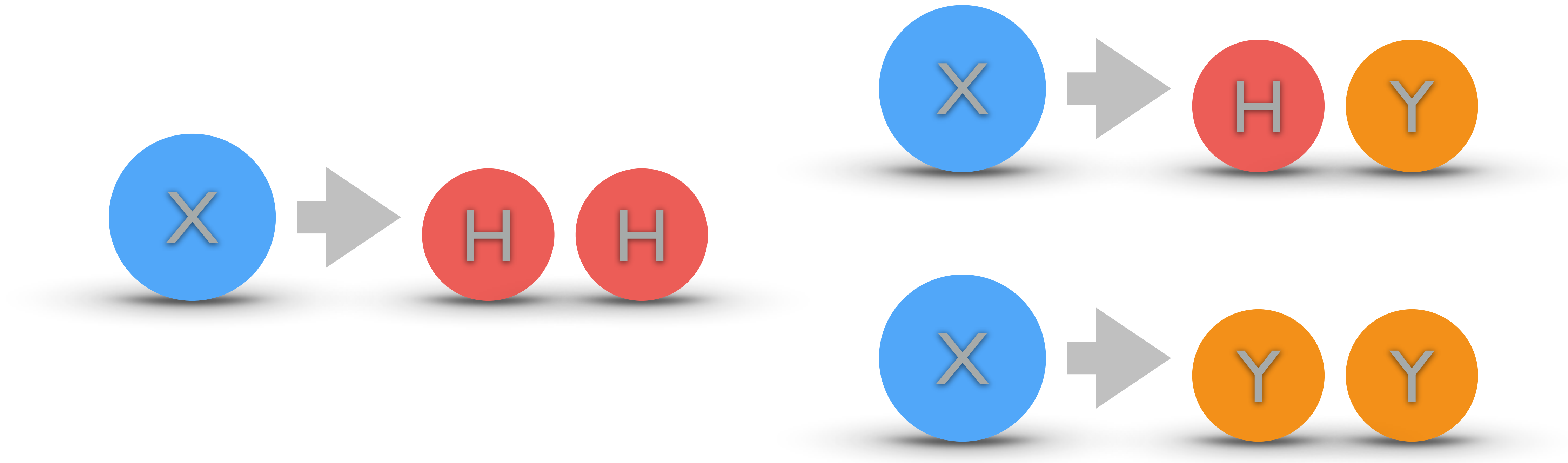


Search for a new resonance decaying into two Higgs boson like particles

E. Di Marco(INFN Roma)

seminario INFN, 15/01/2024

Resonance as a tool for discovery

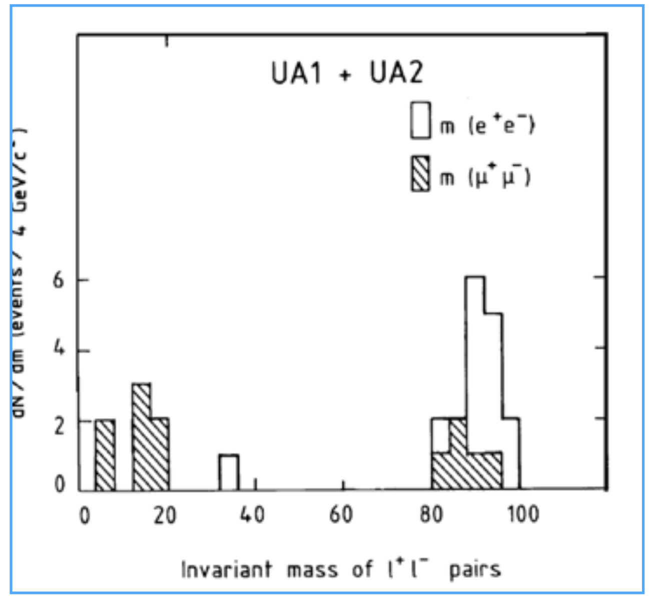
Observation of a resonance as a narrow peak in the cross section has always been a step forward in particle physics

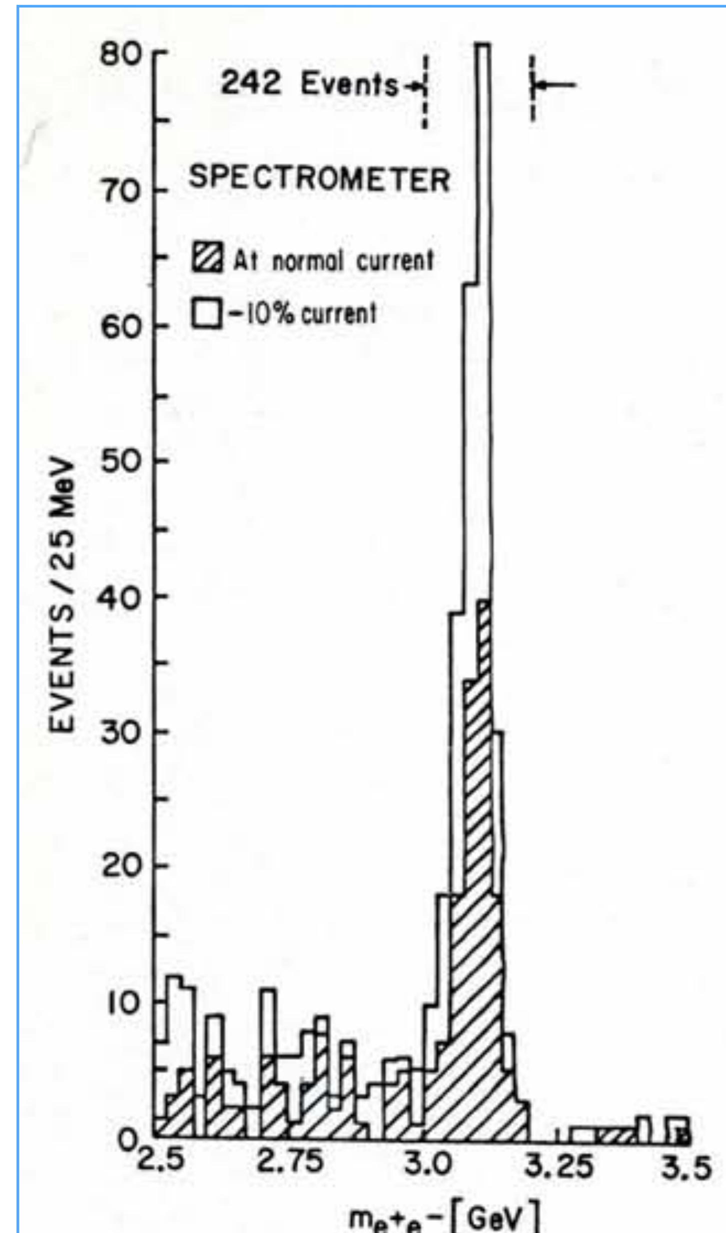
Bound states of elementary particles:

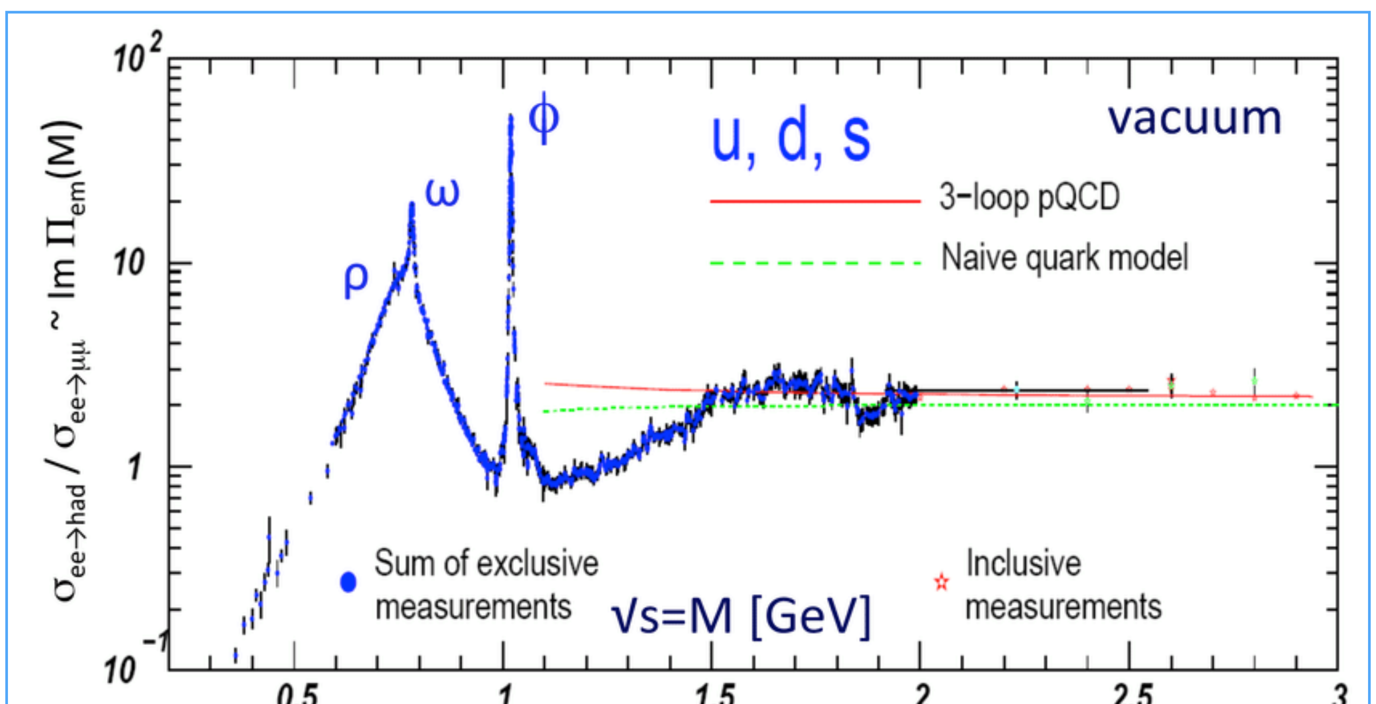
- e.g. **mesons**: $\rho(770)$, $J/\psi(c\bar{c})$,
- e.g. **barions**: $\Delta(1232)$, i.e. 3 u/d-type quarks

Elementary particles:

- **W, Z, H bosons**

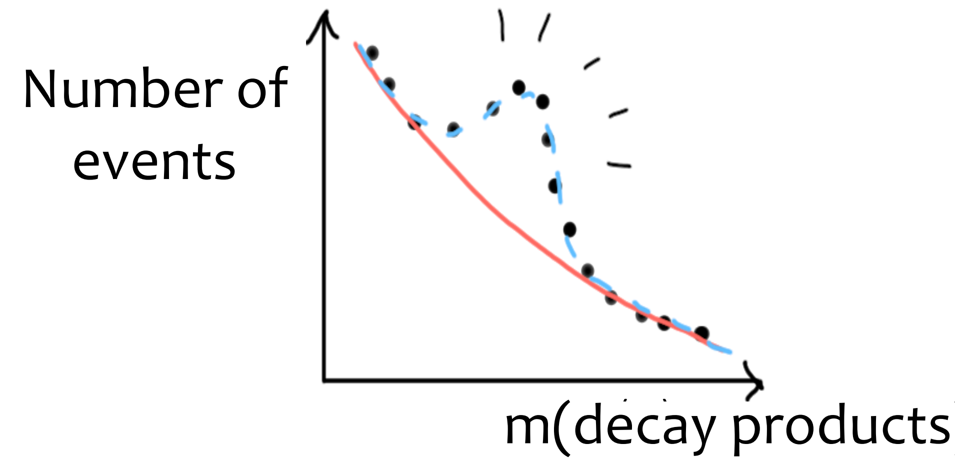


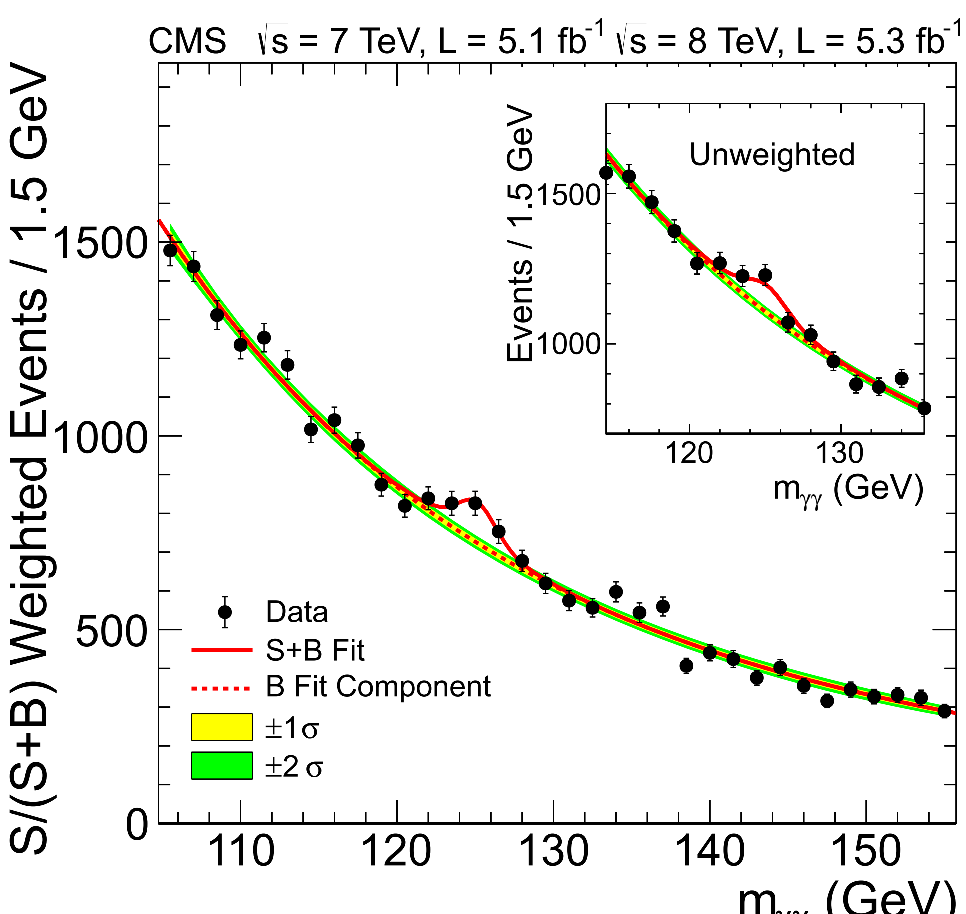




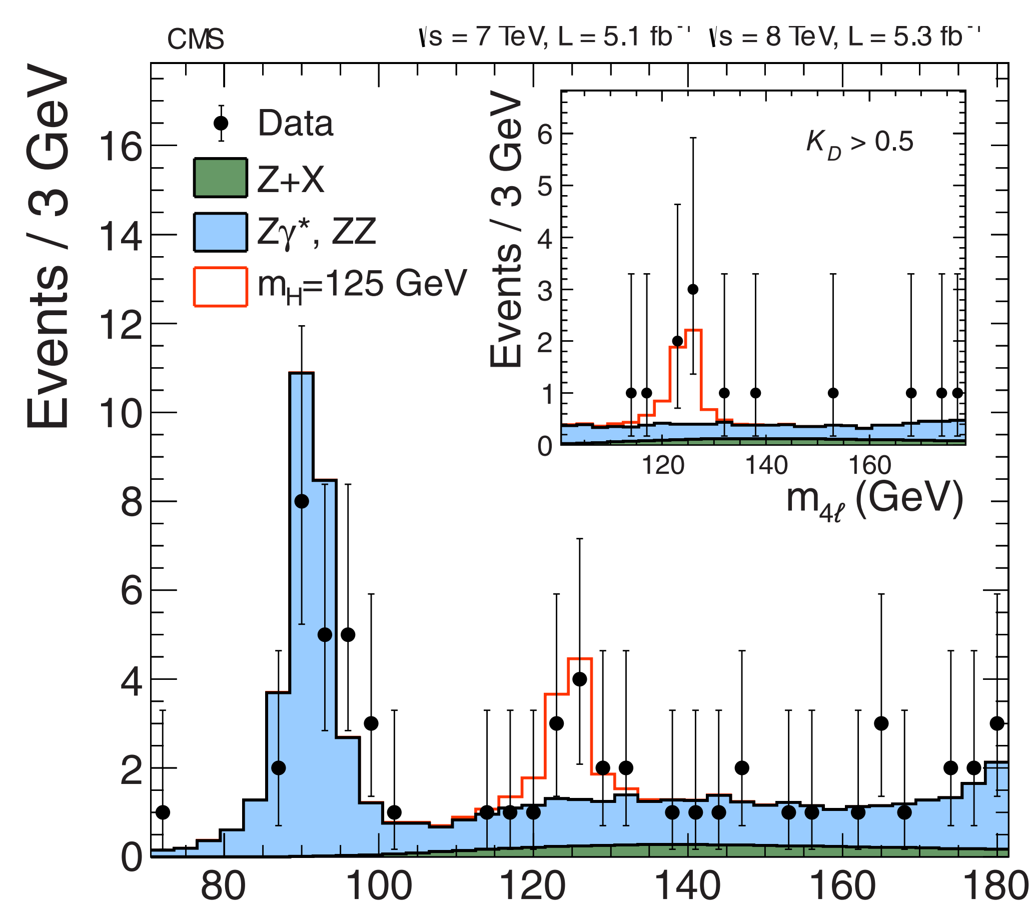
The Higgs boson discovery

- LHC pp collisions can produce new particles, and search for them as a resonance in the mass of the decay products is a robust signature (bump hunt)
- Higgs discovery:
  - $H \to \gamma\gamma$ (**di-photon resonance**),
  - $H \to ZZ \to 4\ell$ (**4-lepton resonance**)





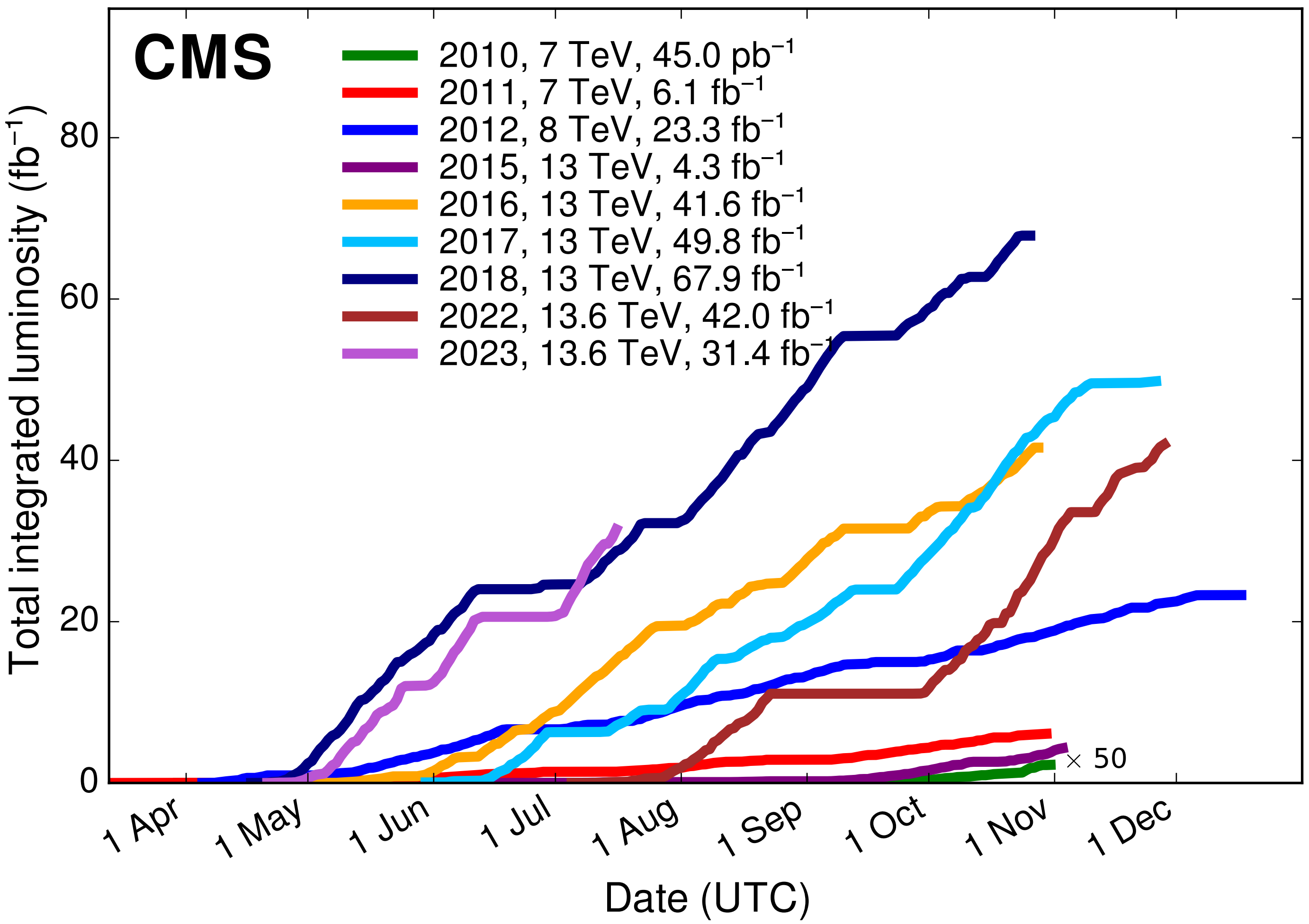
$H \to \gamma\gamma$

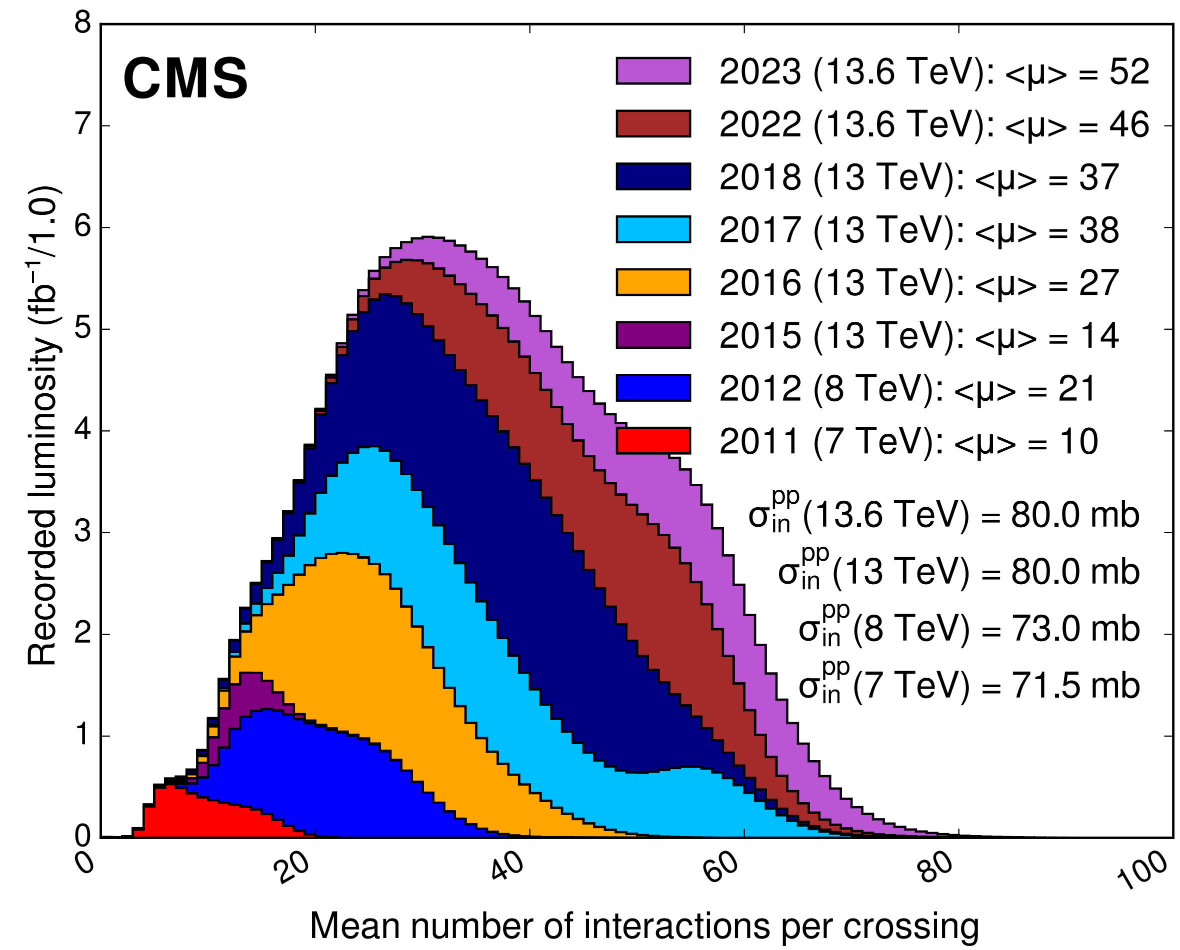


$H \to ZZ \to 4\ell$

LHC Run-1, 2 and 3!

A collider to produce new resonances: LHC





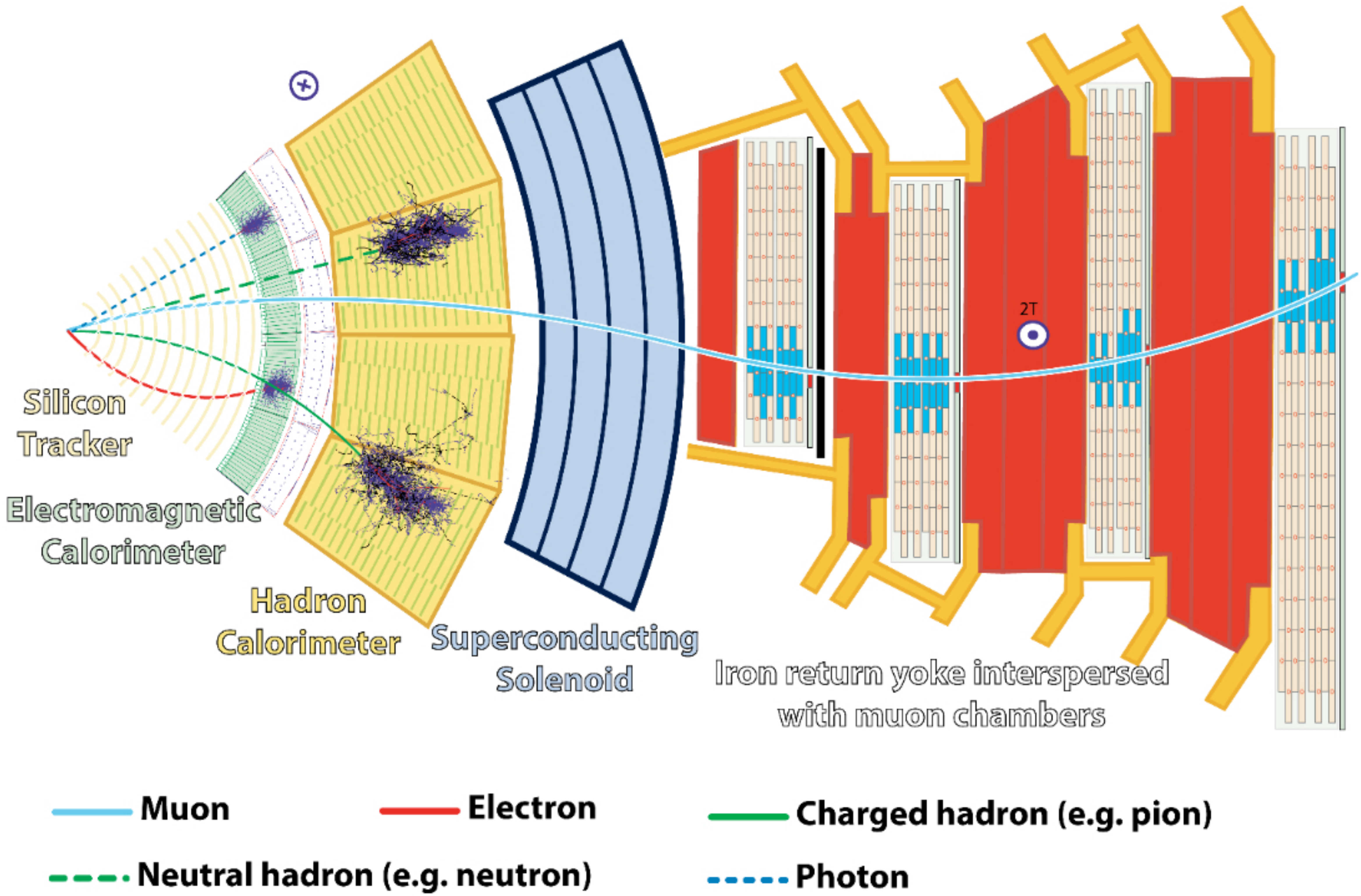
LHC collisions recorded by CMS:

- Run-1, 7 TeV: 6 fb^{-1}
- Run-1, 8 TeV: 23 fb^{-1}
- Run-2, 13 TeV: 151 fb^{-1}
- Run-3, 13.6 TeV: 73 fb^{-1} (and counting)

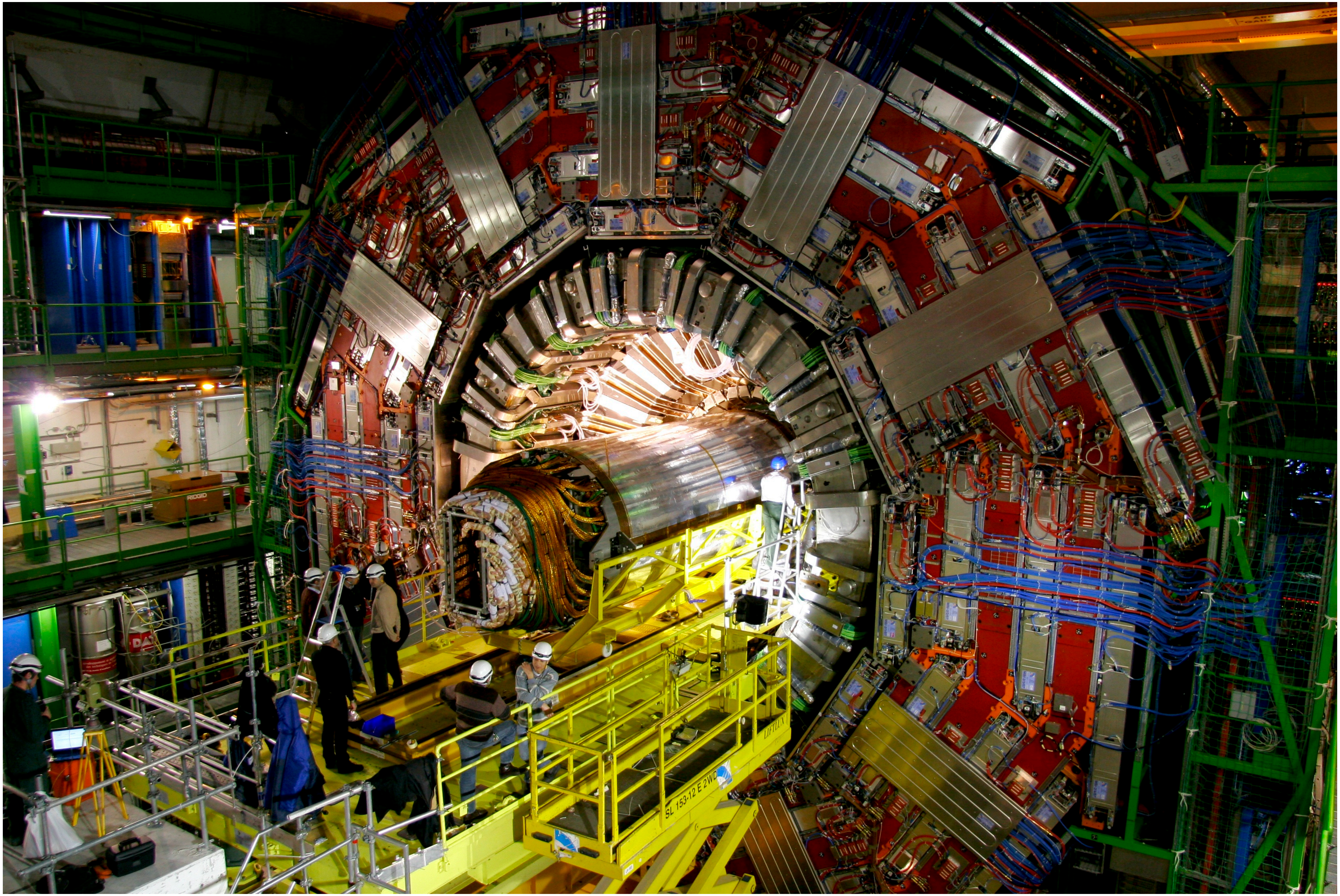
Pileup:

up to 80 interactions / LHC bunch crossing

Schematics of particle interactions with CMS material



CMS detector



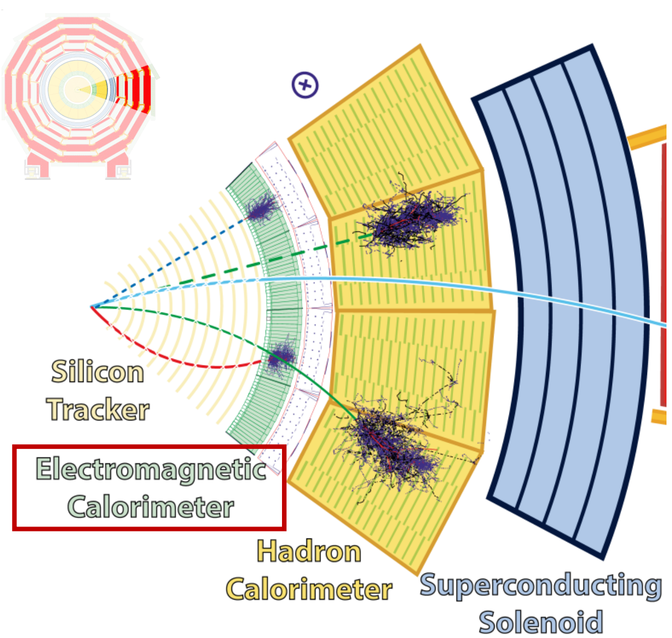
Resonance search in a nutshell

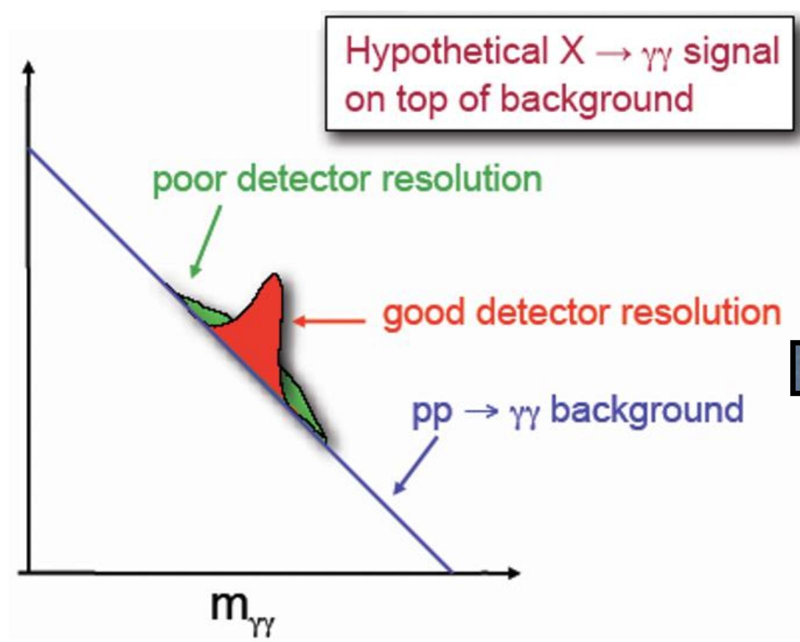
1. Select a clean sample of candidates X into n stable particles:
   $X \to f_1, \ldots f_n$ (f_i = photon, lepton, b-jets, …) => **Particle identification**

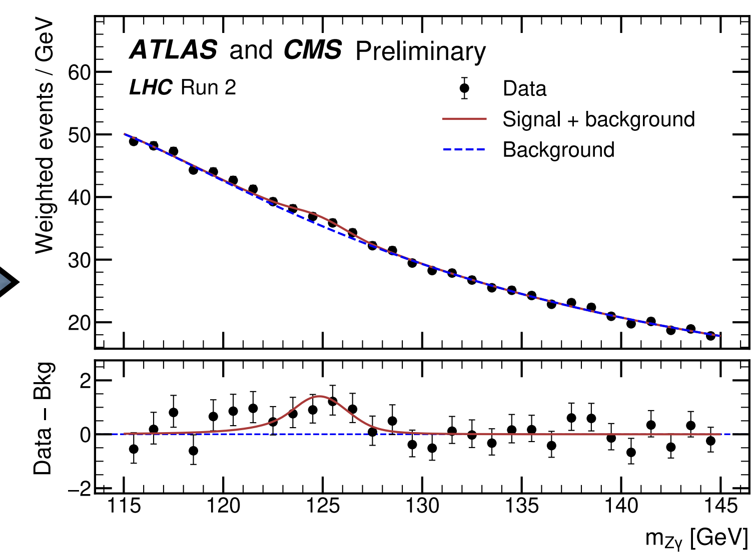
2. Compute the invariant mass of the final state (if $n = 2$: $M_X = \sqrt{2E_1E_2(1-\cos\theta)}$)
   - => better **energy resolution** means narrower peak => higher S / B
   - => precise vertexing defines the particle direction

3. **Extract the signal yield** on top of background in a robust way

$H \to Z\gamma$ bump, ATLAS+CMS







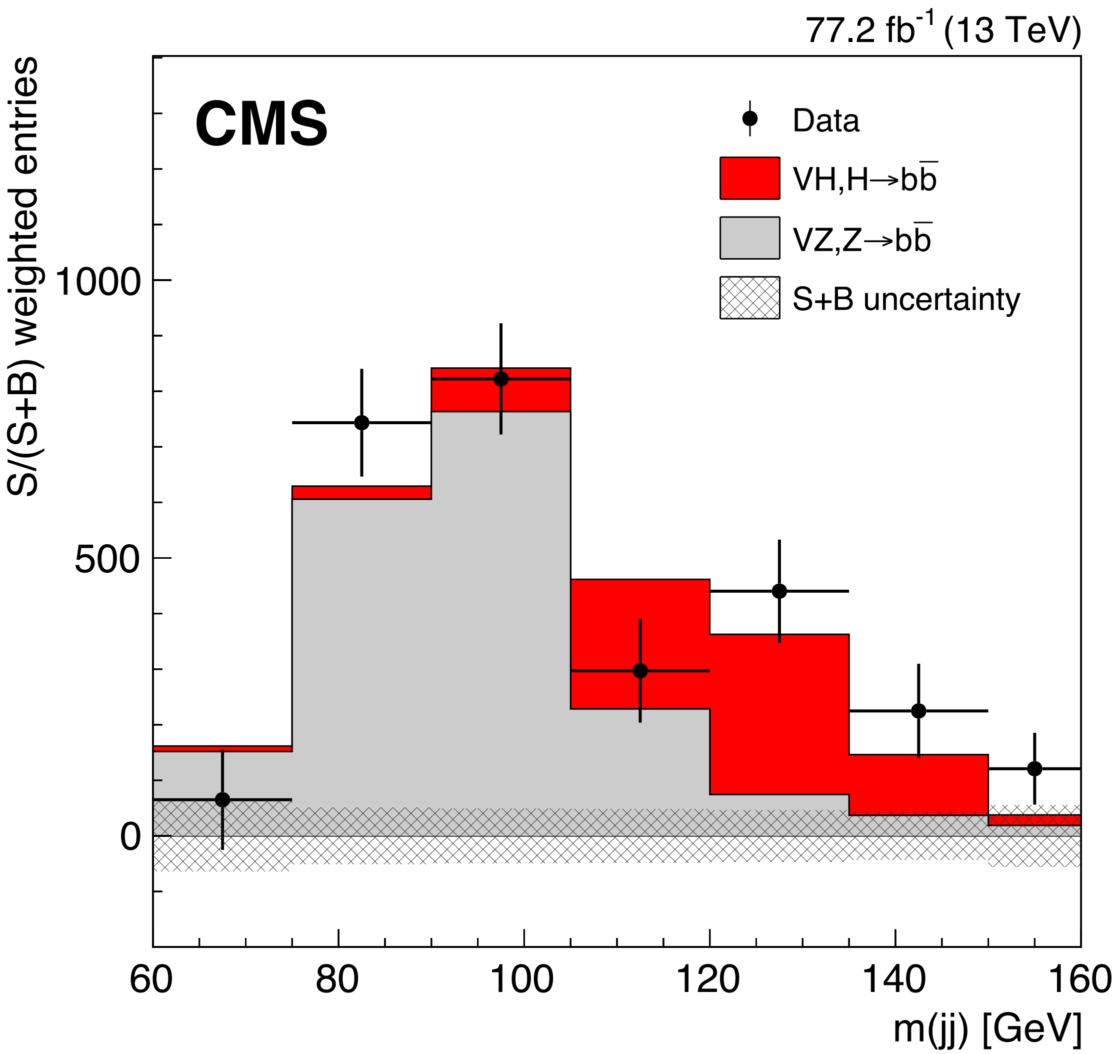
1) identify final state particles

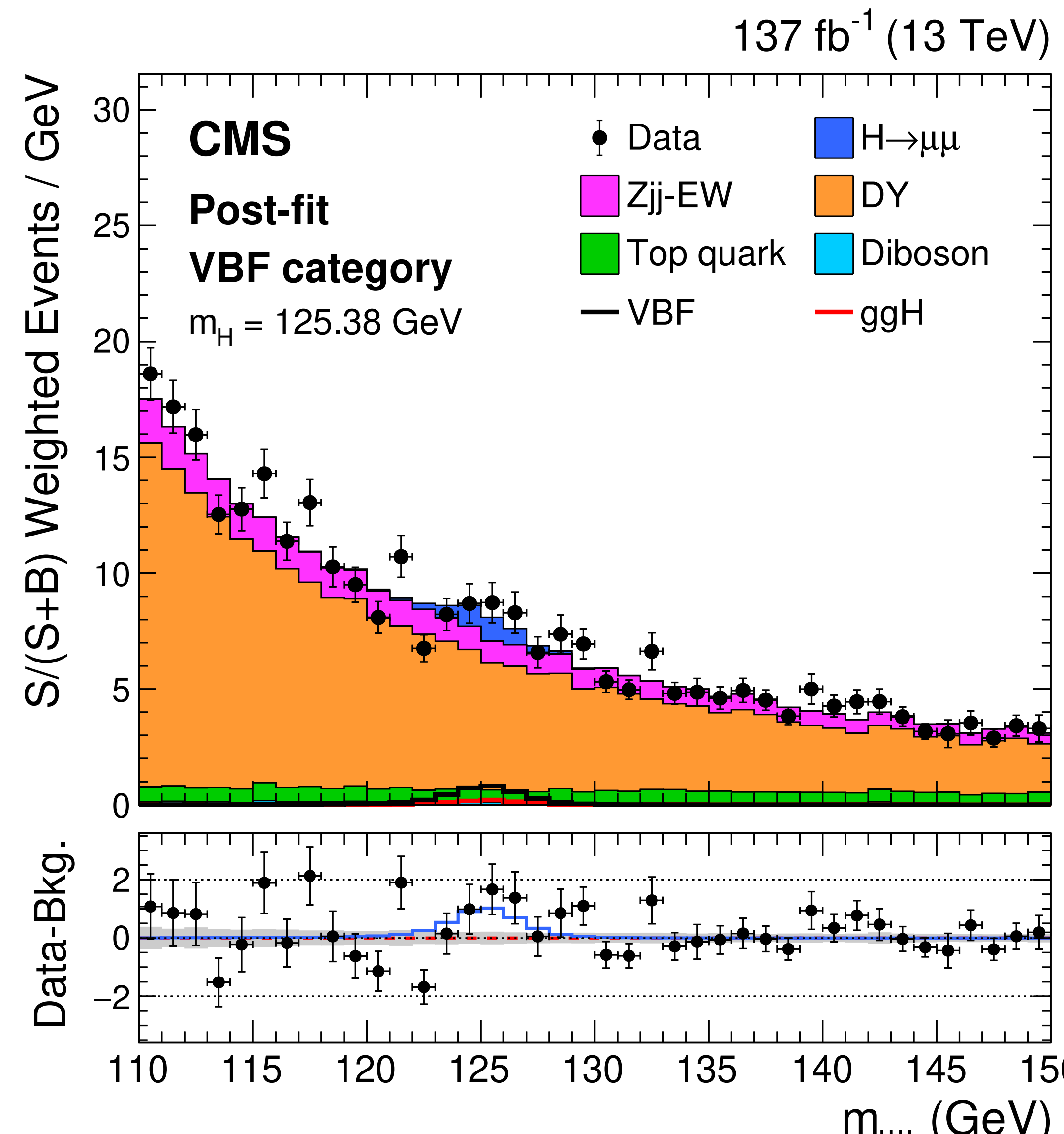
2) calibrate the detector to improve the resolution

3) fit for a narrow peak on a smooth background

Higgs "bumps" after discovery

- After discovery, more modes have been used to measure Higgs couplings to ordinary particles, with more data (LHC Run-2)





bottom-quarks: $H \rightarrow b\bar{b}$

overwhelming QCD di-jet background

-> need rare productions (WH,ZH) to suppress it

-> need advanced b-tagging

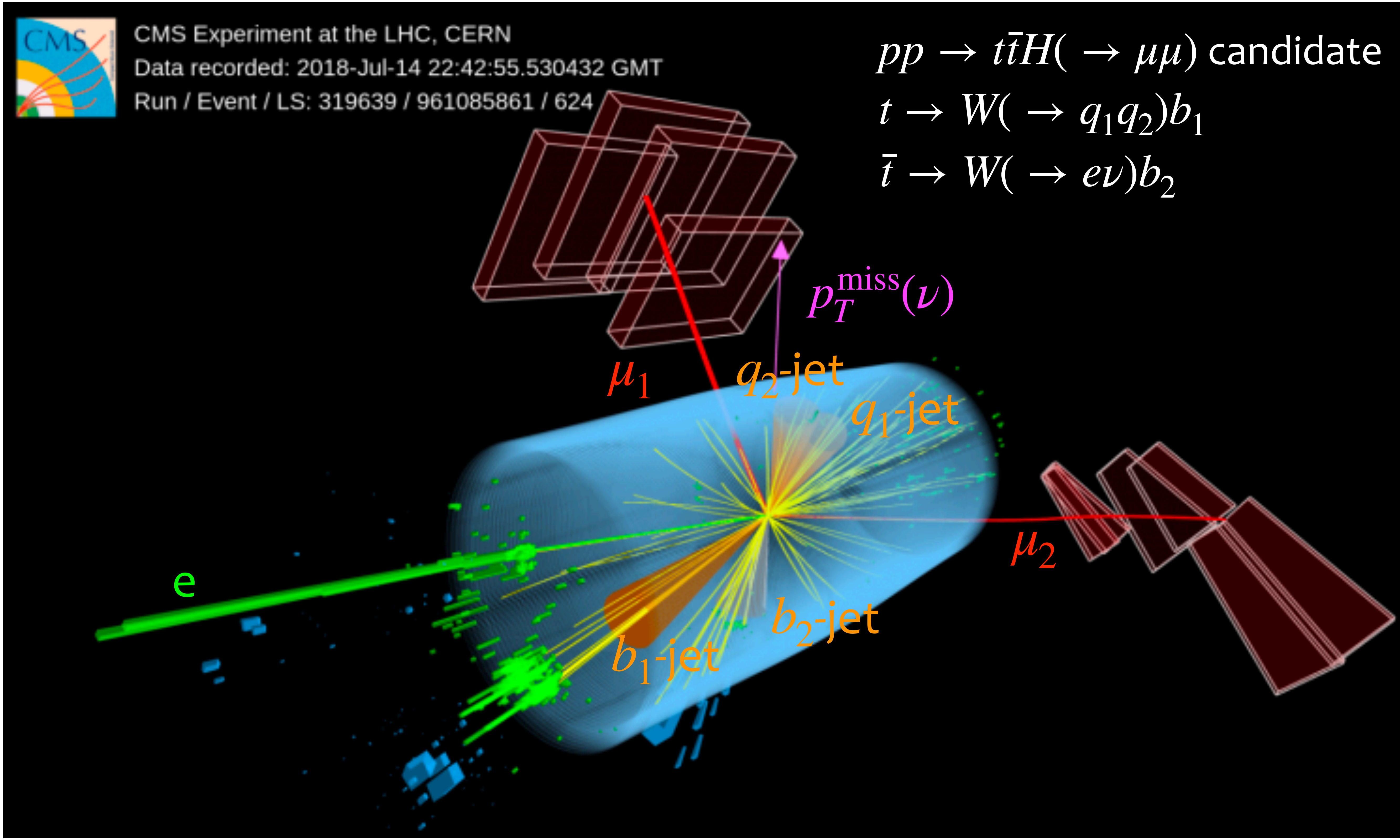
2nd generation fermions: $H \rightarrow \mu\mu$

overwhelming DrellYan background

-> need optimised event selection

-> need to use ALL production modes

$H \to \mu\mu$ candidate



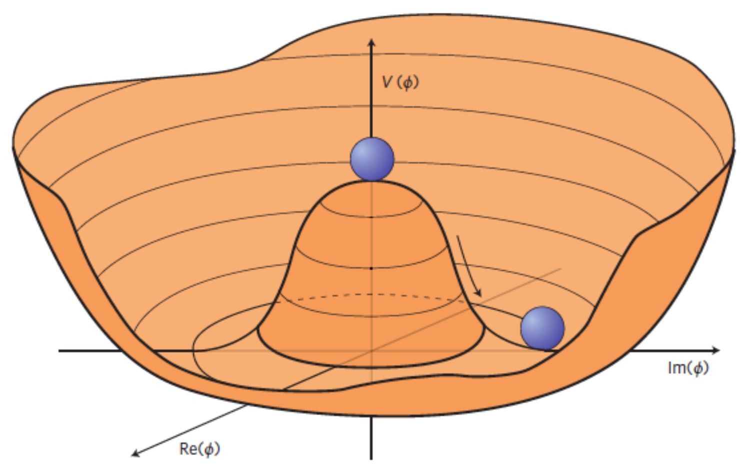
Towards di-Higgs quest

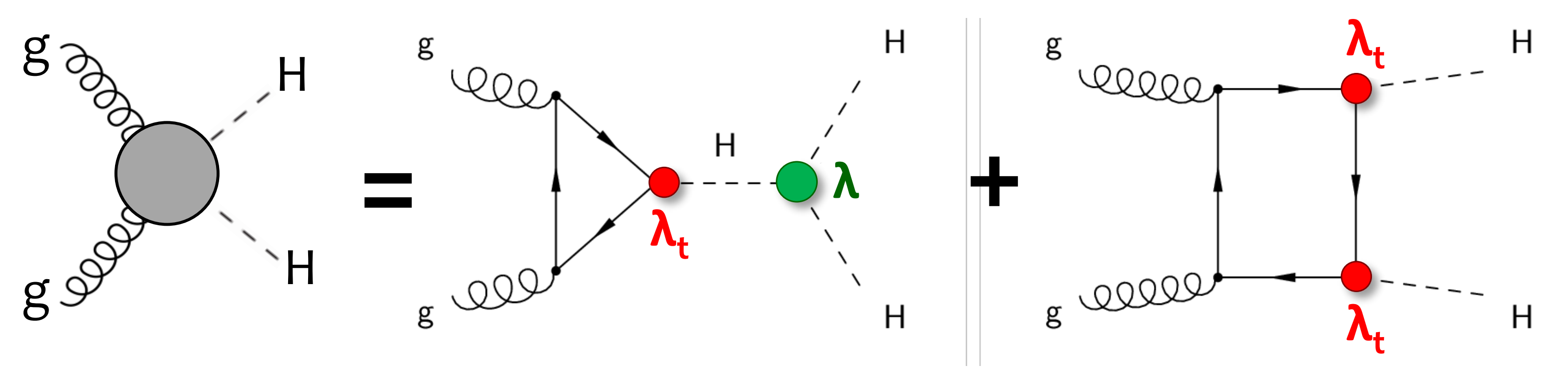
- From single-Higgs to di-Higgs production: the long way for the Higgs self-coupling
  - fundamental test of the SM: defines the Higgs potential

largest production mode in SM (gluon fusion) is rare:

$$\sigma(\text{ggHH}) = 31 \text{ fb} \approx 1/1500 \times \sigma(\text{ggH})$$

$$V(\Phi) = \mu^2\Phi^2 + \lambda\Phi^4$$





self-coupling λ | Higgs-top coupling λ_t

λ defines the shape of the potential, once the H mass is determined

Direct non-resonant HH is still experimentally non-observed:

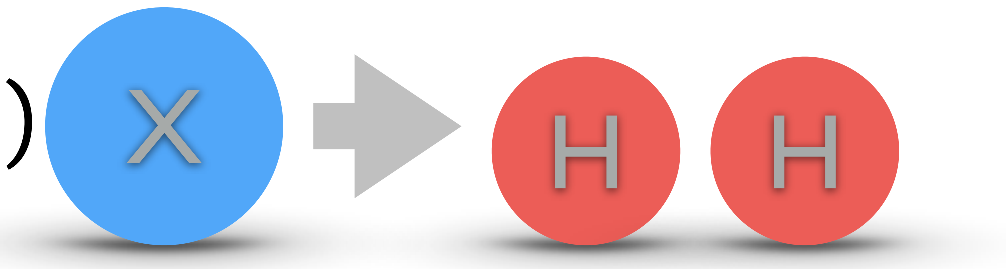
1) need a large dataset (i.e. HL-LHC)
2) and/or use all possible combination of di-H decay modes

Beyond SM: resonant X->HH

HH can appear, beyond the Standard Model, as decay of unknown massive particles, produced at LHC: “resonant” X->HH production

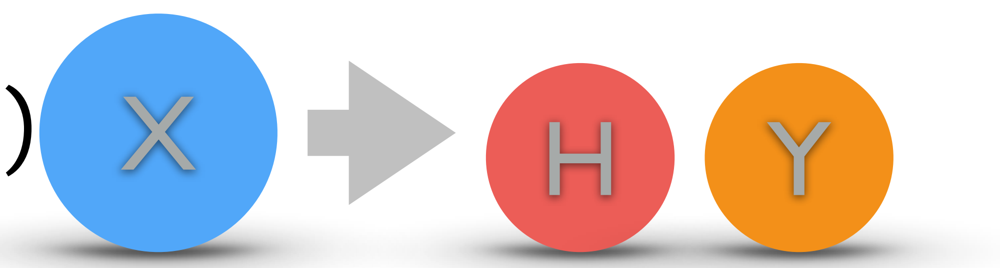
1) X→HH (H = H125)

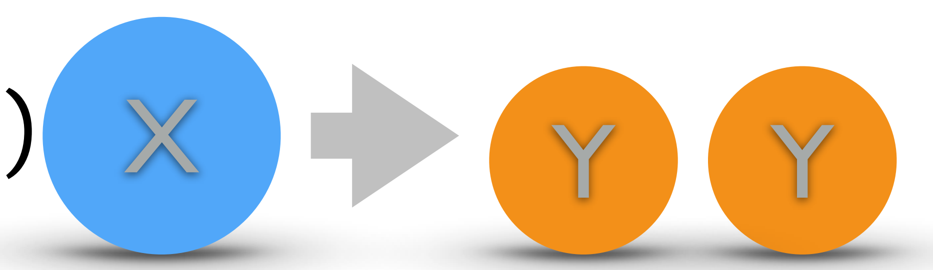
- Appears in all extended Higgs sectors if mX > 250 GeV: 2HDM (including MSSM), real singlet
  -> *suppressed in alignment limit*
- Also generic resonances, e.g. in warped-extra-dimension models

1)


2) X→YH and **3) X→YY**

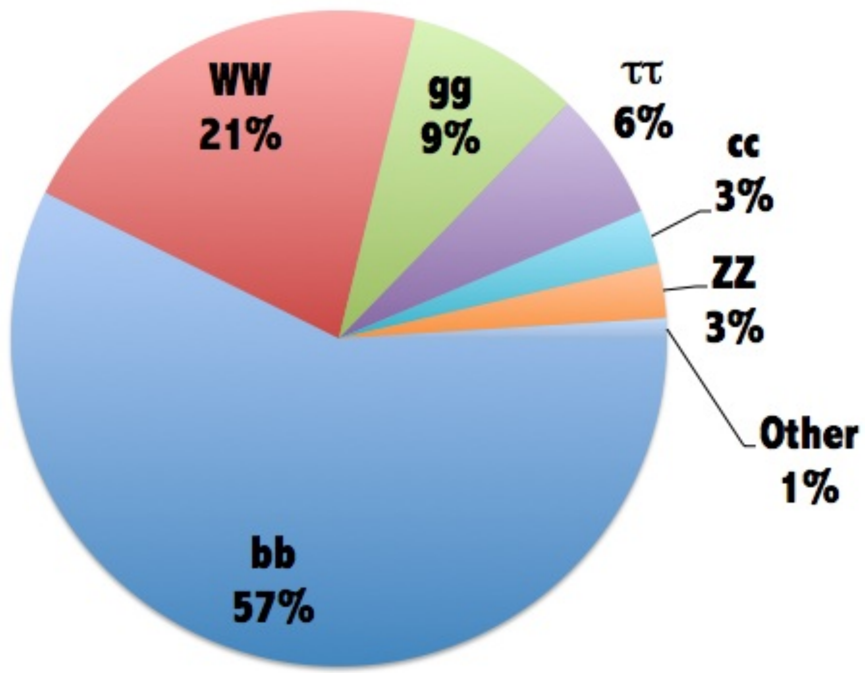
- Larger extended Higgs sectors: E.g. two additional singlets (TRSM), 2-Higgs-doublet + singlet (2HDM+S including NMSSM)
  -> not suppressed in alignment limit, hence often discovery channel if kinematically allowed

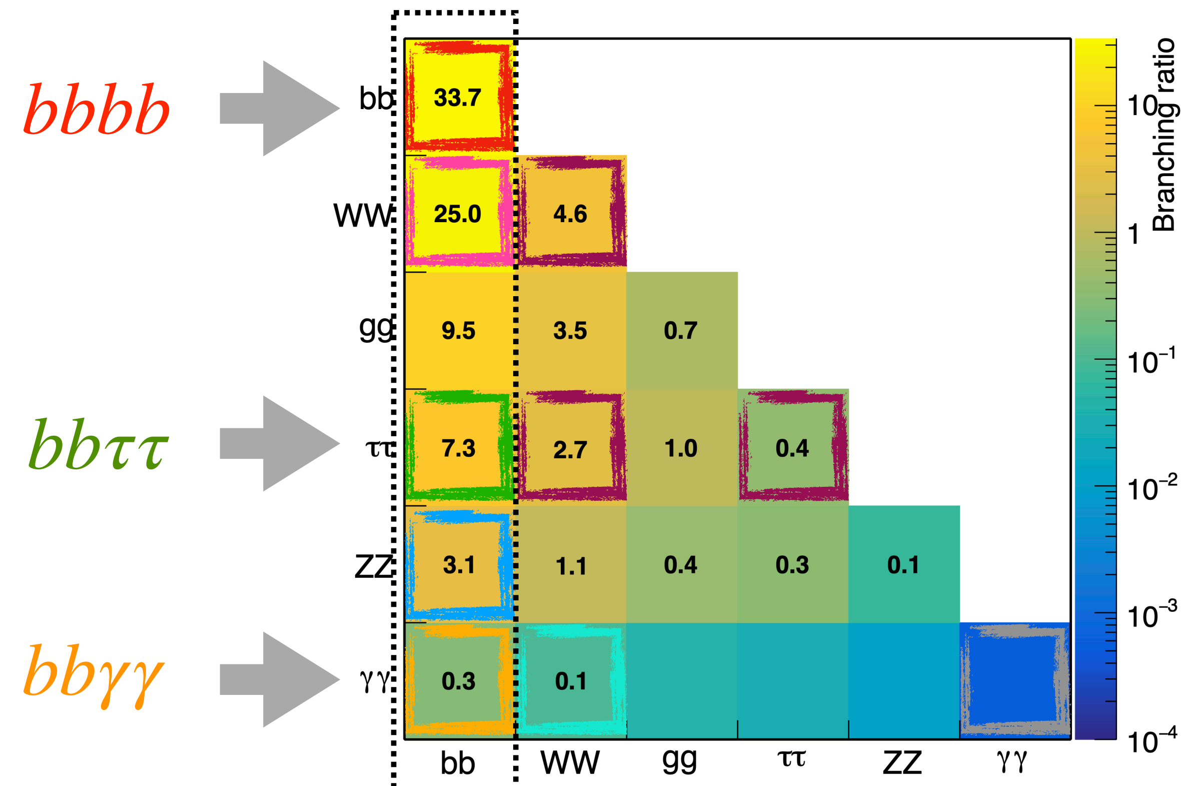
2)


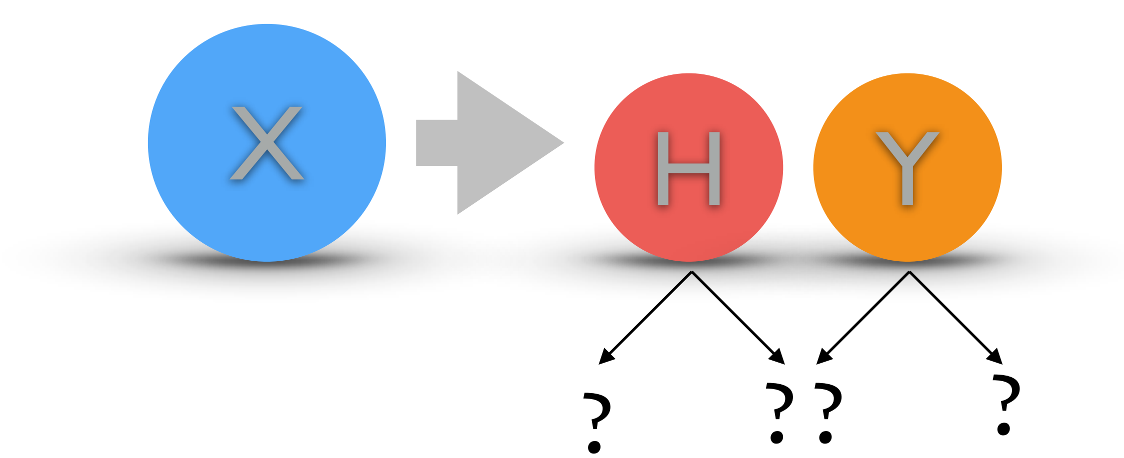
3)


di-Higgs channels

- Combine a high BR channel ($H \to b\bar{b}$) with a high resolution channel (e.g. $H \to \gamma\gamma$)
  - the most sensitive channels are $bb\gamma\gamma$, $bbbb$, $bb\tau\tau$

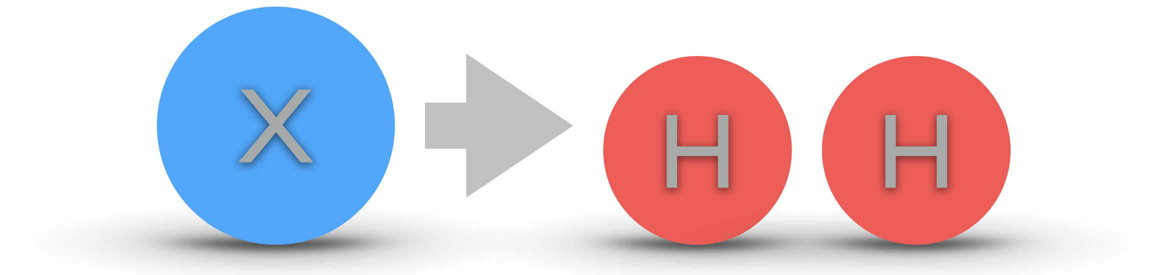






if Y!=H125, BRs can be different, but typically assumed similar (model dependency!)

$X \to HH$ searches



The contributing channels

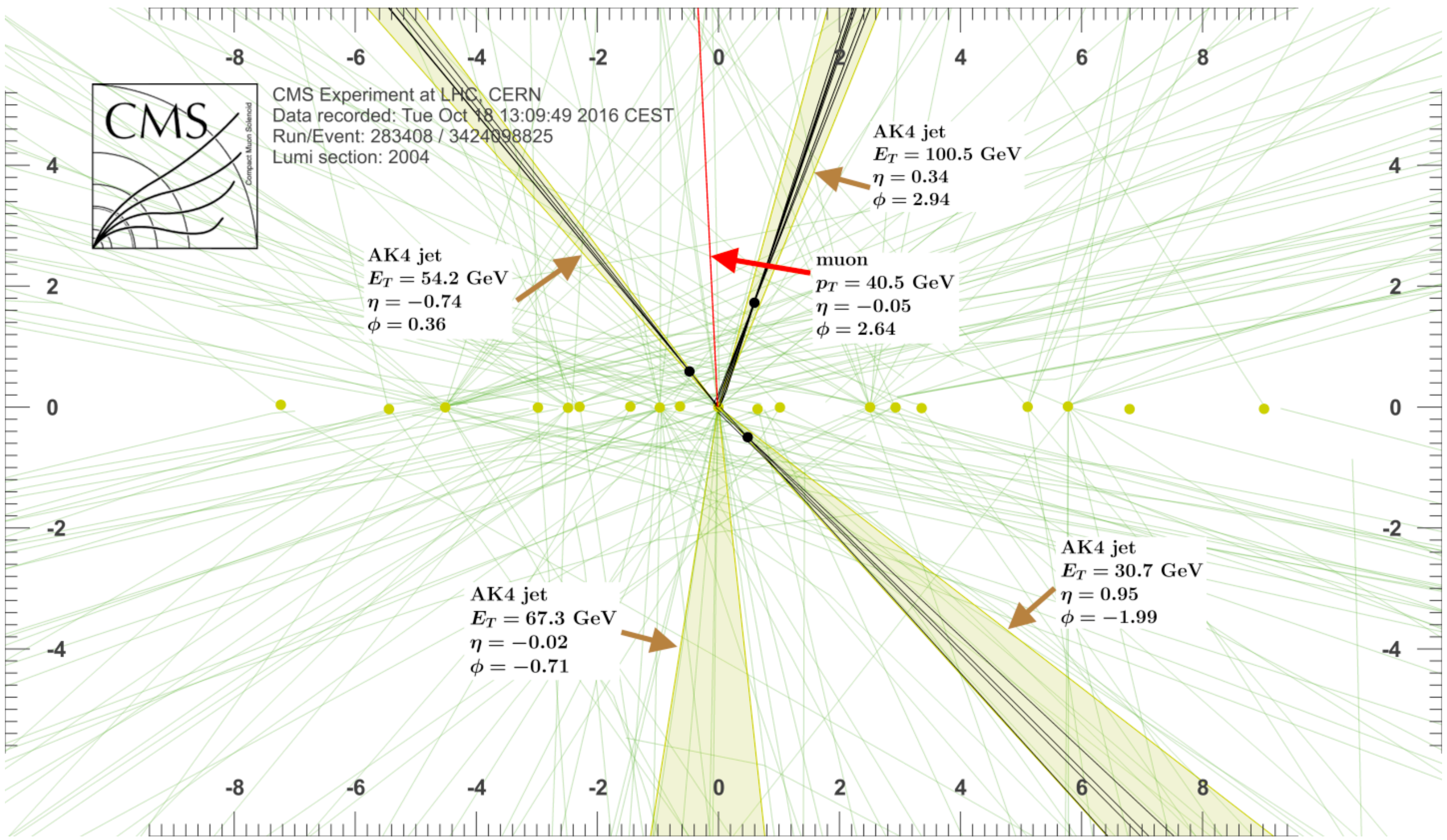
- Three major final states:
  $bb\gamma\gamma$, $bb\tau\tau$, $bbbb$ (from low to high mass)
  - $bb\gamma\gamma$: $H \rightarrow \gamma\gamma$ high purity and resolution + $H \rightarrow b\bar{b}$ high BR, use b-tagging for QCD di-jet background rejection
    - -> yields BR=0.23% for $X \rightarrow HH$ search
  - $bb\tau\tau$: multiple decay modes of the τ leptons (full hadronic, semi-leptonic, fully leptonic)
    - -> sensitive in the same mass range of $bb\gamma\gamma$
  - $bbWW$: helps in intermediate mass range
  - $bbbb$: full-hadronic complicate final state at LHC
    - Exploit b-tagging at maximum
    - Increased reach in bbbb merged-jet analysis from using ParticleNet tagger

m_X

b (and c) tagging challenges

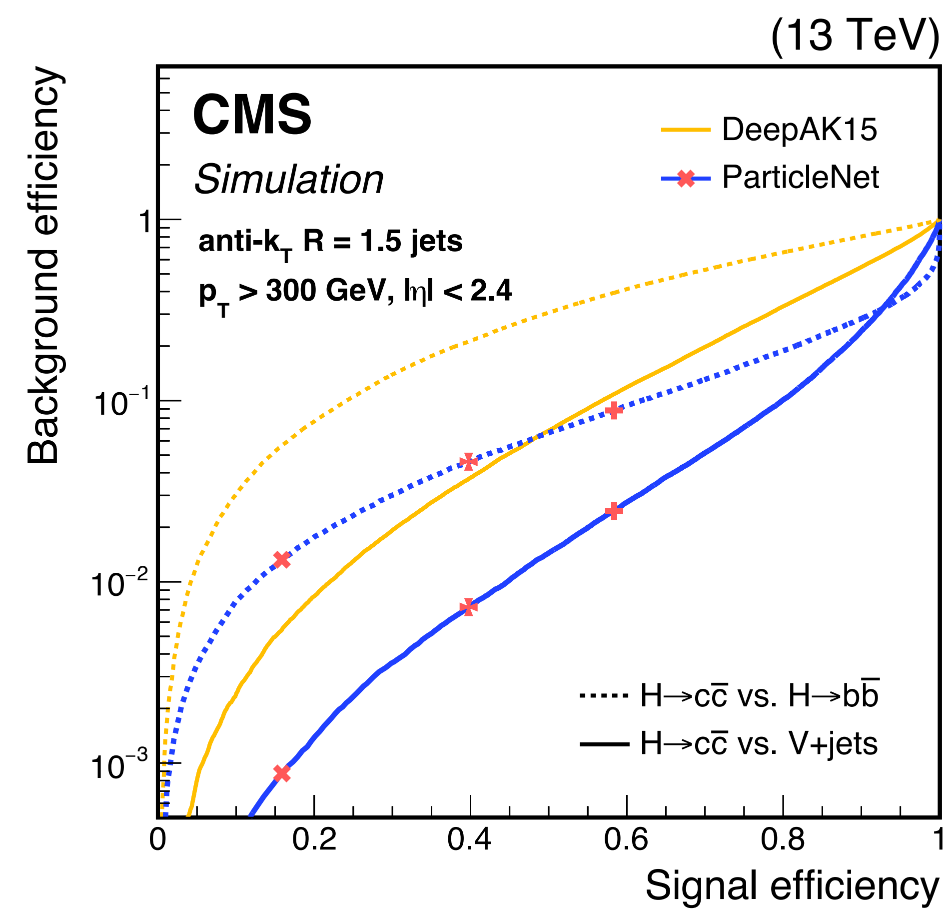
- Hadrons containing b-quarks and c-quarks have a measurable lifetime
  - b-hadrons: $c\tau \sim 450 - 500\,\mu\mathrm{m}$
  - c-hadrons: $c\tau \sim 120 - 300\,\mu\mathrm{m}$
  - -> use information about displaced vertex of decay tracks in sophisticated neural net (NN) to tag a jet as a light-flavor / b-tagged / c-tagged

CMS-DP-2016-032



19 reconstructed vertices
2 b-tagged jets, 1-c-tagged jet

For c-tag efficiency~50%:
mistag rate **vs b ~10%**, vs **light quark~1%**

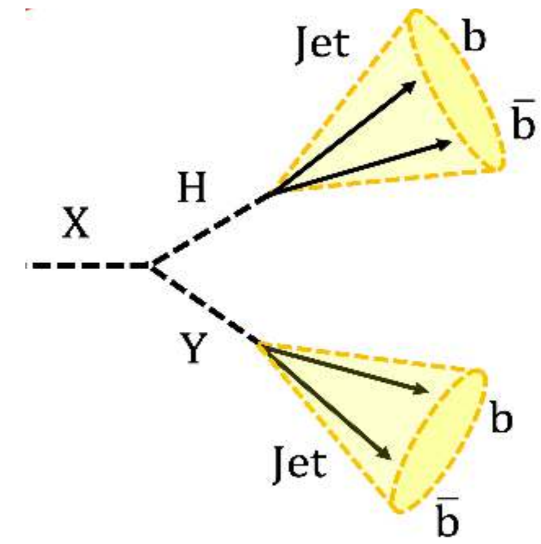


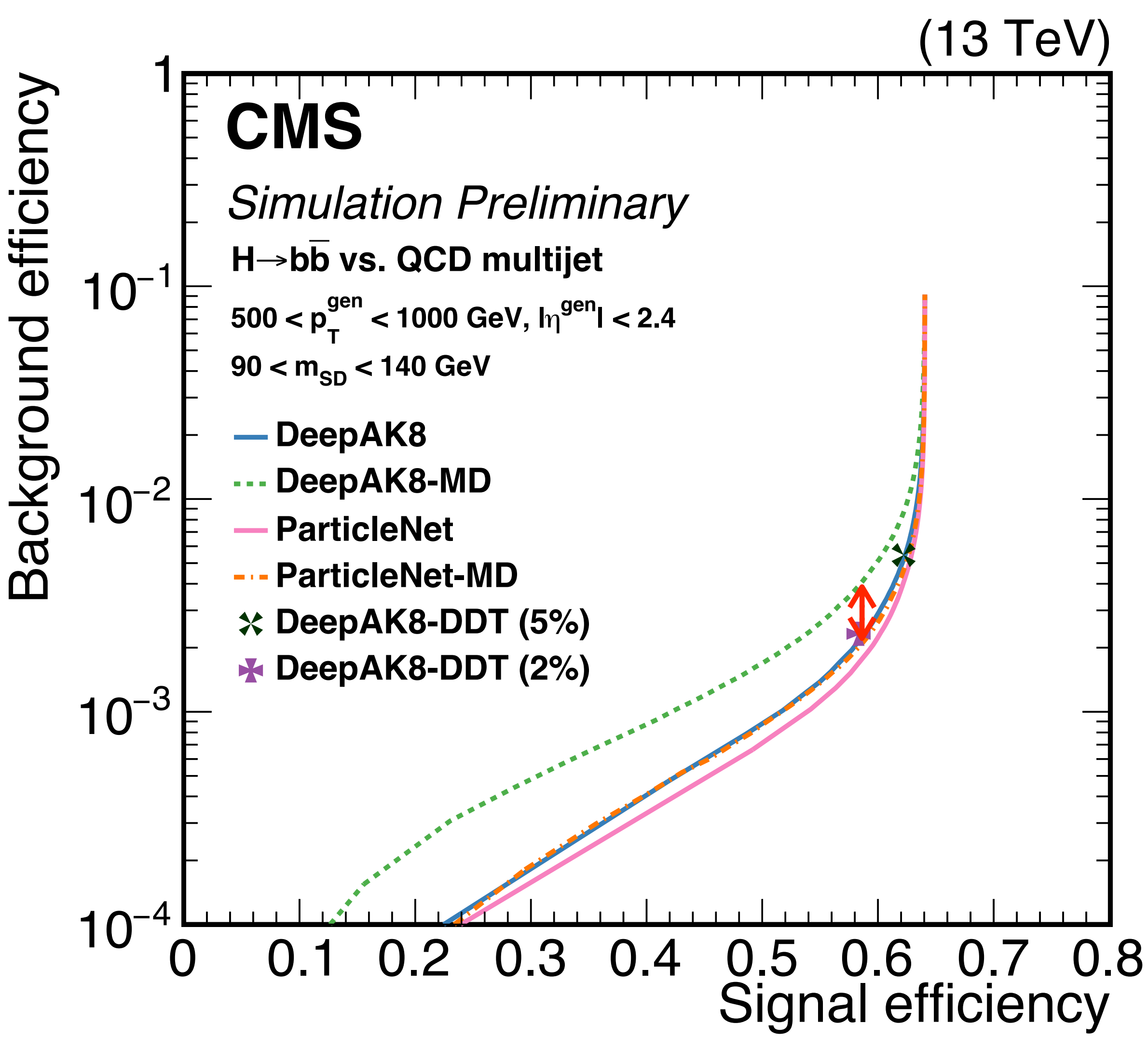
GNN-based c-tagger for $H \to c\bar{c}$

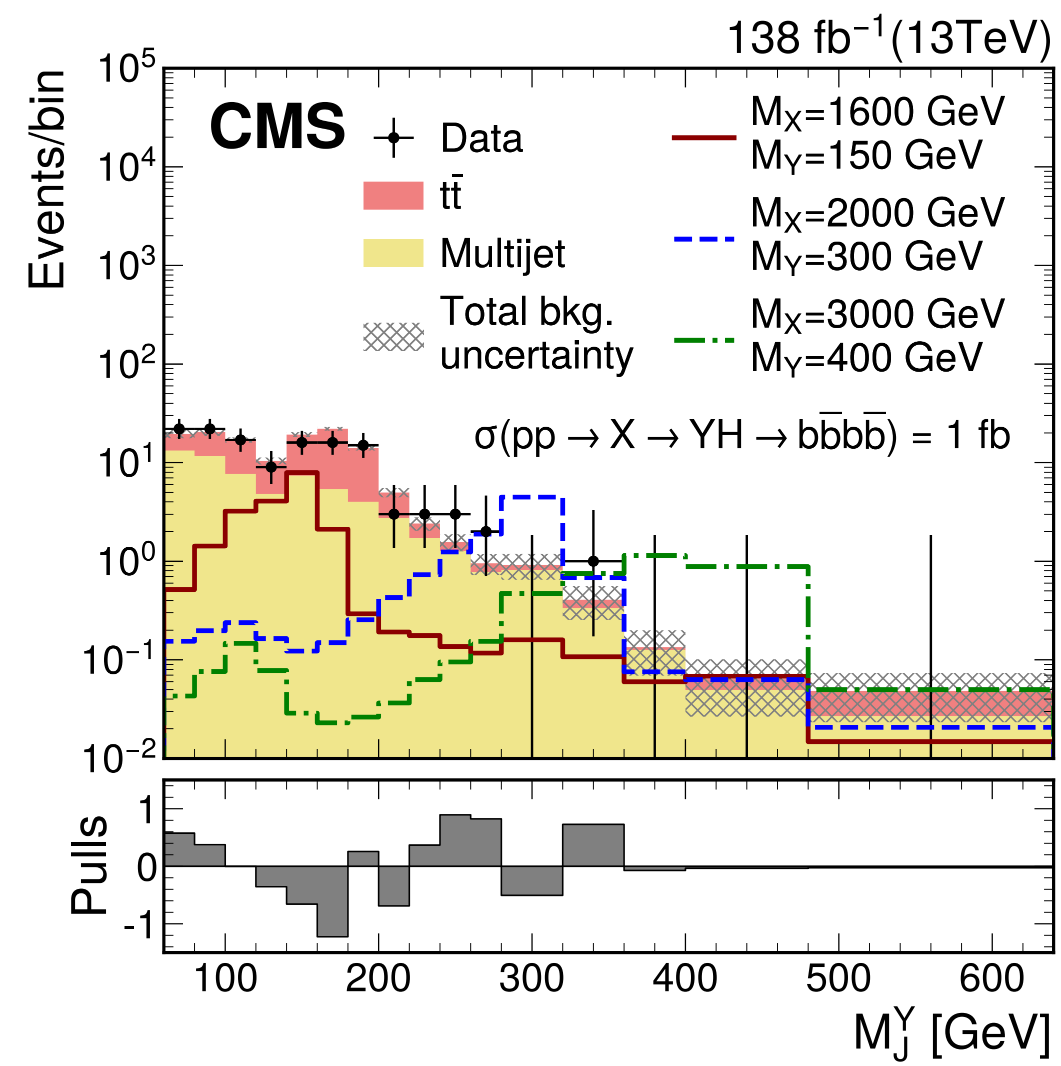
X->HH->4b boosted

- For very high X mass ($M_X \gg M_H$), b-jets are Lorentz-boosted -> 2 b-jets merge in one large jet
  - Increased reach in bbbb analysis using ParticleNet tagger

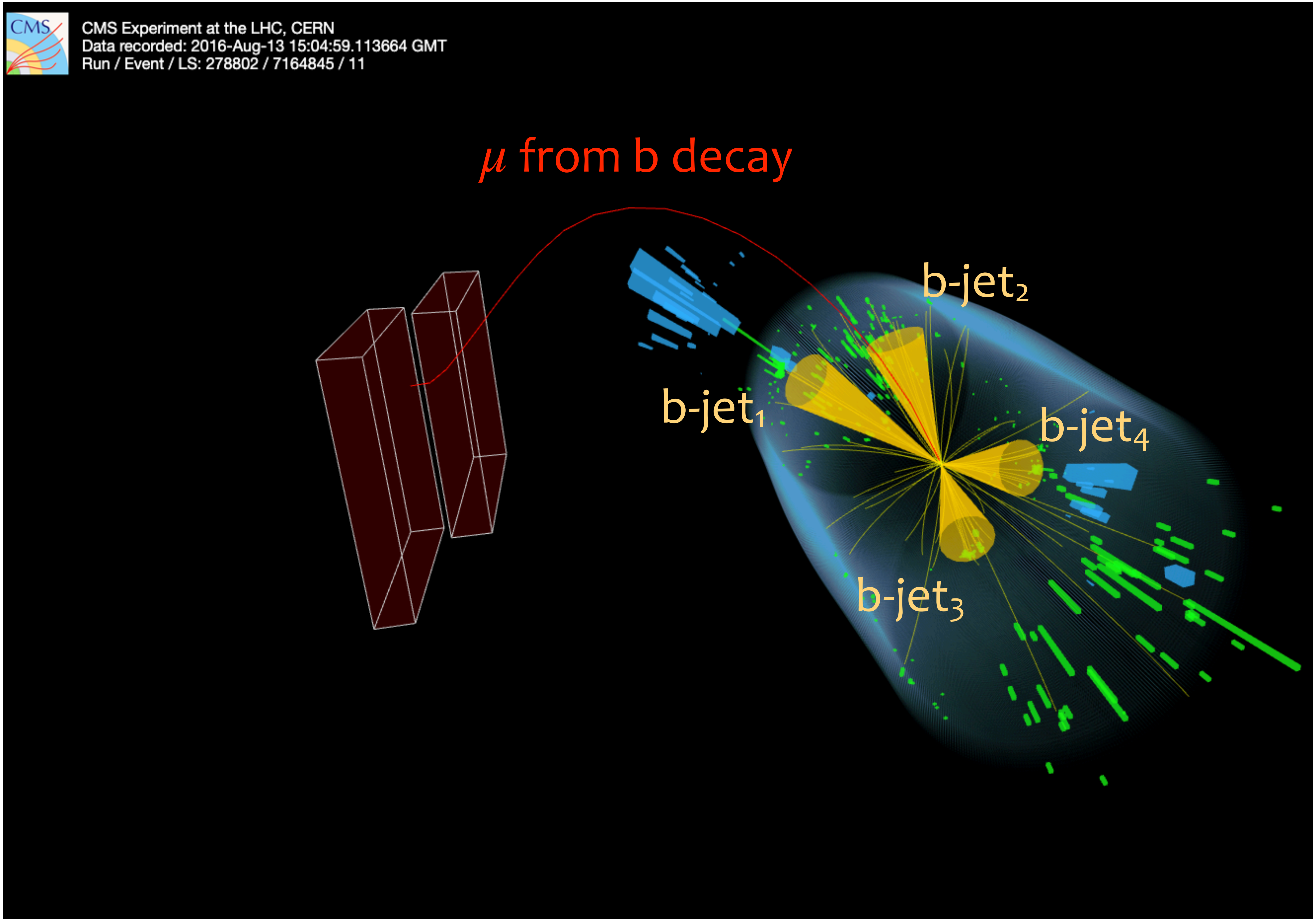
    e.g. at ~60% efficiency, **1/2 mis-tag** of previous tagger (DeepAK8)







$HH \rightarrow 4b$ candidate

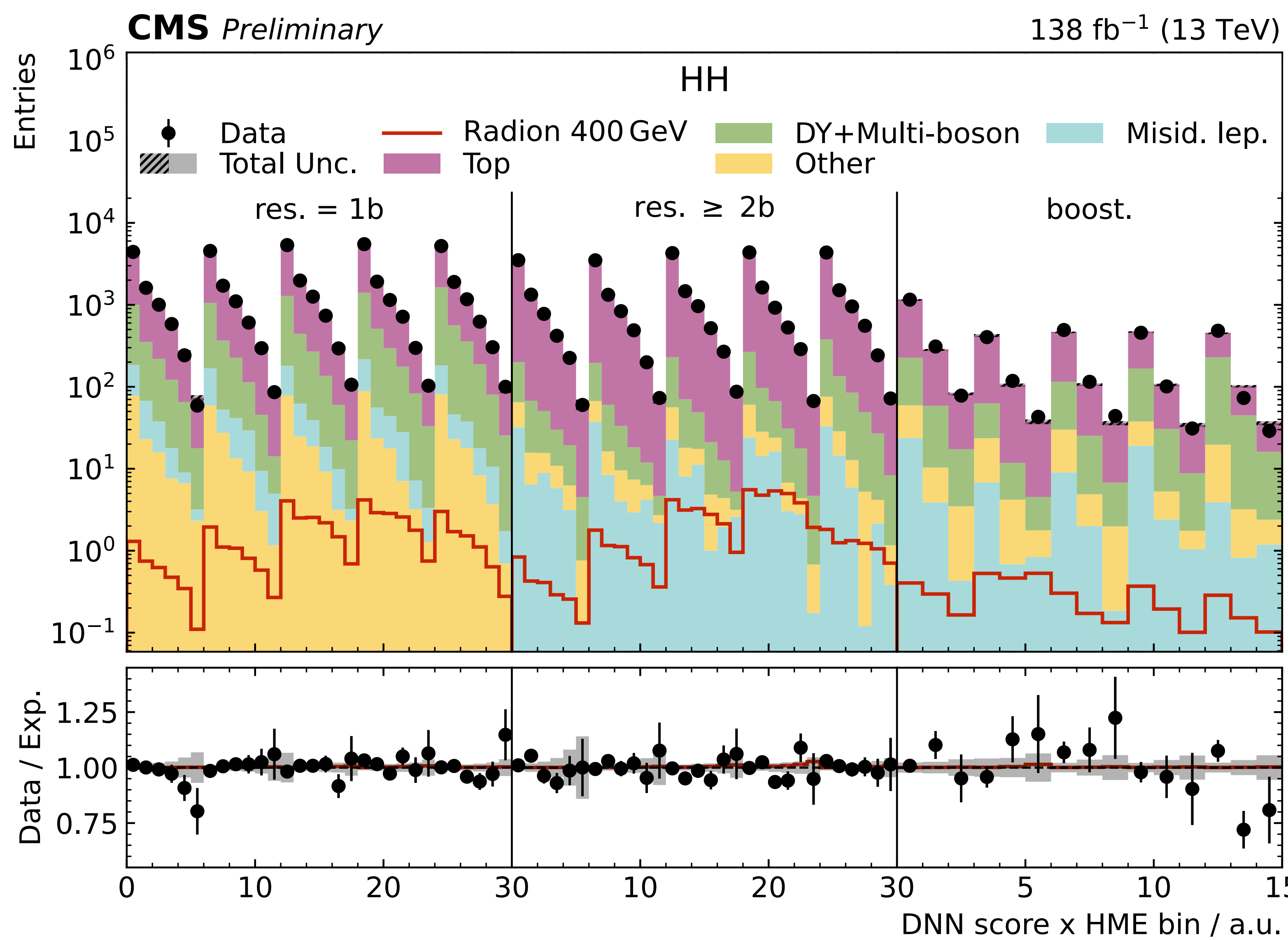


X->HH->bbWW resolved

In addition to the three most important final states bbγγ, bbττ, bbbb, also results in **bbWW** and **multilepton** final states help

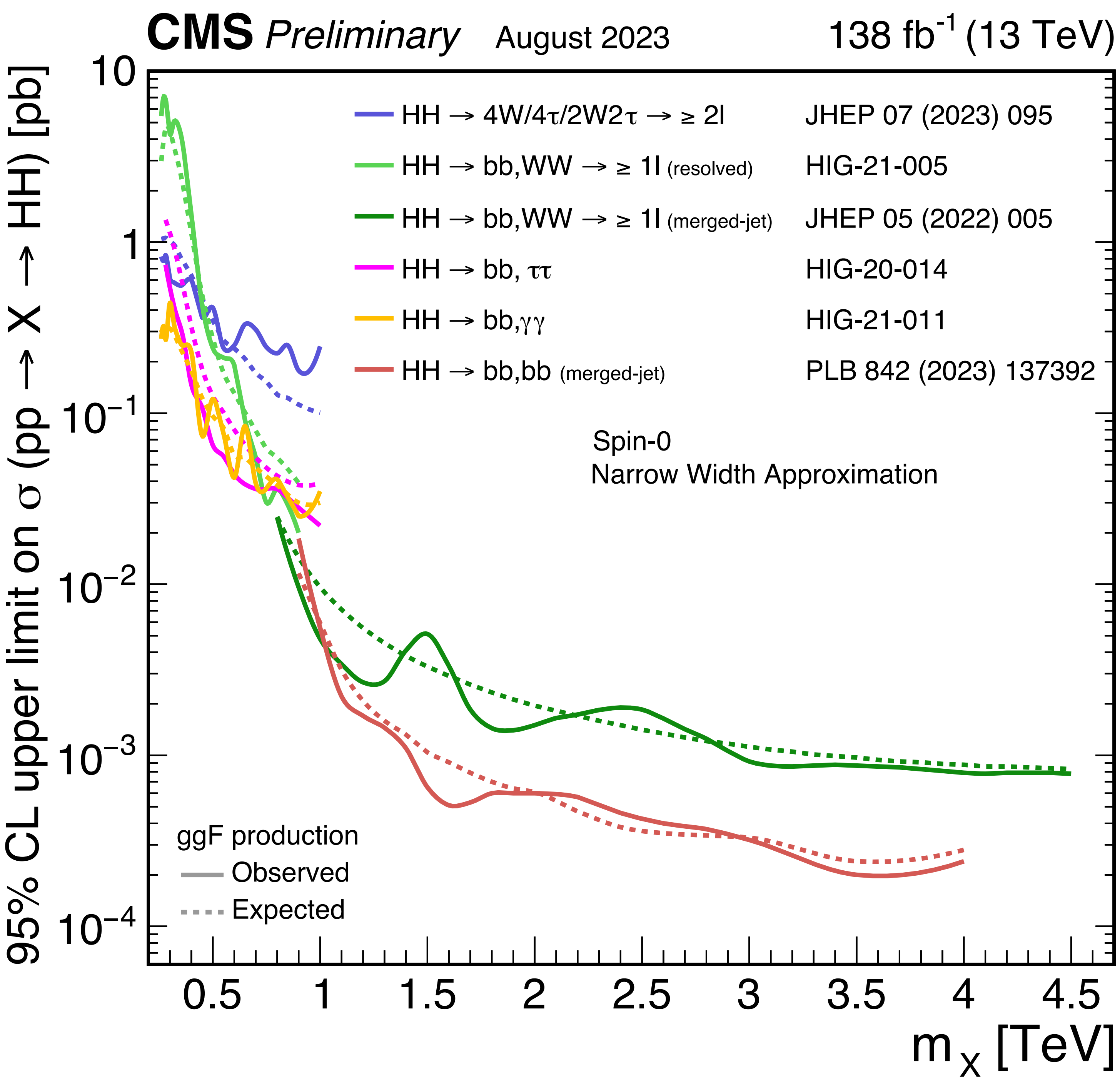
bbWW resolved:

- Di-lepton and single-lepton channels
- Fit DNN scores (times X mass estimator in di-lepton channel) in three signal regions (1b, 2b, boosted) and two control regions
- $t\bar{t}$ is main background



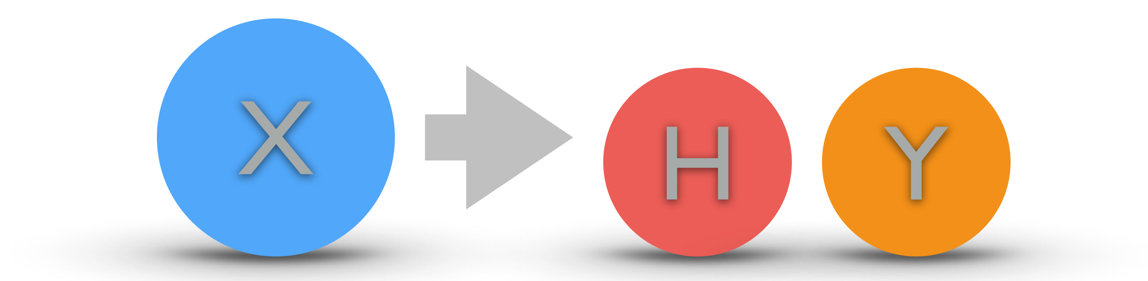
$X \rightarrow HH$ summary

- bbγγ 2310.01643 (subm. to JHEP)
- bbττ JHEP 11 (2021) 057
- bbbb (merged-jet) Phys. Lett. B 842 (2023) 137392
- 4W/4τ/2W2τ JHEP 07 (2023) 095
- bbWW (merged-jet) JHEP 05 (2022) 005
- bbWW HIG-21-005 (March 2023)

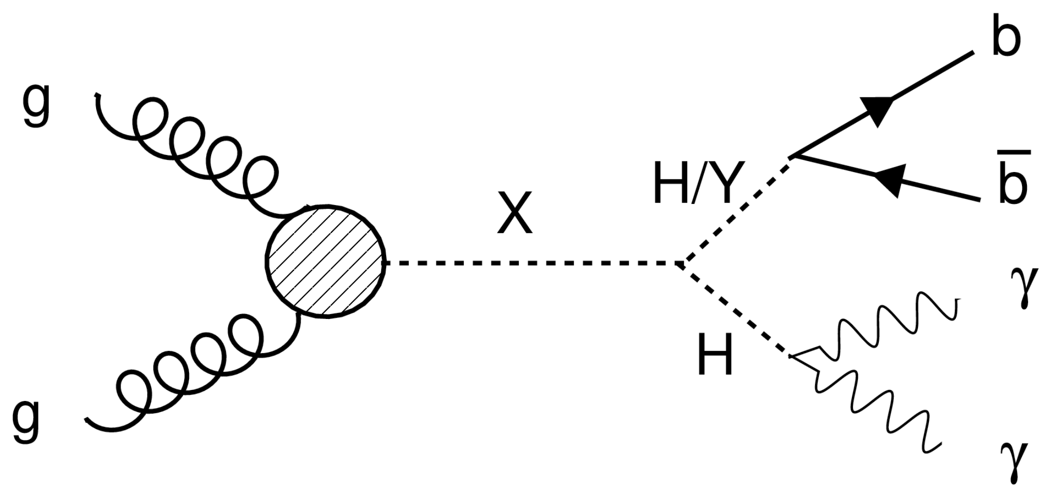


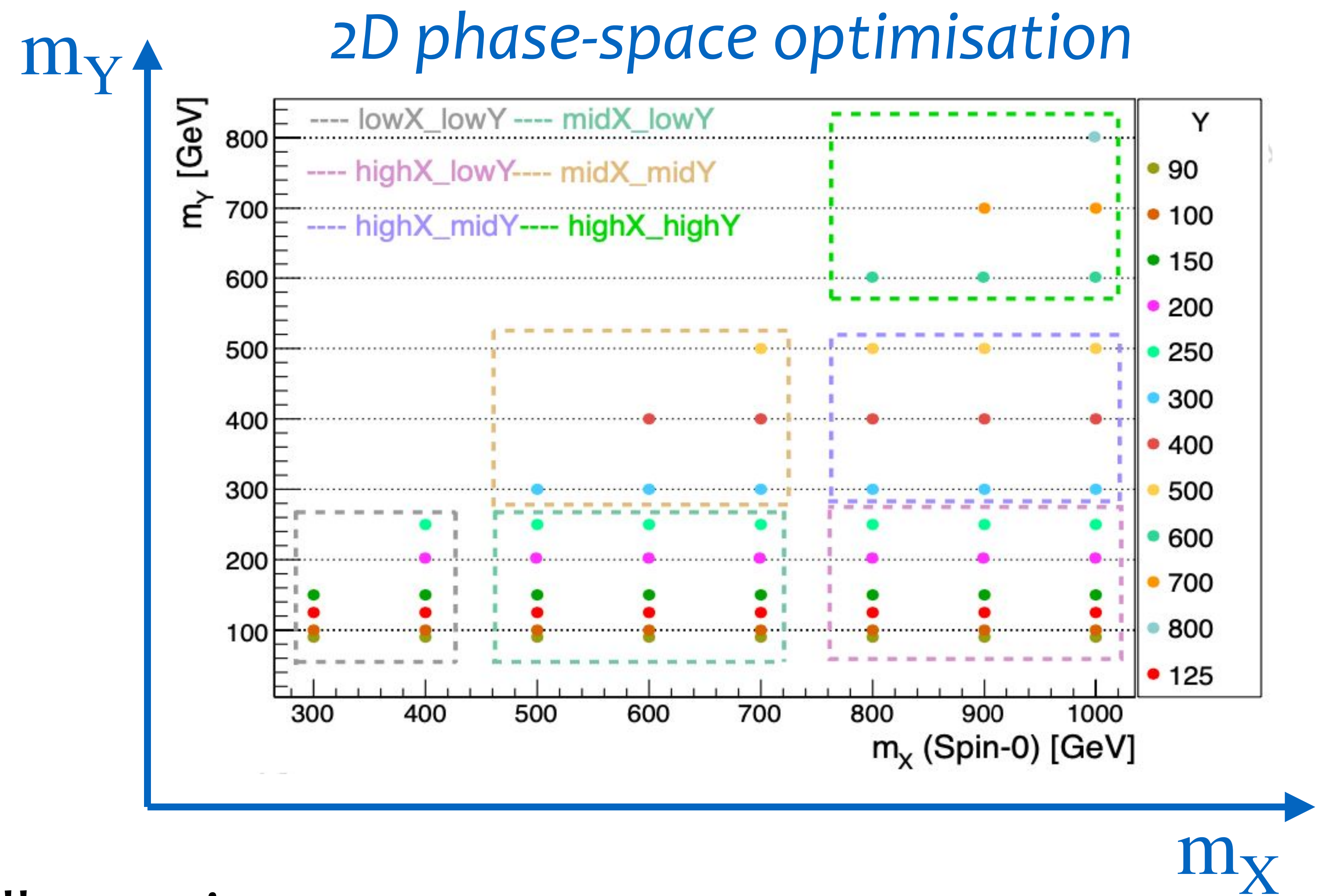
CMS B2G Summary Plots

$X \to HY$ searches



X->YH overview





Compared to X→HH:

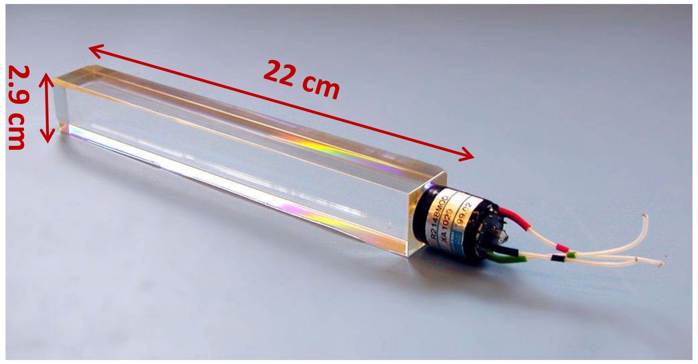
- bbγγ, bbττ, bbbb generally still most important
- However, Y branching fractions can be very non-SM-H-like, so other final states can be most sensitive depending on Y mass and the model!
- Asymmetry: often only one H decay probed (e.g. H→γγ for bbγγ result)
- Two masses to scan: Large phase space to probe, larger look-elsewhere effect

Use bbγγ in the following as an example

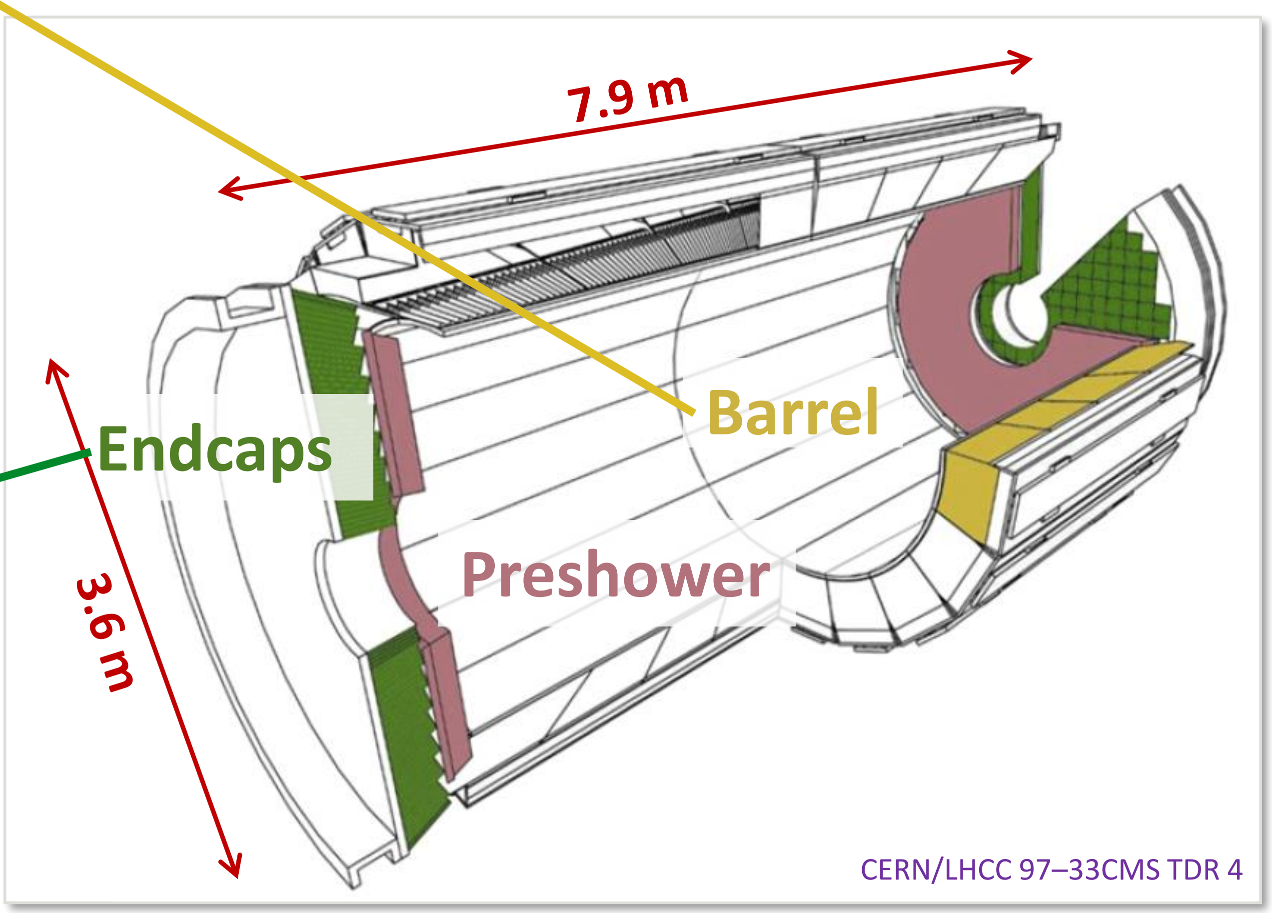
ECAL: the key photon detector

Lead Tungstate ($PbWO_4$) homogeneous calorimeter

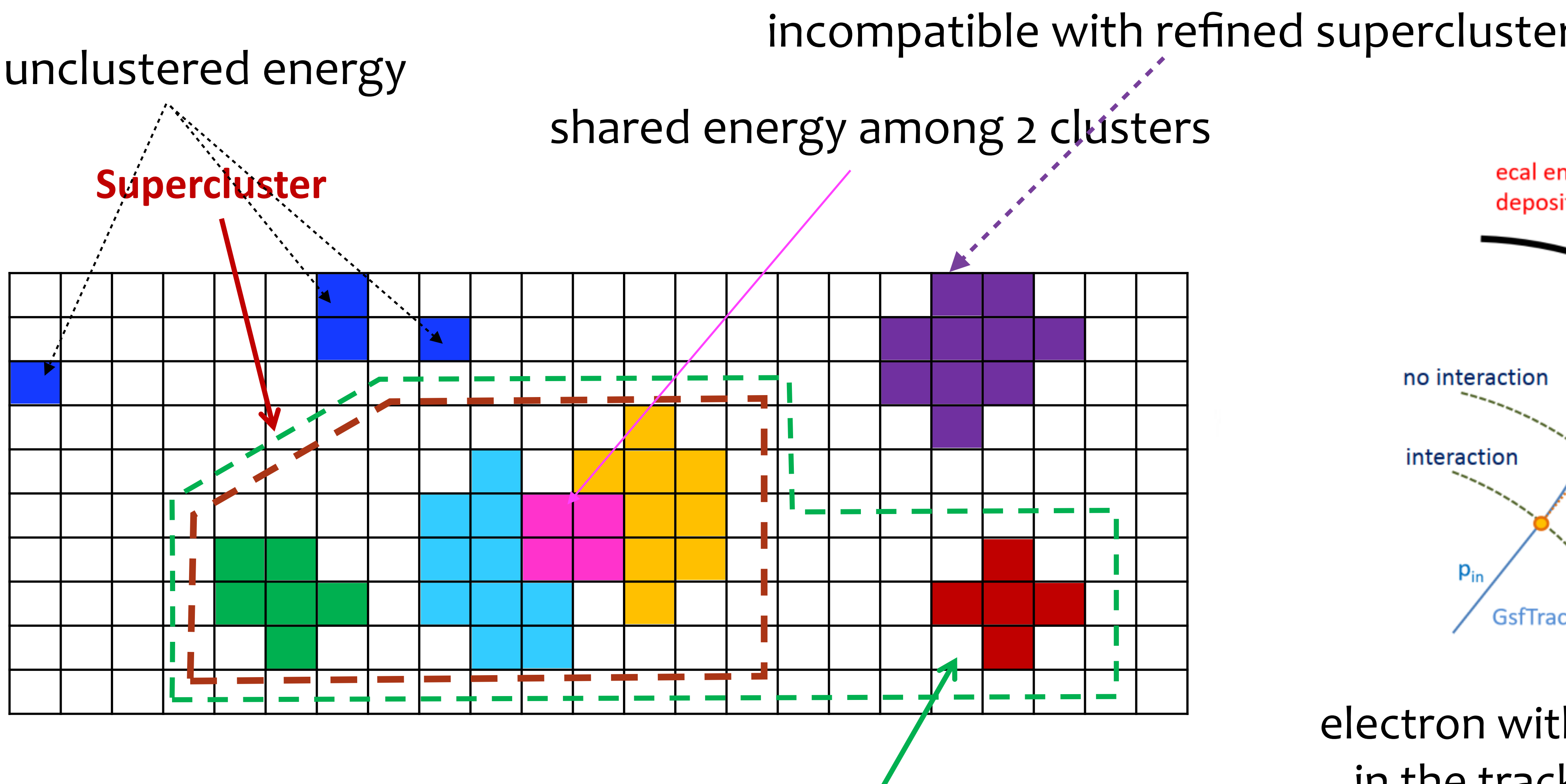
- 75848 crystals read via APD (barrel) or VPT (endcaps)
- depth: $25\,X_0$, width: $1.3\,R_{\text{Moliere}}$
- excellent radiation hardness



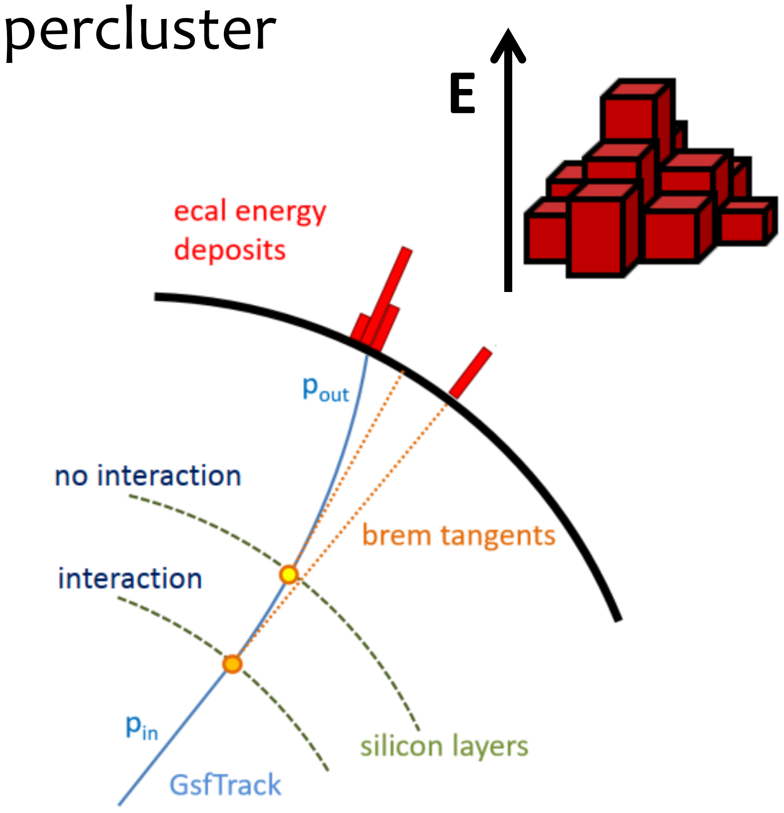
$\times 75848$



A photon (or electron) in ECAL



Recover of a very soft bremsstrahlung photon into the **refined supercluster**



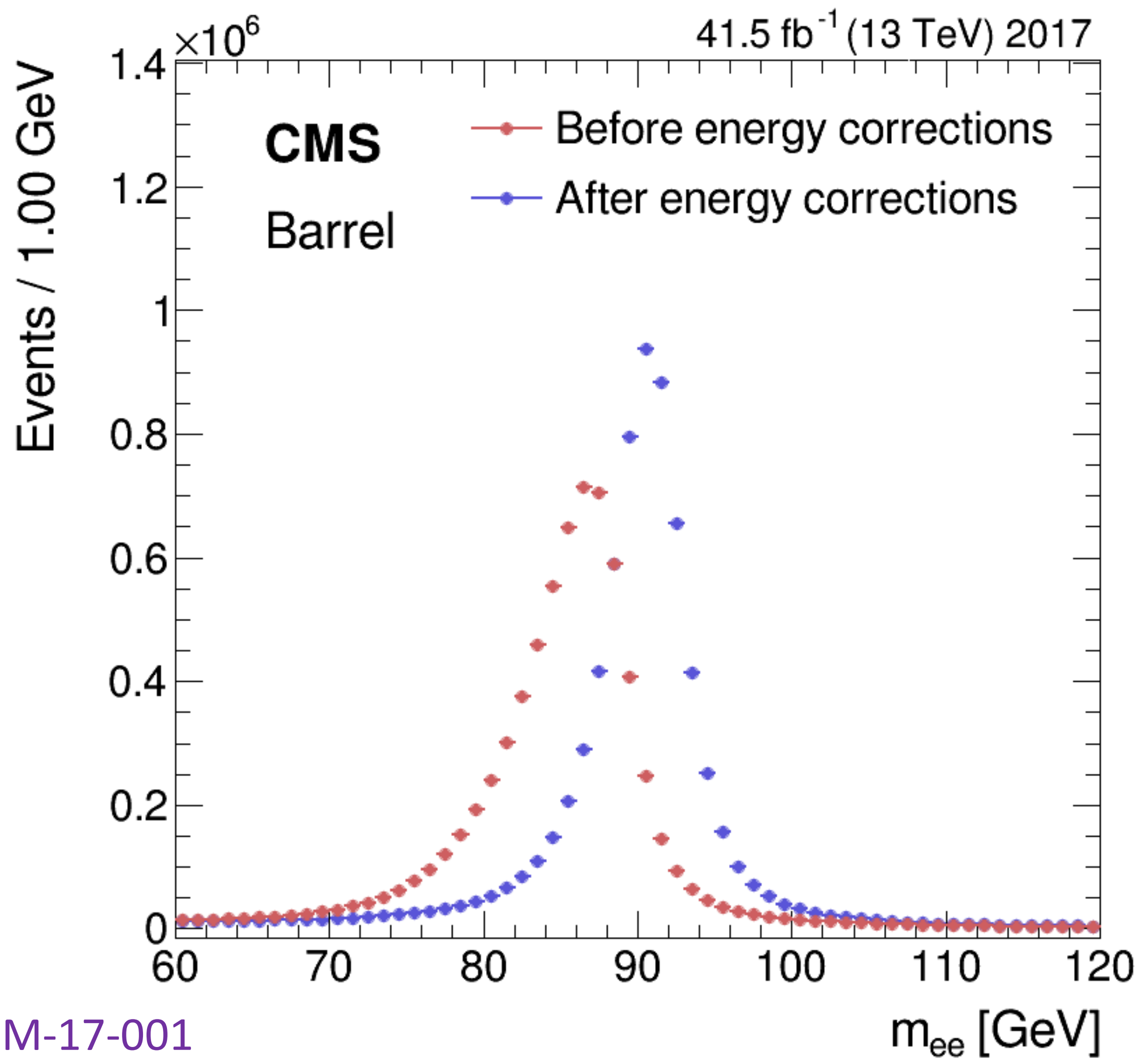
electron with bremsstrahlung in the tracker before ECAL

Dynamic "super"-clustering is the key in electron / photon reconstruction: recover deposits from electron brems or photon conversions

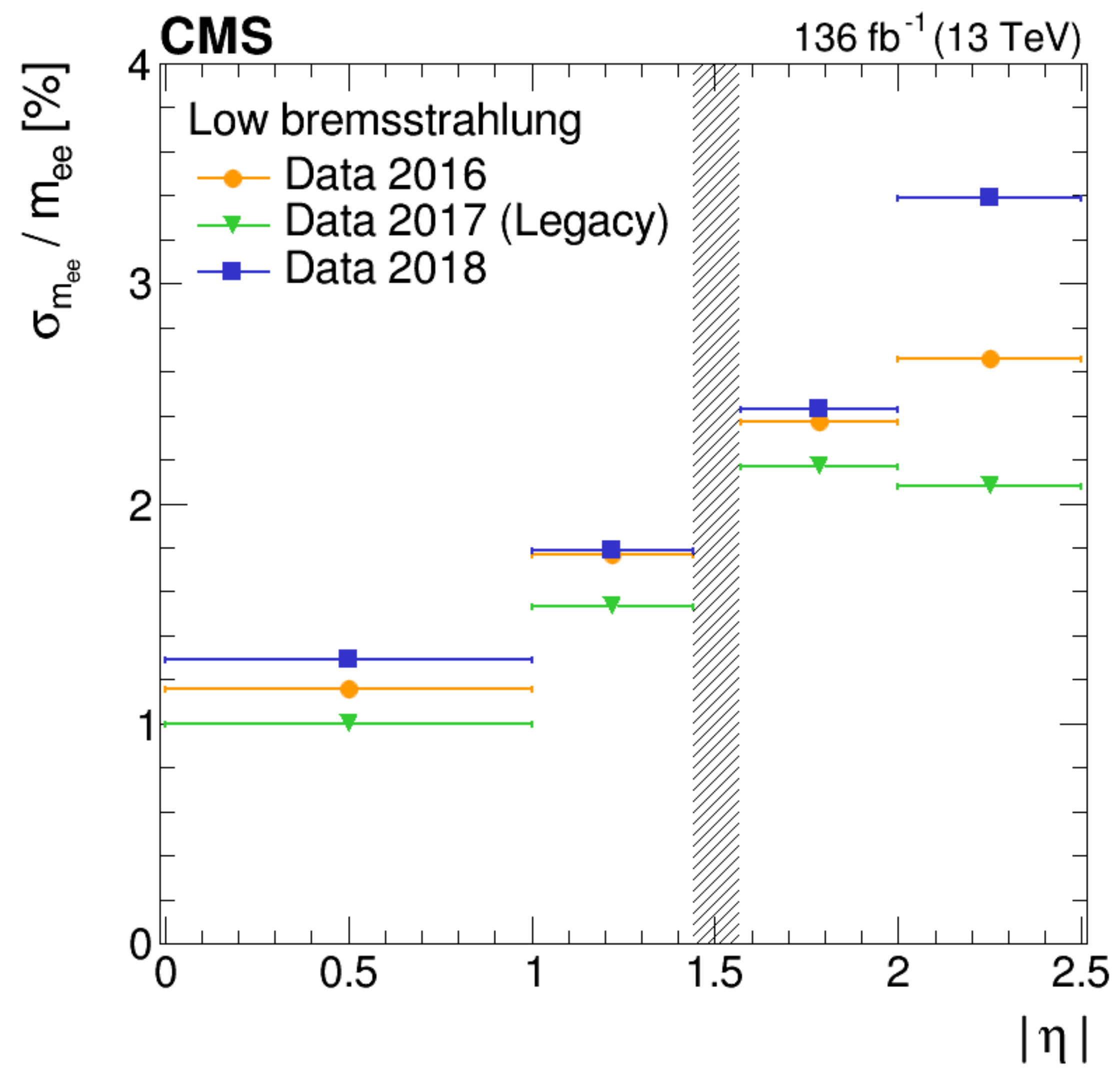
ECAL resolution

Huge work to **calibrate** the detector:

- aligns the energy scale in data with simulation
- improves the resolution -> increases the analysis sensitivity



EGM-17-001



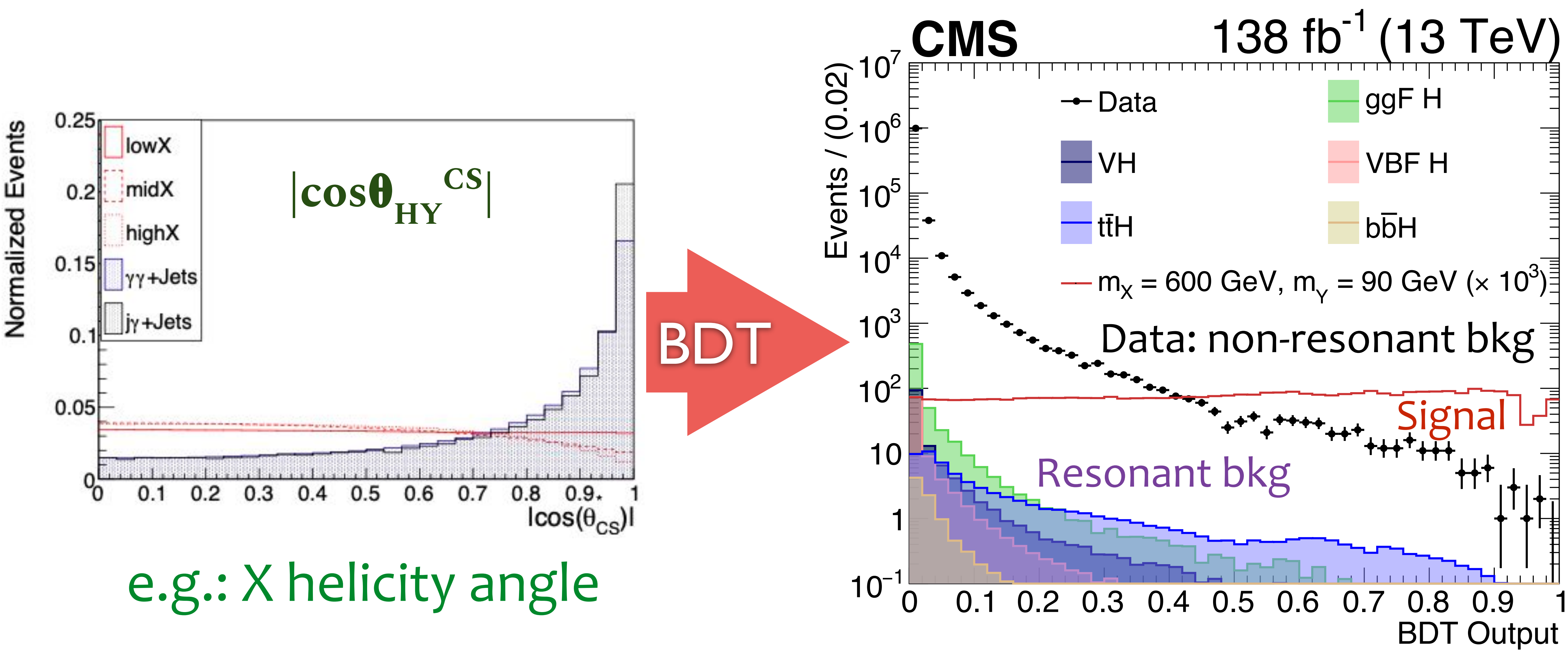
Energy corrections:
cluster containment and residual data/MC scale corrections

Excellent Run-2 resolution:
between 1% - 3.4%

Handles to kill backgrounds

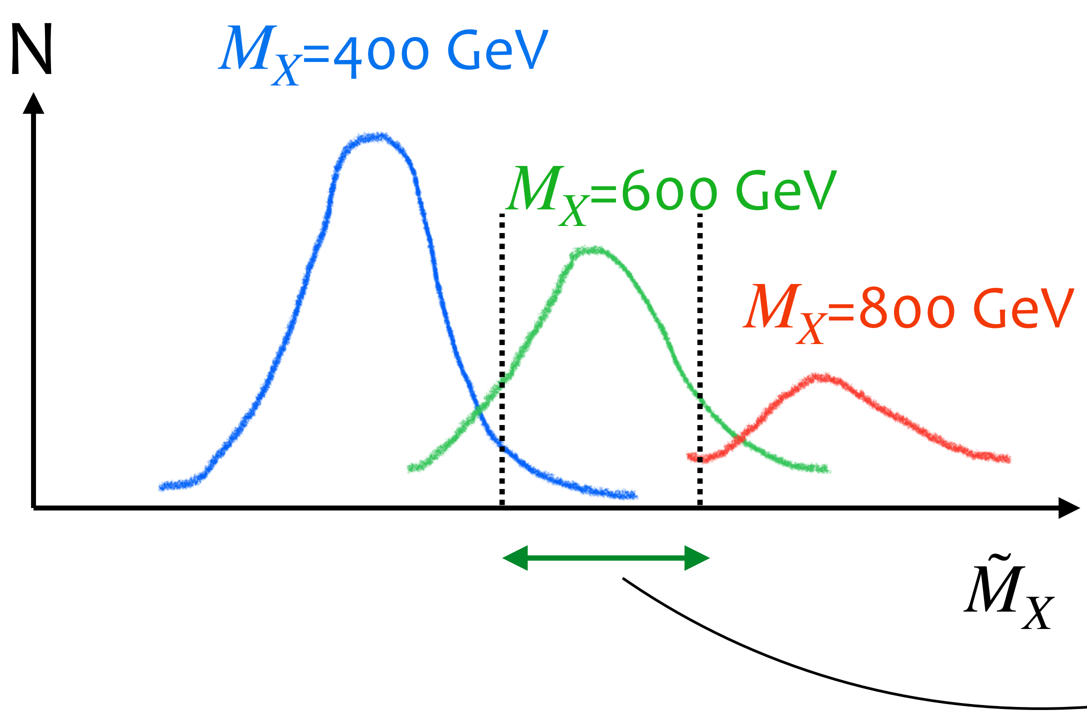
Backgrounds: resonant (~ttH($\gamma\gamma$)) and non resonant ($\gamma\gamma$+jets, γ+jets)

- NN-based ttH killer rejects resonant background (peaking $m_{\gamma\gamma}$)
- Handles to reject non-resonant background:
  1. Kinematics, e.g. three helicity angles
  2. Particle identification (jets -> photons; light jets -> b-jets…)
  3. Energy resolution variables

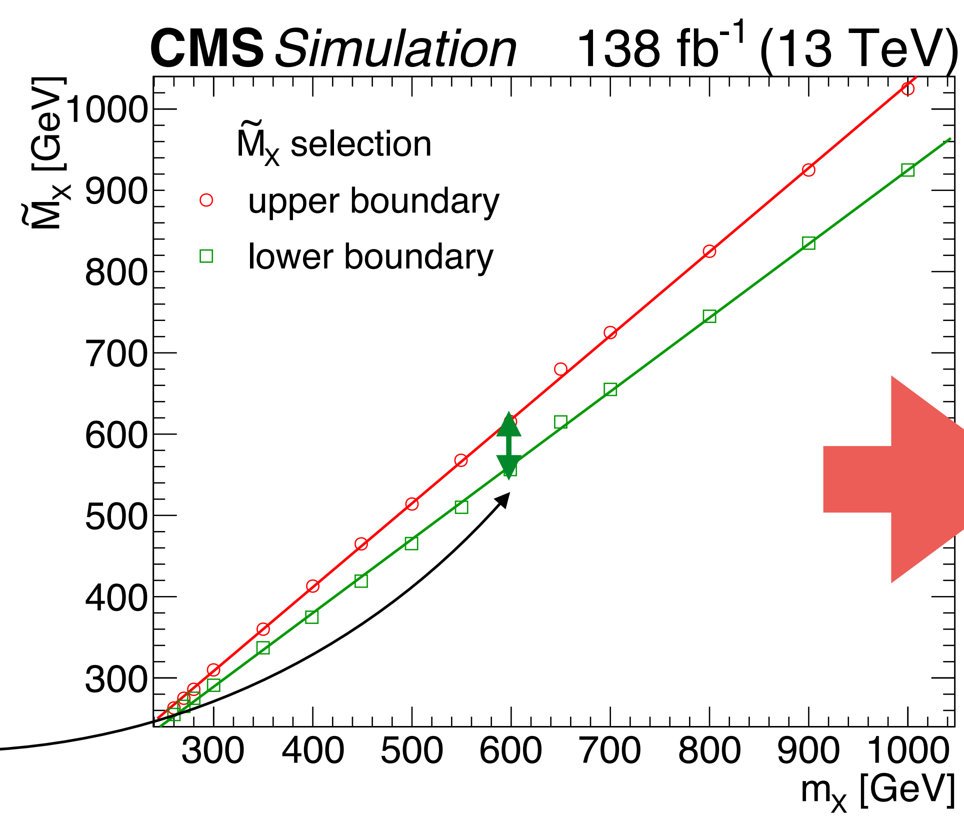


Bump search: $\tilde{M}_X$ usage

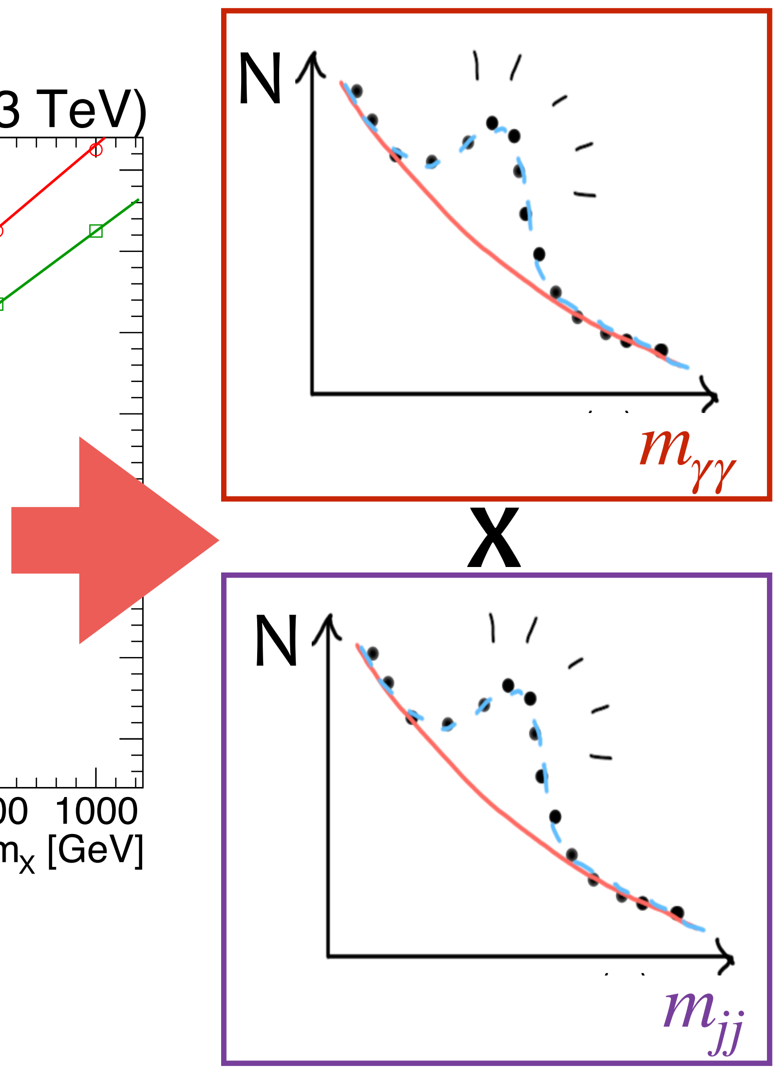
- Bump search: select on 4-body mass: $\tilde{M}_X = (m_{jj\gamma\gamma} - m_{jj} - m_{\gamma\gamma} + m_H + m_Y)$
  - Better resolution (30-90)% wrt using $m_{jj\gamma\gamma}$ alone (cancels correlated fluctuations)



Width increasing with M_X



Window keeping ~60% of events



Fit $m_{\gamma\gamma}$ - m_{jj} as a 2D peak over smooth background

How to robustly fit a bump

The background composition can be unknown, no need to model it with simulation

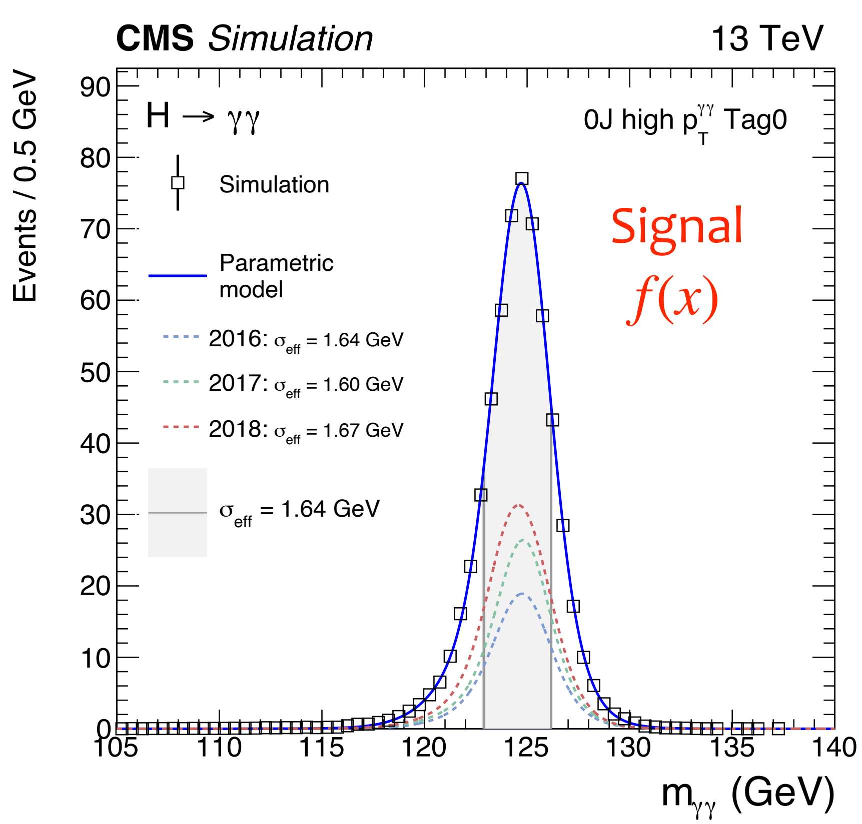
- Only assumption: **smooth bkg shape** vs **peaking signal**

  -> Fit on data with empiric smooth functions $f(x)$

  -> Best χ^2 choose the nominal $f(x)$,

  -> alternatives used as an uncertainty (discrete profiling method)

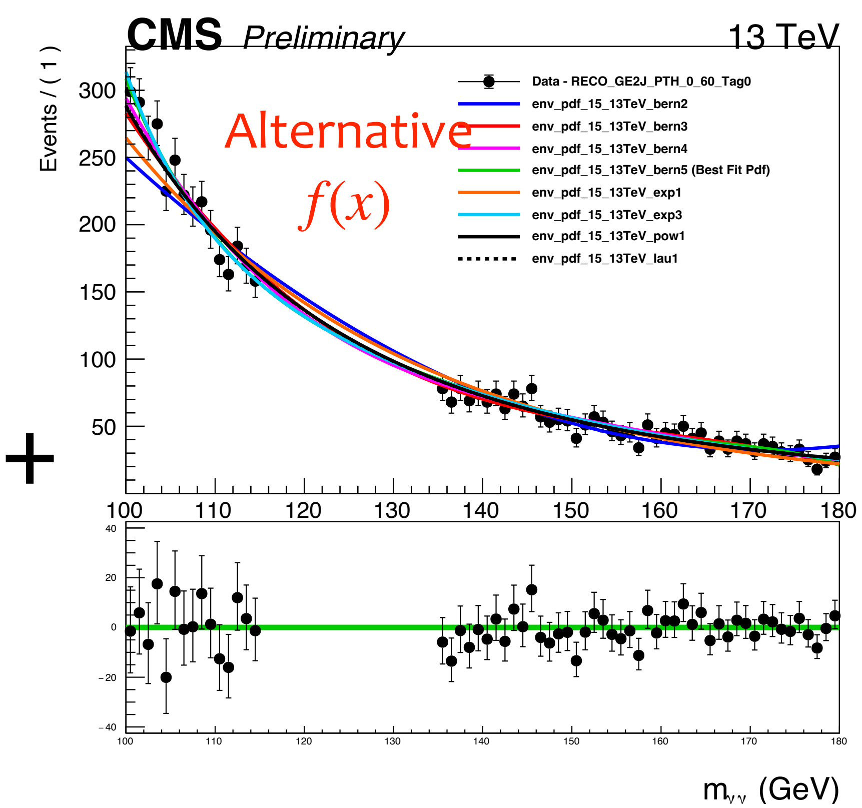
(Example signal)



Prob(Signal)

+

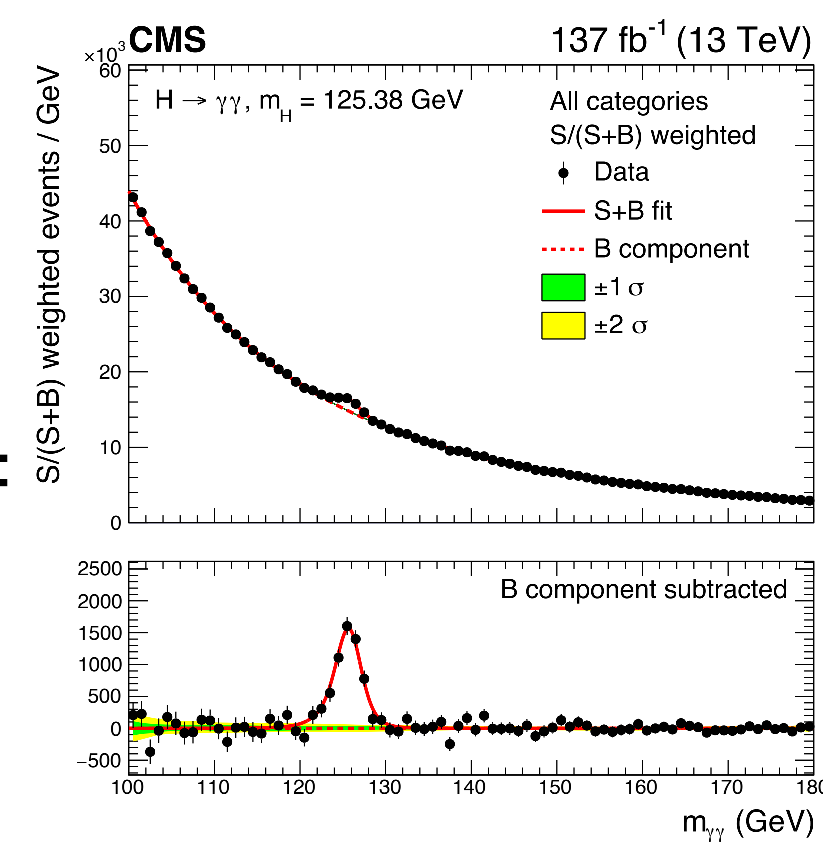
(Example background)



Prob(Background)

=

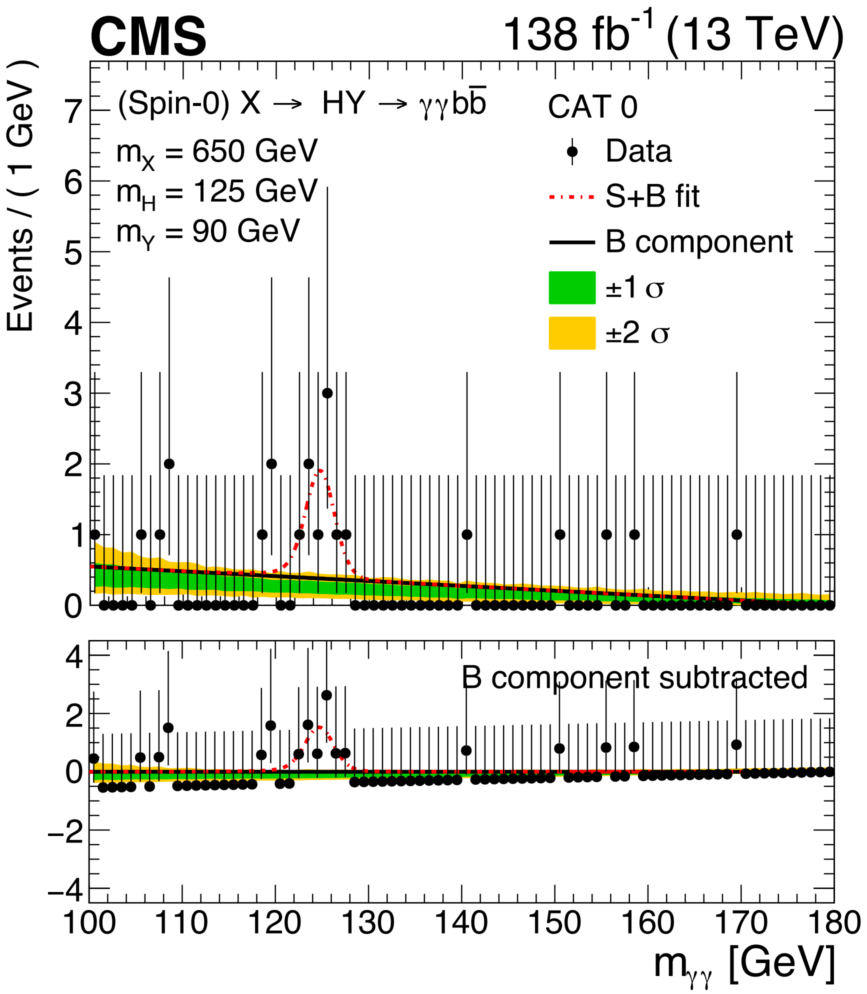
(Example data fit: inclusive Run2 $H \to \gamma\gamma$)



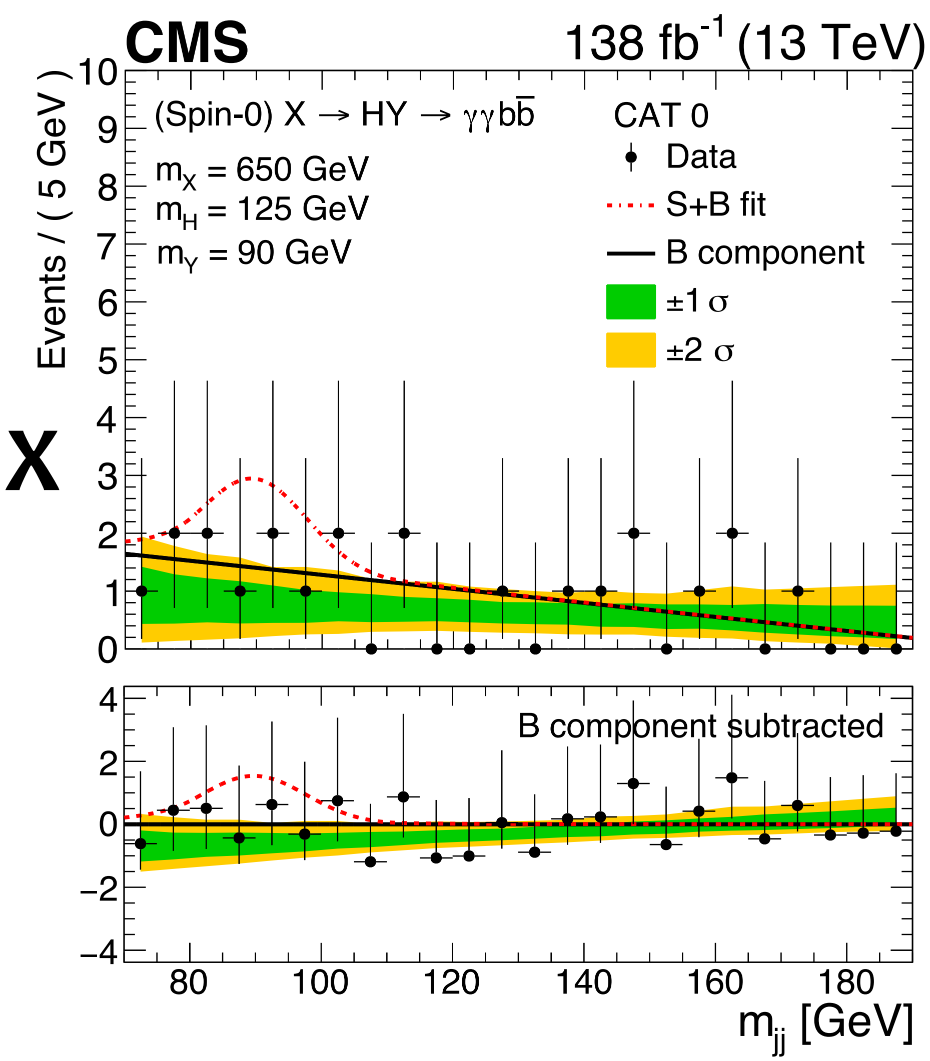
P(S+B)

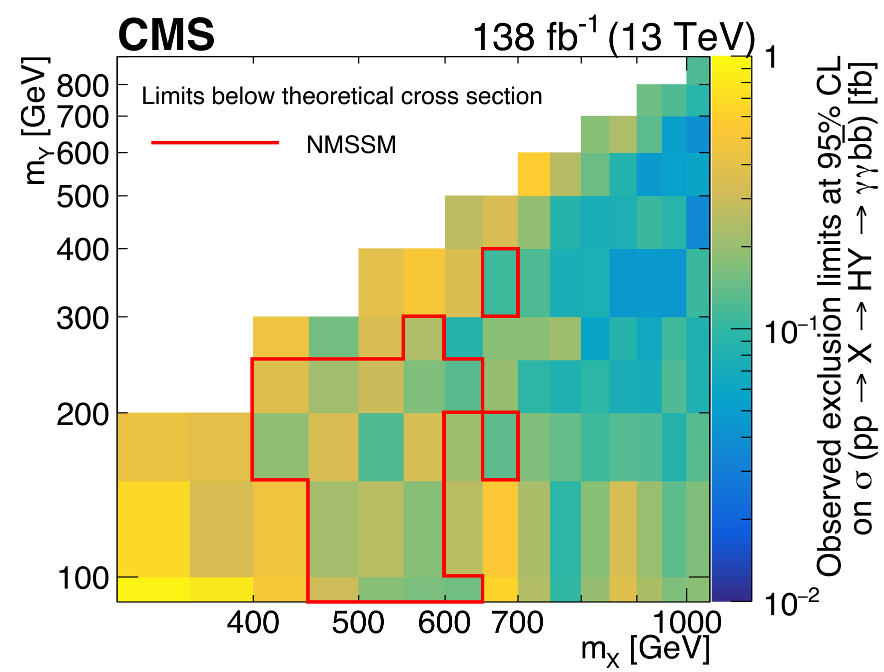
$X \to YH \to bb\gamma\gamma$ results

- From parametric fit in $m_{\gamma\gamma} - m_{bb}$ plane (fit in m_{bb} uses same method as $m_{\gamma\gamma}$)



X



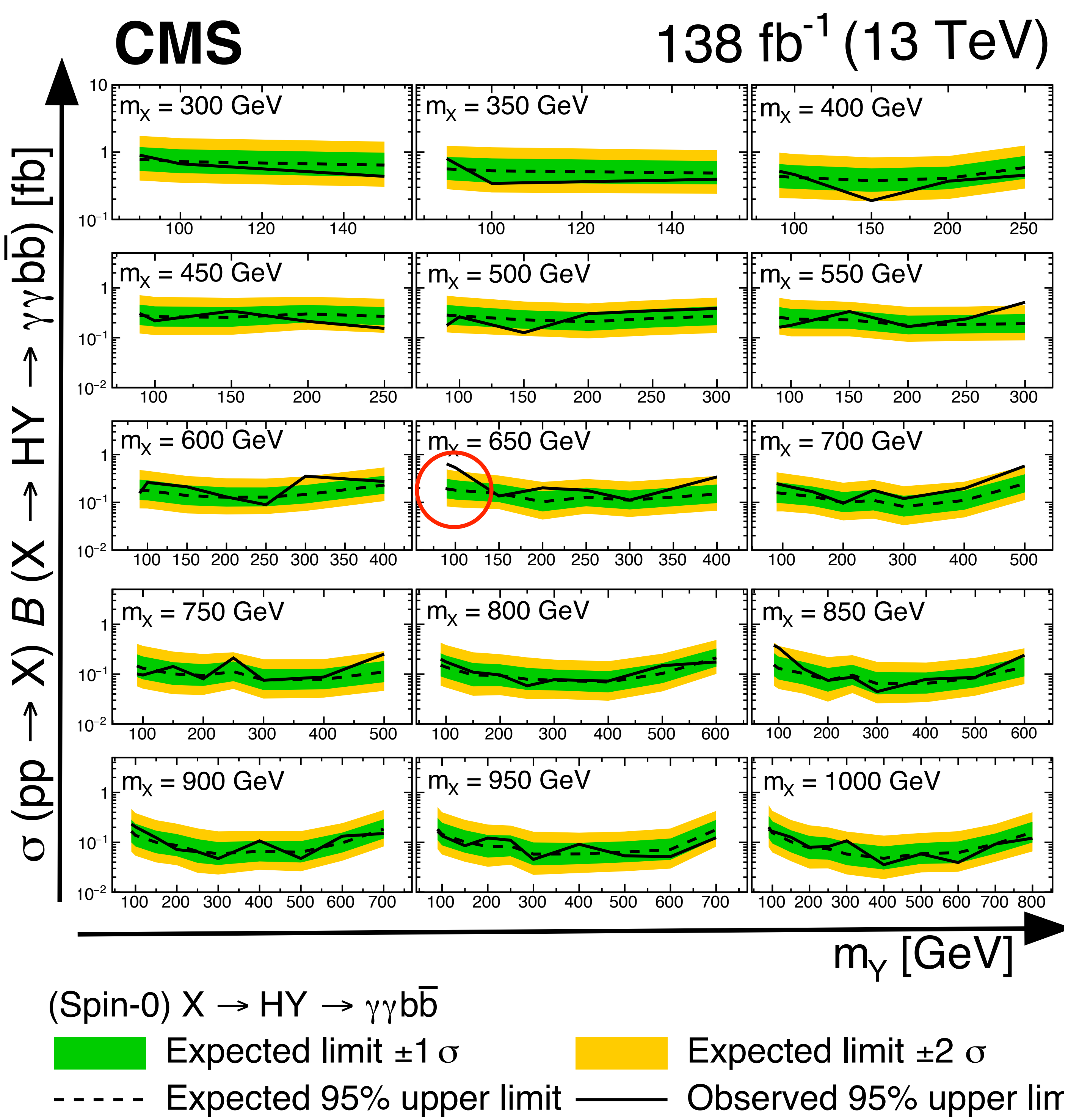


Largest excess at **m_X = 650 GeV, m_Y = 90 GeV** with 3.8 σ local/2.8 σ global significance

Sensitive to NMSSM predictions (max. allowed cross sections from NMSSMTools 5.5.0)

$X \to YH$ vs other channels

- Comparing excess at (125, 90) with 650 GeV heavy resonance mass



Caveat: cherry picking!

- $H \to \tau\tau$ 90-100 GeV excess: 3.1σ local, 2.7σ global
- $H \to WW$ 650 GeV excess: 3.8σ local, 2.6σ global
- $H \to \gamma\gamma$ 95 GeV excess: 2.9σ local, 1.3σ global

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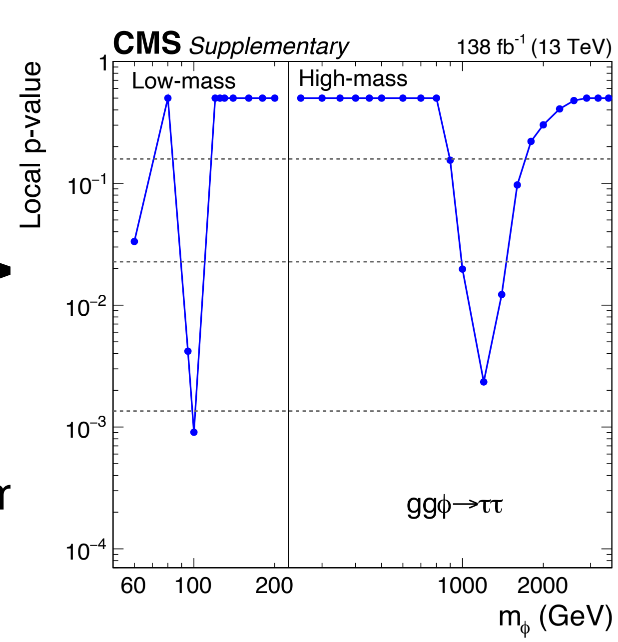

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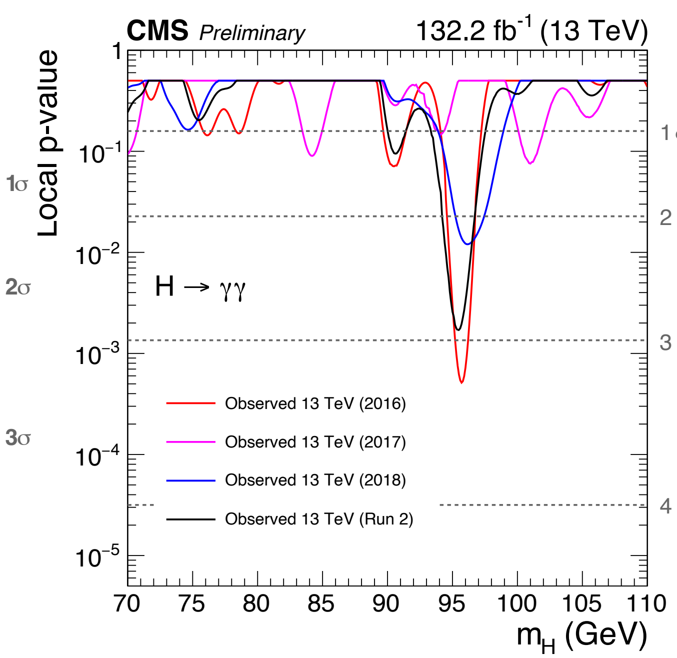


Compare different Y dec modes

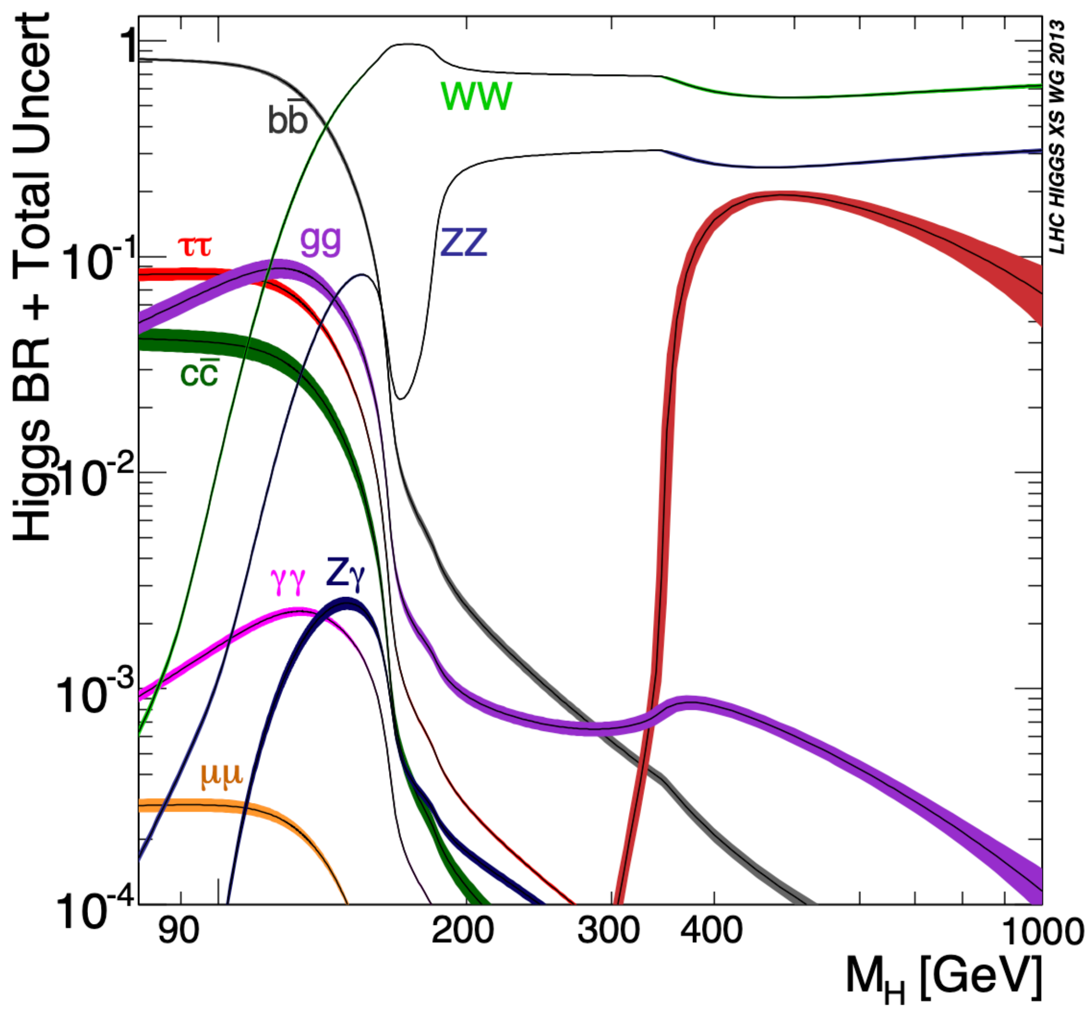
Can we use other modes to check the excess (while waiting for new data from LHC)?

- Yes, but with some caveats: there is no clear model indepenent way to compare channels where Y decays to different modes
  - Y BR's can vary widely (even if it is a scalar, eg an extra Singlet in 2HDM+S / NMSSM model)
  - also H125 BR's can vary
- in extensions involving only singlets, H125 and Y BR's similar to SM H ones

Possible searches covering the excess:

- $X \to Y(bb)H(\tau\tau)$
- $X \to Y(\gamma\gamma)H(bb)$
- $X \to Y(\gamma\gamma)H(\tau\tau)$ or $X \to Y(\tau\tau)H(\gamma\gamma)$
- $X \to H/Y(bb)\, H(bb)$ with 4b resolved
- $X \to WW(4q)\, H(bb)$, WW -> "merged" or "resolved" jets
- … and many more

To combine different modes,
and be model-independent:
-> scan Y BR's



A note on interpretations

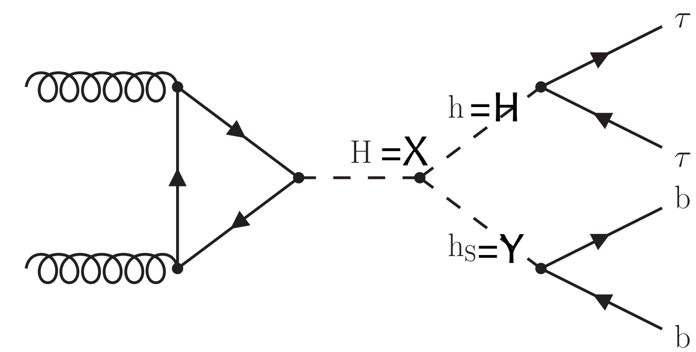
- When not finding an excess we need to be able to interpret our results in a motivated theory
- Extended H-sectors that allow the pp -> X -> HY signature have dozens of parameters (eg NMSSM and TRSM)
  - Theorists resort to the computation of **maximally allowed cross sections**
  - They result from a scan over the multi-dimensional parameter space *discarding points that are excluded by existing measurement*
    - -> **moving target**, predictions evolves with time!

- Possible confusions:
  1. The HH/HY analyses are added in the list of constraints to derive max. allowed XS
  2. For NMSSM the values for 125 GeV H vary between points and theory versions
  3. For TRSM all the channels HY+HY+YY are maximized simultaneously when a channel resolution allows all

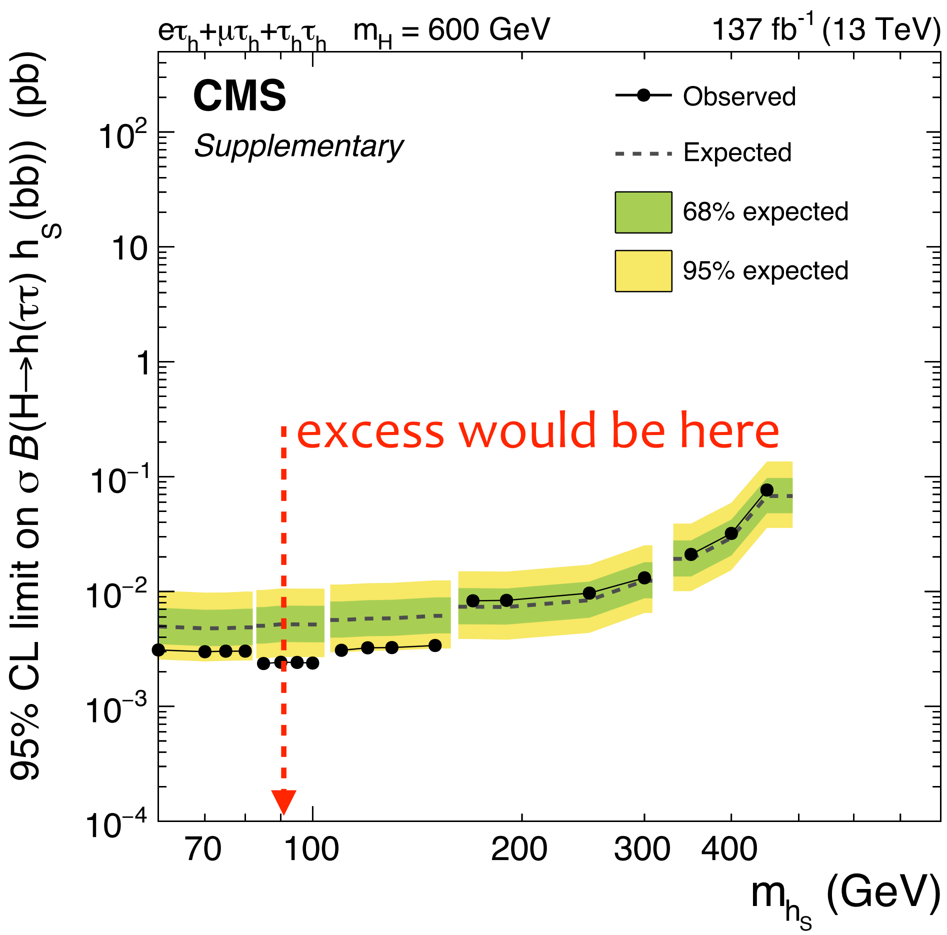
Compare: $X \rightarrow H(\tau\tau)Y(bb)$

Old analysis from CMS, didn't consider m_X=650 GeV at that time

- not possible to interpolate, since between 600 and 700 GeV the analysis changes strategy
- now redoing it, coming soon



$m_X = 600\,\mathrm{GeV}$ $m_X = 650\,\mathrm{GeV}$ $m_X = 700\,\mathrm{GeV}$



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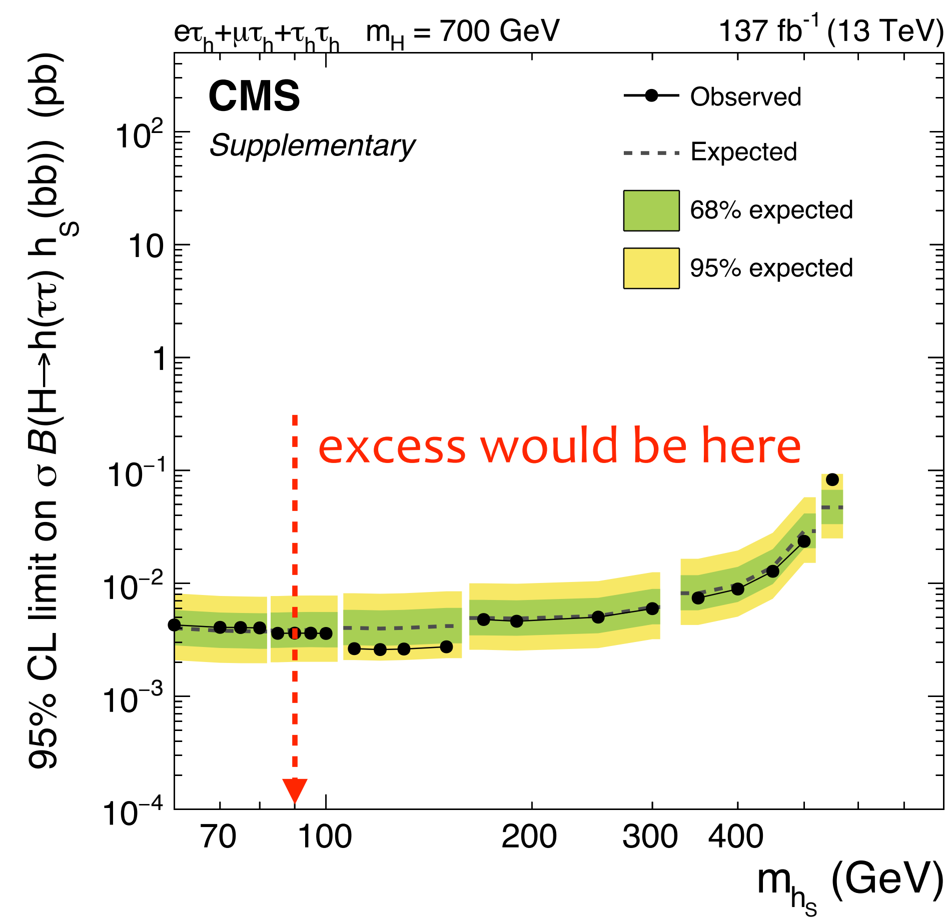

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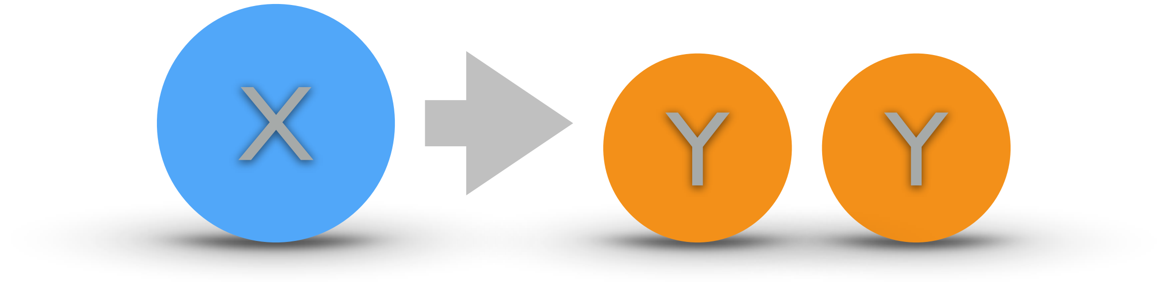
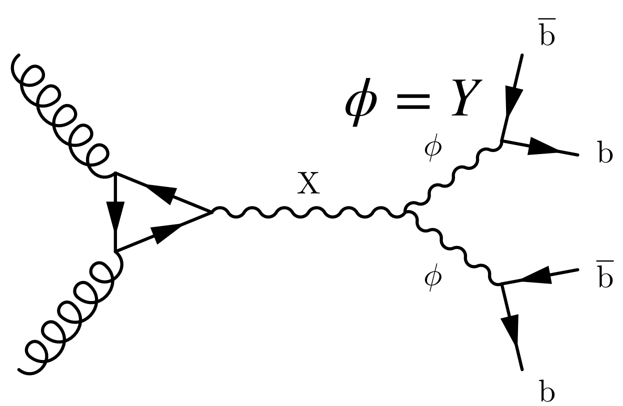
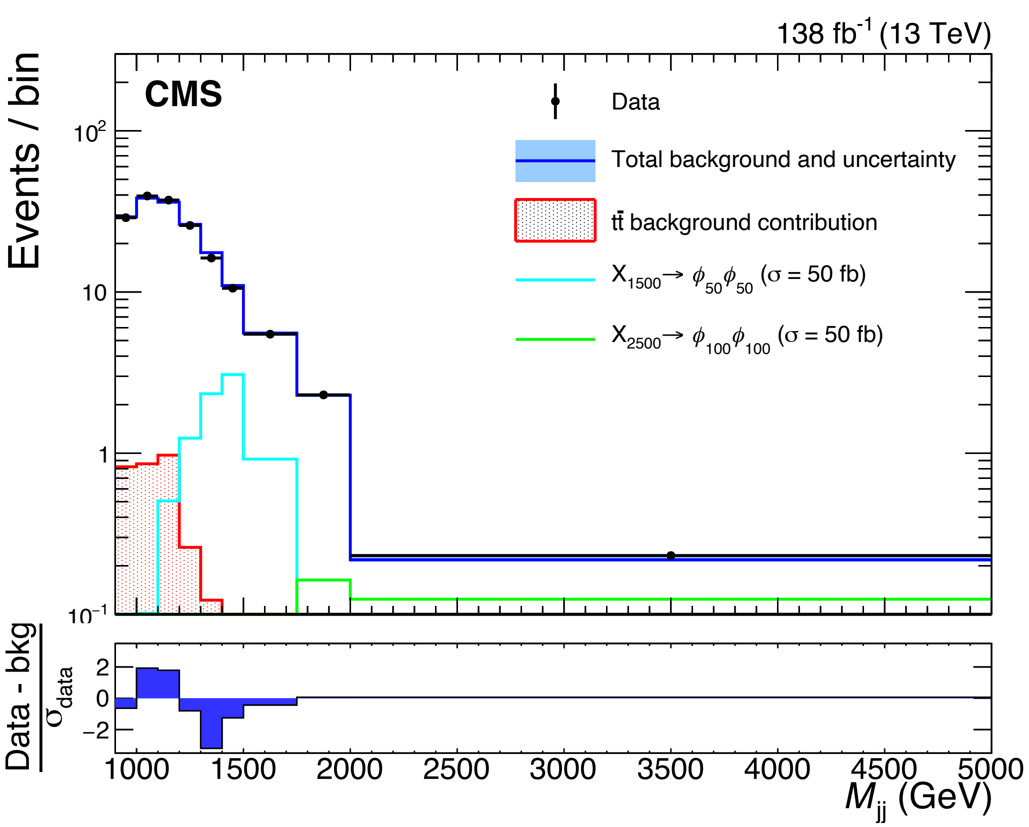
$X \rightarrow YY$ searches

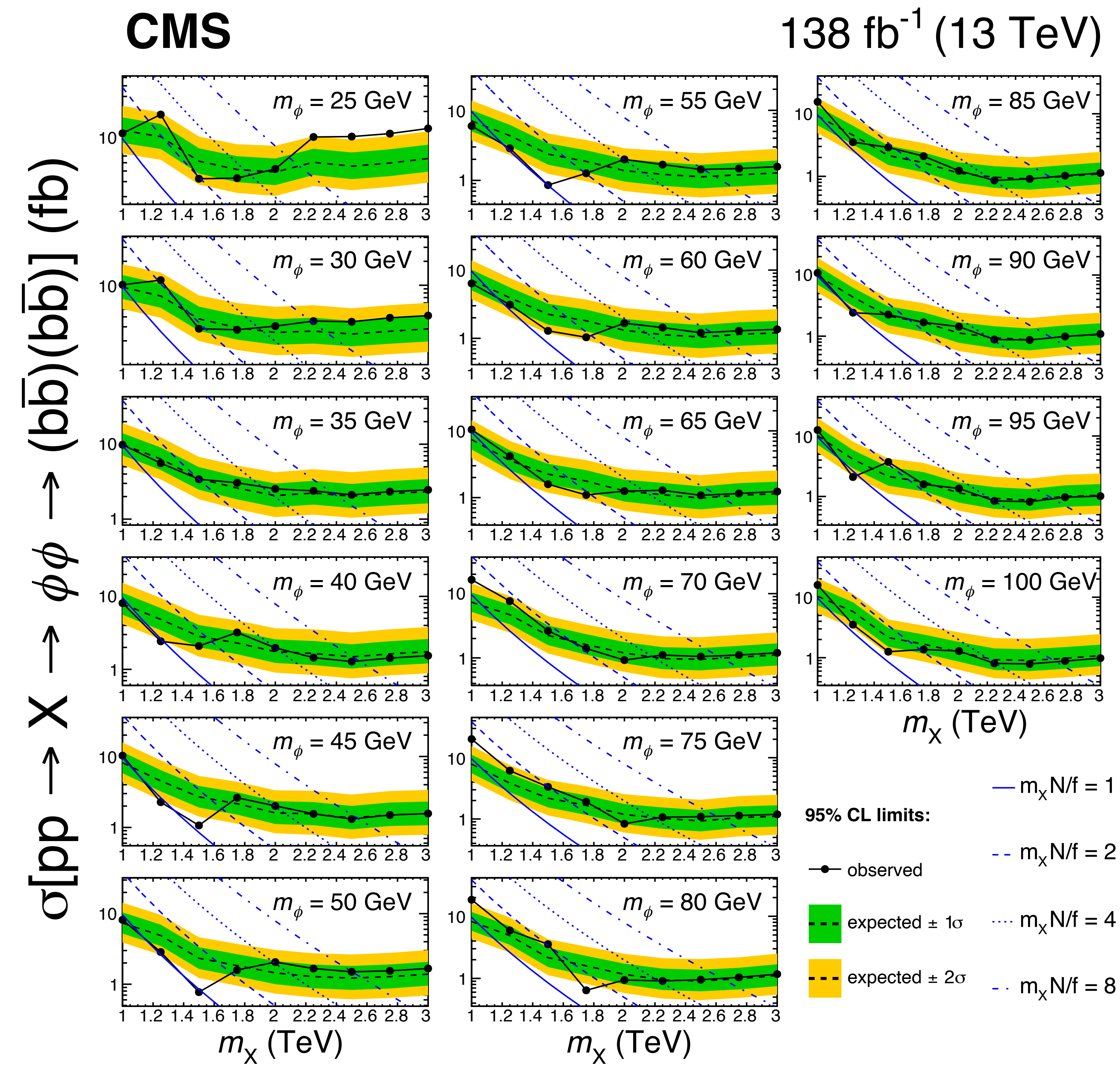


$X \to YY$ overview

- CMS bbbb merged-jet: Phys. Lett. B 835 (2022) 137566
  - M_X: 1-3 TeV
  - M_Y: 25-100 GeV (highly boosted!)



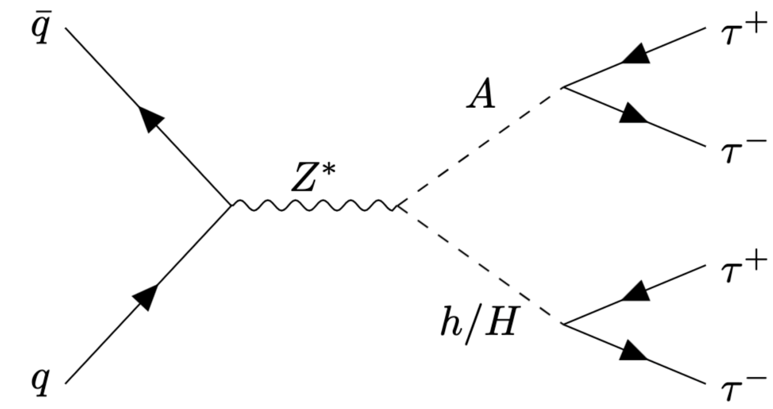




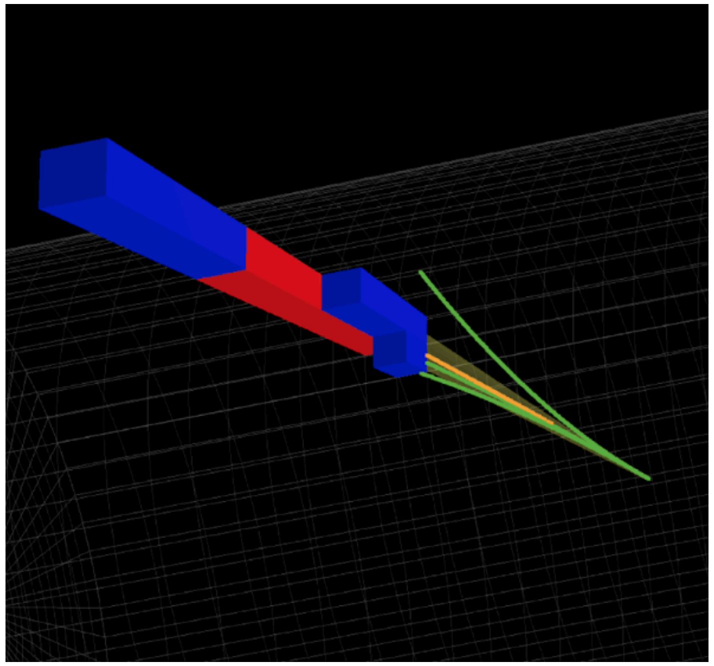
$$Z^* \rightarrow HA$$

$Z^* \to HA \to 4\tau$

- In lepton-specific (or type X) 2HDM at large tan **β** - which could explain g-2 - non-lepton couplings and hence **direct A/H production strongly suppressed**
- HA pair production (via Z*) with decays to 4 tau leptons can probe this scenario!

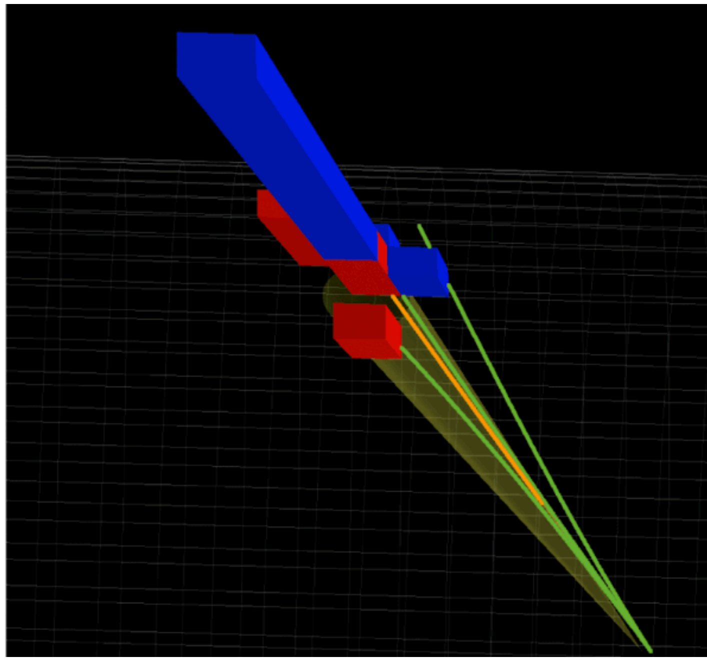


τ lepton decays in multiple ways:
- Fully leptonic: "τ_ℓ" (clean, but with ν's)
- Into charged hadrons "τ_h" (eg. $\rho, \omega \ldots$)
  - Charged hadrons can decay to π^0
    - $\pi^0 \to \gamma\gamma$ immediately



e.g. τ_h decay

$\tau_h^+ \to \pi^+\pi^-\pi^+\pi^0 + \ldots$

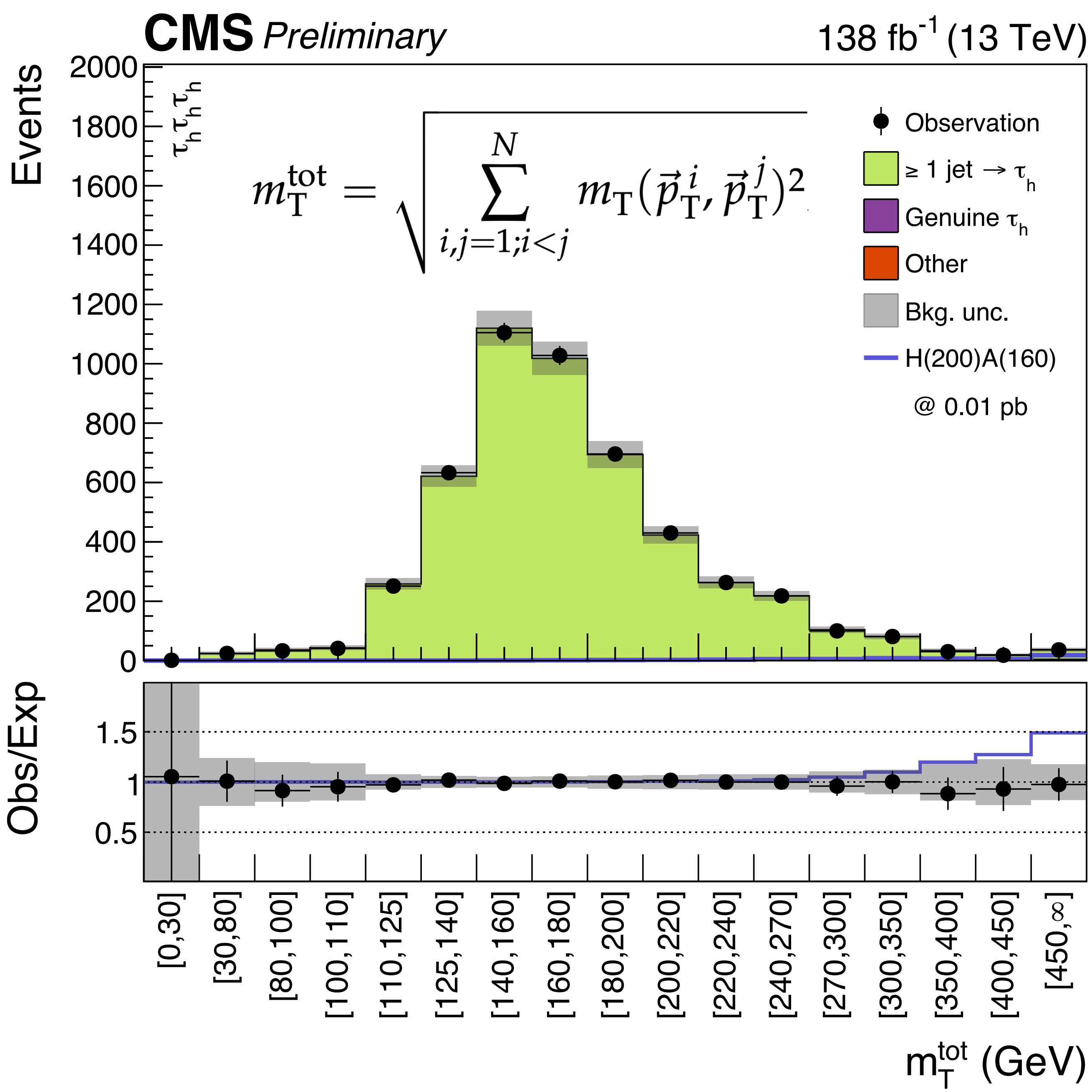


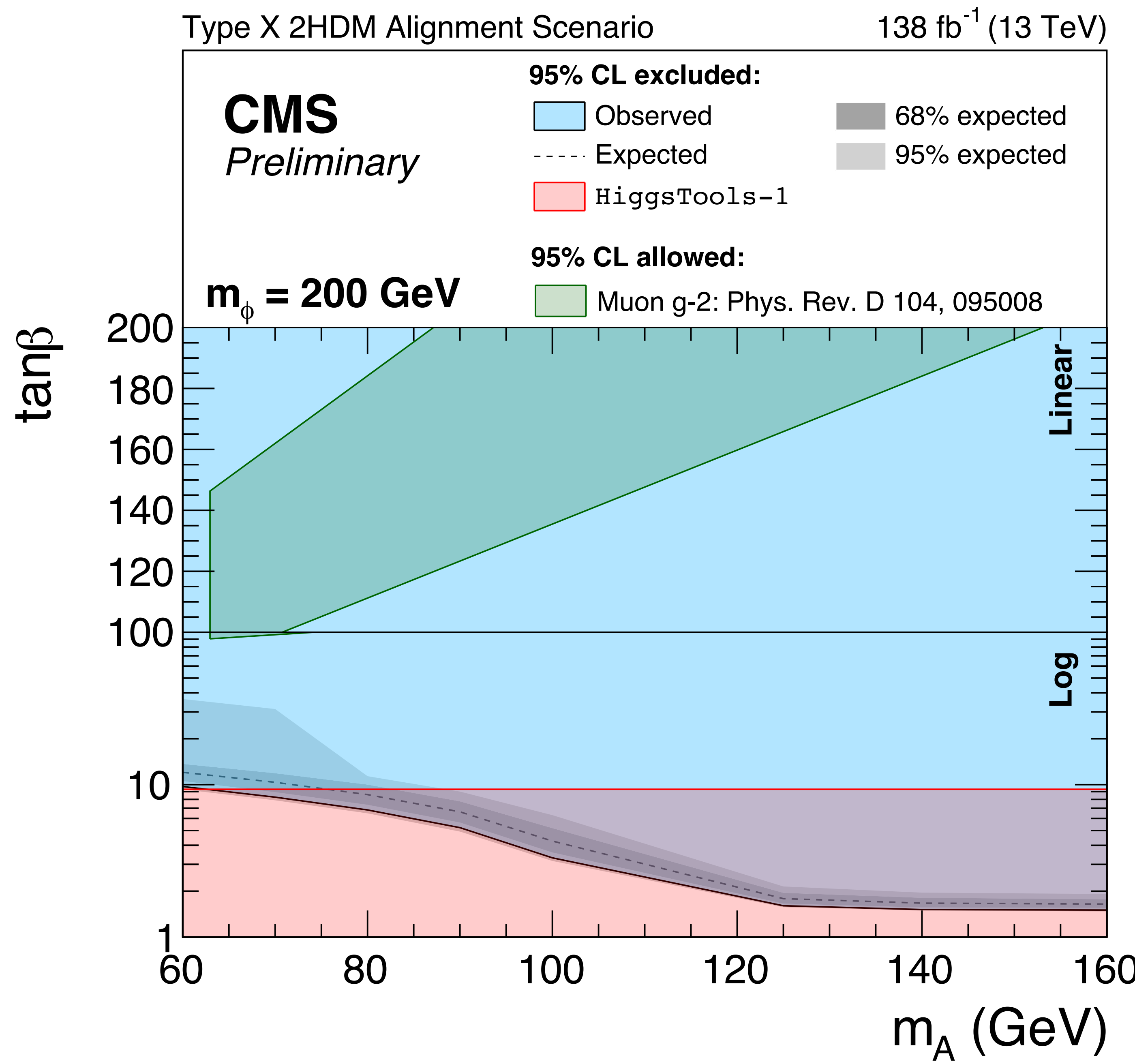
Quark/gluon → Jet

Channels with 6/4/2 τ_h = 87% of signal

-> Main background: **Jet resembling a** τ_h

- Strategy: fit the distribution of transverse mass (presence of neutrinos => no full kinematics closure)





- **Excludes type-X 2HDM as muon g-2 explanation**
- Excludes type-X 2HDM in probed mass range

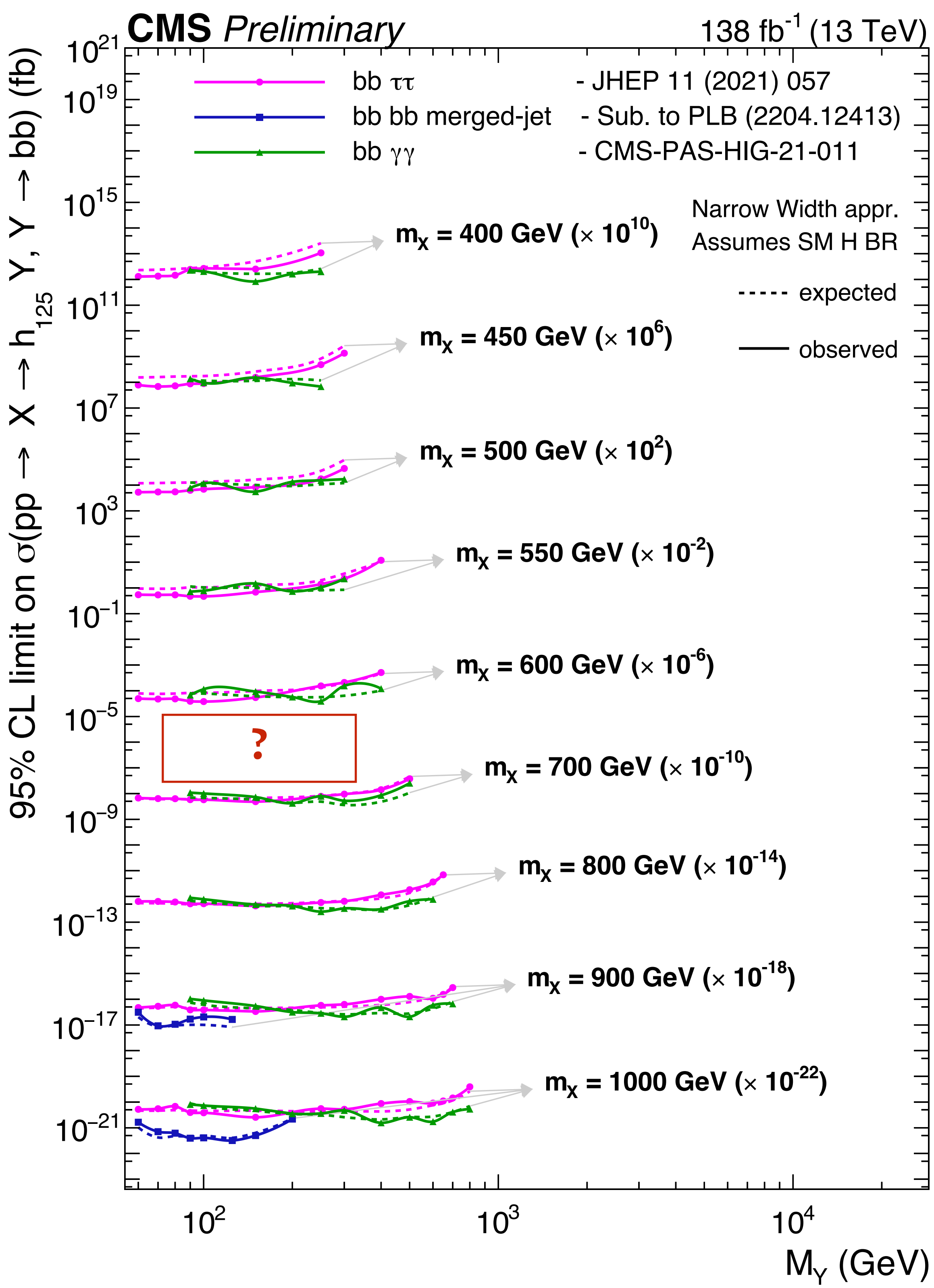
Summary

CMS has a wide variety program for X->HH / HY, done or under finalization with Run-2 data, with many final states

$X \rightarrow H(\gamma\gamma)Y(bb)$ with a small excess at m_X,m_Y = (650,90-95) GeV can be also tested with other channels: **many X->HH, X->HY, X->YY analyses are ongoing**

With some assumptions combinations of the results in different channels can be done

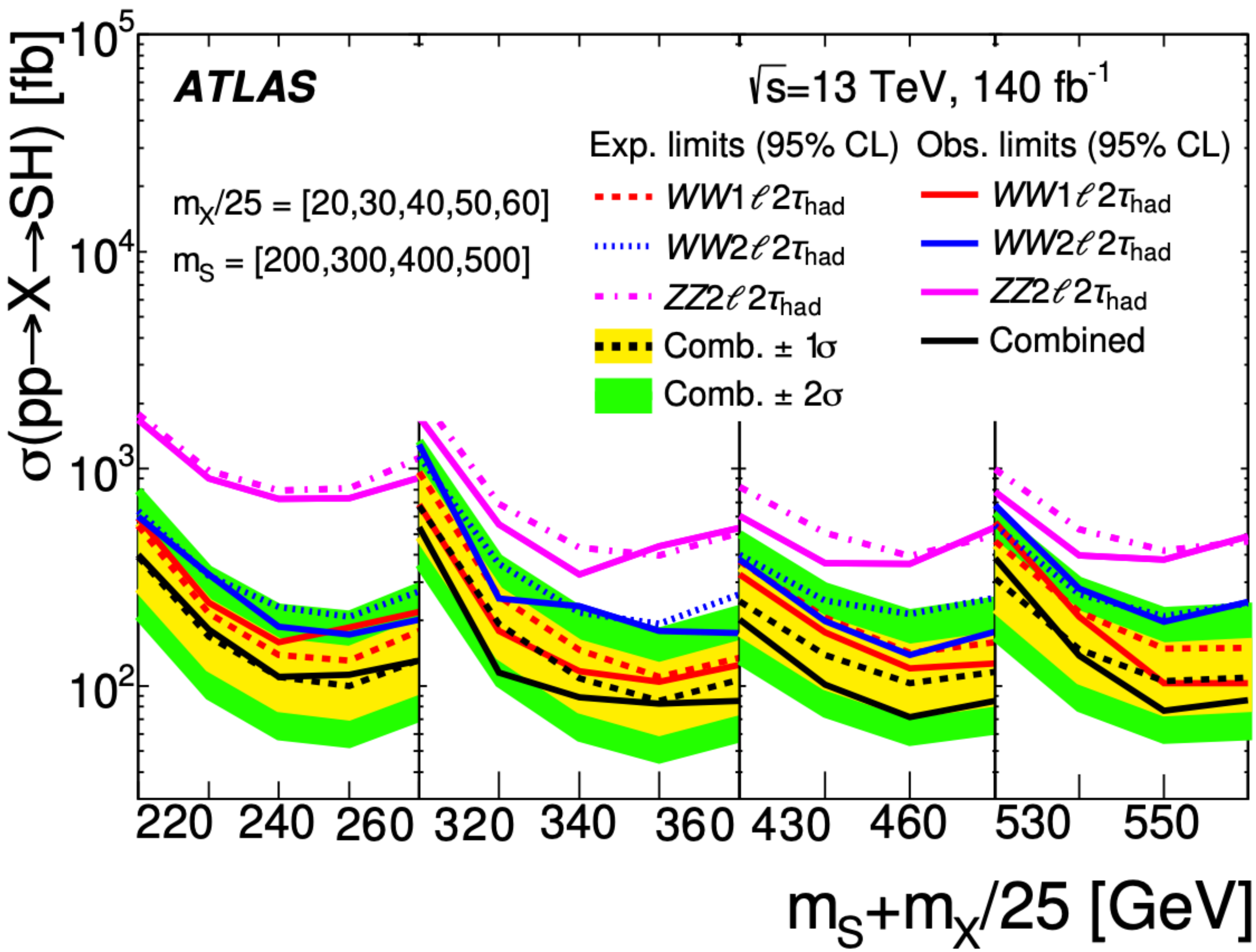
Looking forward to seeing more Run-2 and first Run-3 results!



Additional slides

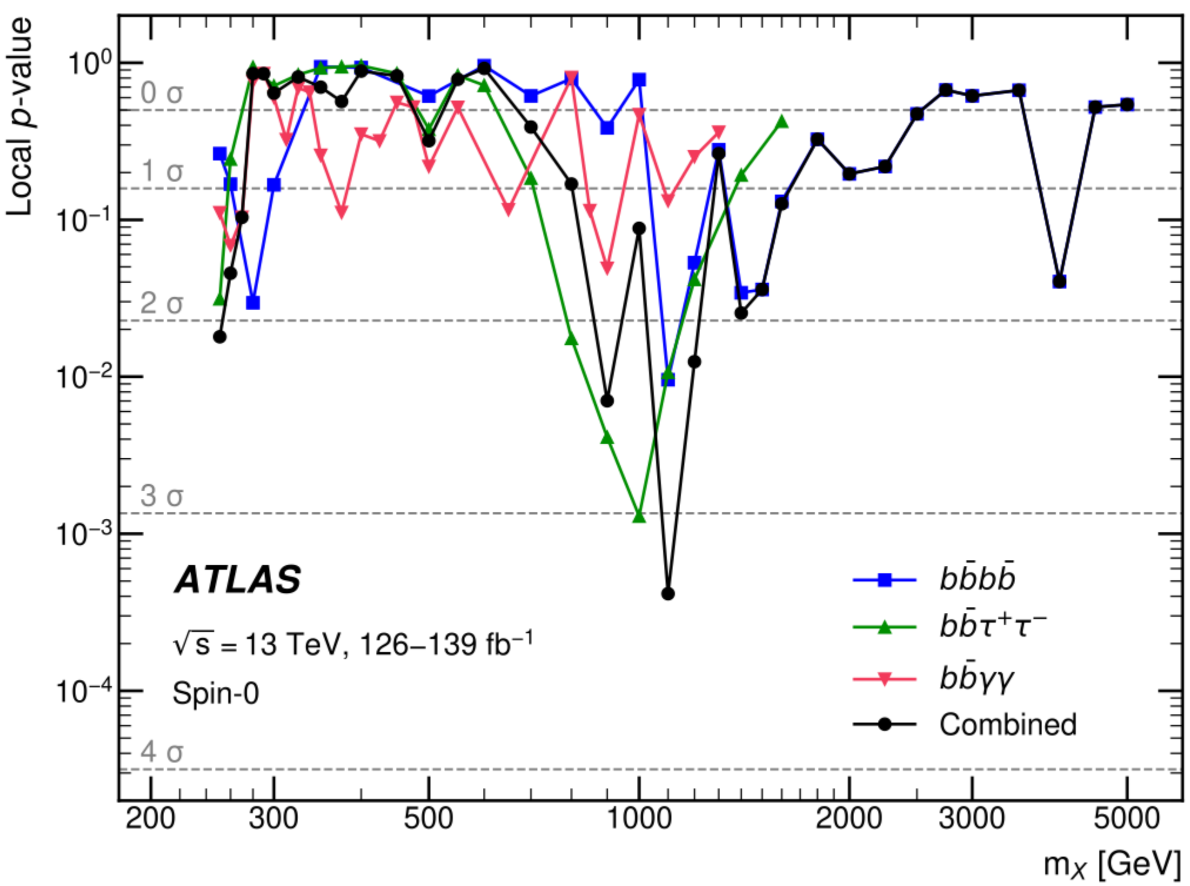
ATLAS X->HY searches

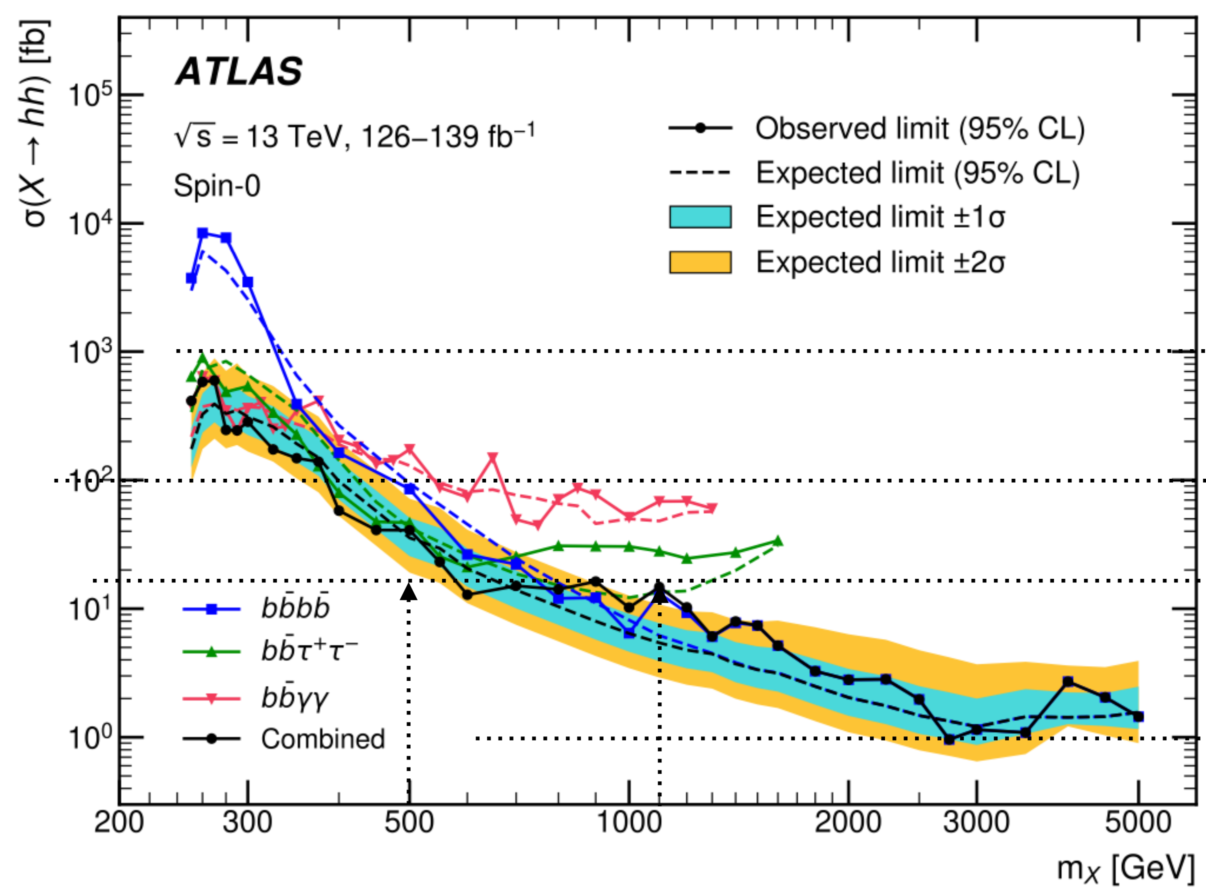
- Most recent HY analysis from ATLAS (JHEP 10 (2023) 009)
  - $X \to YH \to Y(VV)\ H(\tau\tau)$: no excess found



ATLAS X->HH searches

- ATLAS published a new combination of resonant HH analyses in 2311.15956, Submitted to: Phys. Rev. Lett
  - First combination with full run2 luminosity, features 4b, bbττ and bbɣɣ
  - The largest deviation is observed at 1.1 TeV and corresponds to a local significance of 3.3 σ, which corresponds to a global significance of 2.1 σ when the trial factor is taken into account





The Standard Model

$$\mathscr{L}_{SM} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}D\psi$$

Precision Electroweak and QCD

$$+ |D_\mu \Phi|^2$$

Gauge interactions

$$+ V(\Phi)$$

Higgs potential

$$+ \psi_i y_{ij} \psi_j \Phi$$

Yukawa interactions (fermion masses => proton, neutron masses), CKM matrix and CP violation

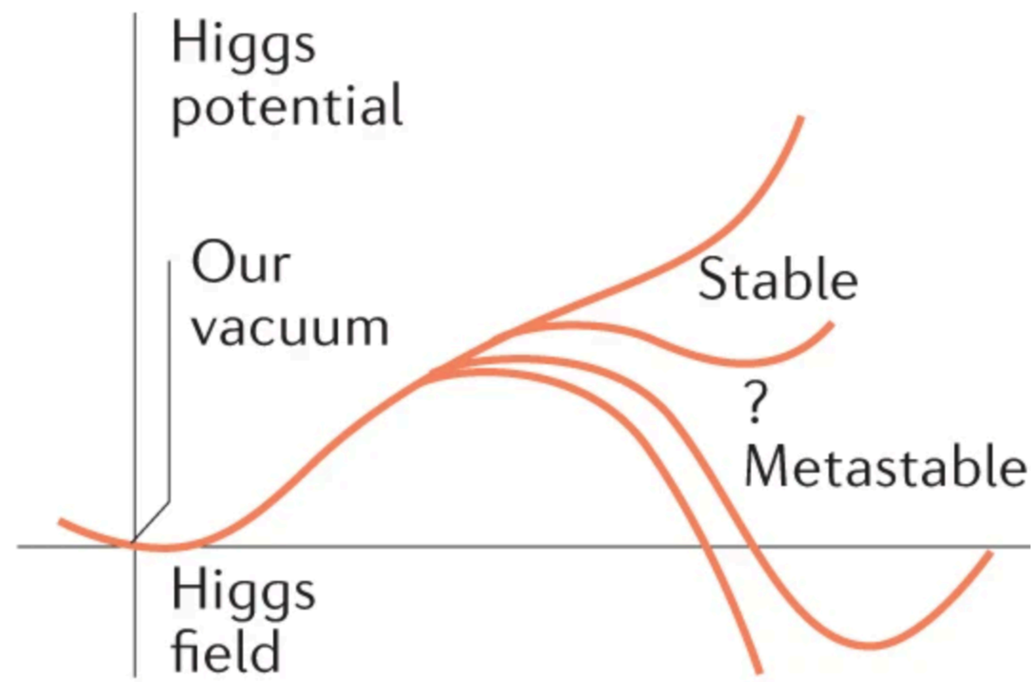
LHC program is to study profoundly the validity of the Higgs and Yukawa sectors of the Standard Model

Look for possible existence of new physics phenomena directly (new particles: $\mathscr{L}_{\text{new}}$), or through breaking of SM predictions in any term of $\mathscr{L}_{SM}$

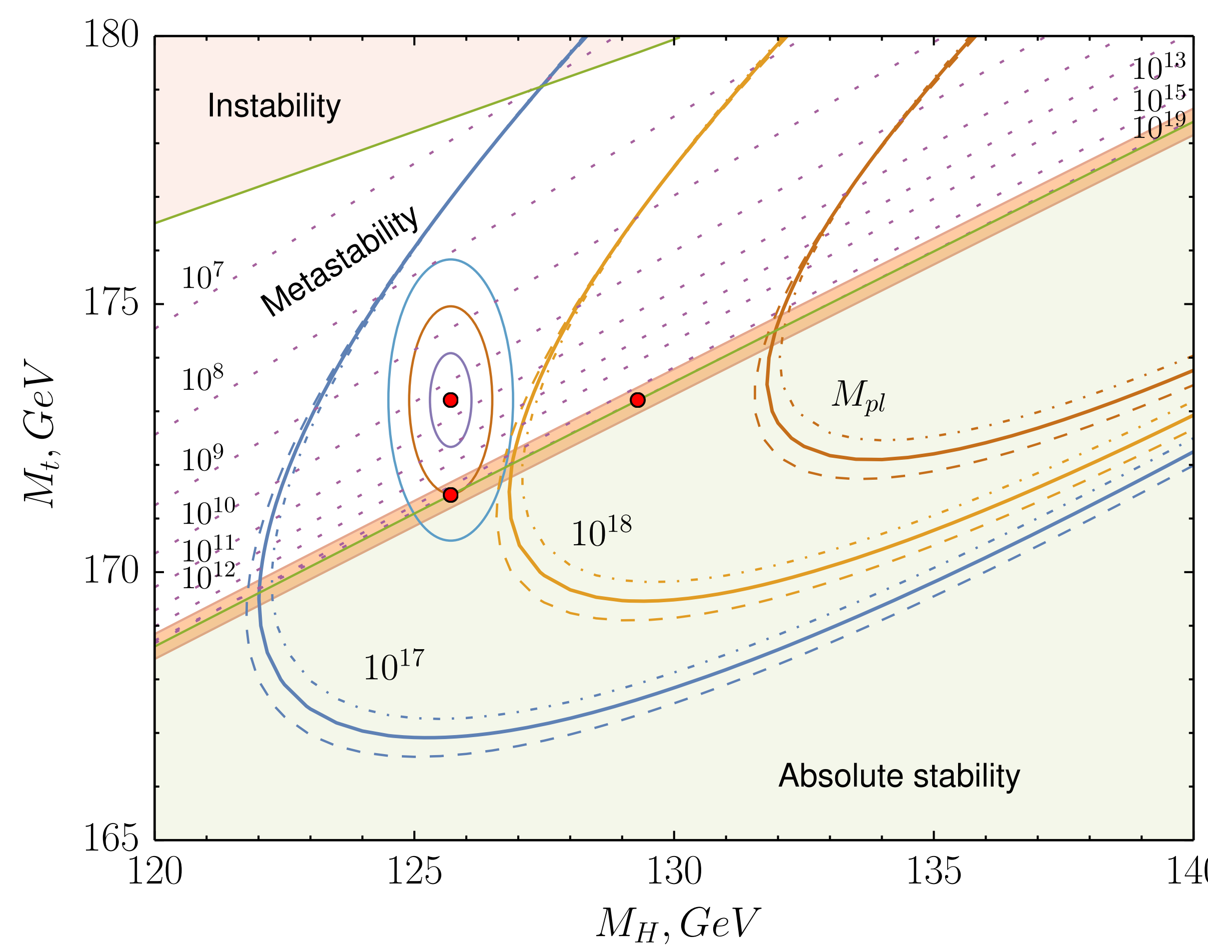
The Higgs potential

$$V(\Phi) = -\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$$

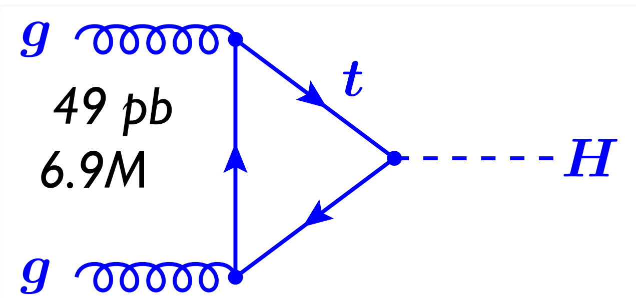
$$= V_0 + \frac{1}{2} m_H^2 H^2 + \lambda v H^3 + \frac{1}{4} \lambda H^4$$



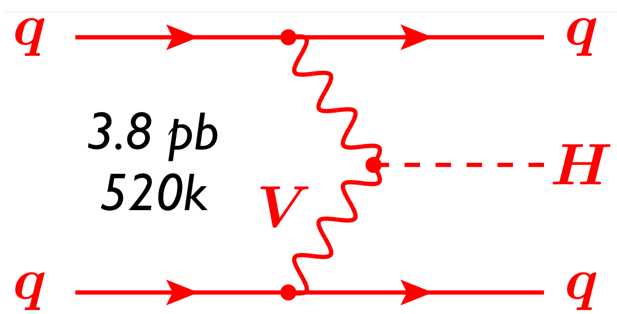
- Responsible of the EWK symmetry breaking and W/Z masses
- Characterizing the Higgs potential means measuring the H boson mass (μ) and the strength of its self coupling (λ)
- $V(\Phi)$ and top mass determine the stability of our vacuum



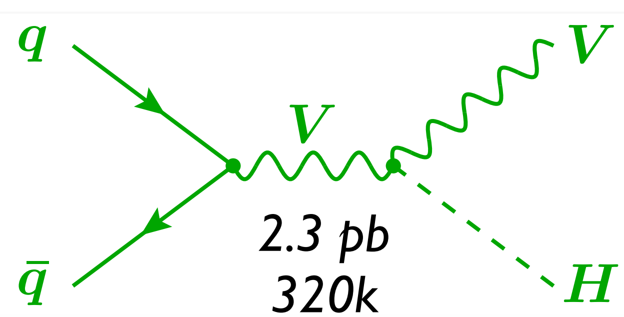
The LHC Higgs factory



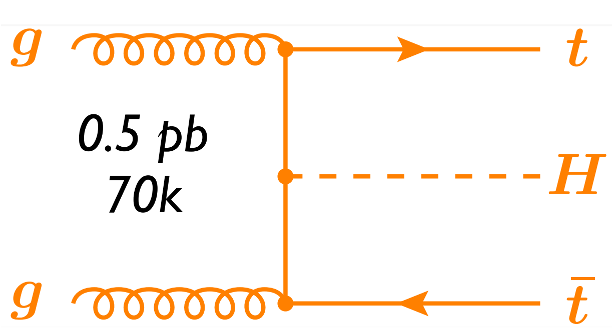
gluon fusion



vector boson fusion (VBF)



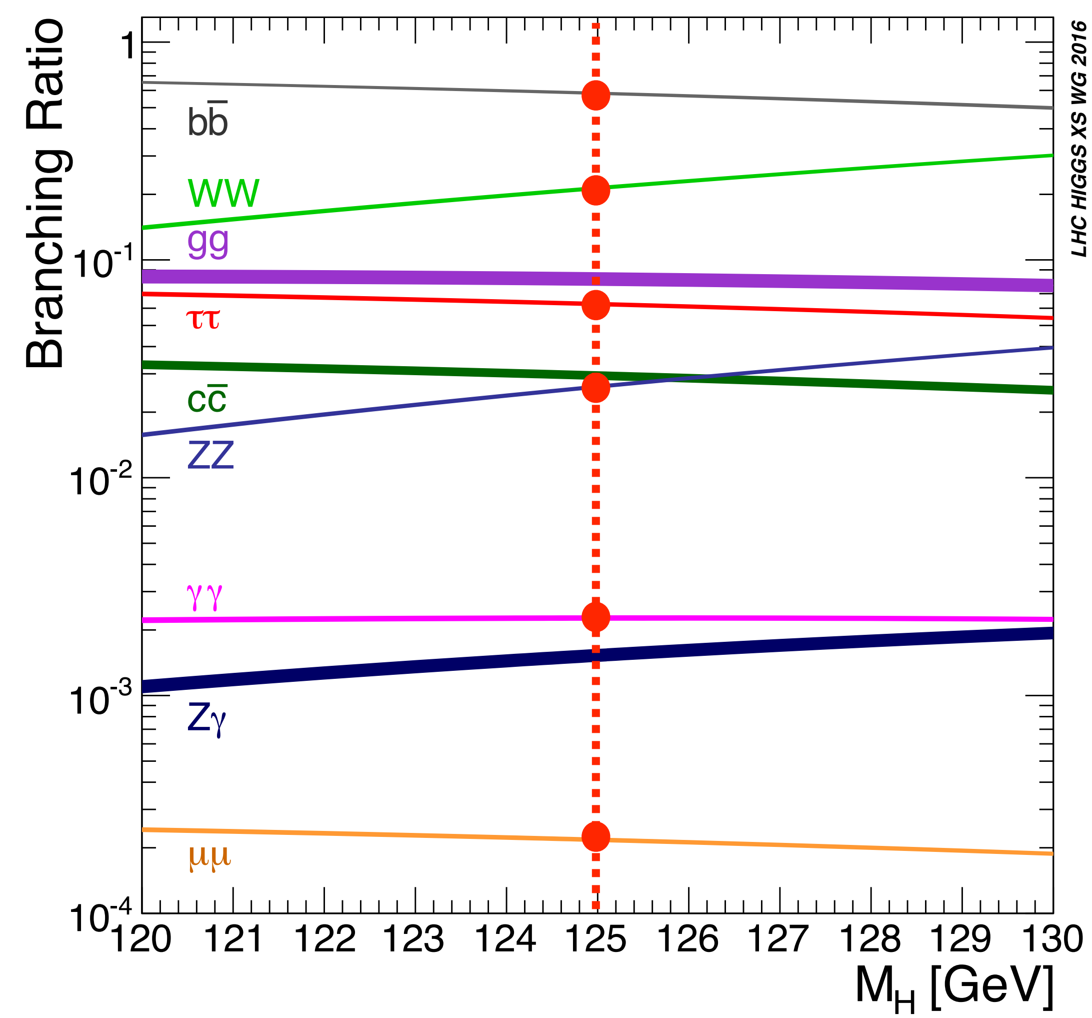
W,Z associated production



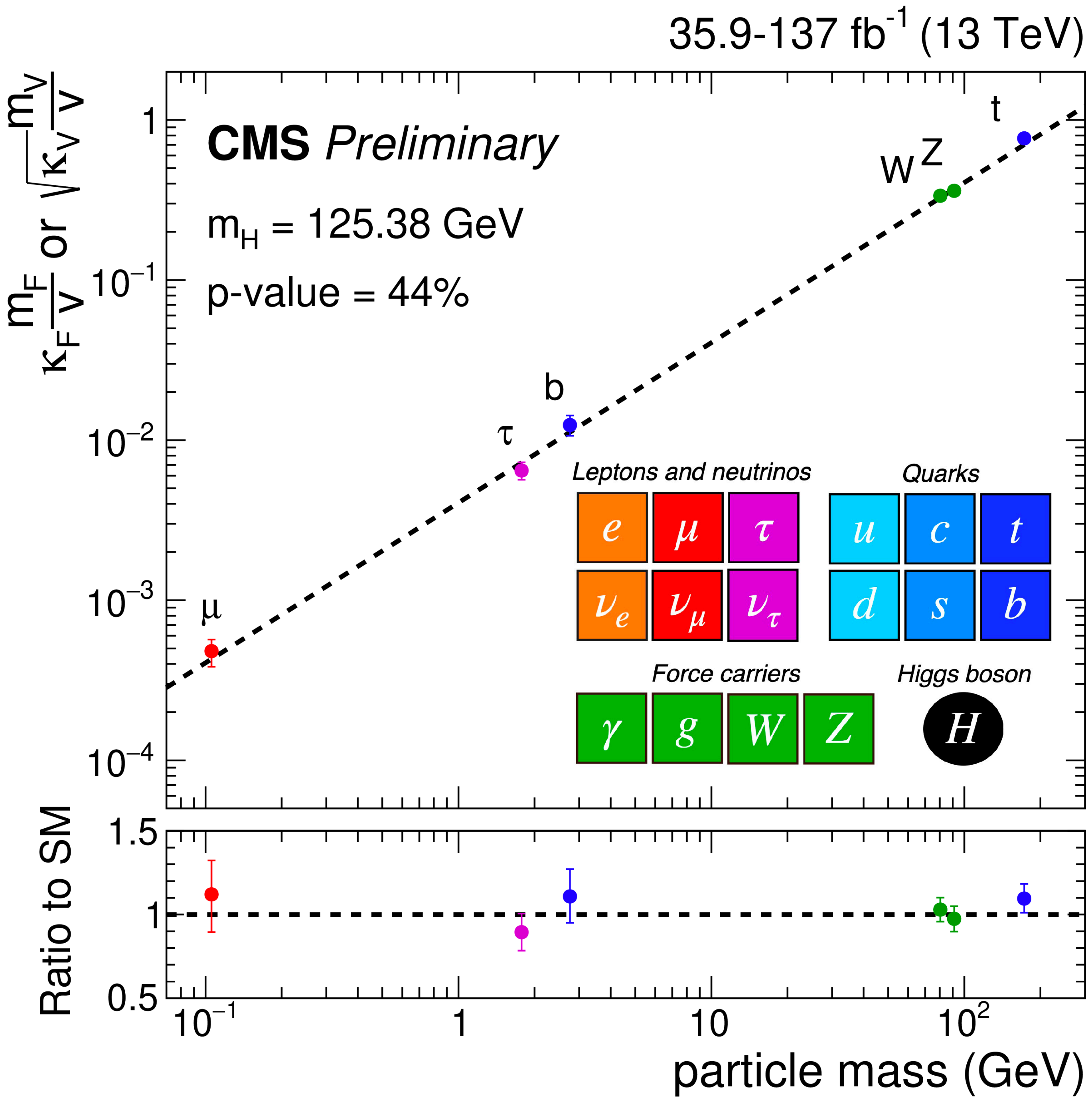
$t\bar{t}H$ associated production

σ [pb]
#Higgs produced during Run-2

- About **8 million Higgs bosons** produced by LHC during Run-2
- For $m_H \sim 125\ \mathrm{GeV}$ a wide range of production and decay modes accessible
- Establishing each production mode and studying its properties



Higgs boson couplings with SM particles

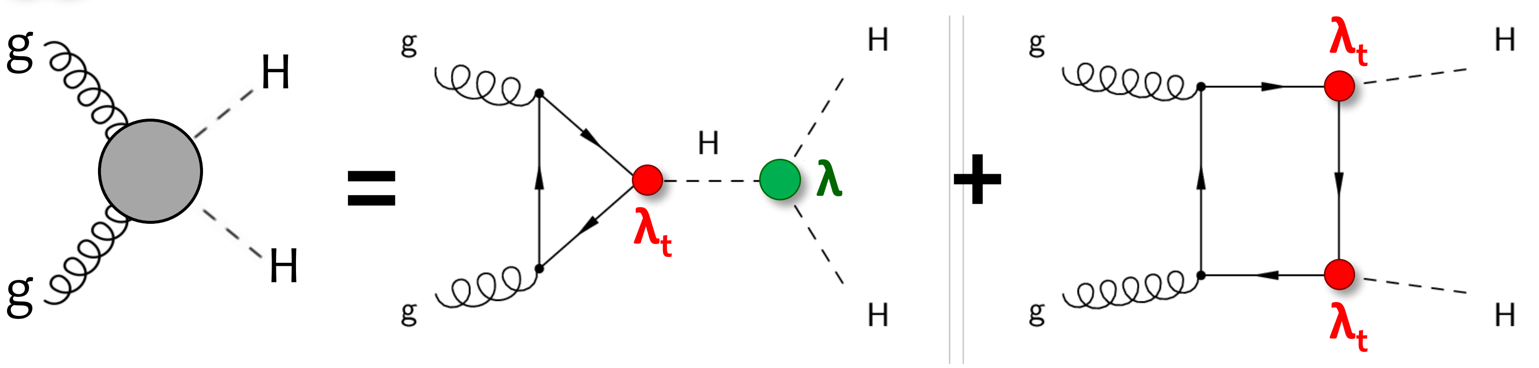


HH production

- Di-Higgs production at the LHC is dominated by the gluon-fusion process, followed (1/20) by VBF production

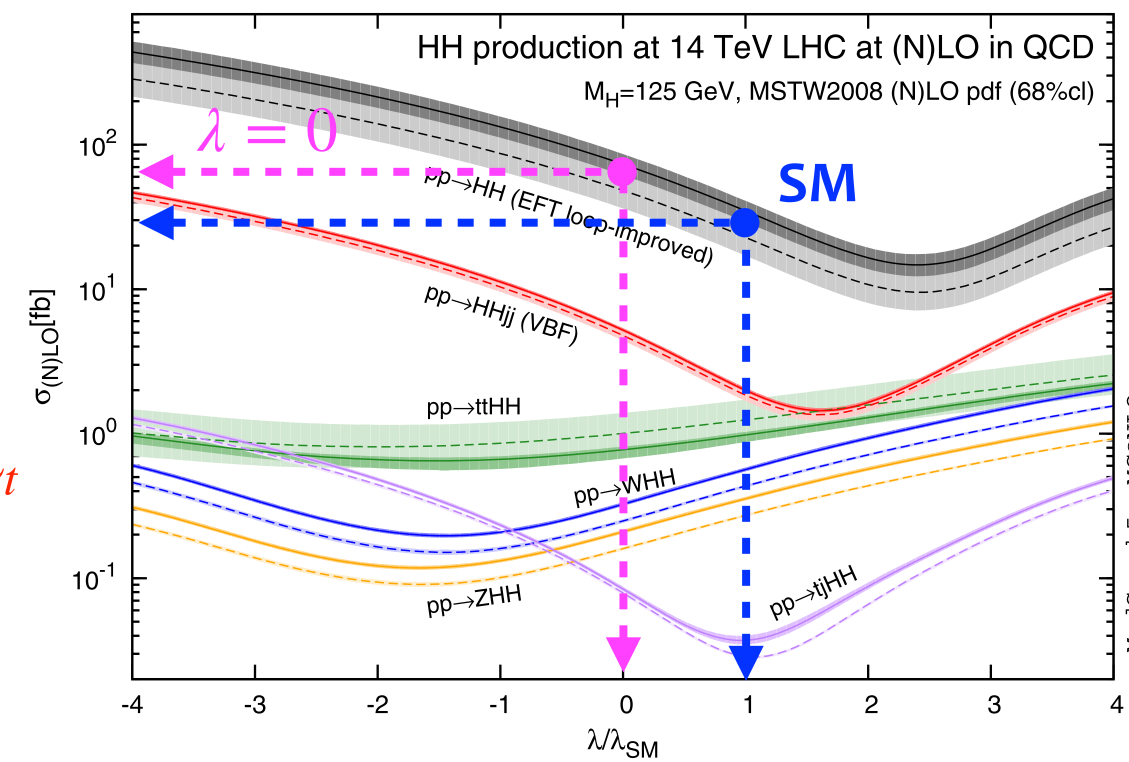
PLB 732 (2014) 142-149

ggF: $\sigma(ggHH) = 31\ \text{fb} \approx 1/1500 \times \sigma(ggH)$

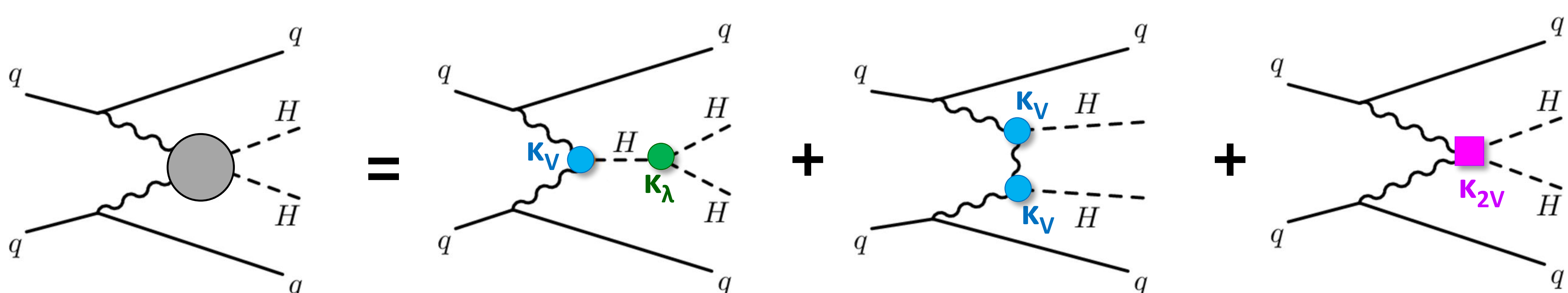


self-coupling λ Higgs-top coupling λ_t

destructive interference makes $\sigma^{\lambda=0} > \sigma^{SM}$



VBF: $\sigma = 1.72\ \text{fb} \approx 1/1500 \times \sigma(ggH)$

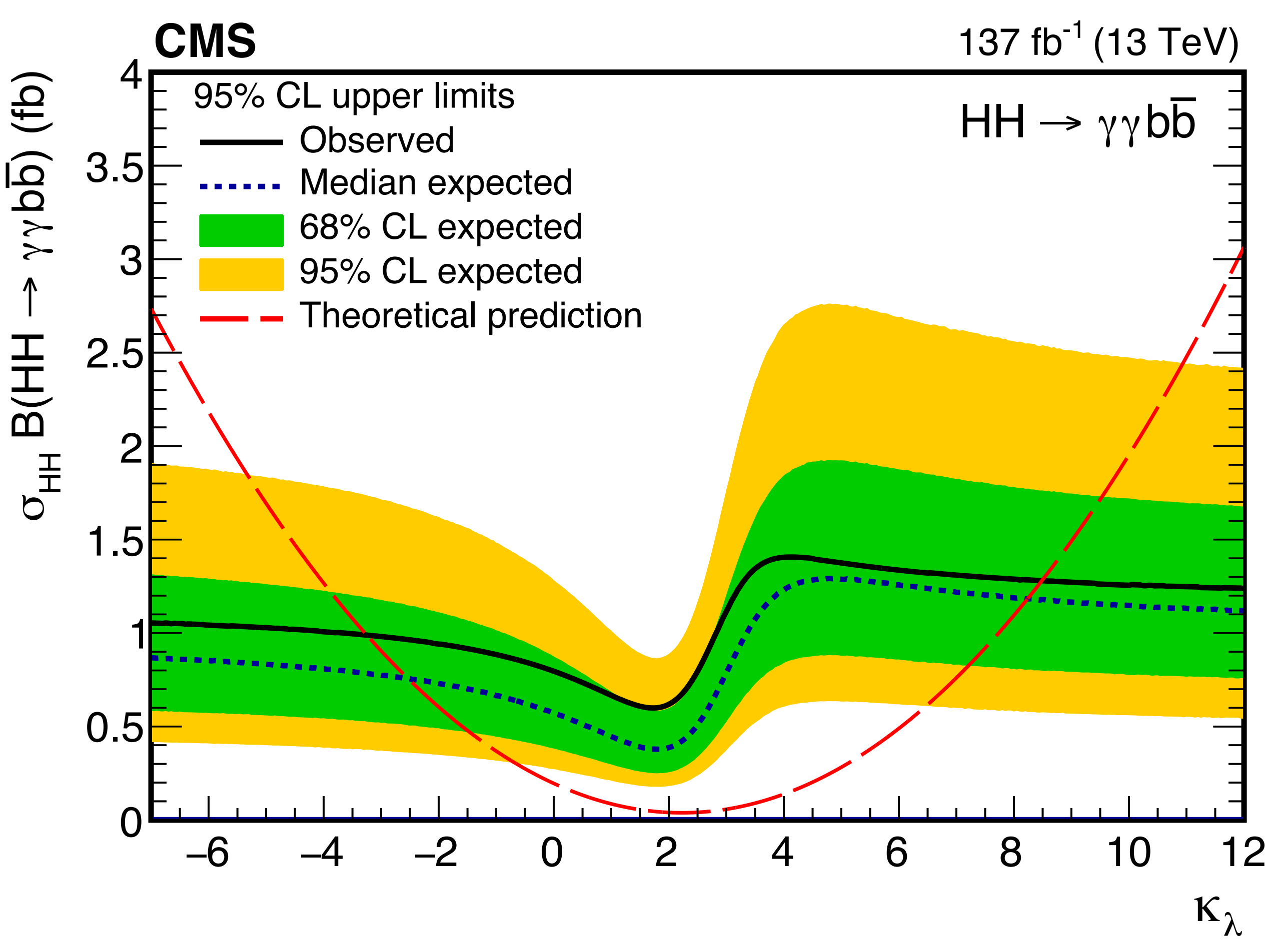


self-coupling λ HHH and HVV single H coupling κ_λ

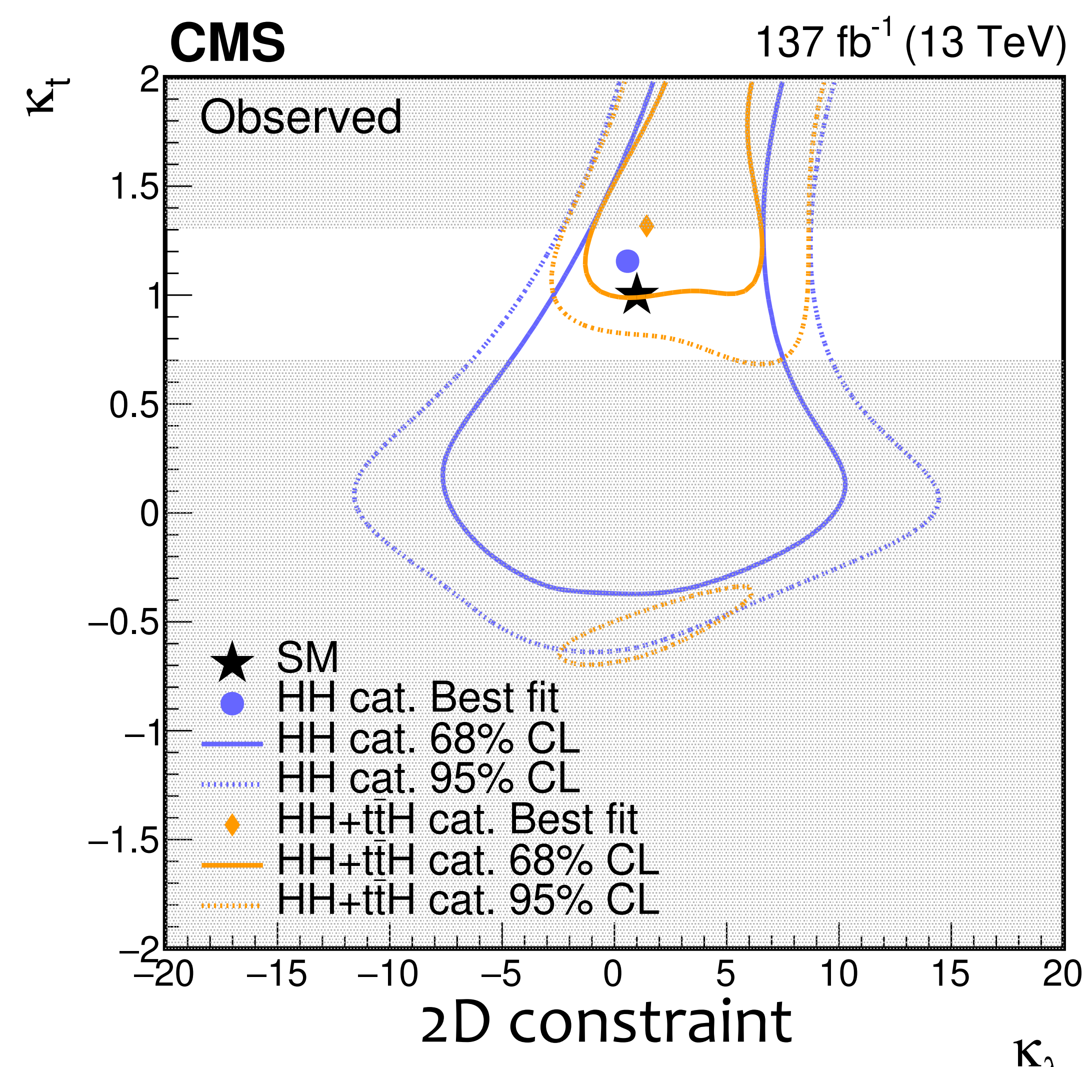
HHVV quartic coupling only in VBF production

$HH \to b\bar{b}\gamma\gamma$

- Phase space of 2 photons and 2 b-tagged jets, with $m_{\gamma\gamma}$ around 125 GeV
  - both CMS and ATLAS also look for a resonant $X \to HH \to b\bar{b}\gamma\gamma$
  - bkgs: $\gamma\gamma + jets$ from data sidebands and single Higgs from MC fullsim
- cross section upper limit = 7.7 (5.2 exp) $\times\, \sigma_{SM}^{HH}$



Constraint on trilinear coupling at 95% CL:
$-3.3 < \kappa_\lambda < 8.5$



2D constraint

self-coupling κ_λ vs Higgs-top coupling κ_t

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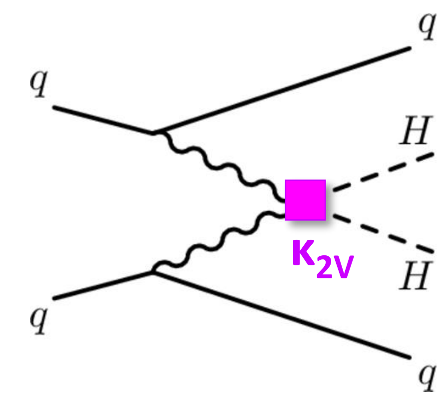
$HH \to 4b$

- Early Run 2 results focused on ggF production in the context of EFT using the three most sensitive channels: $bbbb$, $bb\tau\tau$, $bb\gamma\gamma$ with non-boosted topology:
  - Still far to be sensitive to SM process: $\sigma^{HH}/\sigma^{HH}_{SM} < 7.3$ (10 exp.)
- **VBF** $HH \to 4b$ also targets the extreme kinematic of **$\kappa_{2V} \neq 1$**
  - Two boosted $H \to b\bar{b}$ candidates (two large-R jets)
  - VBF topology, $t\bar{t}$ and QCD bkg discriminated with convolutional NNs



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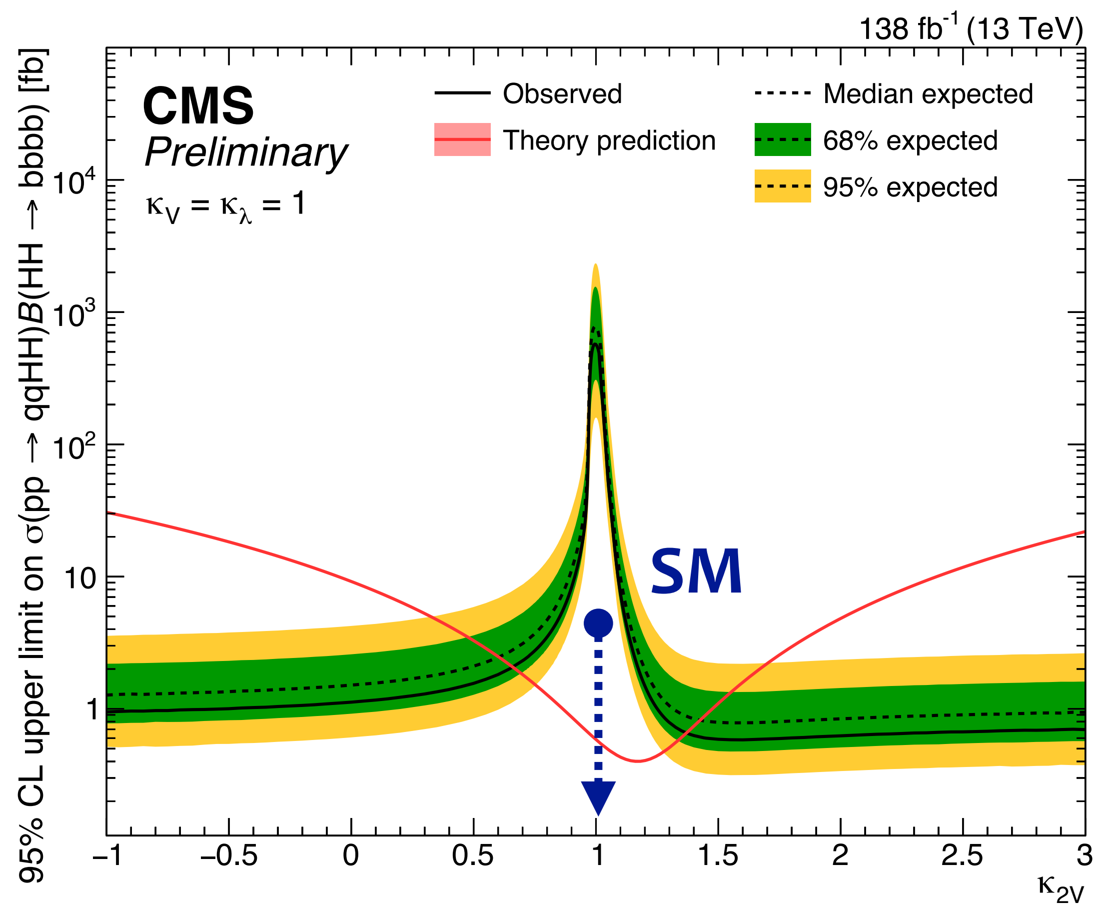
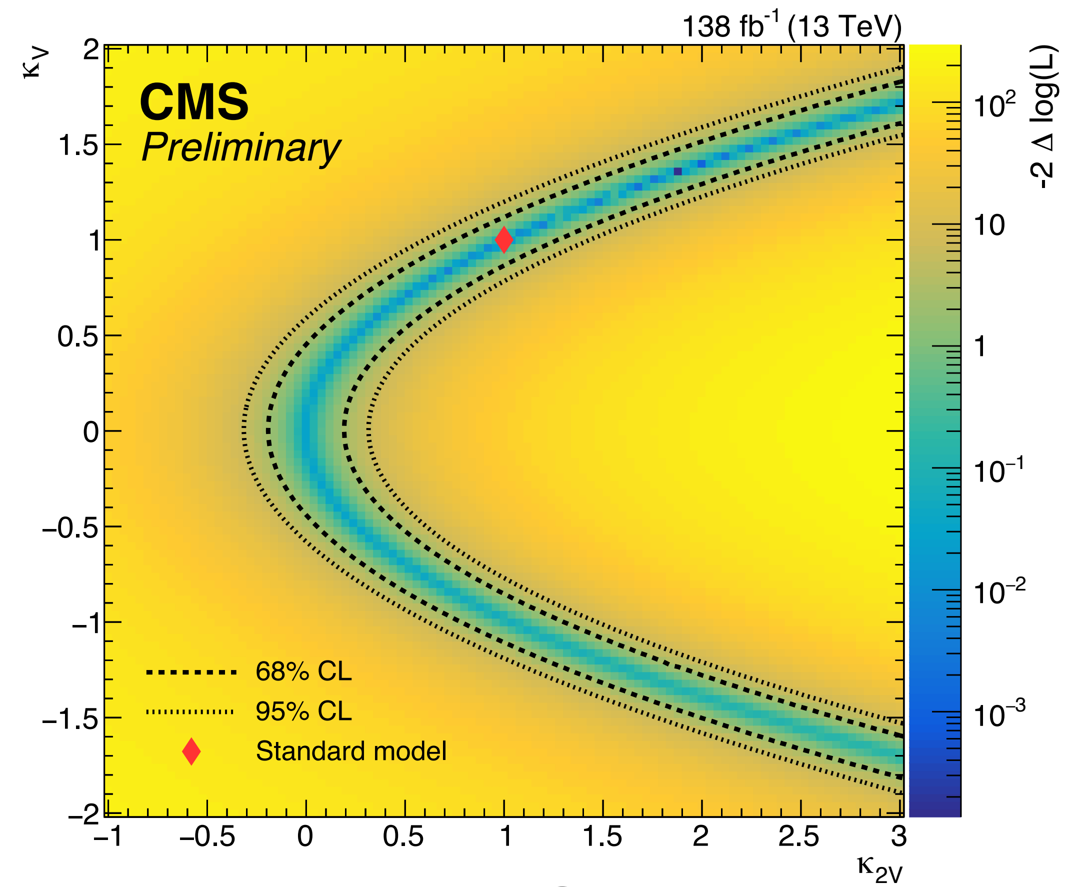




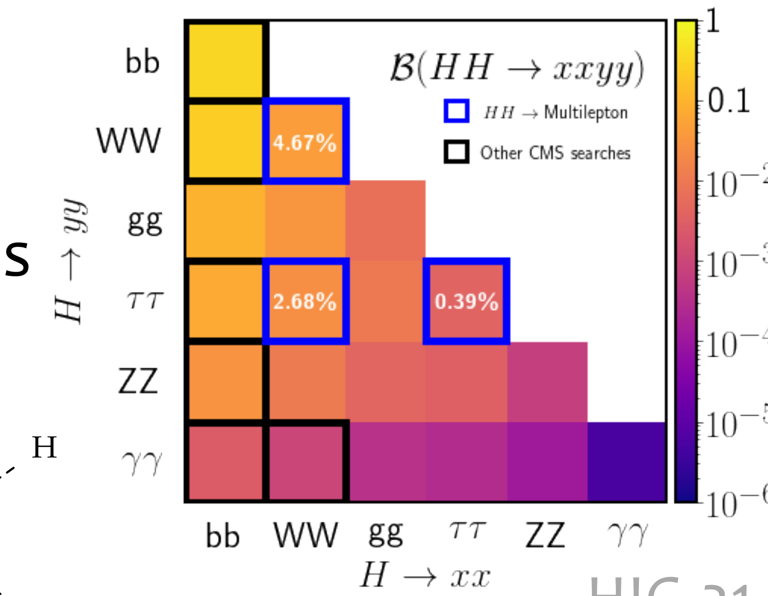
$-0.6 < \kappa_{2V} < 1.4$ @ 95% CL

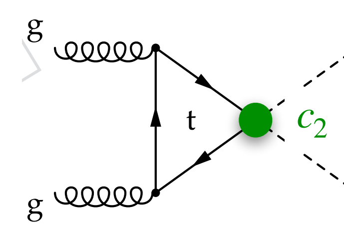
$\kappa_{2V} \neq 0$ excluded @ >99.99% for k_V=1

$0.6 < \kappa_{2V} < 1.4$ @ 95% CL

Multilepton HH search

- Double H decays into 4W, 4τ, $2W2\tau$ in final states with $\ell = e, \mu$ and an hadronically decaying τ_h cover ~7.7% of the HH decays
  - dedicated categories for 7 channels and 2 CRs
  - background estimates from data as ttH multileptons
- Sensitivity $\approx 20 \times \sigma_{SM}^{HH}$





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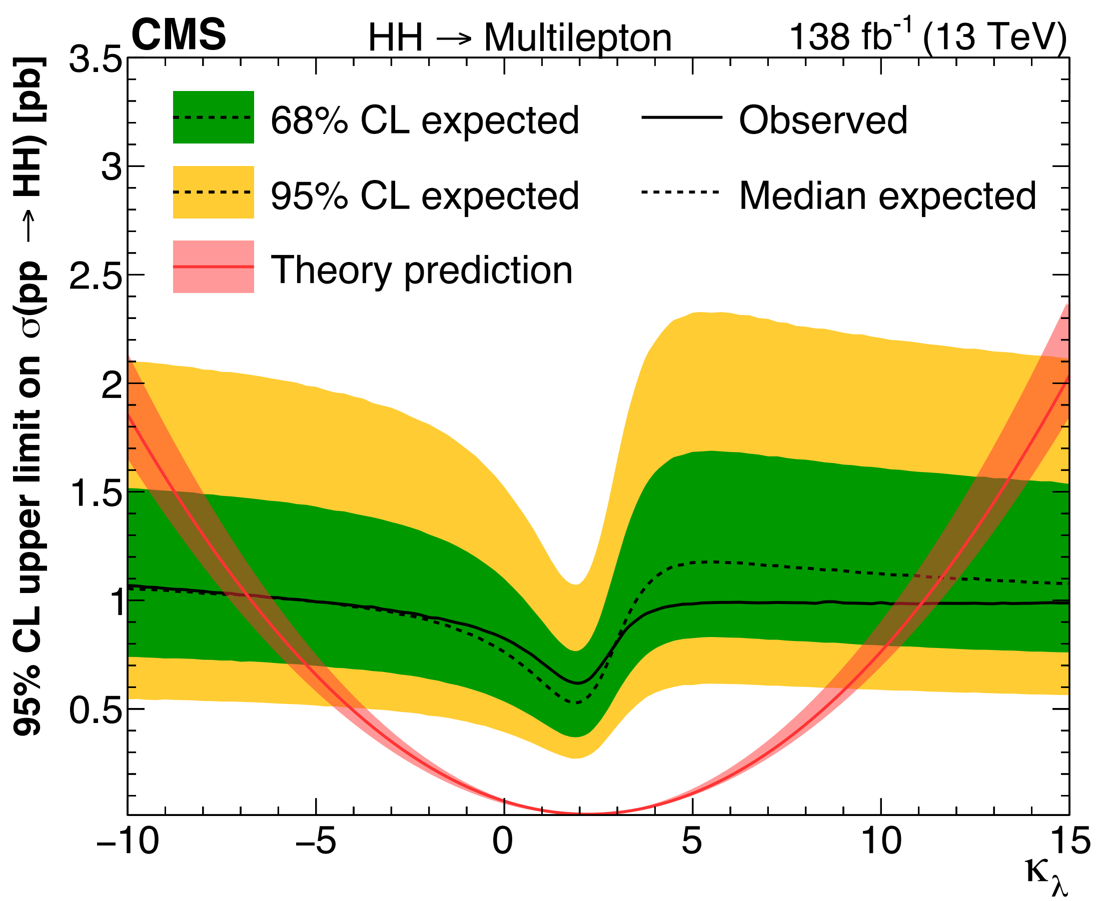

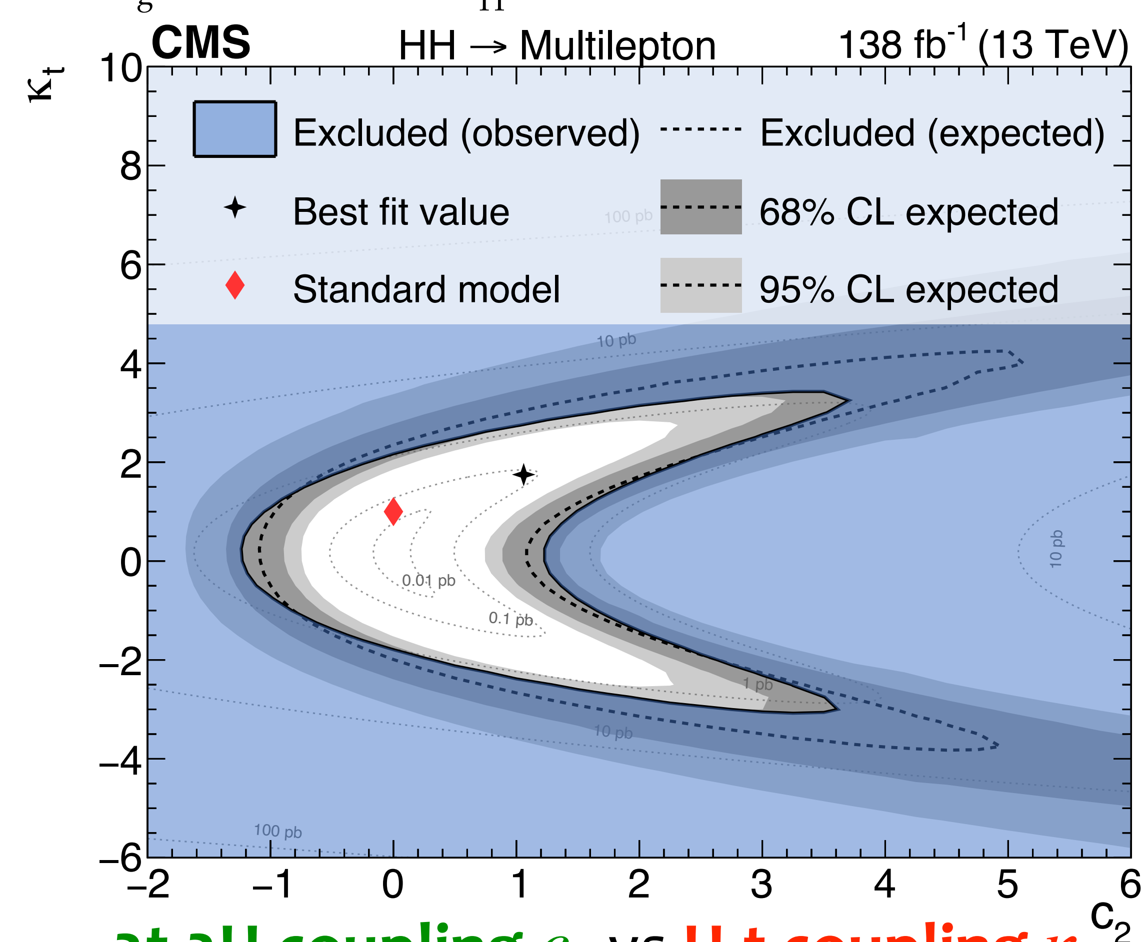

Constraint on trilinear coupling at 95% CL:

New result Jan. 2022

$-7 < \kappa_\lambda < 11$

2t-2H coupling c_2 vs **H-t coupling κ_t**