lambda 1}, f_{\Lambda 1}^{Z\gamma}$

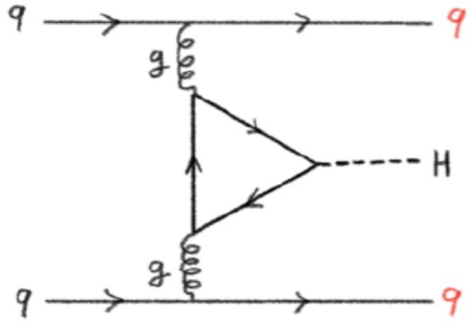
- For ggH we have just one fraction

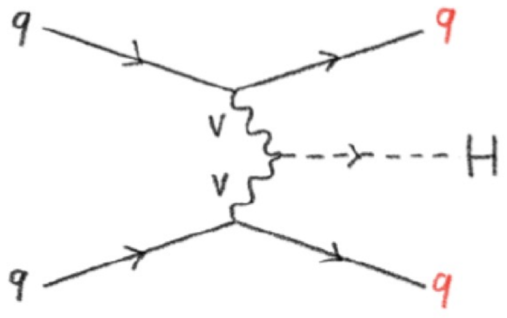
$$f_{a3}^{\mathrm{ggH}} = \frac{|a_3^{\mathrm{gg}}|^2}{|a_2^{\mathrm{gg}}|^2 + |a_3^{\mathrm{gg}}|^2} \operatorname{sgn}\left(\frac{a_3^{\mathrm{gg}}}{a_2^{\mathrm{gg}}}\right)$$

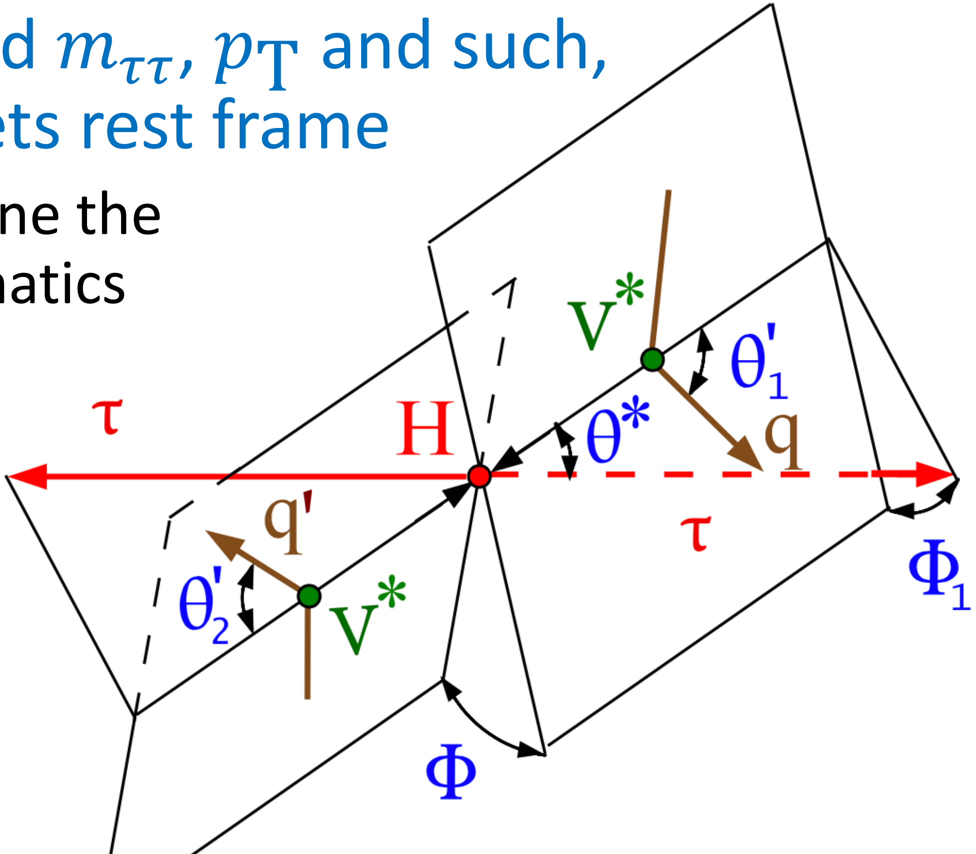
  - As $\sigma_2 = \sigma_3$ we can drop the cross-sections from the definition of the fraction

Kinematics of the production

- Final state is a Higgs and at least two jets
  - Need two jets for ggH to probe the CP of the vertex
- Rather than using correlated $m_{\tau\tau}$, p_{T} and such, use kinematics in the H+2jets rest frame
  - Total of 7 variables fully define the production and decay kinematics
- Reduce the number of observables by forming probability densities for a given hypothesis (SM, CP-odd, etc.)







VBF (ggH+2j)

Matrix Element Likelihood Approach (MELA)

- $\mathcal{P}_i$ is a probability for a process (SM or NP)

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

Separate SM from BSM coupling

$$\mathscr{D}_{\rm int} = \frac{\mathscr{P}^{\rm int}_{\rm SM-BSM}(\vec{\Omega})}{\mathscr{P}_{\rm SM}(\vec{\Omega}) + \mathscr{P}_{\rm BSM}(\vec{\Omega})}$$

Sensitive to interference between SM and BSM couplings

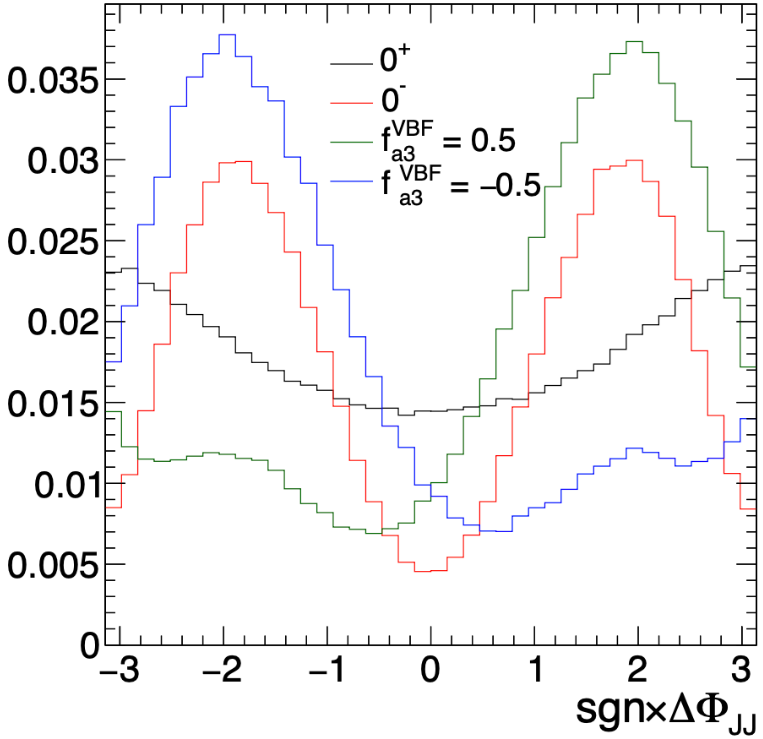
$$\mathscr{D}^{\rm VBF}_{\rm 2jet} = \frac{\mathscr{P}^{\rm ggH}_{\rm SM} + \mathscr{P}^{\rm ggH}_{0-}}{\mathscr{P}^{\rm ggH}_{\rm SM} + \mathscr{P}^{\rm ggH}_{0-} + \mathscr{P}^{\rm VBF}_{\rm SM}}$$

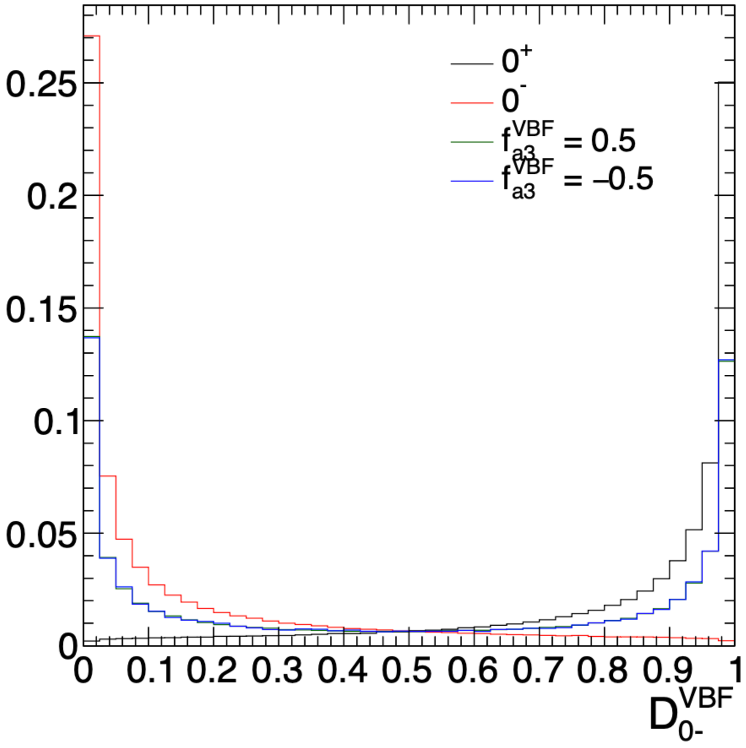
Separate ggH from VBF

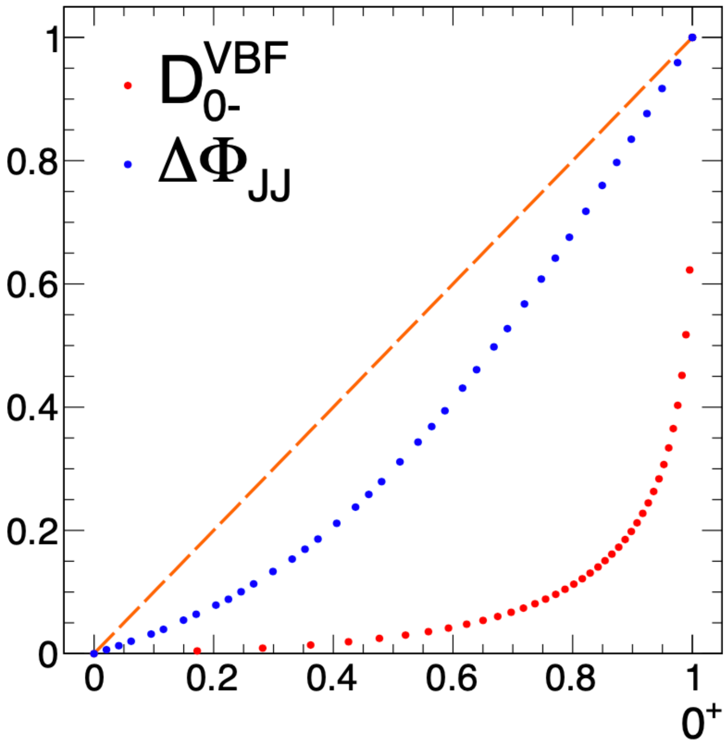
- MELA variables offer optimal sensitivity (at LO level)

MELA Performance: VBF H

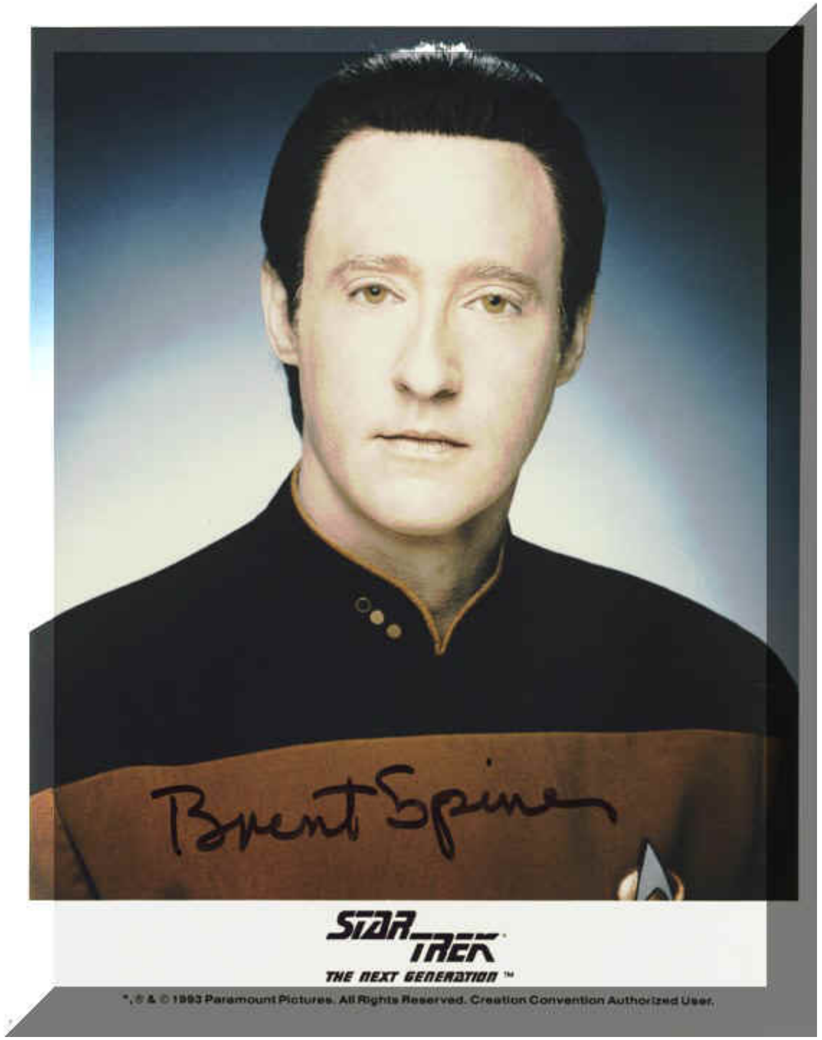
- Compared to simple variables, such as a signed azimuthal difference between the two jets in the even $\mathrm{sgn} \times \Delta\Phi$, MELA offers a significant improvement



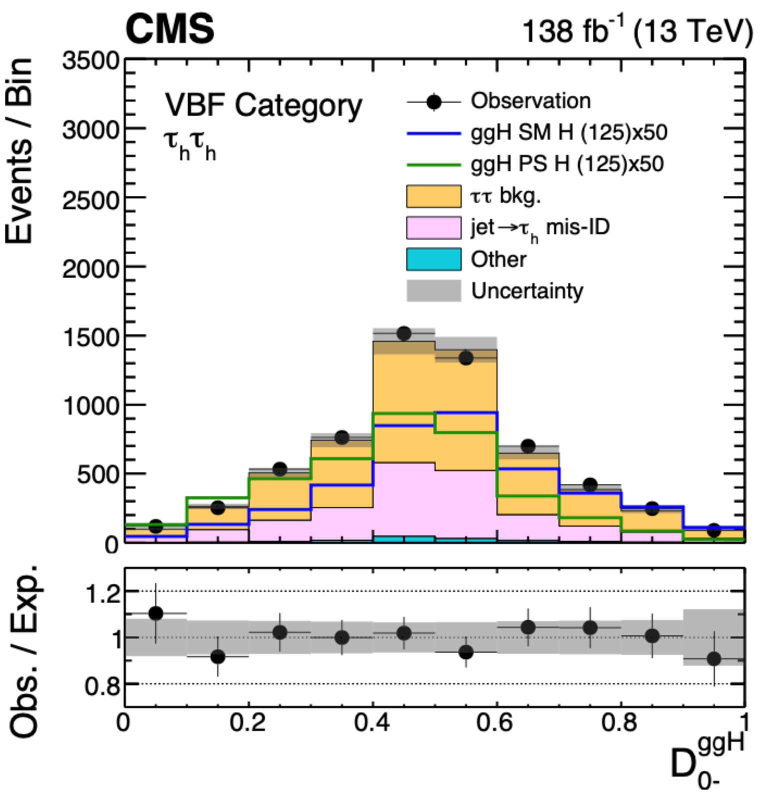


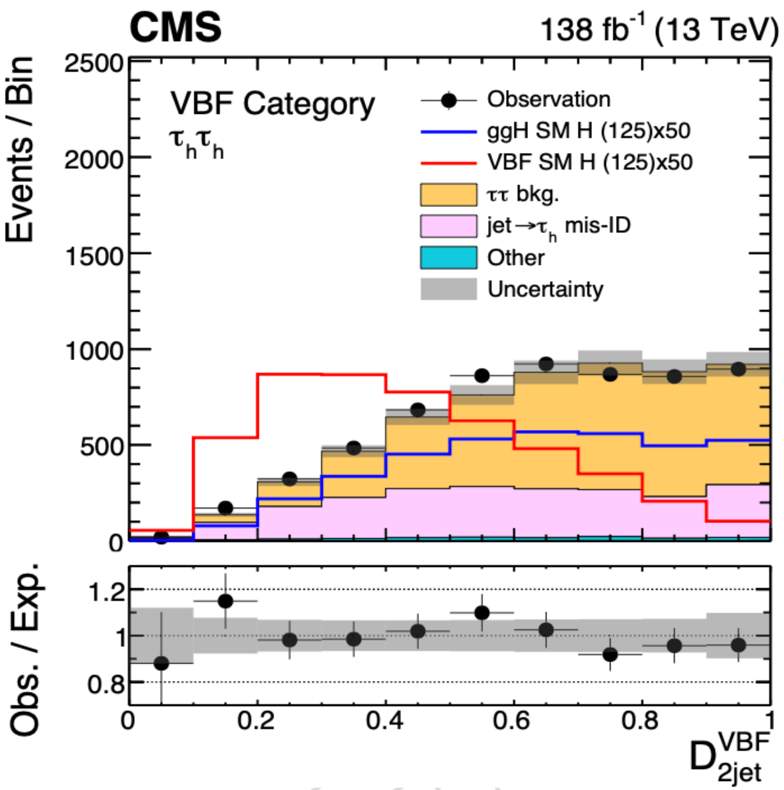


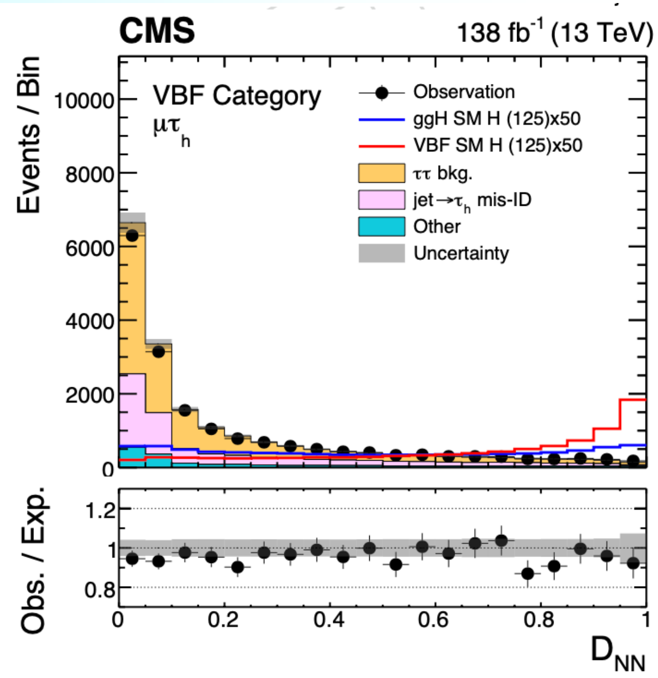
Data – model comparison

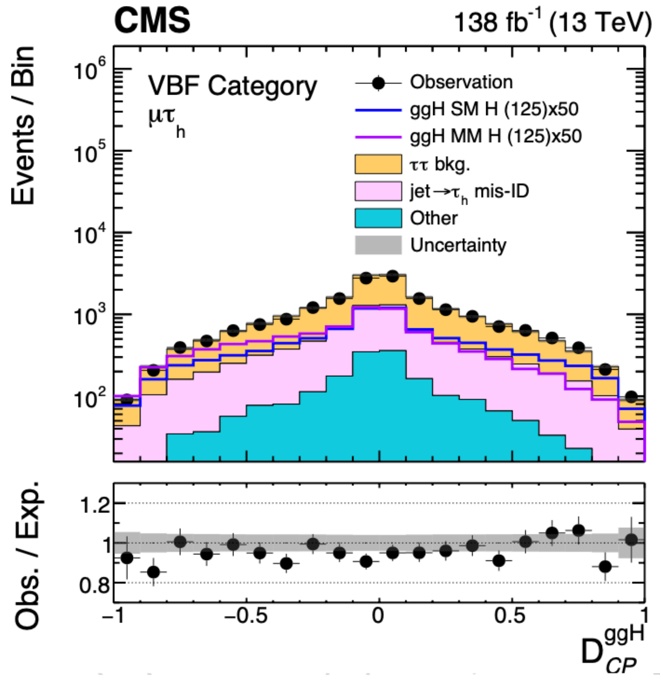


Data – model comparison





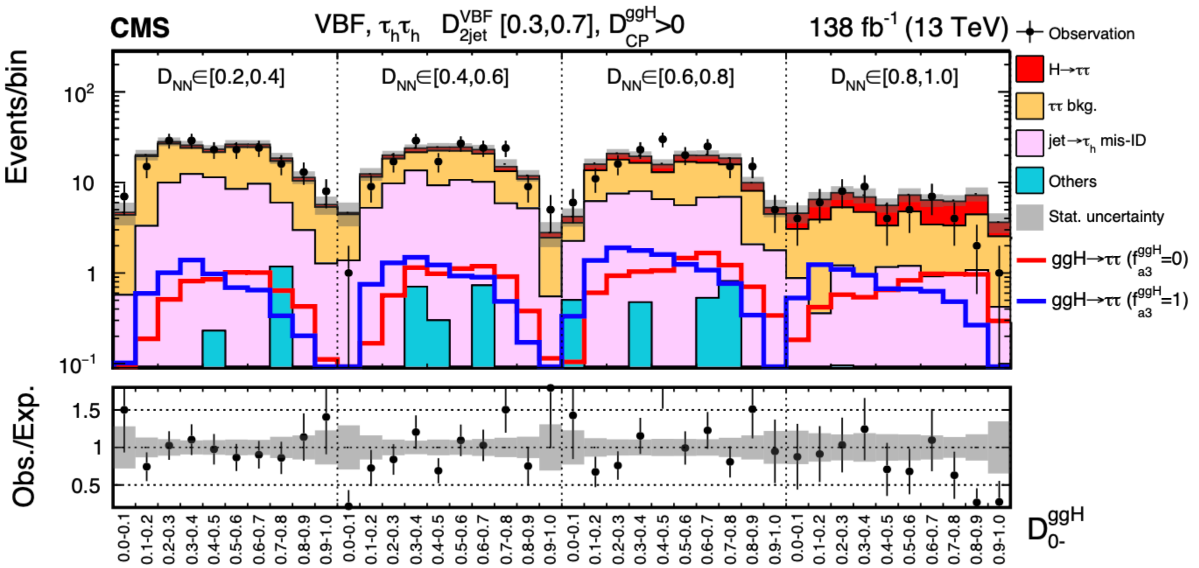


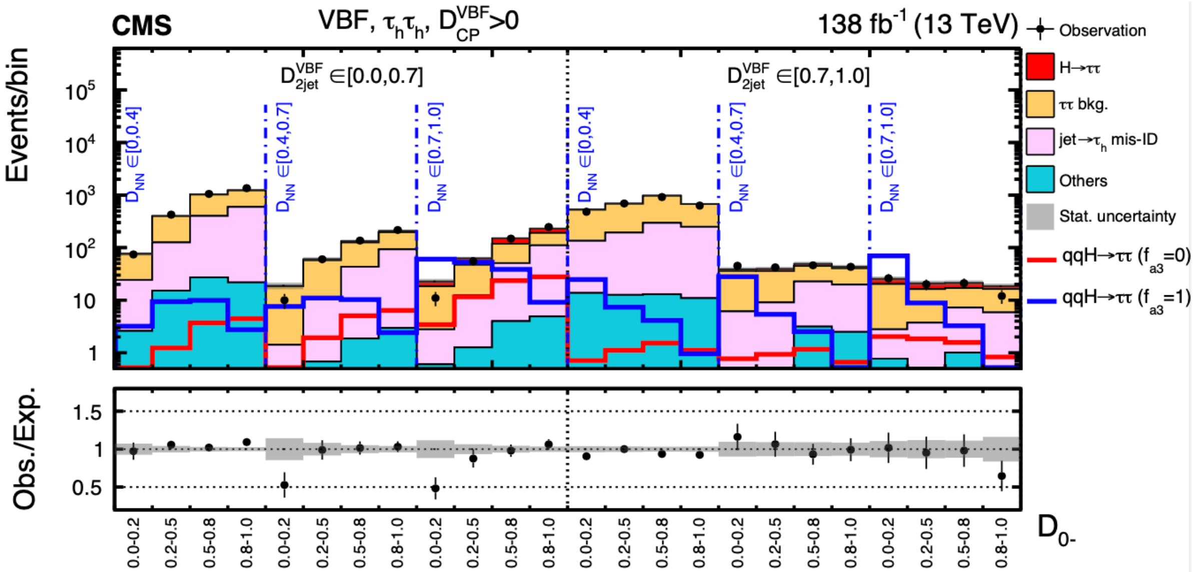


- The agreement is pretty good!

Extracting the results

- A fit in 3D space for CP-even BSM couplings using $\mathcal{D}_{BSM}$, $\mathcal{D}_{2j}$, and $\mathcal{D}_{NN}$
  - For CP-odd f_{a3} measurement, a fourth discriminant is used $\mathcal{D}_{CP}$
- Fit for a specific BSM scenario: fix all others to 0 except for CP-odd f_{a3}
  - Float ggH f_{a3}^{ggH} when fitting for HVV f_{a3} and vice versa
- Two signal strength modifiers for VBF+VH and ggH are freely floated





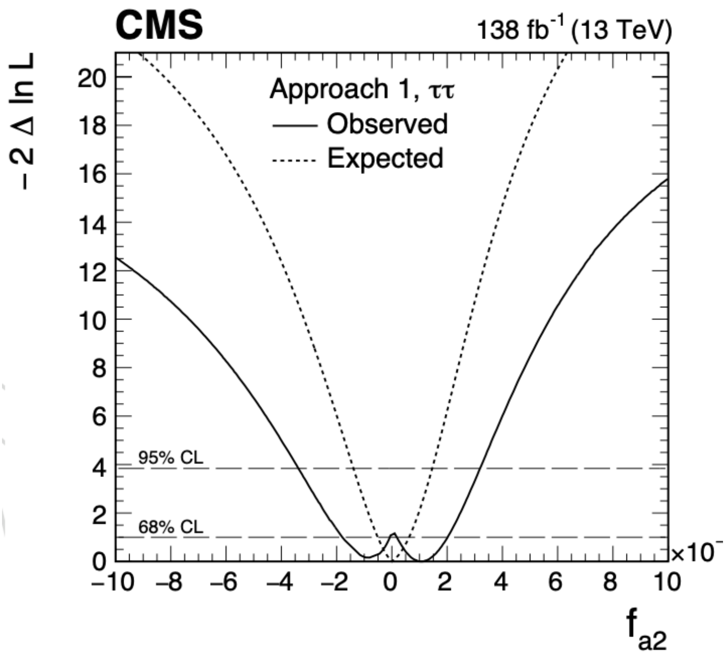
Systematic uncertainties

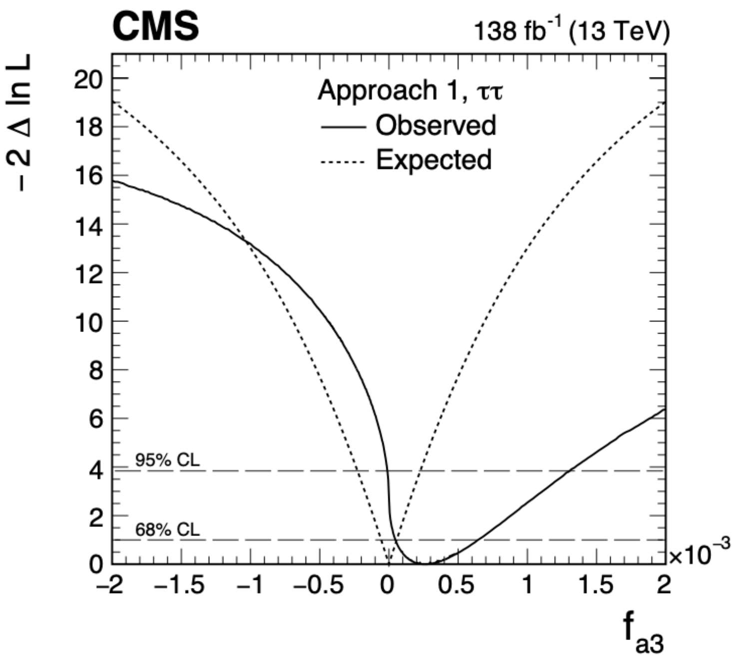
- Follows closely differential cross-section measurement
  1. Tau identification
  2. Lepton misidentification rate
  3. Lepton identification & isolation
  4. Trigger
  5. B-tag efficiencies and misidentification
  6. Luminosity
  7. Background cross-sections
  8. QCD OS/SS ($e\mu$)
  9. Embedded yield
  10. Top quark contribution to embedded samples
  11. Signal XS/BR uncertainties
  12. Signal theory shape/acceptance
  13. Pre-firing
  14. Tau, electron, muon energy-scale
  15. JES/JER
  16. MET recoil/unclustered uncertainties
  17. FF method uncertainties
  18. BBB uncertainties
  19. DY p_T/mass reweighing
  20. Top pT reweighing

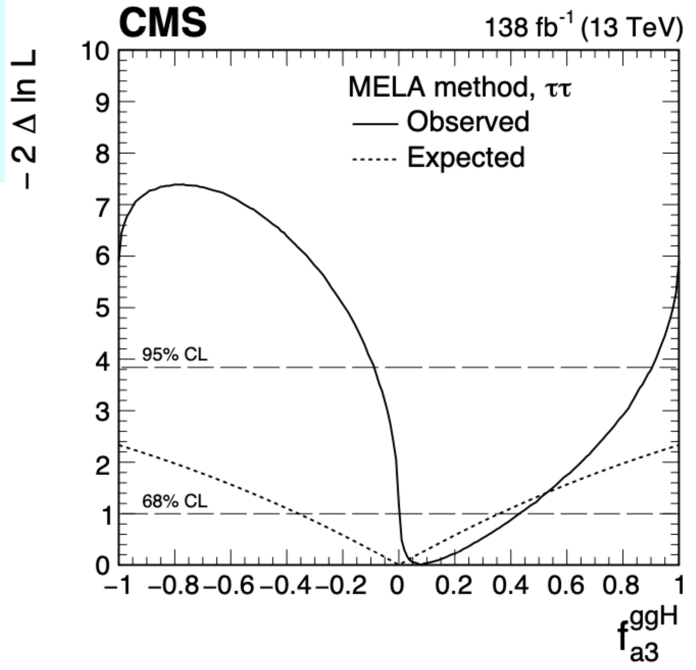
"... What about systematics?
– Say, 10%?
– Sounds about right! …"

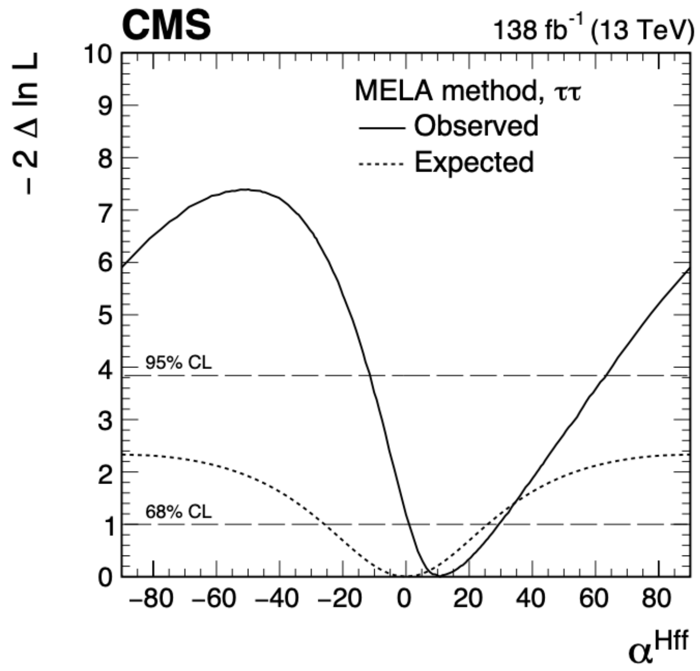
A conversation overheard in one of the D0 Tevatron's cubicles

Results









- Combination with H → 4ℓ leads to a further improvement leading to the best limits on anomalous production couplings of the Higgs boson to date
  - Run 3 plans to use EFT approach to further improve sensitivity

Backup

Studying Higgs boson is not easy

- This H→ττ coupling study was a tour de force: 3 years of work on 4 different final states plus a dedicated HiggsCombine effort for extracting the results, writing physics models, and combination with other Higgs analyses
  - I remember old days of DØ with much warmth and fondness, where a search could be done in a few months
  - Extensive use of multivariate techniques, data-driven estimation of backgrounds, modern statistical methods to fully capitalize on the capabilities of the detector

Tyler Mitchel

Doyeong Kim

Abdollah Mohammadi

Senka Duric

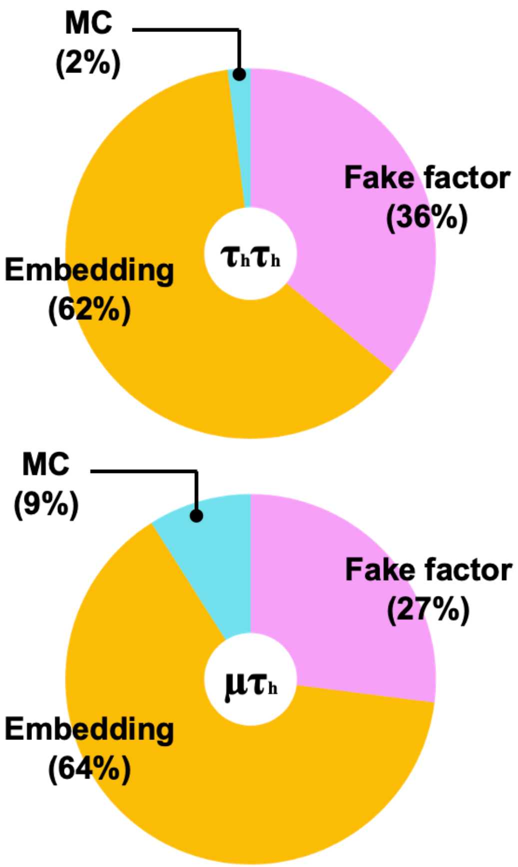
Kyungwook Nam

Keti Kaadze

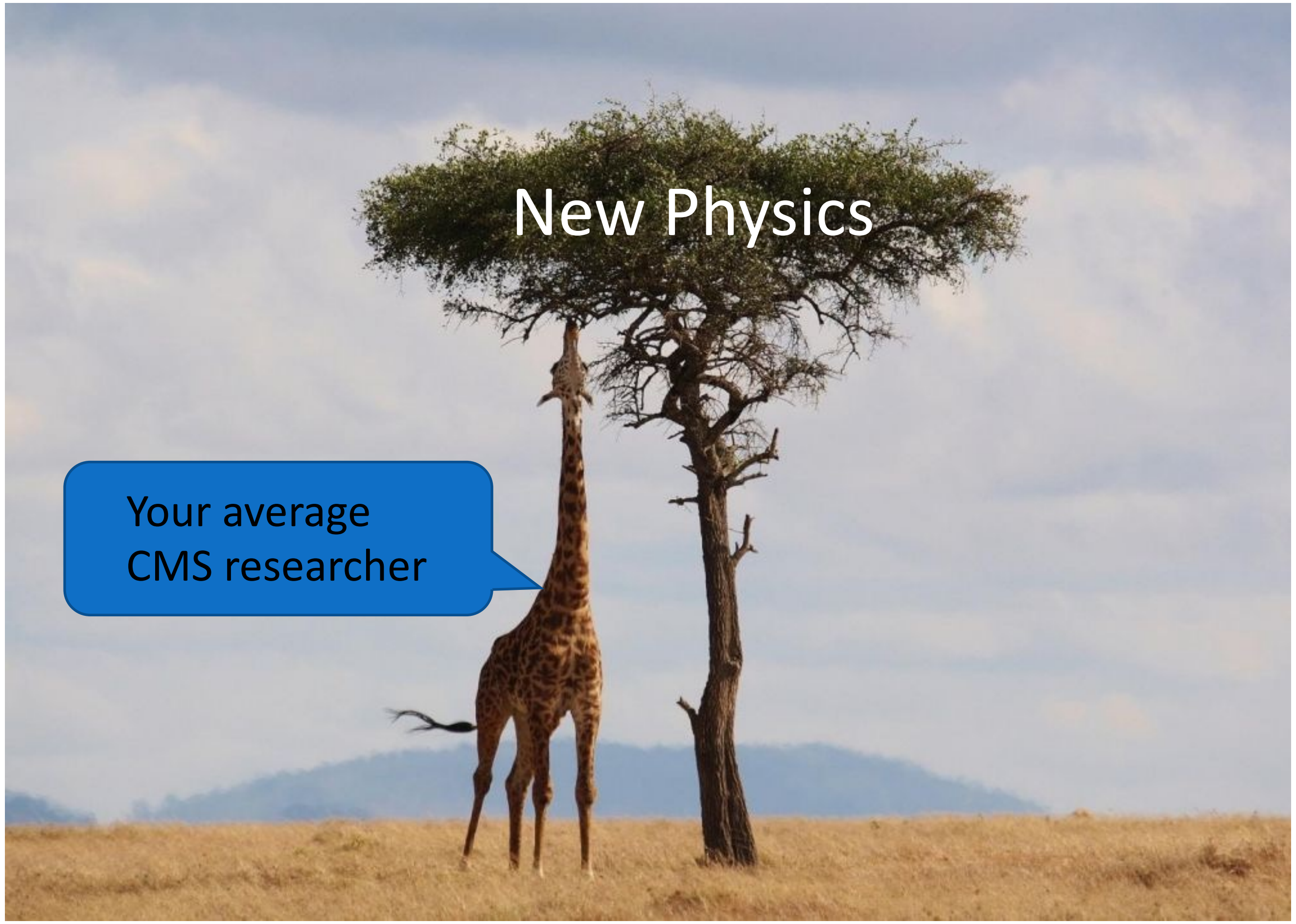
Extracting the signal

- Most of the backgrounds are from processes with genuine tau leptons, followed by jets misidentified as $\tau \rightarrow$ hadrons (τ_h)
  - Measured in data
- Use categorization to improve the sensitivity to signal
  - 0-jet: constrain backgrounds and overall production rate μ
    - Targets mostly ggH
  - Boosted: at least one jet and not VBF
    - Some sensitivity to new physics, but no MELA
  - VBF: at least two jets and
    - $\tau_h\tau_h$: $|\Delta\eta_{jj}| > 2.5$ and $p_T^{\tau\tau} > 100$ GeV
    - Other final states: $m_{jj} > 300$ GeV
    - **Most of the sensitivity to new physics comes from this category**
- Use a NN to separate signal from background: $\mathcal{D}_{NN}$
  - Inputs are MELA variables, m_{jj}, $m_{\tau\tau}$, and $p_T^{\tau\tau}$

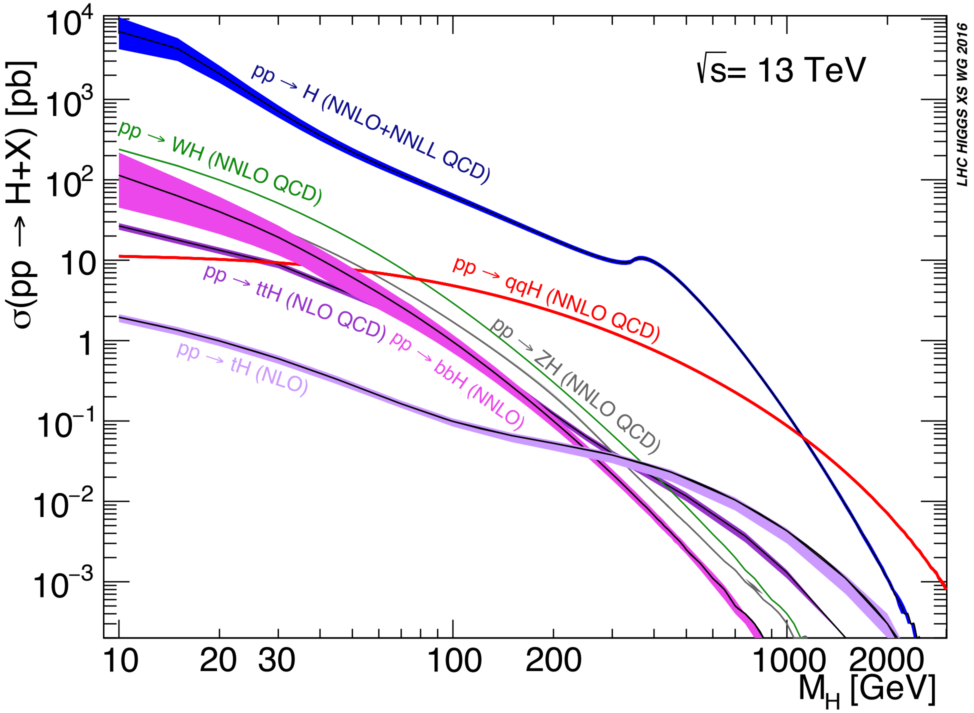
Bkg. Composition & Estimation Methods

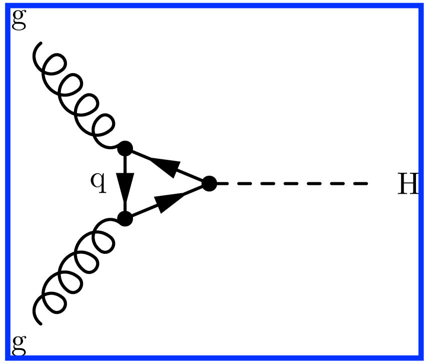


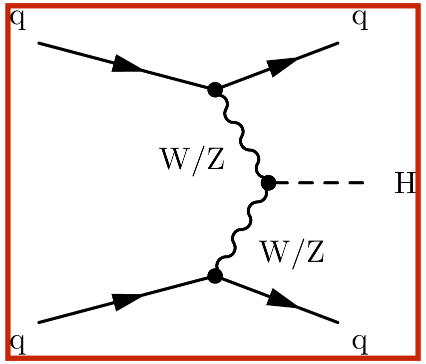
New methods and ideas at the frontier

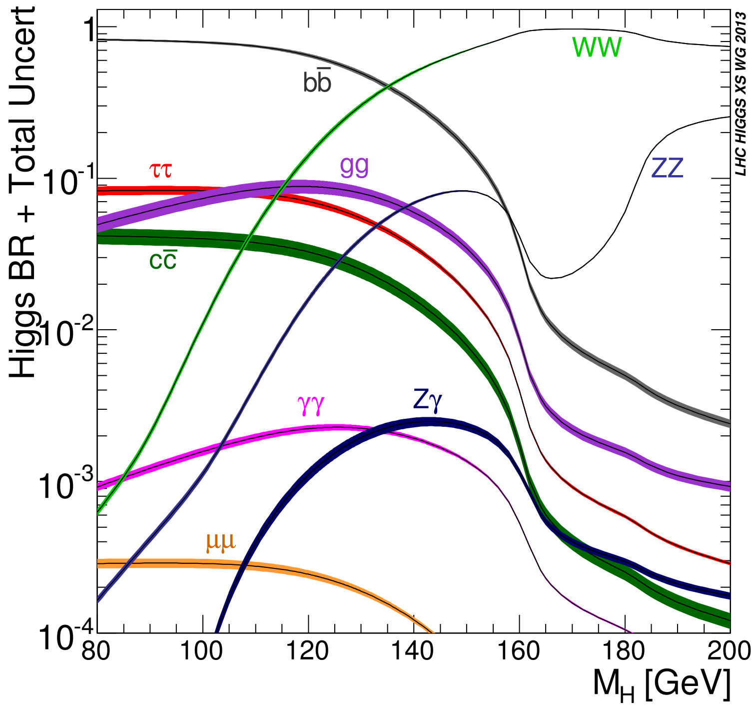


Focus of today's talk: H → $\tau\tau$





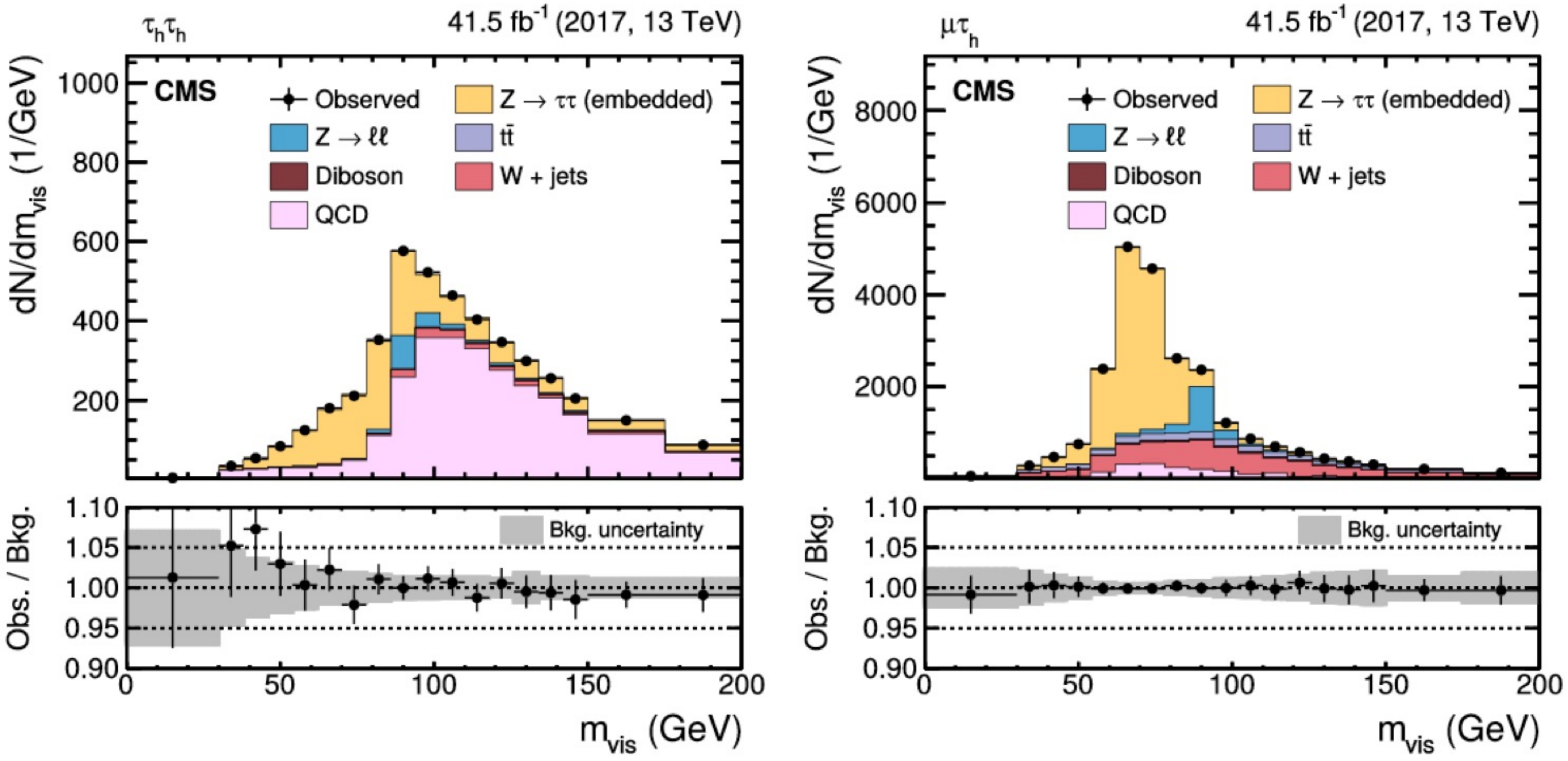


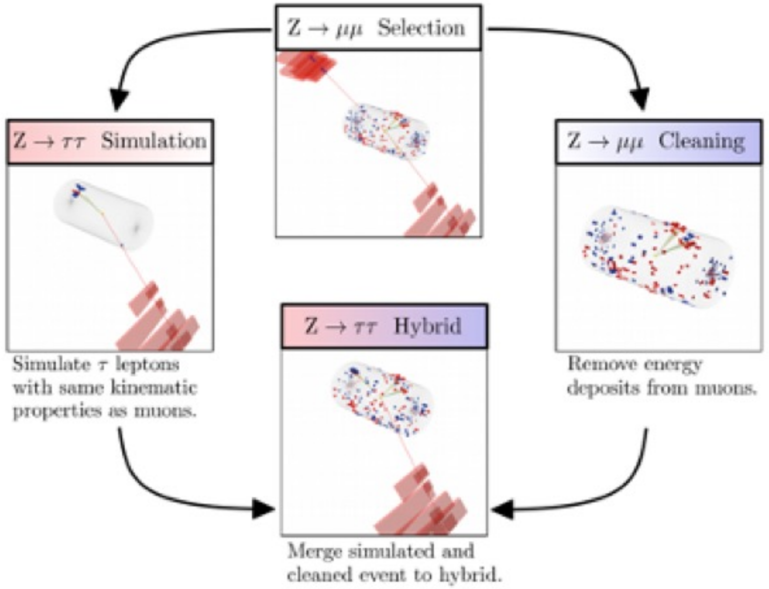


- Higgs boson is a "new" particle with a relatively low production cross section and difficult experimental signature
  - A lot of opportunities for potential discoveries
  - Clean process to study Hff coupling

Background from genuine tau leptons

- Embedded technique is used to predict processes with genuine tau leptons (majority is from $Z \rightarrow \tau\tau$)
  - Use $\mu\mu$ sample: replace muons with simulated tau leptons with the same kinematics

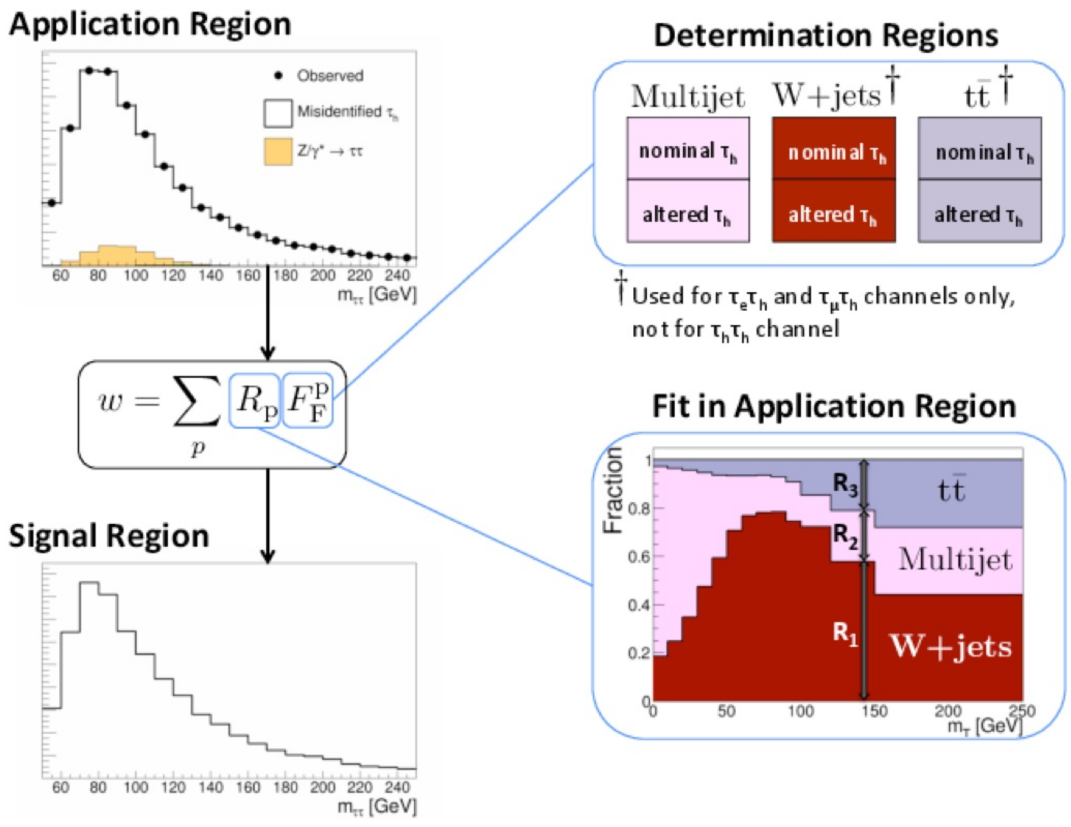




Background from non-genuine tau leptons

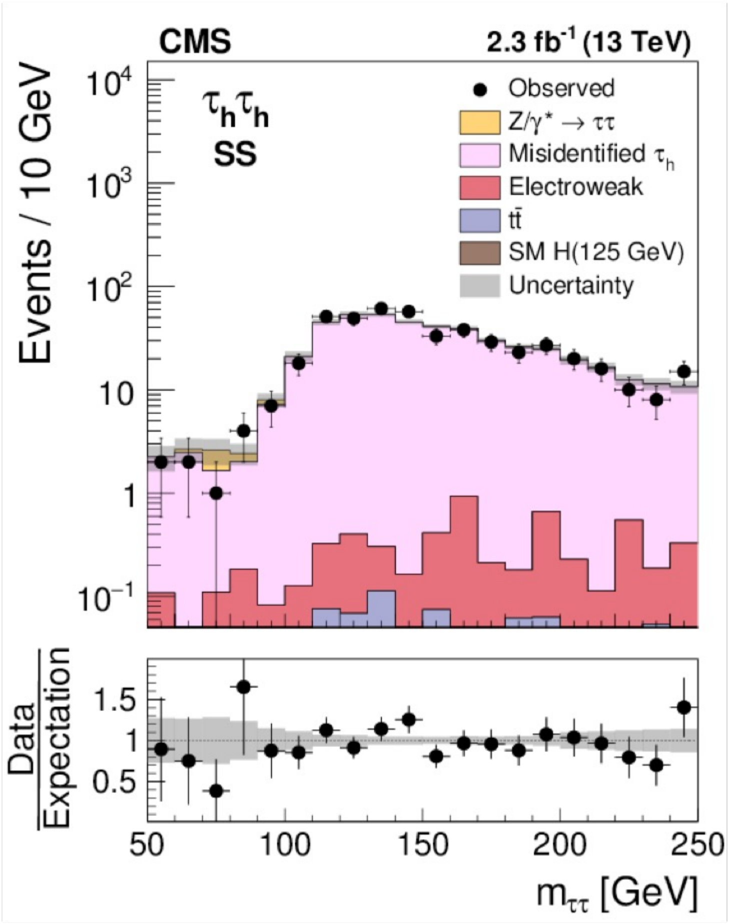
- Data driven method to estimate contributions from QCD, W+jets, and top

$$\left(\mathrm{FF} = \frac{N_{\mathrm{iso}}}{N_{\mathrm{anti\text{-}iso}}}\right) \times \text{Shape from anti-isolated data}$$



† Used for $\tau_e\tau_h$ and $\tau_\mu\tau_h$ channels only, not for $\tau_h\tau_h$ channel

Validation in data



Anomalous H → $\tau\tau$ decay

- Generic Hff amplitude $\mathcal{A}(\mathrm{Hff}) = -\frac{m_f}{v}\bar{\psi}_f\left(\boxed{\kappa_f} + i\boxed{\tilde{\kappa}_f}\gamma_5\right)\psi_f$

  κ_f – CP even coupling (SM)

  $\tilde{\kappa}_f$ – CP off coupling
- Can define fraction or effective mixing angle

$$\alpha^{\mathrm{Hff}} = \tan^{-1}\left(\frac{\tilde{\kappa}_{\mathrm{f}}}{\kappa_{\mathrm{f}}}\right)$$

$$f_{\mathrm{CP}}^{\mathrm{Hff}} = \frac{|\tilde{\kappa}_{\mathrm{f}}|^2}{|\kappa_{\mathrm{f}}|^2 + |\tilde{\kappa}_{\mathrm{f}}|^2}\,\mathrm{sgn}\left(\frac{\kappa_{\mathrm{f}}}{\kappa_{\mathrm{f}}}\right)$$

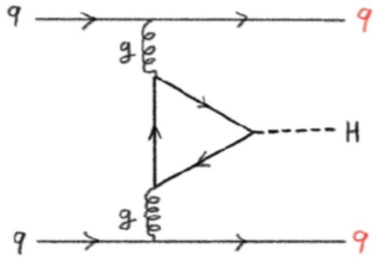
- Can relate to ggH CP fraction under an assumption of only top and bottom quarks contributing to the ggH loop
  - $\kappa_t = \kappa_b = \kappa_f$ and $\tilde{\kappa}_t = \tilde{\kappa}_b = \tilde{\kappa}_f$

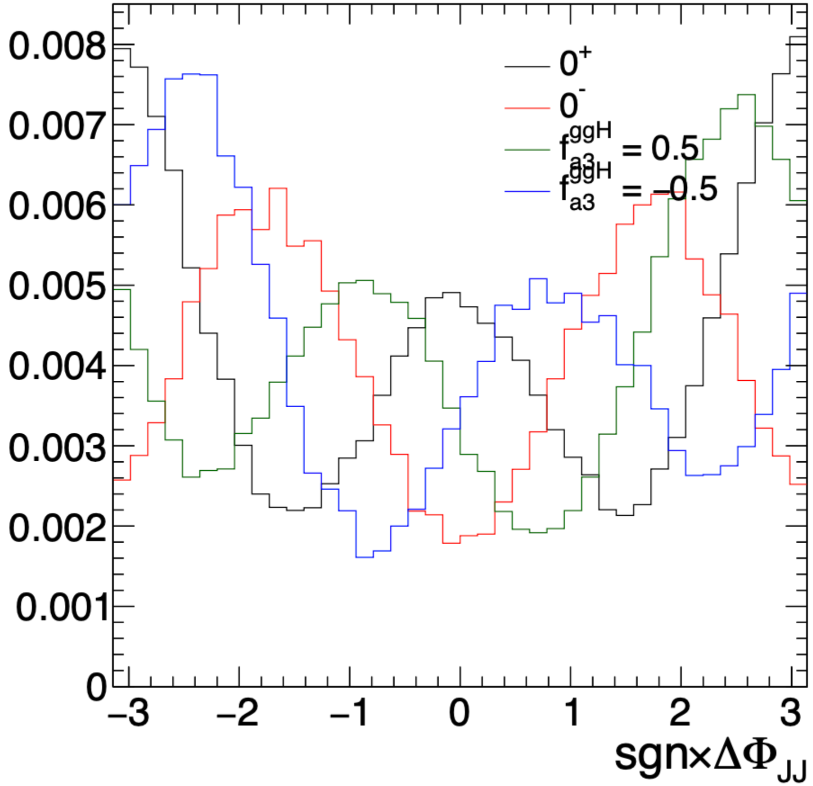
arXiv:2002.09888

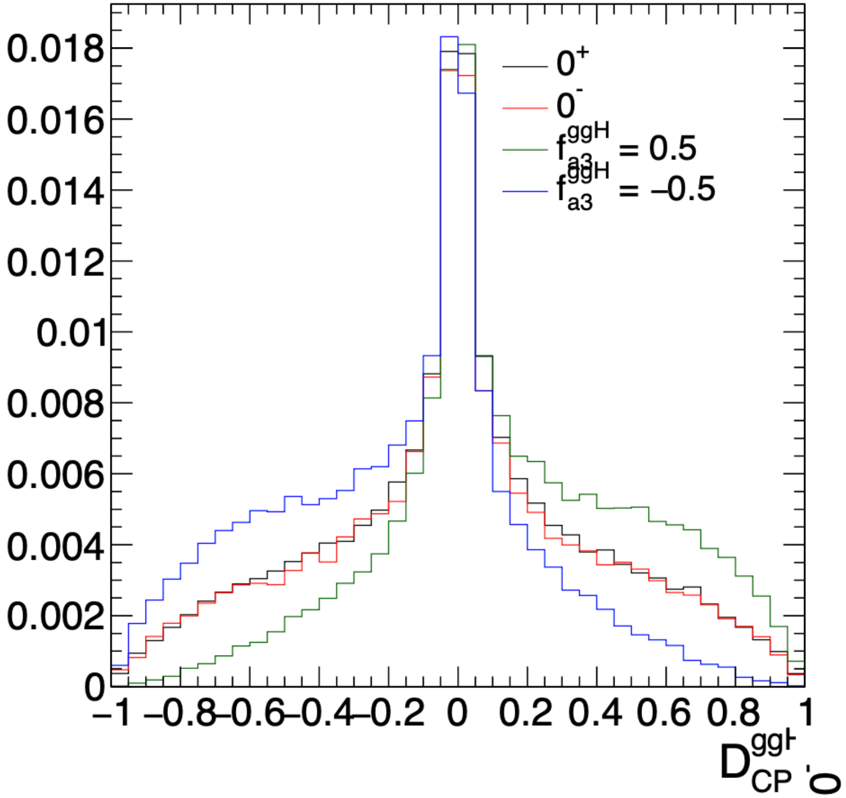
$$\left|f_{\mathrm{CP}}^{\mathrm{Hff}}\right| = \left(1 + 2.38\left[\frac{1}{\left|f_{a3}^{\mathrm{ggH}}\right|} - 1\right]\right)^{-1}$$

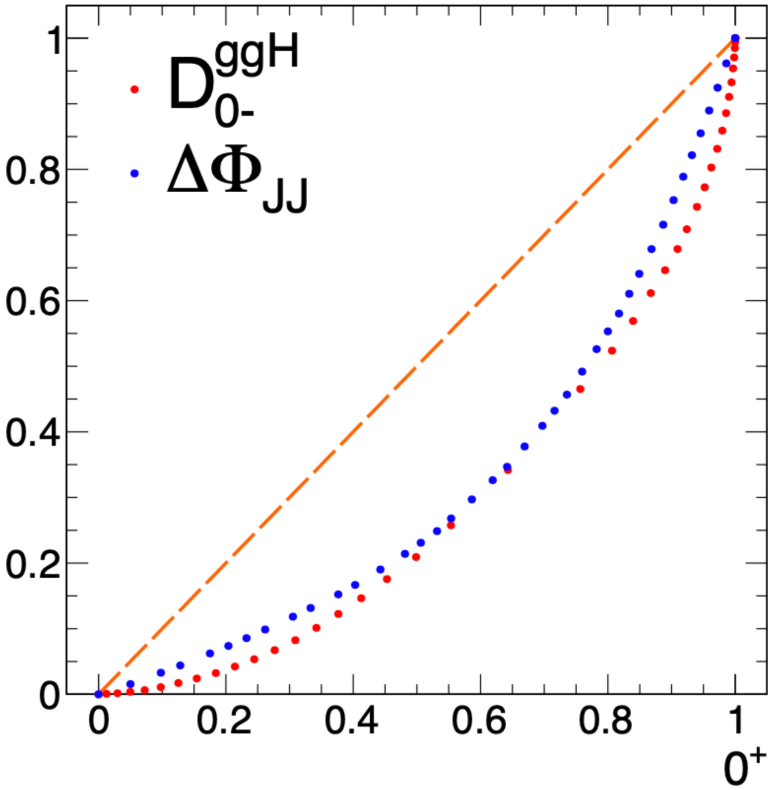
MELA Performance: ggH

- MELA does not help much with testing for CP symmetry in the ggH vertex as most of the information is encoded in the $\mathrm{sgn}\times\Delta\Phi$



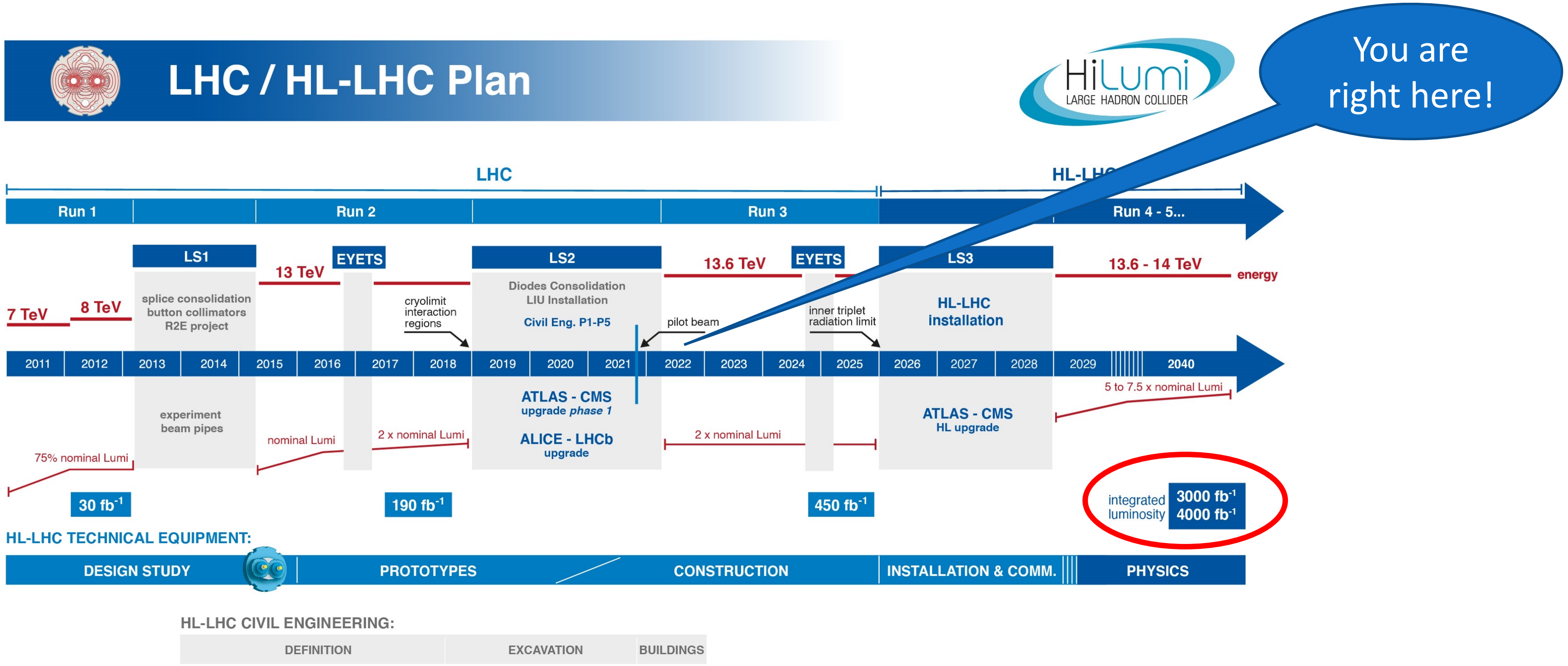






Summary part 2

- Run 3 will bring more statistics and hopefully an ability to do simultaneous fits to all anomalous coupling parameter space for the Higgs boson production + extend the reach to truly boosted $\tau\tau$
  - I, personally, hope to do a quick new physics search before the AC measurement with Run 3 becomes relevant ☺



You are right here!

Pre-selection criteria

	$\mu\tau_h$	$e\tau_h$	$\tau_h\tau_h$	$e\mu$
DeepTau WP vs (jet, e, μ)	(M, VVVL, T)	(M, T, VL)	(M, VVVL, VL)	–
μ ID & iso	Medium & $I_{rel}<0.15$	–	–	Medium & $I_{rel}<0.15$
e ID & iso	–	90% WP & $I_{rel}<0.15$	–	90% WP & $I_{rel}<0.15$
Trigger	Single-muon OR muon-τ_h cross	Single-elec OR elec-τ_h cross	Double-tau	Muon-elec cross
Extra	$m_T<50$ GeV & b-jet veto	$m_T<50$ GeV & b-jet veto	–	$D_\zeta>-35$ GeV & b-jet veto

Corrections to simulated samples

- PU reweighting
- JES/JER
- Electron and muon ID, isolation, and trigger SFs
- Tau ID, and trigger SFs
- Electron smear + scale
- Tau energy scale
  - Separate for genuine tau leptons and mis-identified leptons as single-prong taus
- Lepton to single prong misidentification rate corrections
- B-tagging scale factors
- MET recoil corrections (for Z, W, and Higgs samples)
- Prefiring weights (2016 and 2017 only)
- ggH p_T/N_{jets} reweighting to NNLOPS
- Z p_T/mass reweighting
- Top p_T reweighting