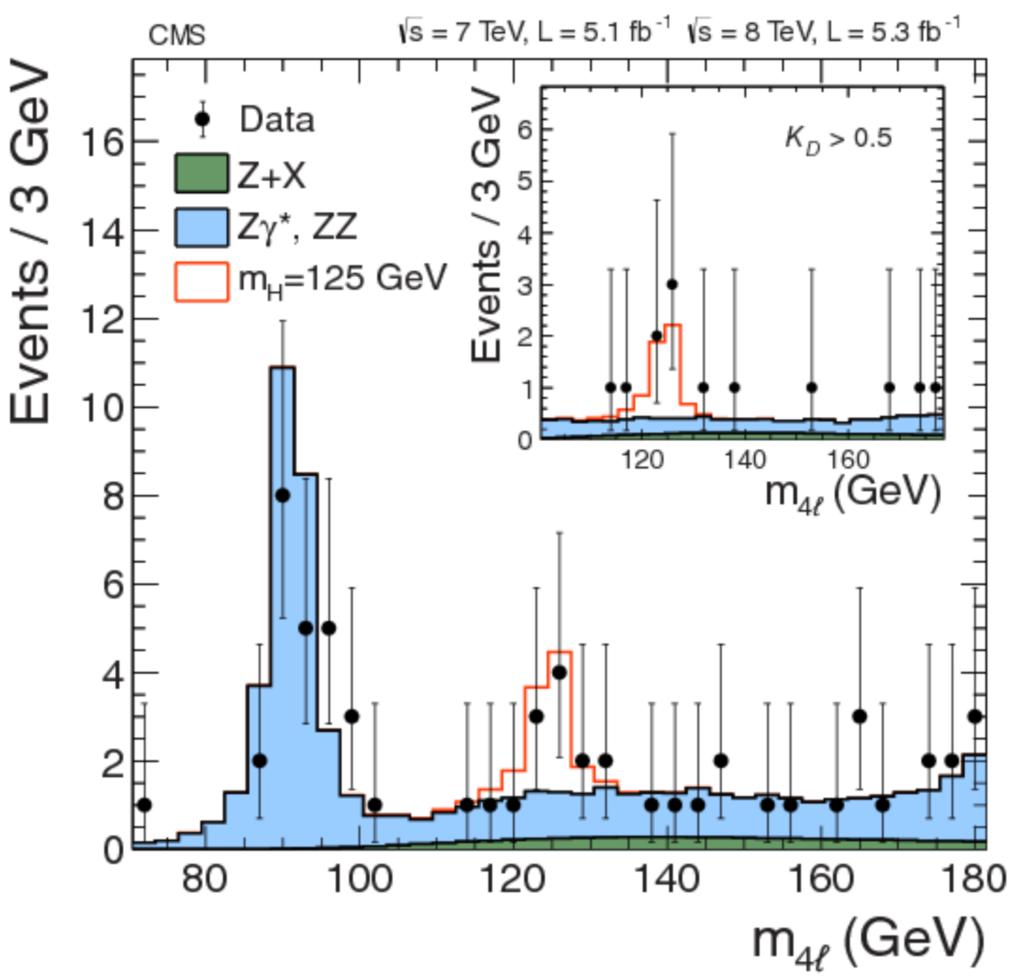
Precision and frontier searches in the Higgs sector

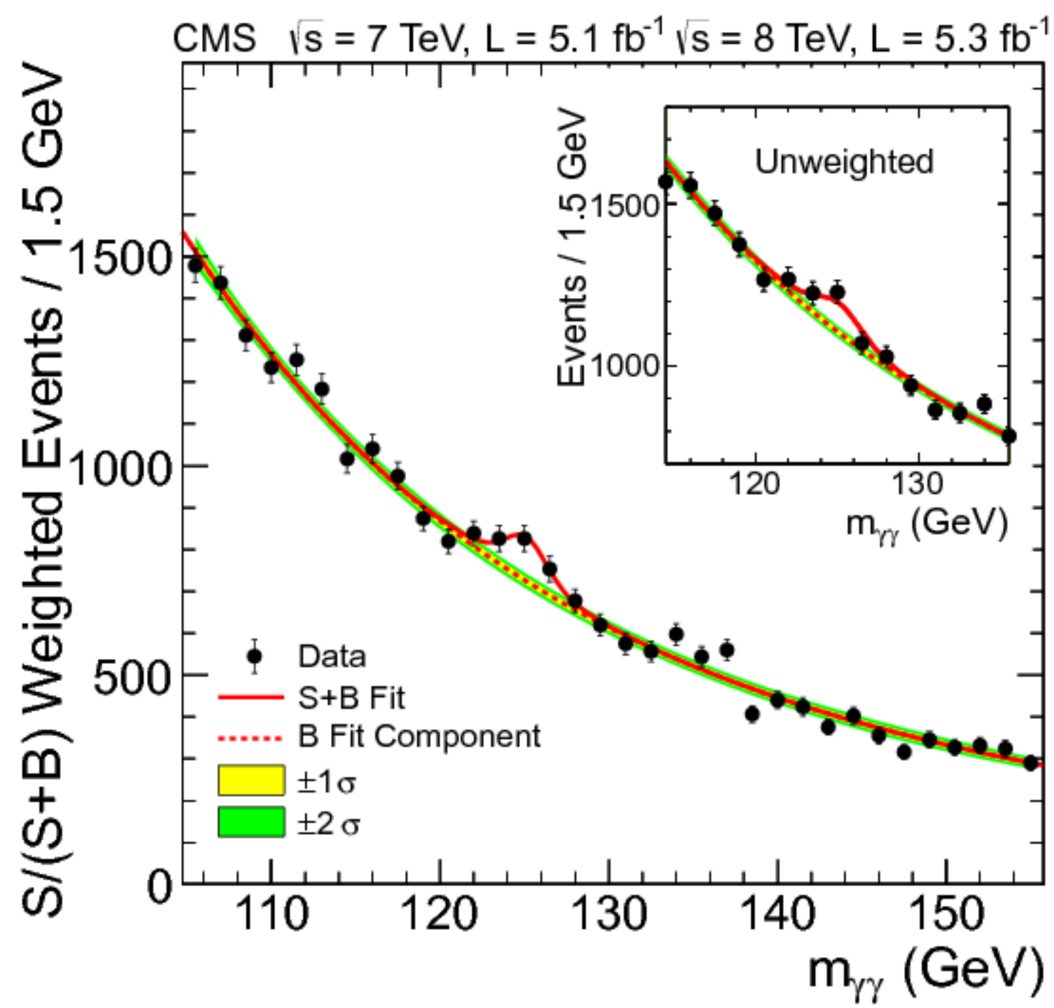
Filippo Errico
on behalf of Bari Gruppo1

21/06/2021, Bari
Congresso di sezione INFN

Overview

Higgs boson discovery was announced on the 4th of July 2012.





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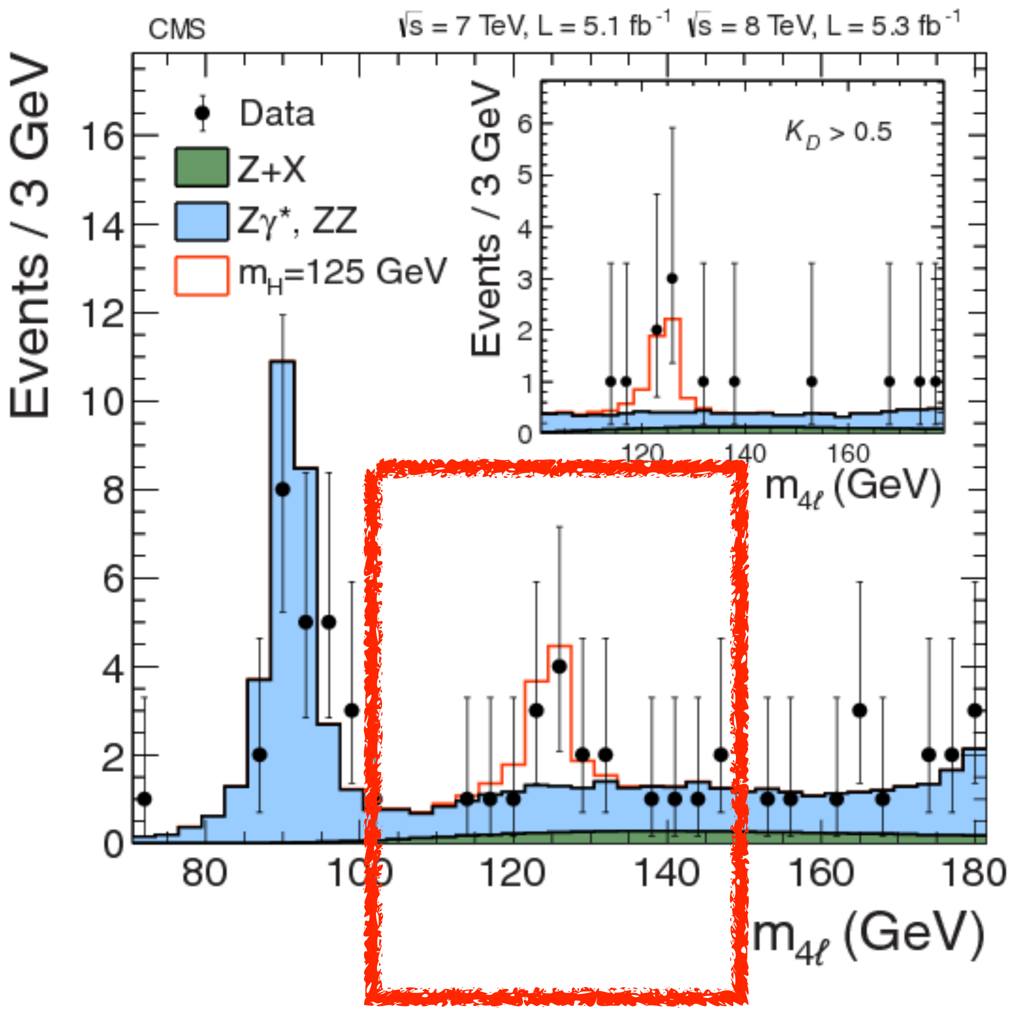
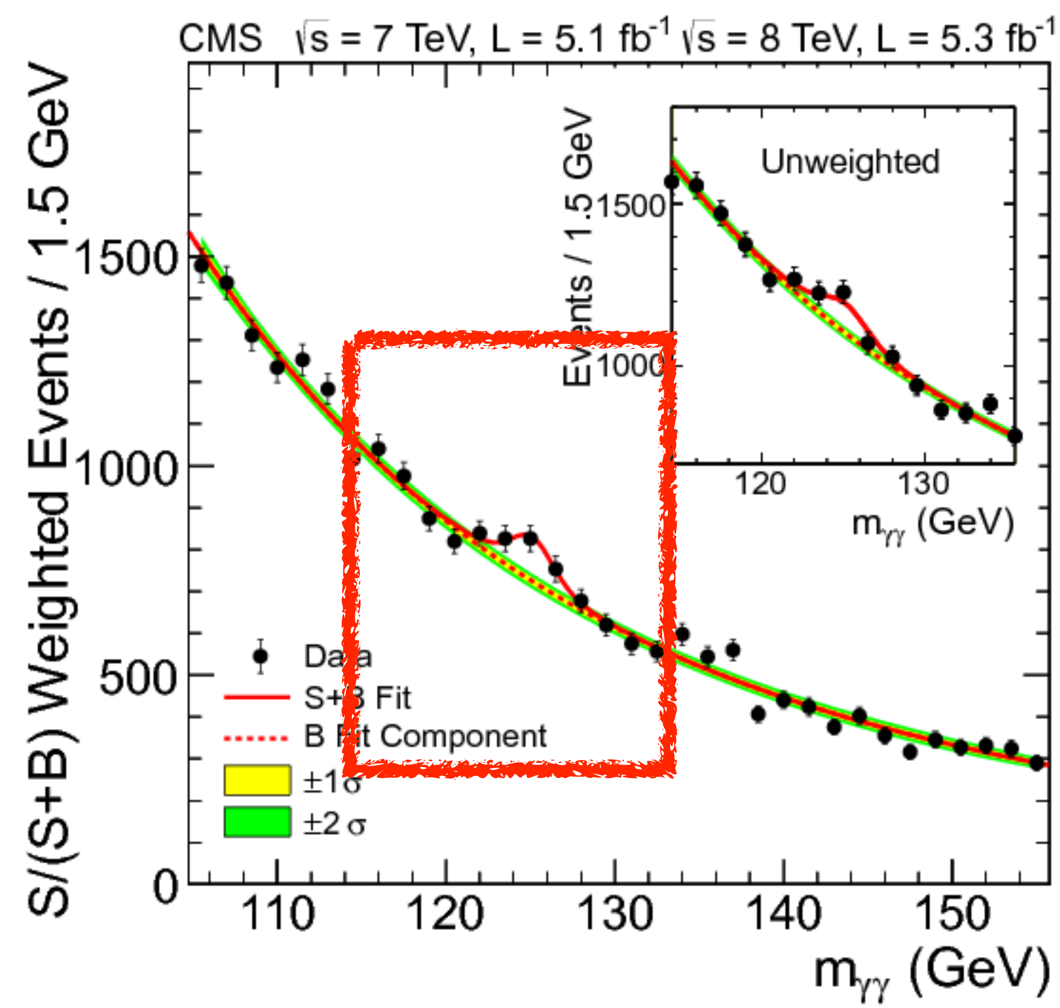
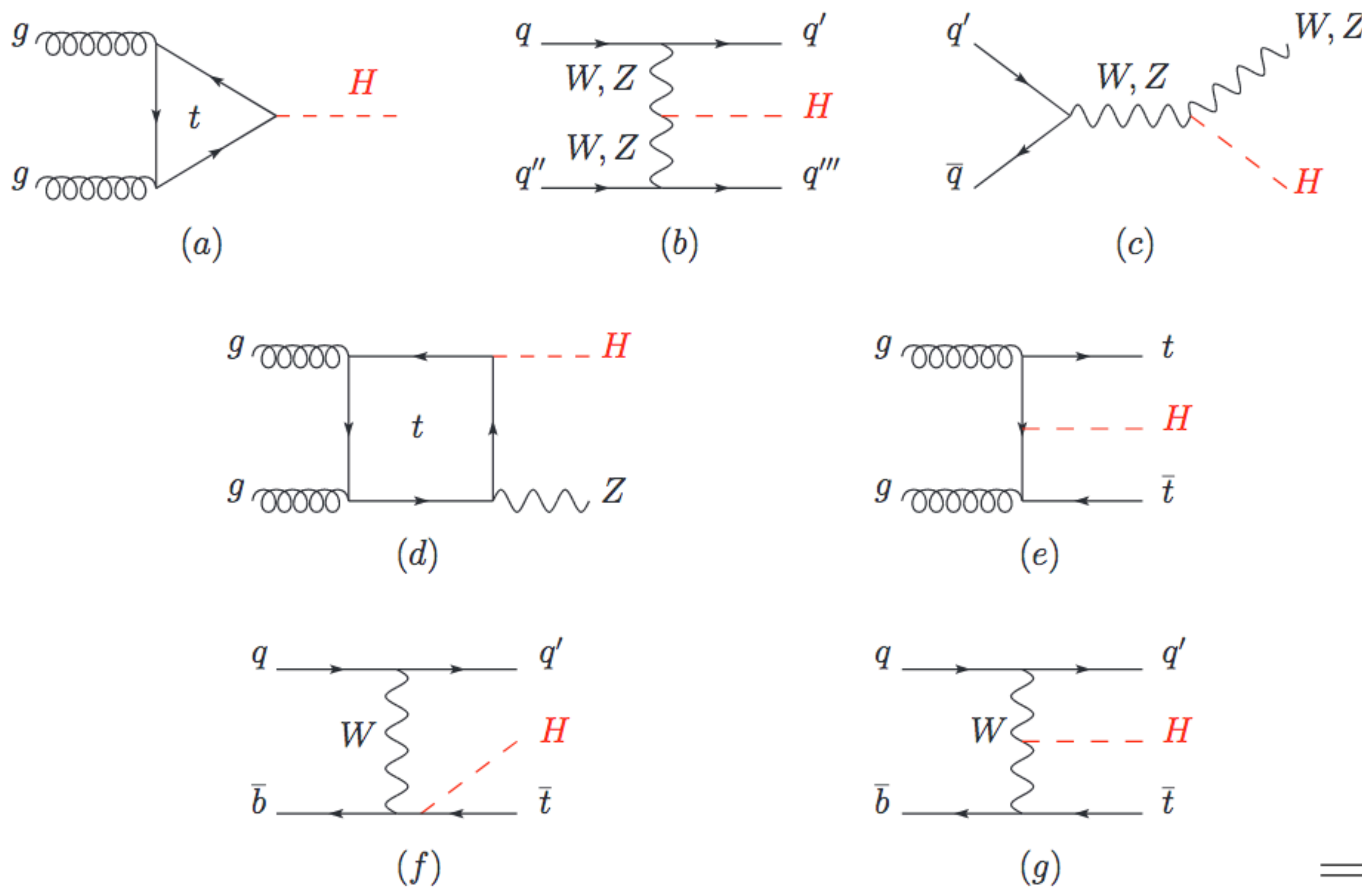


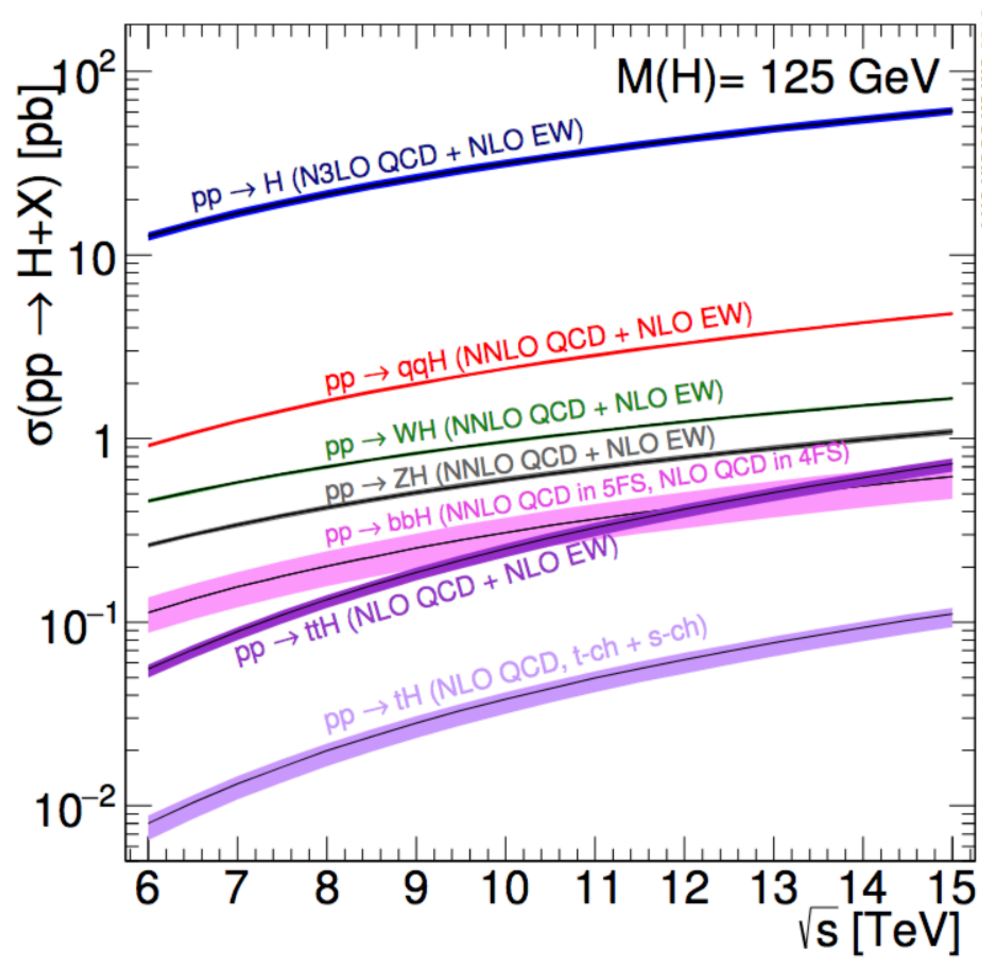


Since then, much effort has been put into determining its properties

Overview

Higgs boson (main) production modes



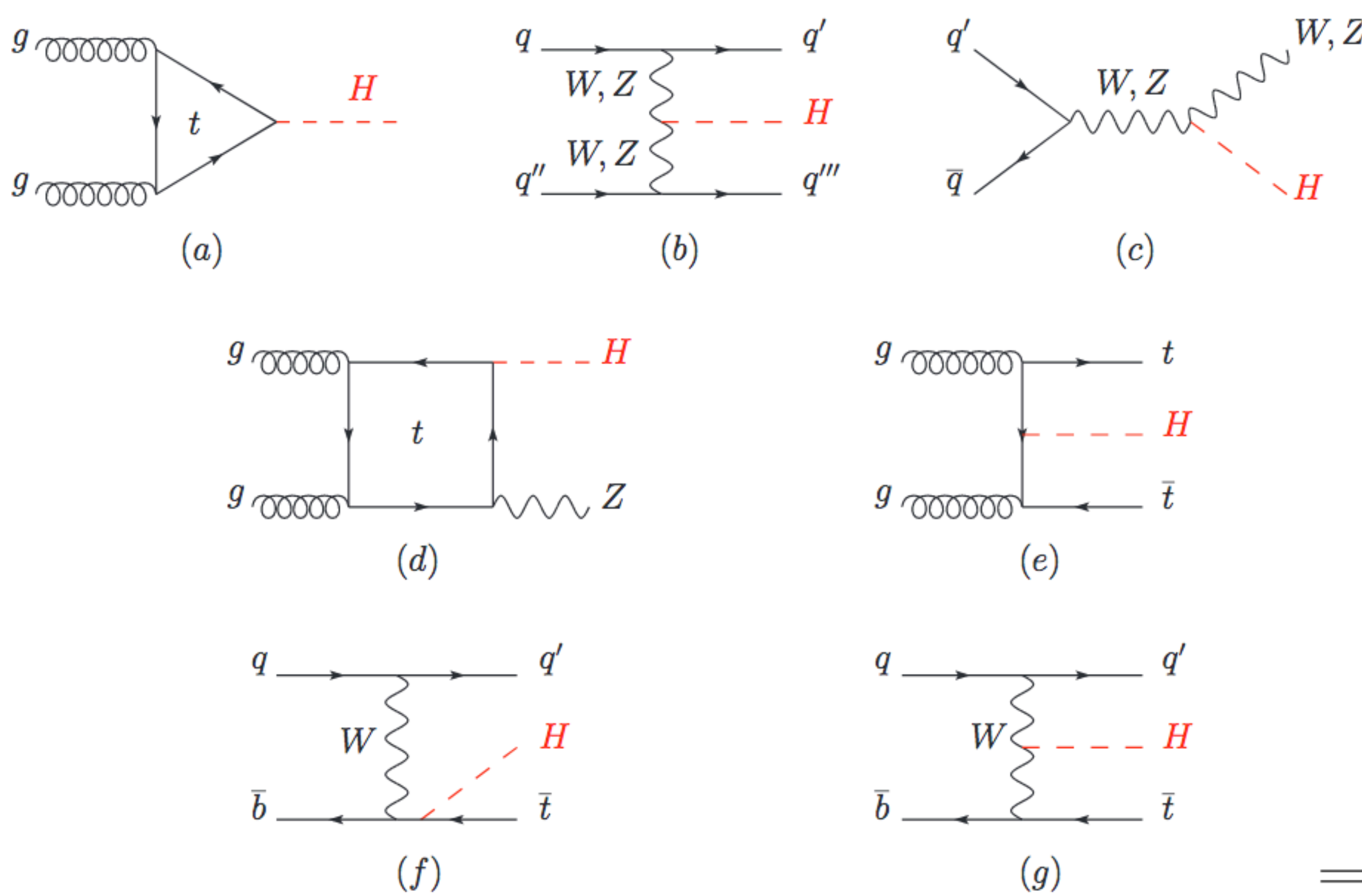


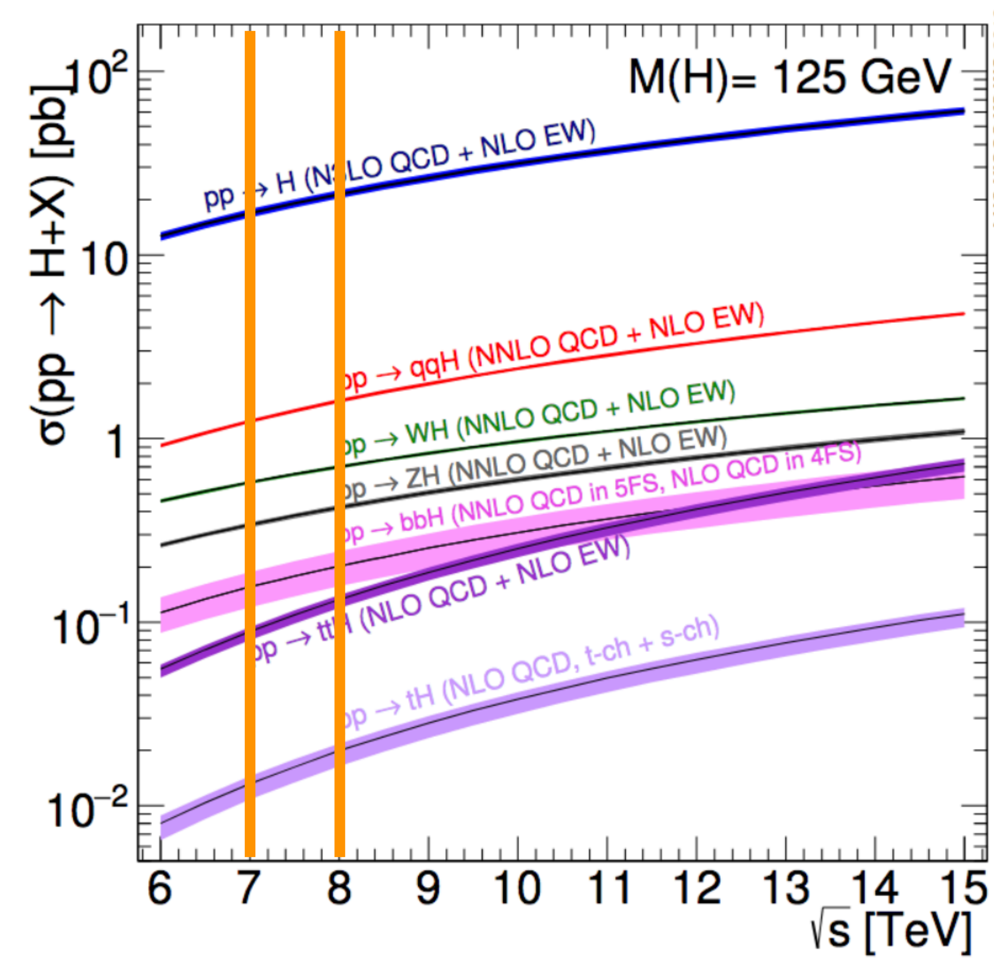
$\sqrt{s}$ (TeV)	Production cross section (in pb) for $m_H = 125\,\text{GeV}$					
	ggF	VBF	WH	ZH	$t\bar{t}H$	total
1.96	$0.95^{+17\%}_{-17\%}$	$0.065^{+8\%}_{-7\%}$	$0.13^{+8\%}_{-8\%}$	$0.079^{+8\%}_{-8\%}$	$0.004^{+10\%}_{-10\%}$	1.23
7	$16.9^{+4.4\%}_{-7.0\%}$	$1.24^{+2.1\%}_{-2.1\%}$	$0.58^{+2.2\%}_{-2.3\%}$	$0.34^{+3.1\%}_{-3.0\%}$	$0.09^{+5.6\%}_{-10.2\%}$	19.1
8	$21.4^{+4.4\%}_{-6.9\%}$	$1.60^{+2.3\%}_{-2.1\%}$	$0.70^{+2.1\%}_{-2.2\%}$	$0.42^{+3.4\%}_{-2.9\%}$	$0.13^{+5.9\%}_{-10.1\%}$	24.2
13	$48.6^{+4.6\%}_{-6.7\%}$	$3.78^{+2.2\%}_{-2.2\%}$	$1.37^{+2.6\%}_{-2.6\%}$	$0.88^{+4.1\%}_{-3.5\%}$	$0.50^{+6.8\%}_{-9.9\%}$	55.1
14	$54.7^{+4.6\%}_{-6.7\%}$	$4.28^{+2.2\%}_{-2.2\%}$	$1.51^{+1.9\%}_{-2.0\%}$	$0.99^{+4.1\%}_{-3.7\%}$	$0.60^{+6.9\%}_{-9.8\%}$	62.1

Overview

Istituto Nazionale di Fisica Nucleare

Higgs boson (main) production modes





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7-8 TeV: Past [2010-2012]

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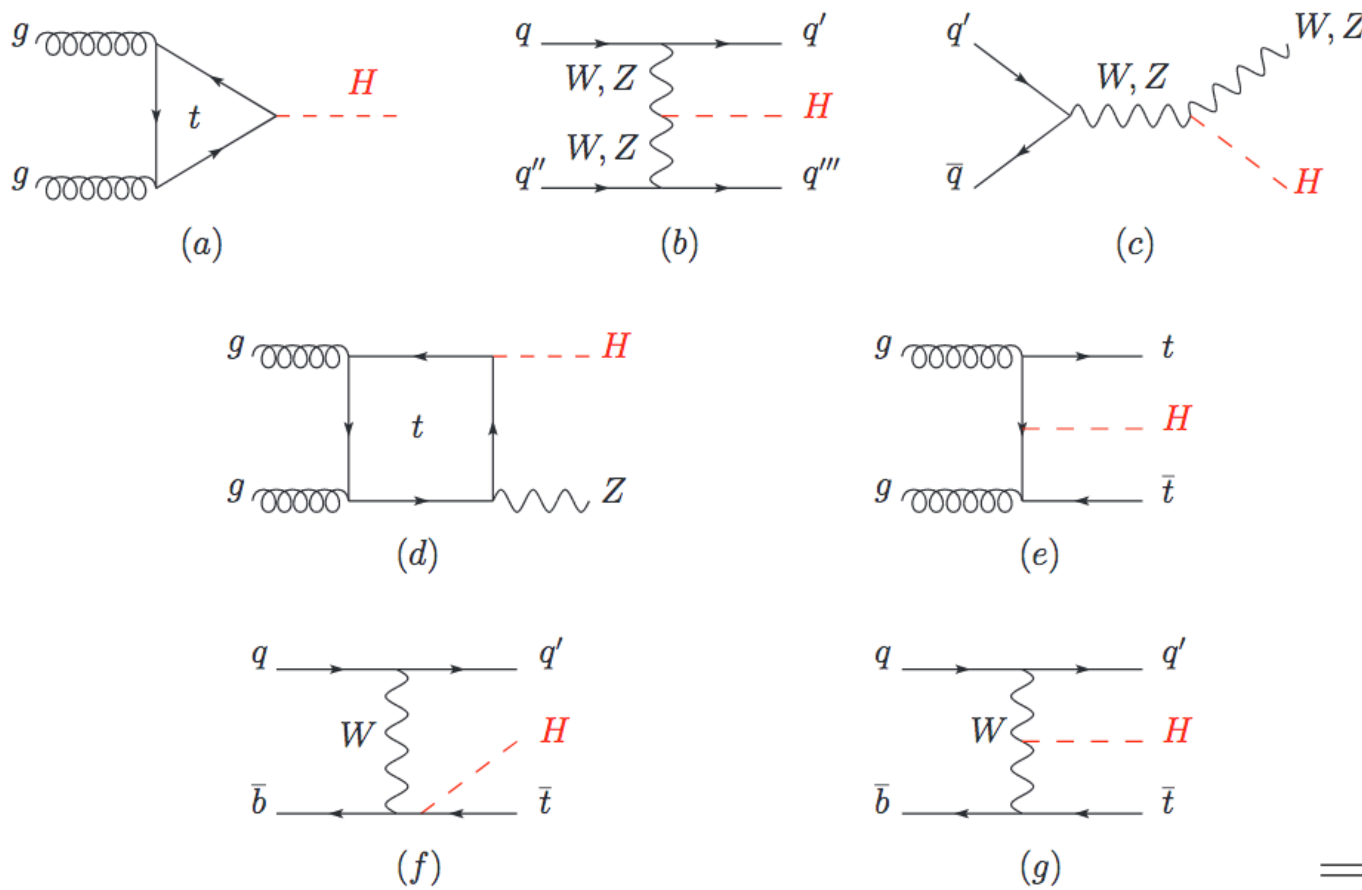

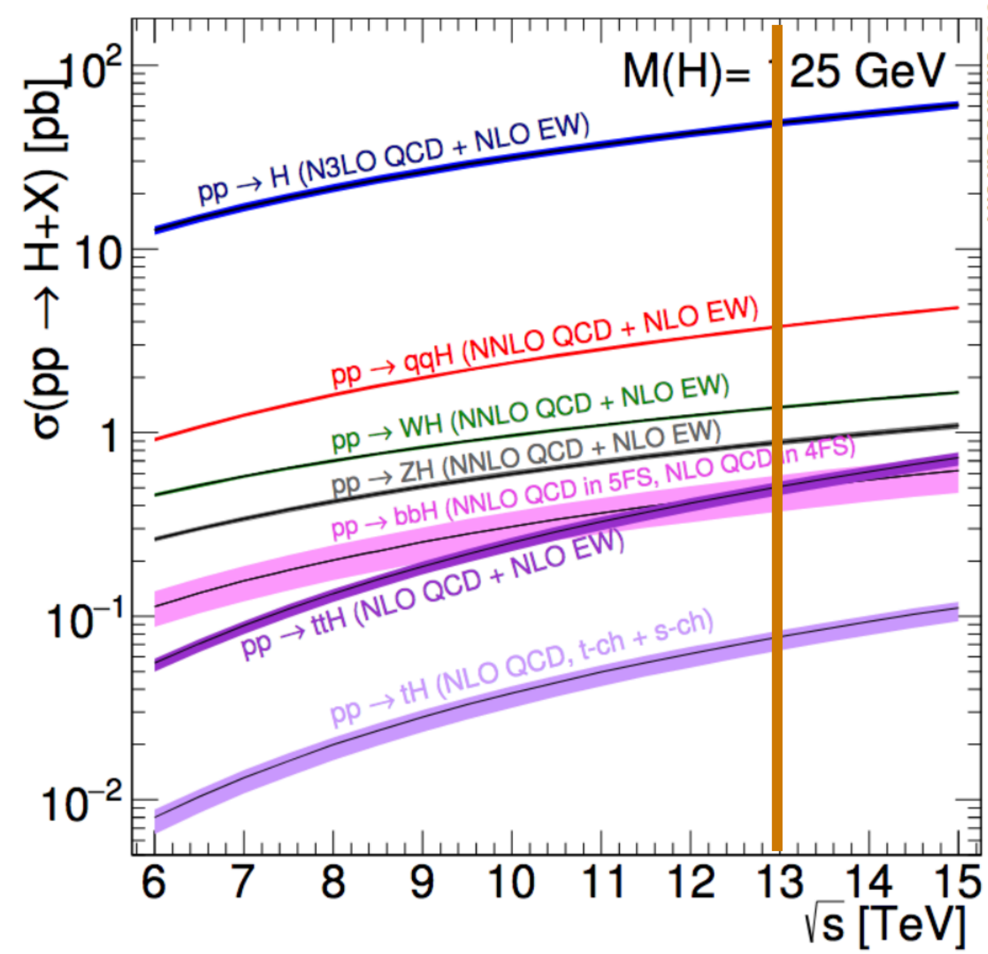

13 TeV: Present [2015-2022]

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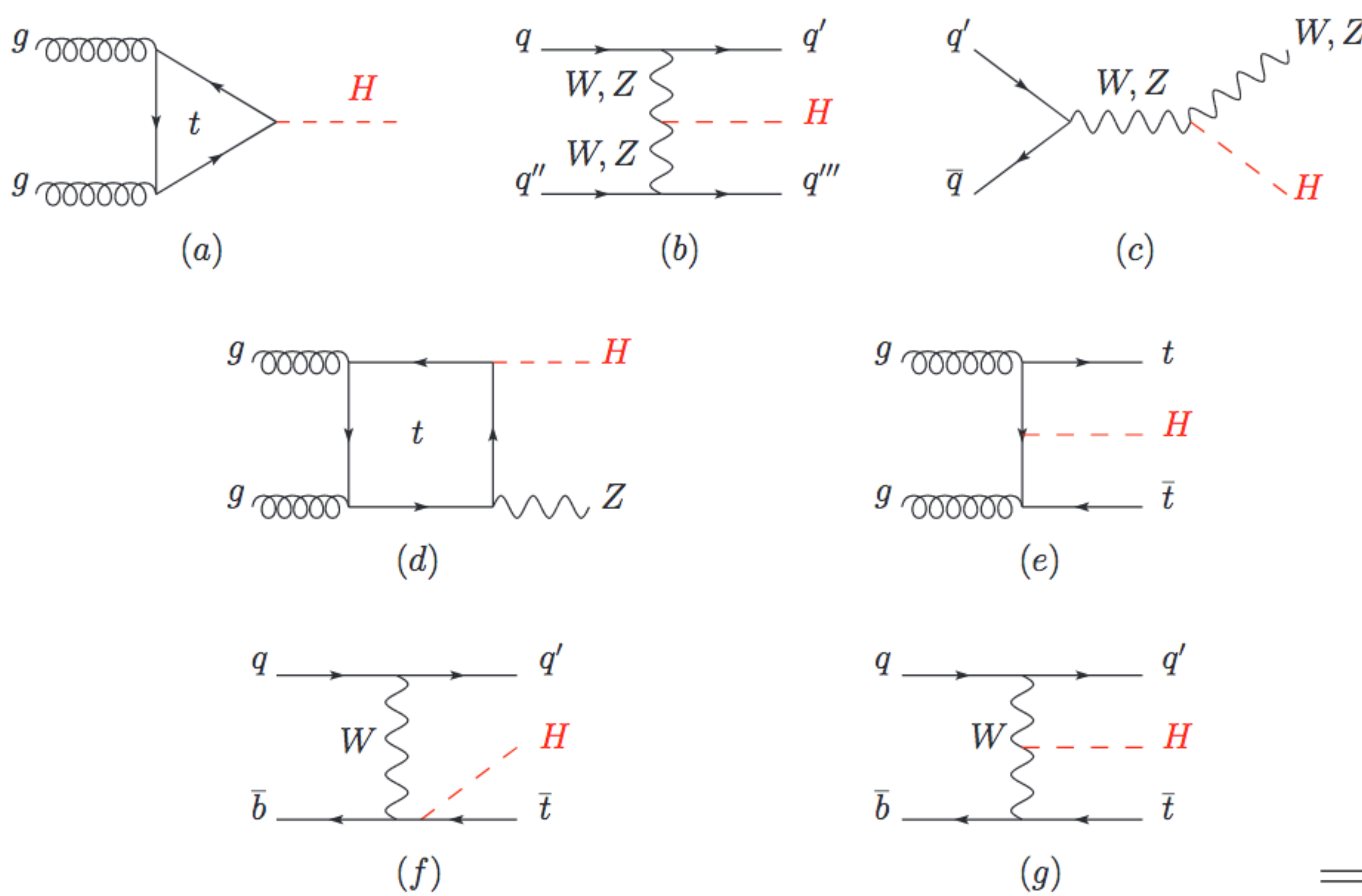

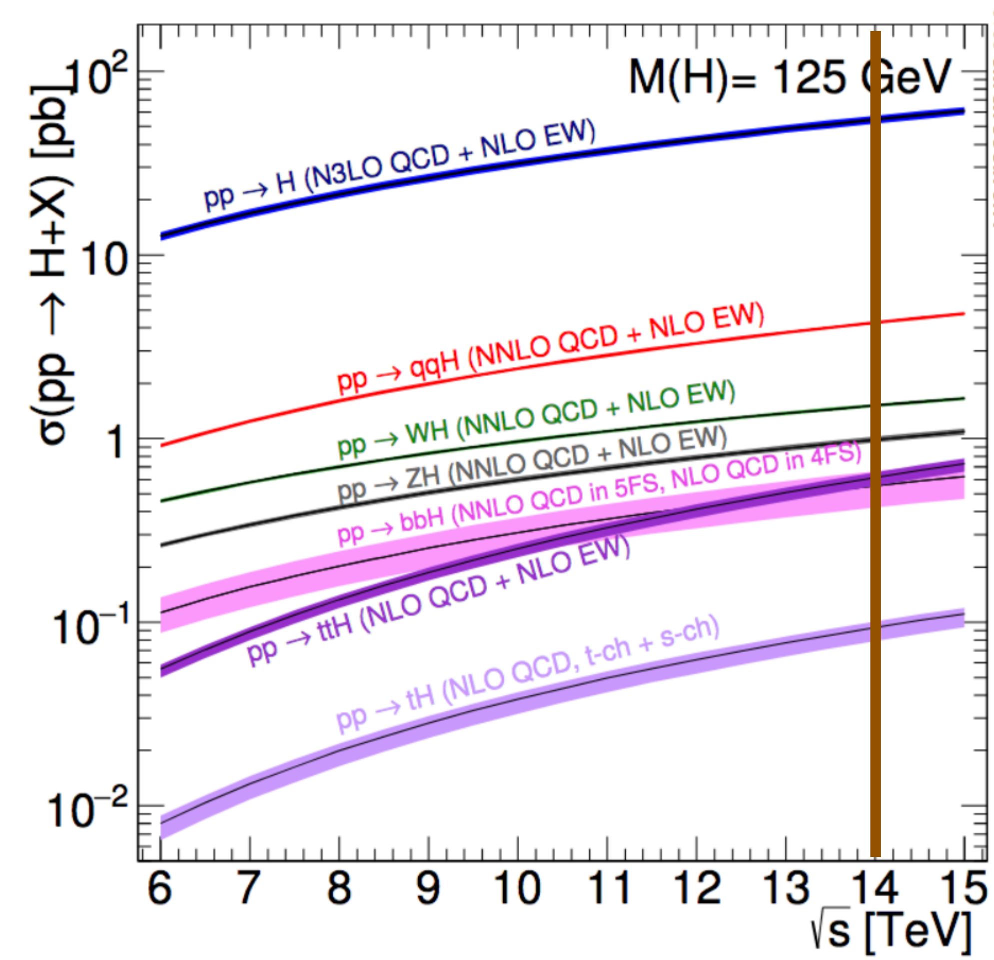

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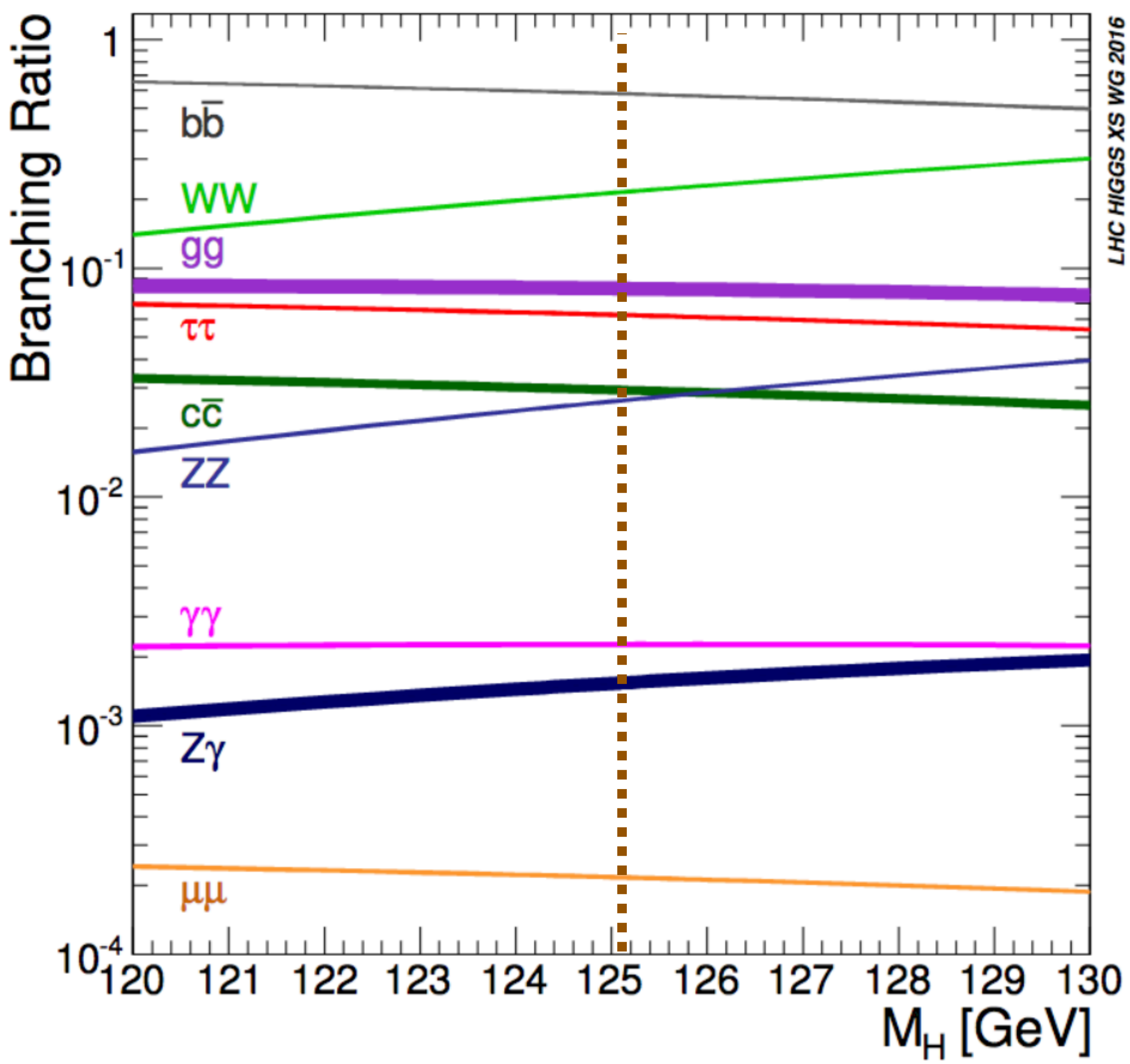
14 TeV: Future [2022(?) - 2035]

Overview

Higgs boson decay channels



H_{BR} @ m_H = 125.09 GeV

Decay channel	Branching ratio	Rel. uncertainty
$H \to \gamma\gamma$	2.27×10^{-3}	2.1%
$H \to ZZ$	2.62×10^{-2}	$\pm1.5\%$
$H \to W^+W^-$	2.14×10^{-1}	$\pm1.5\%$
$H \to \tau^+\tau^-$	6.27×10^{-2}	$\pm1.6\%$
$H \to b\bar{b}$	5.82×10^{-1}	$^{+1.2\%}_{-1.3\%}$
$H \to c\bar{c}$	2.89×10^{-2}	$^{+5.5\%}_{-2.0\%}$
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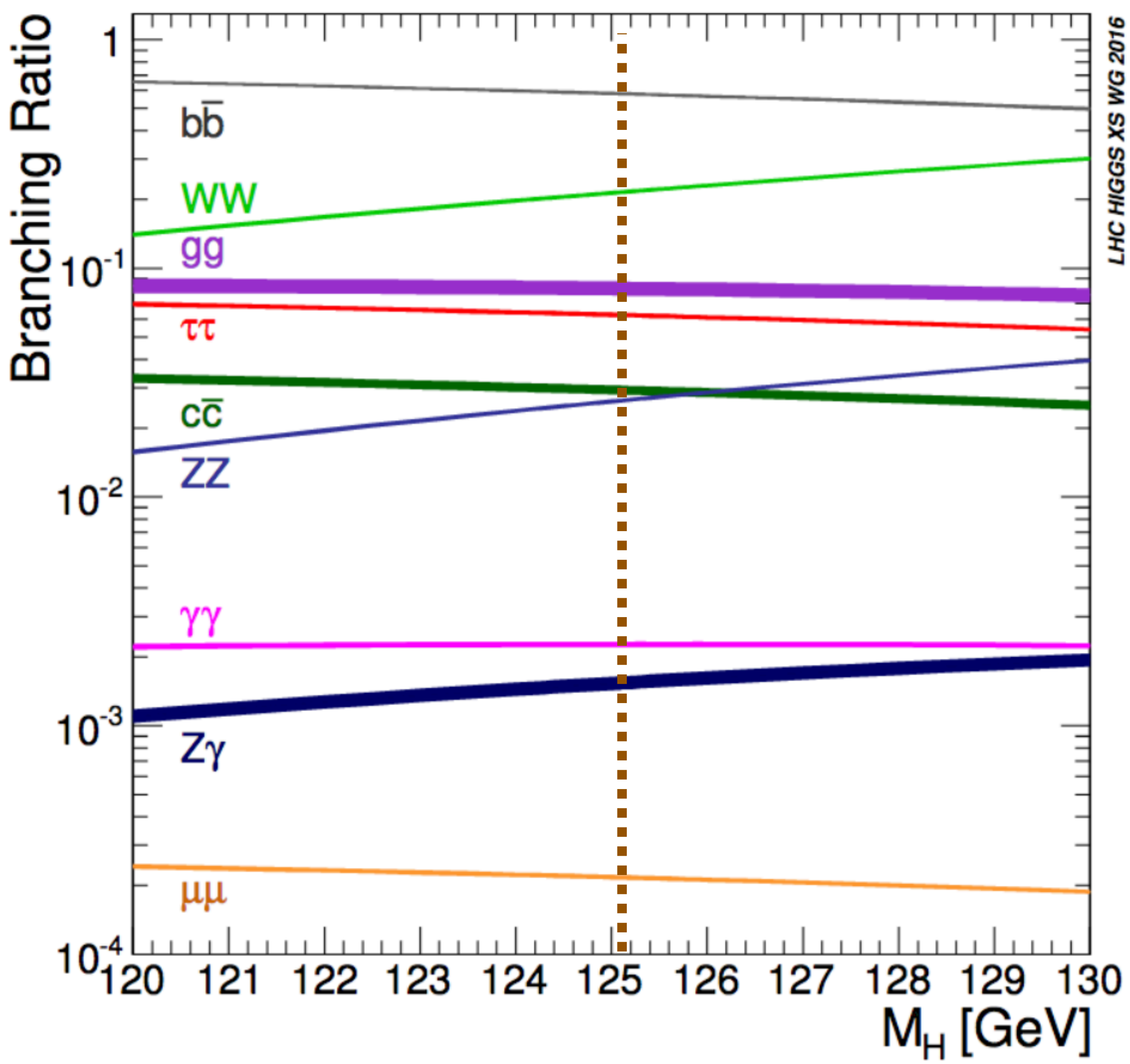
Overview

Higgs boson decay channels



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But are we sure that m_H = 125.09 GeV?

The Higgs boson mass

The Higgs boson mass is one of the most important free parameters of the Standard Model.

It is crucial to properly determine its value since it determines all the others Higgs boson properties (e.g cross section, branching ratio).

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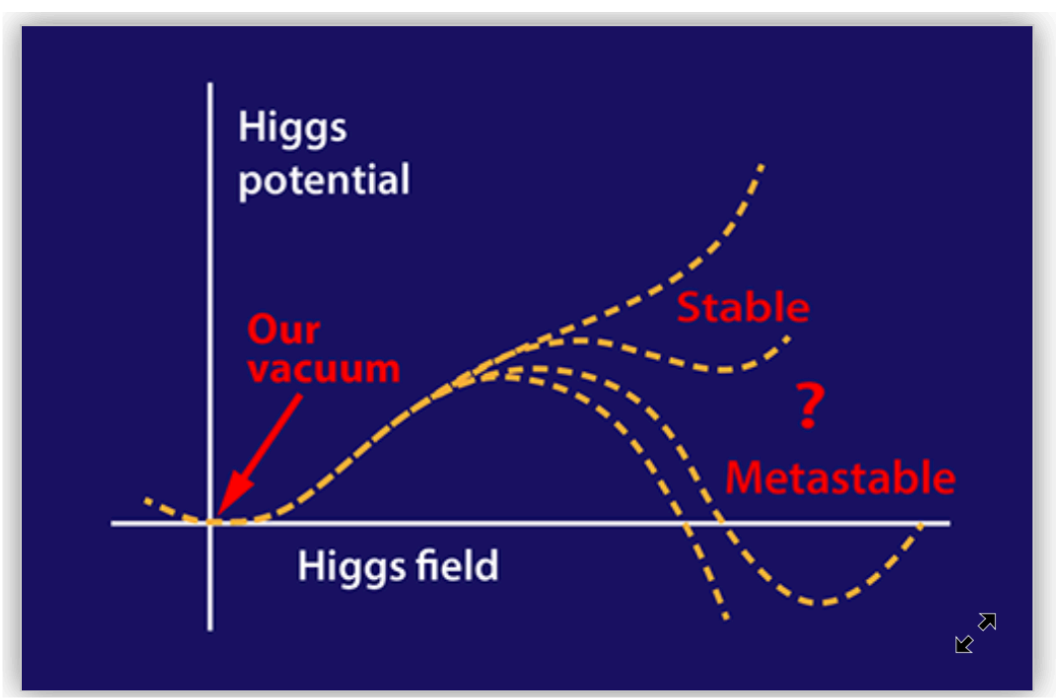
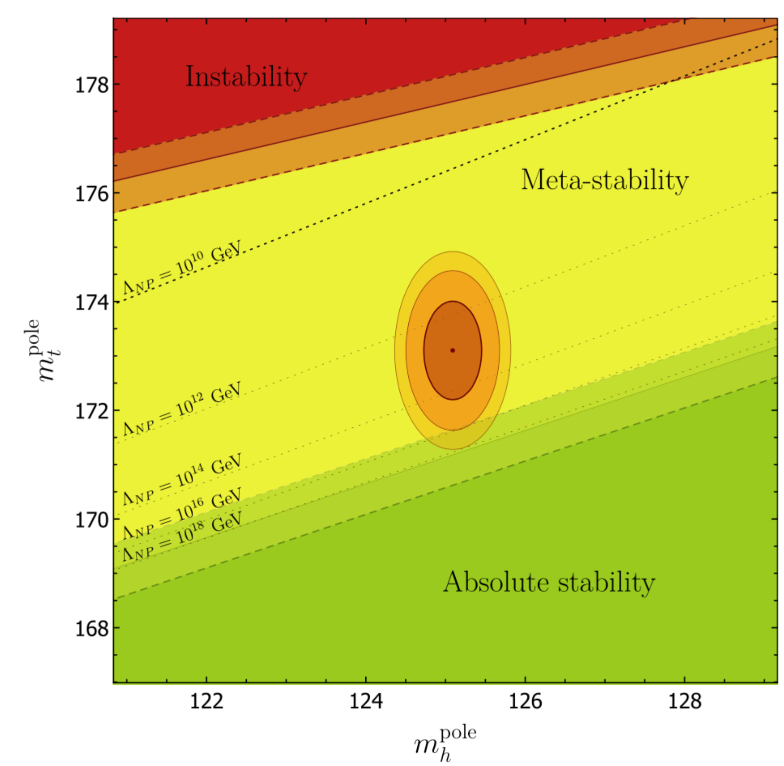
It is also gives information on the shape of the H potential.

Quote





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$$m_H = 125.38 \pm 0.14 \ [\pm 0.11(stat) \pm 0.08(syst)] \ GeV$$

Currently most precise result in the world

The Higgs boson mass

Currently the **best** Higgs boson **mass measurement** was performed using data collected by the **CMS experiment** during 2016 (~36 fb^{-1}).

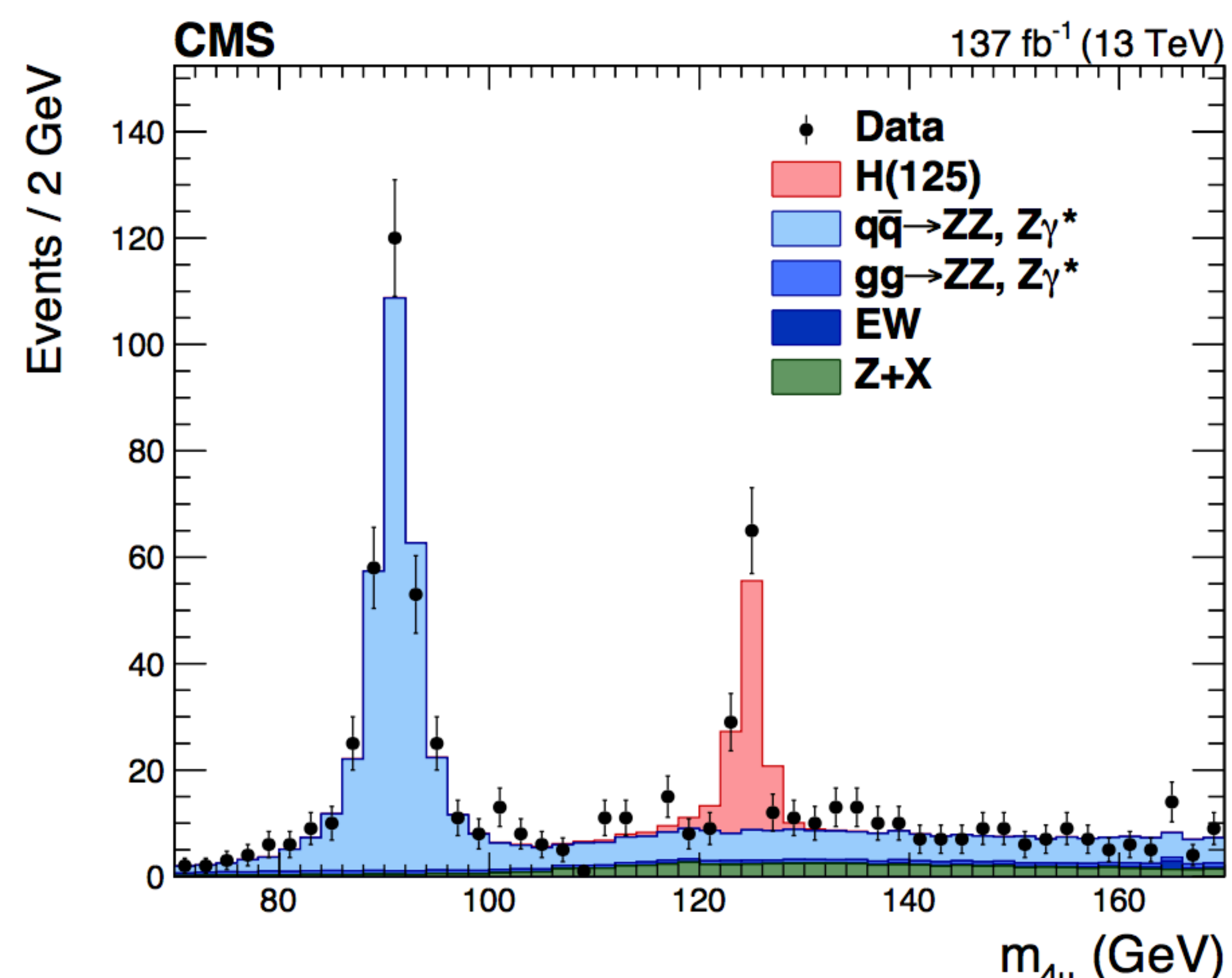
This result has been obtained combining the two most sensitive channels: **H→ZZ** and H→γγ.

CMS Bari group gives its contributions to the HZZ channel

The Higgs boson mass

Even it has a small BR (~2.6%), it is considered a **golden channel** thanks to:

- the full reconstruction of the final states (4μ, 4e or 2e2μ)
- very good background rejection (combining several approaches)
- good mass resolution (**~1%**)



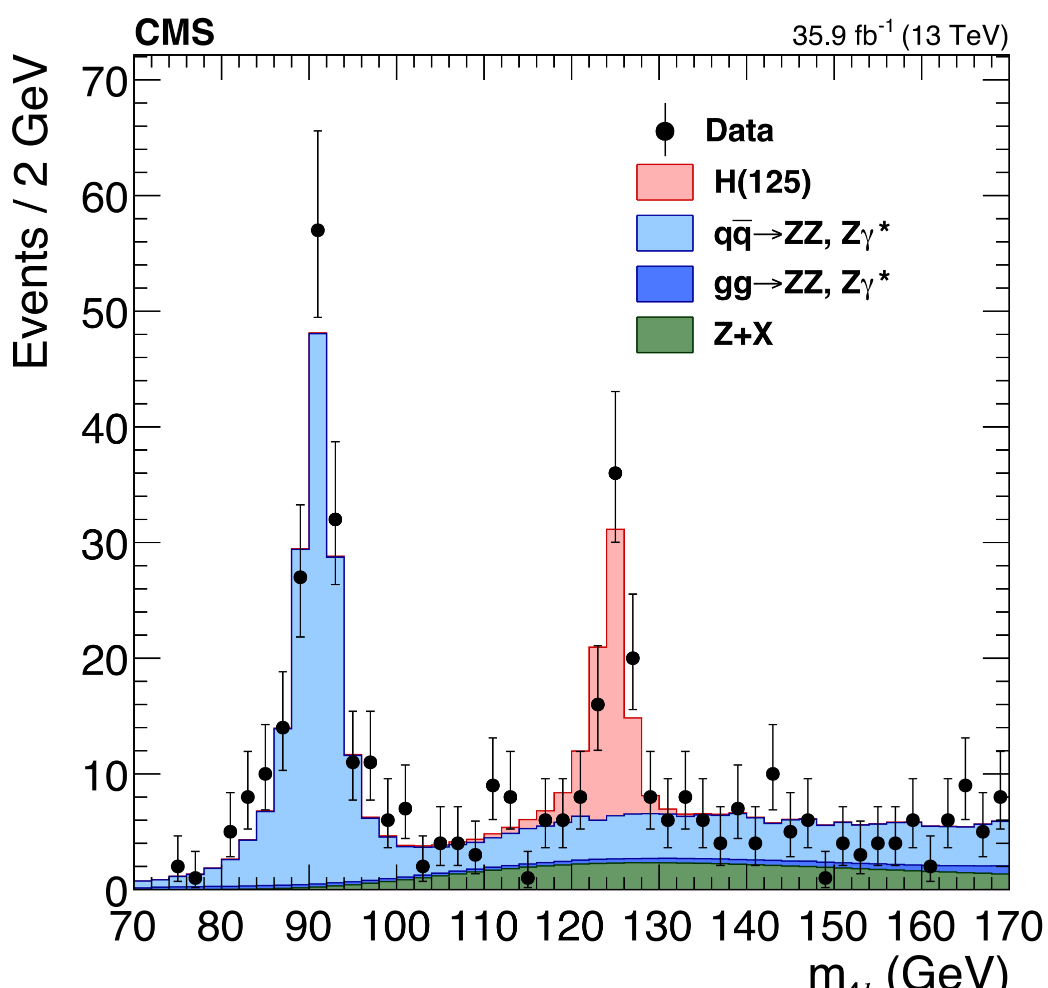
The Higgs boson mass

Latest CMS result on the Higgs boson mass, in the **$H\to ZZ^*\to 4\ell$** channel, uses **2016 data**, (36/fb).

Final results have been extracted using a **3D likelihood**:

- four lepton mass
- kinematic discriminant
- event-by-event mass uncertainty

$$\mathcal{D}^{\text{kin}}_{\text{bkg}} = \left[1 + \frac{\mathcal{P}^{q\bar{q}}_{\text{bkg}}(\vec{\Omega}^{H\to 4\ell}|m_{4\ell})}{\mathcal{P}^{gg}_{\text{sig}}(\vec{\Omega}^{H\to 4\ell}|m_{4\ell})}\right]^{-1}$$

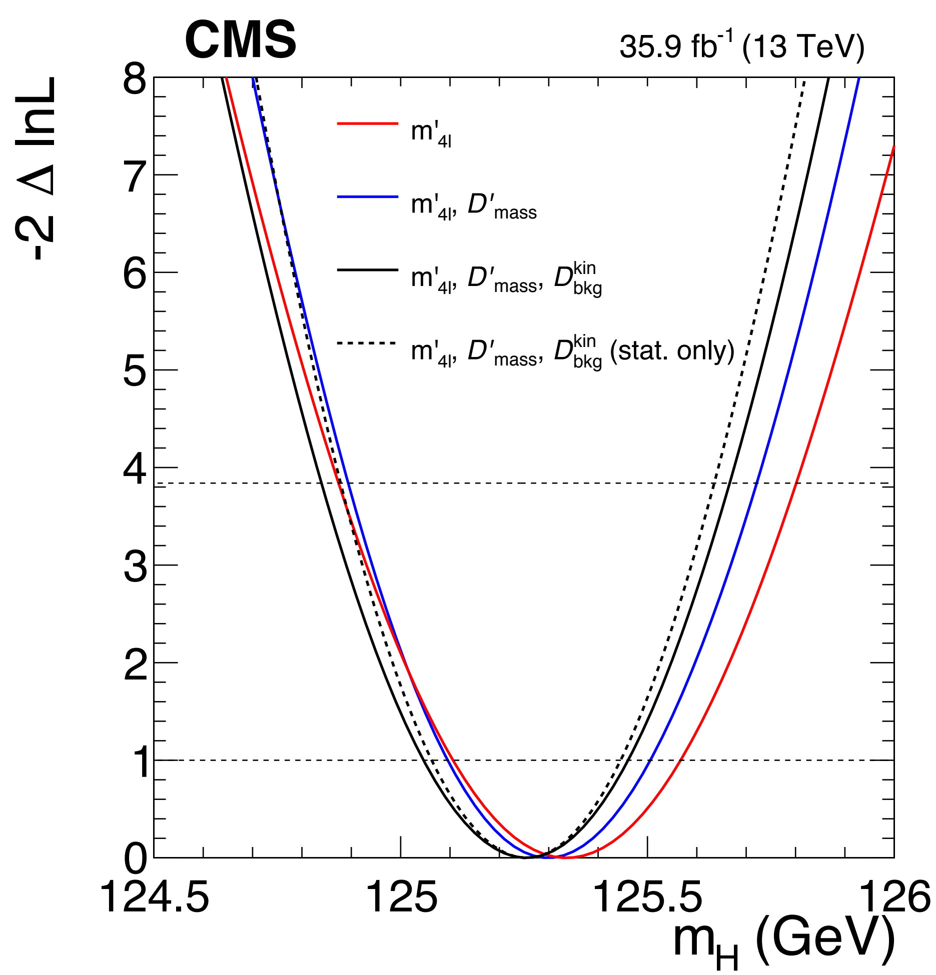


- **Signal line shape**: double-sided Crystal Ball
- **ZZ^* backgrounds**: estimated from MC simulation
- **Z+X**: estimated from data

The Higgs boson mass

Latest CMS result on the Higgs boson mass, in the **H→ZZ*→4ℓ** channel, uses **2016 data**, (36/fb).

No $m(Z_1)$ constraint	3D: $\mathcal{L}(m_{4\ell}, \mathcal{D}_{\text{mass}}, \mathcal{D}^{\text{kin}}_{\text{bkg}})$	2D: $\mathcal{L}(m_{4\ell}, \mathcal{D}_{\text{mass}})$	1D: $\mathcal{L}(m_{4\ell})$
Expected m_H uncertainty change	+8.1%	+11%	+21%
Observed m_H (GeV)	125.28±0.22	125.36±0.24	125.39±0.25
With $m(Z_1)$ constraint	3D: $\mathcal{L}(m'_{4\ell}, \mathcal{D}'_{\text{mass}}, \mathcal{D}^{\text{kin}}_{\text{bkg}})$	2D: $\mathcal{L}(m'_{4\ell}, \mathcal{D}'_{\text{mass}})$	1D: $\mathcal{L}(m'_{4\ell})$
Expected m_H uncertainty change	—	+3.2%	+11%
Observed m_H (GeV)	125.26±0.21	125.30±0.21	125.34±0.23



A **mass constraint** on the intermediate on-shell Z resonance has been exploited in order to **improve m₄ℓ resolution**

$$m_H = 125.26 \pm 0.21\ [0.20(stat) \pm 0.08(syst)]\ GeV$$

Higgs signal strength modifier

Signal strength modifier (μ) is defined as the ratio between the measured signal cross section and the SM expectation.

$$\mu = \mu_\sigma \mu^{BR} = \frac{\sigma}{\sigma_{SM}} \frac{BR}{BR^{SM}}$$

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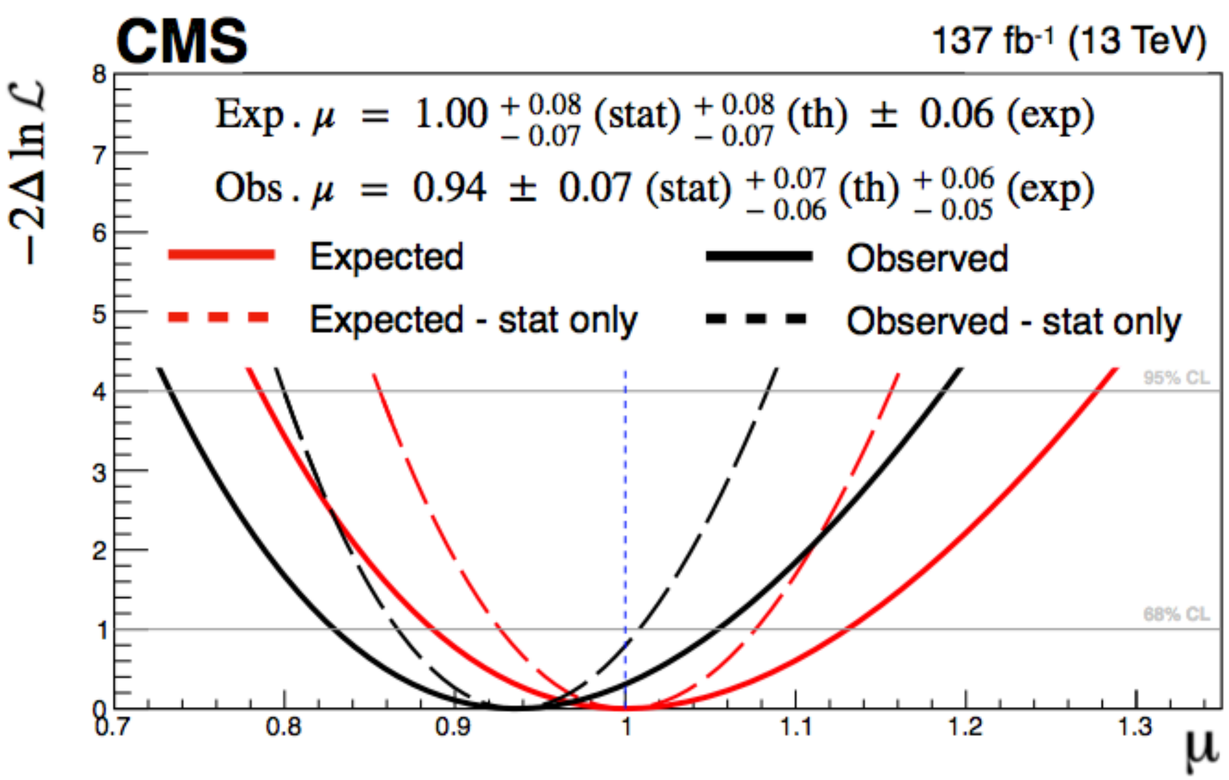
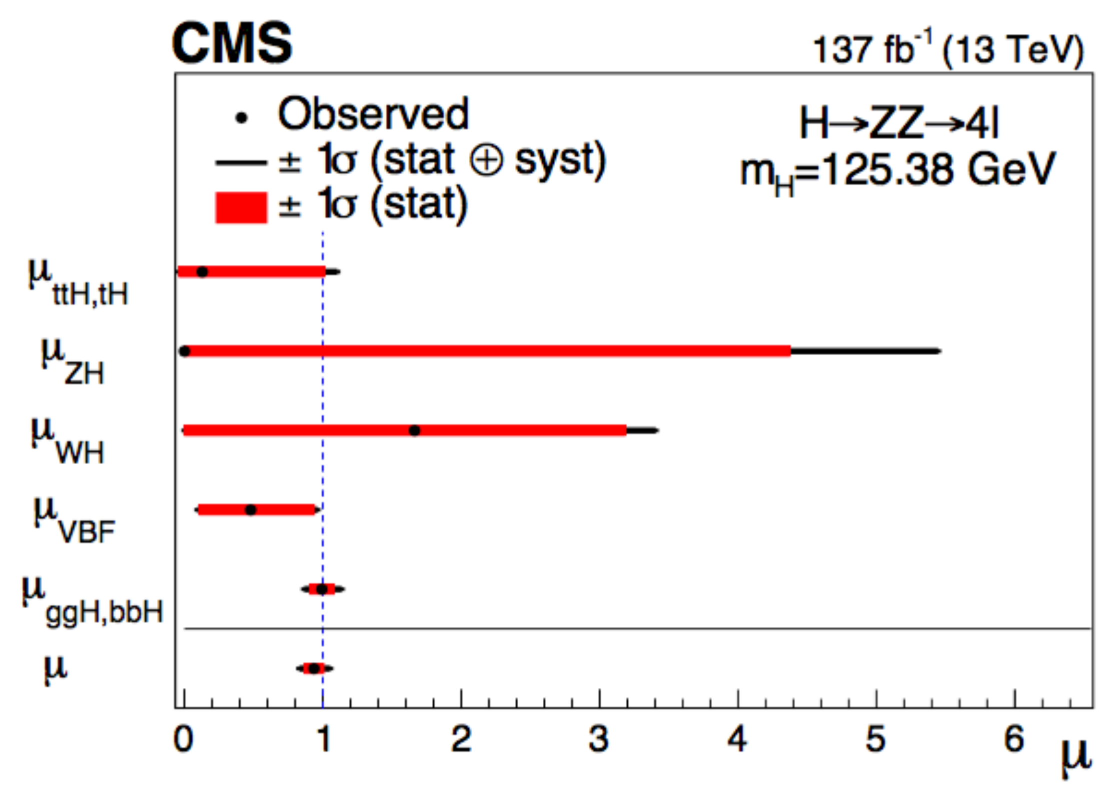




$$\mu_{HZZ} = 0.94 \pm 0.07\ (stat)\ ^{+0.07}_{-0.06}\ (theo)\ ^{+0.06}_{-0.05}\ (exp)$$

Simplified template cross sections

The simplified template cross section (STXS) tries to maximise the sensitivity of the measurement, minimising the dependence on the theory predictions, defining several kinematic regions using generator level information.

Different stages have been defined:
Stage 0: regions are equivalent to the different production modes

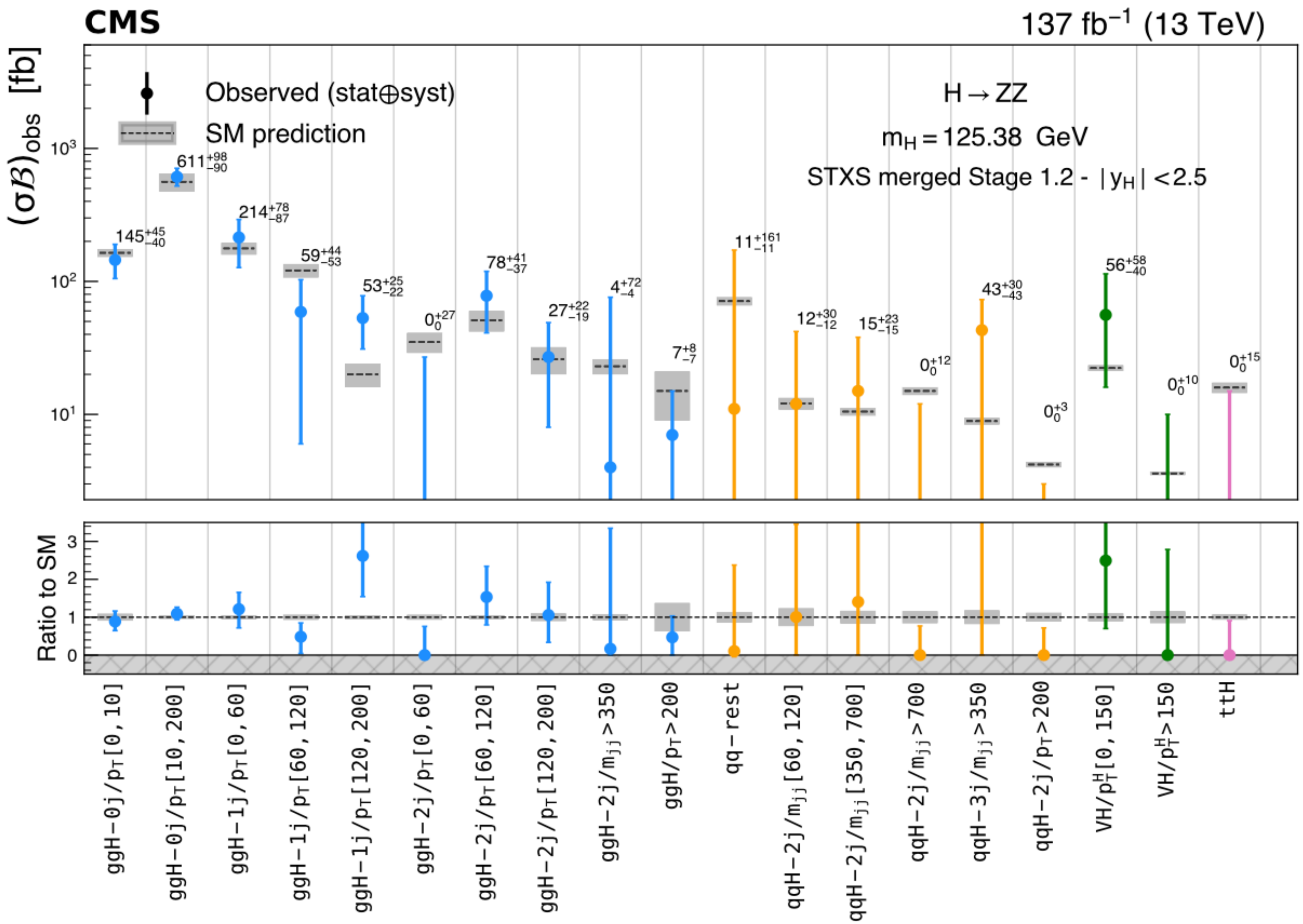
Stage 1

Stage 1.1

	$(\sigma\mathcal{B})_{\text{obs}}$ (fb)	$(\sigma\mathcal{B})_{\text{SM}}$ (fb)	$(\sigma\mathcal{B})_{\text{obs}}/(\sigma\mathcal{B})_{\text{SM}}$
ttH	3^{+16}_{-3}	15.9 ± 1.4	$0.16^{+0.98}_{-0.16}$
VH-lep	41^{+52}_{-35}	25.9 ± 0.8	$1.56^{+1.99}_{-1.34}$
qqH	61^{+53}_{-44}	122 ± 6	$0.50^{+0.44}_{-0.36}$
ggH	1214^{+135}_{-125}	1192 ± 95	$1.02^{+0.11}_{-0.10}$
Inclusive	1318^{+130}_{-122}	1369 ± 164	$0.96^{+0.10}_{-0.09}$

Stage 1.2: other regions at high p_T or high mass have been introduced to study BSM physics.

Simplified template cross sections



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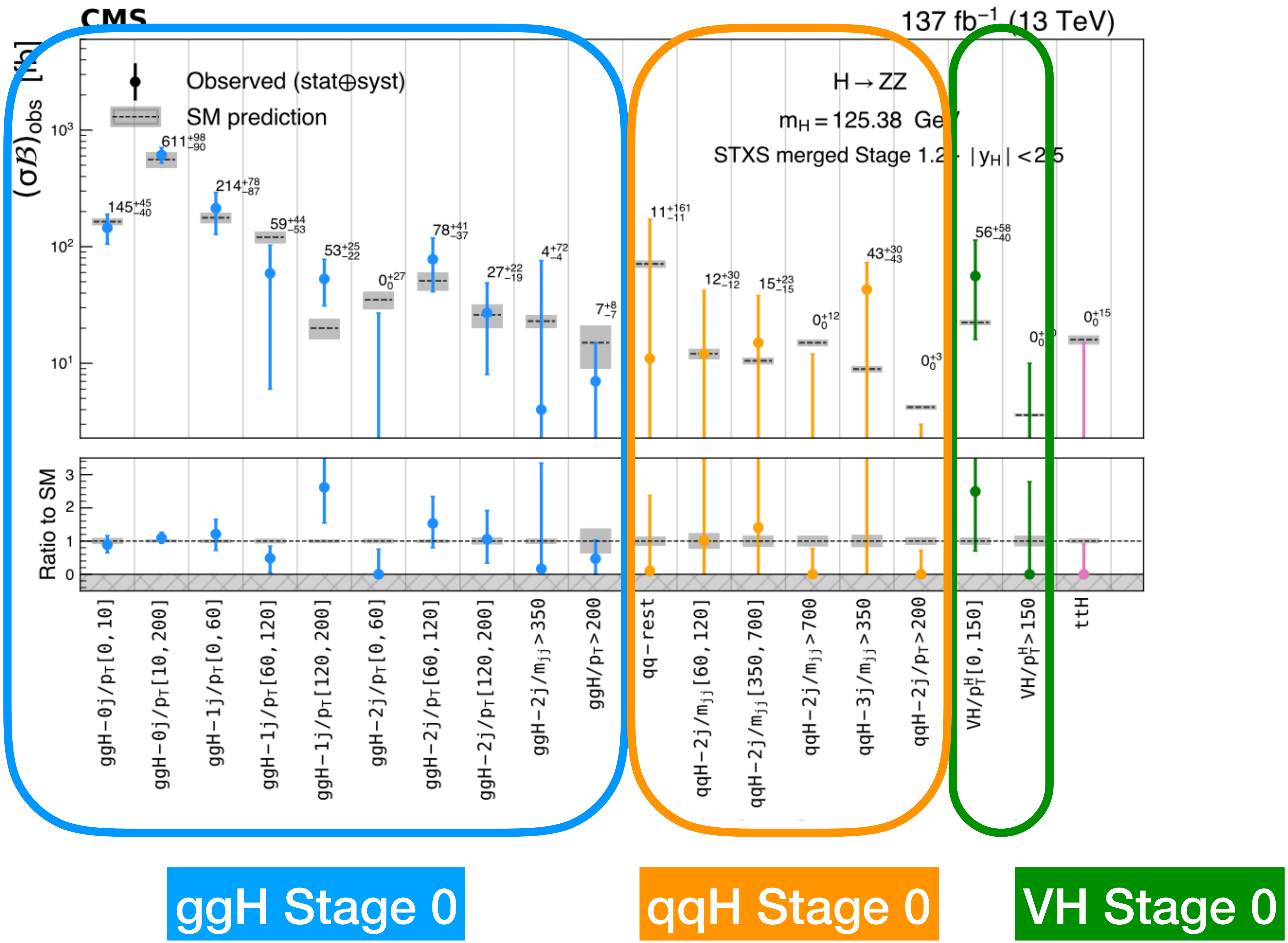


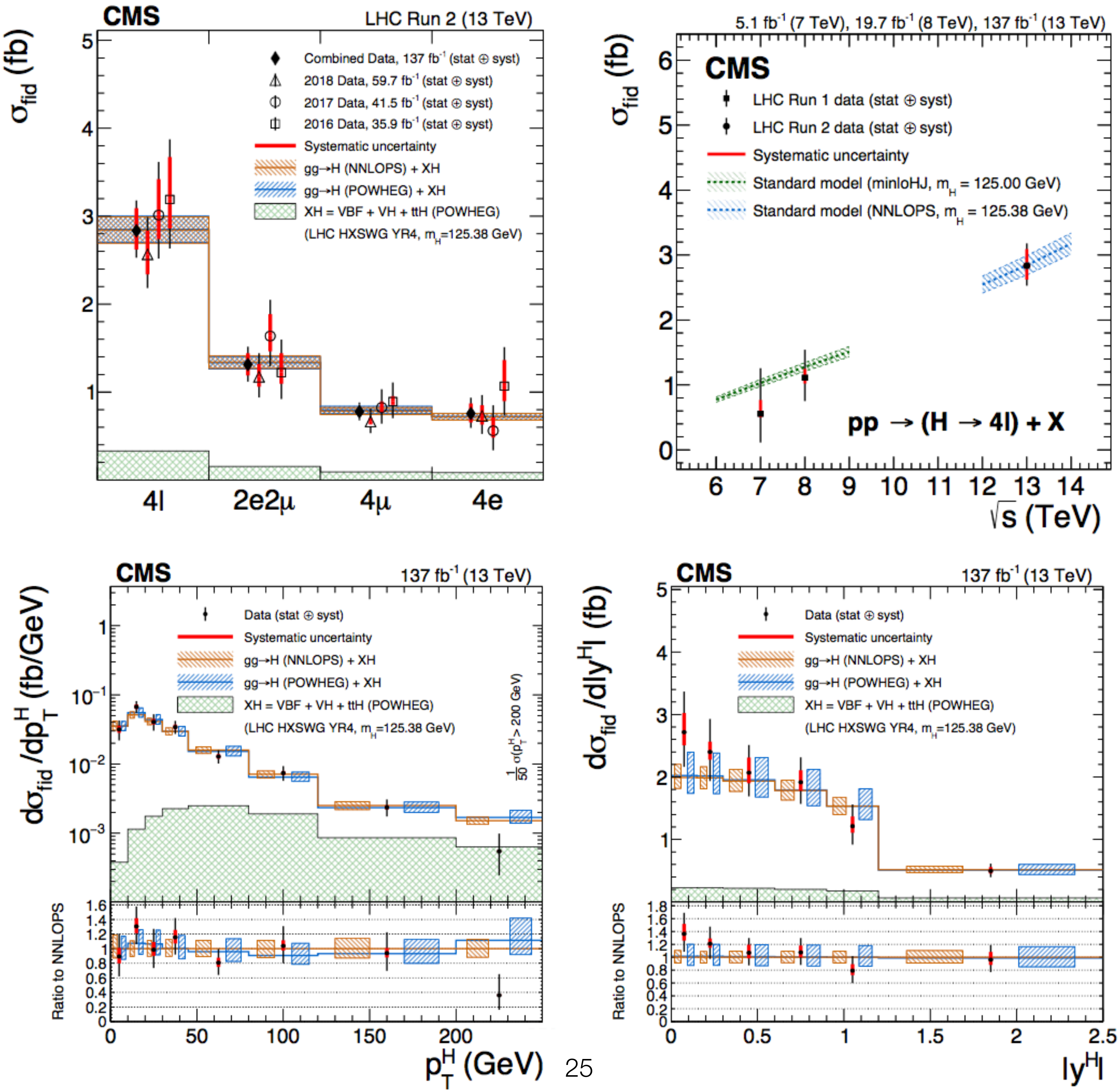
Fiducial cross sections

- Cross section defined in a **fiducial phase space**.
- Volume defined by a set of **selection criteria at generator level** based on kinematic, geometrical variables and on the topology of the event.
- The idea is to **minimise the dependence on theoretical uncertainties**.

HZZ fiducial volume

unique definition independent from the observable under study.
Based on lepton kinematic cuts and isolation requirements with some restrictions on the dilepton and four-lepton system.

Fiducial cross sections

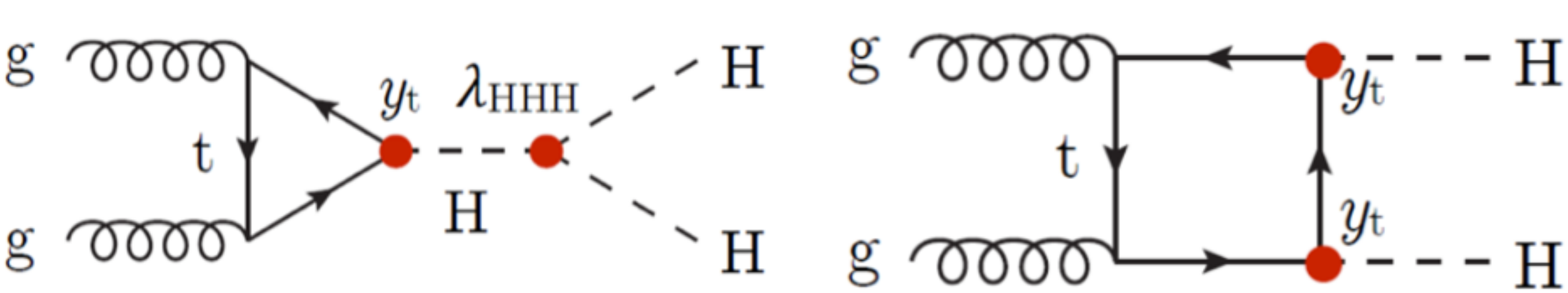


Higgs self coupling

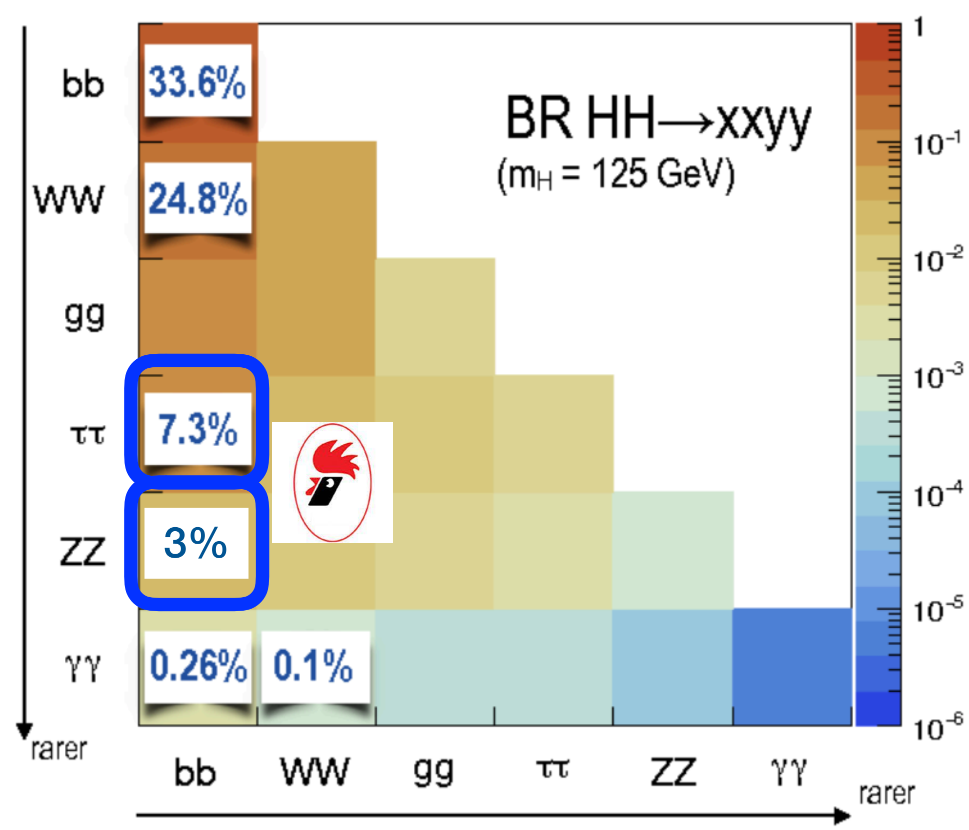
The Higgs boson self coupling (known as λ_{HHH}; k_λ if compared to its SM value) is strictly connected to its mass.

One of the easiest way to measure this parameter is to look for di-Higgs production

di-Higgs (gluon-gluon) production has a XS of ~30 fb, 1000 times small than Higgs gluon-gluon fusion.



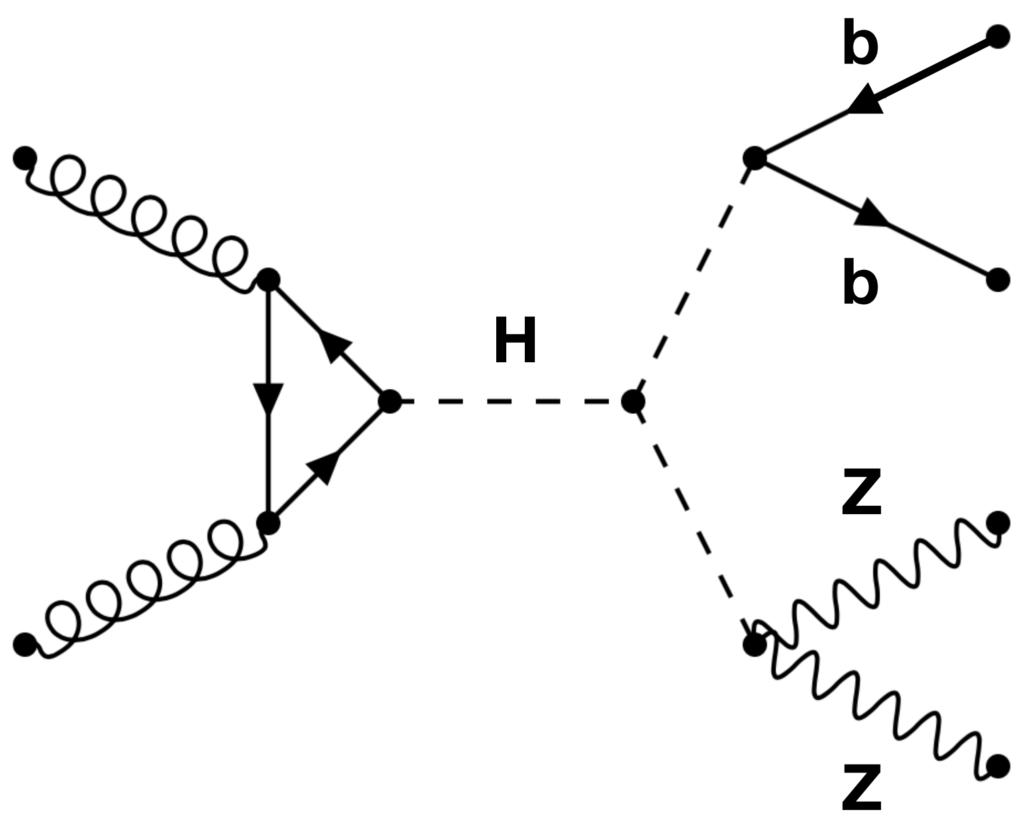
$$\sigma(k_t, k_\lambda) \approx k_t^4 |B|^2 + k_t^3 k_\lambda (BT + TB) + k_t^2 k_\lambda^2 |T|^2$$

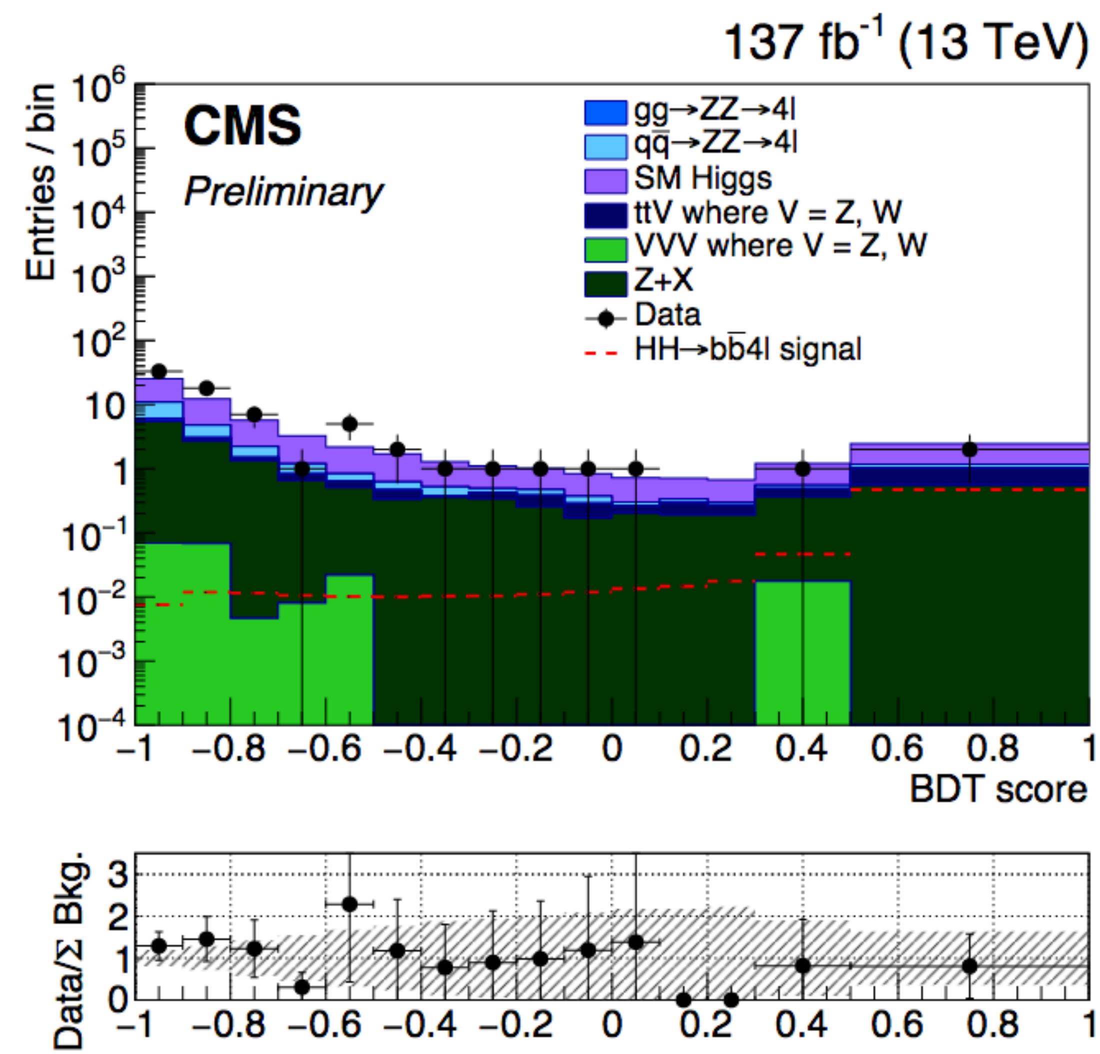


Higgs self coupling

Bari studied k_λ in the bbZZ final state.

Profit of the multivariate analysis (BDT) to extract final results.





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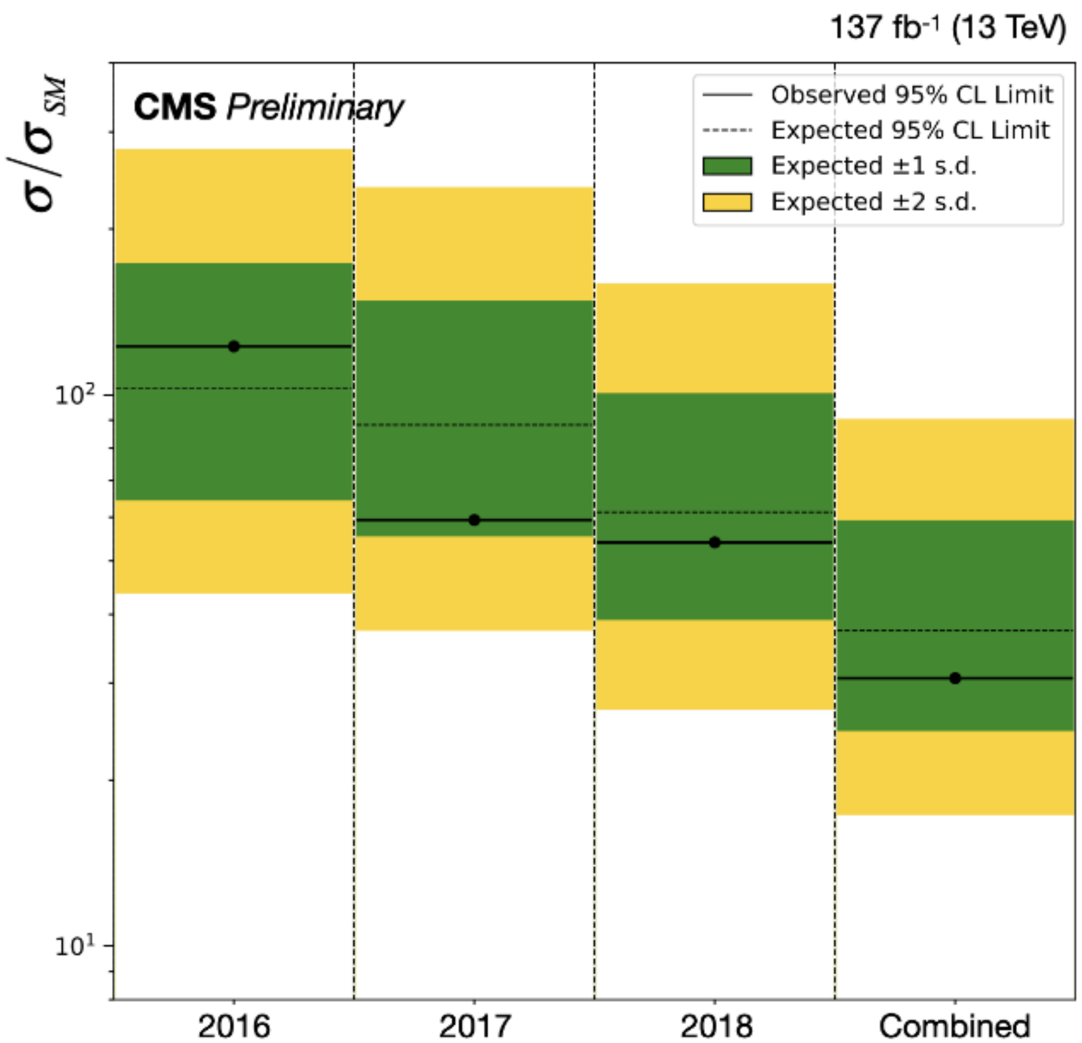
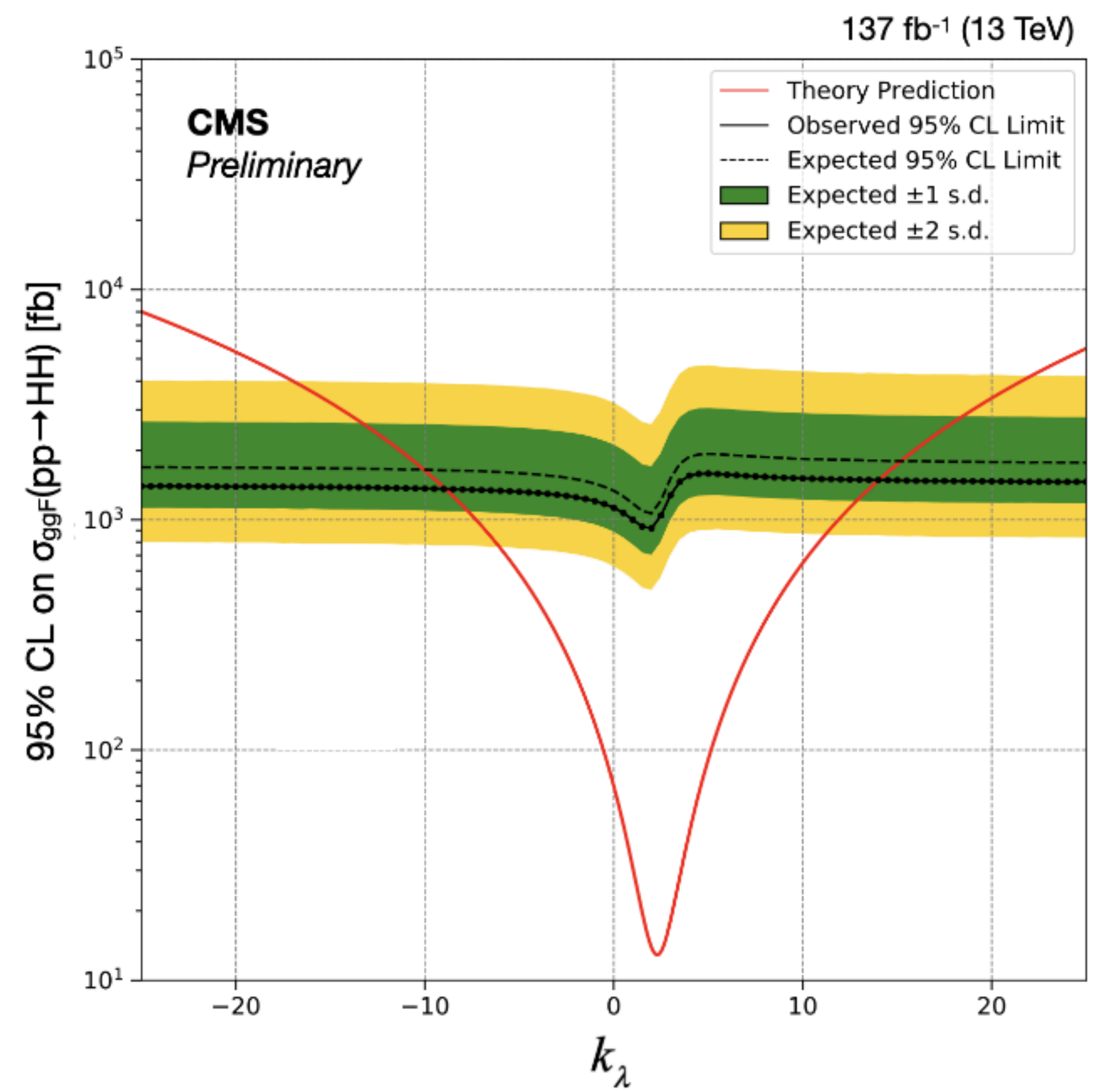


$\sigma/\sigma_{SM} < 30$

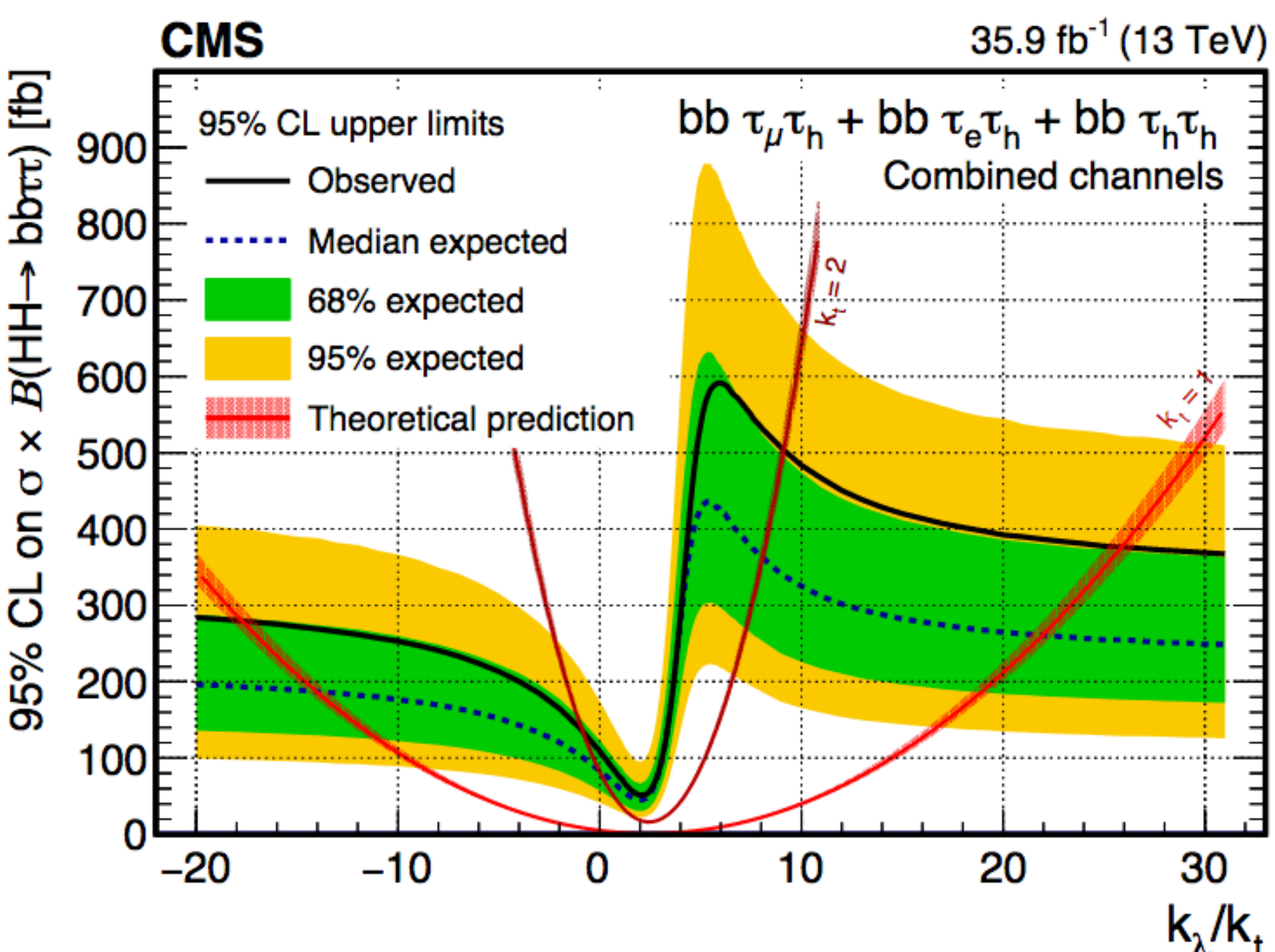


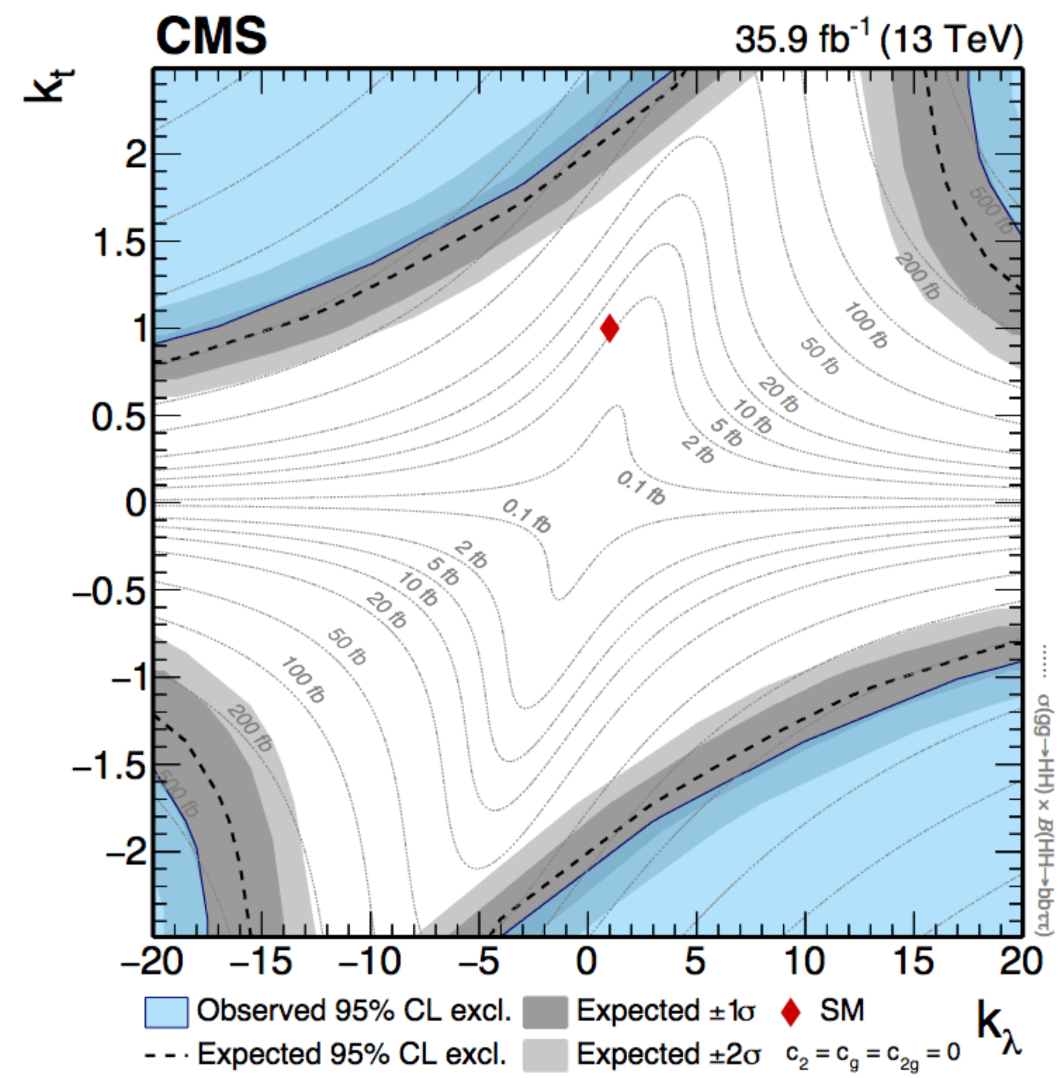
$-9 < k_\lambda < 14$

Best results in this channel!

Higgs self coupling

Bari contributed to the k_λ and HH XS measurements also looking at the $bb\tau\tau$ final states



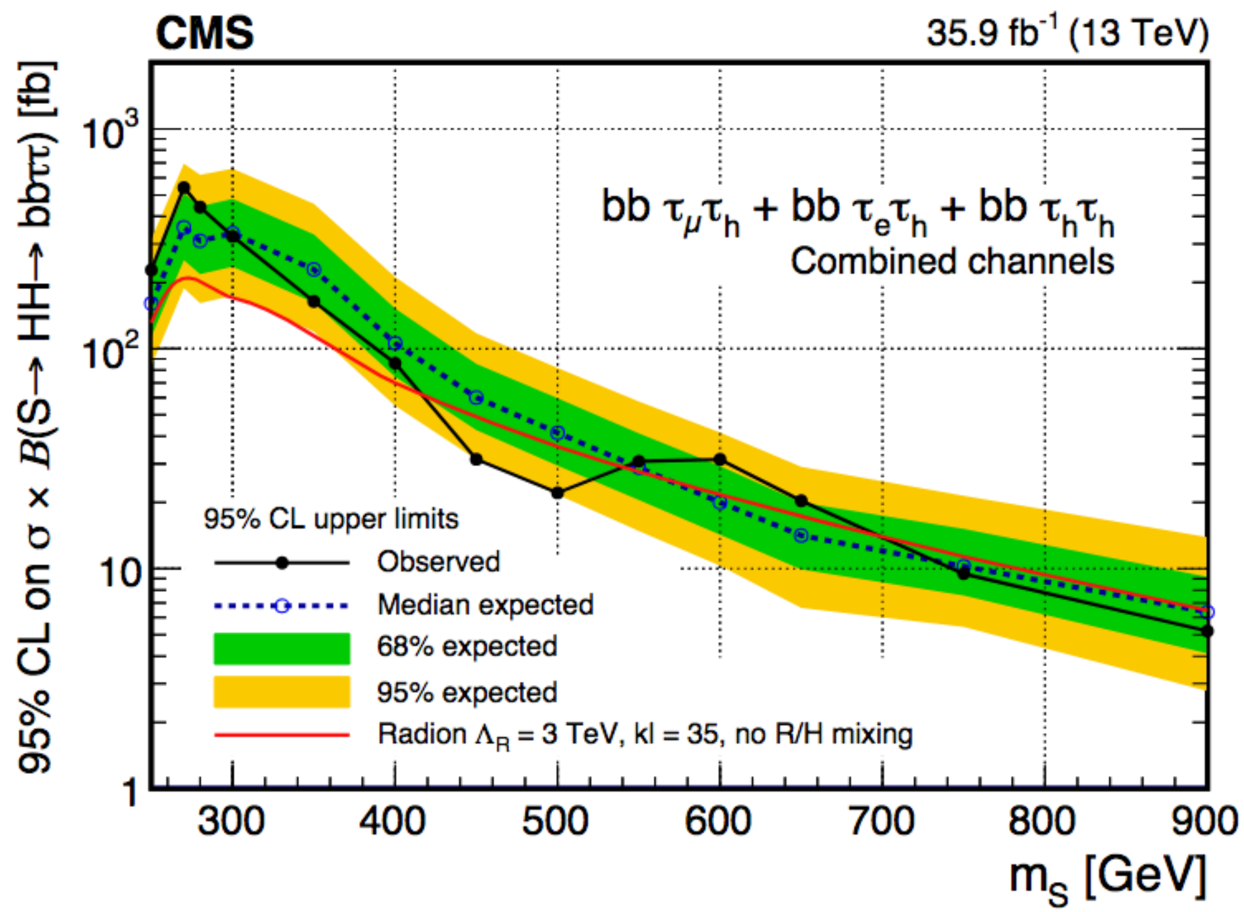


$$\sigma < 75.4(61)\ fb$$

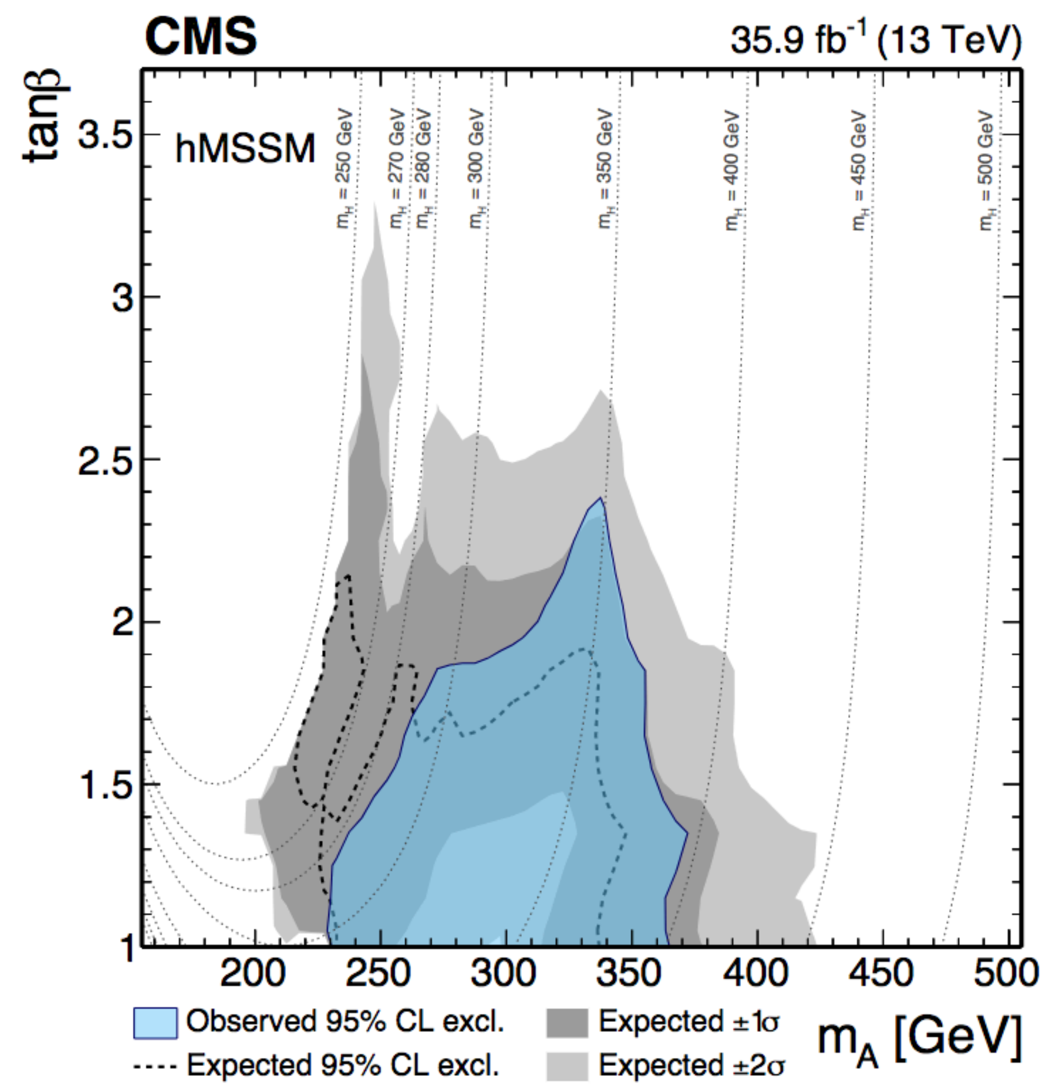
$$\sigma/\sigma_{SM} < 30(25)$$

Higgs resonant production

Resonant double Higgs boson production has been also investigated still using HH→bbττ channel



WED model



hMSSM model

“What next?”

Beyond HL-LHC

Muon collider is one of the apparatus under studies at CERN to further investigate the unknown question that LHC is not able to tackle

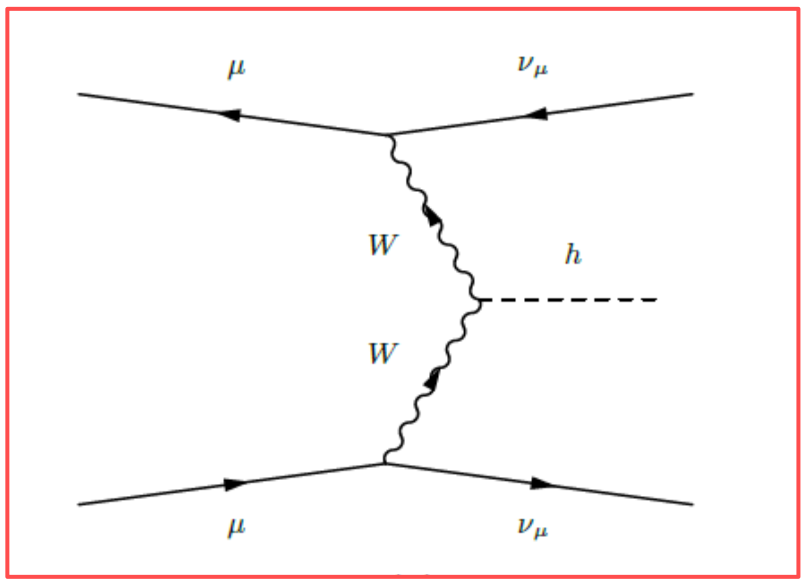
It could reach very high precision in the Higgs sector:

%	HL-LHC	CLIC (3 TeV)	FCC-ee (365 GeV)	MuonCollider (10 TeV)
k_W	1.7	0.11	0.43	**0.06**
k_Z	1.5	0.23	0.17	**0.23**
k_t	3.3	2.7	-	**6.0**
k_μ	4.6	5.8	8.9	**2.0**
k_c	-	1.4	1.3	**0.89**

Bari group is contributing not only to the **FCC project**, but also to the **MuonCollider**

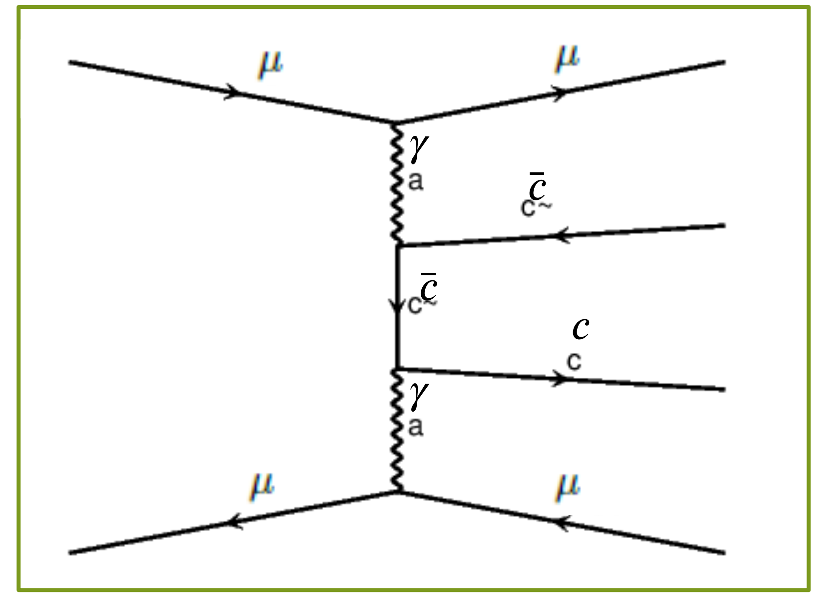
H→cc

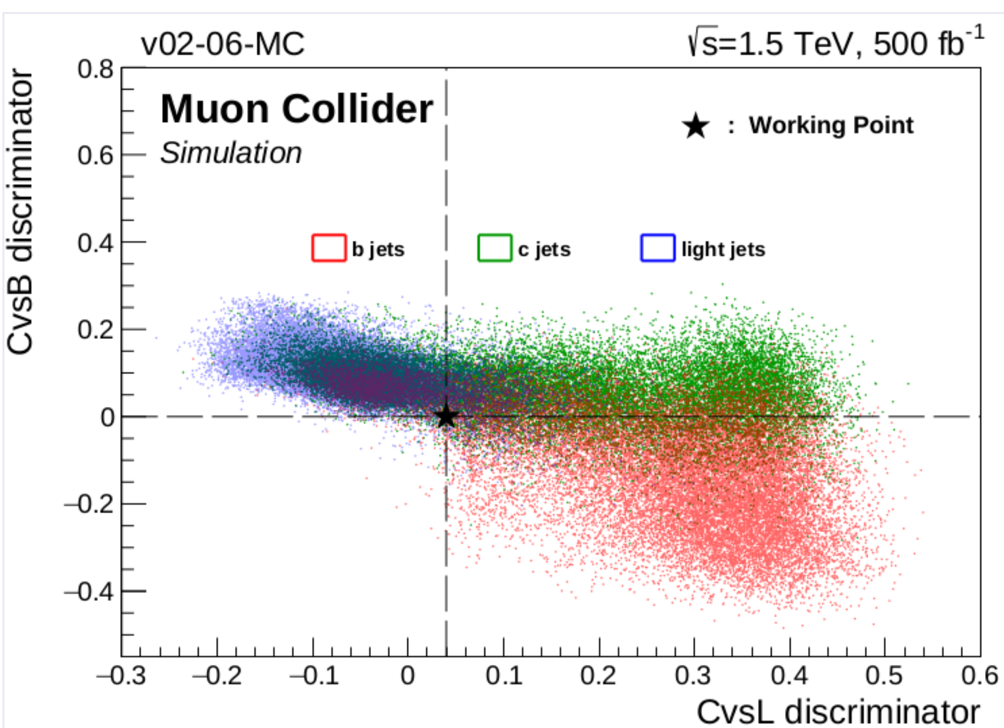
Signal process: H boson produced via **WW fusion** and **decaying into a pair of c quark**

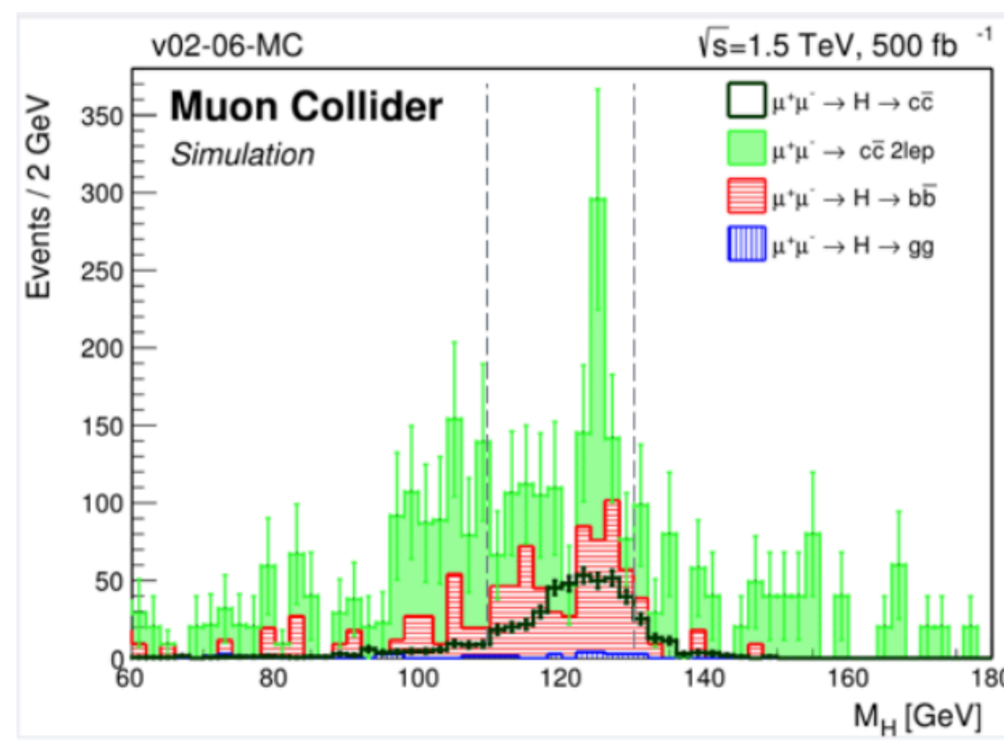


Background process:

- cc + 2 leptons (charged or not)
- bb + 2 leptons (charged or not)

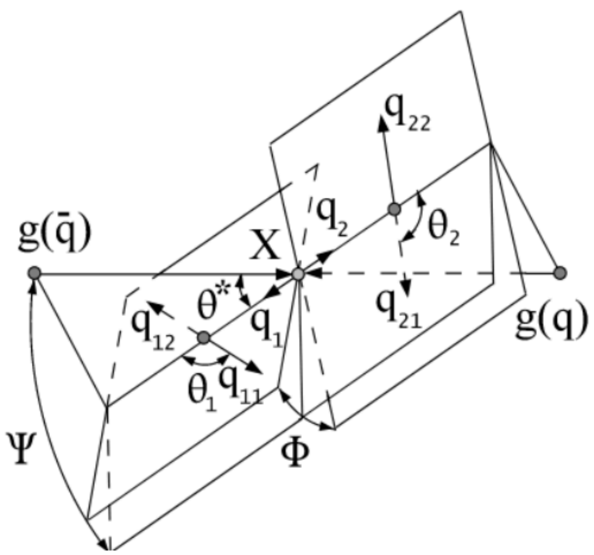






H→ZZ*→4μ

Angular variables sensitive to **spin** and **parity** of a **resonance**:



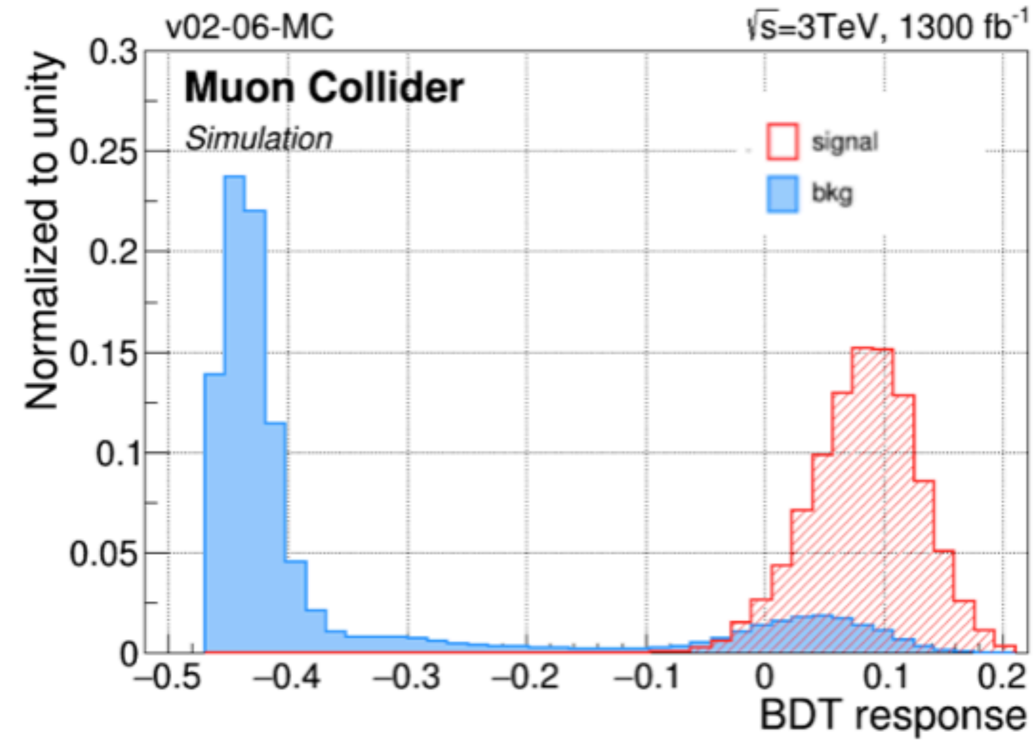
$$X \to V_1V_2 \to f_{11}f_{12}f_{21}f_{22}$$

q_i: V_i momentum in X rest frame

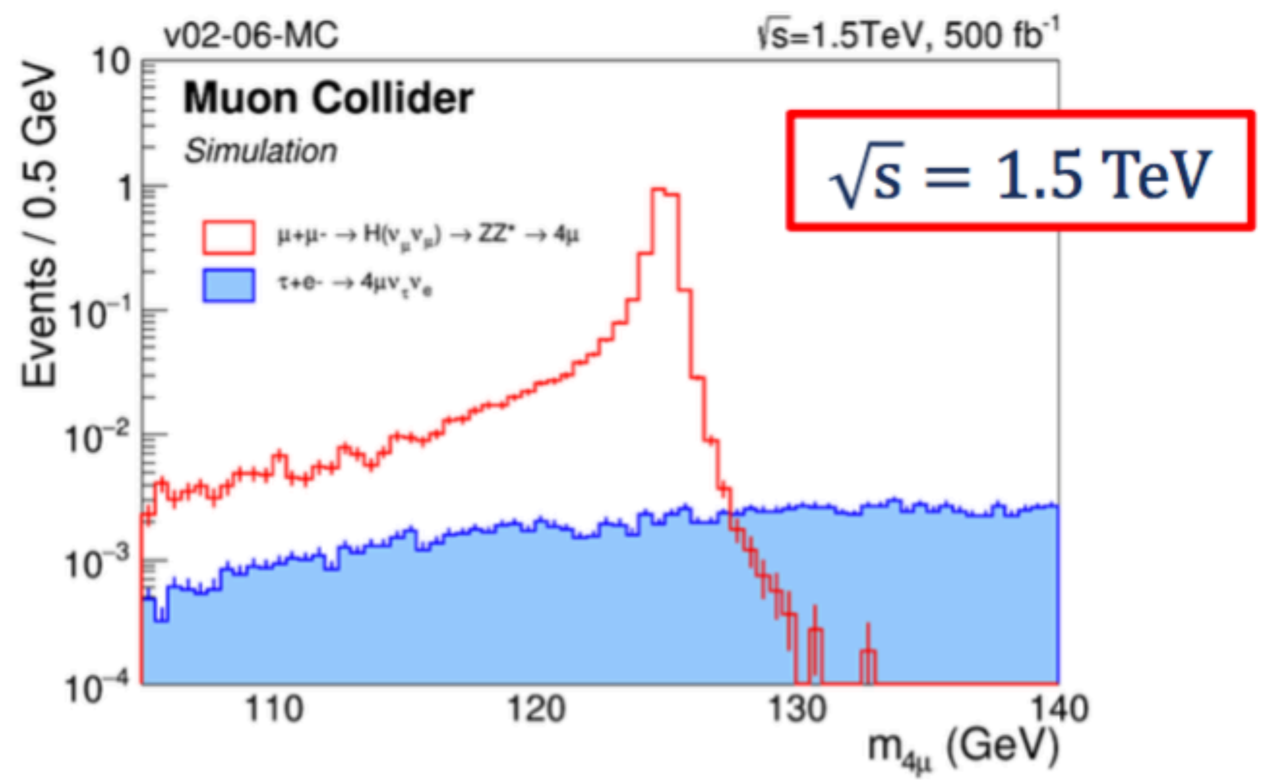
q_{ij}: f_{ij} momentum in V_i rest frame

Angles defined by:

- The directions of V_i in X rest frame;
- the directions of fermions in their parent boson rest frame.



- All these results have been extracted using simulated only events
- No impact from BIB has been taken into account



Summary

A brief summary on the precision measurement in the Higgs boson sector has been shown.

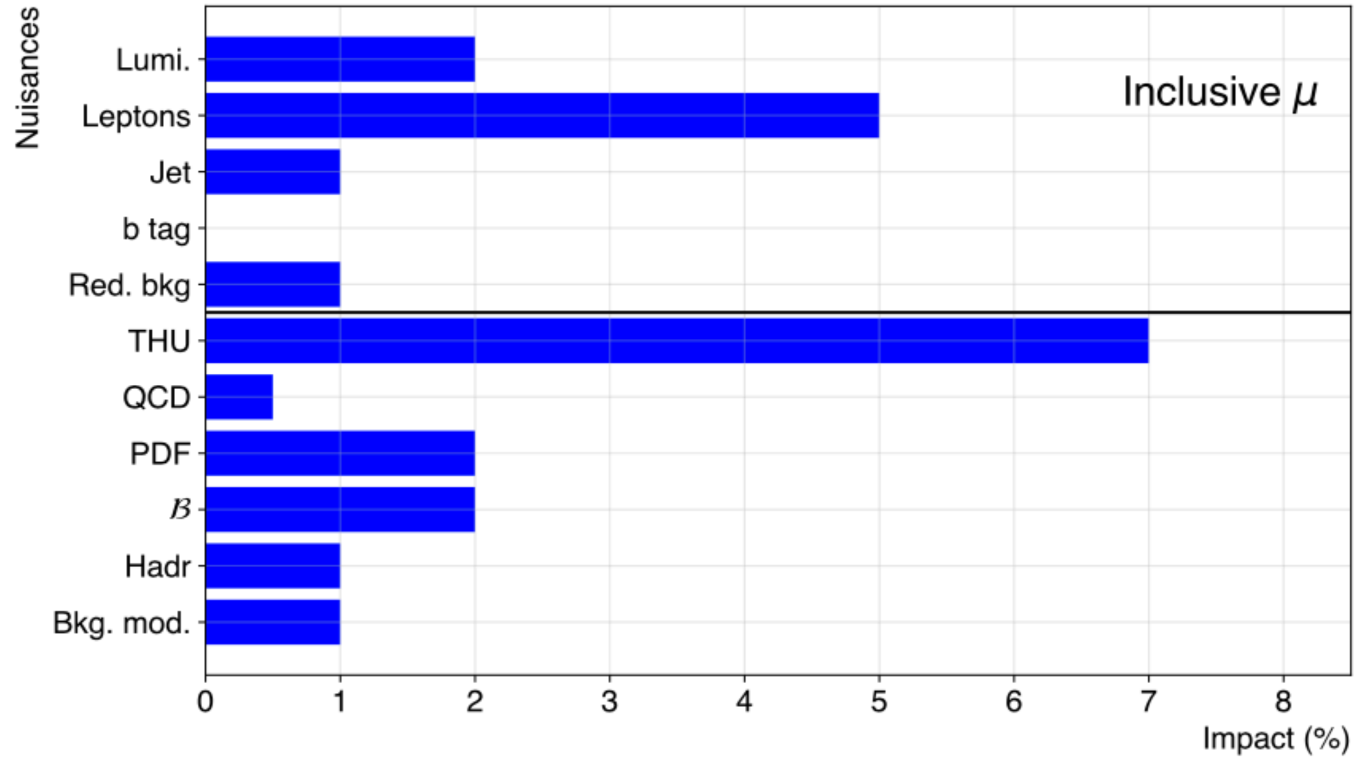
Bari group gave its contribution in the CMS experiment:

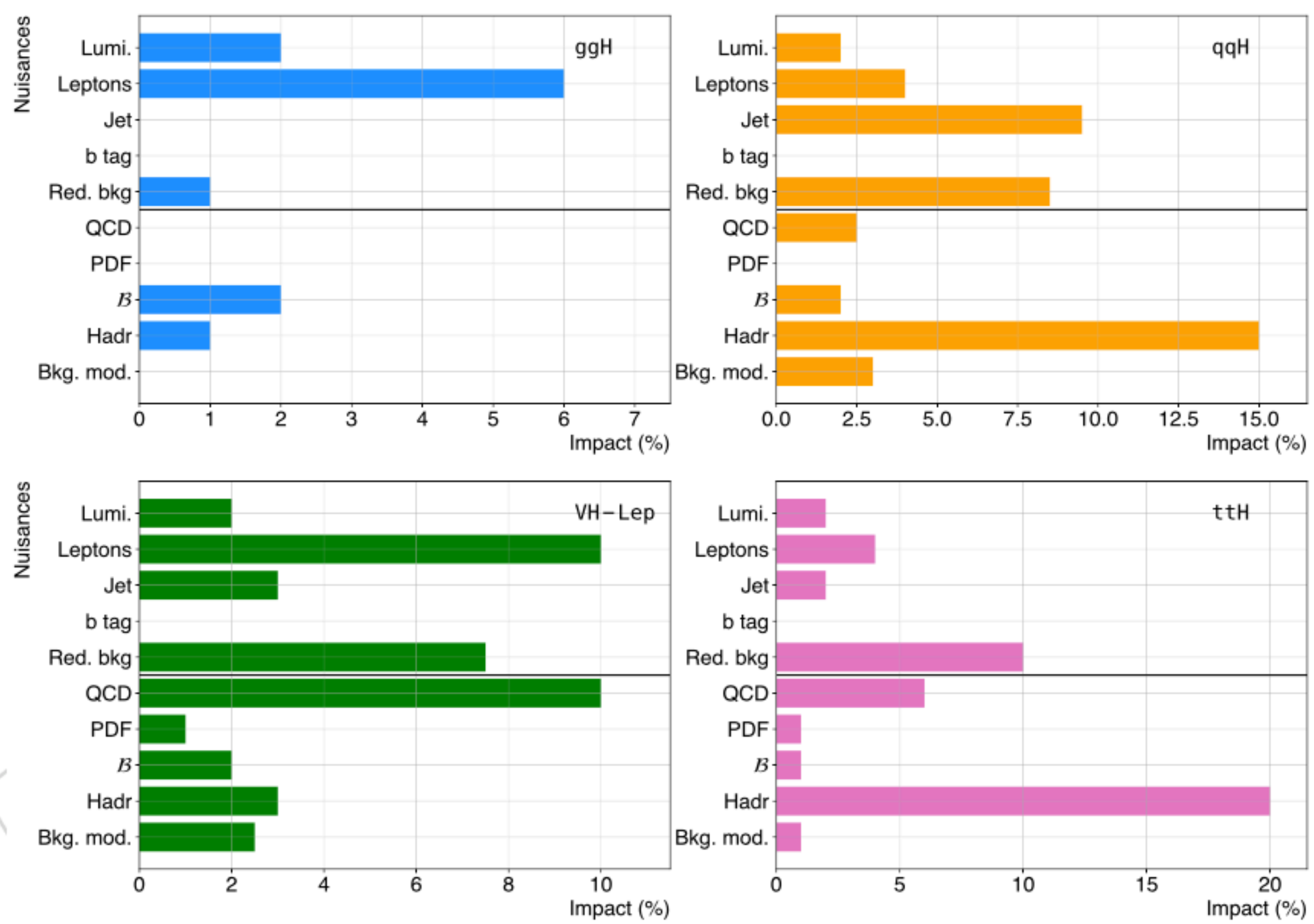
- looking at the golden channel H→ZZ to 4 leptons:
  - ✦ best result (in the world) for the **mass**
  - ✦ very precise **cross section** measurement, either within STXS framework either using fiducial volume
- exploit di-Higgs sector (looking at bbZZ and bbττ channels):
  - ✤ setting limits on the **cross section** and on the trilinear coupling k_λ
  - ✤ looking for new resonances predicted in many models BSM

Bari is also giving its contribution to the MuonCollider and to the FCC projects.

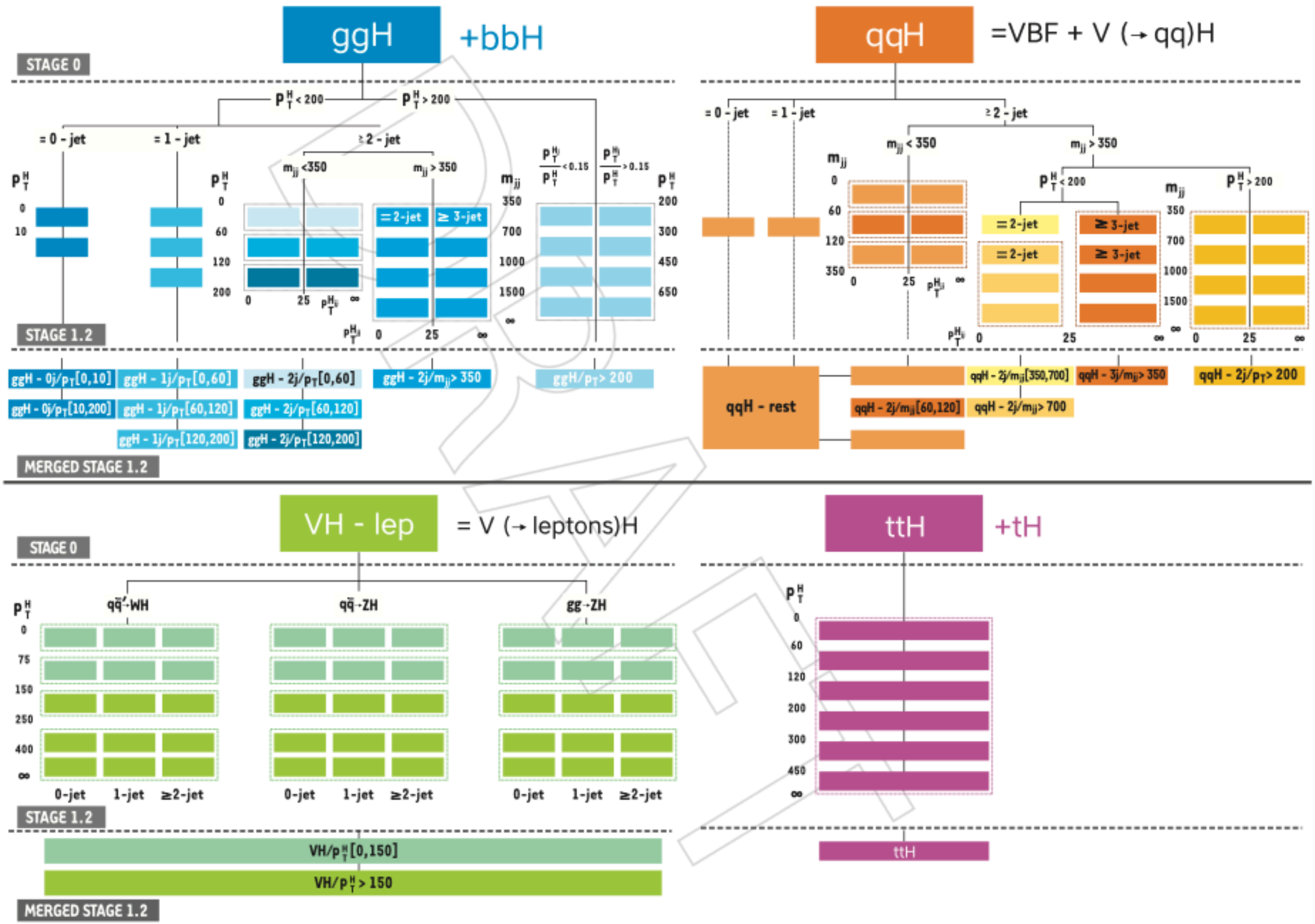
Backup

Systematics





STXS



ggH
+bbH
qqH
=VBF + V (→ qq)H
STAGE 0
p_T^H < 200
p_T^H > 200
= 0 - jet
= 1 - jet
≥ 2 - jet
m_{jj} <350
m_{jj} > 350
= 2-jet
≥ 3-jet
STAGE 1.2
ggH - 0j/p_T[0,10]
ggH - 0j/p_T[10,200]
ggH - 1j/p_T[0,60]
ggH - 1j/p_T[60,120]
ggH - 1j/p_T[120,200]
ggH - 2j/p_T[0,60]
ggH - 2j/p_T[60,120]
ggH - 2j/p_T[120,200]
ggH - 2j/m_{jj}> 350
ggH/p_T> 200
MERGED STAGE 1.2
qqH - rest
qqH - 2j/m_{jj}[60,120]
qqH - 2j/m_{jj}[350,700]
qqH - 2j/m_{jj}> 700
qqH - 3j/m_{jj}> 350
qqH - 2j/p_T> 200
VH - lep
= V (→ leptons)H
ttH
+tH
$q\bar{q}'$→WH
$q\bar{q}$→ZH
gg→ZH
0-jet
1-jet
≥2-jet
VH/p_T^H[0,150]
VH/p_T^H > 150
ttH

HZZ fiducial phase space

Requirements for the $H \to 4\ell$ fiducial phase space	
Lepton kinematics and isolation	
Leading lepton p_T	$p_T > 20$ GeV
Next-to-leading lepton p_T	$p_T > 10$ GeV
Additional electrons (muons) p_T	$p_T > 7$ (5) GeV
Pseudorapidity of electrons (muons)	$\lvert\eta\rvert < 2.5$ (2.4)
Sum of scalar p_T of all stable particles within $\Delta R < 0.3$ from lepton	$< 0.35 p_T$
Event topology	
Existence of at least two same-flavor OS lepton pairs, where leptons satisfy criteria above	
Inv. mass of the Z_1 candidate	$40 < m_{Z_1} < 120$ GeV
Inv. mass of the Z_2 candidate	$12 < m_{Z_2} < 120$ GeV
Distance between selected four leptons	$\Delta R(\ell_i, \ell_j) > 0.02$ for any $i \neq j$
Inv. mass of any opposite sign lepton pair	$m_{\ell^+\ell'^-} > 4$ GeV
Inv. mass of the selected four leptons	$105 < m_{4\ell} < 140$ GeV

Signal process	$\mathcal{A}_{fid}$	ϵ	f_{nonfid}	$(1 + f_{nonfid})\epsilon$
ggH (POWHEG)	0.402 ± 0.001	0.598 ± 0.002	0.054 ± 0.001	0.631 ± 0.002
VBF	0.445 ± 0.002	0.615 ± 0.002	0.043 ± 0.001	0.641 ± 0.003
WH	0.329 ± 0.002	0.604 ± 0.003	0.078 ± 0.002	0.651 ± 0.004
ZH	0.340 ± 0.003	0.613 ± 0.005	0.082 ± 0.004	0.663 ± 0.006
$t\bar{t}H$	0.315 ± 0.004	0.588 ± 0.007	0.181 ± 0.009	0.694 ± 0.010

H→γγ

The latest measurement of Higgs boson mass at CMS was done in the **H→γγ** decay channel, analysing **2016 data** (36/fb).

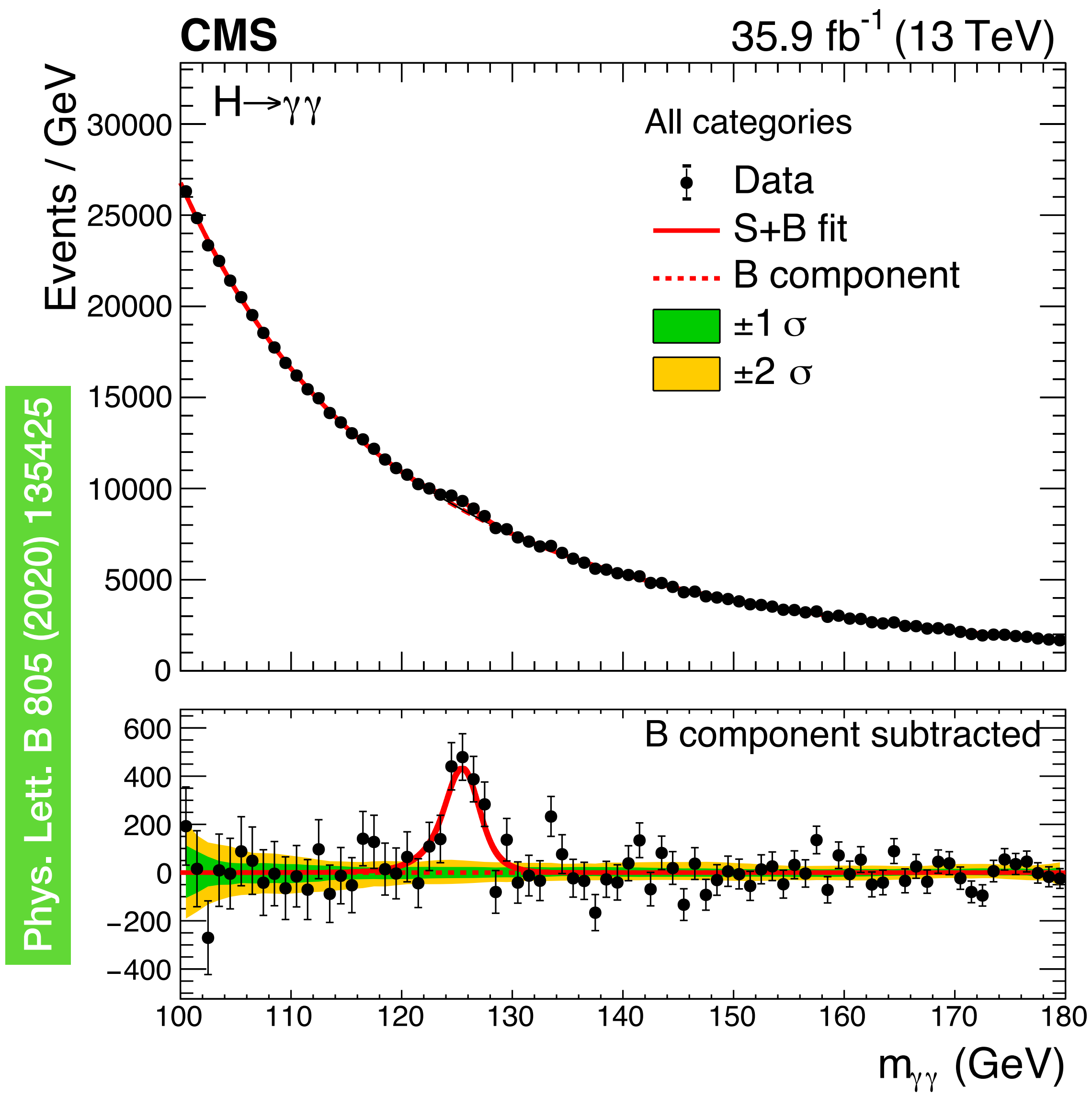
Critical component → energy calibration of the response of the detector to photons. Correction are derived using a multivariate regression technique

Dedicated method developed → deals with residual differences between data and MC, after applying corrections

Events classification → according to their production mode, mass resolution and their predicted signal-to-background ratio; S/(S+B) value is obtained using a multivariate discriminant (BDT).

H→γγ

The latest measurement of Higgs boson mass at CMS was done in the **H→γγ** decay channel, analysing **2016 data** (36/fb).



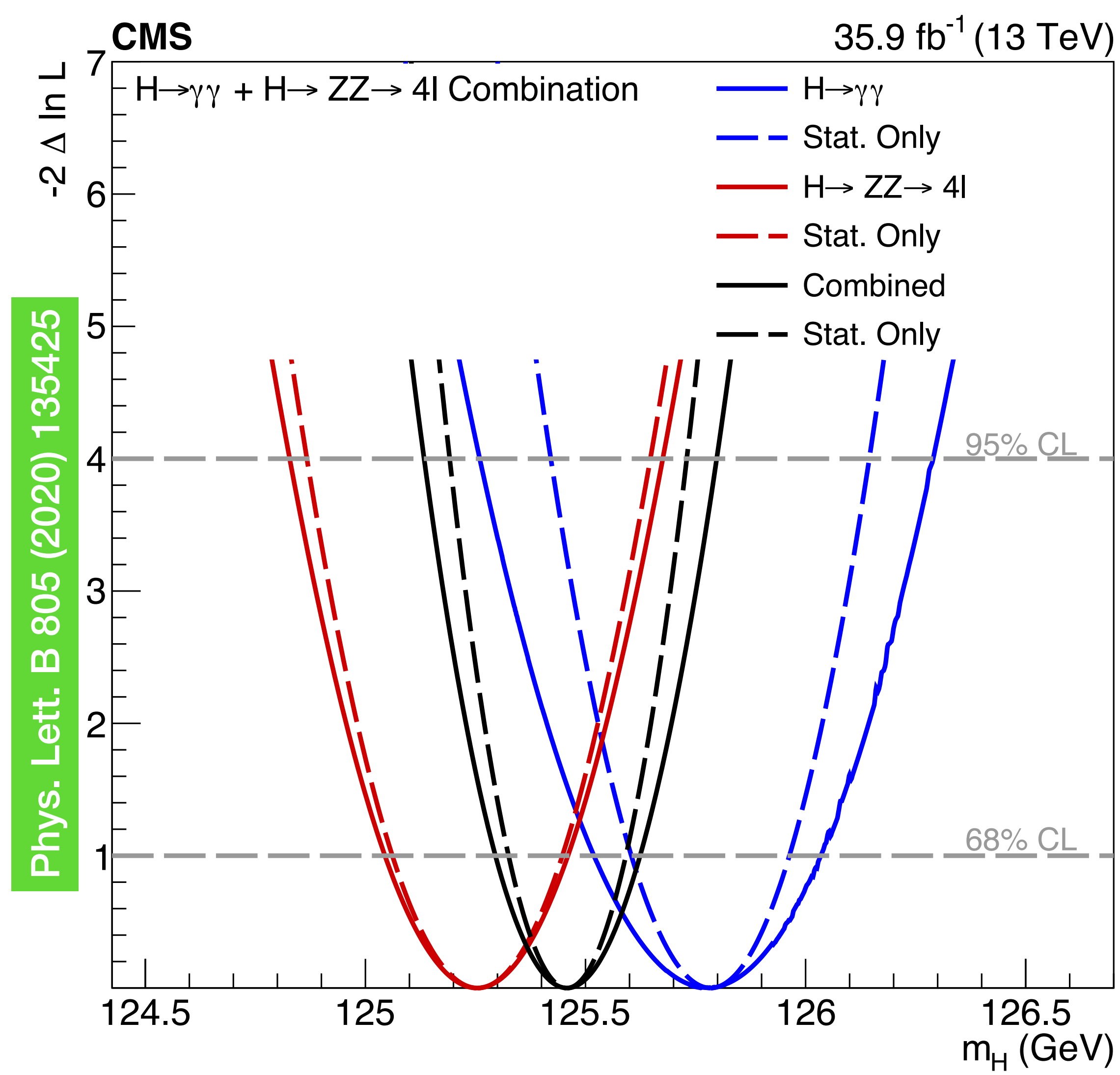
- **Signal line shape**: sum of Gaussian functions
- **Background model**: obtained from data using the discrete profiling method (function families considered include exponential functions, Bernstein polynomials, Laurent series, and power law functions)

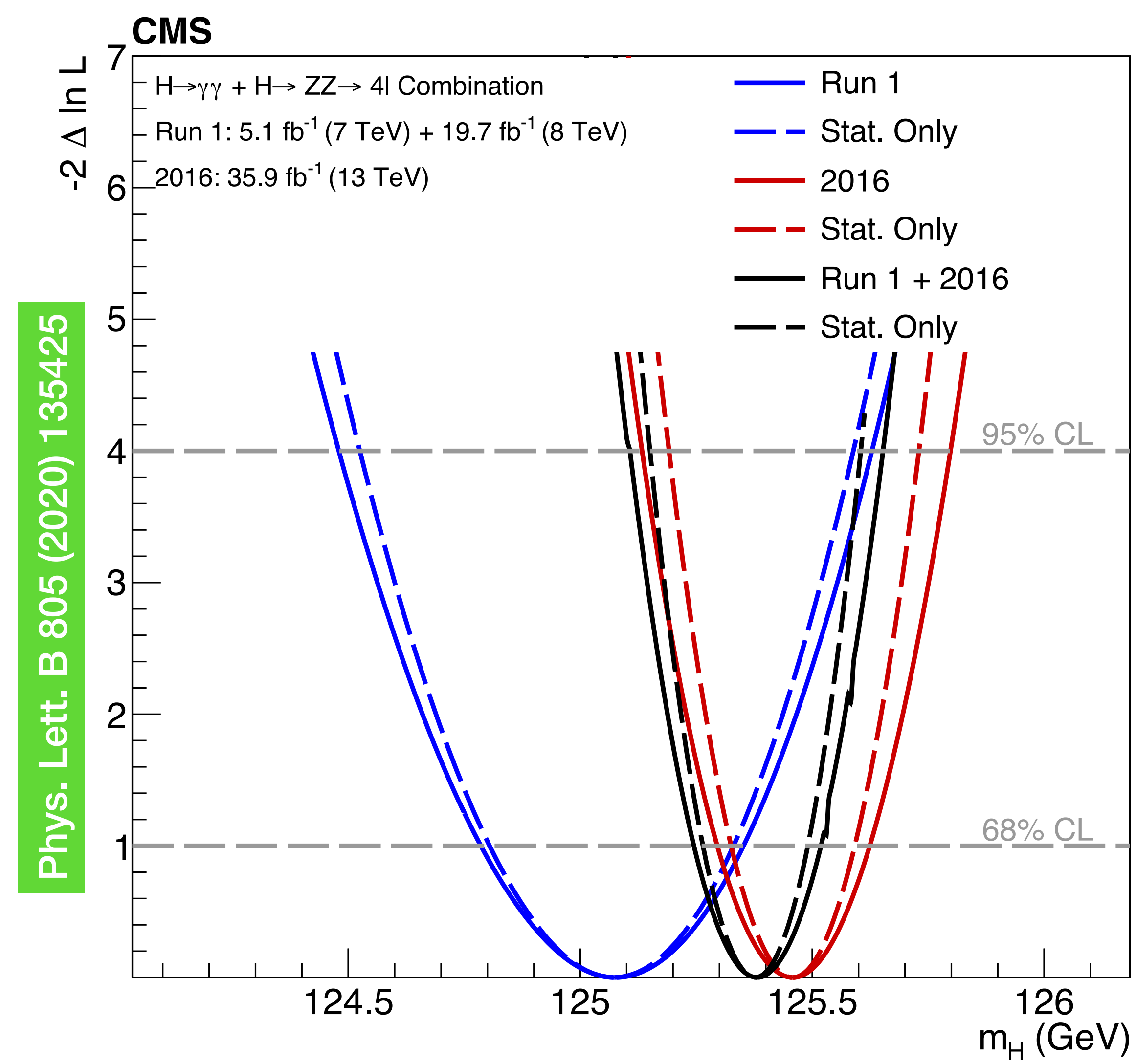
Latest result in **H→γγ**

$$m_H = 125.78 \pm 0.26\ [\pm 0.18(stat) \pm 0.18(syst)]\ GeV$$

Combination

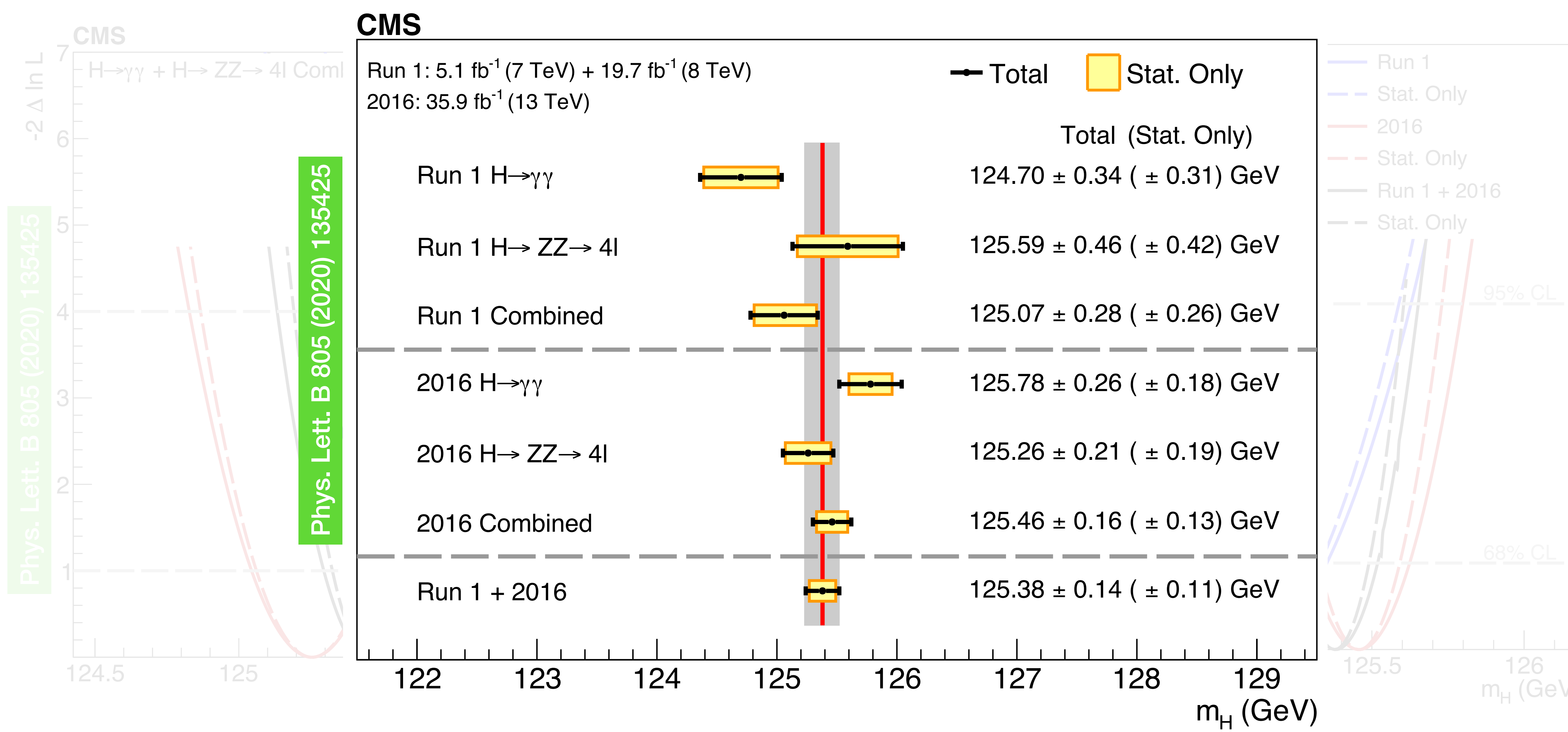
Currently most precise Higgs boson mass measurement was done using **CMS 2016 data** (36/fb), combining **H→γγ** and **H→ZZ*→4ℓ** channels, with **Run 1** results.





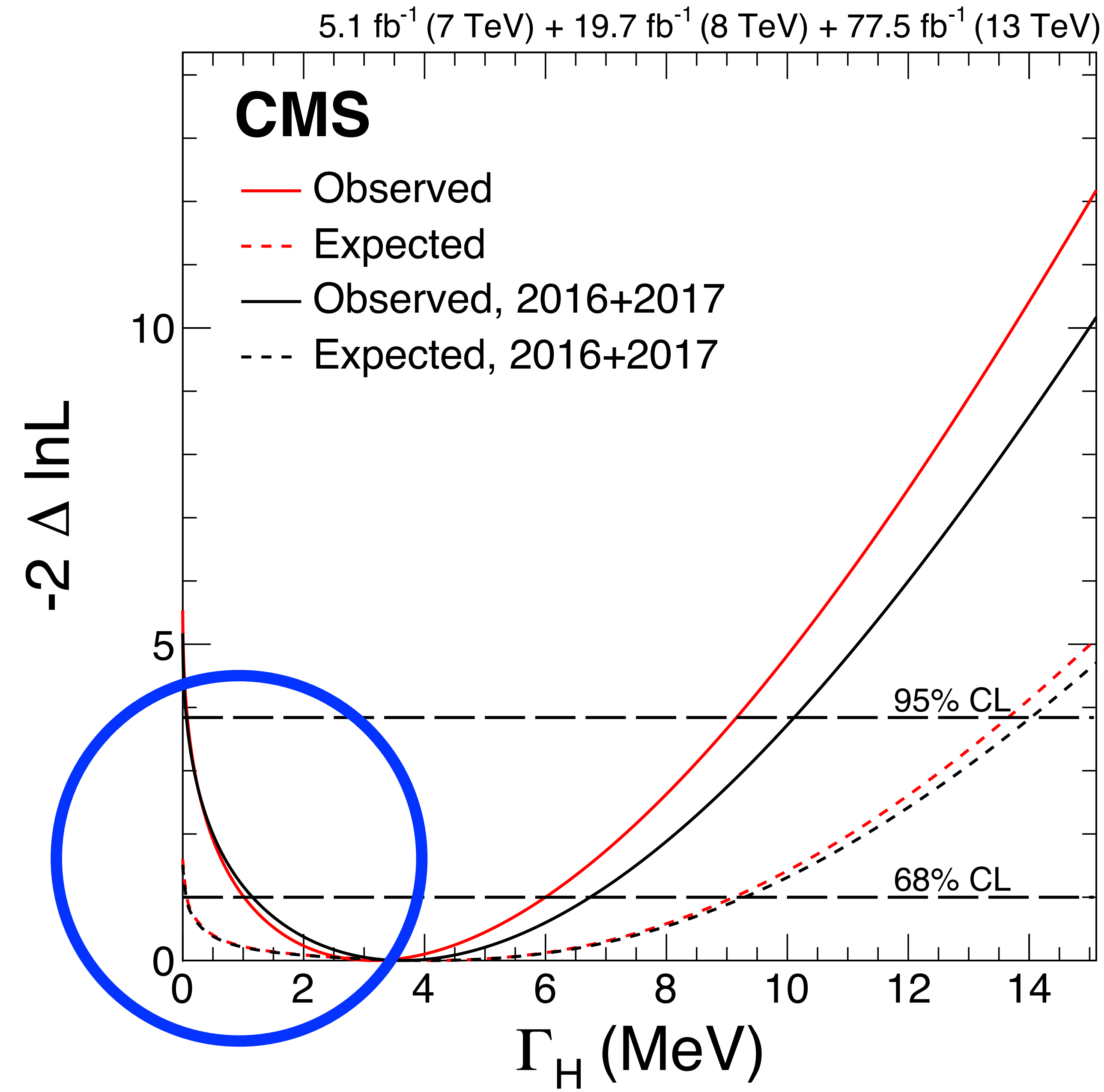
Combination

Currently most precise Higgs boson mass measurement was done using **CMS** **2016 data** (36/fb), combining **$H\rightarrow\gamma\gamma$** and **$H\rightarrow ZZ^{*}\rightarrow 4\ell$** channels, with **Run 1** results.



$$m_H = 125.38 \pm 0.14\ [\pm 0.11(stat) \pm 0.08(syst)]\ GeV$$

The Higgs boson width



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Difficulties in directly measuring the width (4.07 MeV) due to detector resolution.

Measured in the H to 4ℓ channel, combining 2016-2017 data with RunI, comparing on-shell and off-shell production:

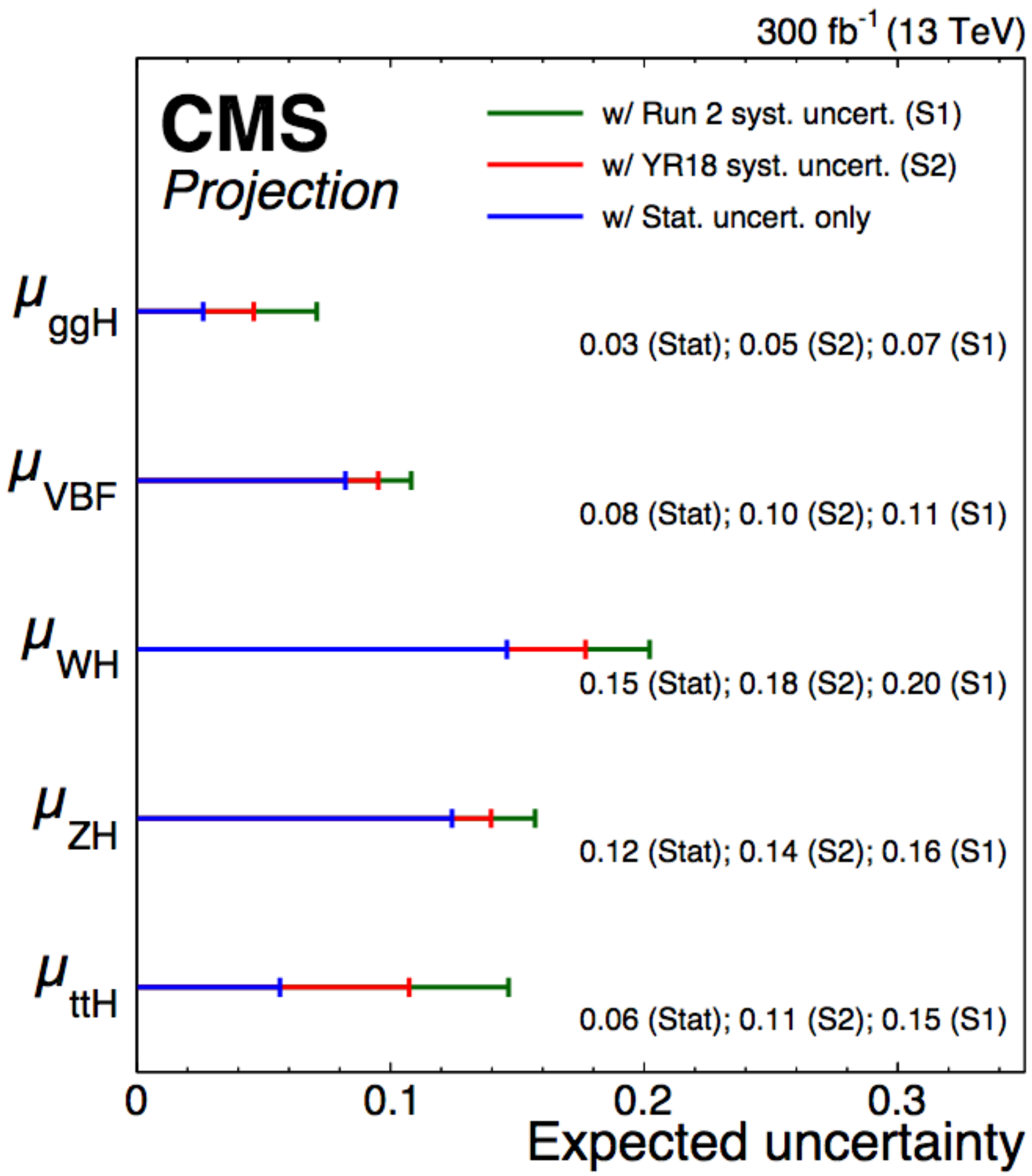
$$\frac{\sigma^{\text{on-shell}}_{gg\to H\to ZZ^*} \sim \dfrac{g^2_{ggH} g^2_{HZZ}}{m_H \Gamma_H}}{\sigma^{\text{off-shell}}_{gg\to H^*\to ZZ} \sim \dfrac{g^2_{ggH} g^2_{HZZ}}{(2m_Z)^2}}$$

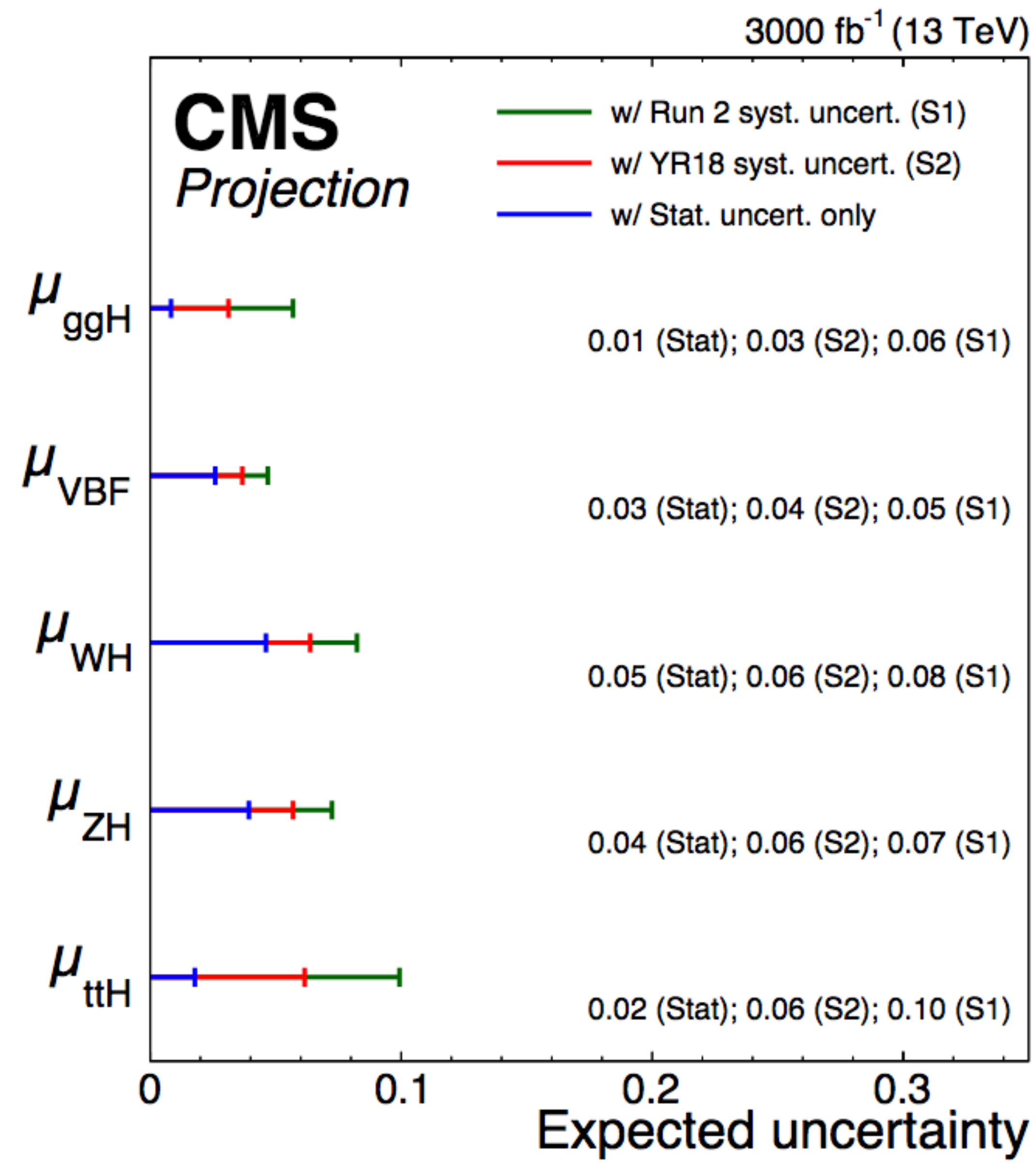
Set a lower bound for the first time

Best result up to now:

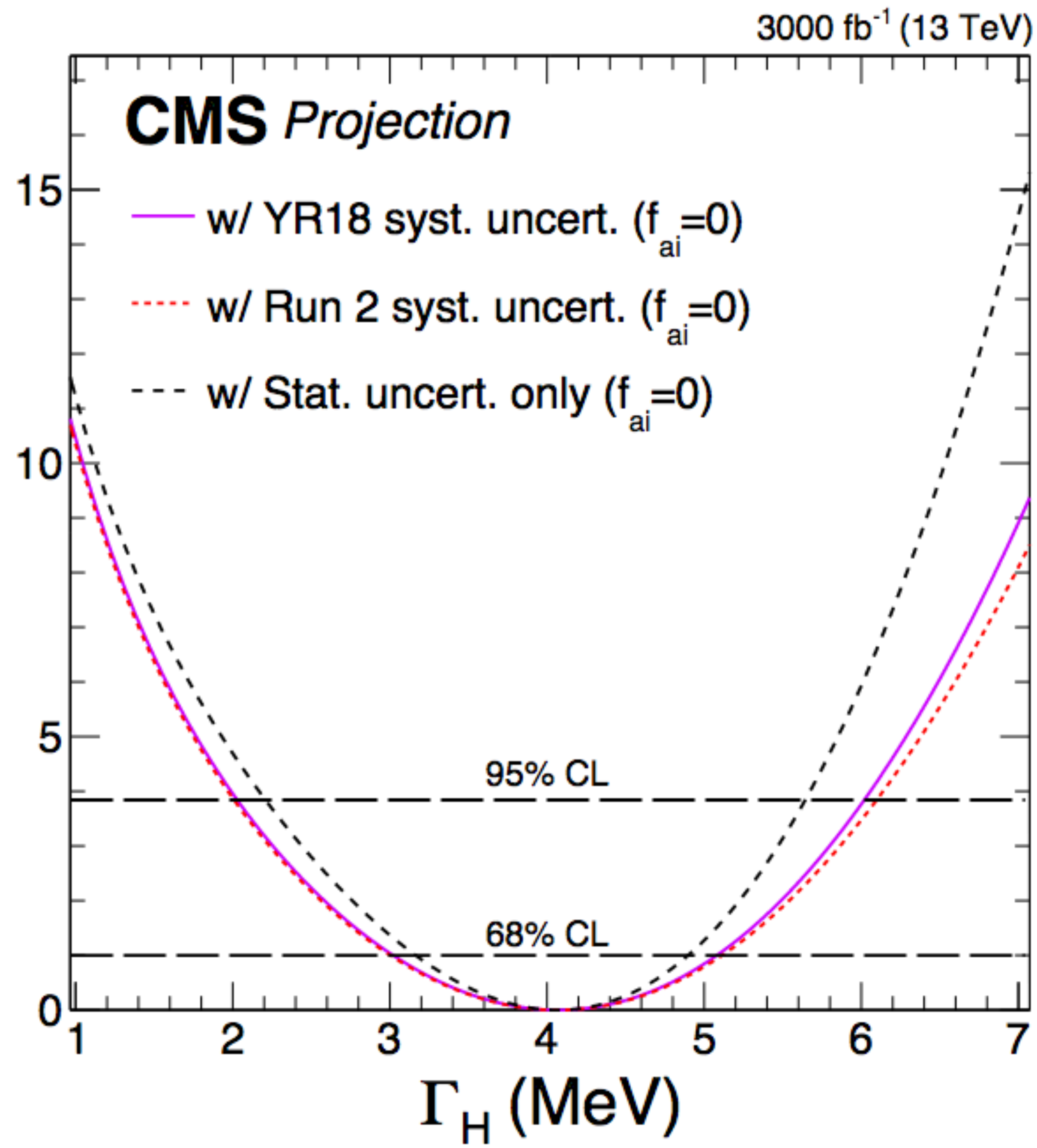
$$\Gamma_H < 9.16\ (exp\ 13.7)\ MeV\ @95\%\ C.L.$$

H prospects


300 fb^{-1} (13 TeV)
CMS
Projection
w/ Run 2 syst. uncert. (S1)
w/ YR18 syst. uncert. (S2)
w/ Stat. uncert. only
μ_{ggH}
0.03 (Stat); 0.05 (S2); 0.07 (S1)
μ_{VBF}
0.08 (Stat); 0.10 (S2); 0.11 (S1)
μ_{WH}
0.15 (Stat); 0.18 (S2); 0.20 (S1)
μ_{ZH}
0.12 (Stat); 0.14 (S2); 0.16 (S1)
μ_{ttH}
0.06 (Stat); 0.11 (S2); 0.15 (S1)
0
0.1
0.2
0.3
Expected uncertainty


3000 fb^{-1} (13 TeV)
CMS
Projection
w/ Run 2 syst. uncert. (S1)
w/ YR18 syst. uncert. (S2)
w/ Stat. uncert. only
μ_{ggH}
0.01 (Stat); 0.03 (S2); 0.06 (S1)
μ_{VBF}
0.03 (Stat); 0.04 (S2); 0.05 (S1)
μ_{WH}
0.05 (Stat); 0.06 (S2); 0.08 (S1)
μ_{ZH}
0.04 (Stat); 0.06 (S2); 0.07 (S1)
μ_{ttH}
0.02 (Stat); 0.06 (S2); 0.10 (S1)
0
0.1
0.2
0.3
Expected uncertainty

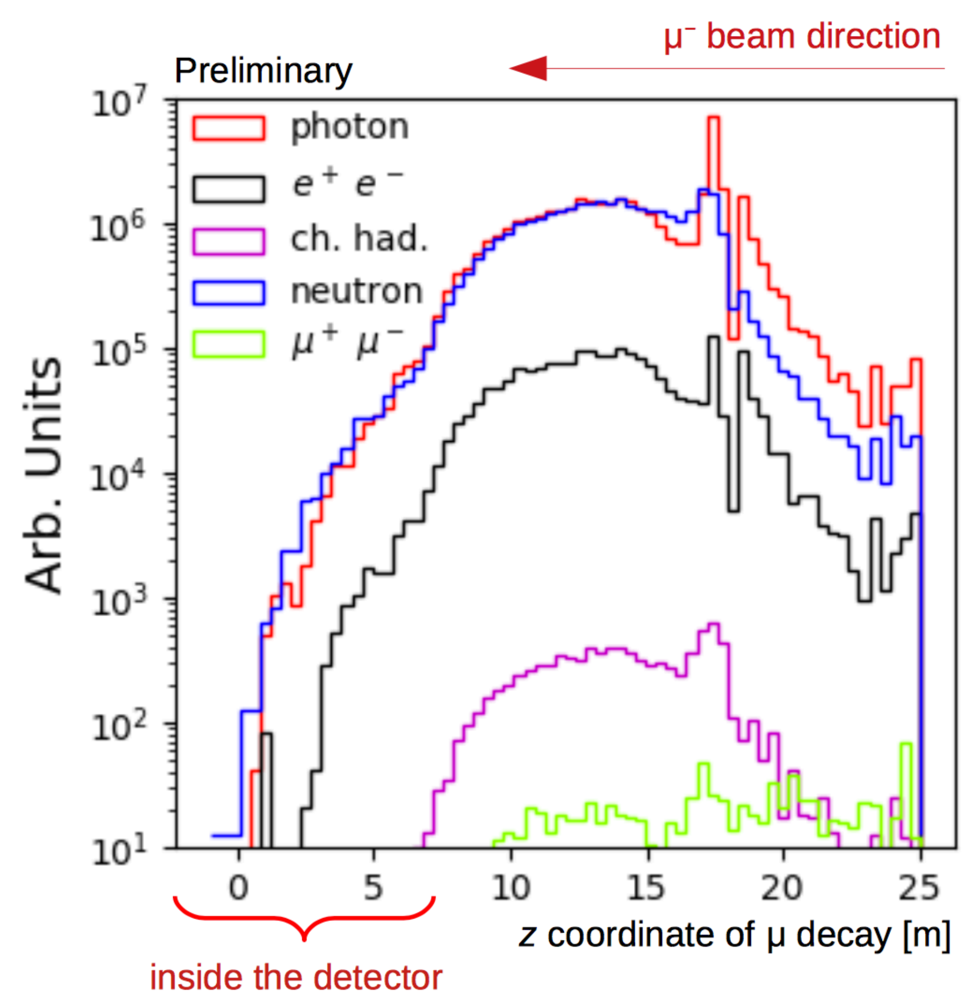
H prospects


3000 fb-1 (13 TeV)
CMS Projection
w/ YR18 syst. uncert. (f_ai=0)
w/ Run 2 syst. uncert. (f_ai=0)
w/ Stat. uncert. only (f_ai=0)
95% CL
68% CL
0
5
10
15
1
2
3
4
5
6
7
Γ_H (MeV)

Muon collider

Cons:

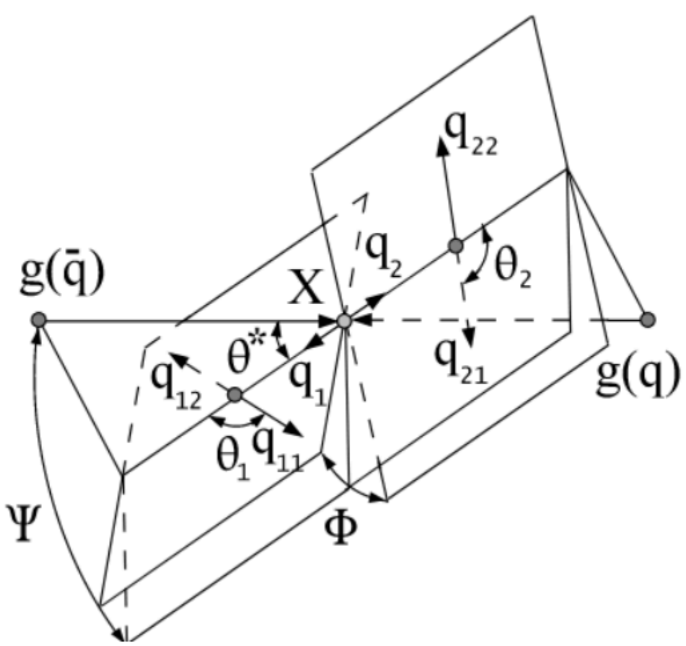
- muons are decaying particles (2.2μs) but a 5 TeV beam allows to proper treat the leptons in the lab system (t_μ ~ 100ms)
- Intense and highly collimated neutrino beams, emerging on the earth surface even very far from the muon collider complex, may be responsible for a severe ionisation radiation hazard for the population and the environment —> 3 TeV is safe, 10 TeV could be safe with mitigation measures in place.
- Beam induced background (BIB)



H→ZZ*→4μ

Developed a background discriminator (known as MELA in CMS), combining angular distributions into a single discriminator.

Angular variables sensitive to **spin** and **parity** of a **resonance**:



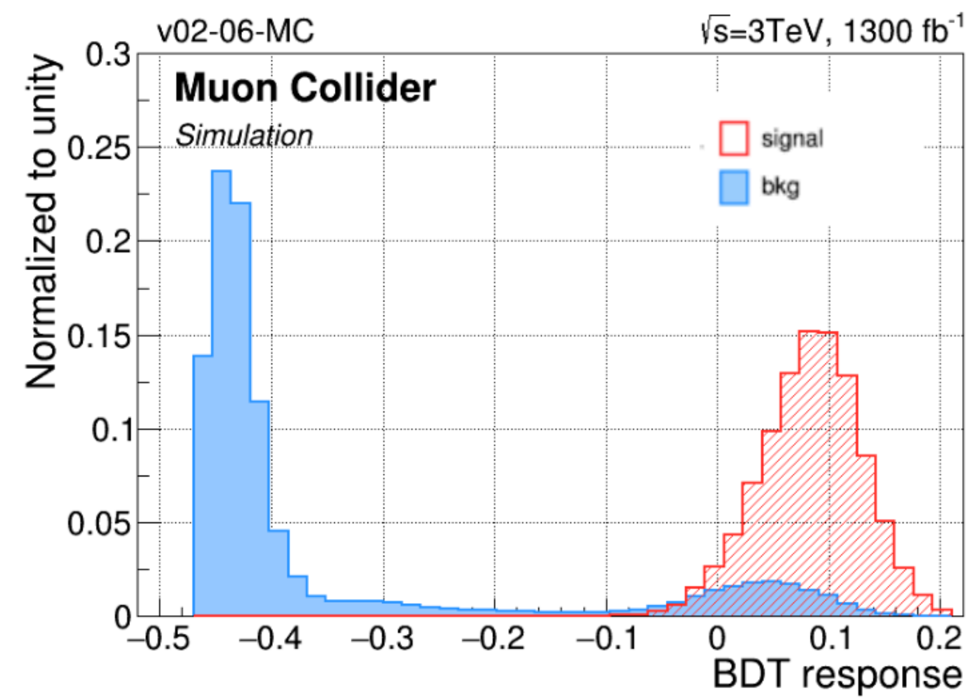
$X \to V_1 V_2 \to f_{11} f_{12} f_{21} f_{22}$

q_i: V_i momentum in X rest frame

q_{ij}: f_{ij} momentum in V_i rest frame

Angles defined by:

- The directions of V_i in X rest frame;
- the directions of fermions in their parent boson rest frame.

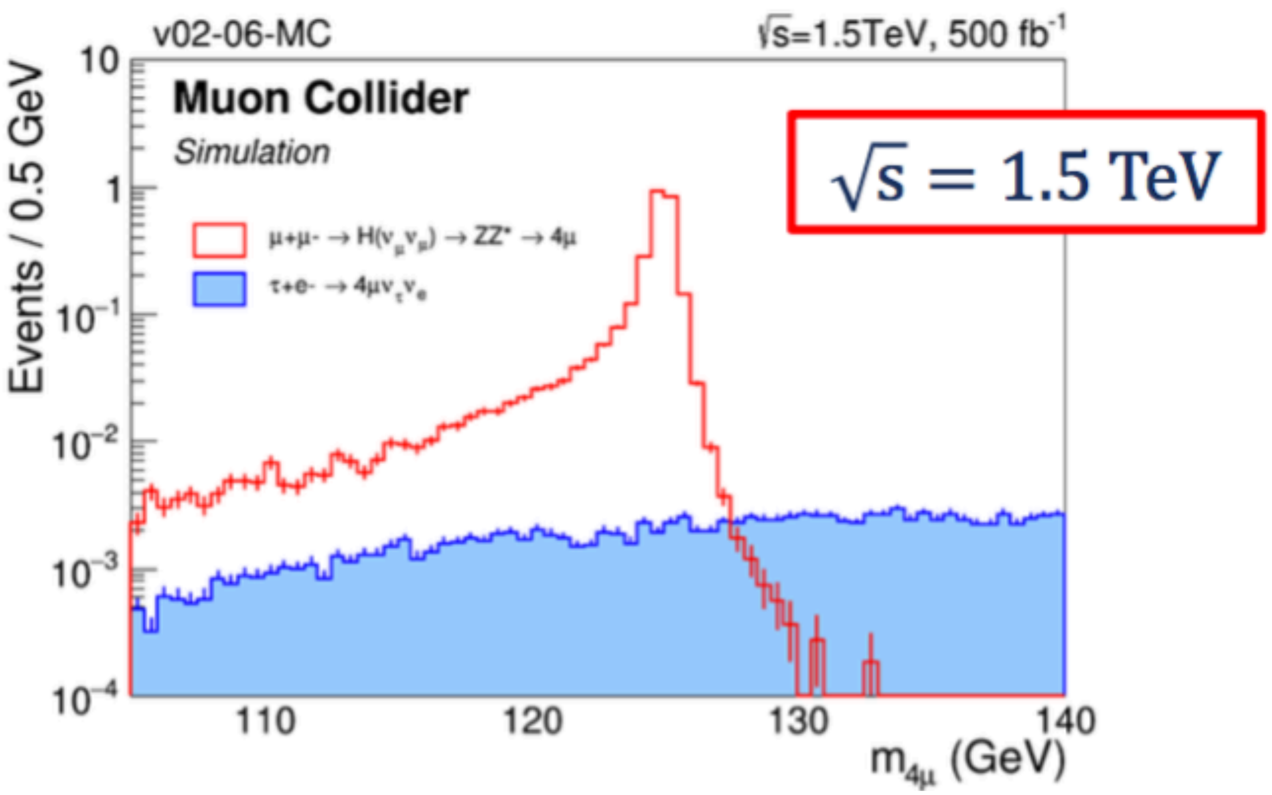


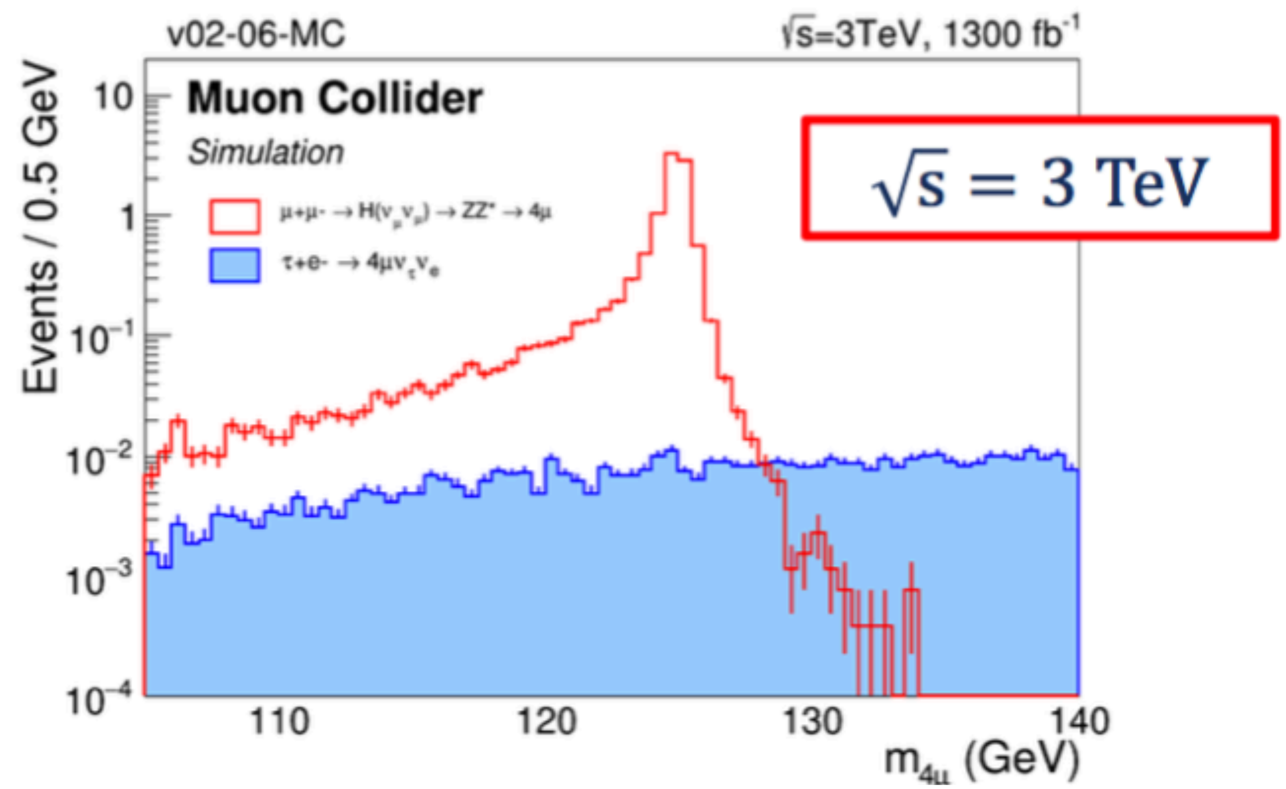
Signal efficiency 99% → background rejection 87%

	$\sqrt{s} = 1.5$ TeV	$\sqrt{s} = 3$ TeV
BDT cut	-0.036	-0.041
Σ	1.99	4.06

$$\Sigma = \frac{S}{\sqrt{S+B}}$$

$H \to ZZ^* \to 4\mu$





$\sqrt{s} = 1.5$ TeV L=500fb^{-1}			$\sqrt{s} = 3$ TeV L=1300fb^{-1}		
Z	$\frac{\Delta\sigma}{\sigma}$ (%)	$\frac{\Delta g_{HZZ}}{g_{HZZ}}$	Z	$\frac{\Delta\sigma}{\sigma}$ (%)	$\frac{\Delta g_{HZZ}}{g_{HZZ}}$
3.65	60.16	**30.12**	6.91	31.64	**15.85**

By including 4e and 2e2μ, the uncertainty on the HZZ coupling can be improved by a factor ~2

Muon collider

Direct searches

Pair production,
Resonances, VBF,
Dark Matter, …

High-rate measurements

Single Higgs,
self coupling, rare and
exotic Higgs decays,
top quarks, …

High-energy probes

Di-boson, di-fermion,
tri-boson, EFT,
compositeness, …

Muon physics

Lepton Flavor
Universality, $b \to s\mu\mu$,
muon g-2, …