Search for BSM Higgs physics at CMS

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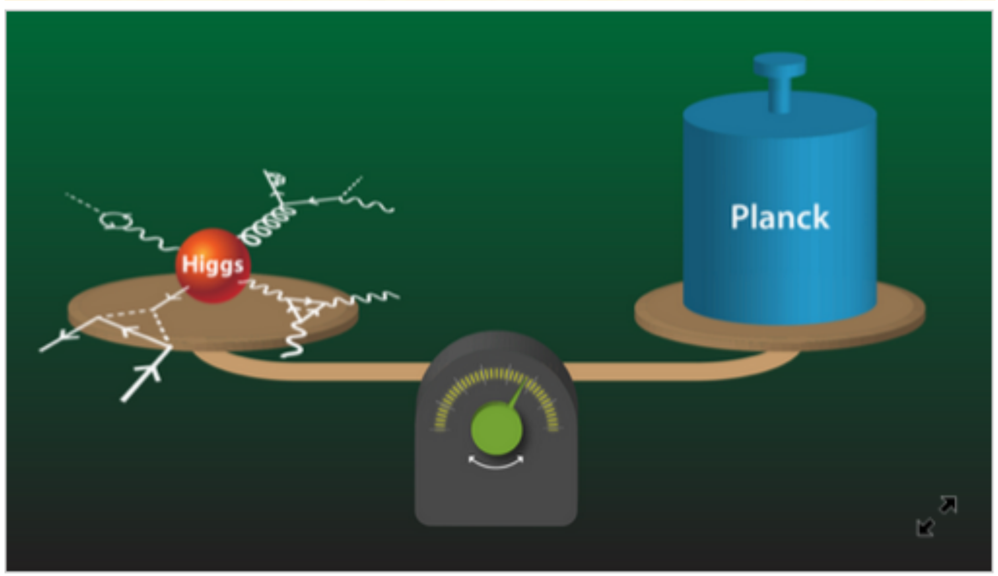
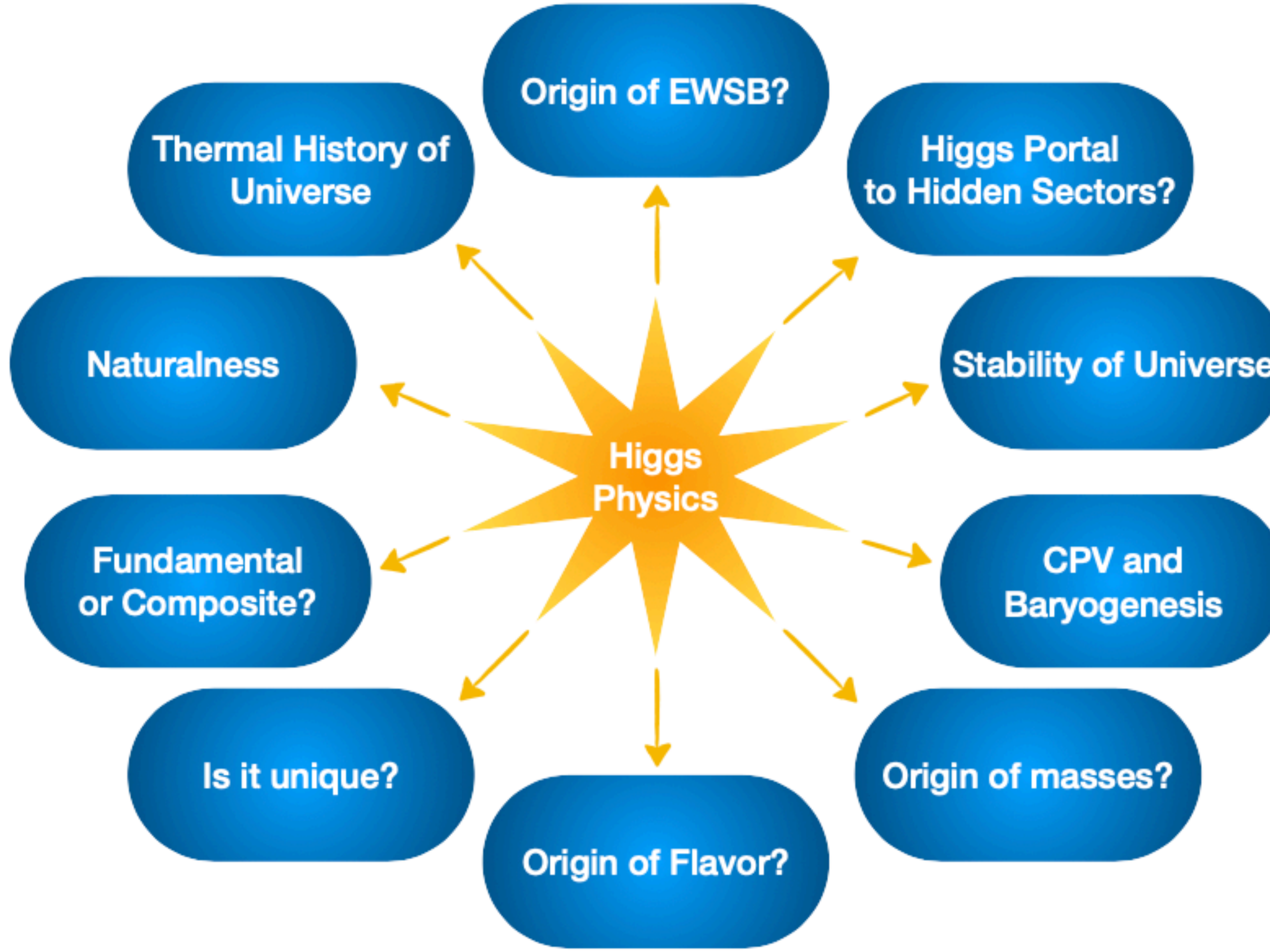
On behalf of CMS Collaboration

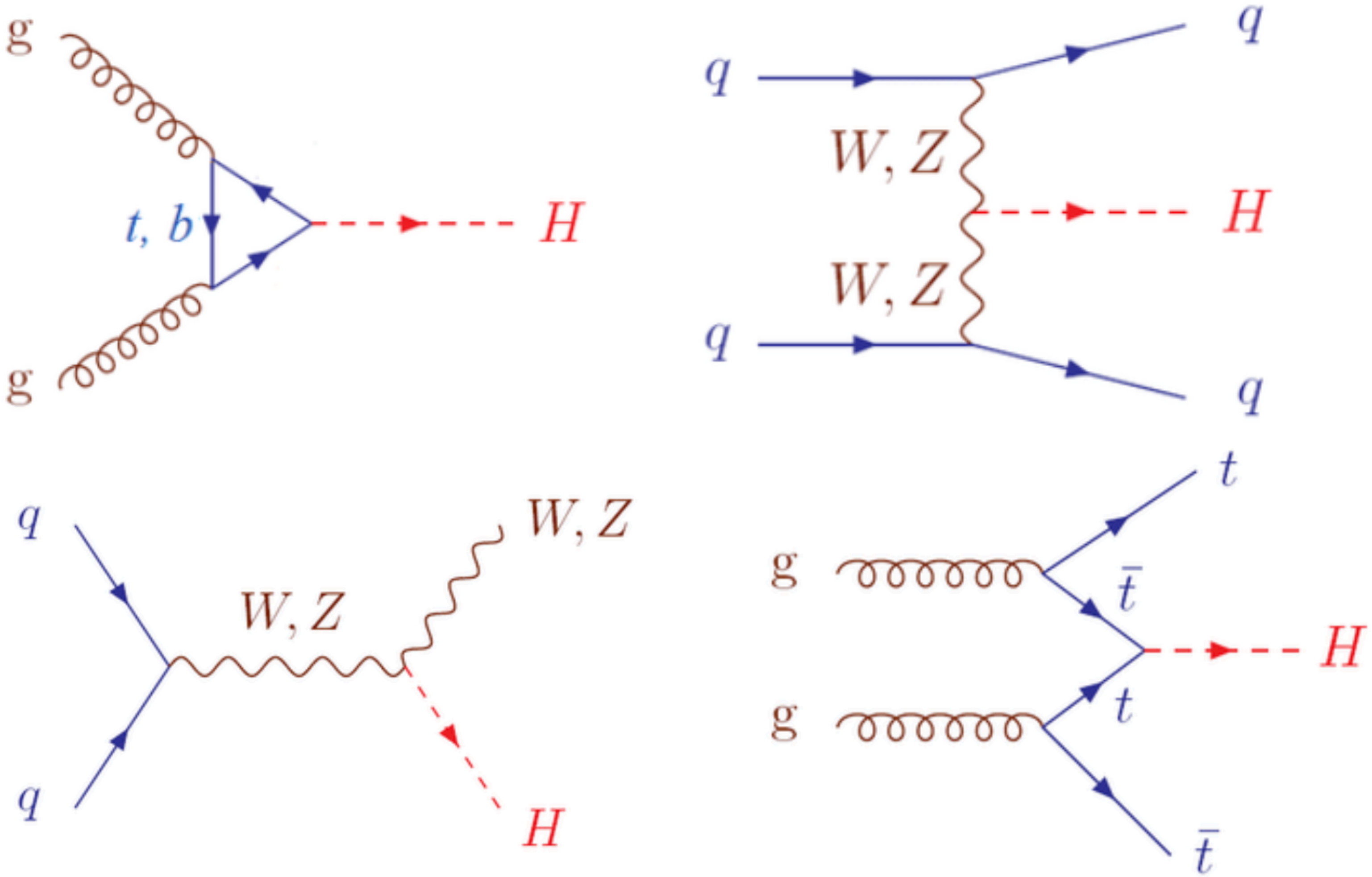
Why Higgs Physics?

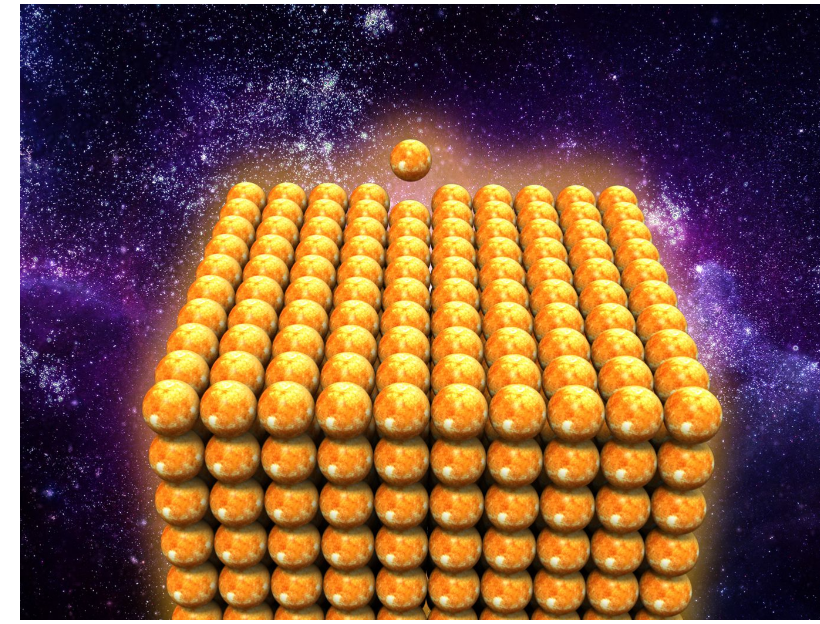




- The most important particle in the HEP program?
- The portal connected multiple modern puzzling questions
- Many observables map to different questions related to Higgs boson
- Any deviations in Higgs feature indicate NEW PHYSICS

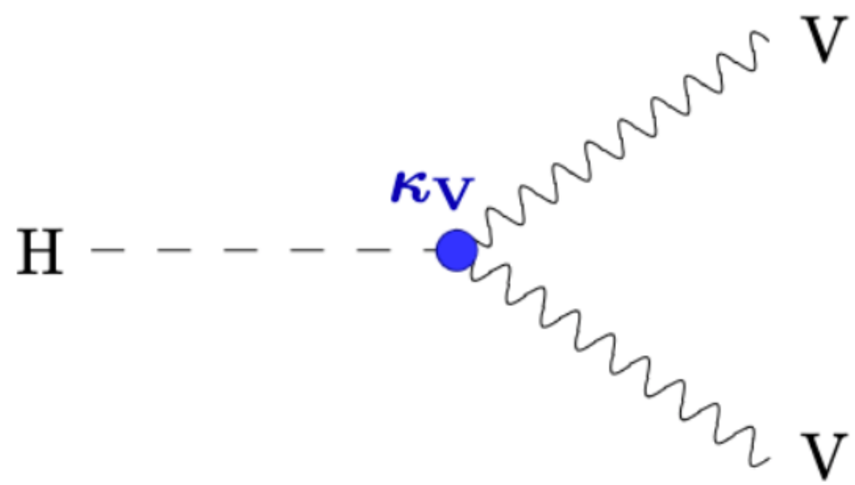
Higgs Production at the LHC

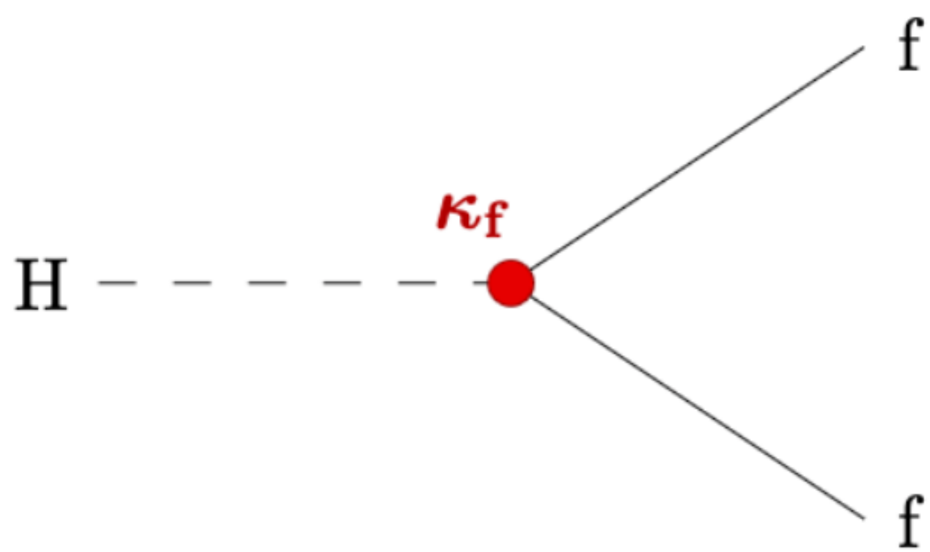


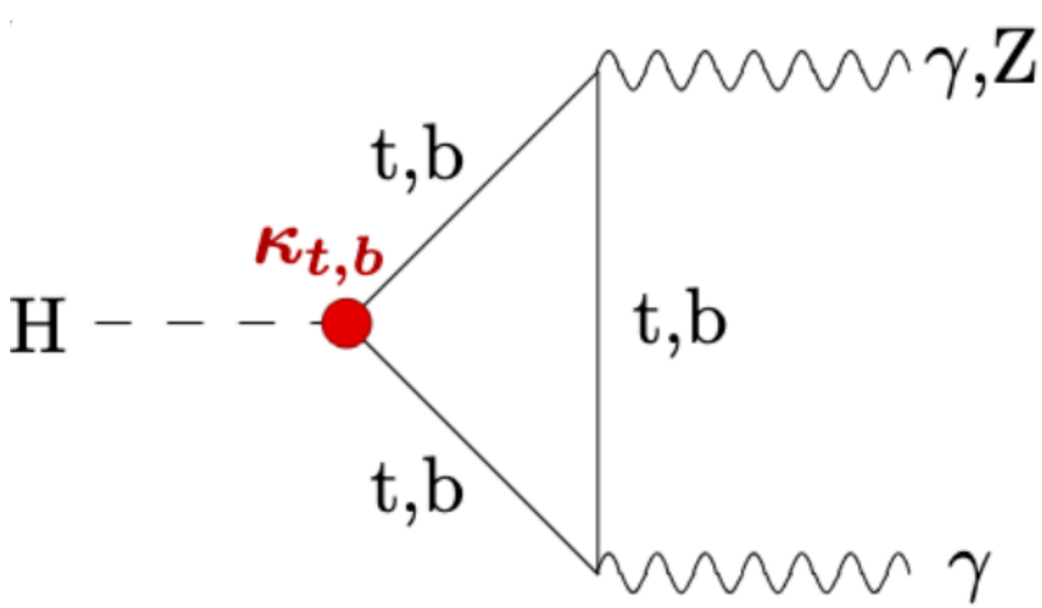


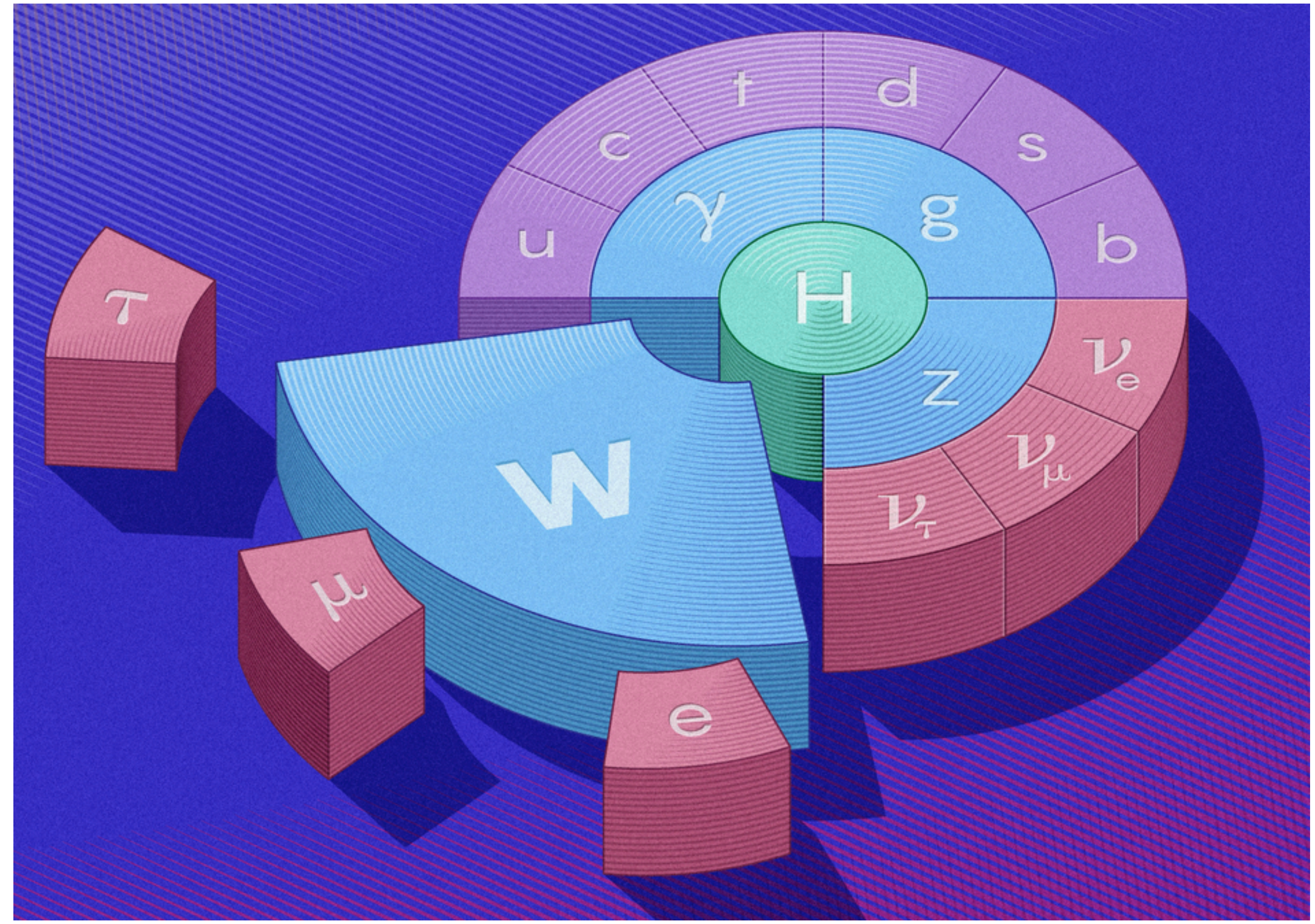
LHC RunII delivered
8 million Higgs bosons

Higgs coupling & decays

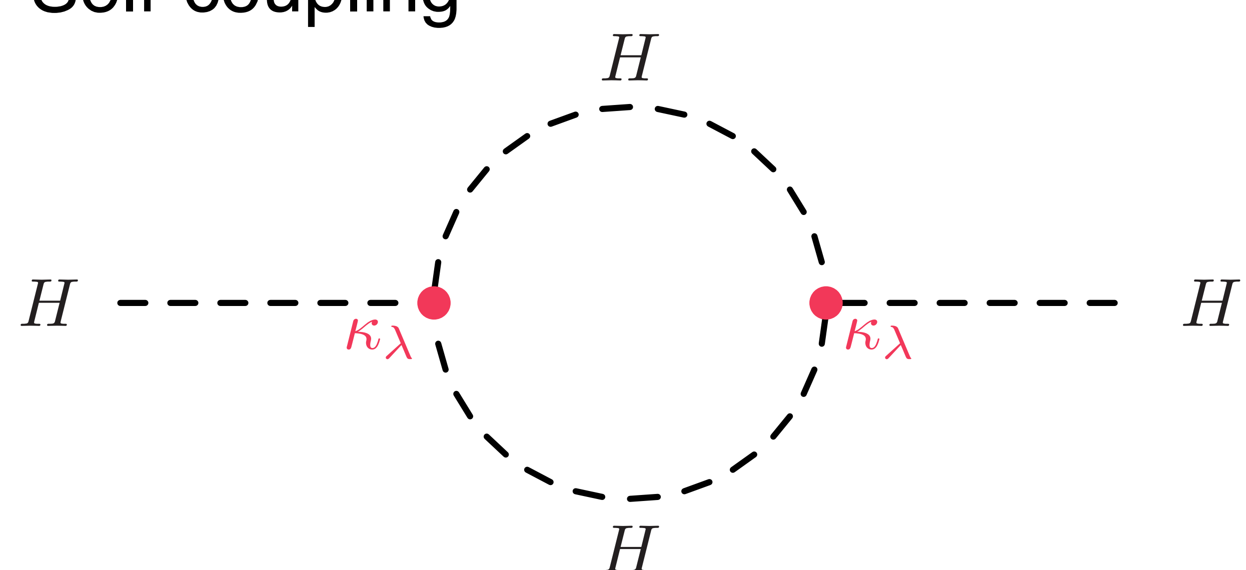






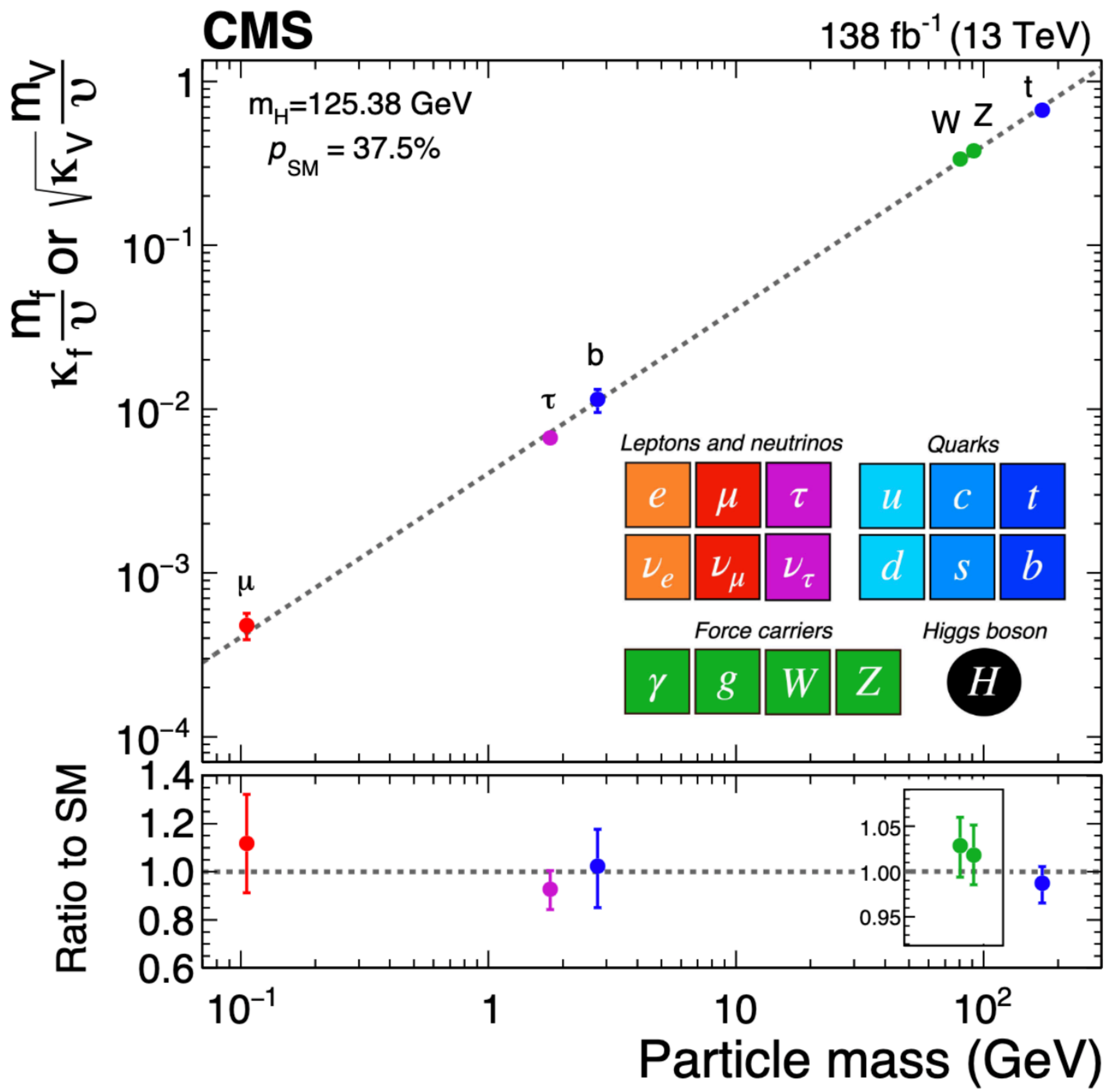


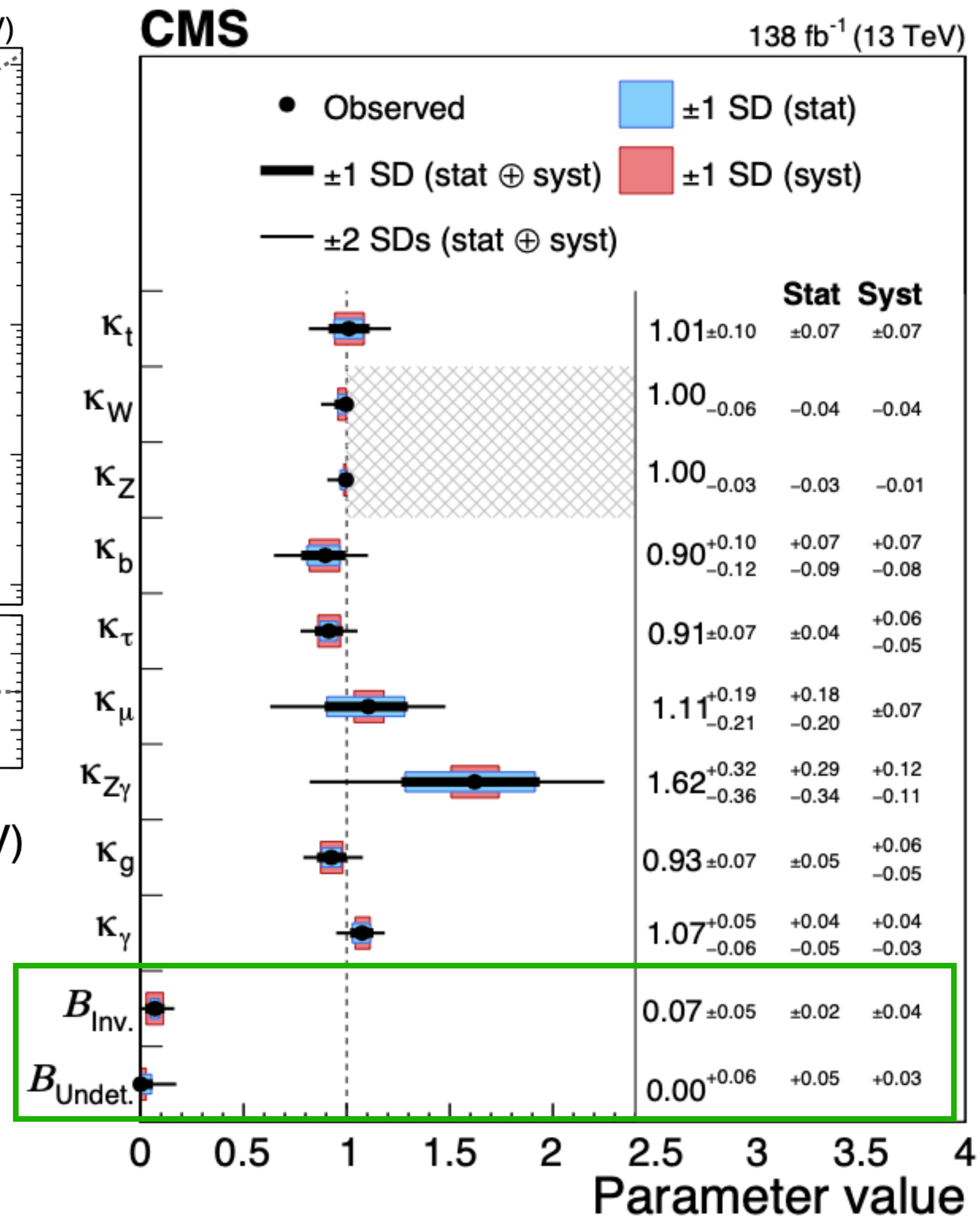
- Gauge coupling to weak force mediators
- Yukawa coupling (eg. fermions)
- Self-coupling



SM/BSM Higgs coupling & decays

Nature 607 (2022) 60

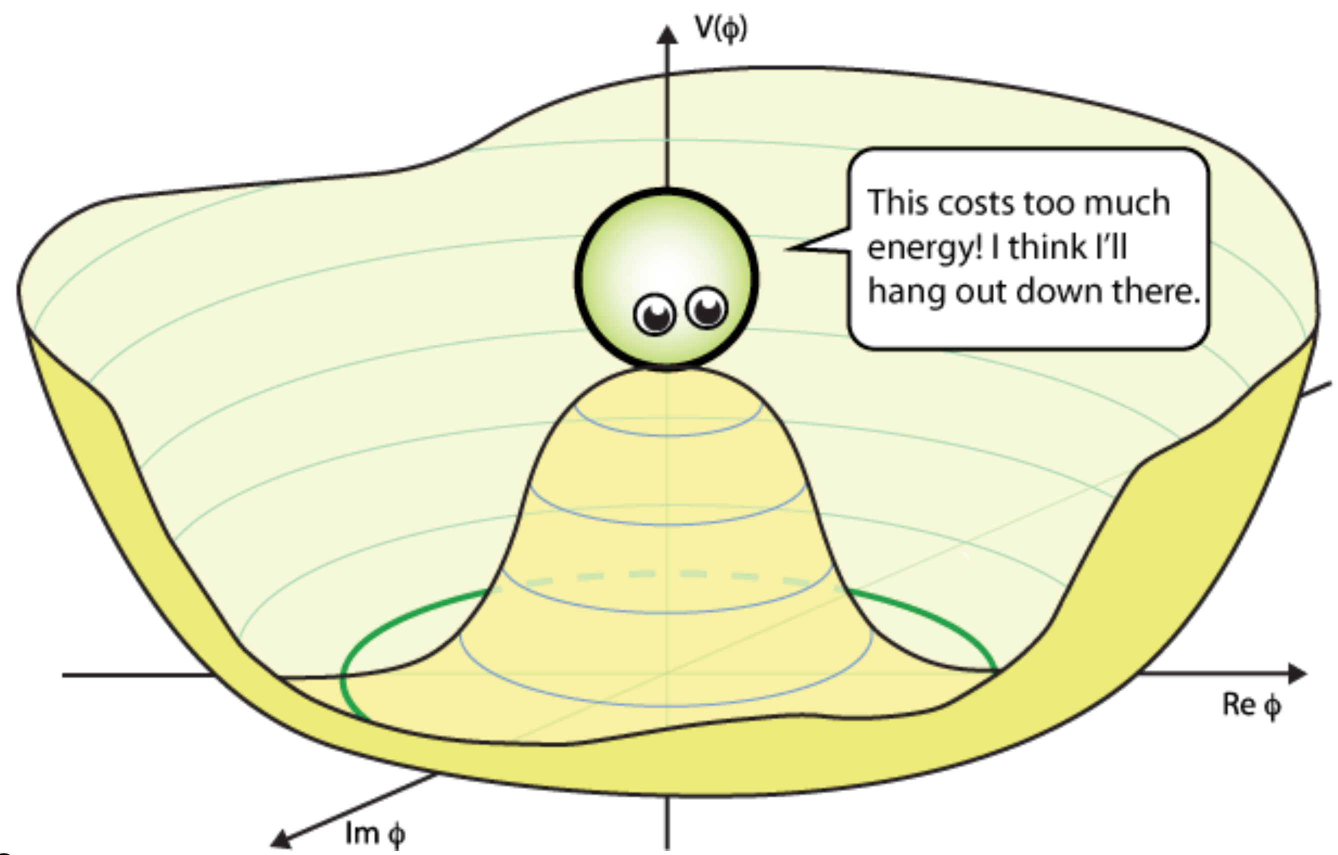




- Comparable Higgs coupling to different particles predicted by SM, invisible and undetected decays are not excluded

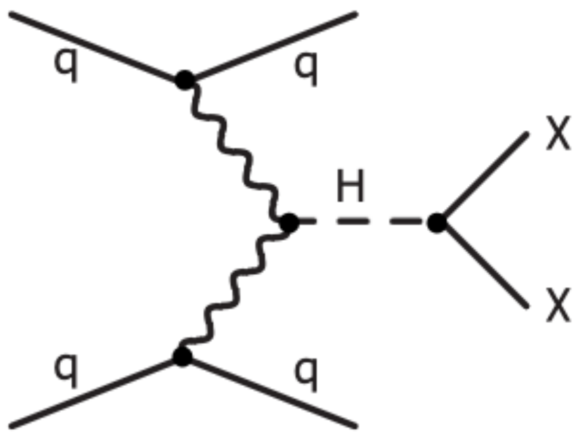
Outline

- Invisible Higgs decays
- Higgs exotic decays
- Higgs self-coupling & pair searches

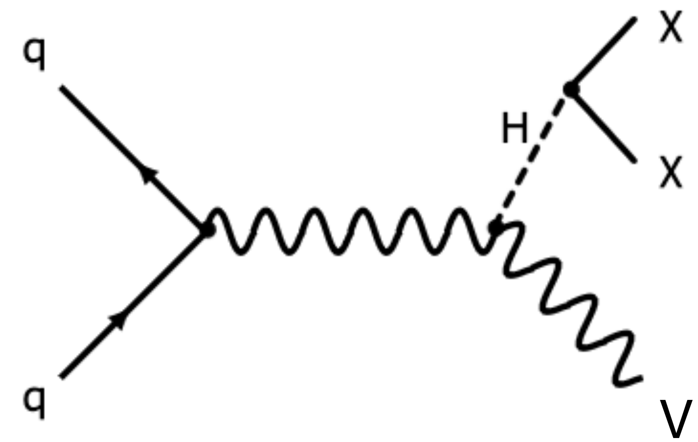


Higgs invisible decays

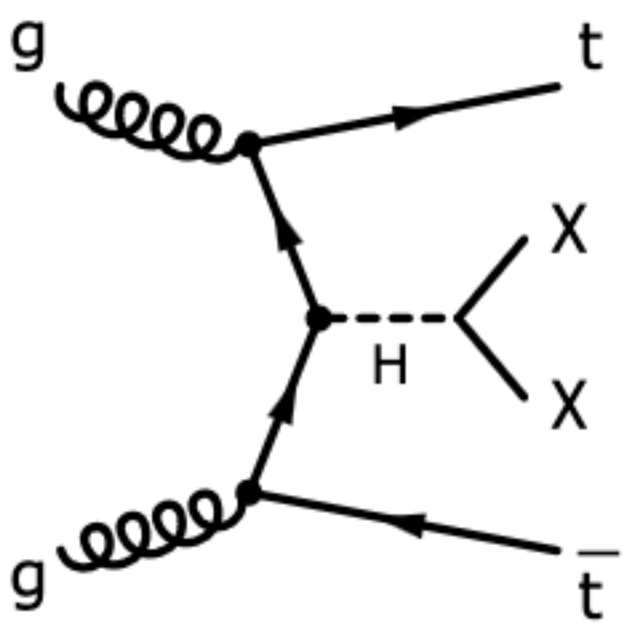
Invisible Higgs decays: a portal to dark matter



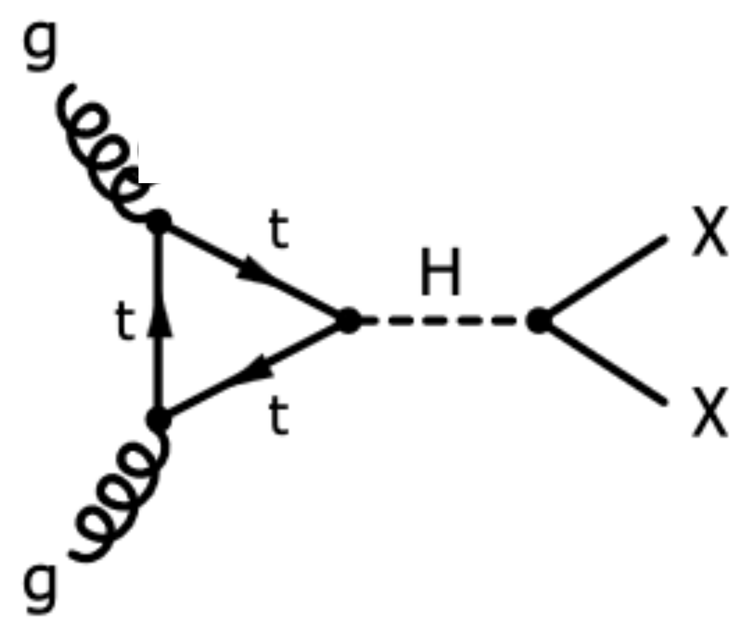
VBF (most sensitive)



VH



ttH

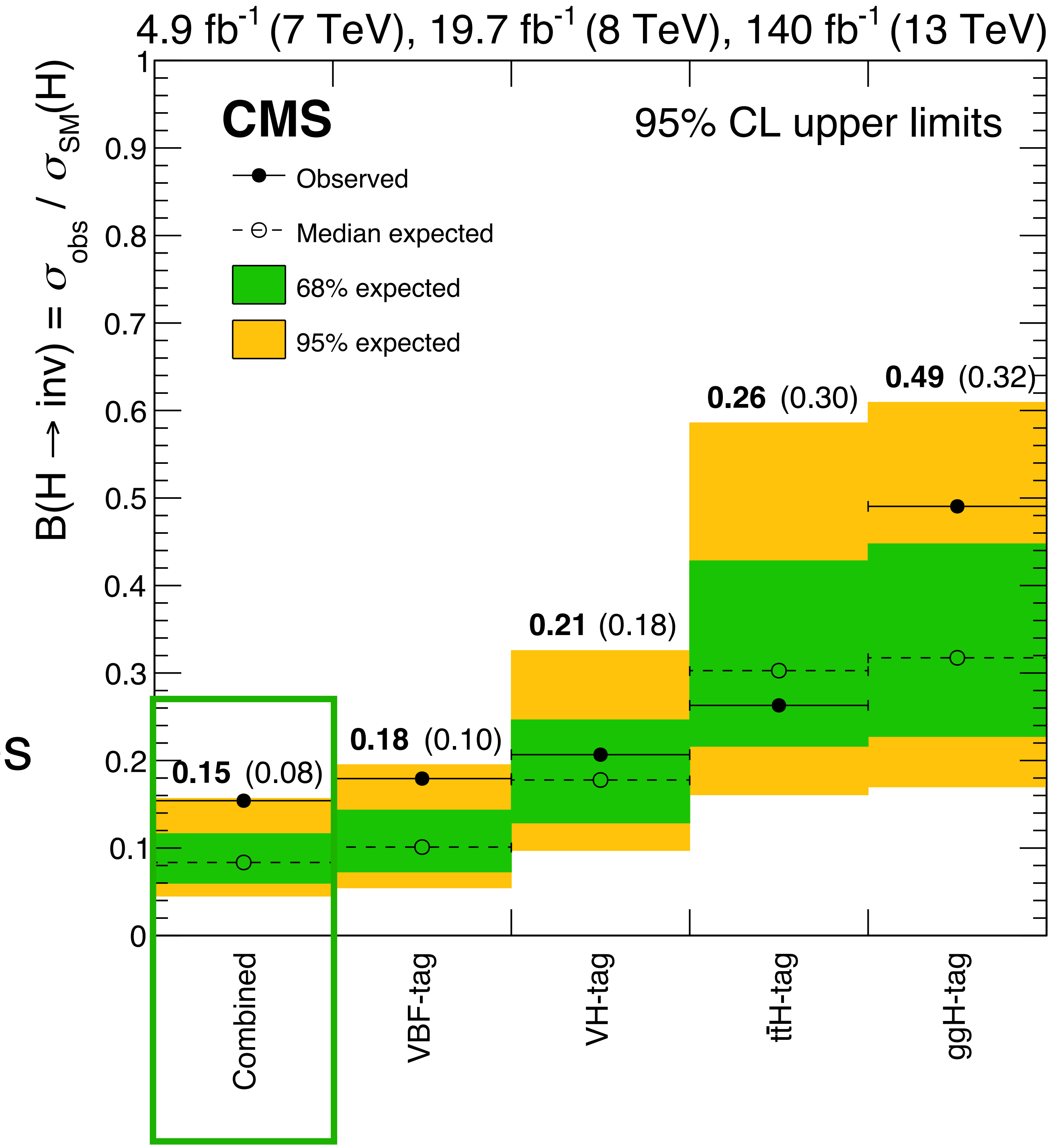


ggF

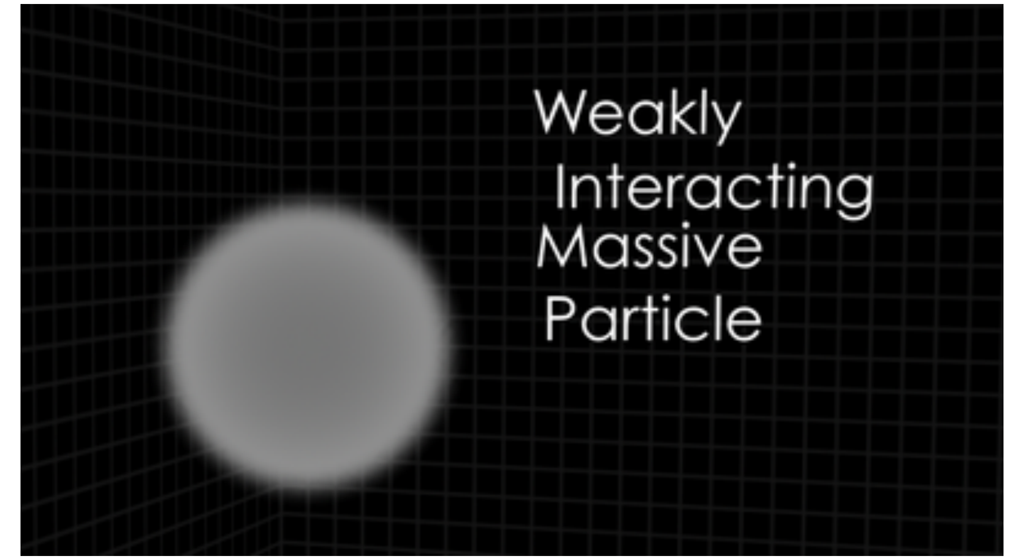
Invisible Higgs decays: branching ratio constraints

arXiv:2303.01214(Submitted to EPJC)

- Improvement in sensitivity of 20% than single VBF channel
- Improvement of 5% relate to the combination of all RunII results
- The most stringent from direct searches at CMS to date



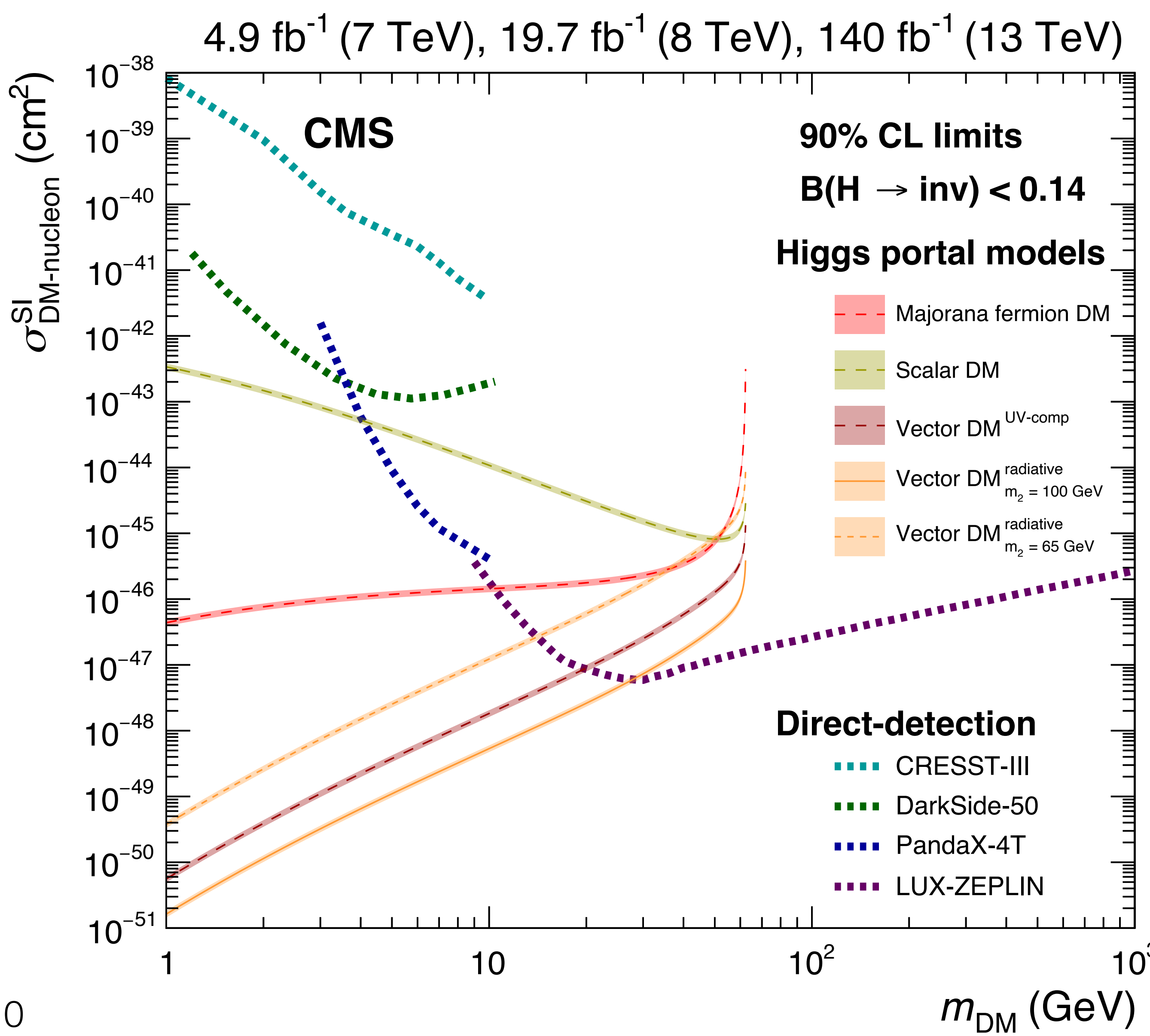
Invisible Higgs decays: a portal to WIMP



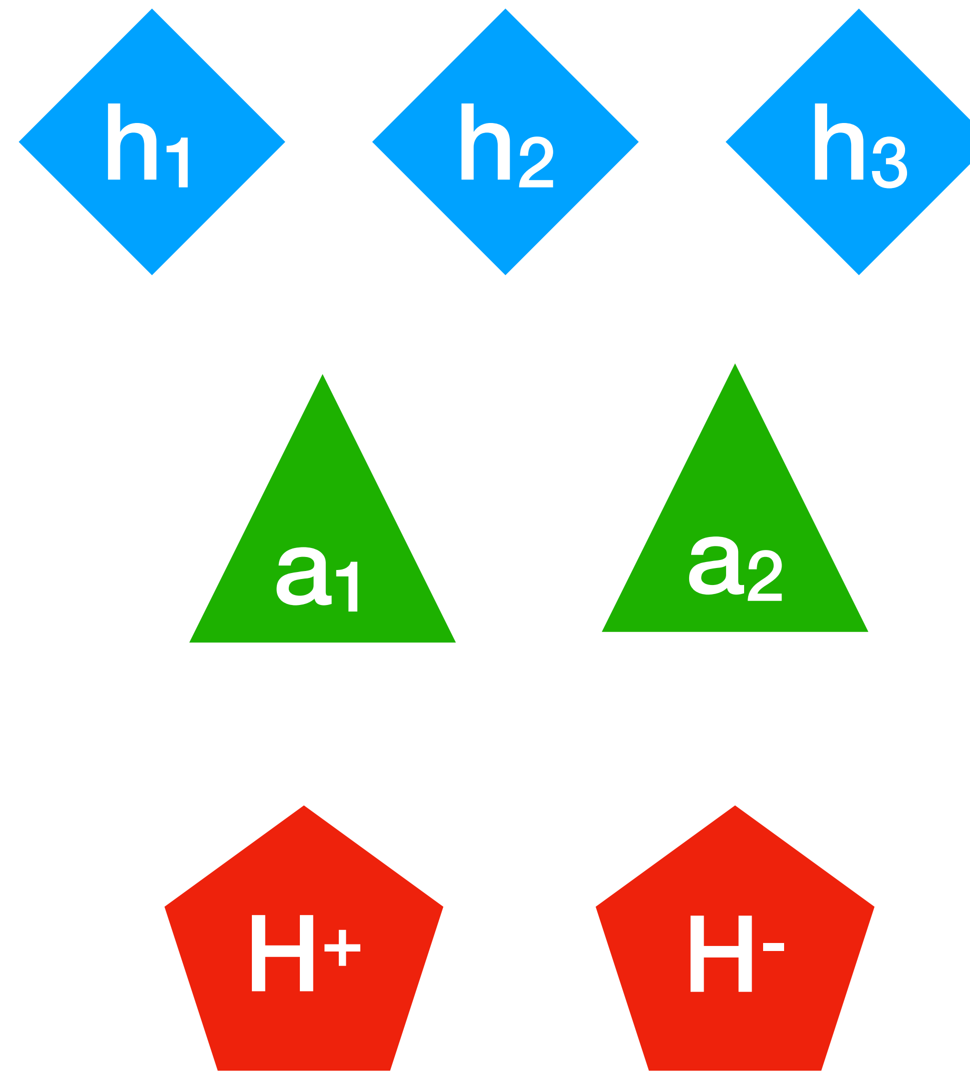
- Significant complementarity between LHC and direct detection experiments

arXiv:2303.01214(Submitted to EPJC)

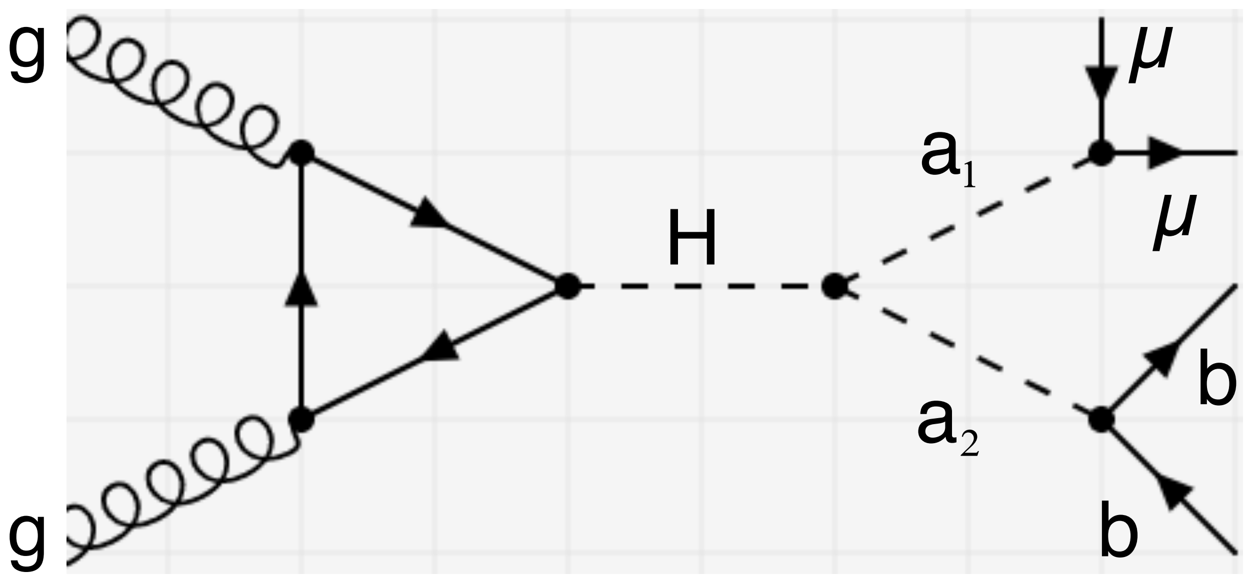
- Effective Field Theory framework and UV-complete model both constrain the WIMP-nucleon cross section down below 10^{-50} cm^2

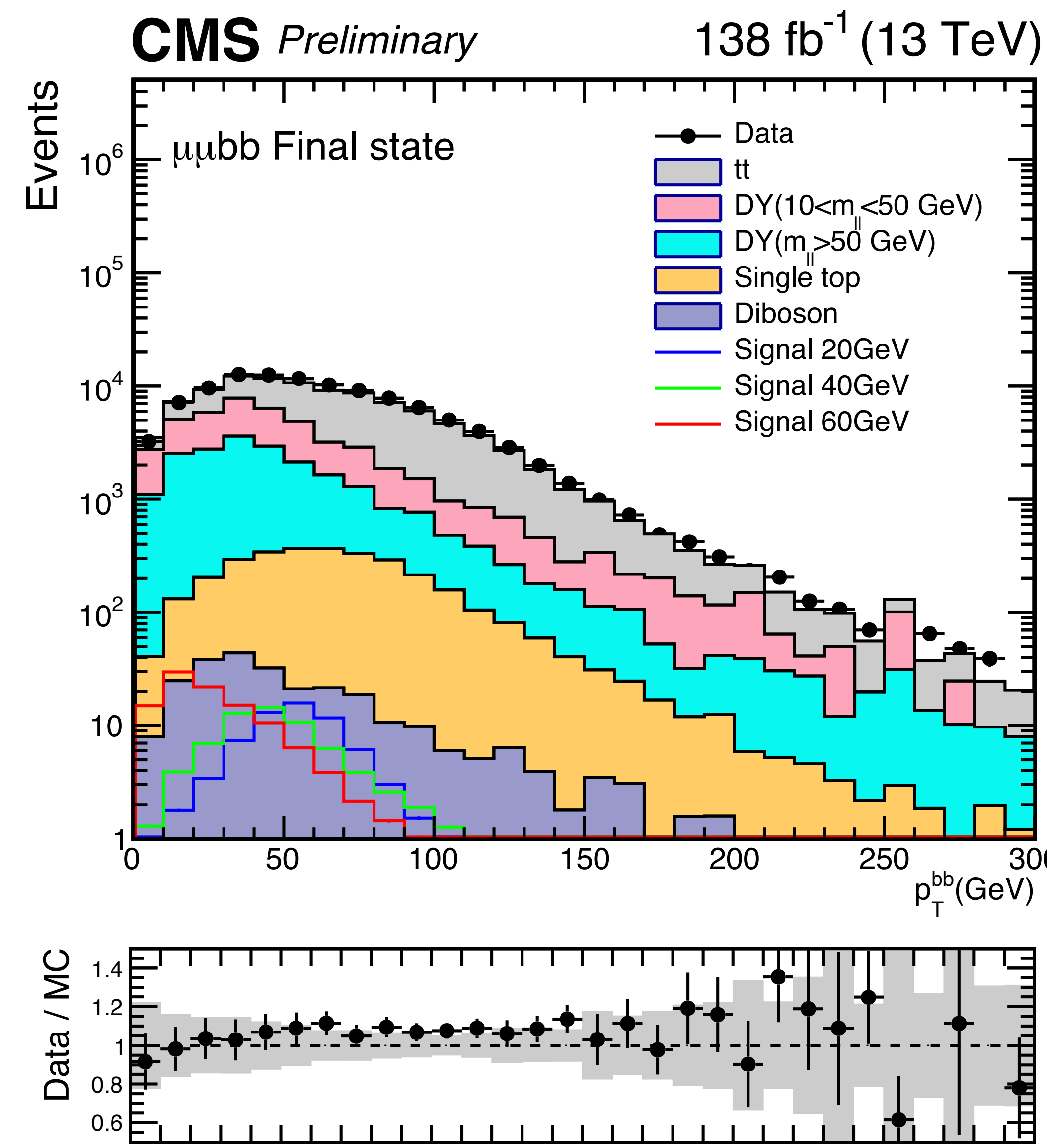


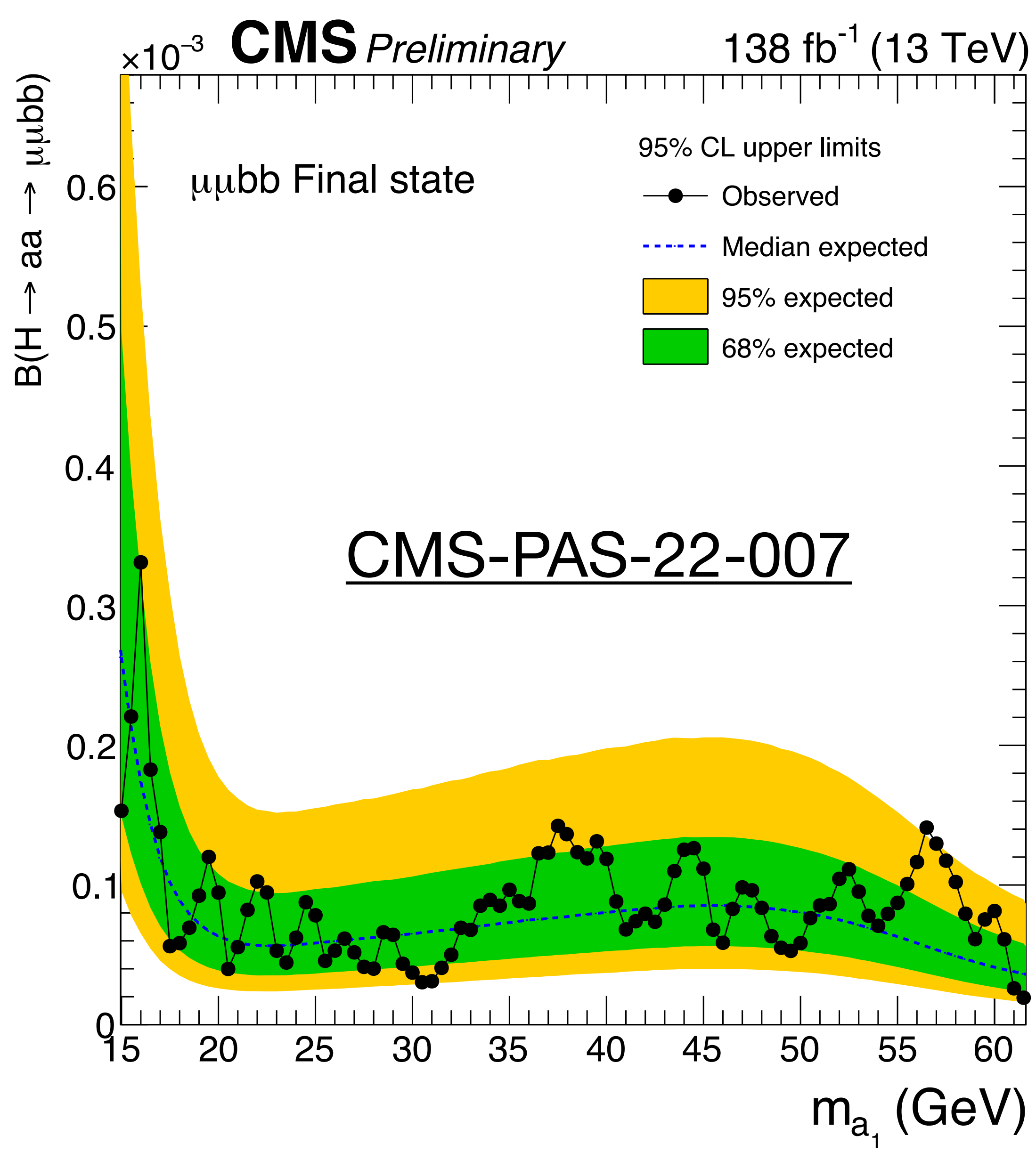
Exotic Higgs searches



H → aa → μμbb

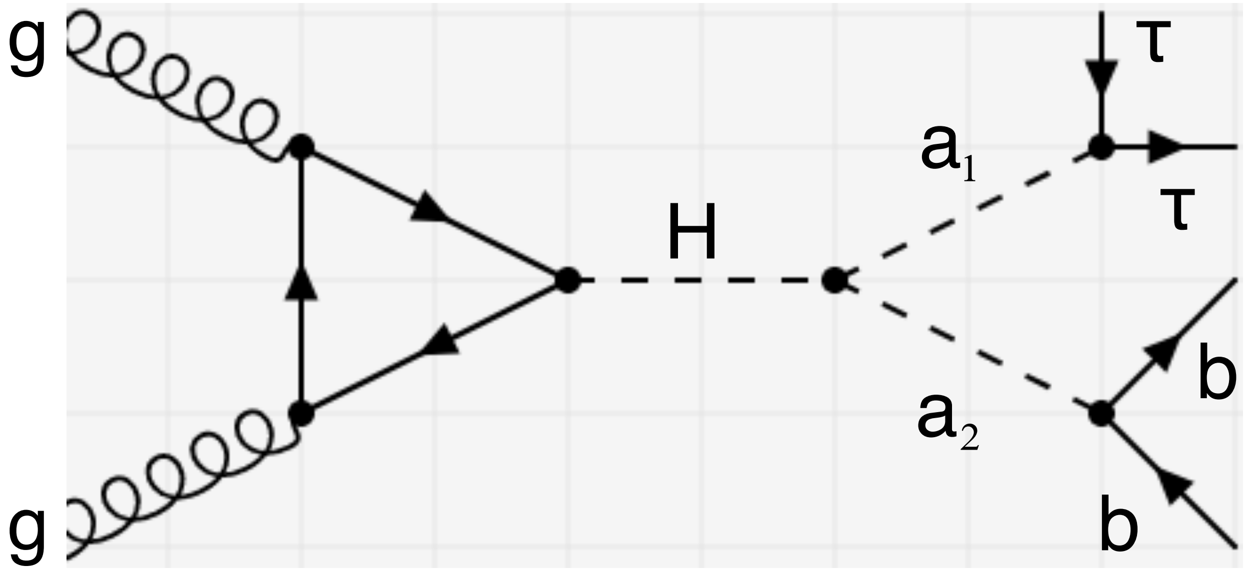


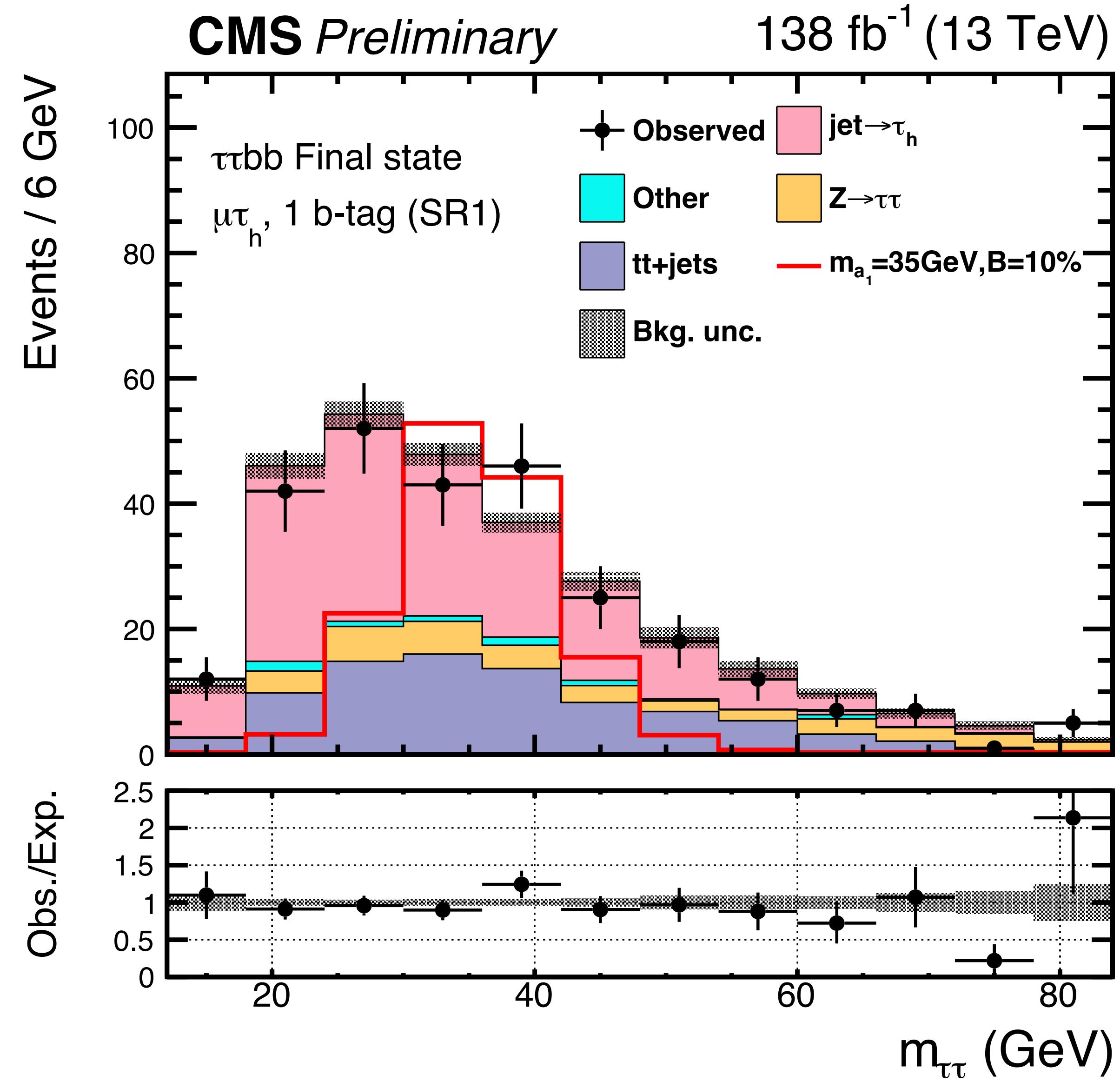


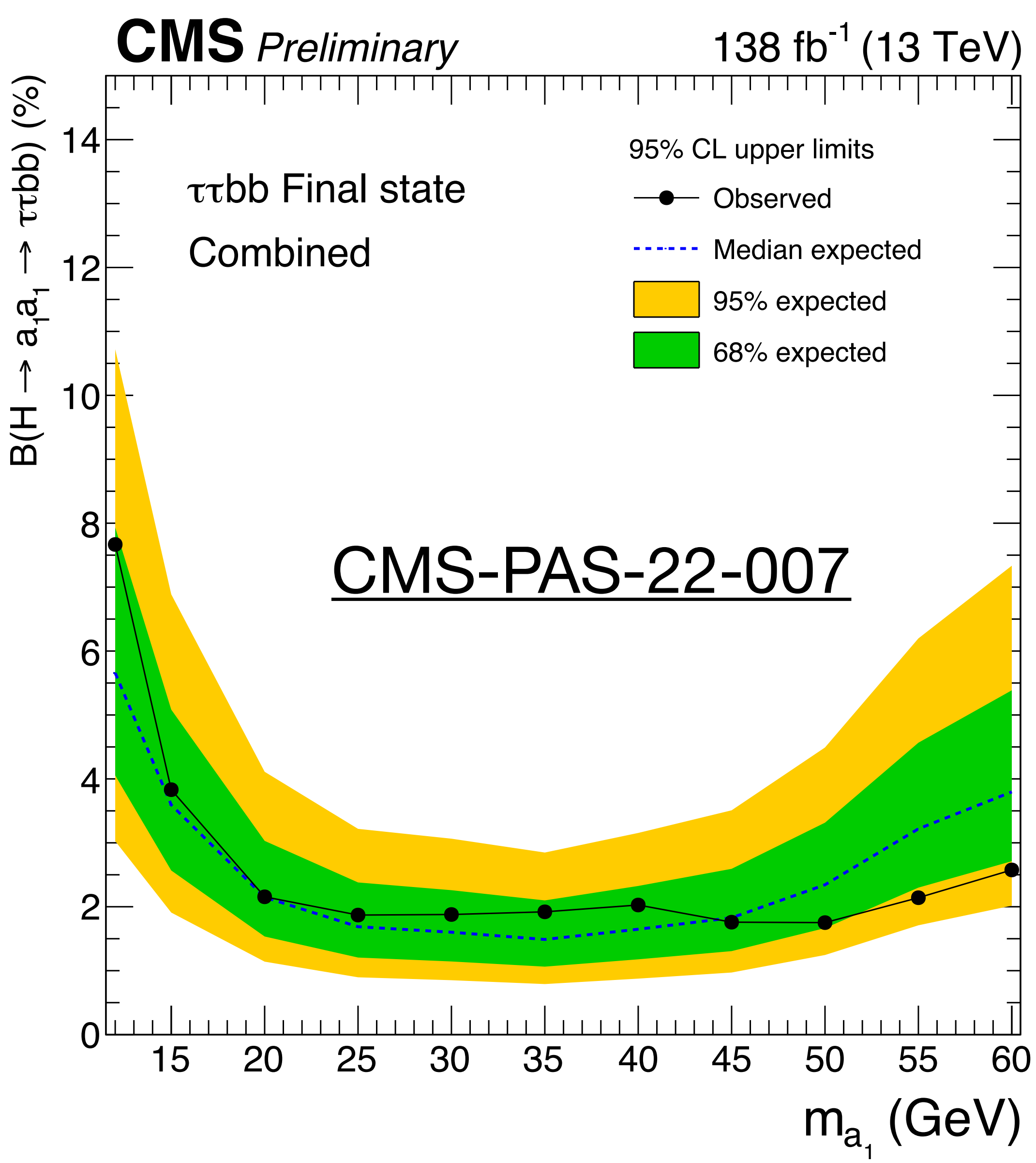


- Final state bb has the largest branching fraction from pseudo-scalar boson decays
- Improvement of sensitivity over earlier CMS results by a factor of 2

H → aa → ττbb

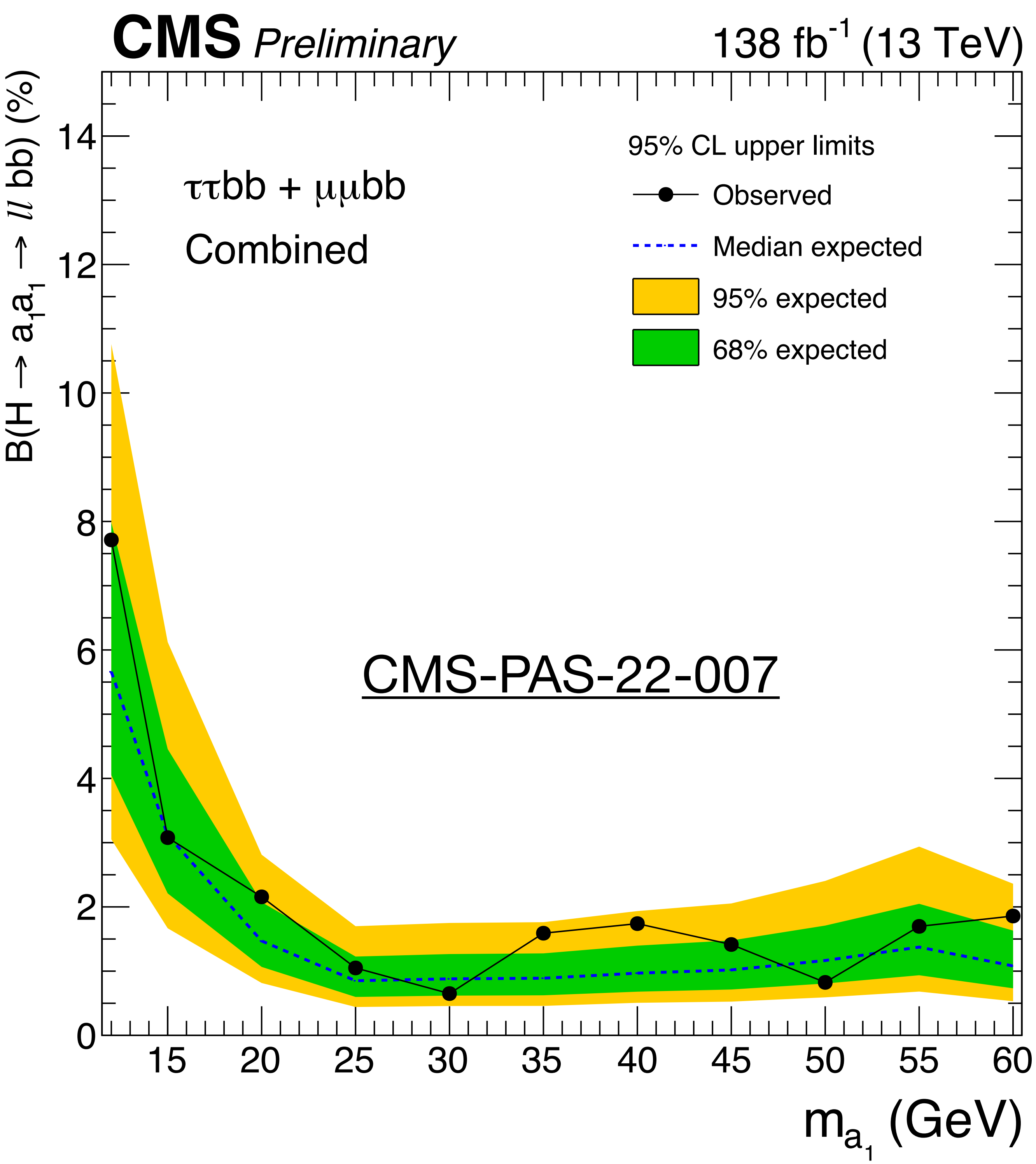


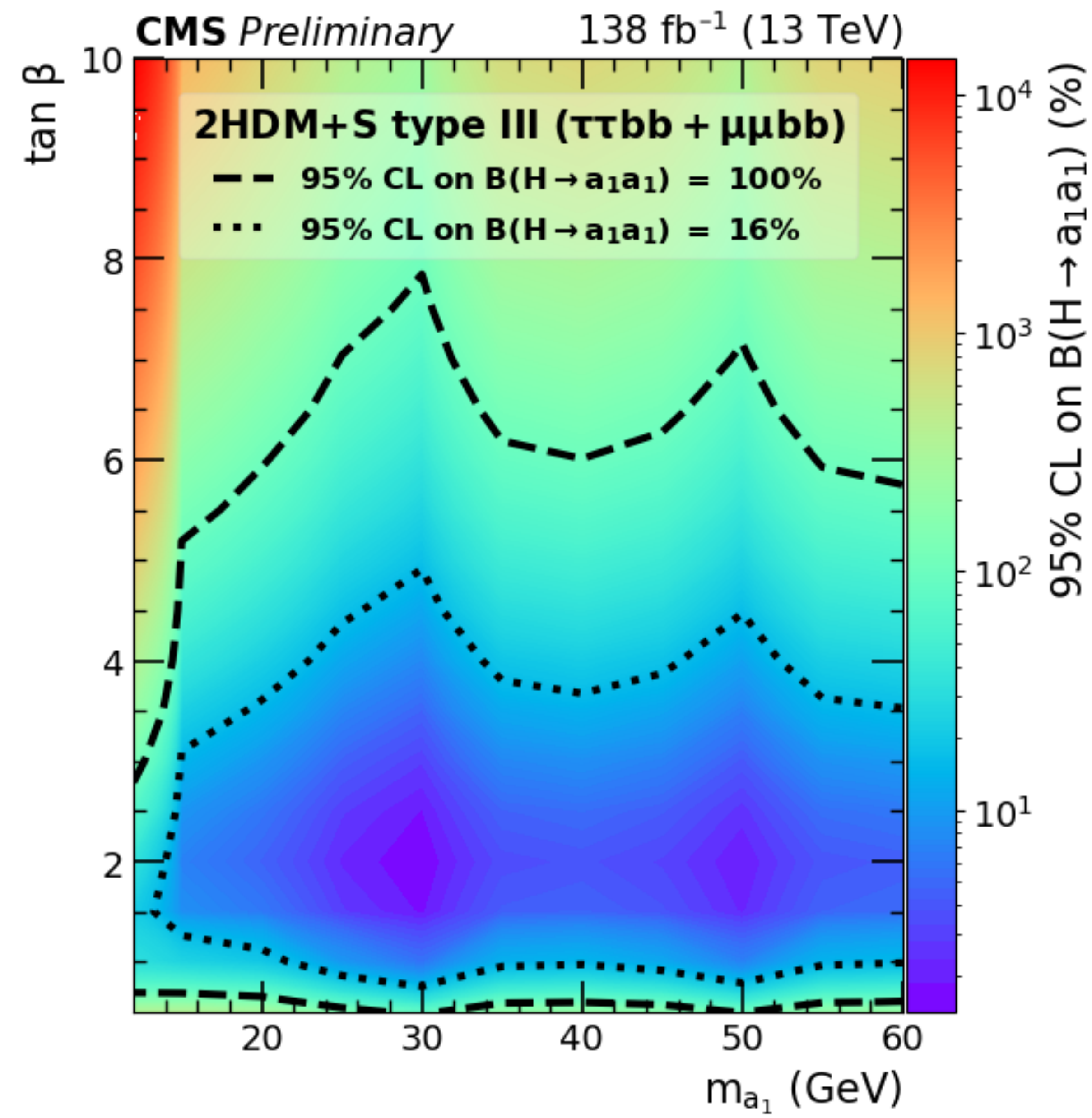




- Final state bb has the largest branching fraction from pseudo-scalar boson decays
- Final state ττ has the second largest branching fraction from pseudo-scalar boson decays

H → aa → ττbb combined with H → aa → μμbb



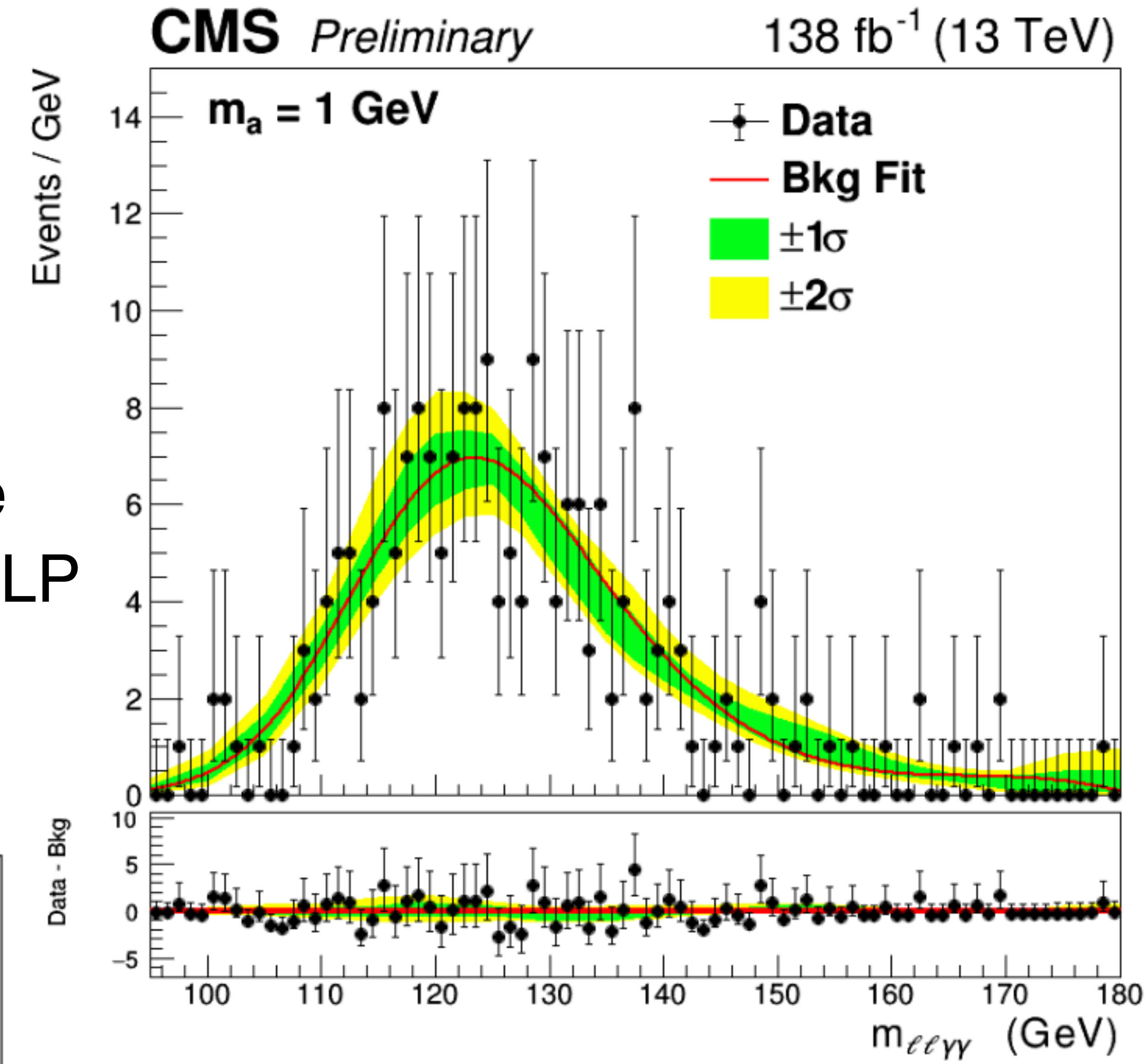


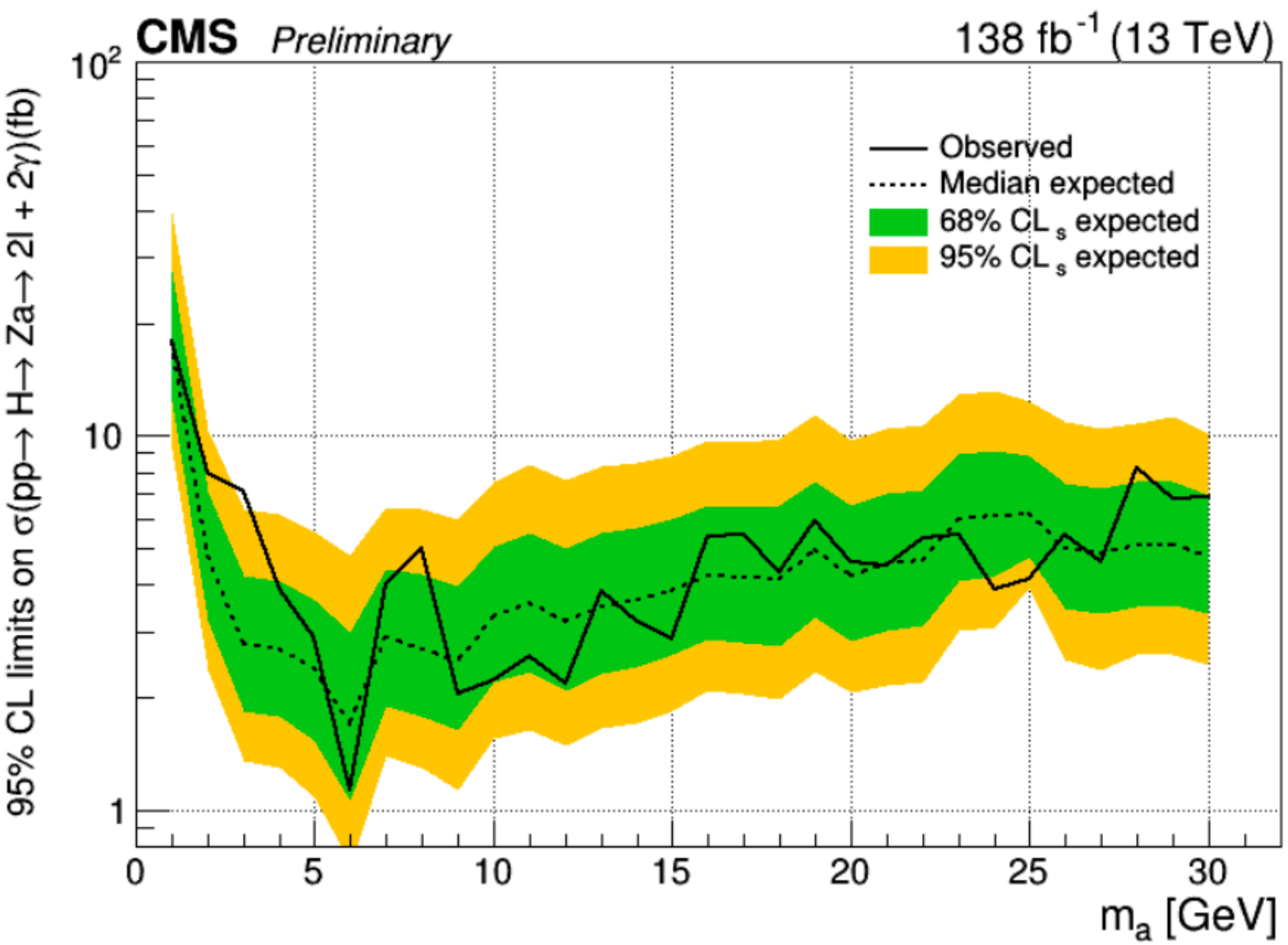
- Most of type-2 models:
  - branching ratio of H→aa above 23% are excluded for 15 < M(a) < 60 GeV at 95% confidence level

H → Za → llγγ

CMS-PAS-22-003

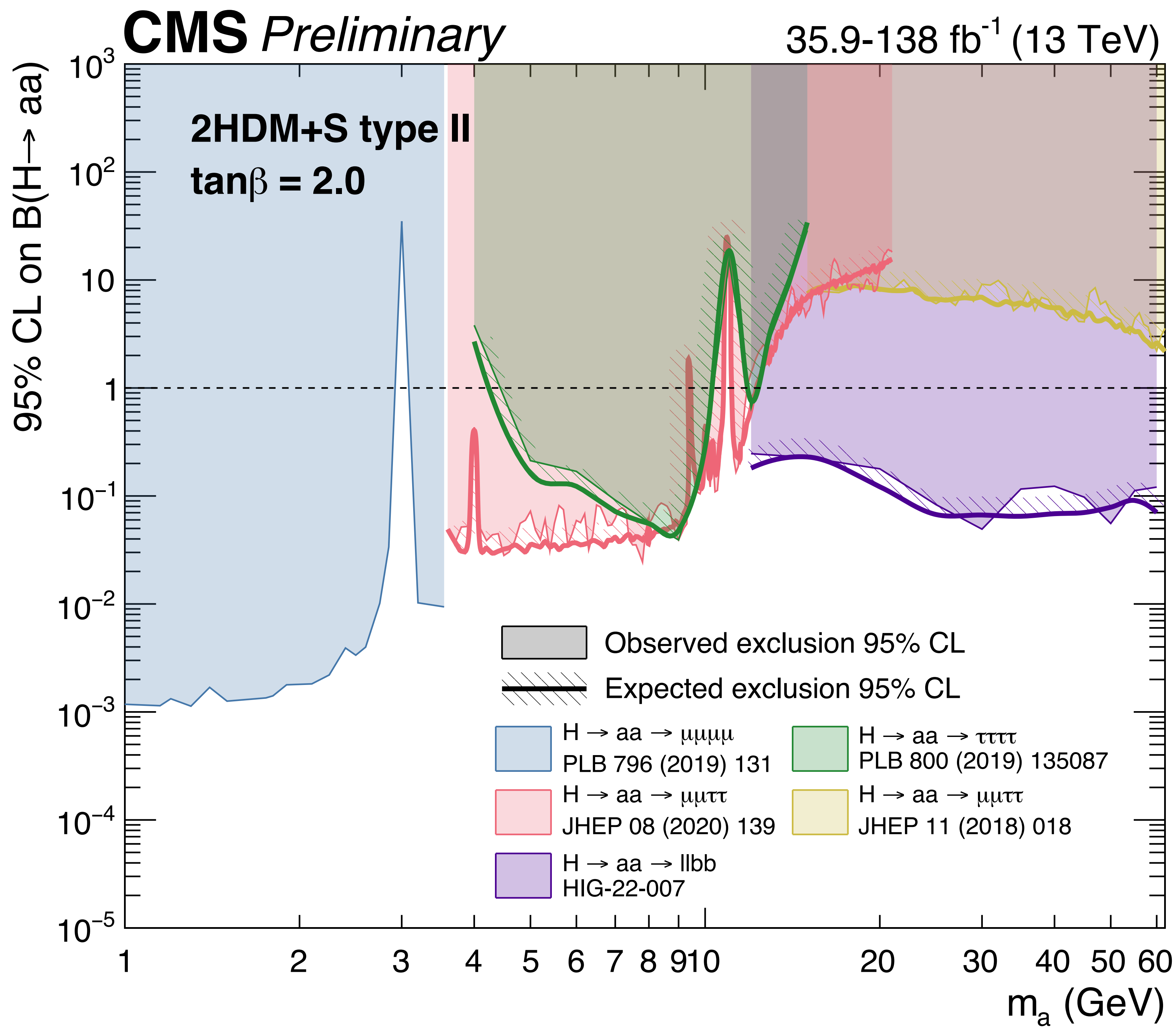
- Constraints are set on the axion-like-particle model parameter, which describe the coupling between the H and Z, and ALP





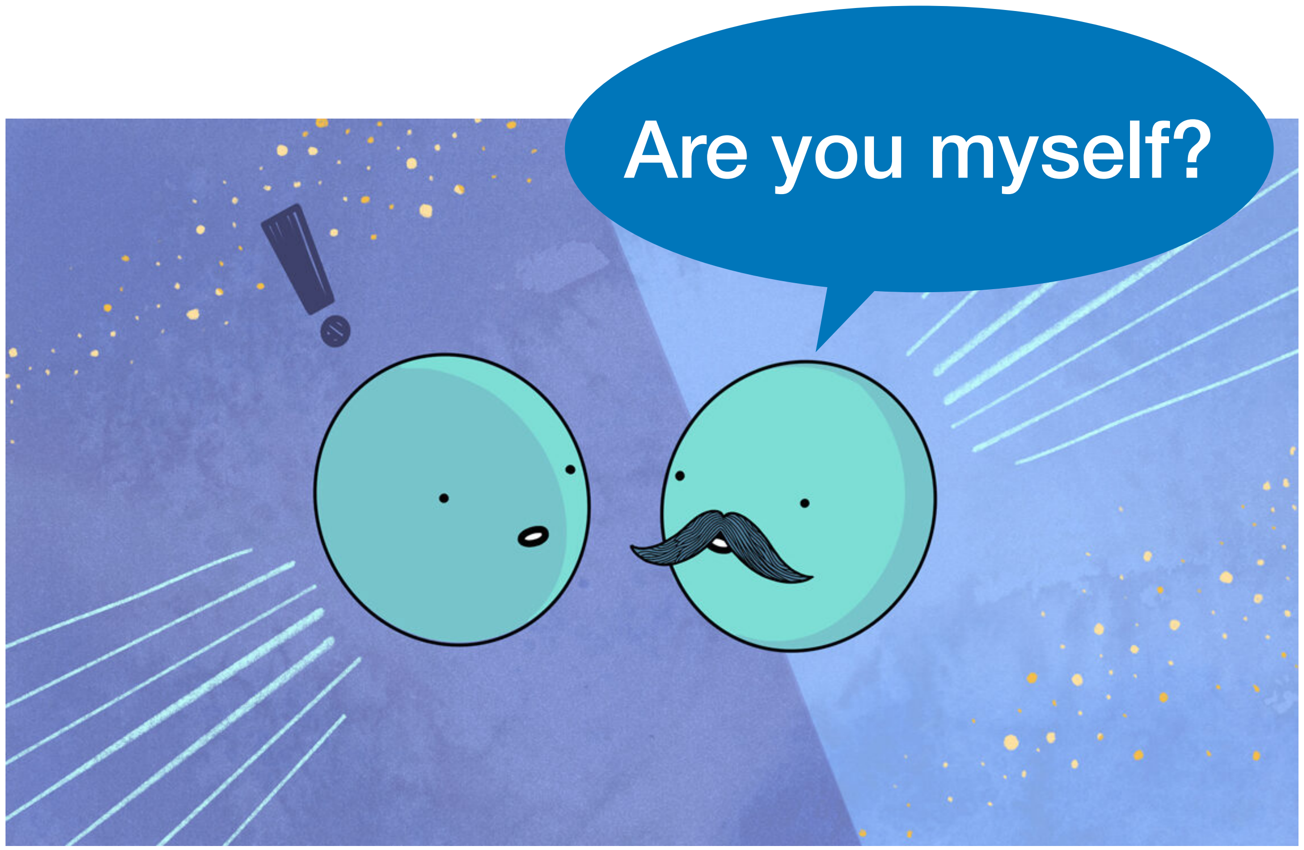
- First search on this final state
- It provides complementary channel for search for axion-like particles (ALPs)
- It could be extended to lower ALP mass in future

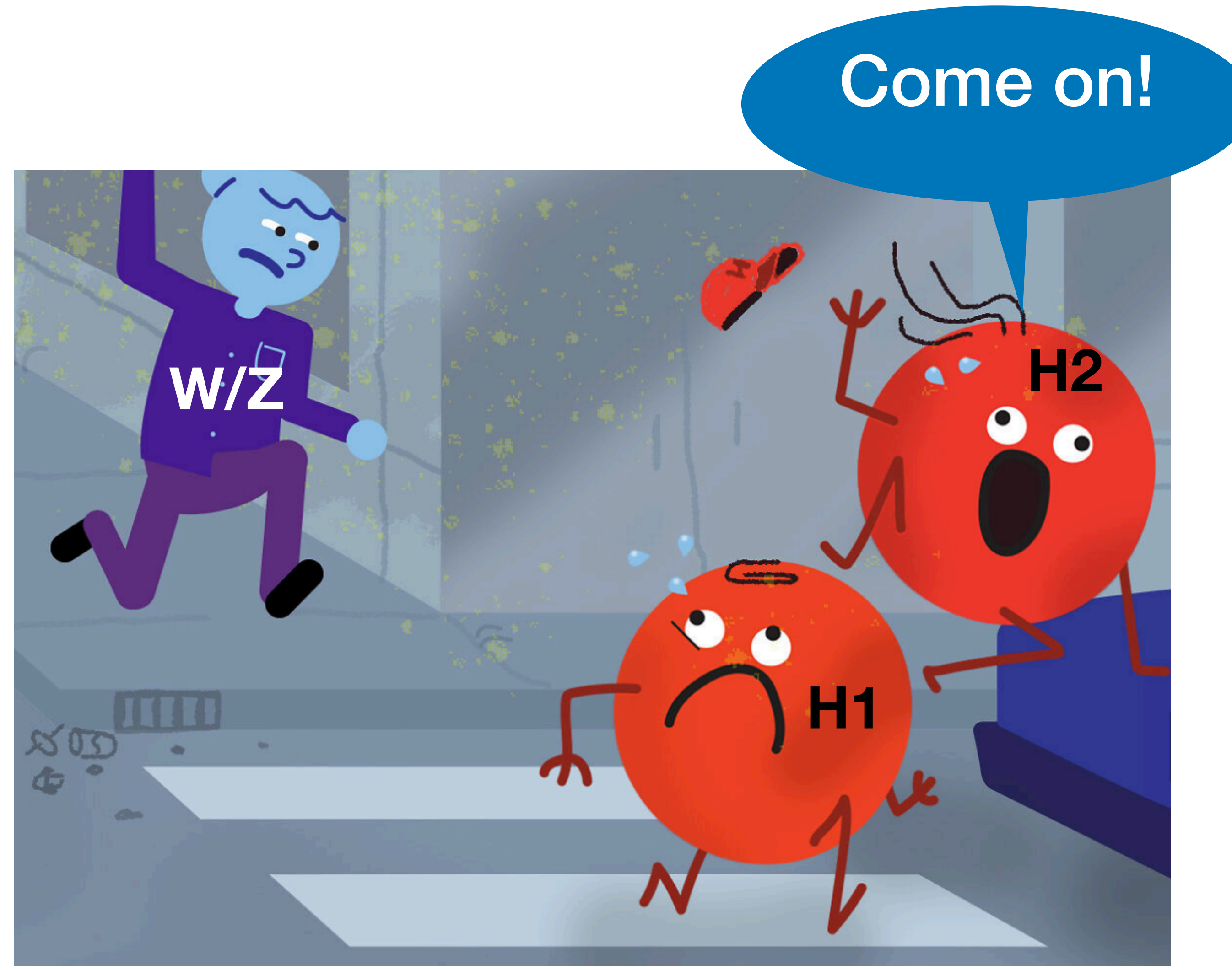
Summary: H → aa



CMS-HDMS-Run2

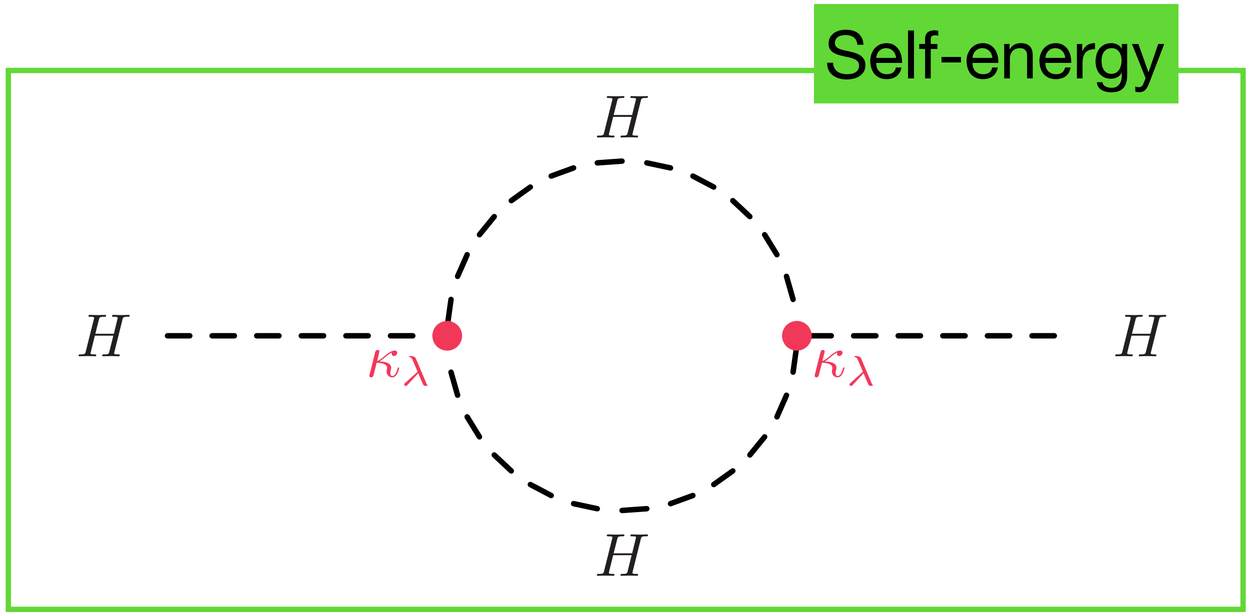
Higgs self coupling & pair searches

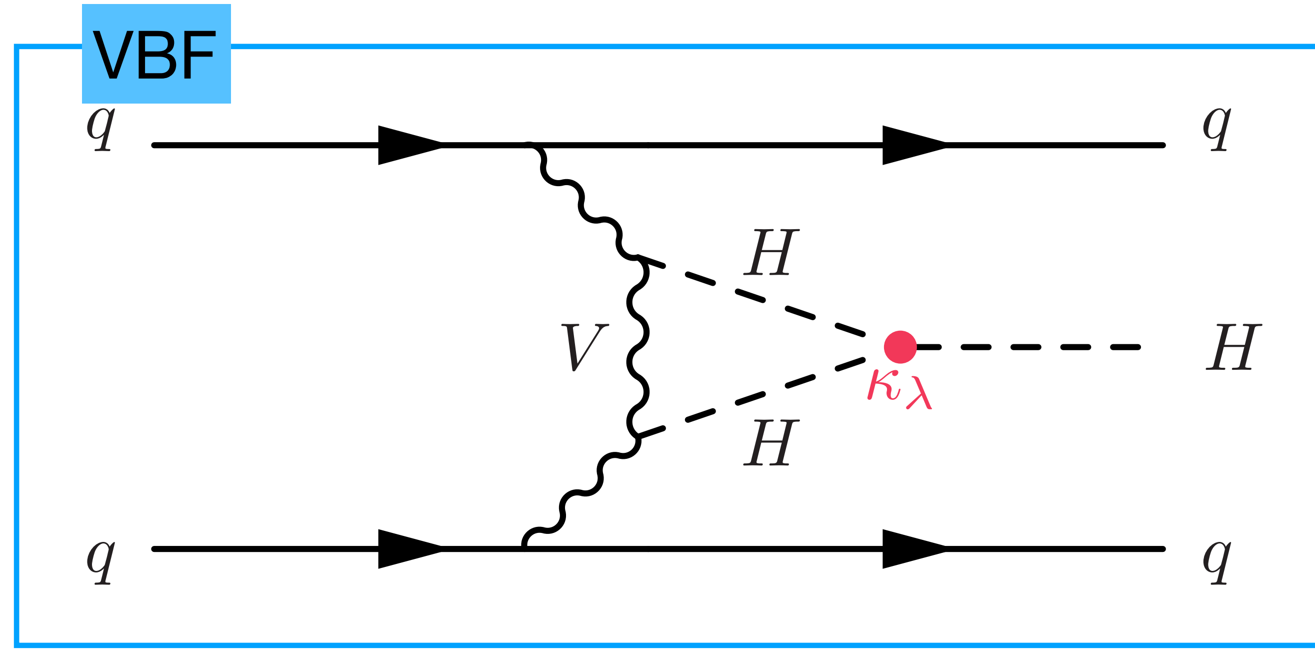


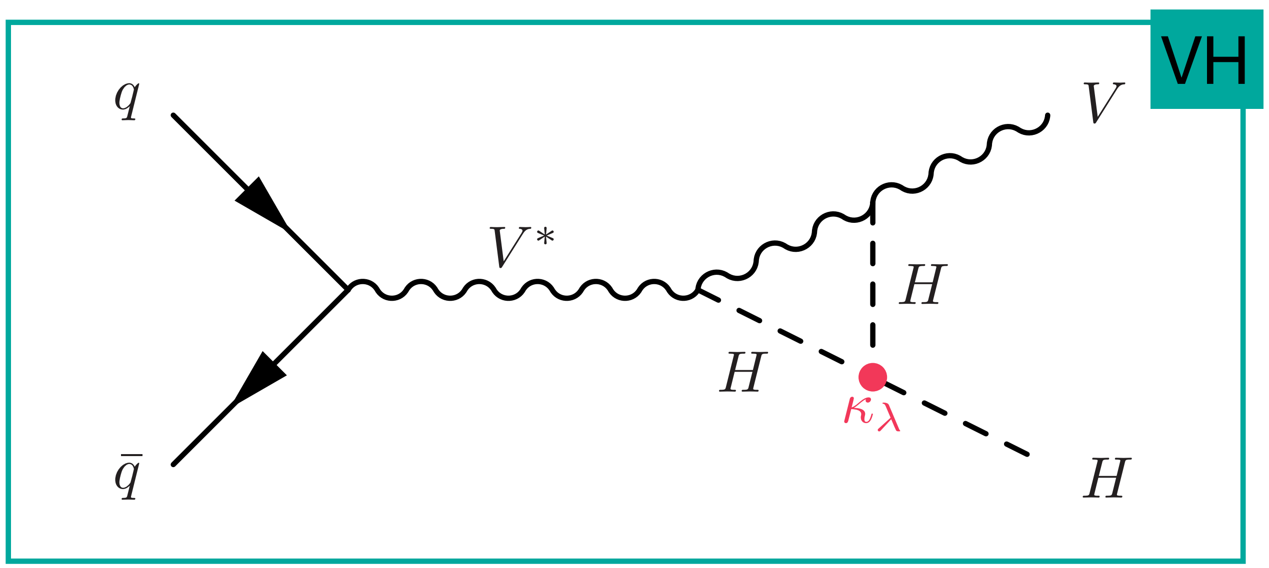


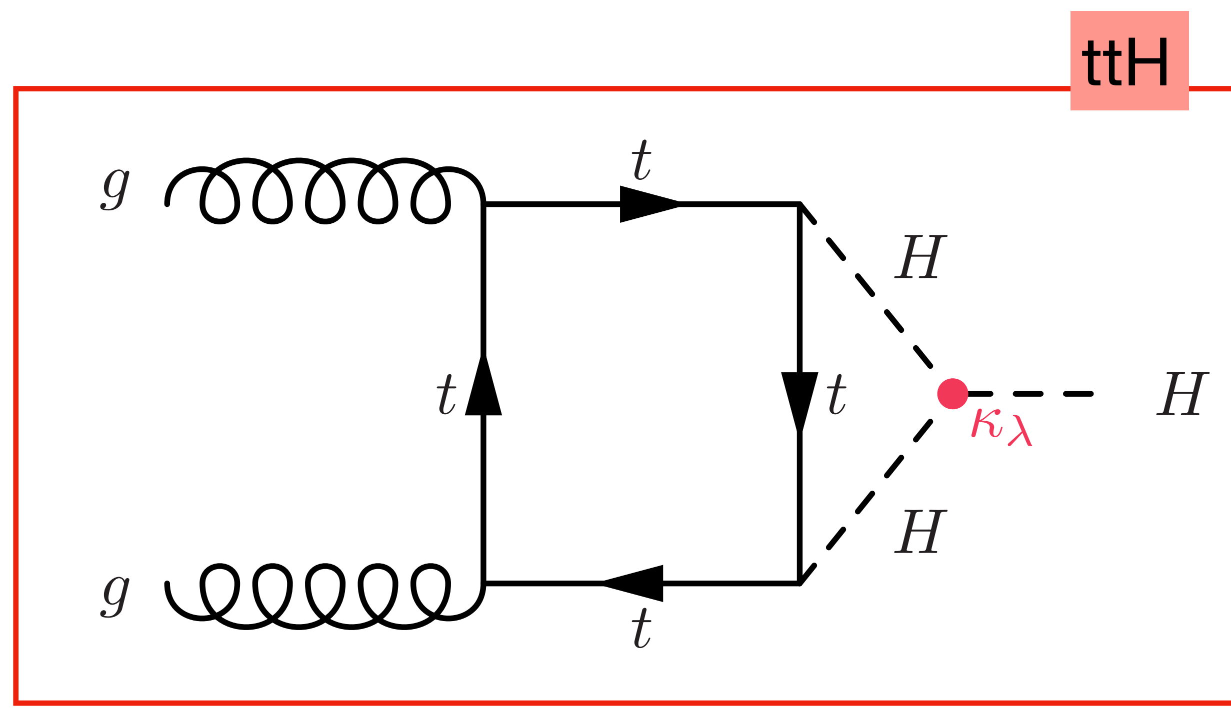
- Two Higgs doublet models
- Minimal supersymmetric extension of SM
- Composite Higgs models
- Twin Higgs models (partially explain the hierarchy problem)

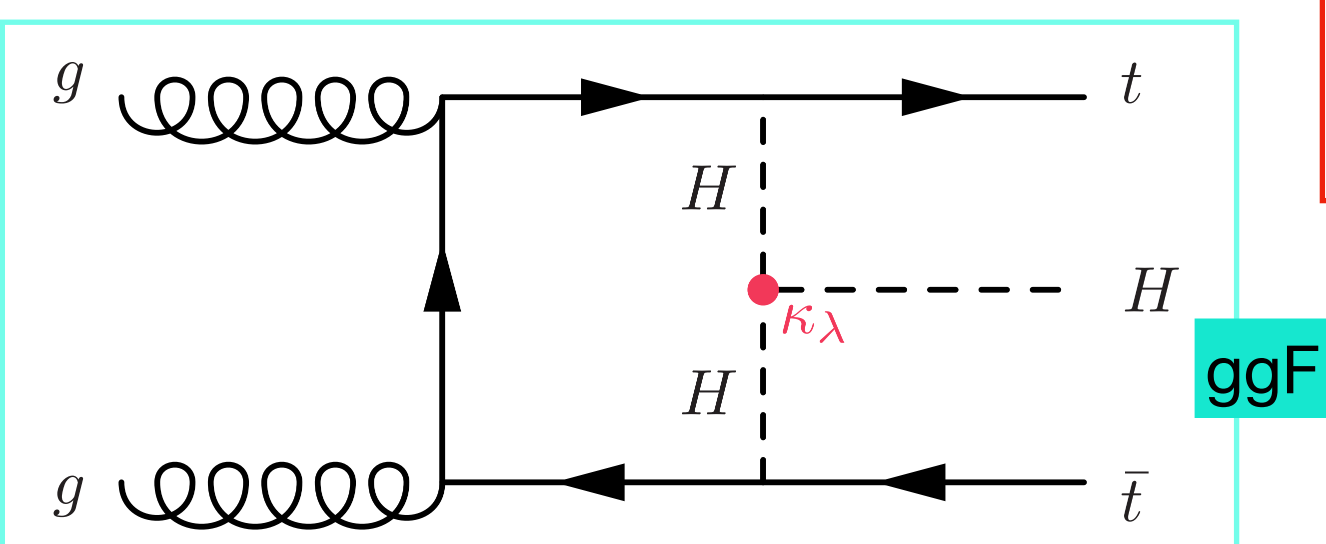
Higgs self coupling: examples





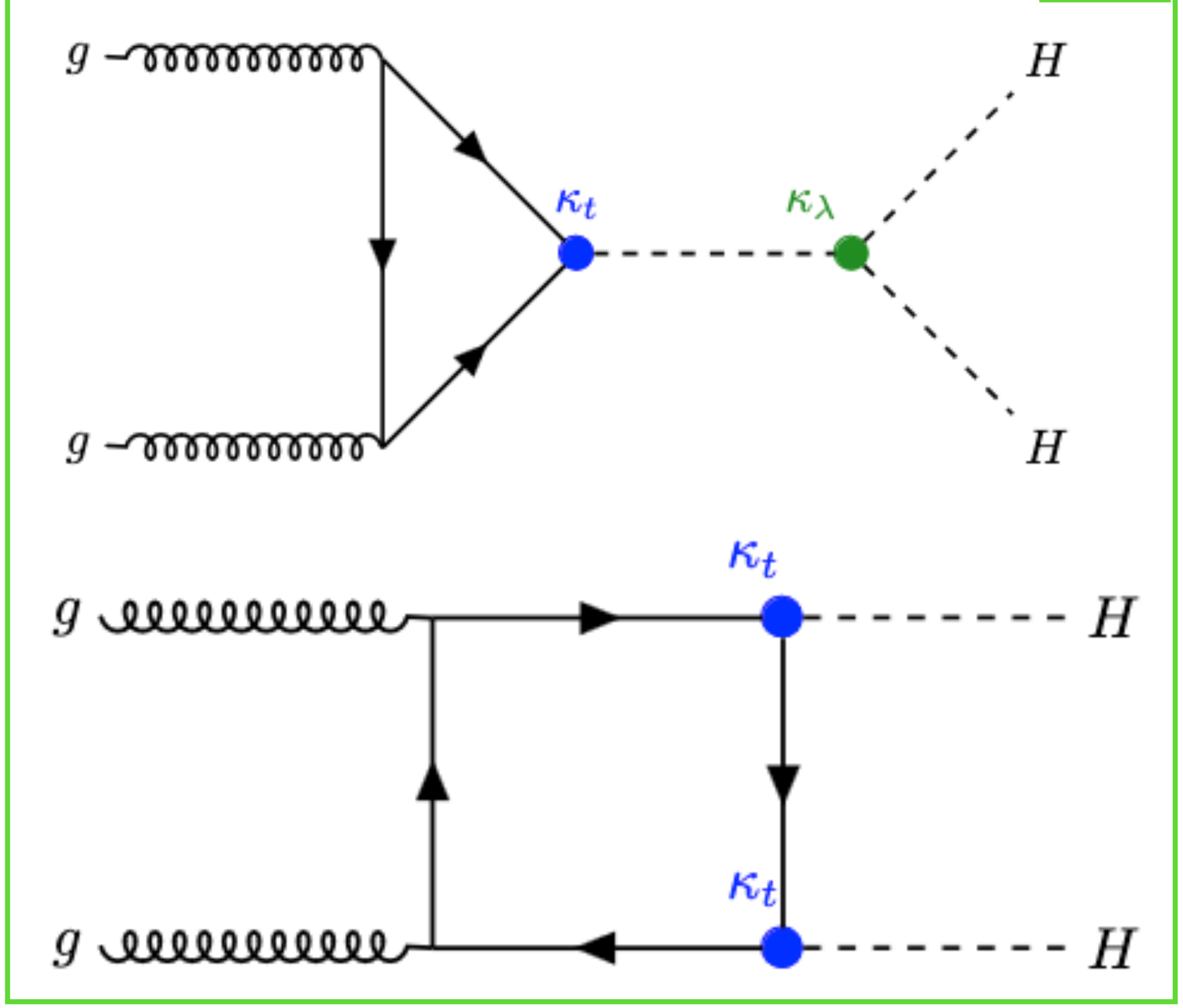




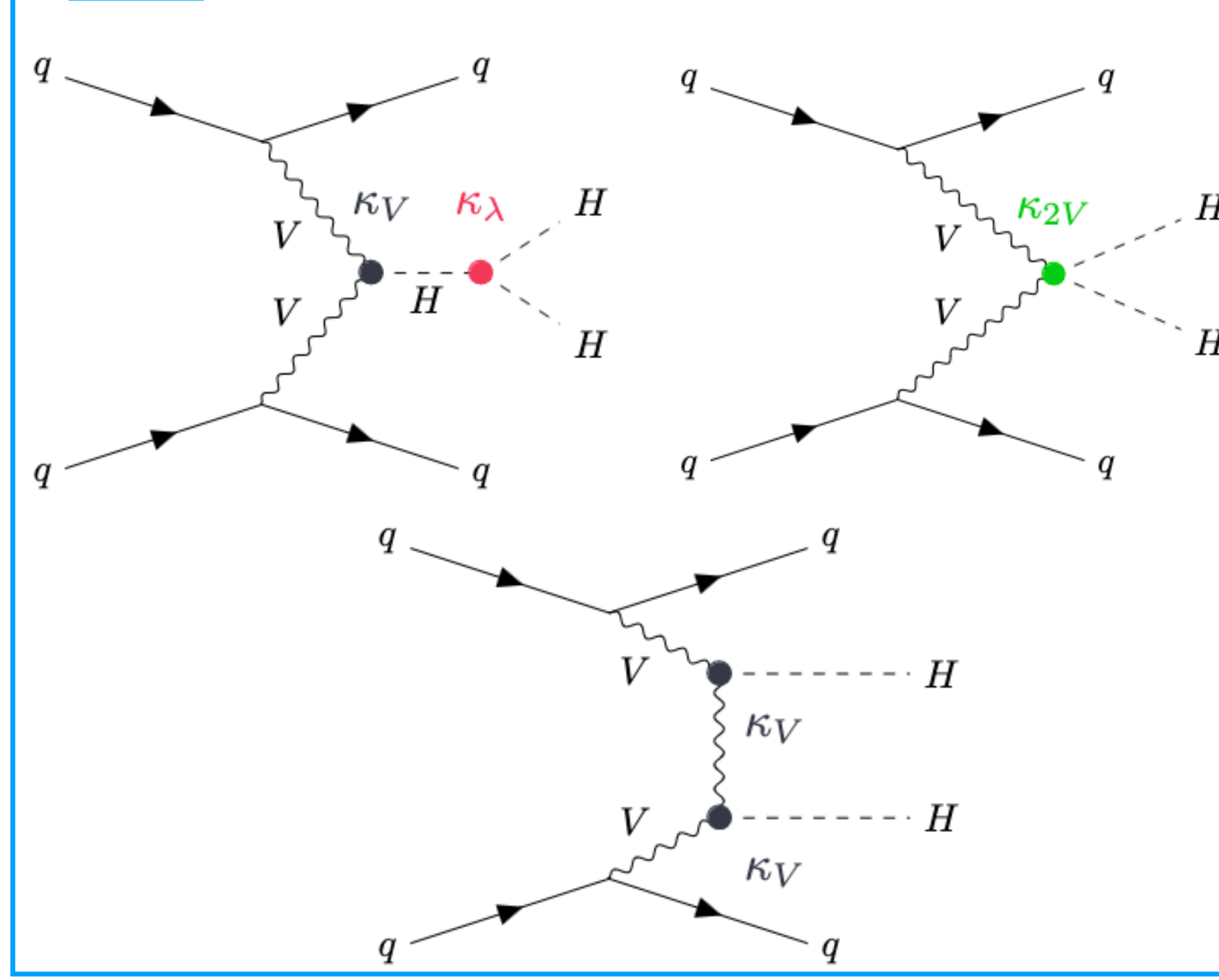


Higgs pair searches: examples

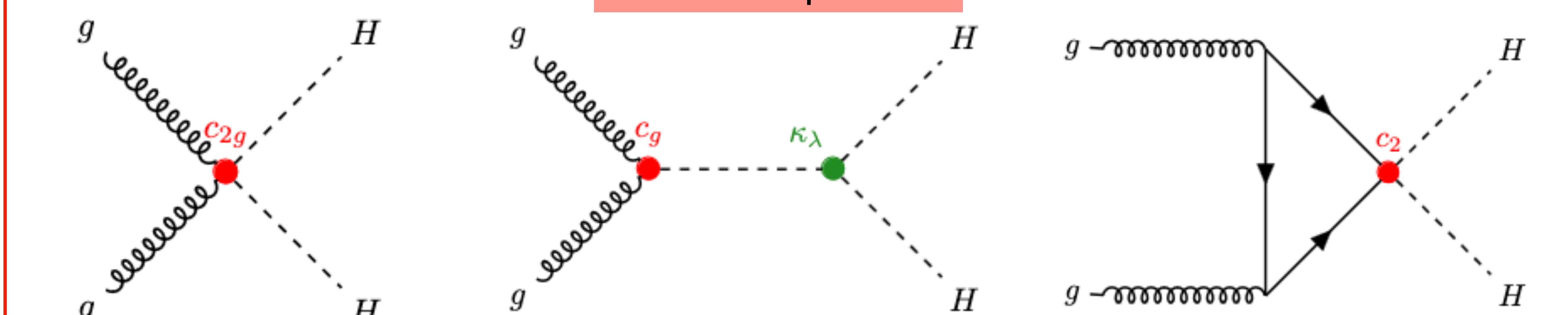
ggF



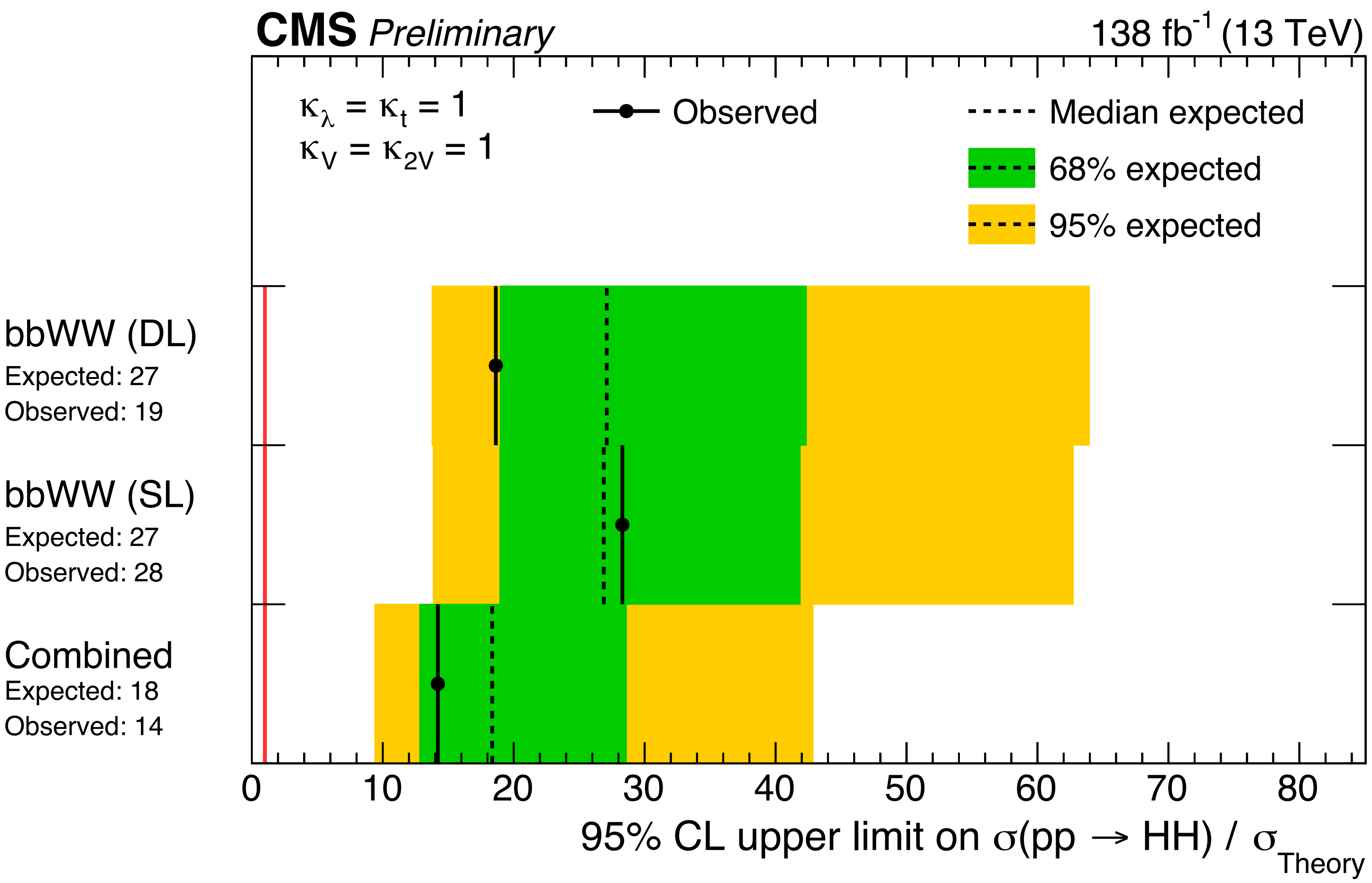
VBF



Pure BSM process

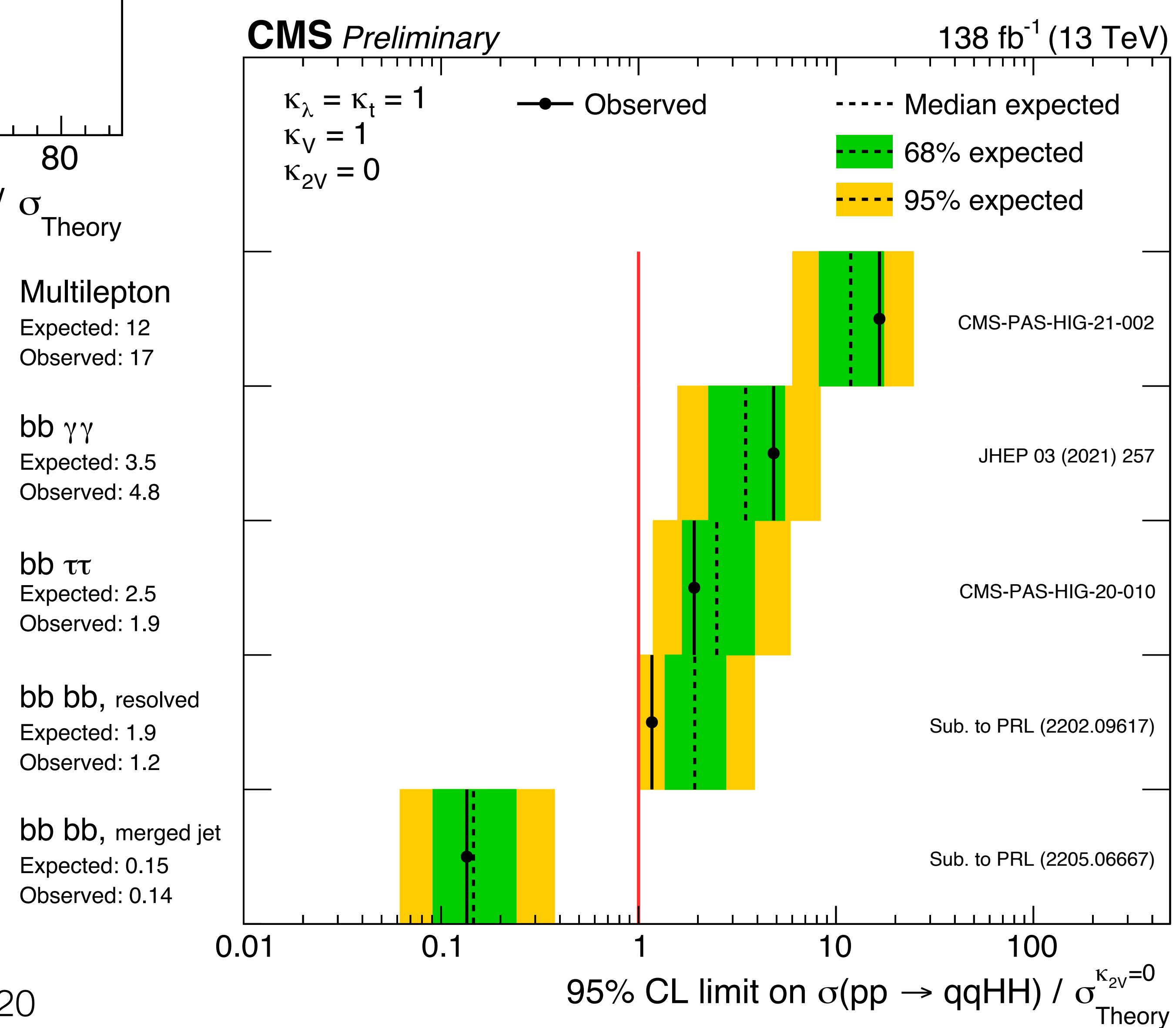


Higgs pair searches (non-resonant)



CMS-PAS-HIG-21-005

- Multiple channels of Higgs pair decays have been searched using advanced DNN technique

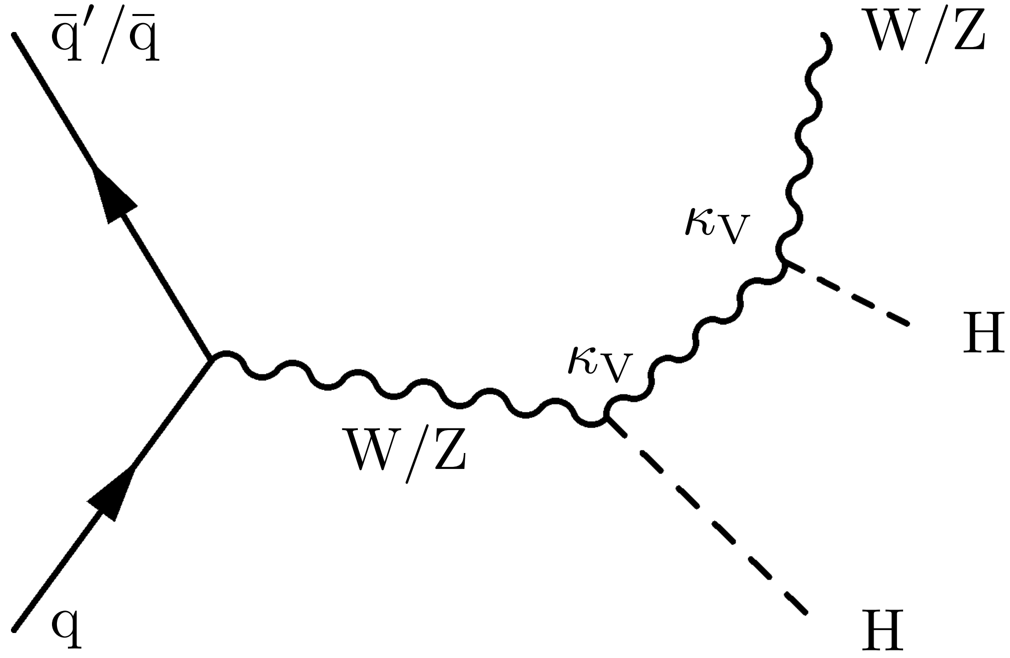


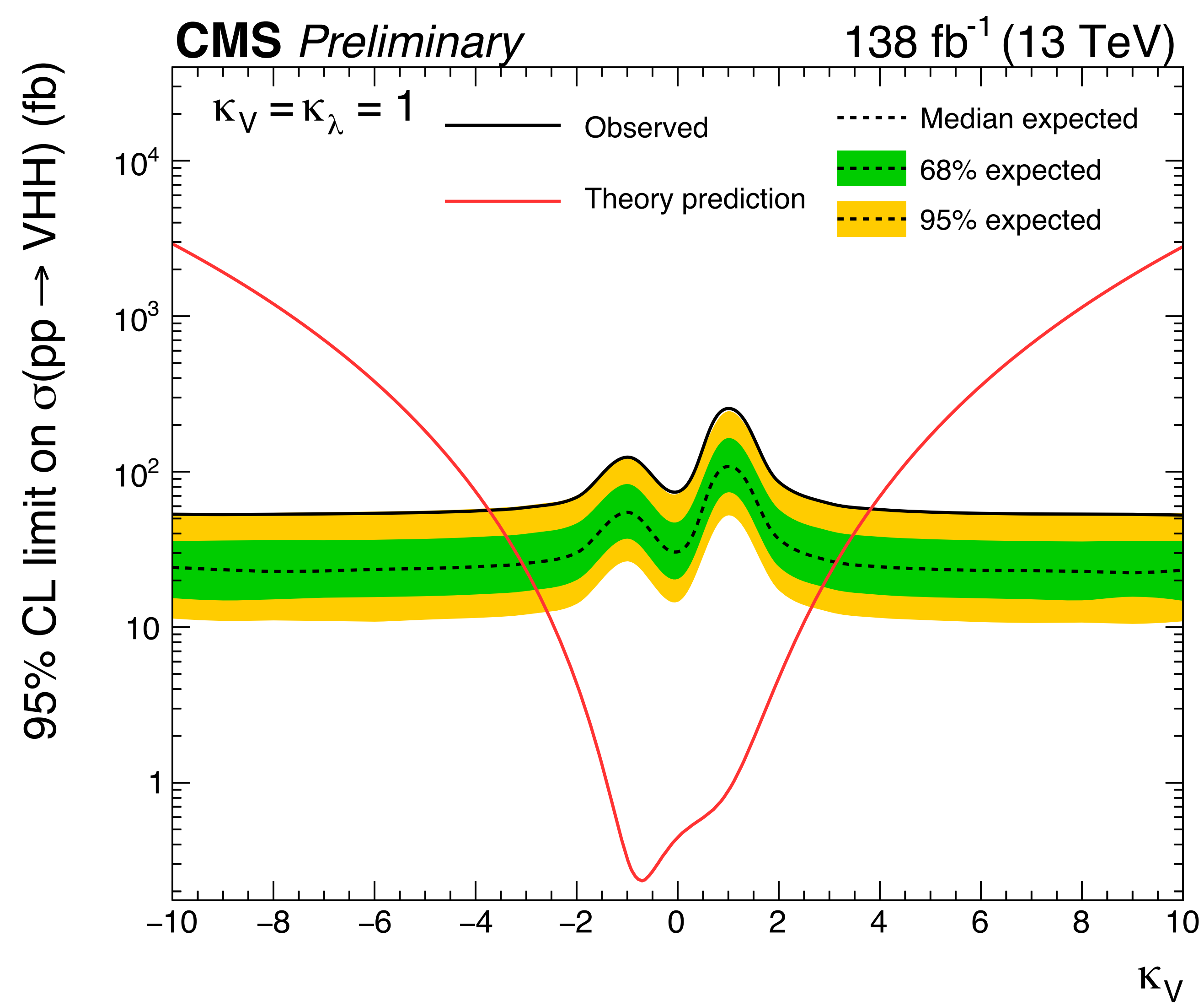
- The combined limits are compatible with the background-only hypothesis using the full RunII dataset

CMS-HIG-PublicResults

VV coupling with Higgs pair searches (non-resonant)

CMS-PAS-HIG-22-006

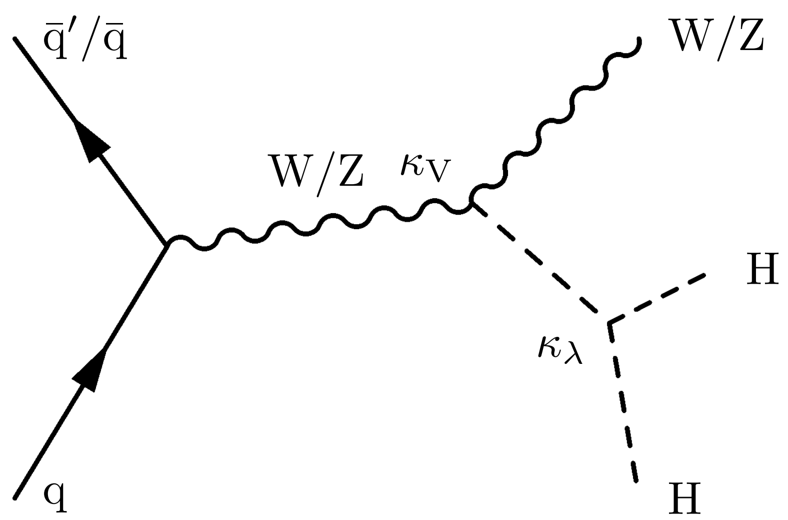


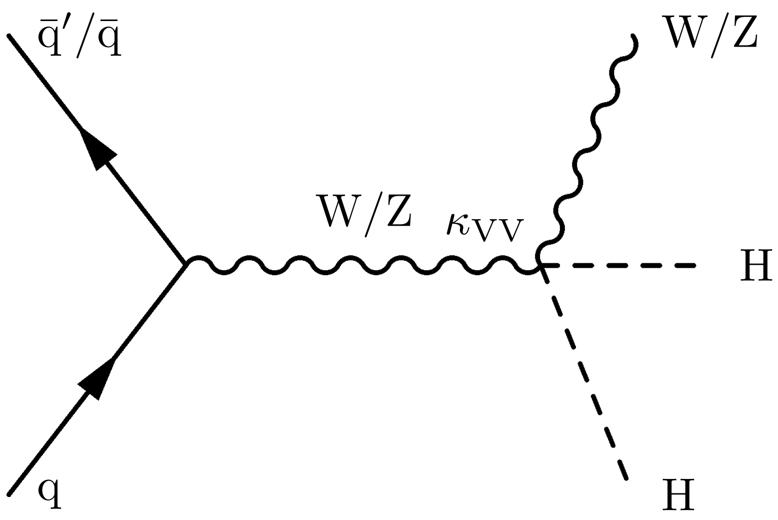


- First analysis to include a fully hadronic channel in the search for non resonant VHH in the HH → bbbb channel
- Each Higgs boson decays into bb pair (branching fraction: 33.9 ± 0.9%)

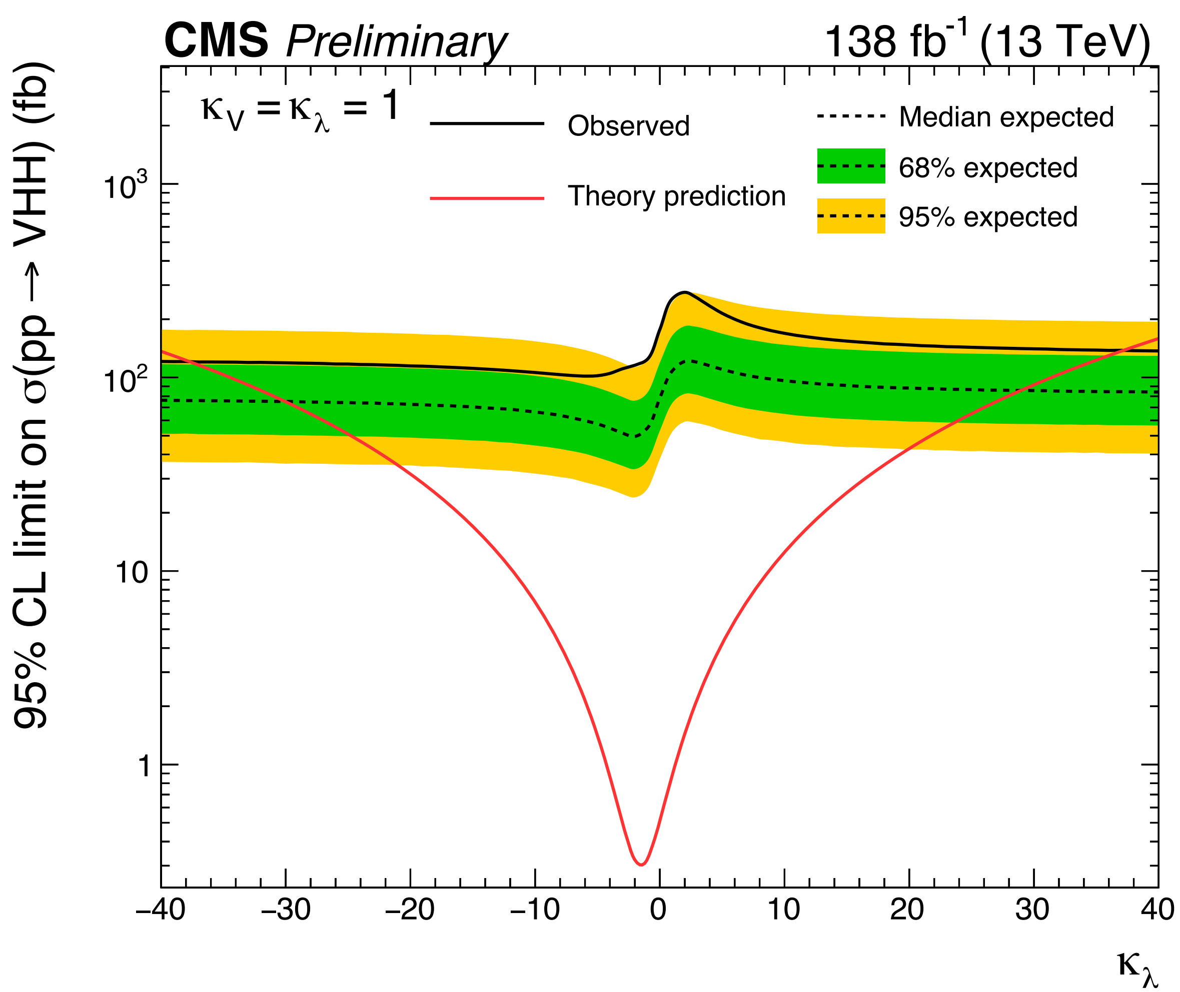
VV coupling with Higgs pair searches

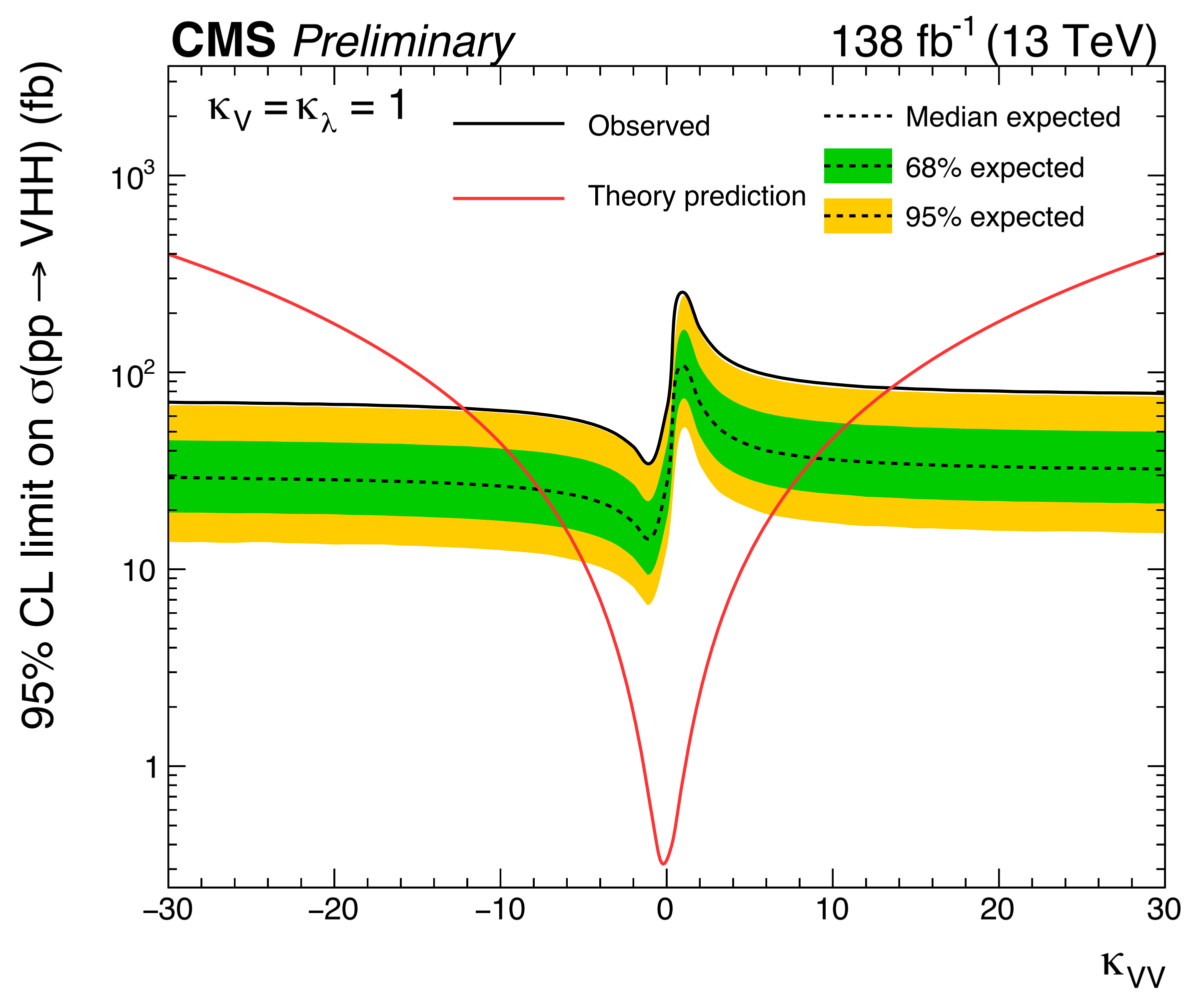
CMS-PAS-HIG-22-006





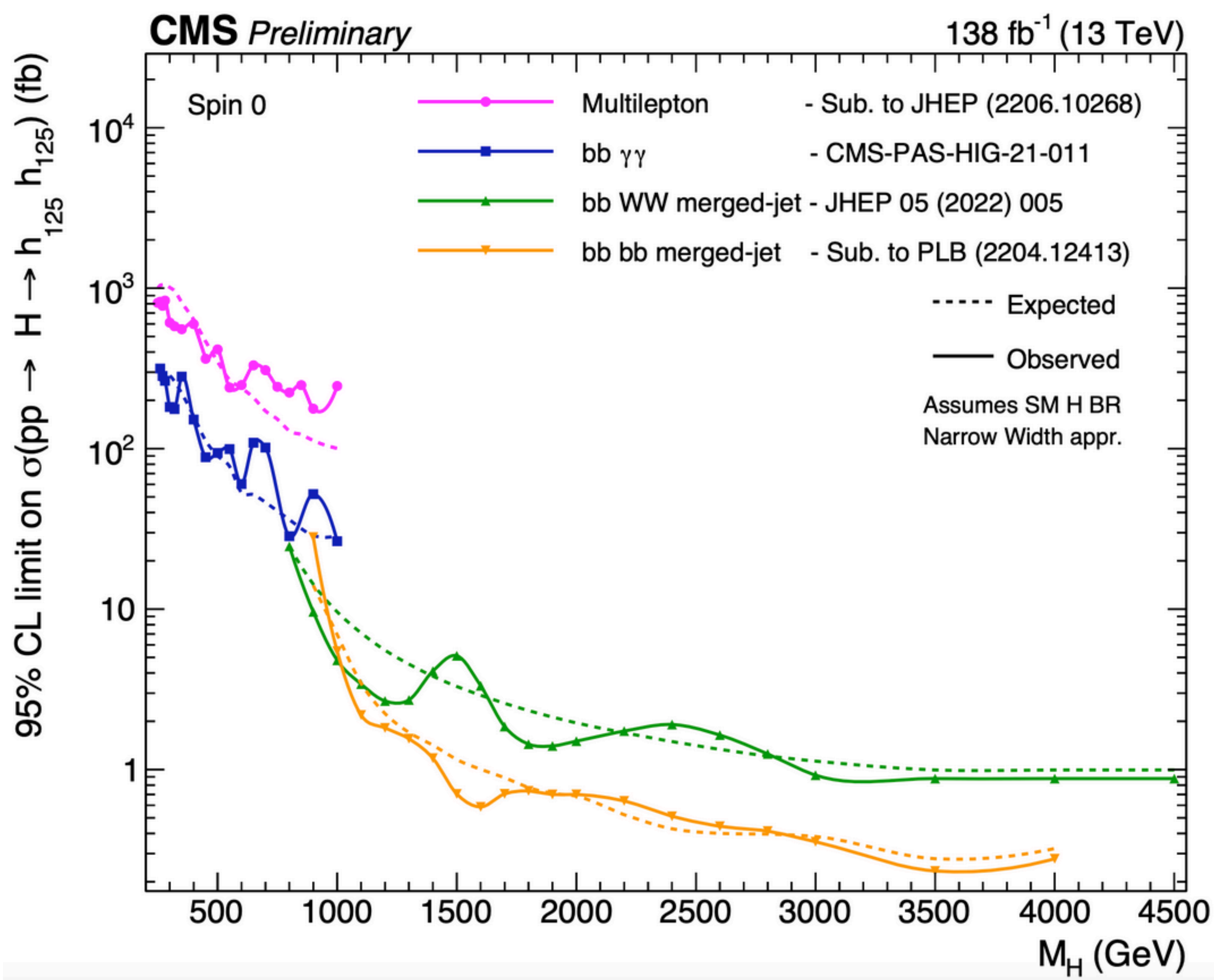
- It could provide us an important information on the EWSB





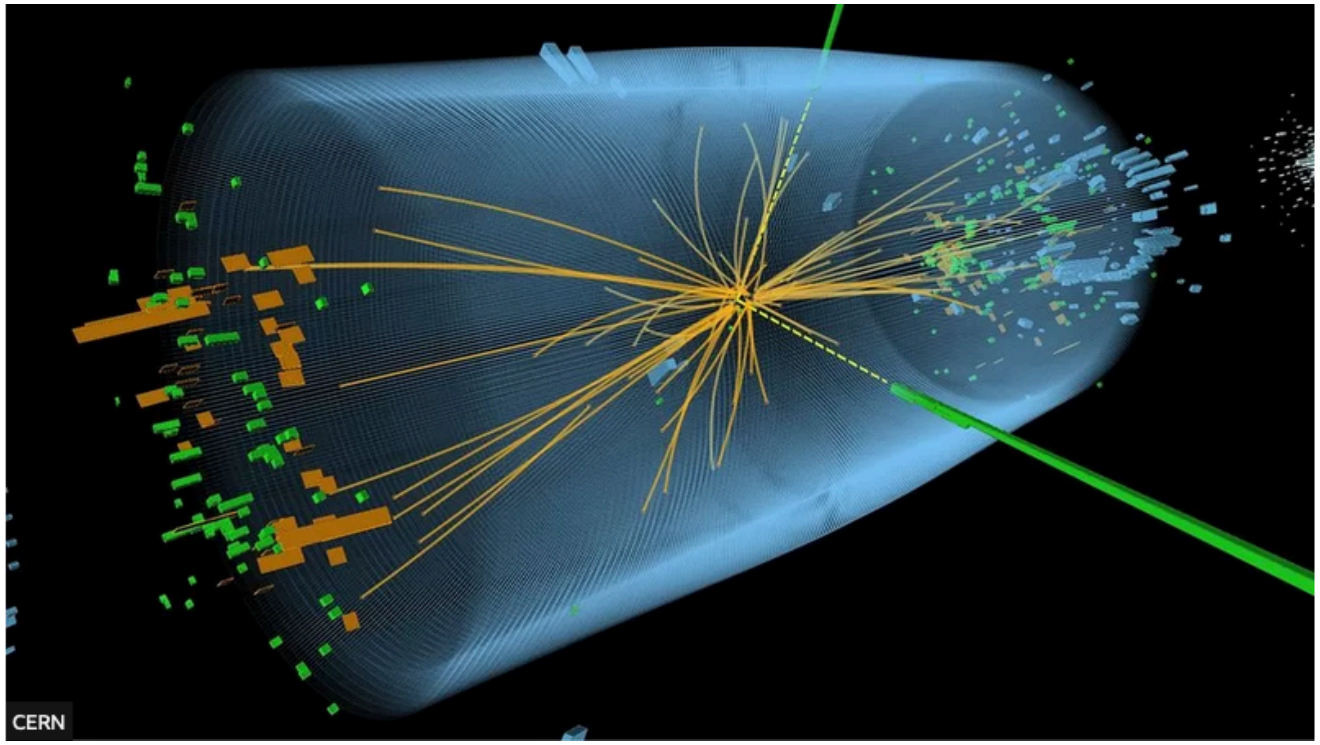
Higgs pair searches (resonant)

CMS-HIG-PublicResults

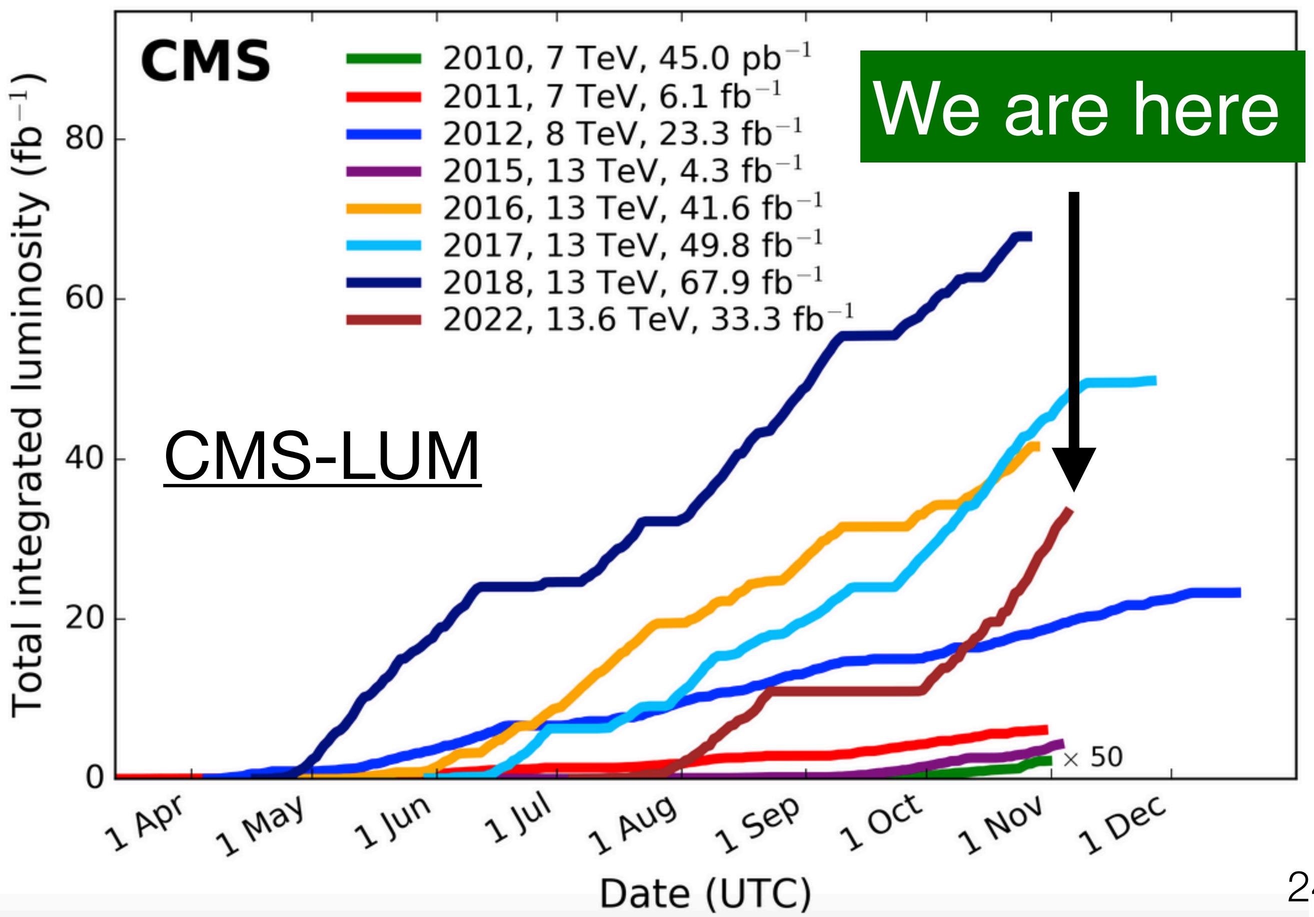


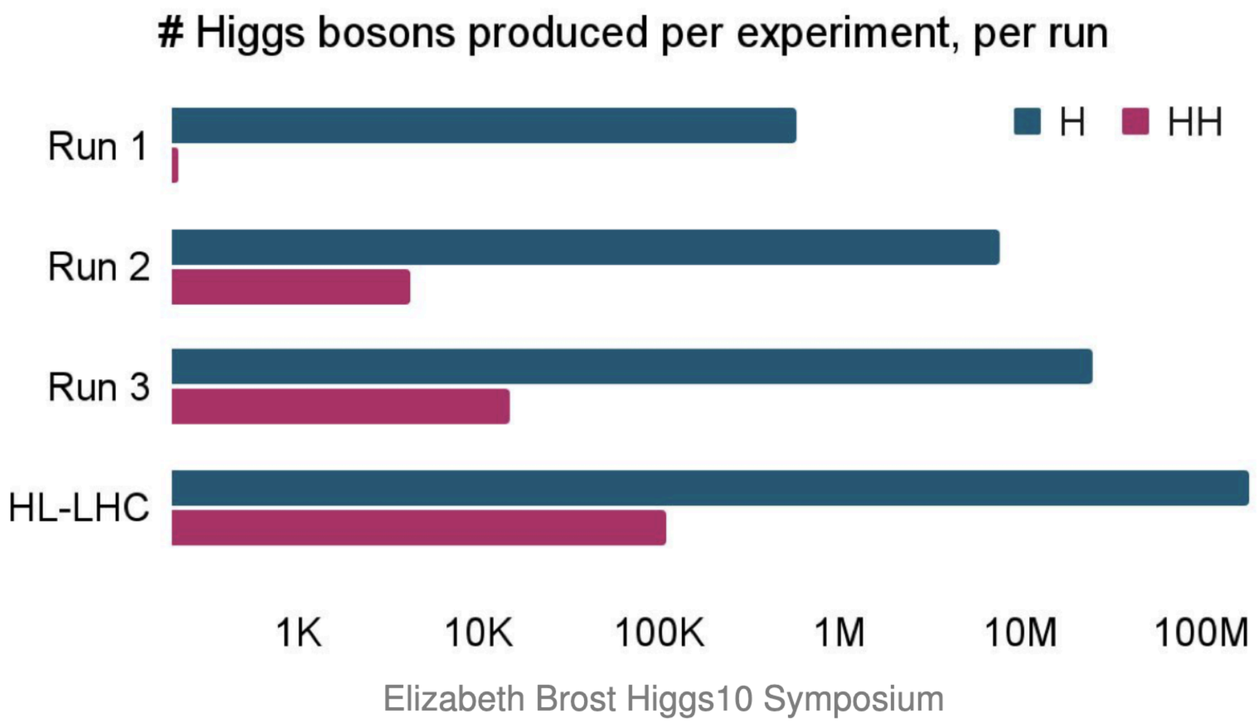
- Discontinuities are caused by the partial availability of different analysis limits
- Two hypotheses from Higgs Effective Field Theory:
  - spin-0 (radion) & spin-2 (graviton)

A few words about the history and future…



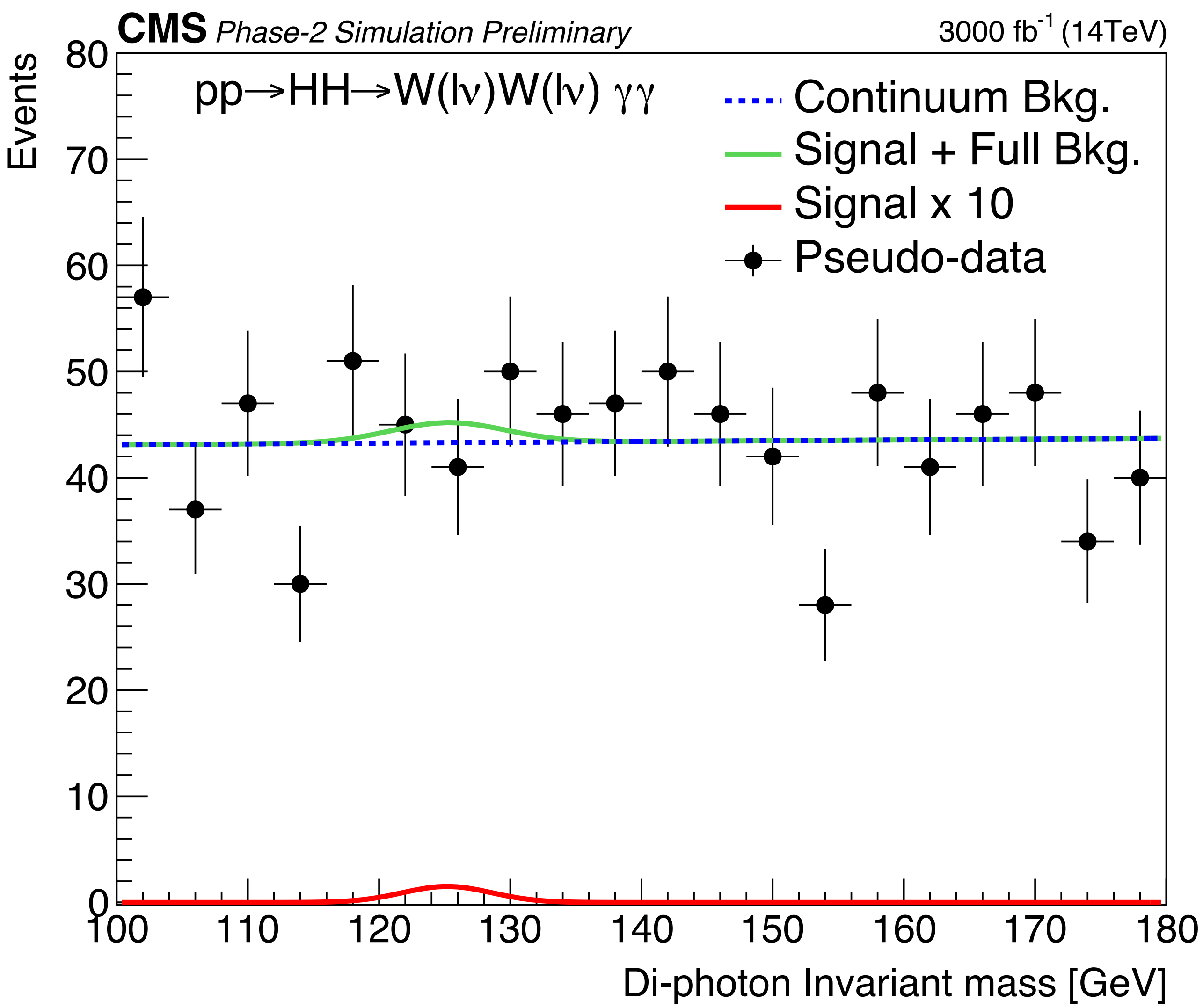
- LHC RunIII with 13.6 TeV has started despite the energy crisis
- It is expected to collect physics data about 1.5 times than RunII

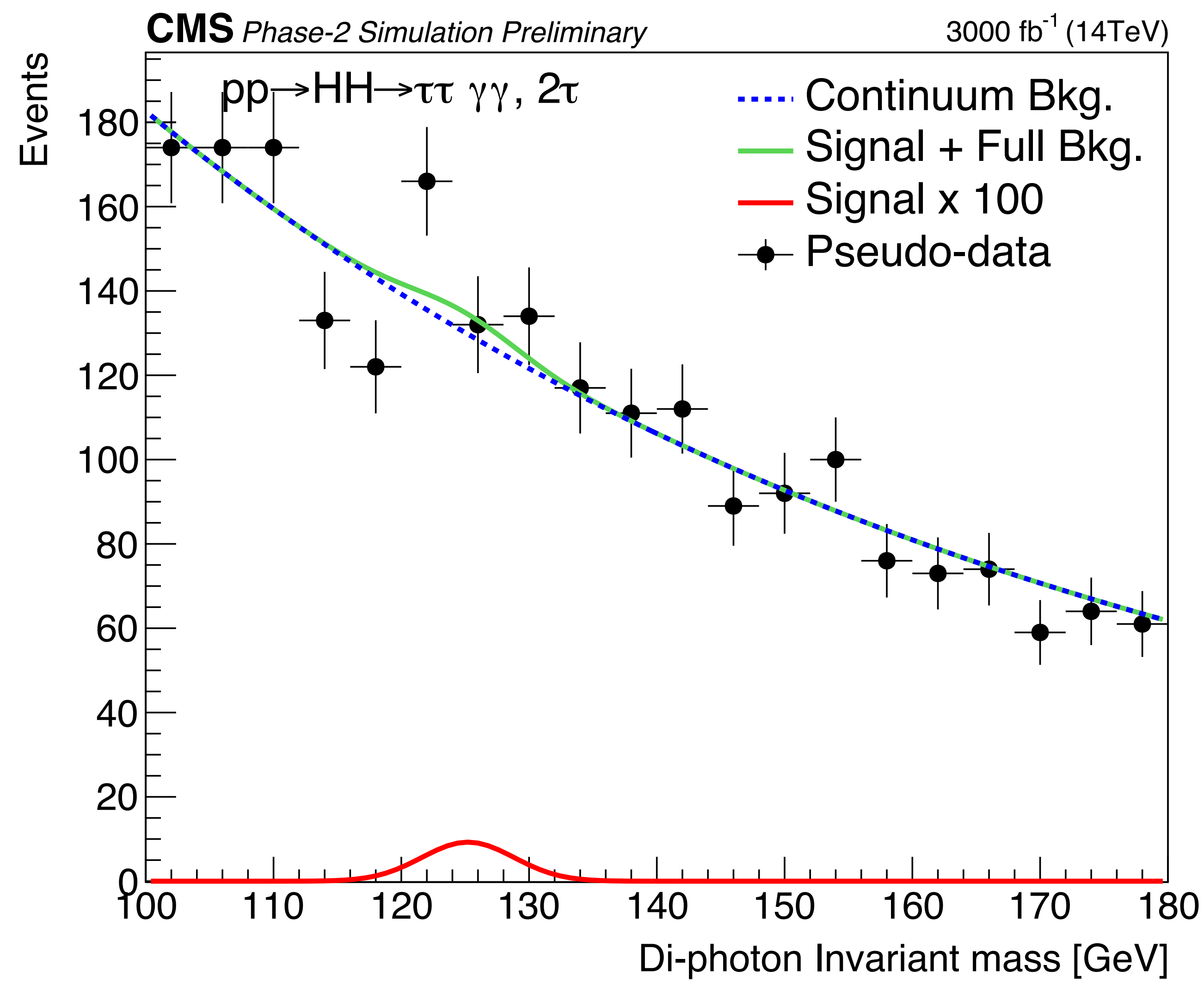




The road to di-Higgs observation?

CMS-PAS-FTR-21-003





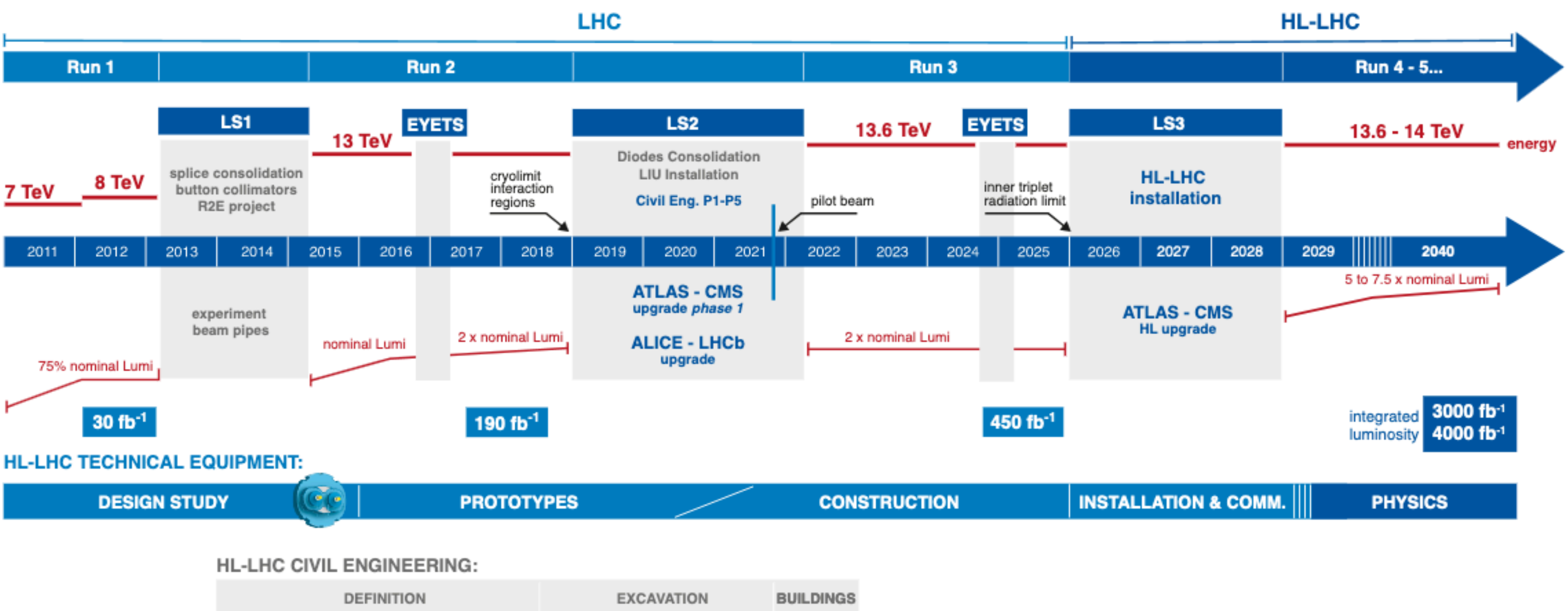
- BR(H → bb) = 58%: Main HH channels require one H → bb: bbbb, bbγγ, bbττs
- First study on these new channels using DELPHES package

Summary & Outlook

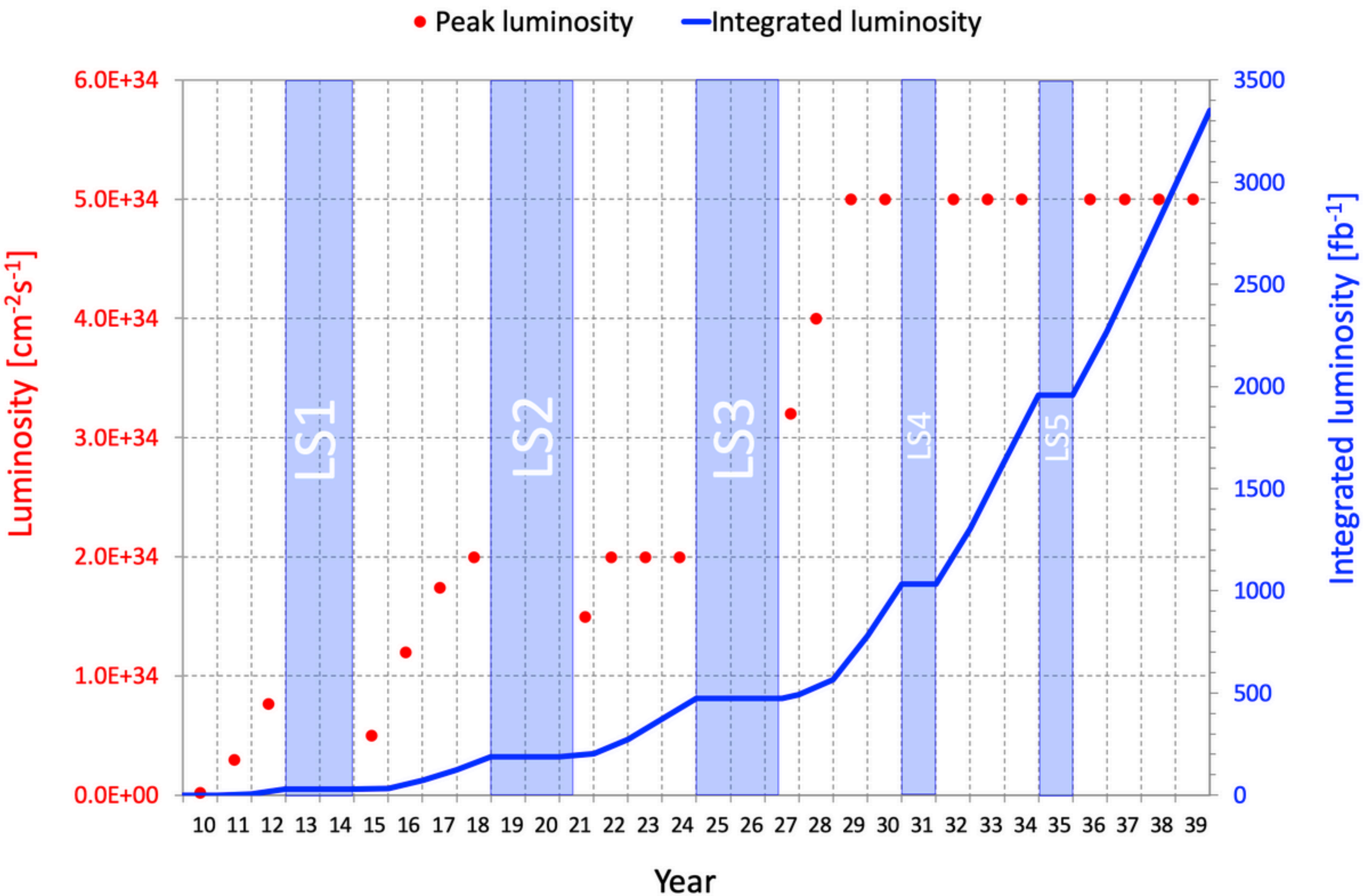
- CMS have made a lot of progress in Higgs physics using full Run II datasets
  - Searches on BSM Higgs boson decays & production show no significant excess from SM predictions
  - In general, more stringent constraints were set using full RunII data than RunI
- More results to come with the RunII & RunIII & HL-LHC datasets

Backup

LHC / HL-LHC Plan



LHC & HL-LHC luminosity evolution



Systematic uncertainties at HL-LHC

- Projections are based on educated estimates, especially regarding systematic uncertainties
  - Experimental uncertainties expected to decrease
    - Clever use of larger datasets and new detectors
    - 1% goal for luminosity uncertainty

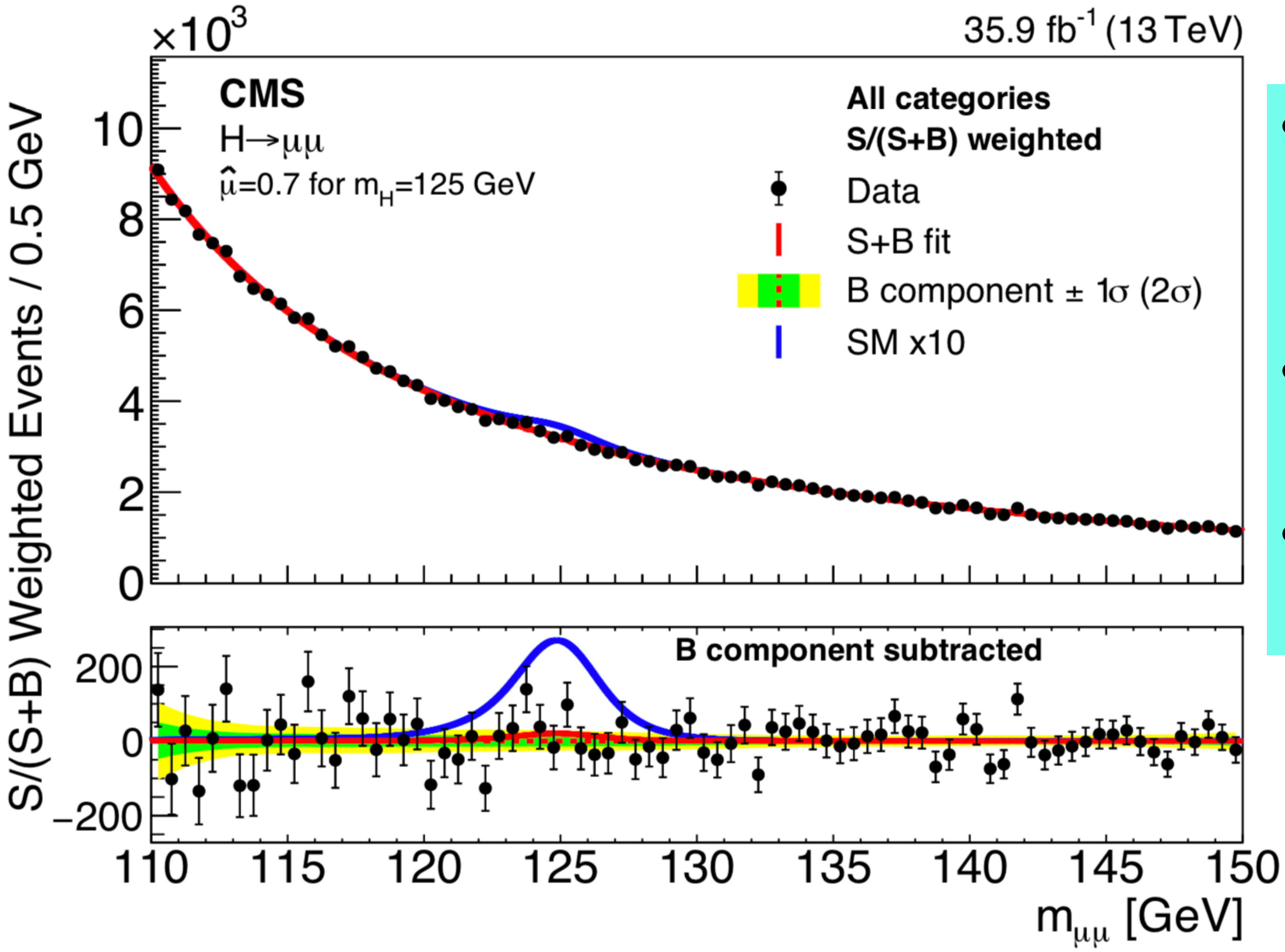
- Theoretical uncertainties halved with respect to current values
  - Improvements expected in perturbative corrections, PDFs, α_S

- Larger available dataset
  - Will help to define more control regions or allow to optimise differently the analysis strategy in general

- Many analysis uncertainties will shrink
  - Use of profiling / better control regions

- MC statistical uncertainties expected to be negligible
  - Requires huge improvements for generators
  - Requires improvements to our simulation and reconstruction software, in order to fit within our CPU and disk storage limits

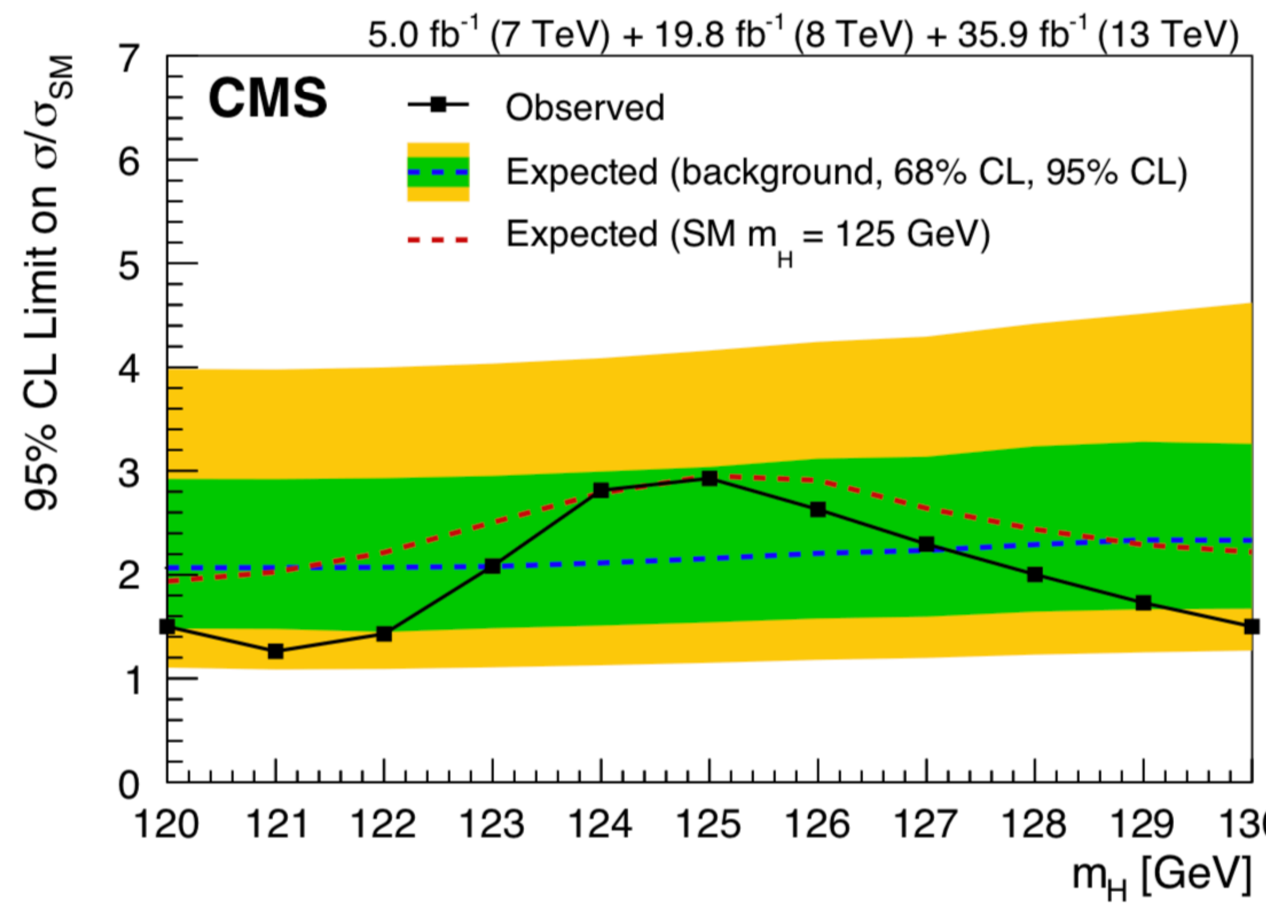
Higgs decays to $\mu^+\mu^-$ pair



Phys. Rev. Lett. 122, 021801

- To measure the signal strength:
  - Maximum likelihood fit to **dimuon invariant mass** spectrum:
- Main experimental uncertainties:
  - Jet energy scale & resolution: 6%
- Main theoretical uncertainty:
  - Factorization & renormalization scales: 6%

Combined RunI and RunII data



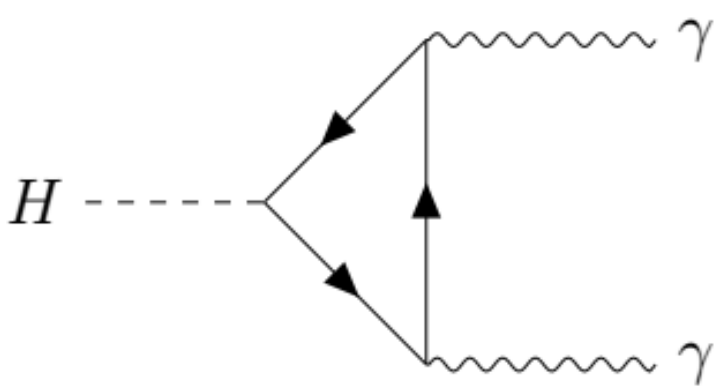
- SM branching ratio: 2.17×10^{-4}
- Observed branching ratio upper limits: 6.4×10^{-4}

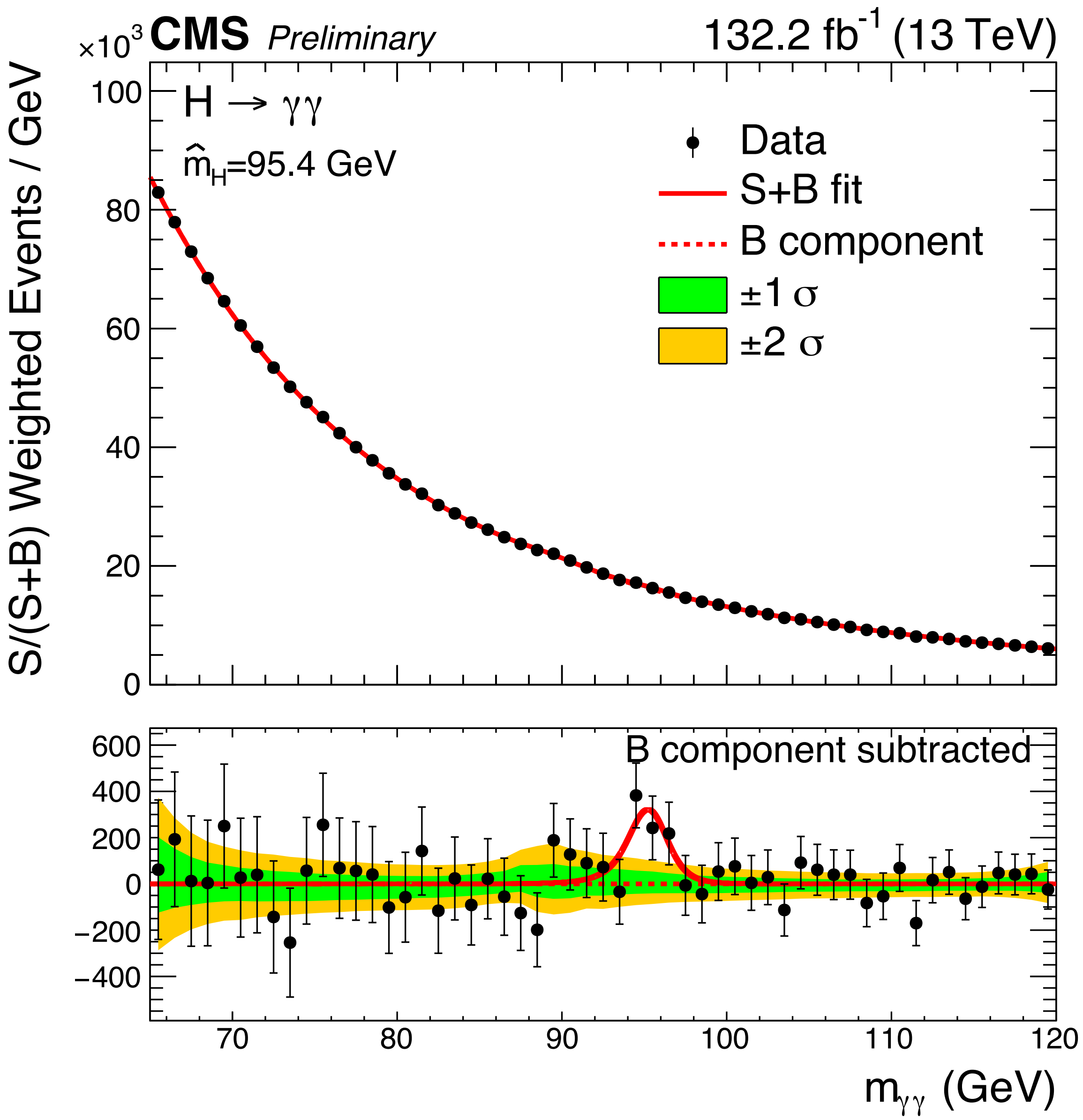
- Expected upper limits: 2.2 σ
- Observed upper limits: 2.9 σ

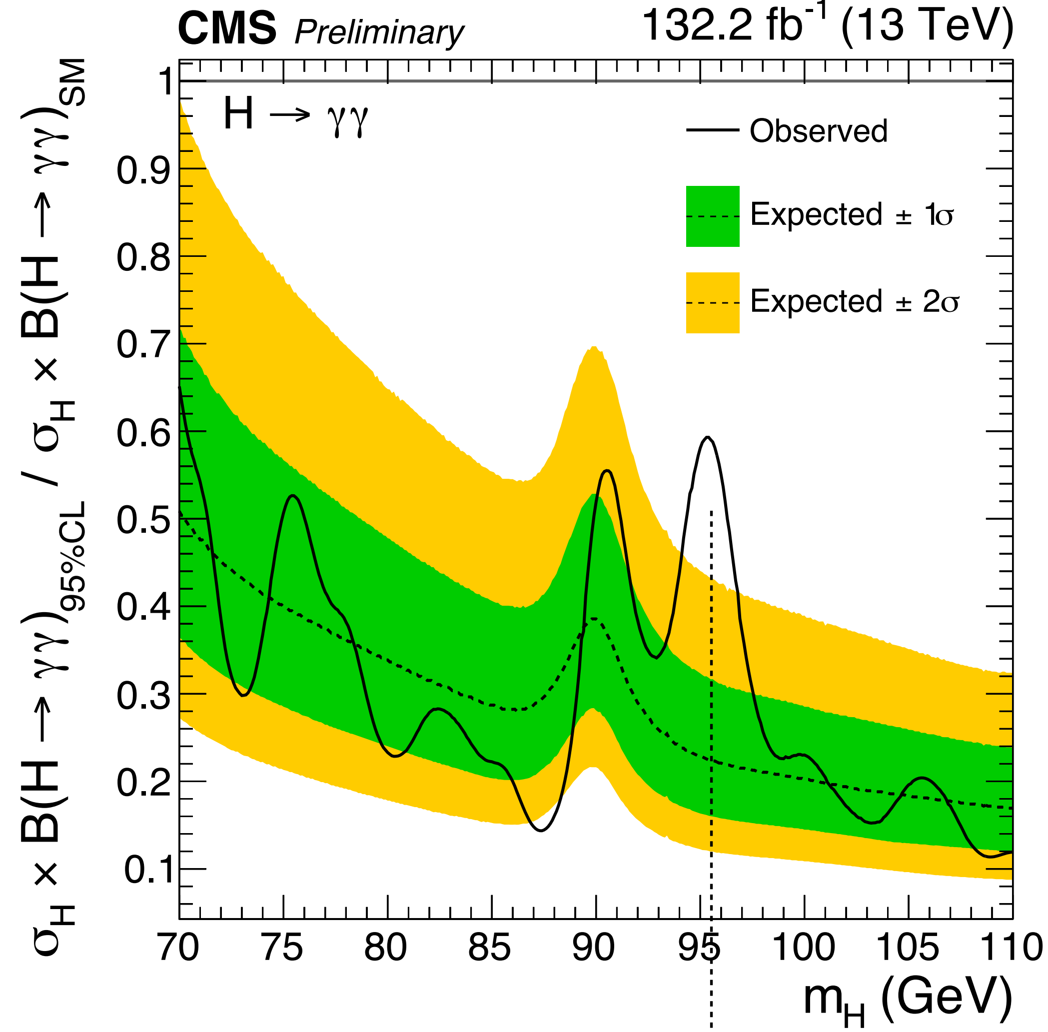
- Expected signal significance: 0.9
- Observed signal strength: 1.0 ± 1.0 (stat.) ± 0.1 (syst.)

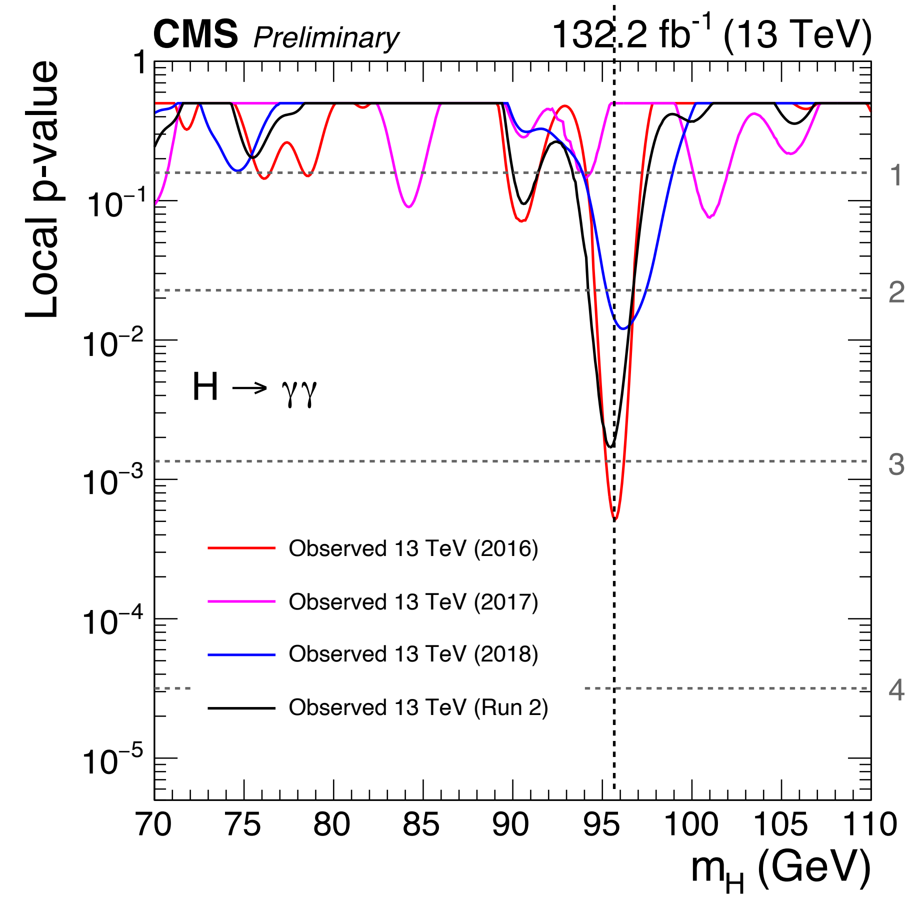
SM-like Higgs boson decay to γγ

CMS-PAS-HIG-20-002



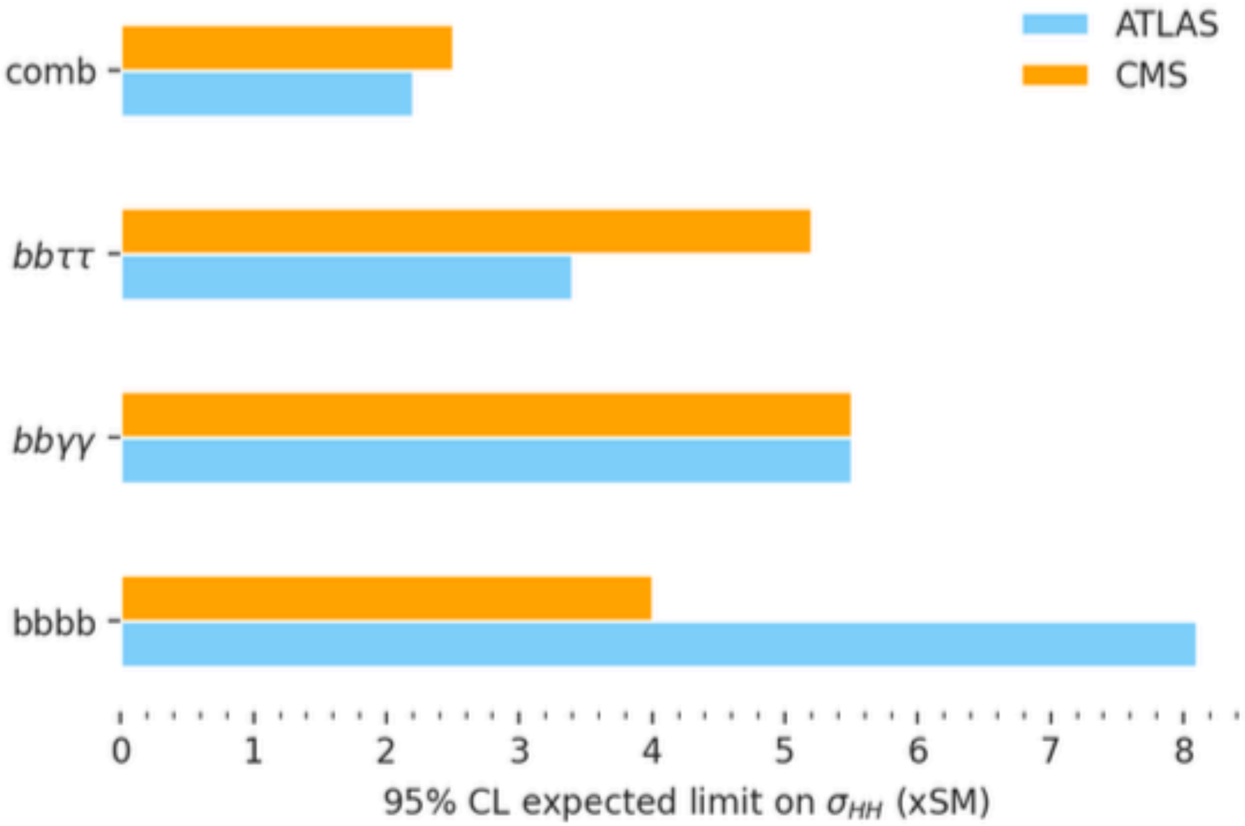


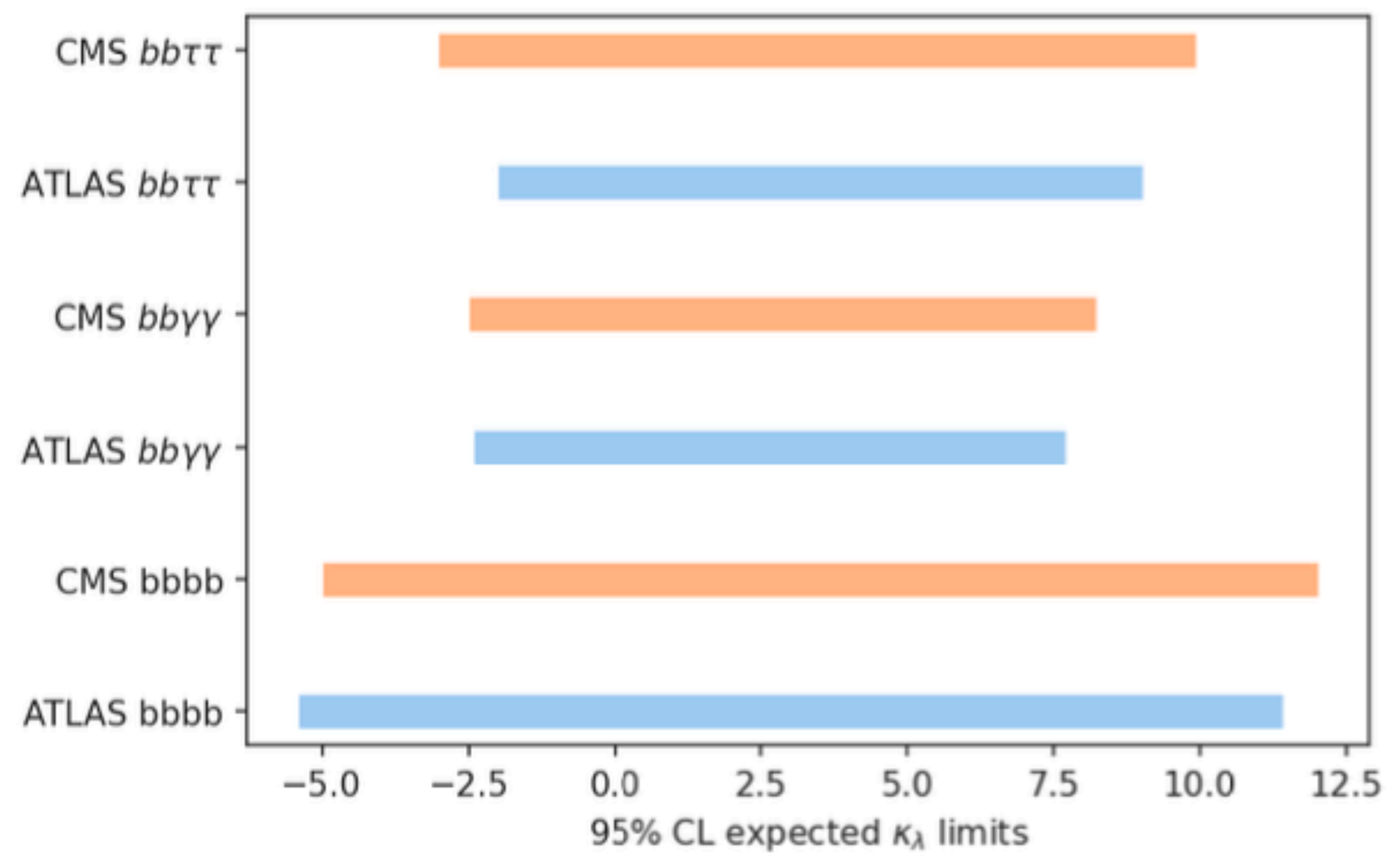




- The local significance of the largest excess at 95.4 GeV is about 2.9σ

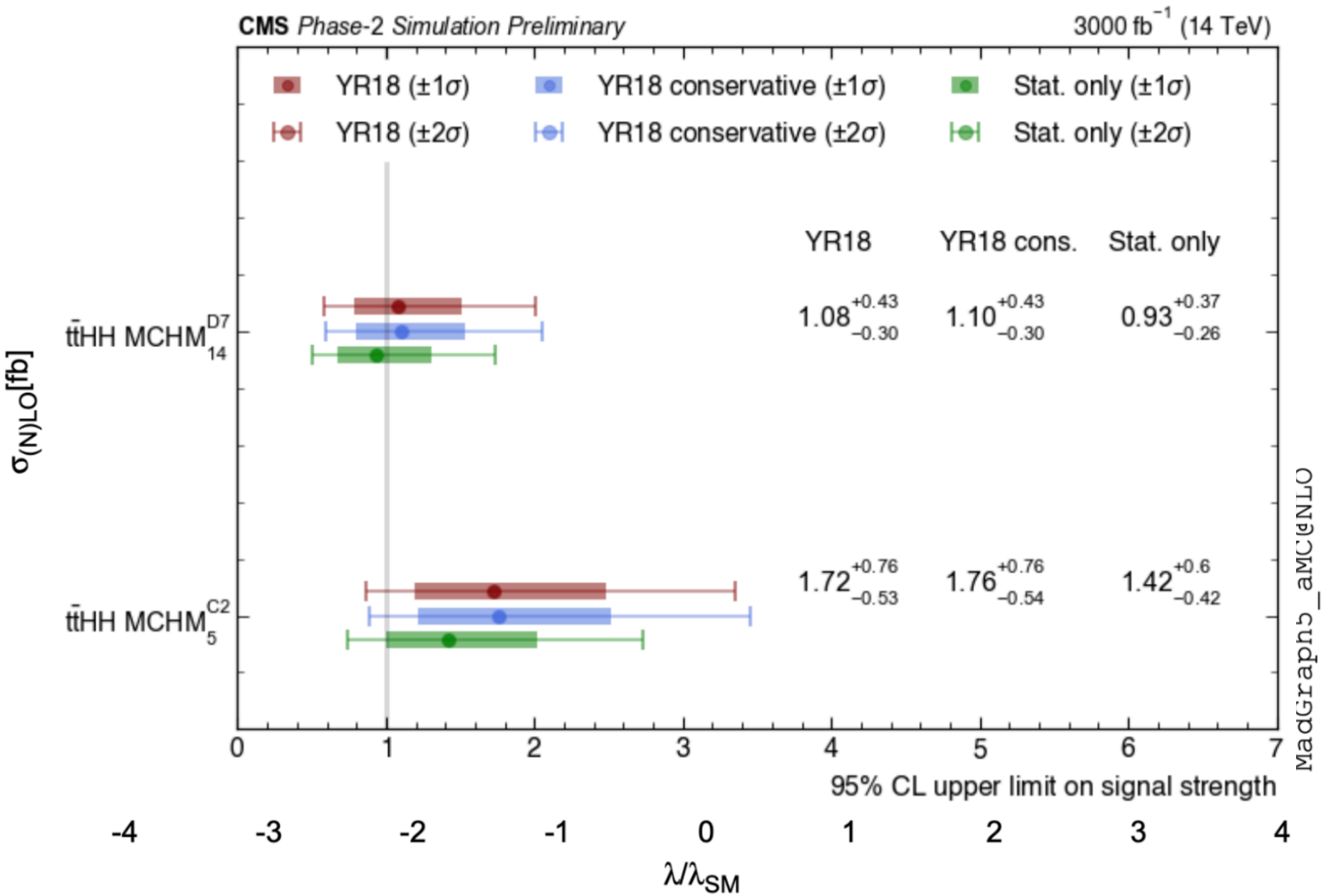
Double Higgs production





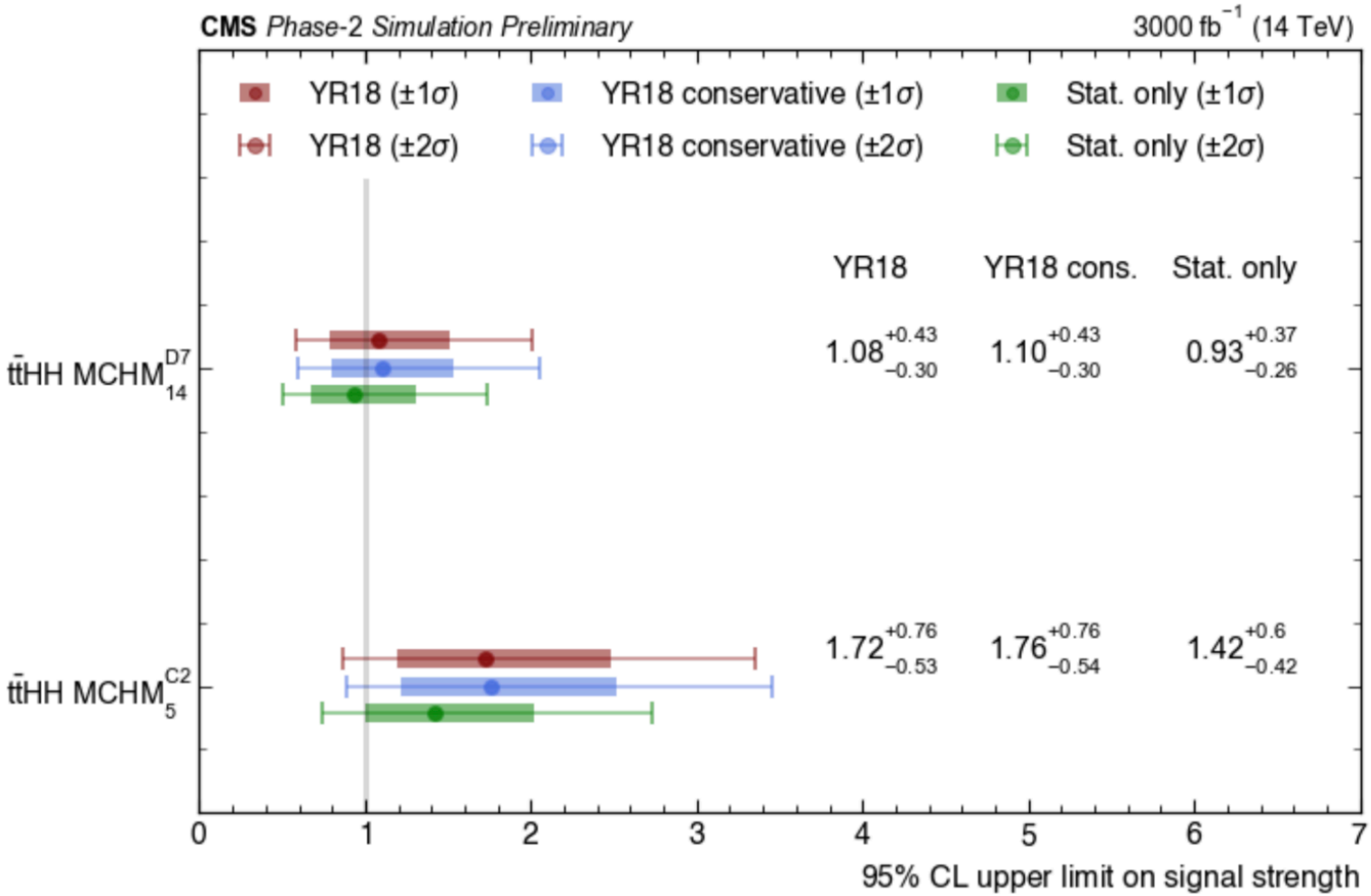
Search for ttHH at HL-LHC

CMS-PAS-FTR-21-010



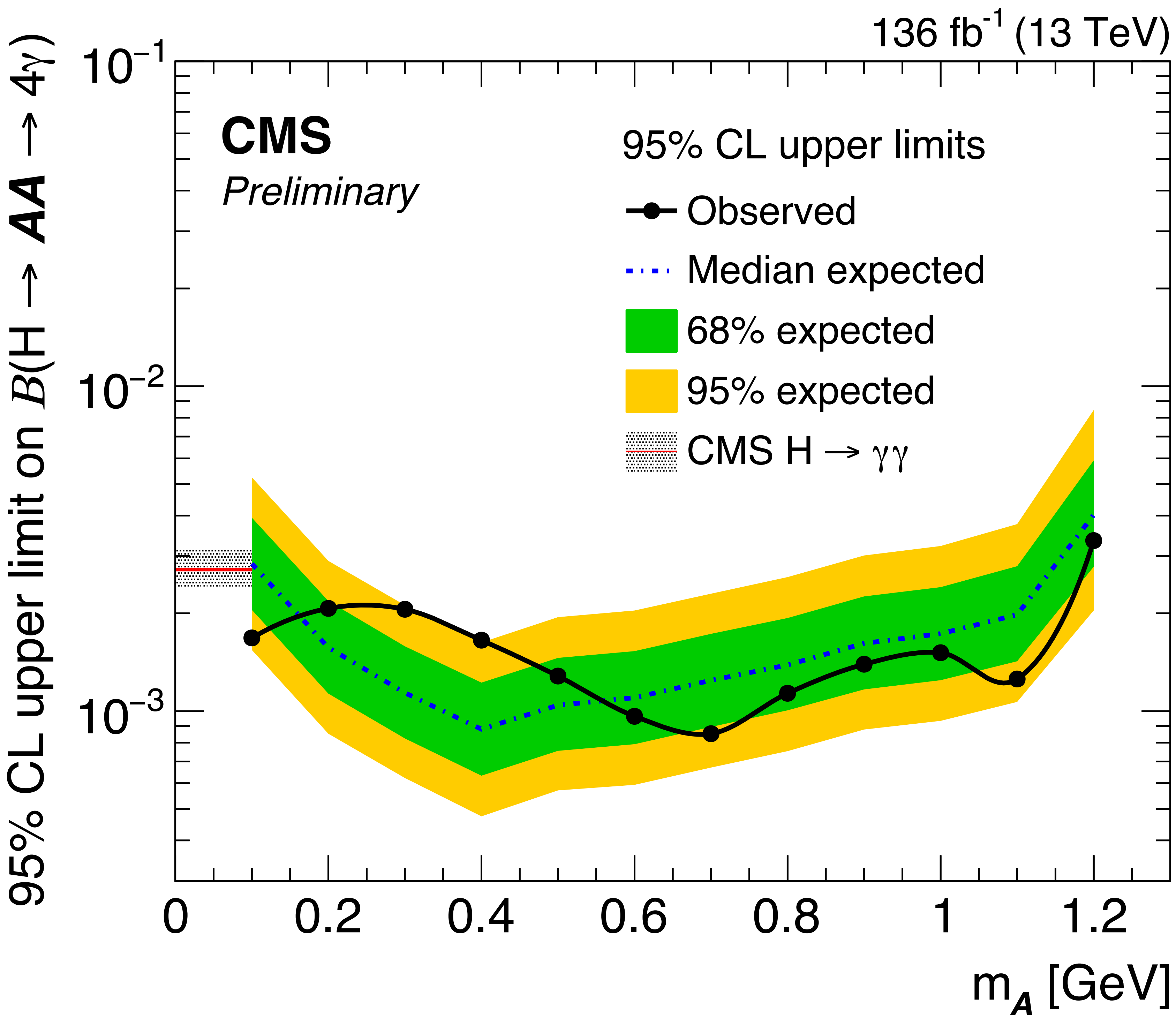
Search for ttHH at HL-LHC

CMS-PAS-FTR-21-010



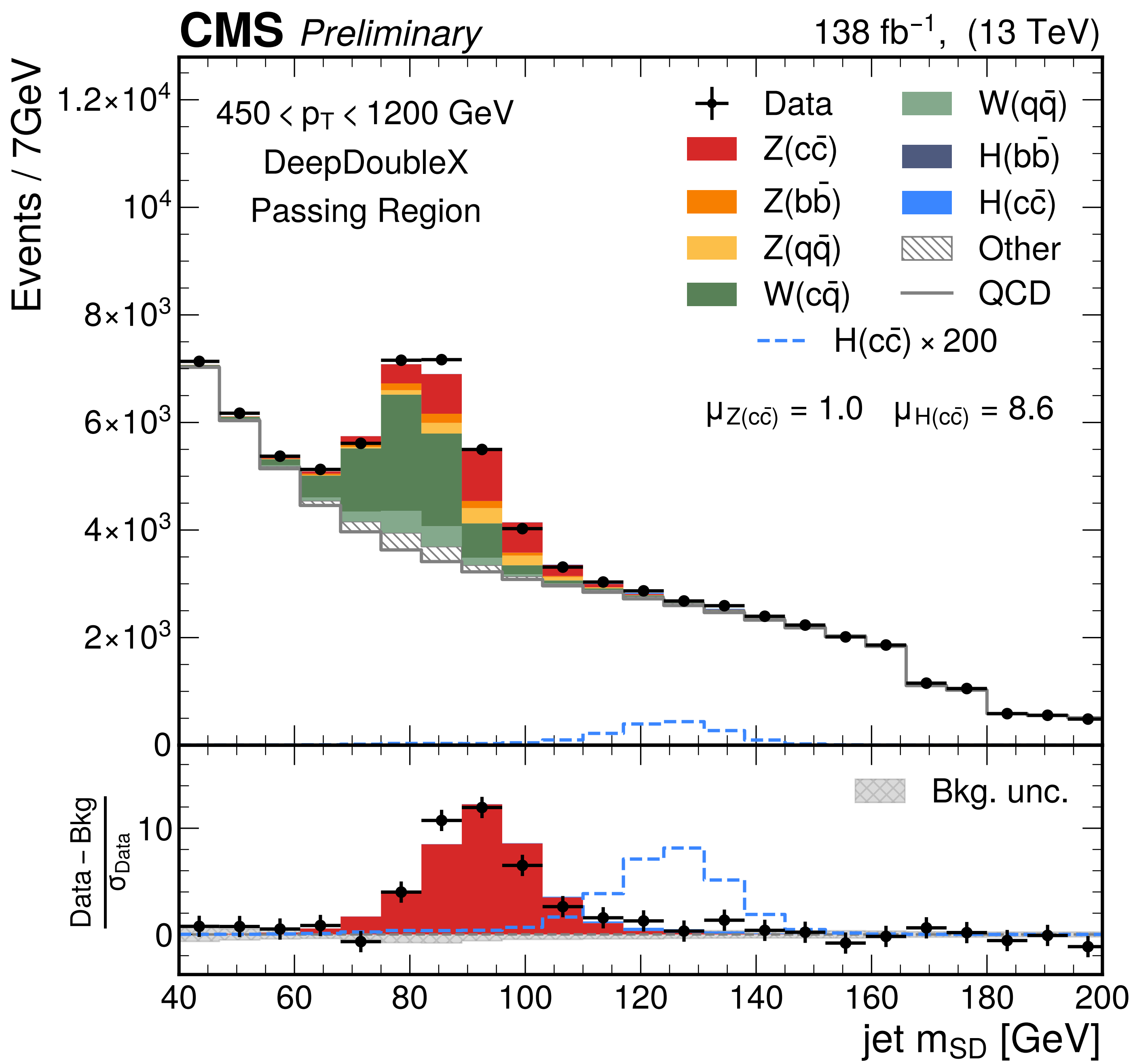
H → AA → γγγγ

CMS-HIG-21-016 (submitted to PRL)



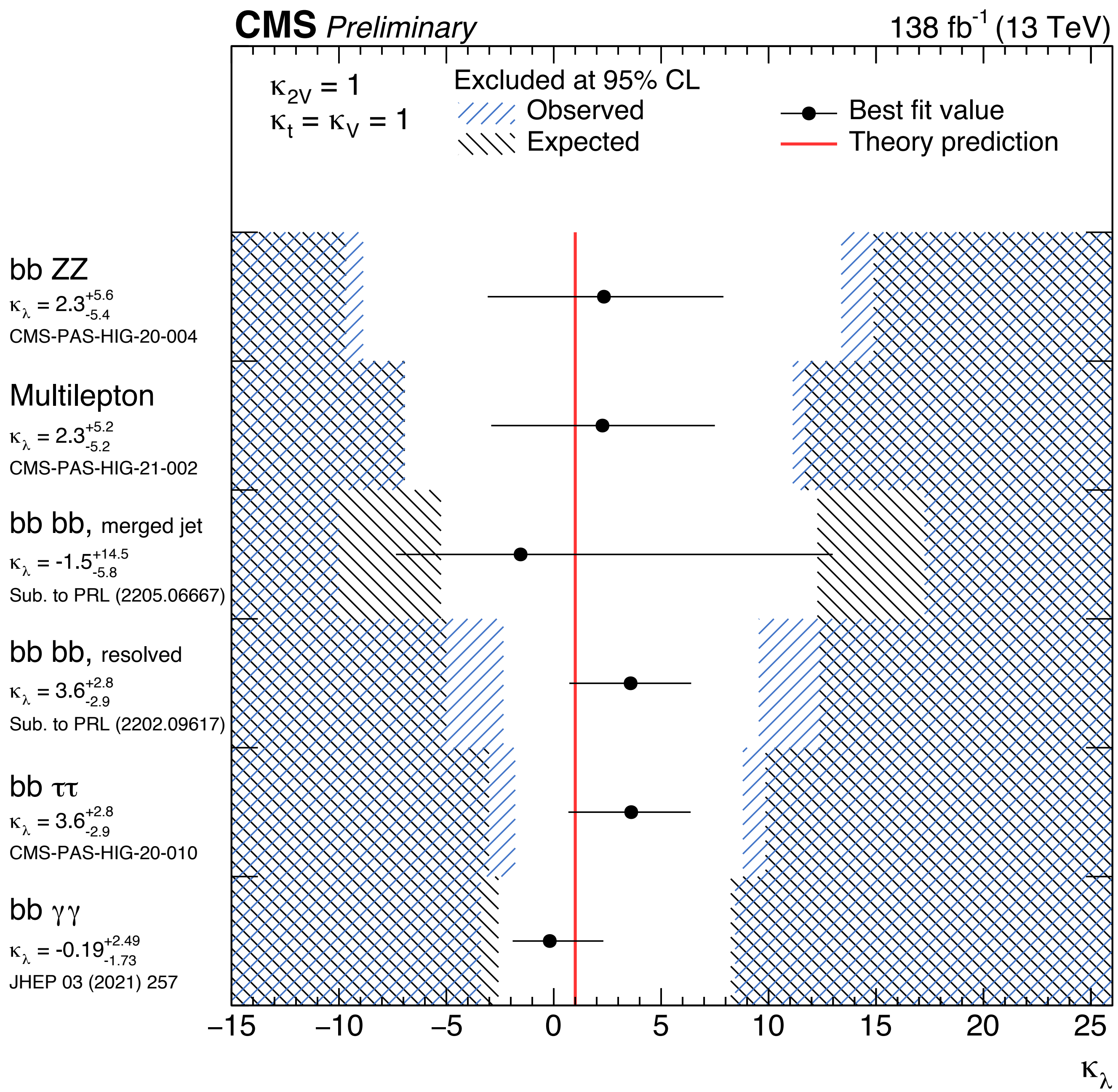
ZH → cccc

[CMS-HIG-21-012 (submitted to PRL)](#)



An observed (expected) upper limit on the inclusive Higgs boson cross section times cc decay. branching ratio of 45 (38) times the standard model expectation is set at the 95% confidence level

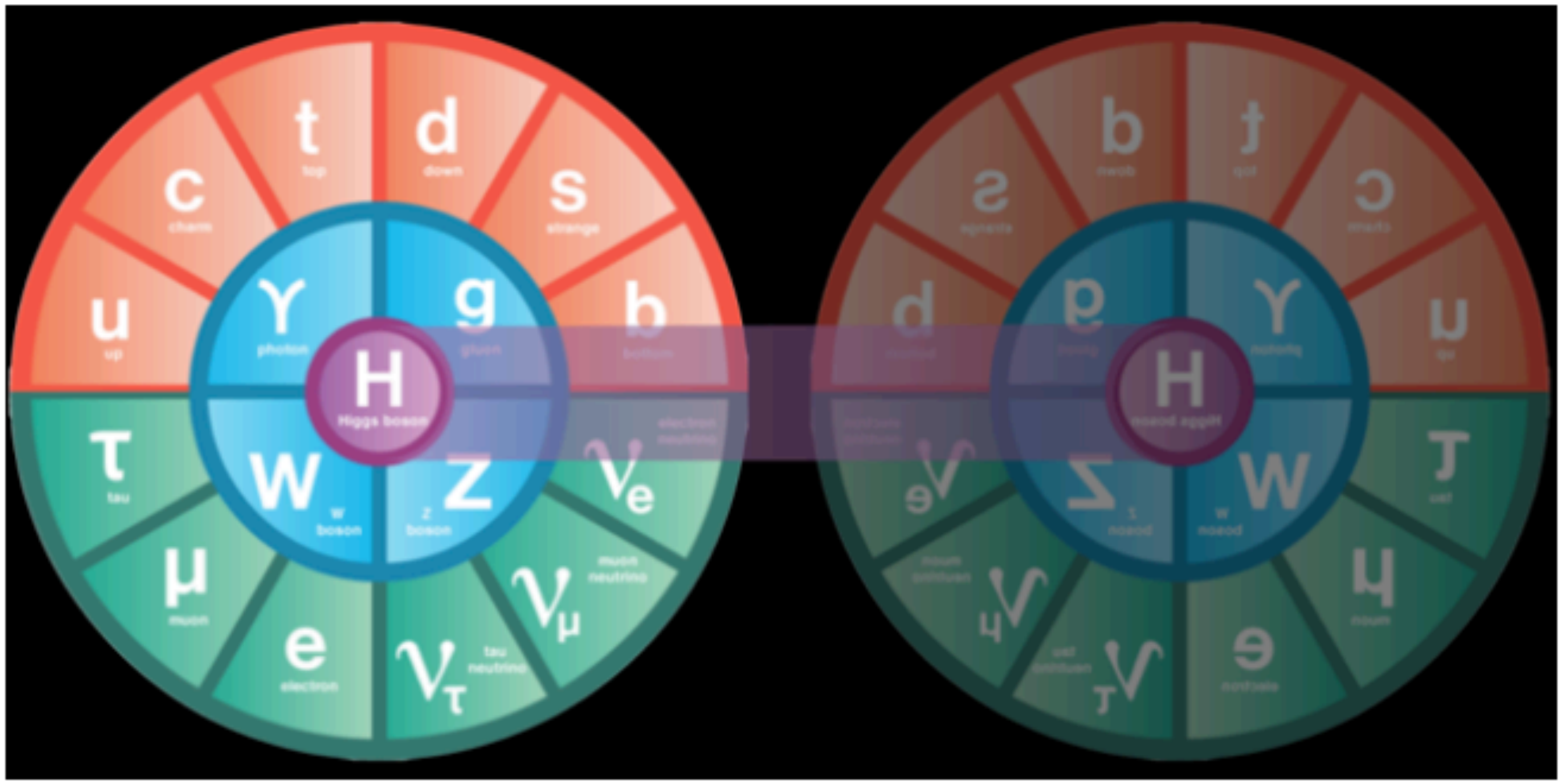
Higgs pair searches (non-resonant)



CMS-HIG-PublicResults

95% confidence intervals on κ_λ superimposed by the best fit value on this parameter. The blue (black) hashed band indicates the observed (expected) excluded regions, respectively. The band around the best fit value corresponds to the one sigma interval. The bb bb resolved and bb bb boosted results are derived using a phase space with a minor overlap of signal events.

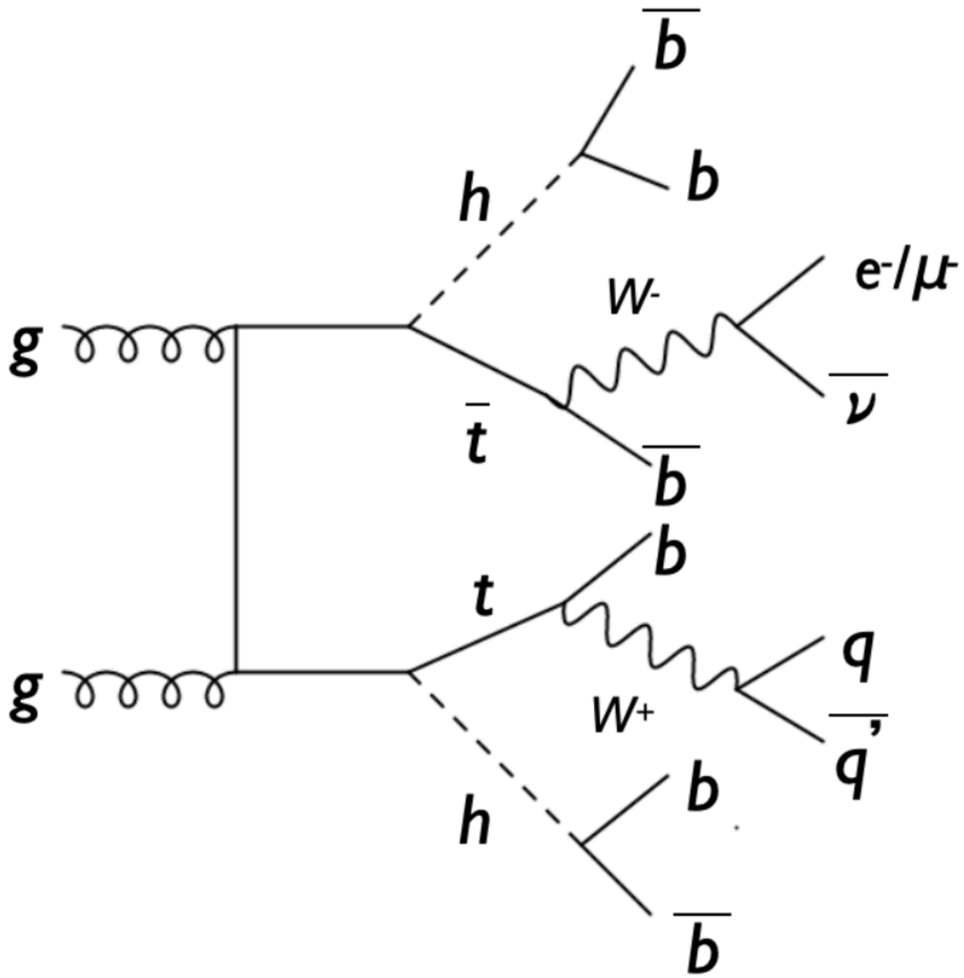
Twin Higgs model for partially explaining hierarchy problem

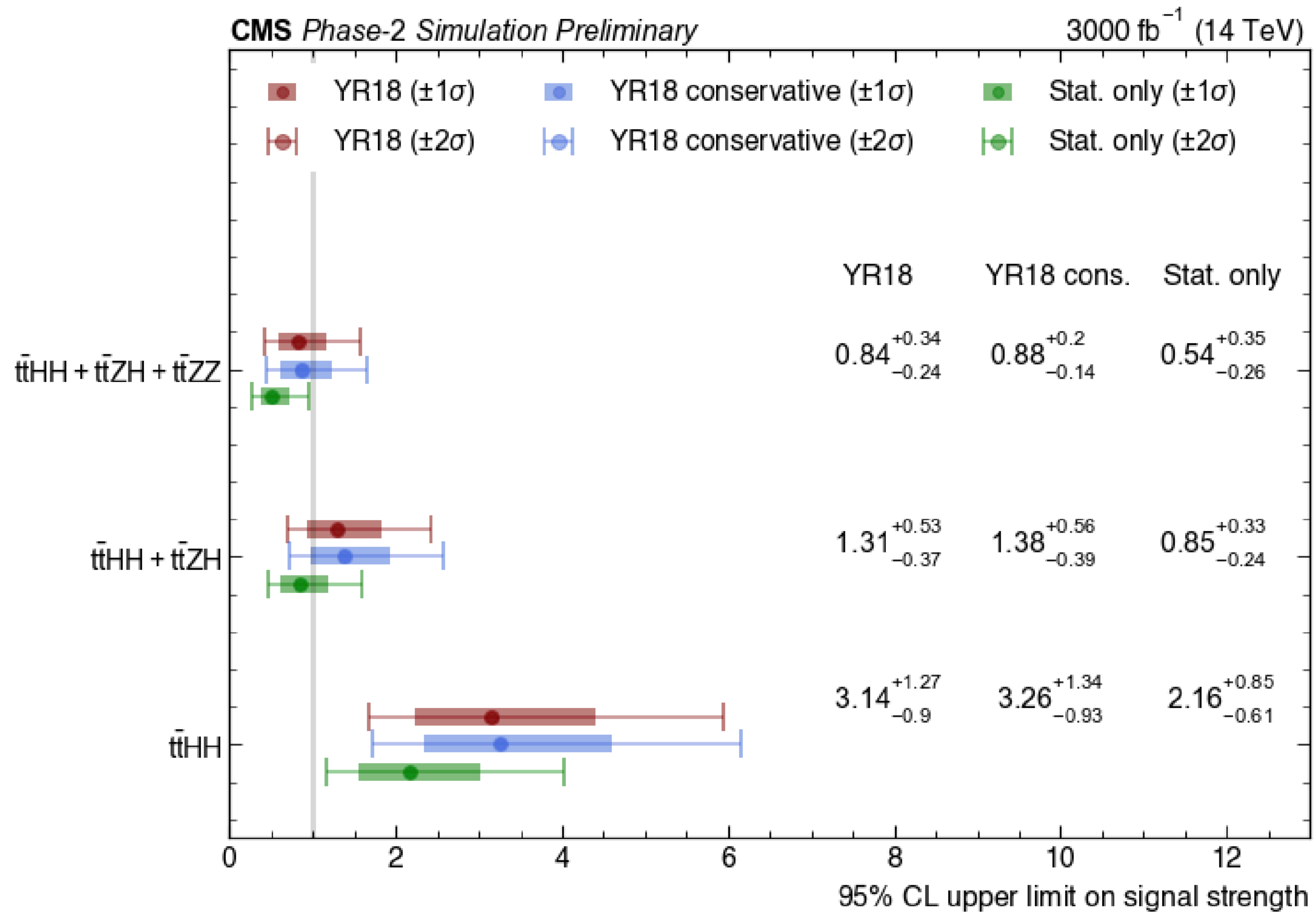


- The twin Higgs model assumes that the particles of the standard model (left) have mirror counterparts in a hidden sector (right). The two sets of particles could communicate through a coupling between our standard-model Higgs and the mirror Higgs

The road to di-Higgs observation (2) ?

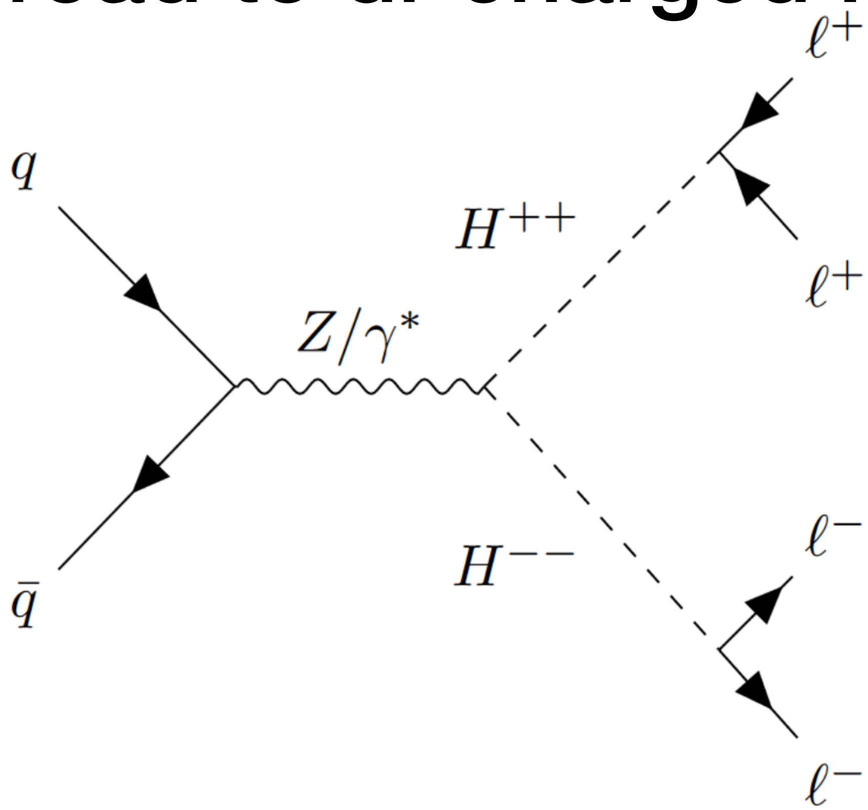
CMS-PAS-FTR-21-010

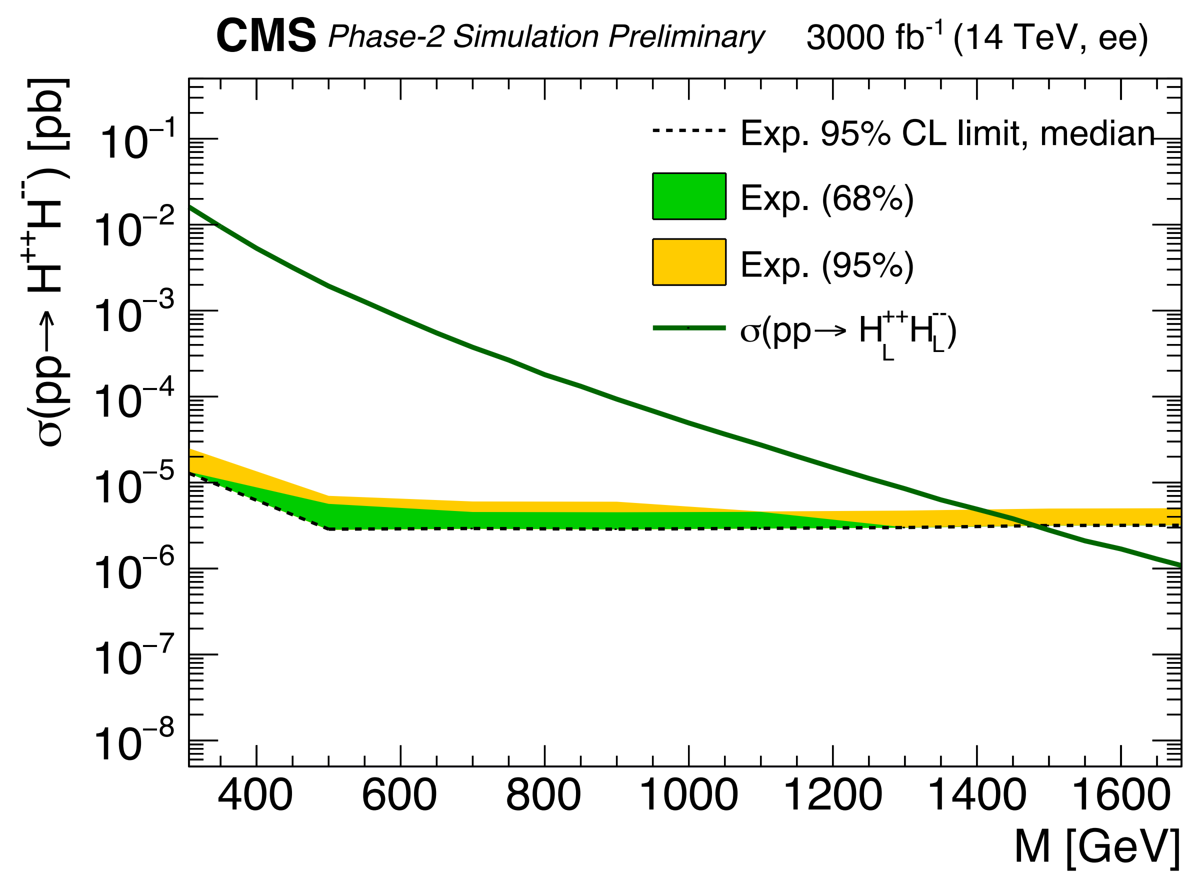




- A new way to explore the top-Higgs sector in an interplay with the double Higgs production both for BSM Higgs
- An access to the measurement of the triple Higgs coupling complementary to the double Higgs production, and to the top quark Yukawa coupling

The road to di-charged Higgs observation? CMS-PAS-FTR-22-006

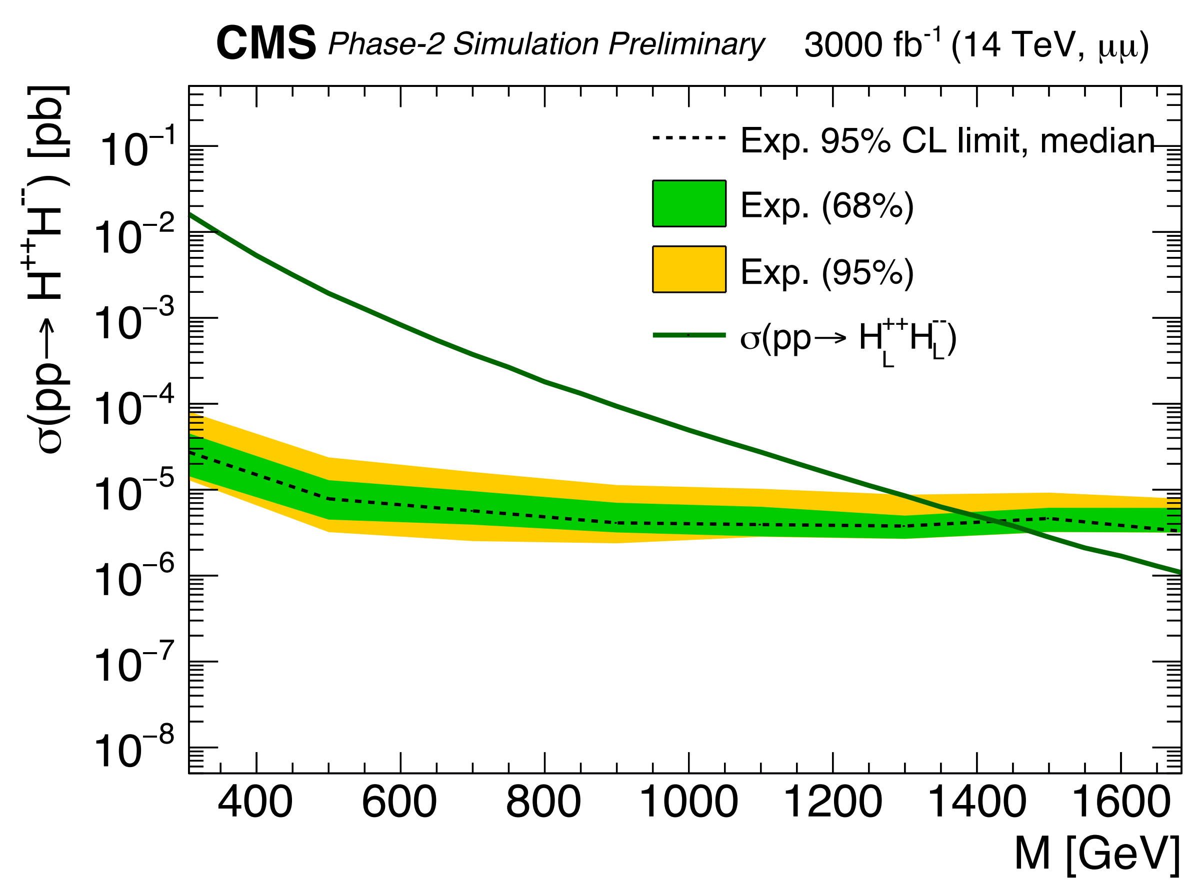




- These results indicate that the HL-LHC will be able to rule out masses up to at least 1400 GeV at 95% CL

Higgs mass	300	500	700	900	1100	1300	1500	1700
H^{++}	15552	2231	412	104	30	9.1	2.8	1.0
$t\bar{t}$	.61	.09	.02	0	0	0	0	0
Drell-Yan	0	0	0	0	0	0	0	0
QCD	1.2	.52	.30	.20	.14	.11	.09	.07

Higgs mass	300	500	700	900	1100	1300	1500	1700
H^{++}	18581	2758	478	125	31	10	2.8	1.0
$t\bar{t}$	3.4	.48	.13	.05	.02	.01	.01	0
Drell-Yan	6.6	1.6	.70	.38	.24	.16	.11	.08
QCD	17	5.5	2.7	1.6	1.1	.78	.59	.46

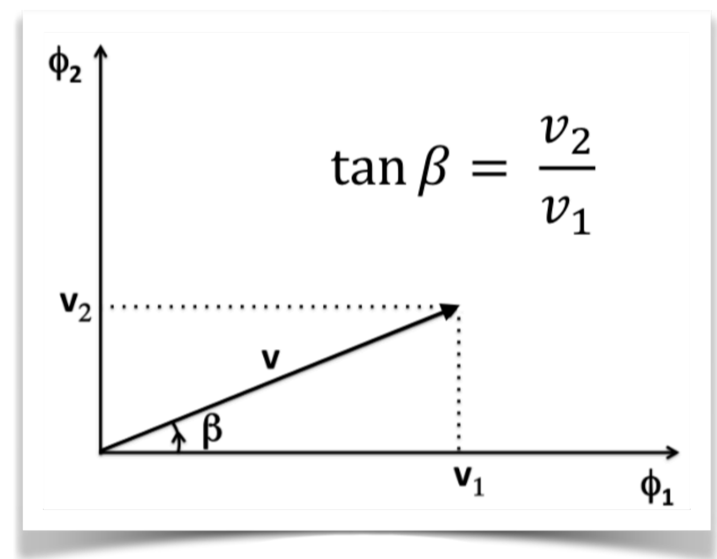


Theoretical background

- **Two-Higgs-Doublet Model (2HDM)**
  - Type-2 : **minimal supersymmetry model (MSSM)**

- Further extension: **a scalar singlet (2HDM + S)**
  - Type-2 : **Next-to-minimal-supersymmetry-model (NMSSM)**

- Symmetry breaking → 5 predicted physical states:
  - Neutral scalars: h_1, h_2, h_3
  - Neutral pseudo-scalars: a_1, a_2
  - Charged scalars: $H^{\pm}$



	Type-1	Type-2	Type-3 (lepton-specific)	Type-4 (flipped)
Up-type quarks	Φ_2	Φ_2	Φ_2	Φ_2
Down-type quarks	Φ_2	Φ_1	Φ_2	Φ_1
Charged leptons	Φ_2	Φ_1	Φ_1	Φ_2

Interplay between experimental observables and fundamental questions