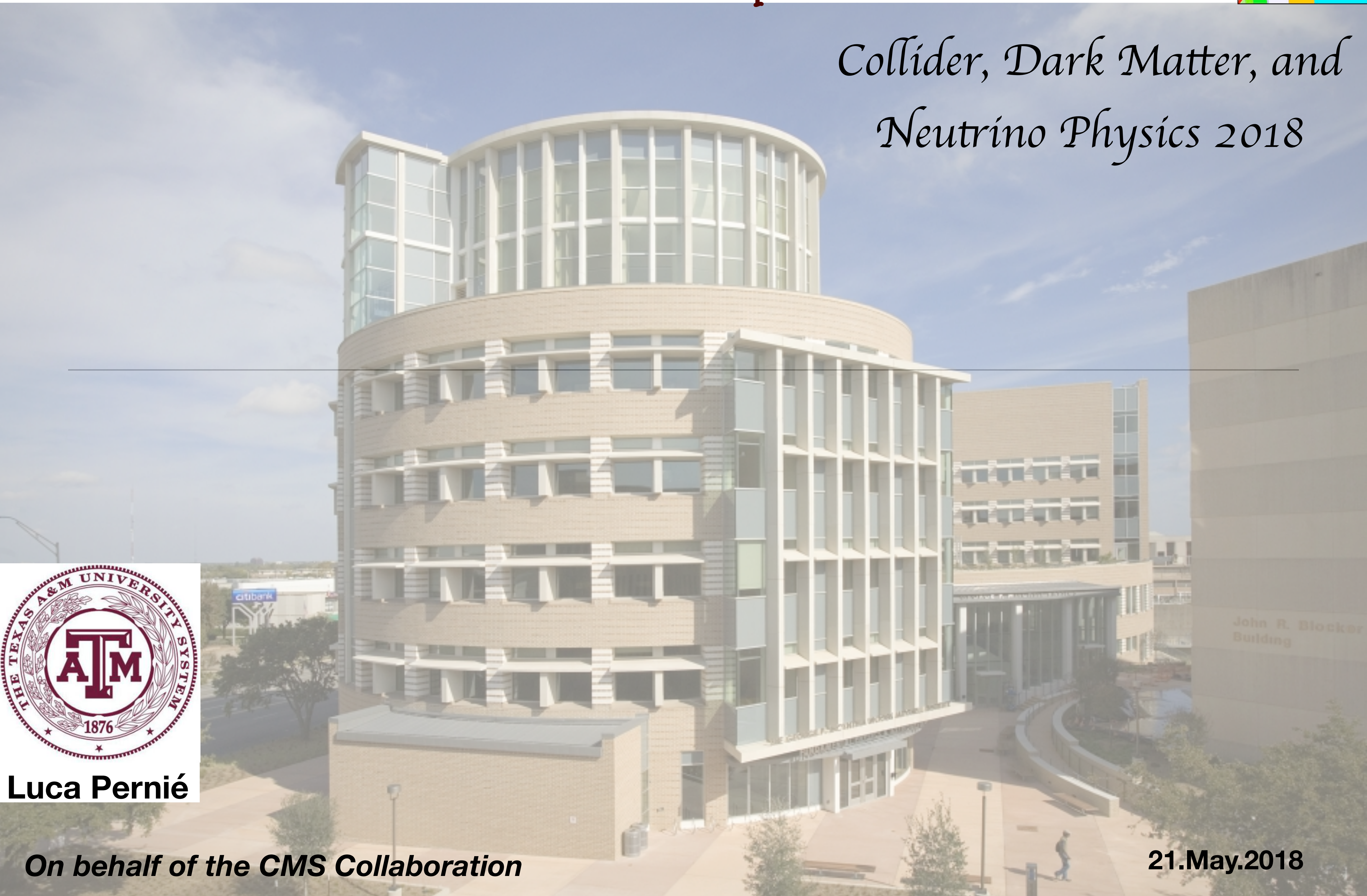
Exotic Higgs searches at the CMS Experiment

Collider, Dark Matter, and Neutrino Physics 2018



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On behalf of the CMS Collaboration

21.May.2018

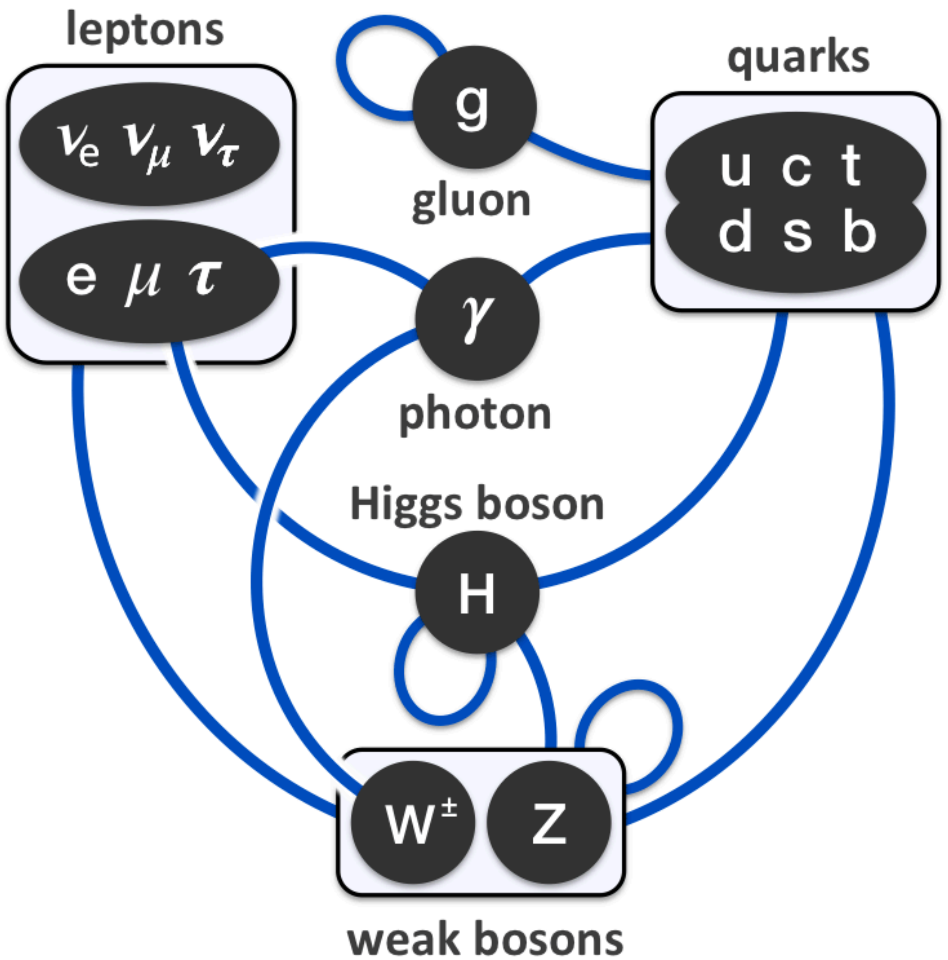
Gazing beyond the Standard Model

- Standard Model (SM): our current theory of matter and interaction

- Unfortunately, it cannot provide a complete description of the Universe:
  - → Higgs Mass is unprotected against quantum corrections in the SM: $m_h^2 \sim m_{h0}^2 - \alpha\lambda_f^2\Lambda^2$
  - → Baryogenesis:

$$\frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 10^{-9}$$

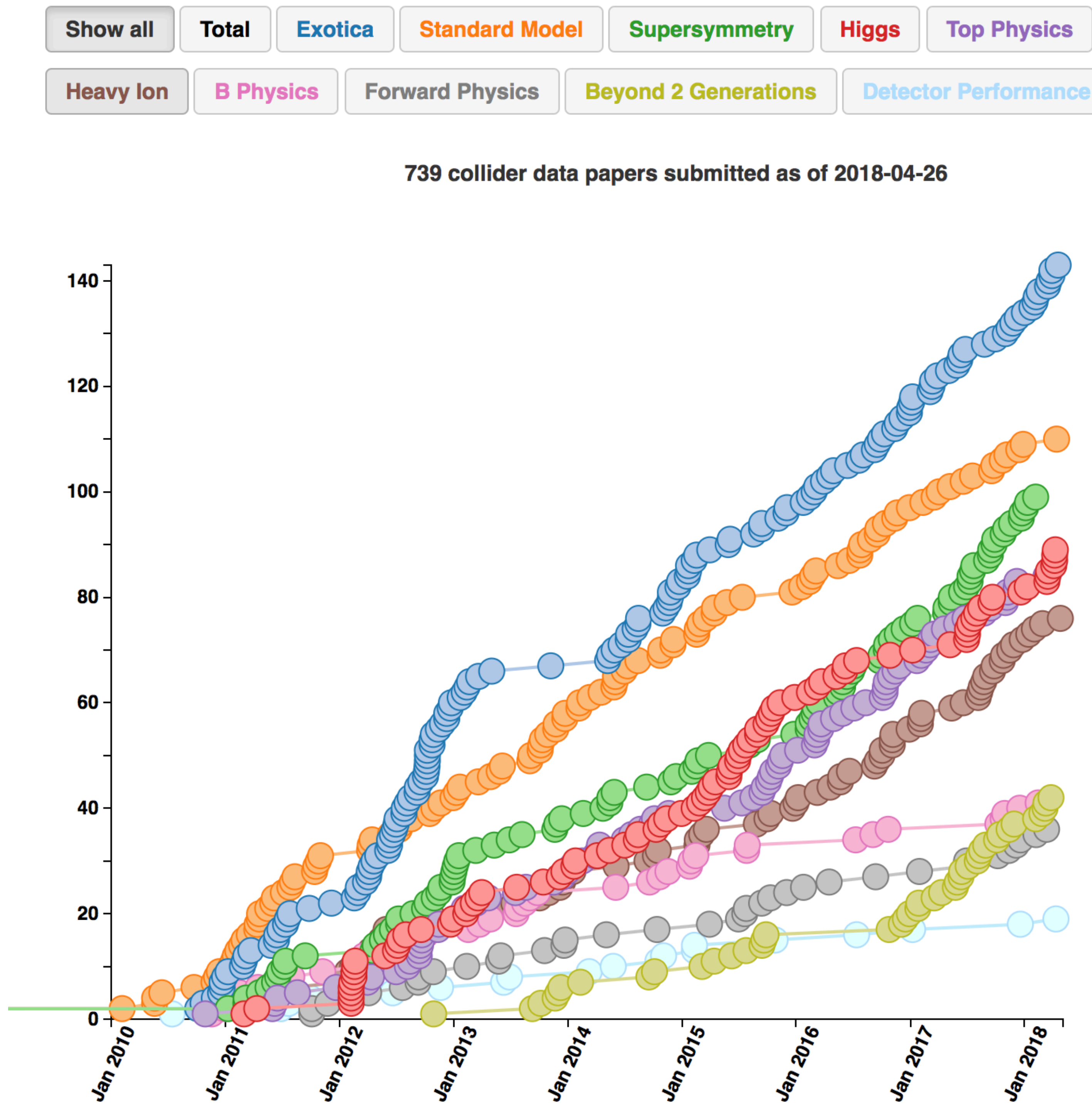
  - → Neutrino physics
  - → Dark Matter…



- No hints of physics beyond the Standard Model, but:
  - → Still room for BSM decay of Higgs boson (Branching Fraction h→BSM < 34% at 95% CL)
  - → Also: <u>are we looking in the right place</u>?
    - → Hidden sectors with only tiny interactions with the SM (displaced signatures, stopped LLP, etc..)

Leave no stone unturned

- We want to make the best use of the data produced by the LHC



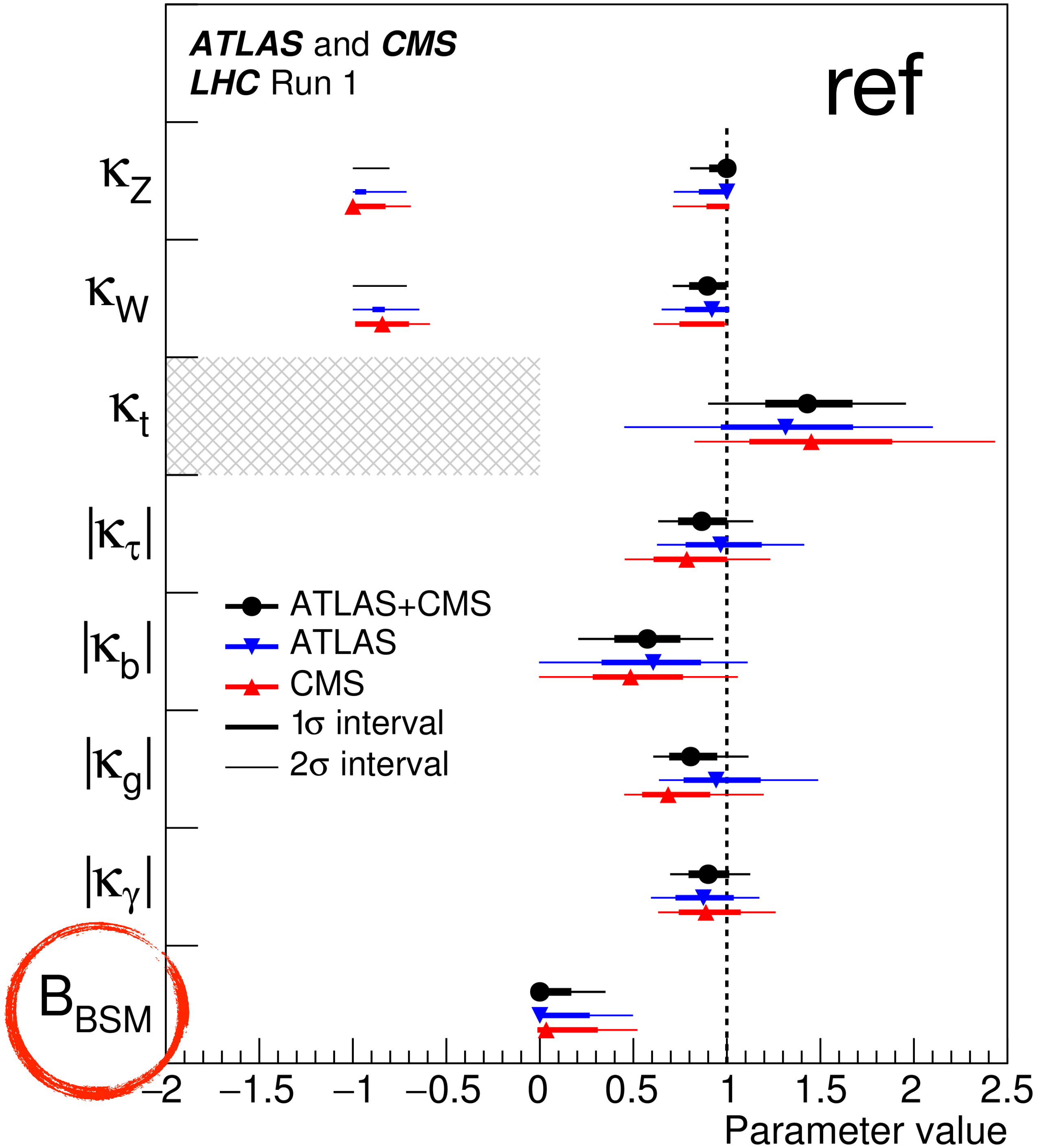
- Many searches (> 700 papers)
  - → Exotica leads the #publications
  - → SM lead only until 2012

- Rushing over tons of results is not interesting (results are <u>public</u> anyway)
  - → Focus on a couple of areas:
    - Higgs decay to light bosons
    - Di-Higgs searches

- Bonus slides: novel techniques
  - → Heavy Mass Estimator
  - → Parametric Deep Neural Network

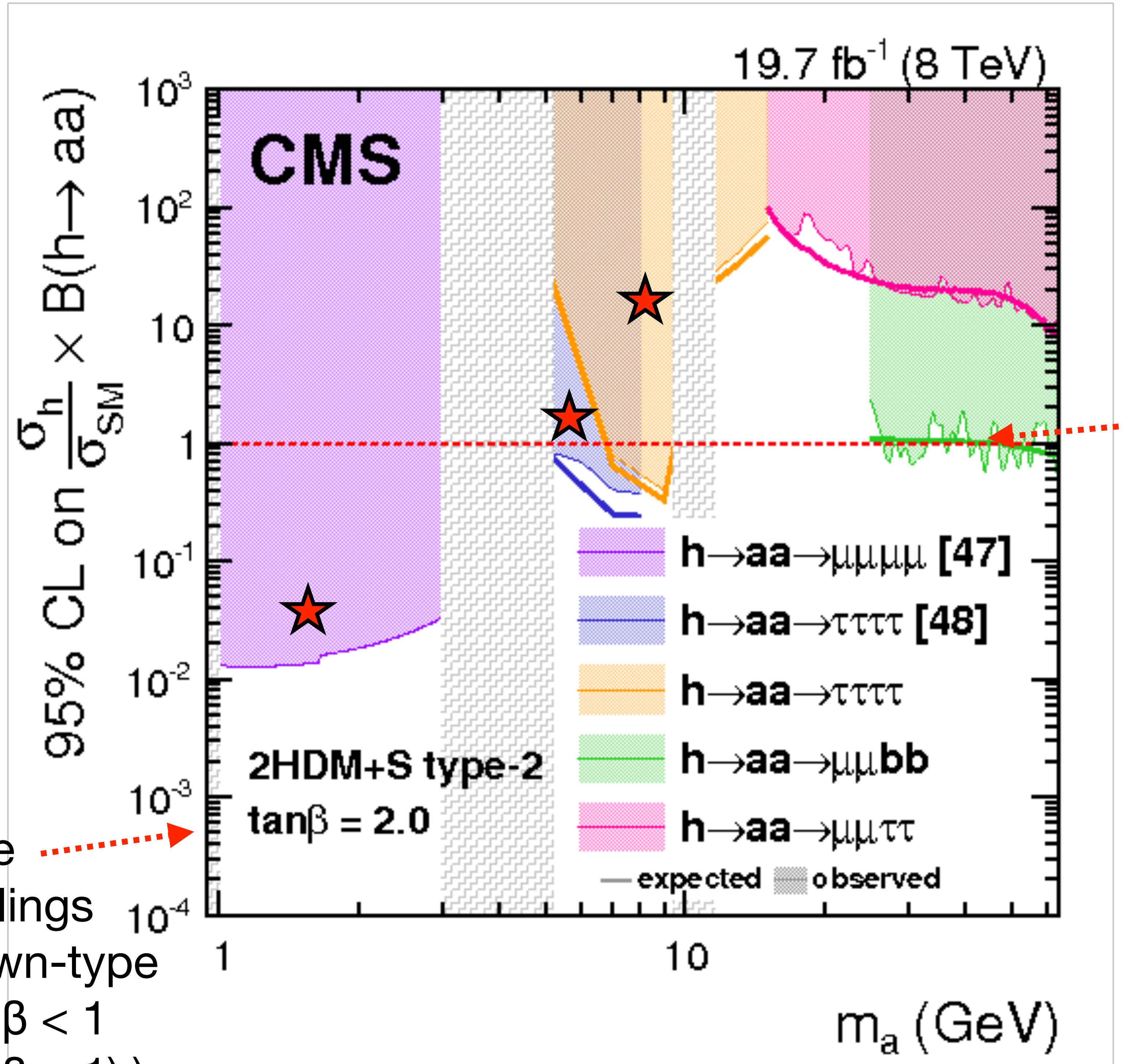
Higgs decay to light bosons: why?

- Scalar sector: the least known sector!
- Higgs has a narrow width: small coupling could lead to sizable Br(h→BSM)
- Possible portal to dark matter
- Compatible with several models: (2HDM+S including NMSSM, DM…)
- Could allow model independent limits to be interpreted in you favorite model (even dark SUSY with displaced γ_D)
- Rich topology:
  - → bb, μμ, ττ final states
  - → Depends on the light boson mass (i.e. its BR)



http://cms-results.web.cern.ch/cms-results/public-results/publications/HIG-15-002/index.html

★ Boosted Reconstruction techniques



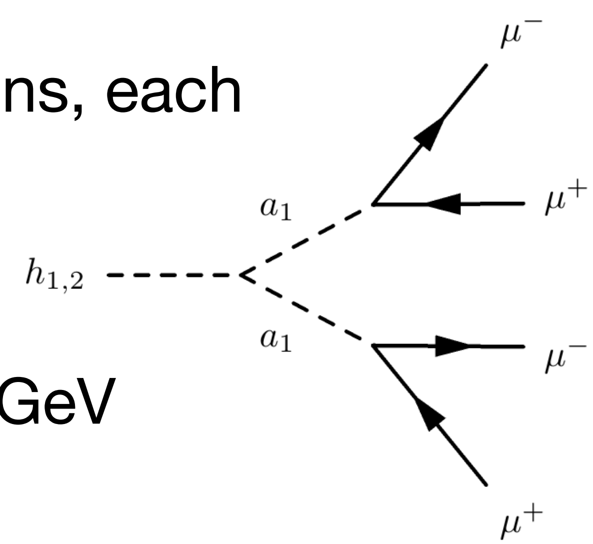
arXiv:1701.02032

Sensitive to $Br(h \to aa)=1$ if $\sigma(h)=\sigma_{SM}$

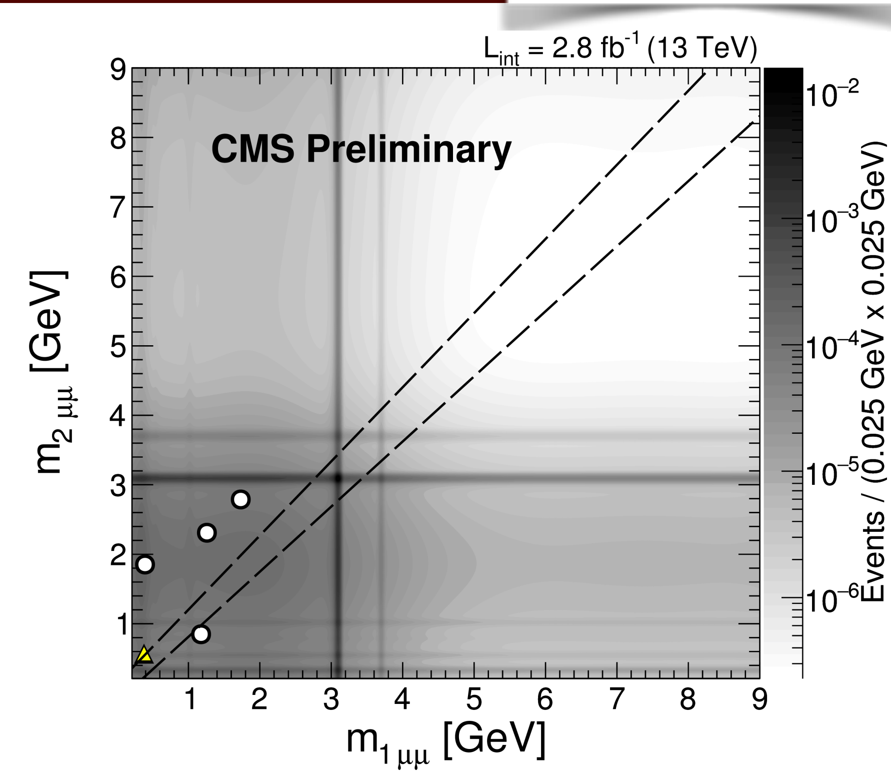
NMSSM-like (fermionic couplings suppressed for down-type fermions for $\tan\beta < 1$ (enhanced for $\tan\beta > 1$))

H→aa→μμμμ (NMSSM)

- Signal:
  - → Pair production of new light bosons, each decaying into a pair of muons

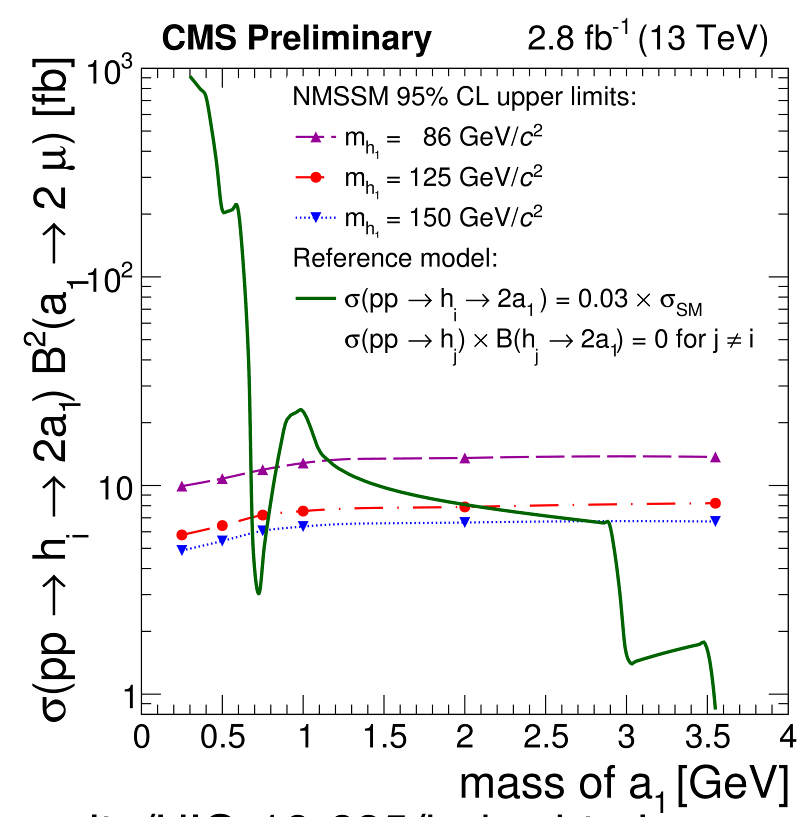


- Selection:
  - → P_{T1}>17 GeV; $|\eta_1|$ <0.9; $P_{T2,3,4}$ > 8 GeV
  - → $|z_{1\mu\mu} - z_{2\mu\mu}| < 1$ mm



- Main background:
  - → $b\bar{b}$, double J/Ψ (SPS and DPS)
  - → Data-driven estimation

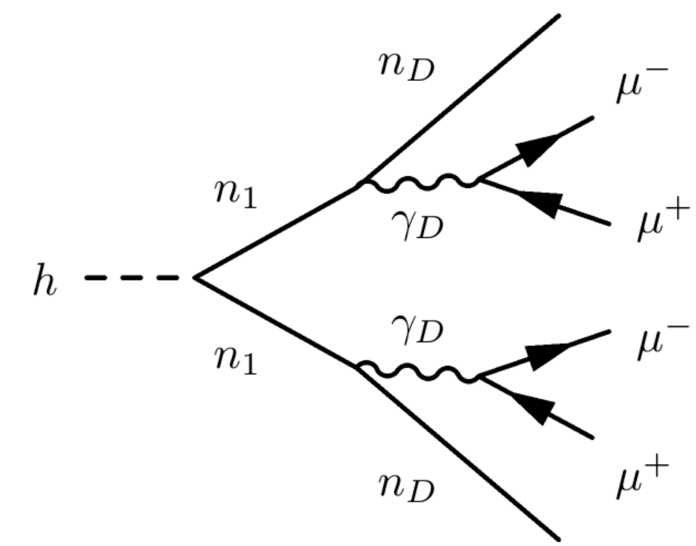
- Excess searched on the diagonal:
  $|m_{1\mu\mu} - m_{2\mu\mu}| < 0.13$ GeV $+ 0.065(m_{1\mu\mu} + m_{2\mu\mu})/2$
  - → Model independent search
  - → Right: NMSSM benchmark model
    - Assume SM-like production σ for $h_{1,2}$ to simplify interpretation



http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/HIG-16-035/index.html

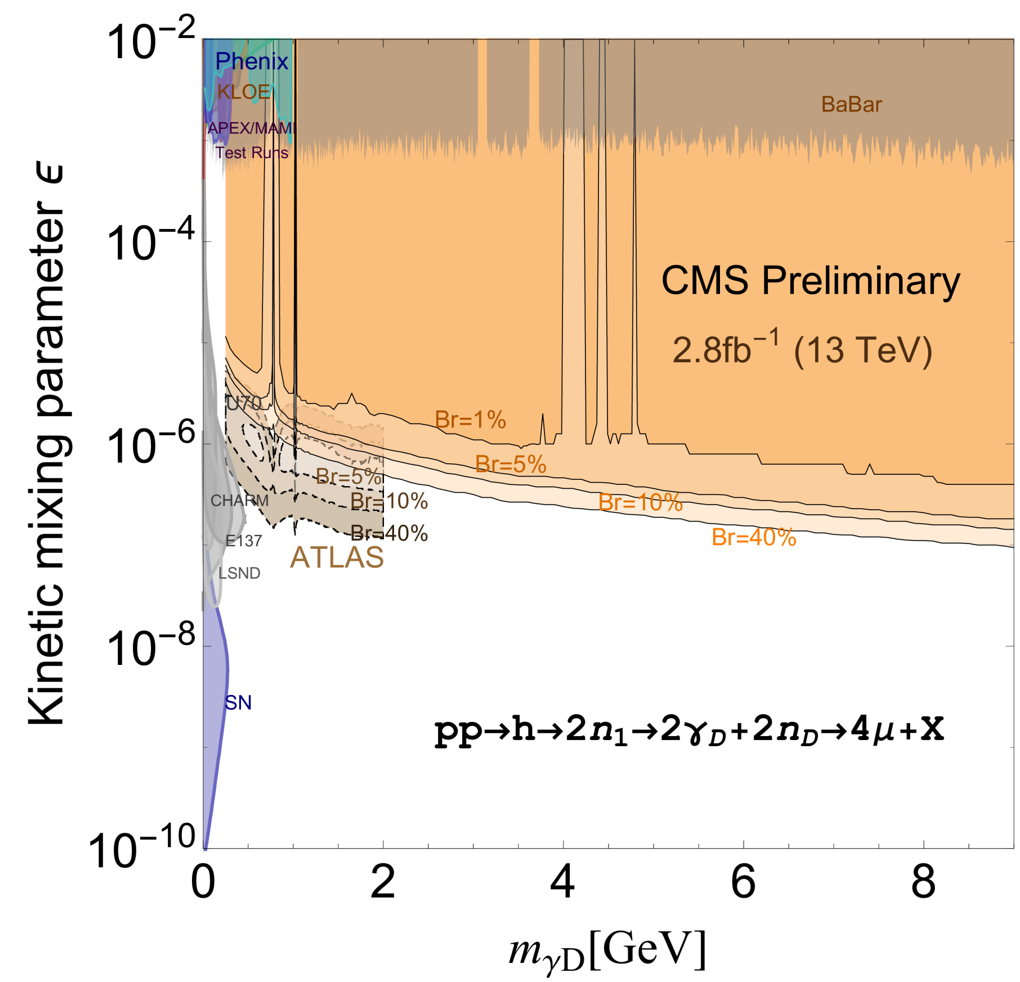
H→aa→μμμμ (dark SUSY)

- Additional benchmark: dark SUSY
  h → $n_1 n_1$ → $n_D n_D \gamma_D \gamma_D$+X
  - → Dark photons could have an appreciable life-time before decay
  - → Dark photons are generated with m(γ) in the range 0.25–2.0 GeV and a decay length in the range of 0–20 mm



- Flat reconstruction efficiency vs cτ (to assure model independence)

- 95% CL limit on H boson production σ·B.R.
  - → The limit set in the [m(γ_D),ε] plane.
  - → Nice complementarity with ATLAS analysis searching for decays far from the interaction point

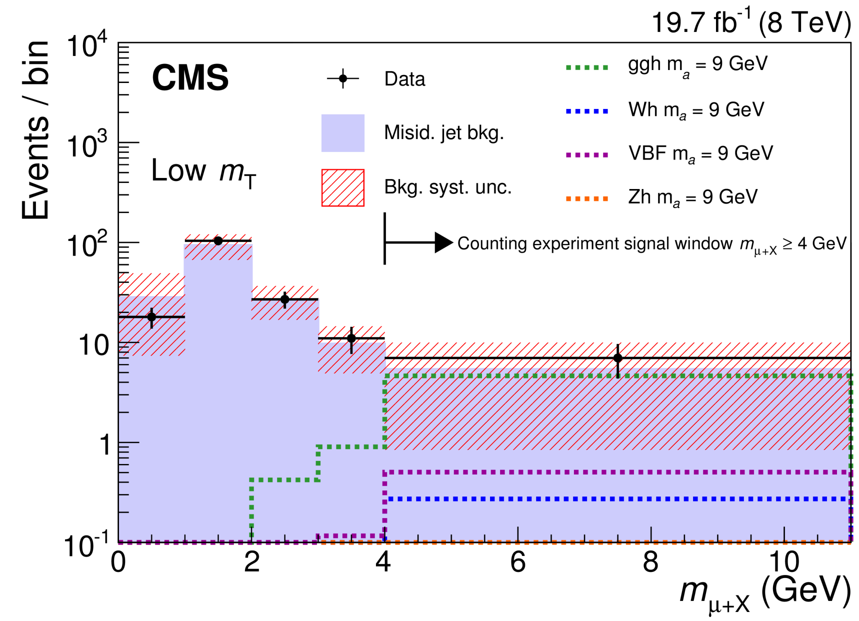


- Plans:
  - → Search with full 2016 dataset close to approval
  - → Legacy RunII paper with mass extended up to 60 GeV

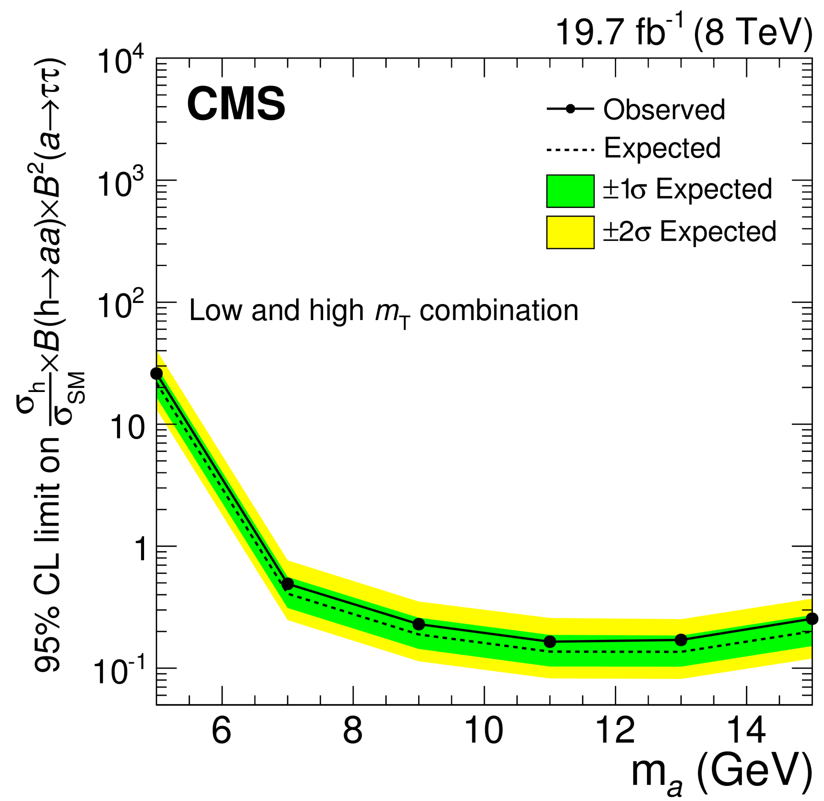
http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/HIG-16-035/index.html

H→aa→ττττ

- Large branching fraction if coupling proportional to mass
  - → One high p_T muon and boosted ττ (one decaying to muon)
  - → Required same sign leptons to reduce DY



- Considered ggH/Zh/Wh/VBF production modes
  - → m(a) є[5-15] GeV due to Br(a→ττ)
  - → Special technique for boosted $\tau_\mu \tau_X$:
    - All jets checked for presence of τ_μ
    - Jets with ≥ 1μ passing τ_μ cond. are used as seed
    - Such μ is excluded from τ rec. algorithm (HPS)
  - → 2 search regions: low/high m_T to separate production modes



- Background:
  - → DY+jets, tt, QCD
  - → Data driven estimation in control region

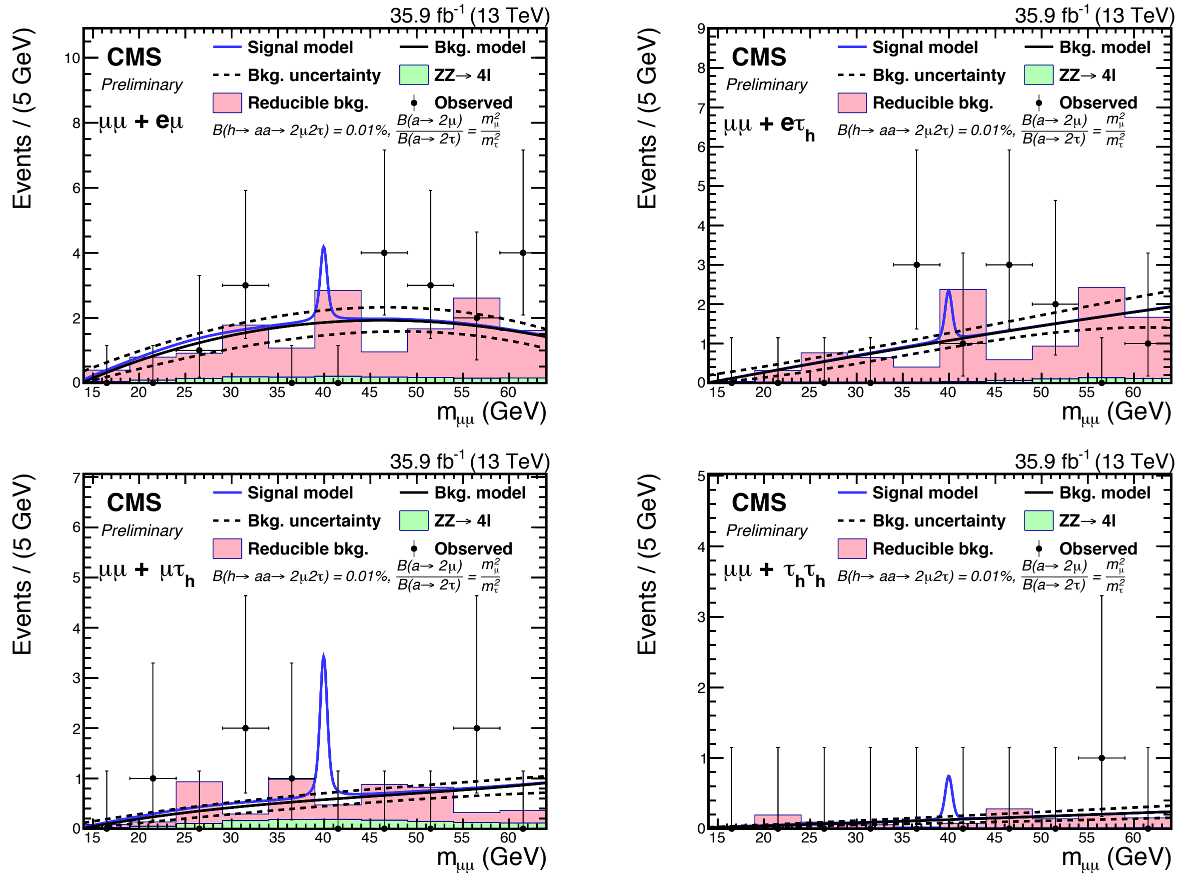
https://link.springer.com/article/10.1007%2FJHEP10%282017%29076

H→aa→μμττ

❖ Four final states depending on τ decay:
  → $\mu\mu\tau_e\tau_\mu$, $\mu\mu\tau_e\tau_h$, $\mu\mu\tau_\mu\tau_h$, $\mu\mu\tau_h\tau_h$
  (no $\tau_\mu\tau_\mu$ & $\tau_e\tau_e$, due to ambiguity)

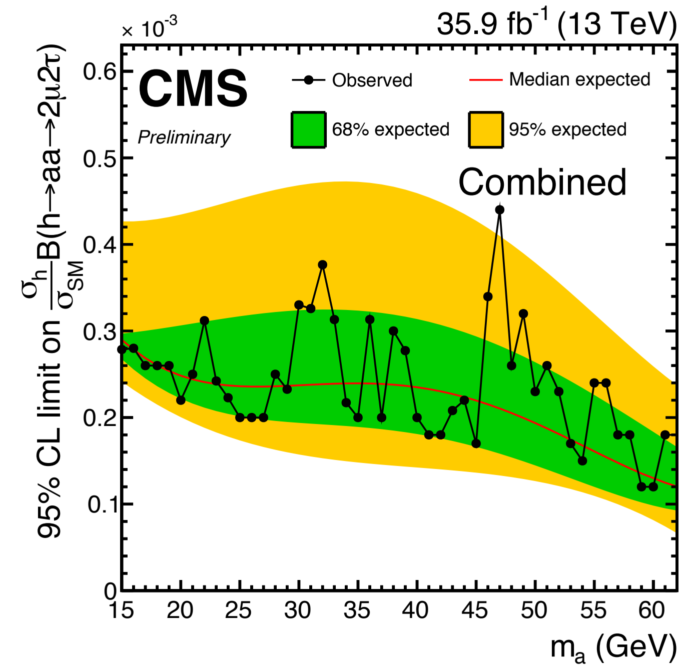
$$\frac{\mathcal{B}(\mathrm{a}\to 2\mu)}{\mathcal{B}(\mathrm{a}\to 2\tau)} = \frac{m_\mu^2\sqrt{1-(2m_\mu/m_\mathrm{a})^2}}{m_\tau^2\sqrt{1-(2m_\tau/m_\mathrm{a})^2}} \simeq \frac{m_\mu^2}{m_\tau^2}$$

Assuming 2HDM-like scenarios



❖ In 3-muon final state the highest in p_T is paired with the opposite one in sign
  → 90% of the time is correct

❖ Large bkg removed by asking $m_{4l} \lesssim 120$
If jet is b-tagged event is rejected

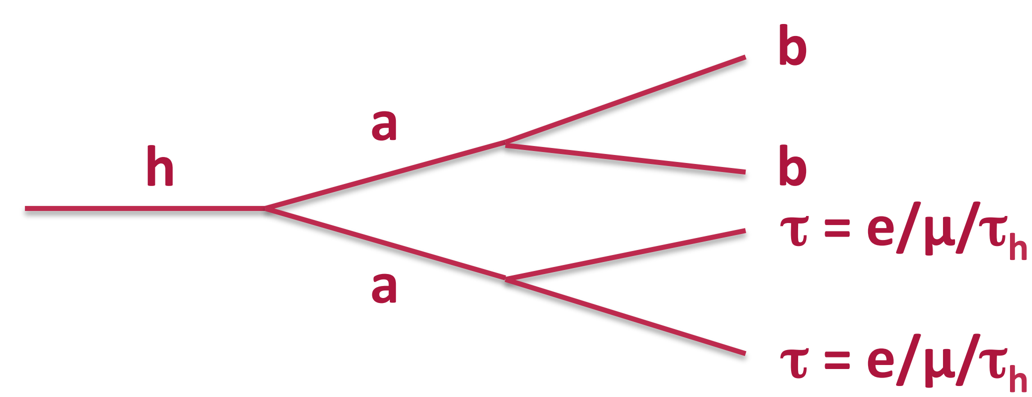


❖ Background:
  → ZZ (from MC, NNLO)
  → Z-WZ+jets
    ▪ Shape: from data CR, where τ have same charge
    ▪ Normalization: from data with 1 or 2 non-isolated τ (reweighted for misidentification probability)

https://cds.cern.ch/record/2308654?ln=en

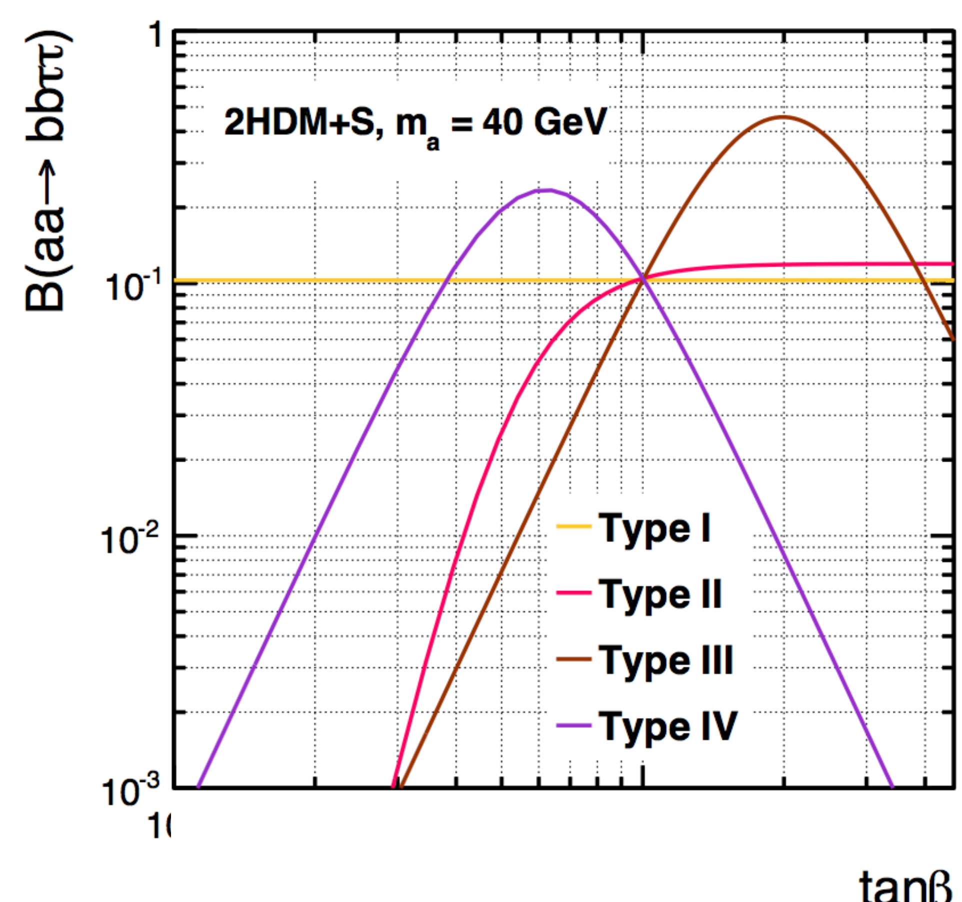
$H \to aa \to bb\tau\tau$ (New!)

- Events can be triggered in ggF based on the leptonic decay of one of the τ



- Final states: $bbe\tau_h$, $bb\mu\tau_h$, $bbe\mu$
  - → $\tau_h\tau_h$ discarded because of high trigger thresholds
  - → ee and μμ discarded because of low BR/high bkg

- At least 1 b-tagged jet

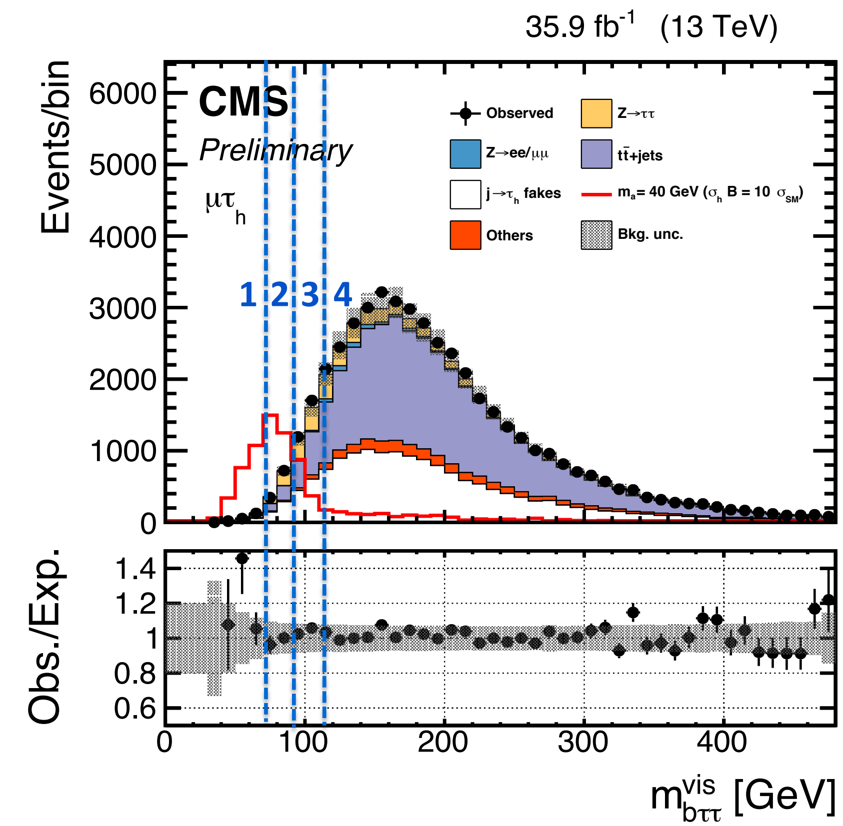


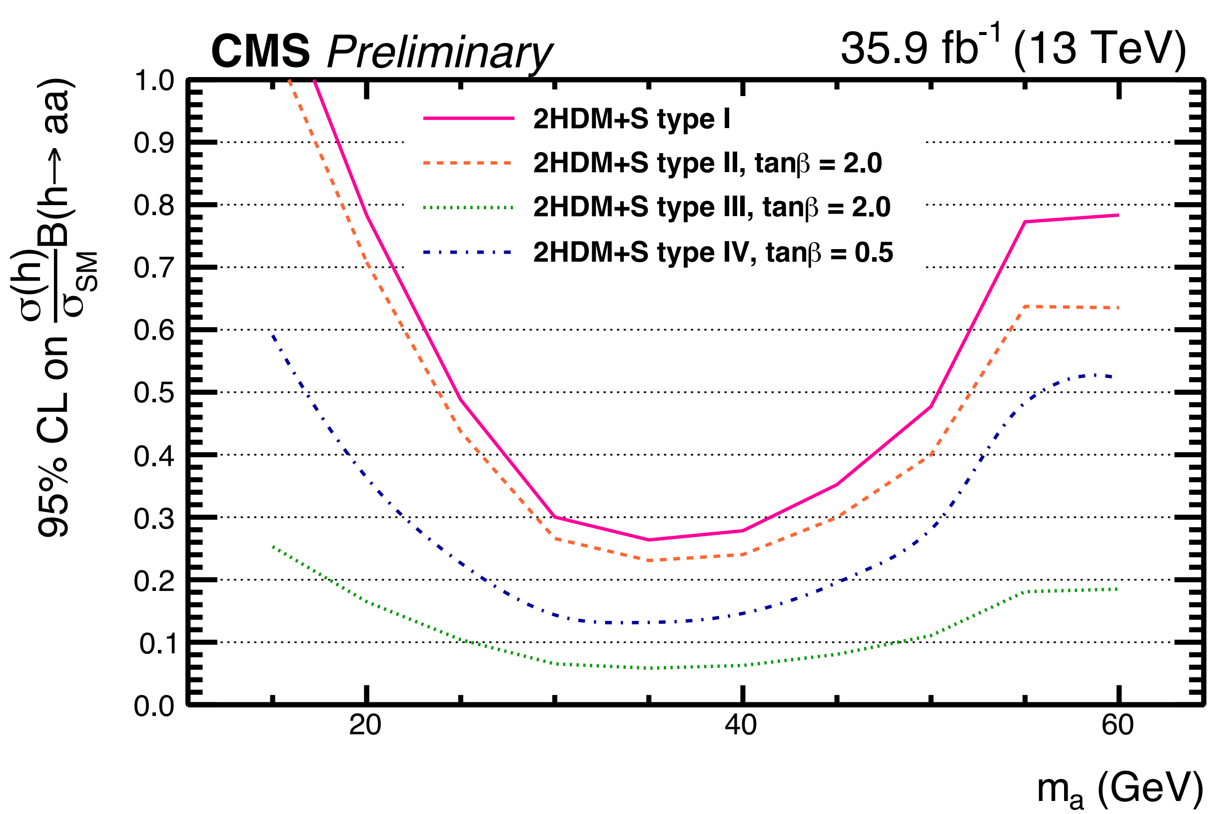
- Backgrounds:
  - → tt from NLO Powheg
  - → W+jets, $Z \to ee/\mu\mu/\tau\tau$ LO Madgraph (estimated from data)
  - → SM Higgs treated as background
  - → Single top and VV: Powheg/aMC@NLO
  - → QCD multi-jet from same sign data

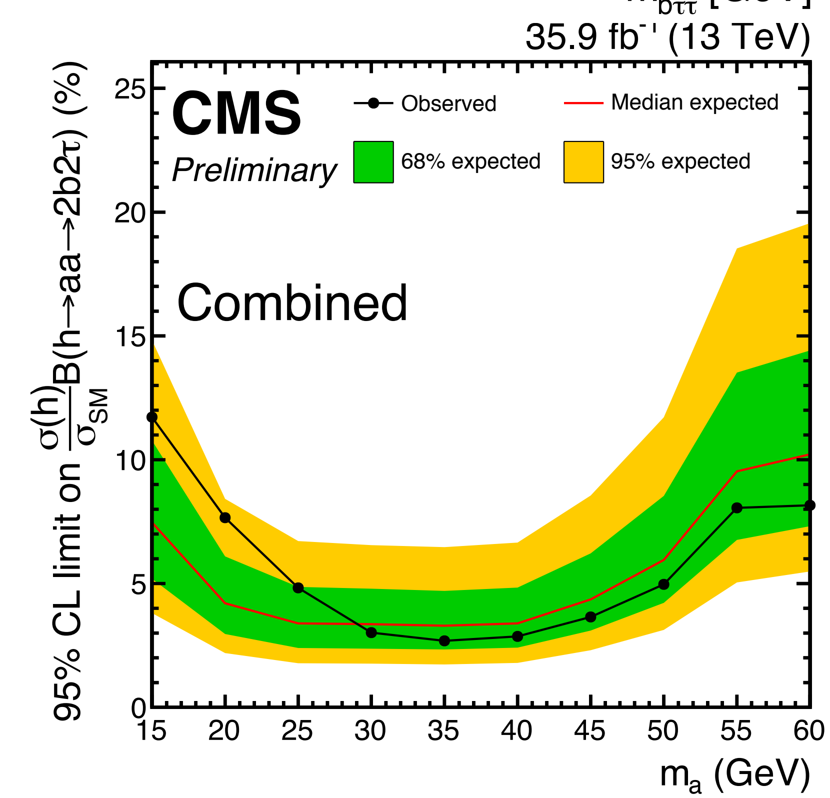
http://cds.cern.ch/record/2306329?ln=en

H→aa→bbττ (New!)

- ❖ Categories (4) based on visible mass
  → S/B in each category depend on m(a)
- ❖ Further selection based on MET and transverse mass
- ❖ Leading systematic unc. from bkg normalization and τ identification







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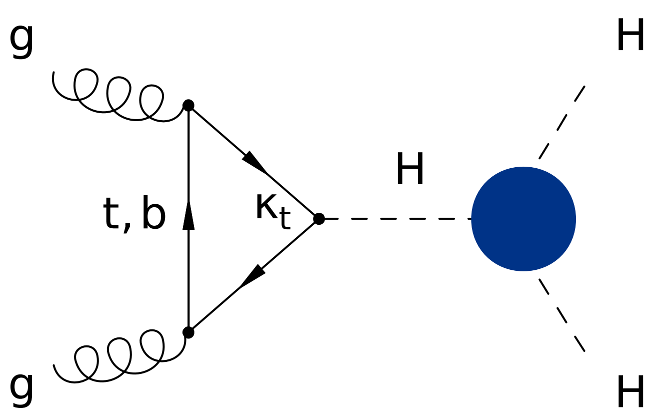
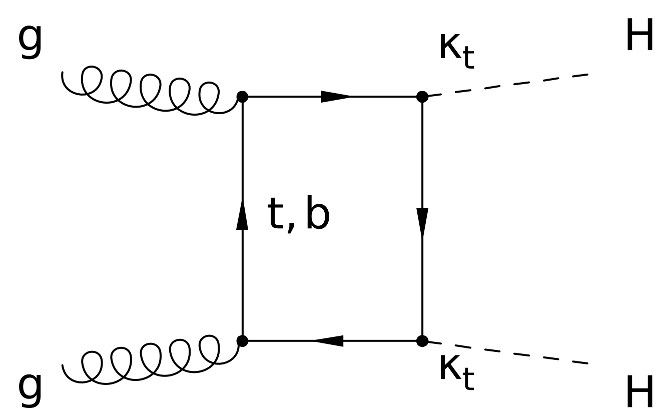
DiHiggs motivations

Non-Resonant

- Direct access to Higgs self-coupling λ





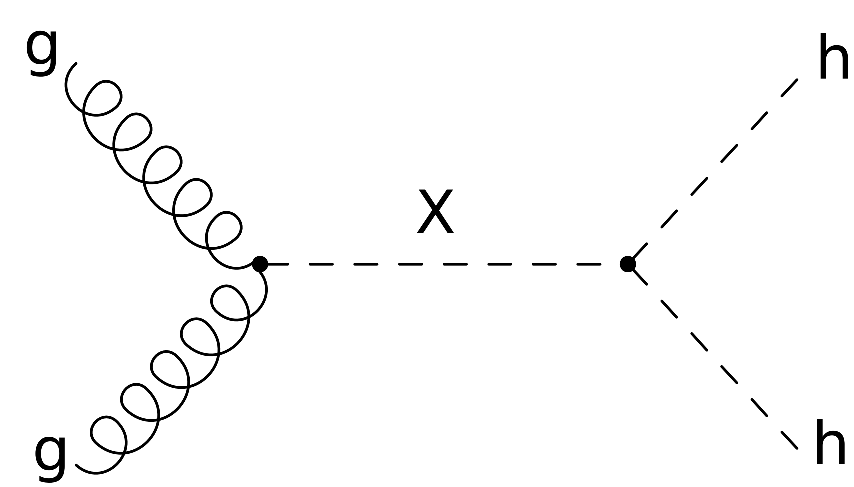
- Destructive interference: small rate
  → $\sigma_{HH,SM}$ = 33 fb @13 TeV

- BSM effect: early discovery
  → Strong effect on rates and kinematics

Resonant

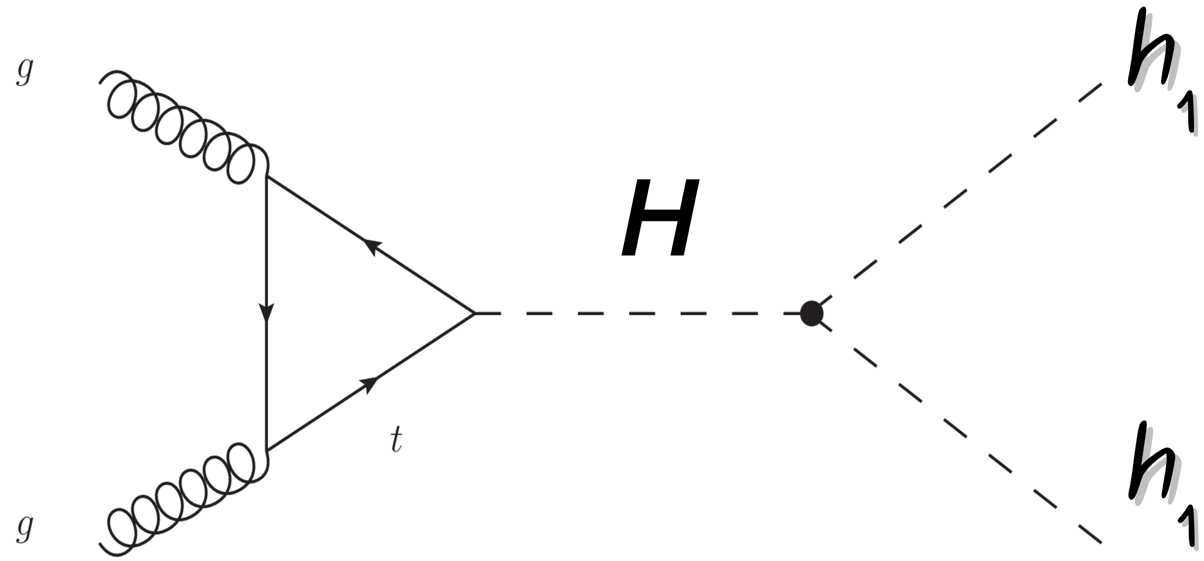
- Several motivations:
  → XSM (baryogenesis)
  → MSSM/2HDM
  → Warped extra-dimension
    - Radion
    - Graviton

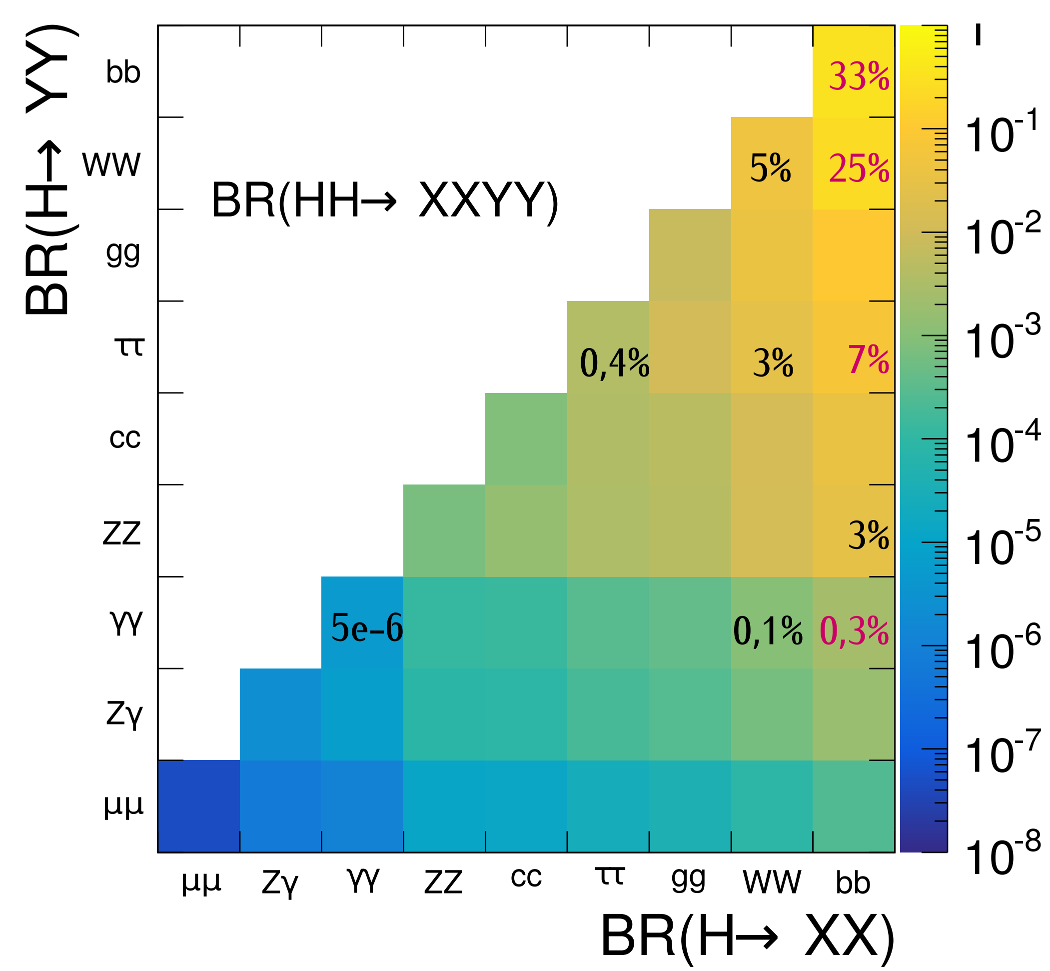
- Searches assume narrow width
  → Spin 0 and 2 benchmark



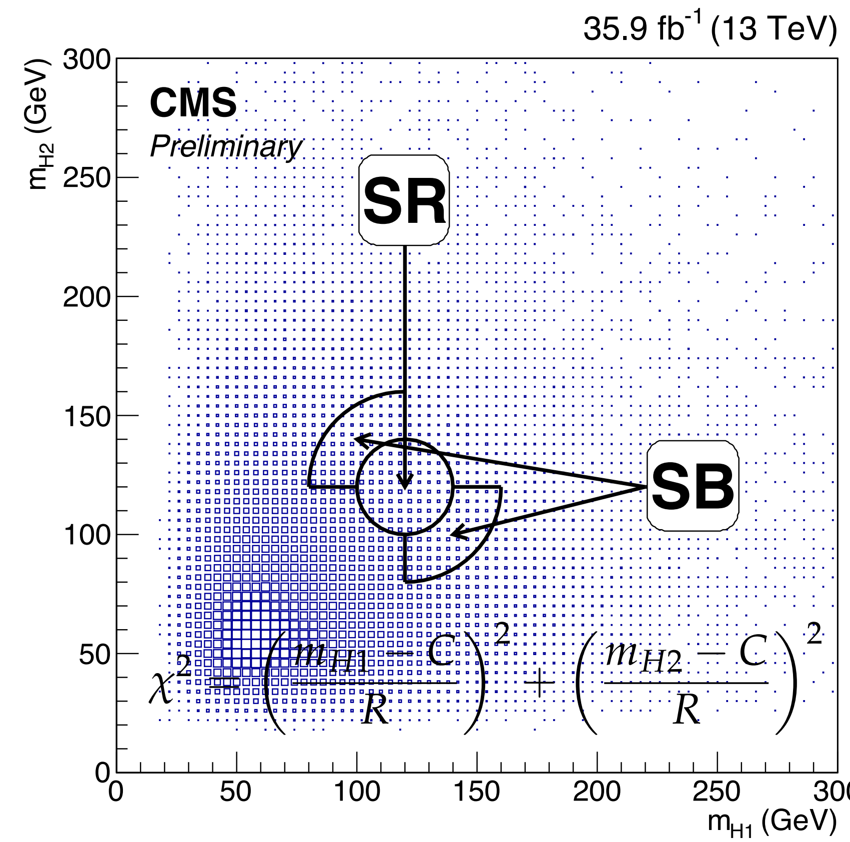
DiHiggs (in RunII) in practice

- bbbb: high BR, high bkg
  - → Non resonant and resonant
  - → bb can be resolved or not
- bbγγ: low BR, moderate bkg
  - → Non resonant
- bbττ: moderate BR and tt
  - → Non resonant and resonant
- bbWW: high BR, high bkg, neutrinos!
  - → Non resonant and resonant
  - → Can we overcome the neutrinos issue?
- Interesting perspective for HL-LHC!





- Novel techniques:
  - → New DeepCSV algorithm applied! (DNN using also up to 6 tracks)
  - → B-jet energy regression from H→bb (BDT which recover invisible b decay)

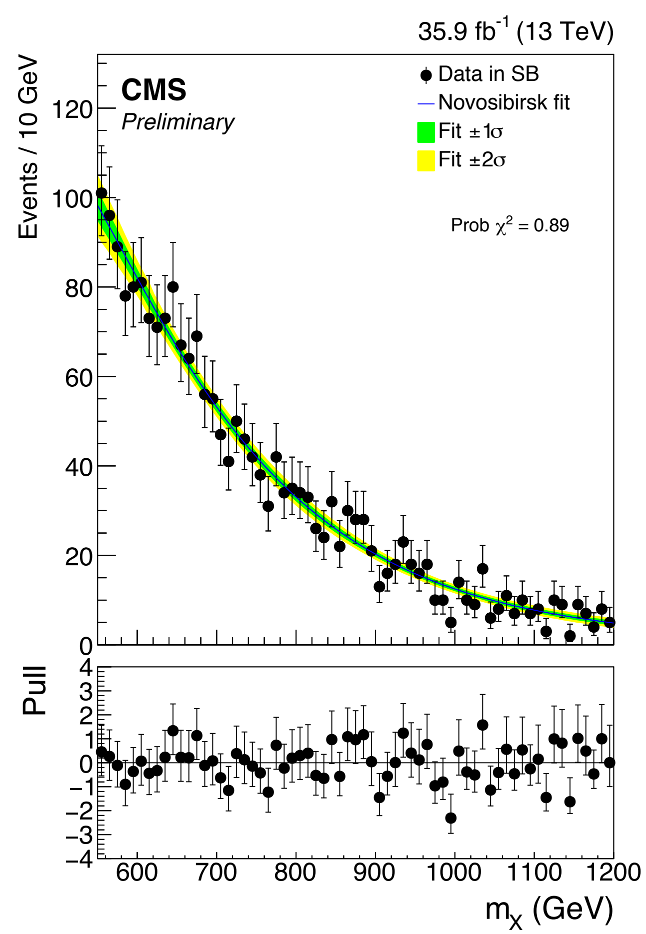


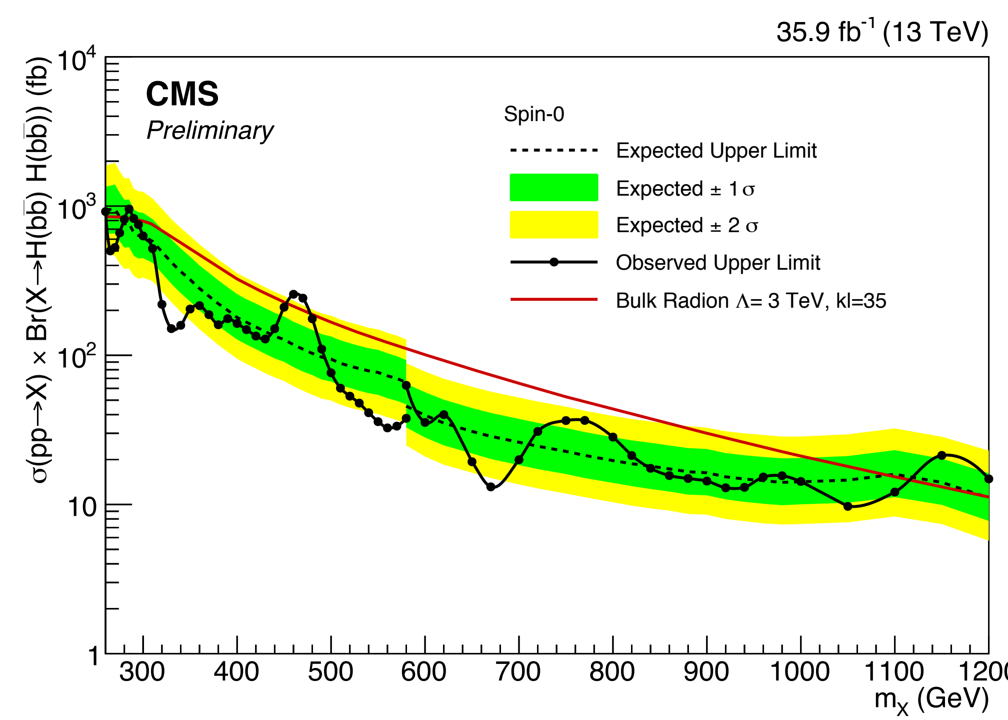
- QCD multijet background in SB (mass and b-tag reverted cuts)
  - →ABDC method

- Kin. fit to m(hh) spectrum

- B-tagging scale factors are the leading syst. uncertainty

- Limits on spin 0 & 2 resonances

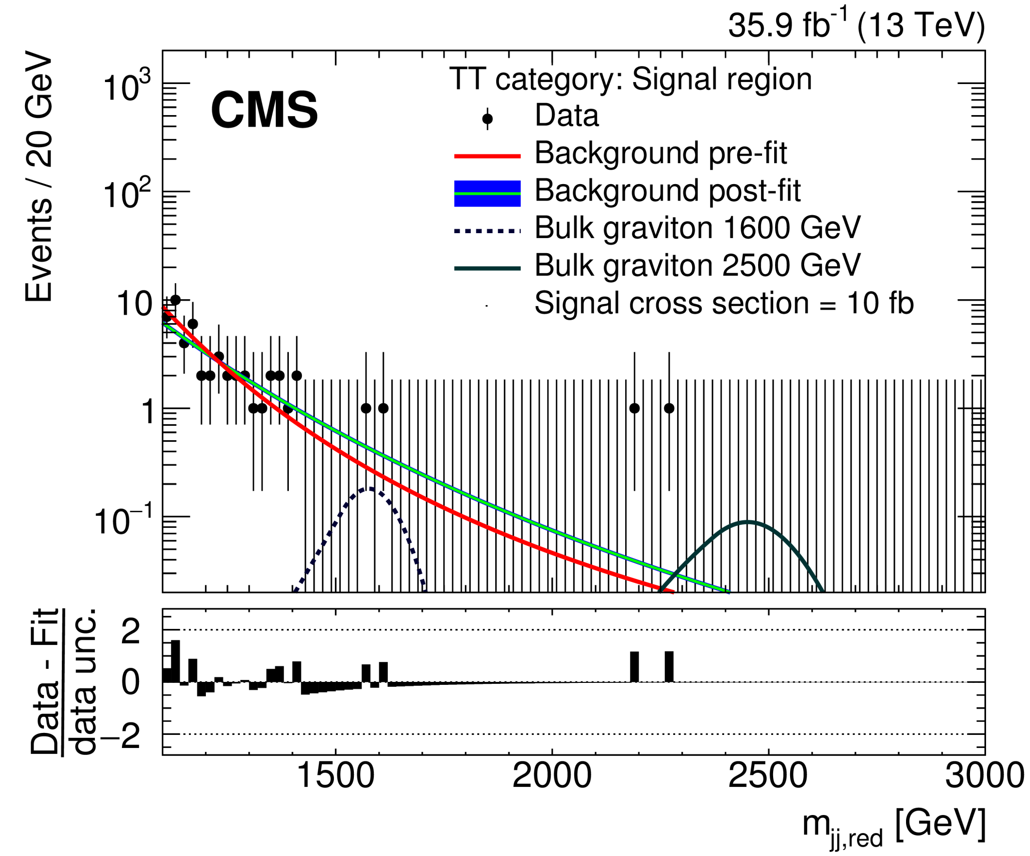


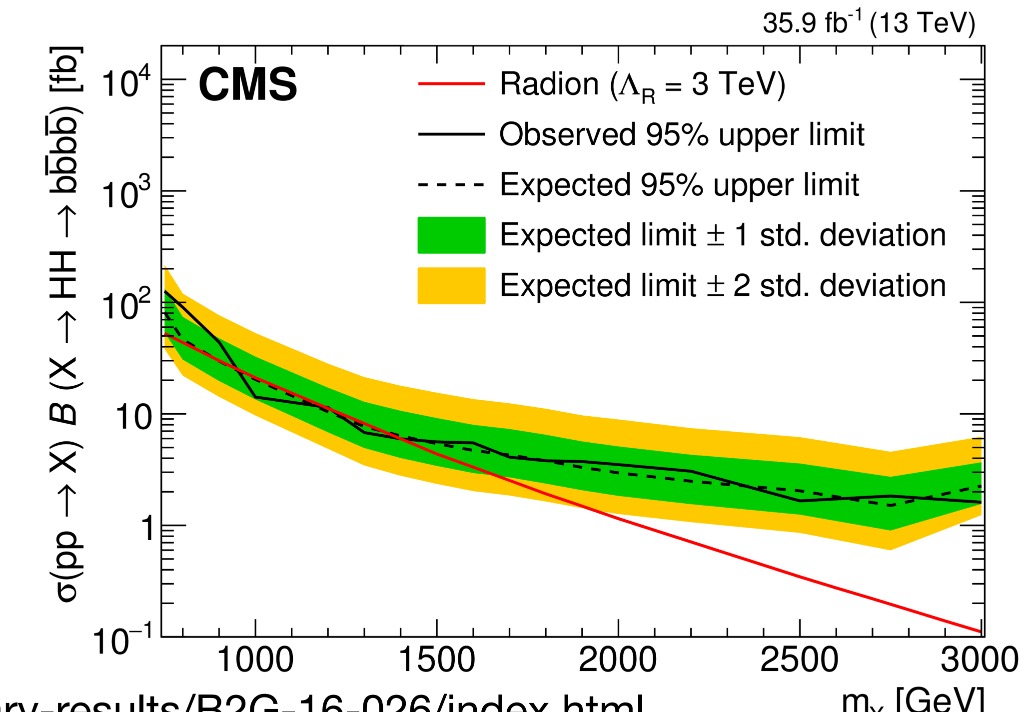


http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/HIG-17-009/index.html

H → hh → bbbb (boosted)

- Starting from M_X ~ 800 GeV
  - → 2 jets (R=0.8; double-b tagging)
  - → Jet is groomed to remove soft and wide-angle radiation (soft-drop algorithm)
  - → Soft-drop jet mass peaks at the H mass for signal events and reduces the mass of background quark- and gluon-initiated jets
- Reduced mass for signal extraction:
  - → $M_{red} = m_{JJ} - (m_{J_1} - m_H) - (m_{J_2} - m_H)$
- Background distribution falls monotonically
  - → Normalized by simultaneous fit CR and SR
  - → Signal modeled by a Gaus. and a Crystal Ball
- Limits on spin 0 & 2 resonances



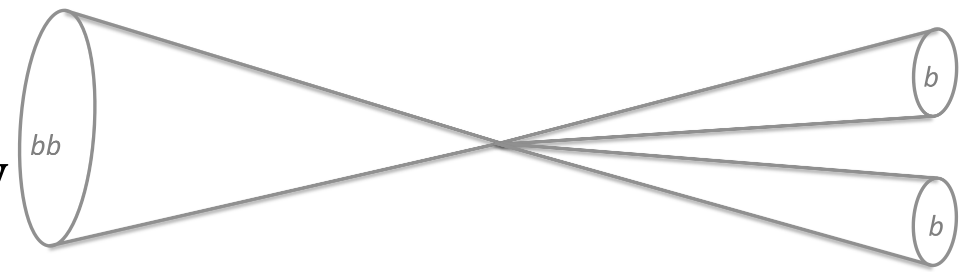


http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/B2G-16-026/index.html

H → hh → bbbb (semi-resolved)

One AK8 jet

- p_T > 300 GeV, $|\eta|$ < 2.4, tight ID
- Double b-tagger > 0.3 (loose)
- 105 < Softdrop mass < 135 GeV
- Puppi τ_{21} < 0.55 (loose)



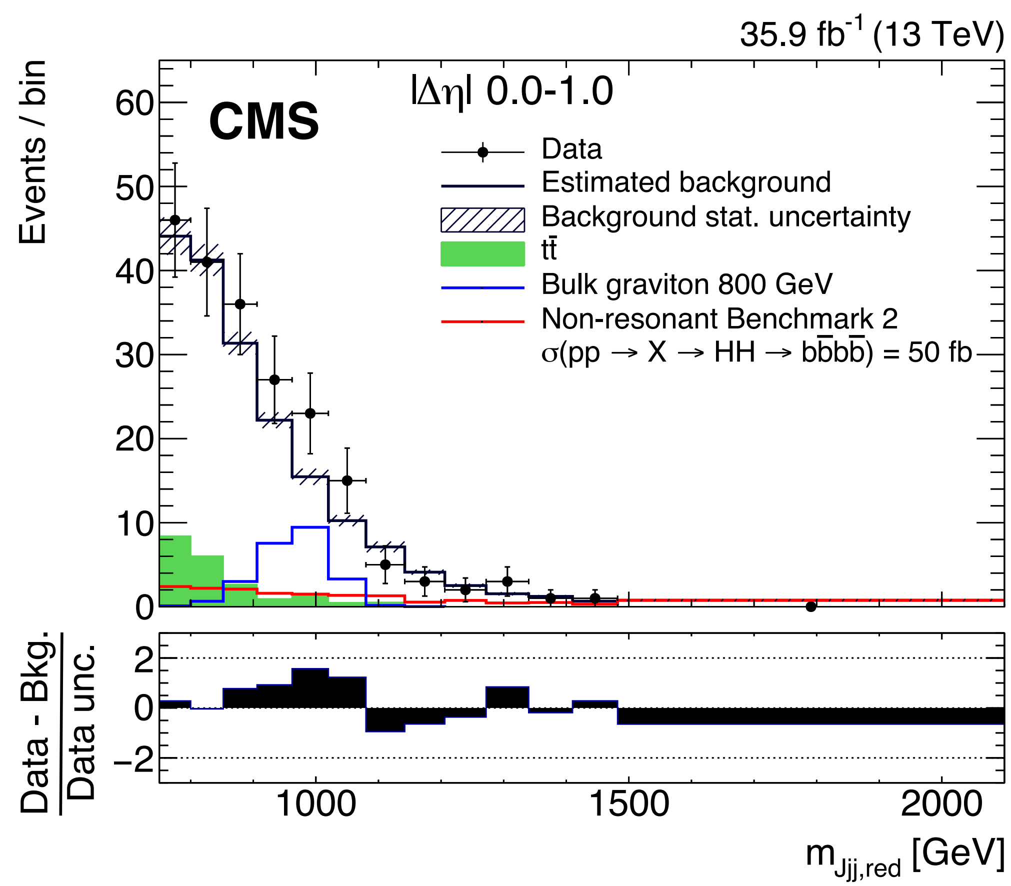
Two AK4 jets

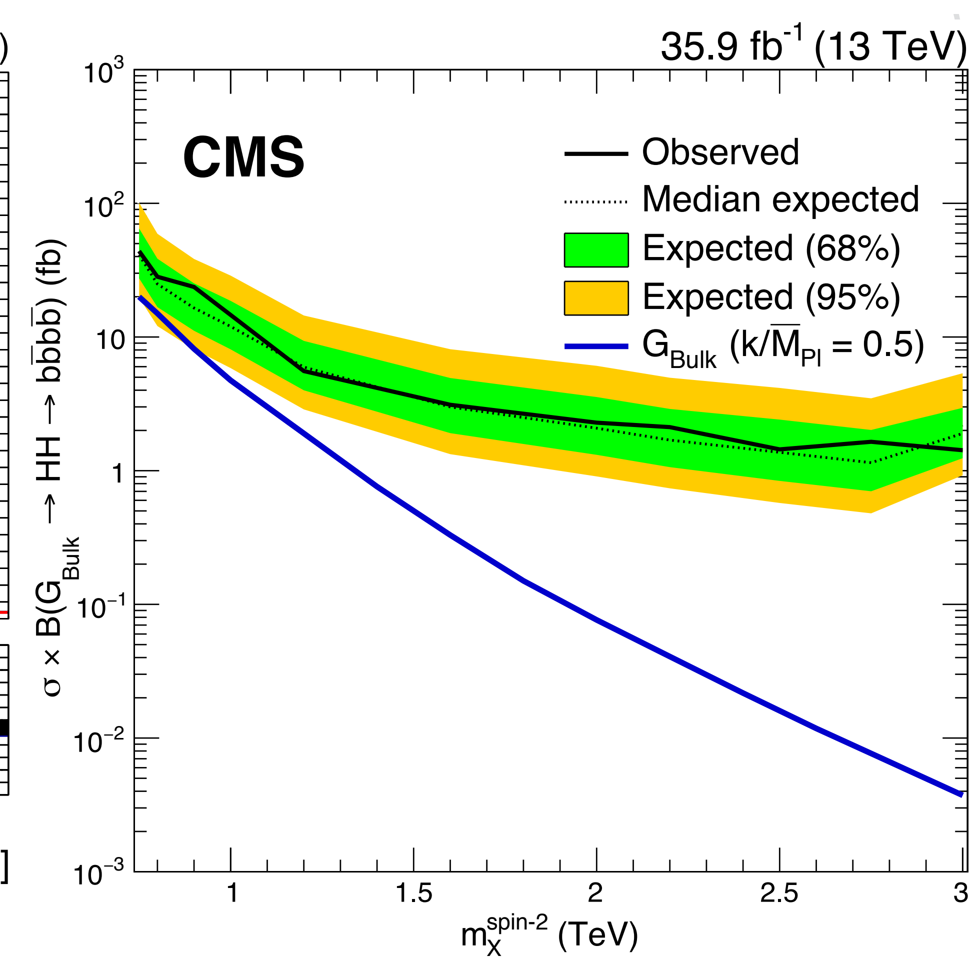
- p_T > 30 GeV, $|\eta|$ < 2.4
- Outside of AK8 jet cone, $\Delta R(j1, j2)$ < 1.5
- Deep CSV > 0.6632 (medium)
- 90 < Dijet mass < 135
- (j1+j2+nearest unselected AK4).M() > 200 GeV

❖ Lepton veto + selection based on $\Delta\eta$ and $M_{Jjj_{red}} = m_{Jjj} - (m_J - m_H) - (m_{j1+j2} - m_H)$

❖ Main background QCD (and tt which is ~10%)

❖ Limits on spin 0 & 2 resonances

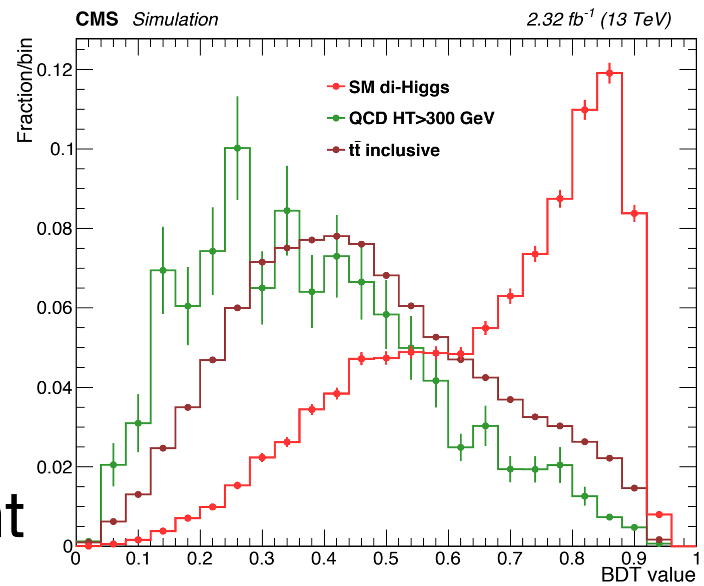


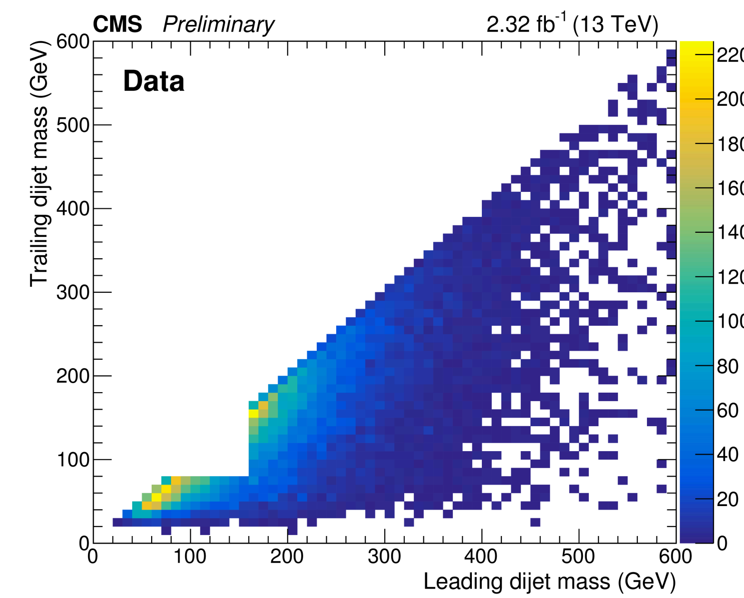


B2G-17-019

hh → bbbb

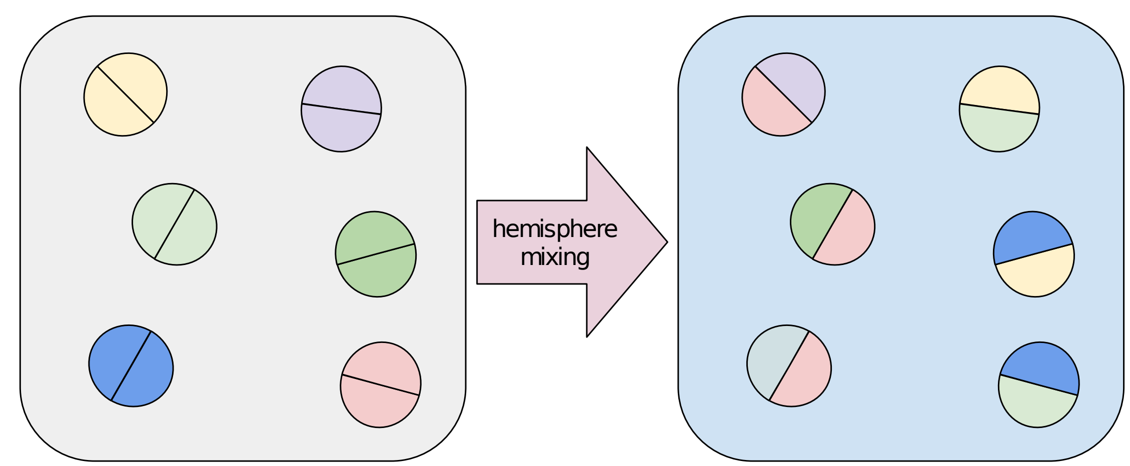
- b-pairs are resolved
  - → 0.4 anti-kt PFjets
  - → CSV algorithm





- Selection based on kinematic
  - → Pair of b-jets by trying comb
  - → BDT separate S and B (xgboost)
    - → An improved version of gradient descending

- Accurate bkg modeling is fundamental!
  - → Hemisphere mixing technique (fully data-driven)
  - → Multijet events: result of 2 to 2 parton-parton scattering, plus ”second order” effects
  - → Divide data events in two hemispheres
  - → Create new events from combination of those hemispheres
  - → Mixed events insensitive to small signal



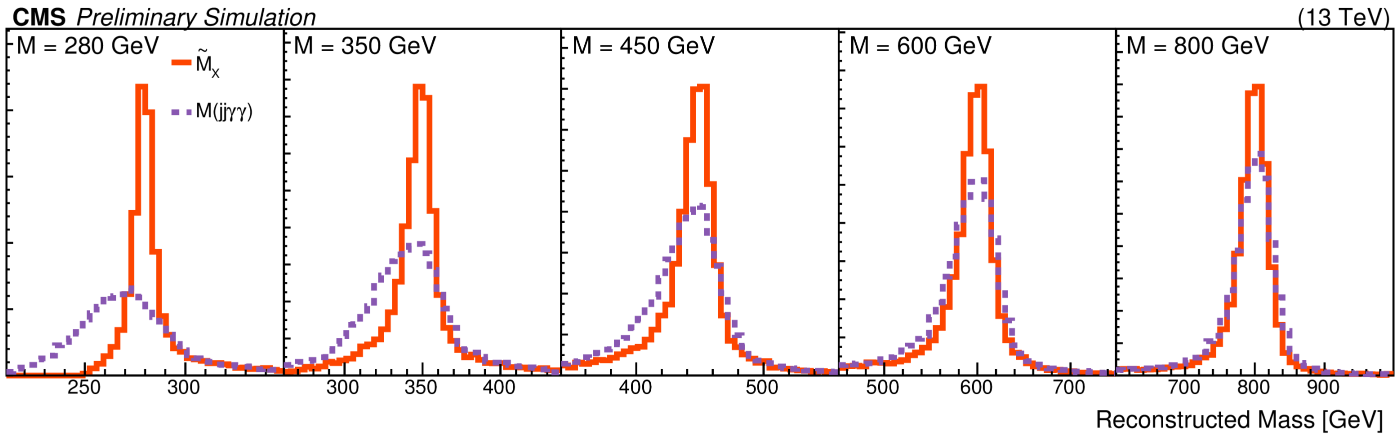
Original dataset: bkgs and potentially a small signal fraction

Mixed dataset: new composed event that represent bkg-only

http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/HIG-16-026/index.html

(H →) hh → bbγγ

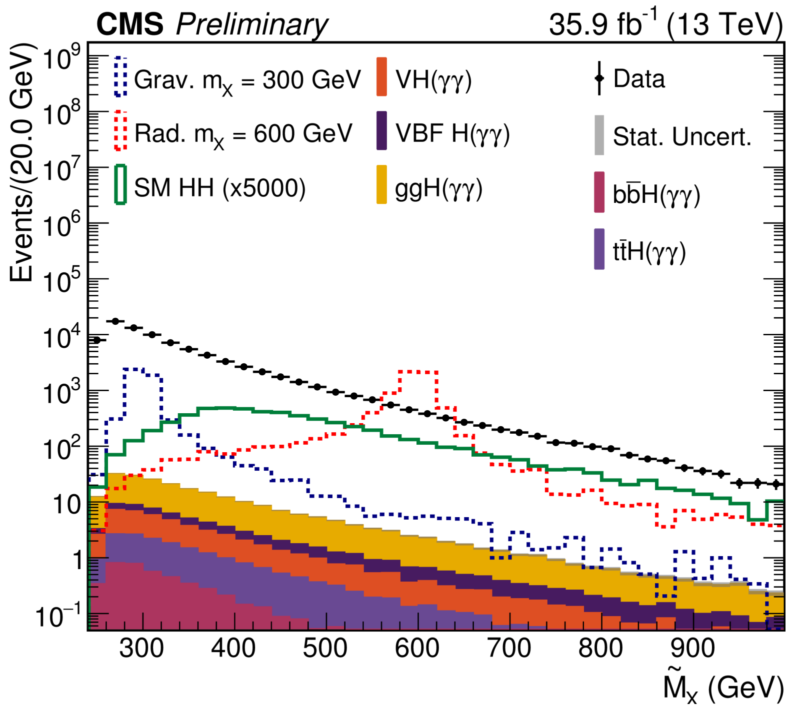
- Resonant and non resonant production
  - → 2 photons, 2 tagged b-jets
  - → M_X= m(jjγγ) – m(jj) - m(γγ) + 250 GeV
  - → Categories in M_X and BDT output

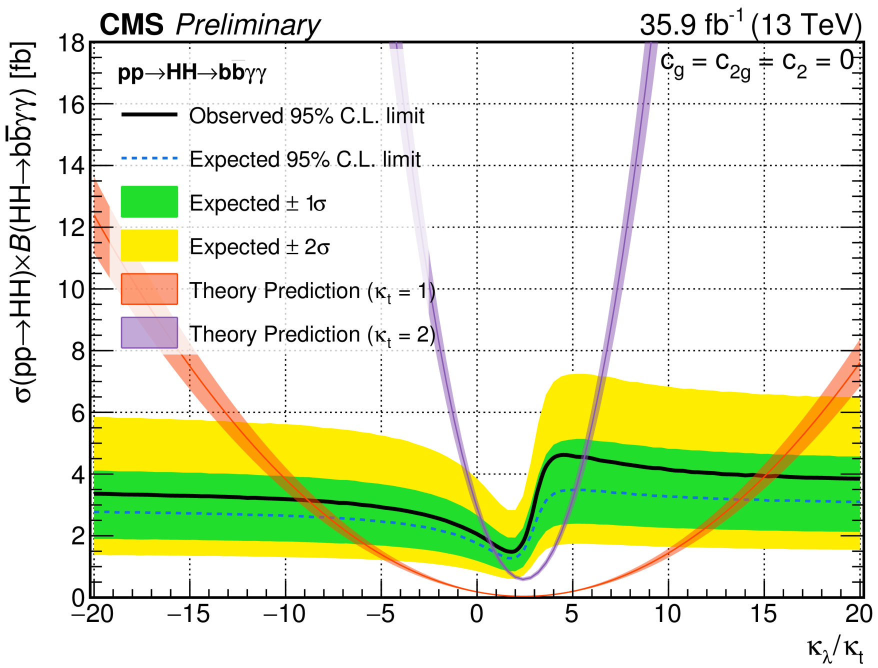


- Background:
  - → Multi-jet + photons, fake photons (polynomials in the Bernstein basis)
  - → SM Higgs (from MC)

- 2D parametric fit on $m_{\gamma\gamma}$ vs m_{jj}

- Non resonant:
  - → Low σ·Br from SM: 1.67 fb
  - → Obs (exp): σ/σ_{SM}<19.2 (16.5)





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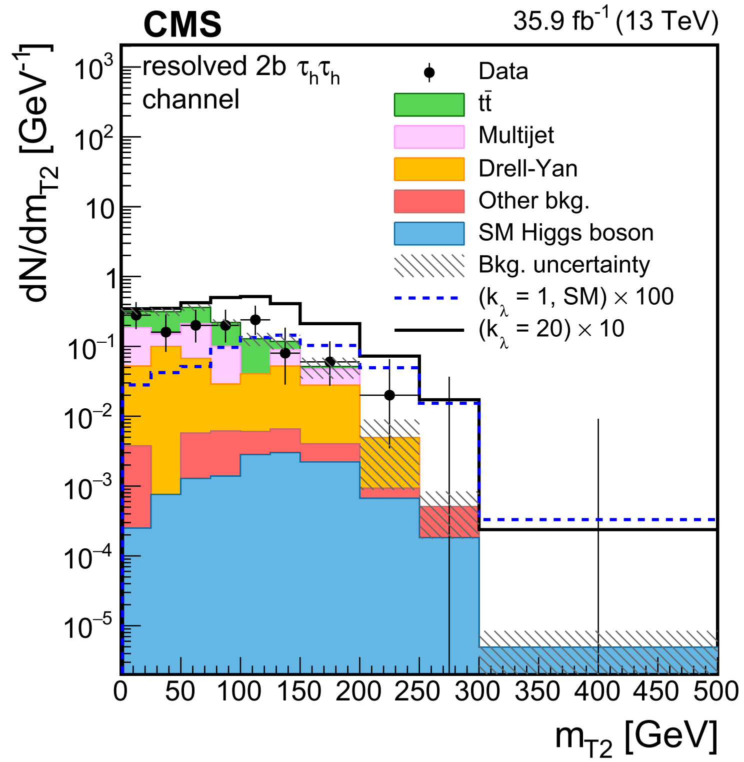
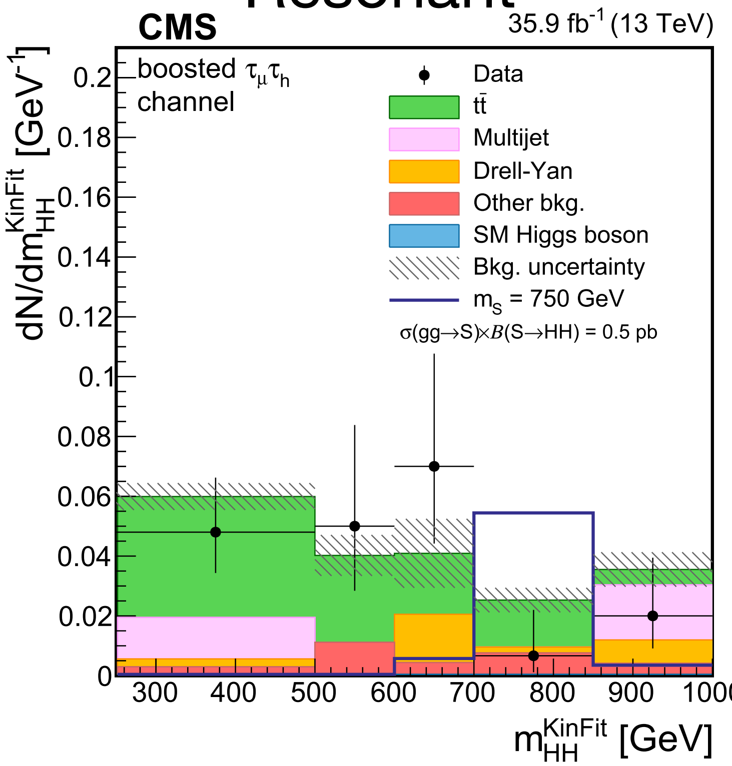
(H →) hh → bbττ

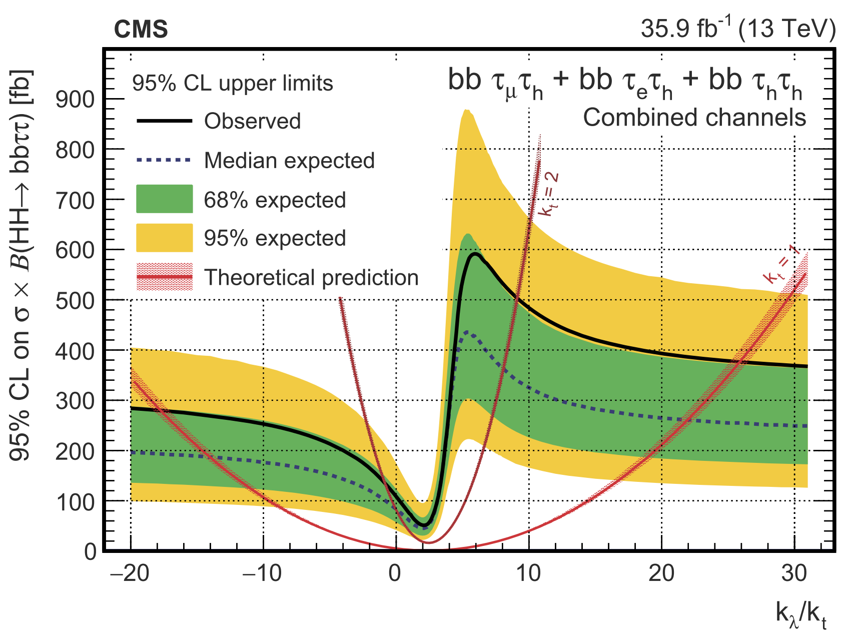
- 3 channels:
  - → $\tau_h\tau_h$, $\tau_h\tau_\mu$, $\tau_h\tau_e$
  - → Kinematic fit to m(ττ)
  - → 2 jets with R=0.4
- Resolved:
  - → b-tag: 2b, 1b1j
  - → Elliptical m(ττ) vs M(jj) area
- Boosted
  - → 1 Jet (R=0.8), Sub-jet tagging
  - → Rectangular m(ττ)-M(jj) selection
- Backgrounds
  - → QCD (data-driven)
  - → tt, Z+jet: MC

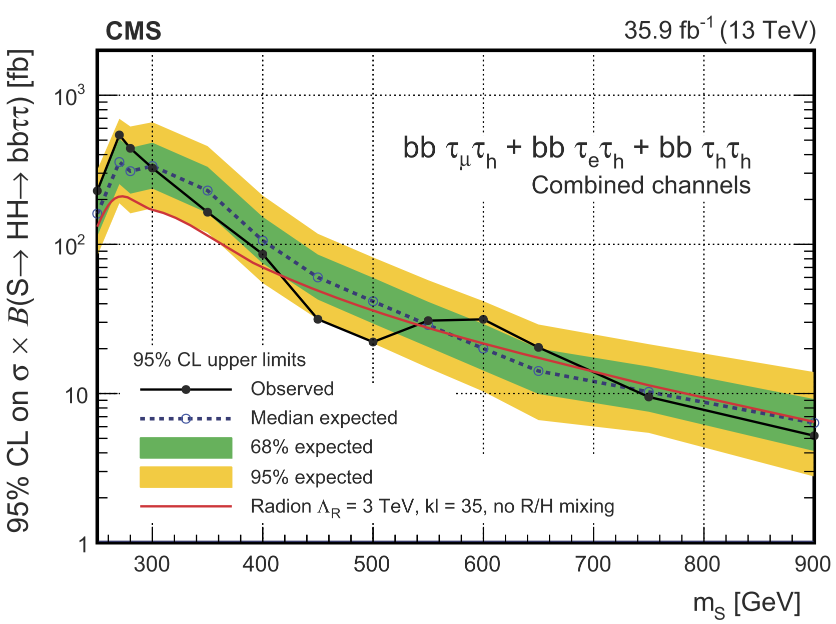
Non-Resonant



Resonant







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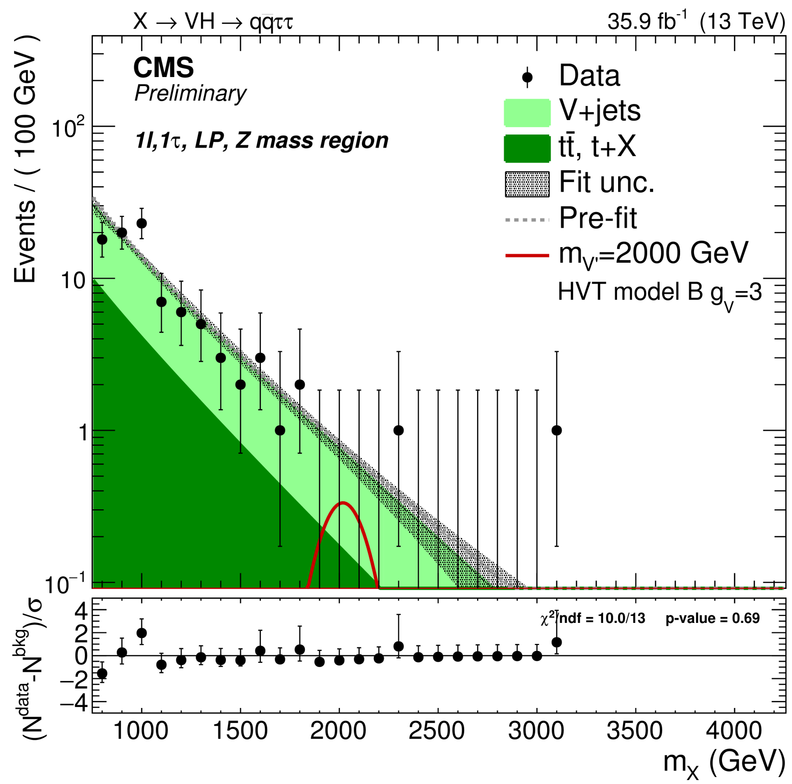
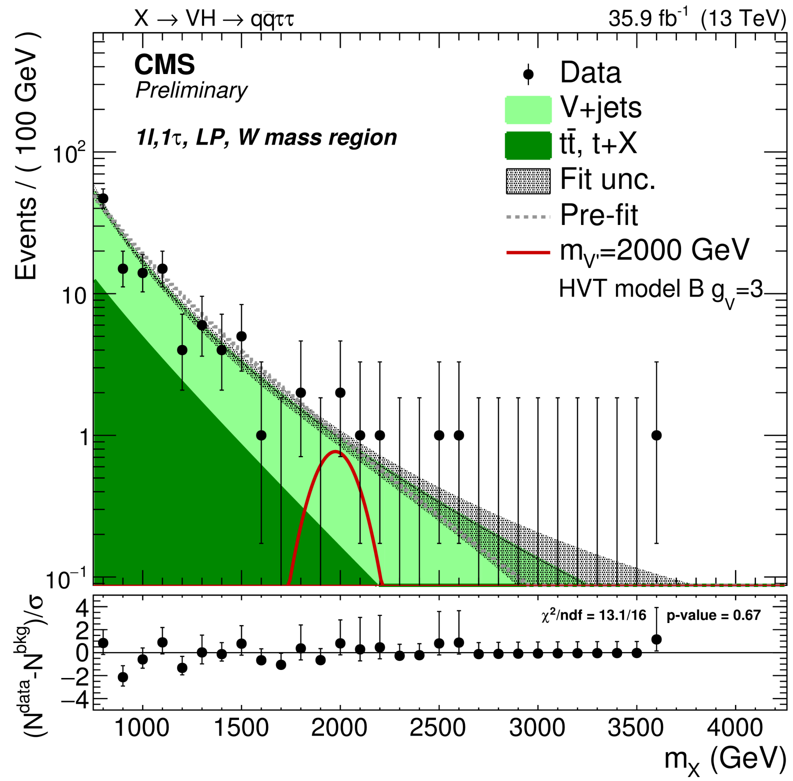
H → Vh → qqττ / H → hh → bbττ

- Substructure techniques

$$\tau_N = \frac{1}{d_0}\sum_k p_{T,k} min(\Delta R_{1,k}, \Delta R_{2,k}, \ldots, \Delta R_{N,k}).$$

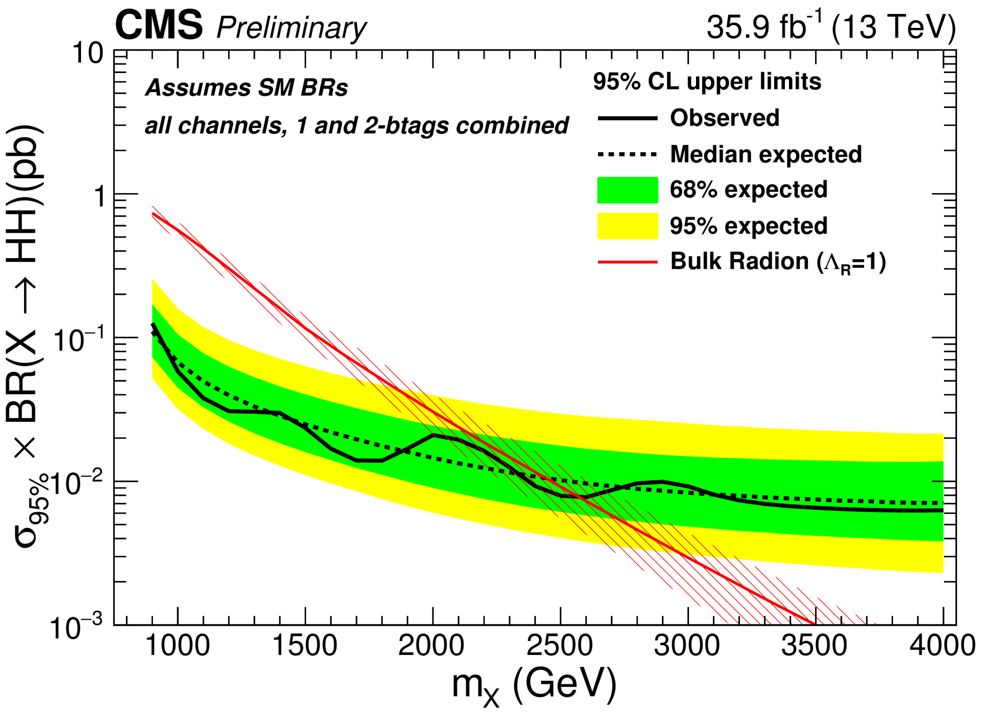
- Final state/selection:
  - → h to τ_h/τ_h, $\tau_\mu\tau_h$, $\tau_e\tau_h$
  - → m_{softd}(jj) ϵ [105-135] GeV
  - → m(ττ) from kin. fit
  - → Categories based on $\#\tau_h$, τ_{12} and b-tag jets
  - → No τ_{12} cut if b-jets are present





- Background:
  - → tt, t+X:
    - Shape from simulation
    - Normalization from a CR
  - → V+jets
    - Shape from m(jj) sidebands correct for MC
    - Normalization from fit to m(jj) distribution

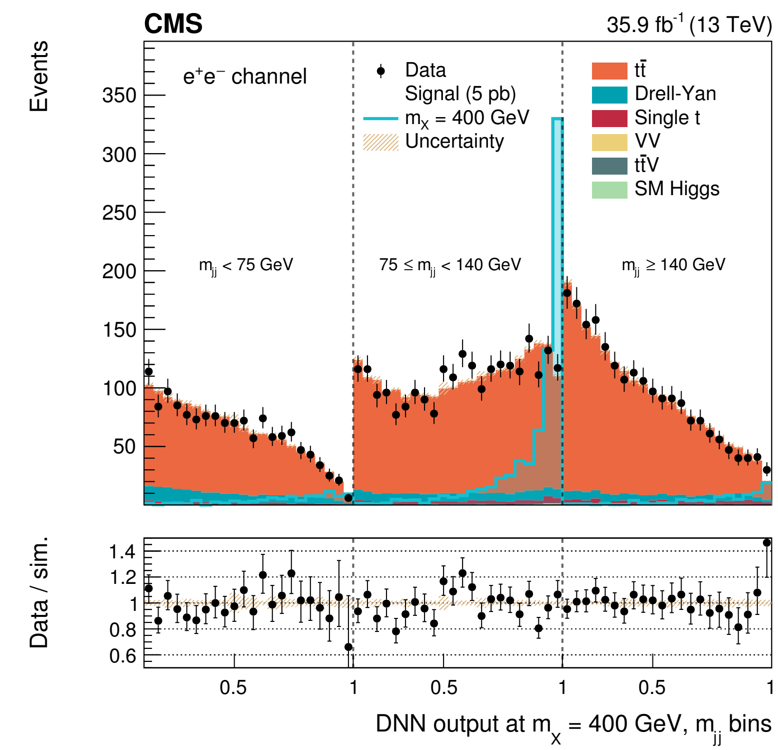
$$\alpha(m_X) = \frac{N_{SR}^{MC,bkg}(m_X)}{N_{SB}^{MC,bkg}(m_X)}$$

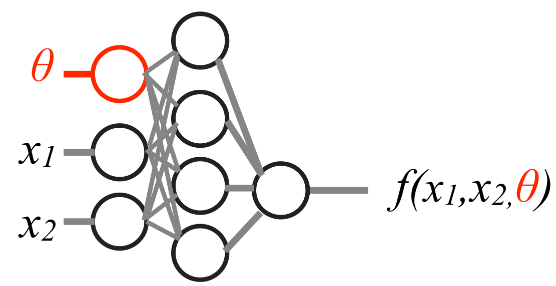


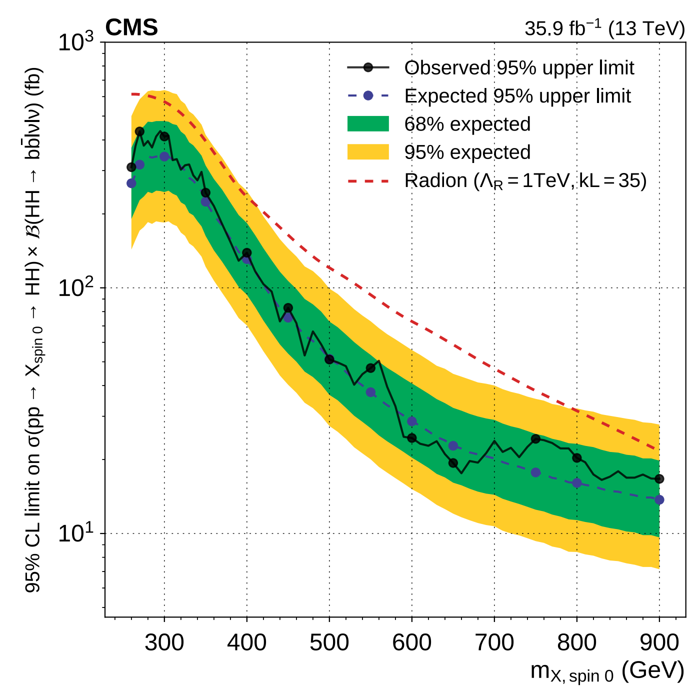
http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/B2G-17-006/index.html

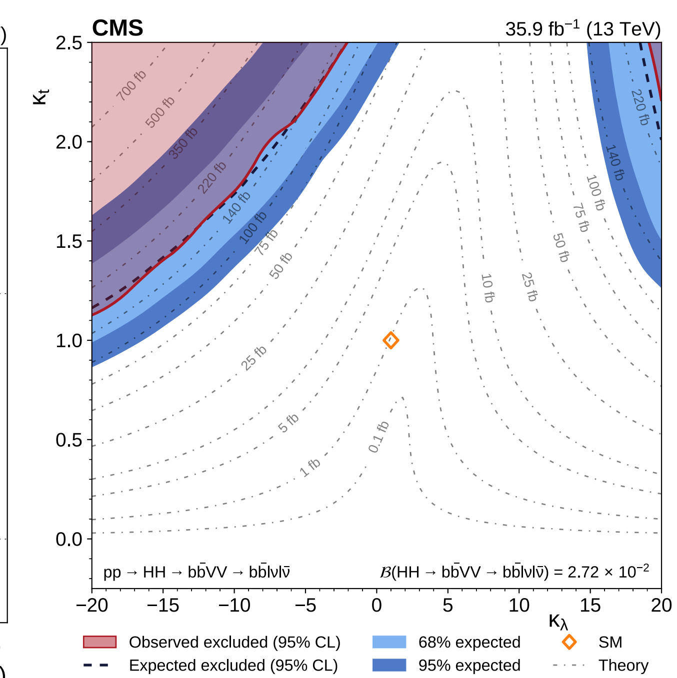
(H →) hh → bbWW

- 2 OS leptons and 2 b-jets
  - → Background: tt (MC) and DY (from data enriched with DY+jets)
  - → Loose kin. selection, DNN will do the rest
- Parametric training of the DNN will compensate shortcomings arising from:
  - → Train with single mass point and apply the training to all masses
  - → Train a mix of unlabelled mass points
- Three m_{jj} bins, limits derived on the DNN output shape
- Largest syst. uncertainty on tt normalization
- Potential room for improvements?
  - → Bringing HME into the game!









https://link.springer.com/article/10.1007%2FJHEP01%282018%29054

Bonus: Heavy Mass Estimator

- To explain the method… let's make some initial assumption:
  - → All visible variables are perfectly measured (no pileup)
  - → Both SM Higgs bosons on-shell
  - → At least one of two W bosons off-shell ("1" marks the on-shell one: $W_1 \rightarrow \mu_1 \nu_1$)

- Under the above assumptions, kinematics described by:

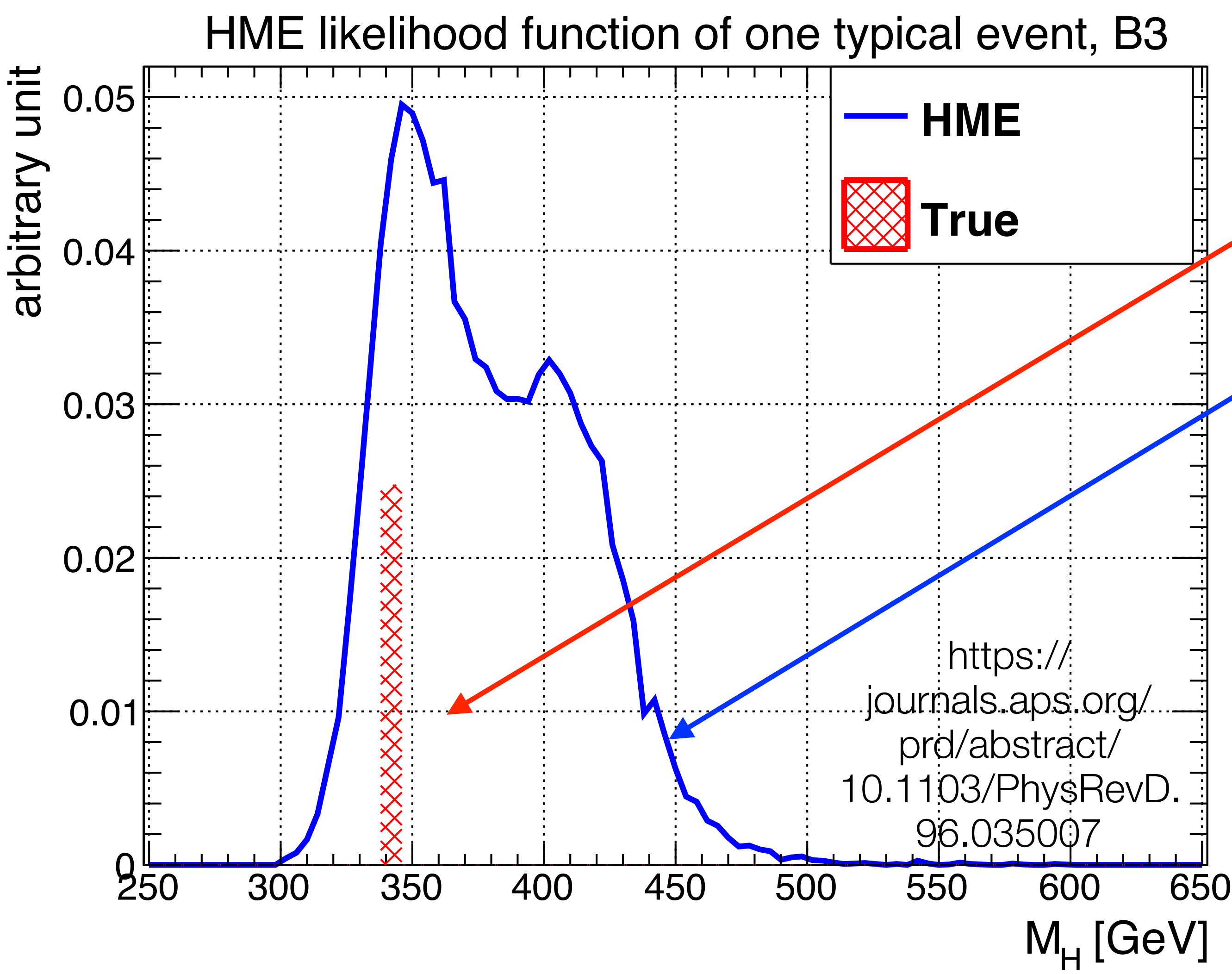
$$\not{E}_{Tx} = p_x(\nu_1) + p_x(\nu_2)$$
$$\not{E}_{Ty} = p_y(\nu_1) + p_y(\nu_2)$$
$$\sqrt{p_4^2(\ell_1, \nu_1)} = M_W, 20 < \sqrt{p_4^2(\ell_2, \nu_2)} < 45 \text{ GeV}$$
$$(p_4(\ell_1) + p_4(\ell_2) + p_4(\nu_1) + p_4(\nu_2))^2 = M_h^2$$

- The momentum of each neutrino described by 3 unknown parameters: 6 unknowns
  - → 4 constraints could reduce the number of unknowns to two
  - → We randomly generate the two unknowns: η and ϕ of one neutrino
  - → We solve the system
  - → A single generation of the two unknowns is called one iteration, and, if the equations admit solution, it produces a MMC value (the estimator for M_H value)

https://journals.aps.org/prd/abstract/10.1103/PhysRevD.96.035007

Bonus: Heavy Mass Estimator

- Produced large amount of iterations, the η and ϕ of neutrino, according to probability density function from simulation
- To include resolution effects in MMC, correction on jets and E_T^{miss} are applied with constraint that invariant mass of two jets equals to m(h). In addition, the higgs boson mass and W boson mass used in MMC are generated according to gaussian function to take care of intrinsic width of H and W boson respectively.



True M_H value

Each MMC iteration produce a value that fill this distribution (Y axis value corresponding to maximum is the MMC probability)

The maximum of the distribution estimates the true M_H value

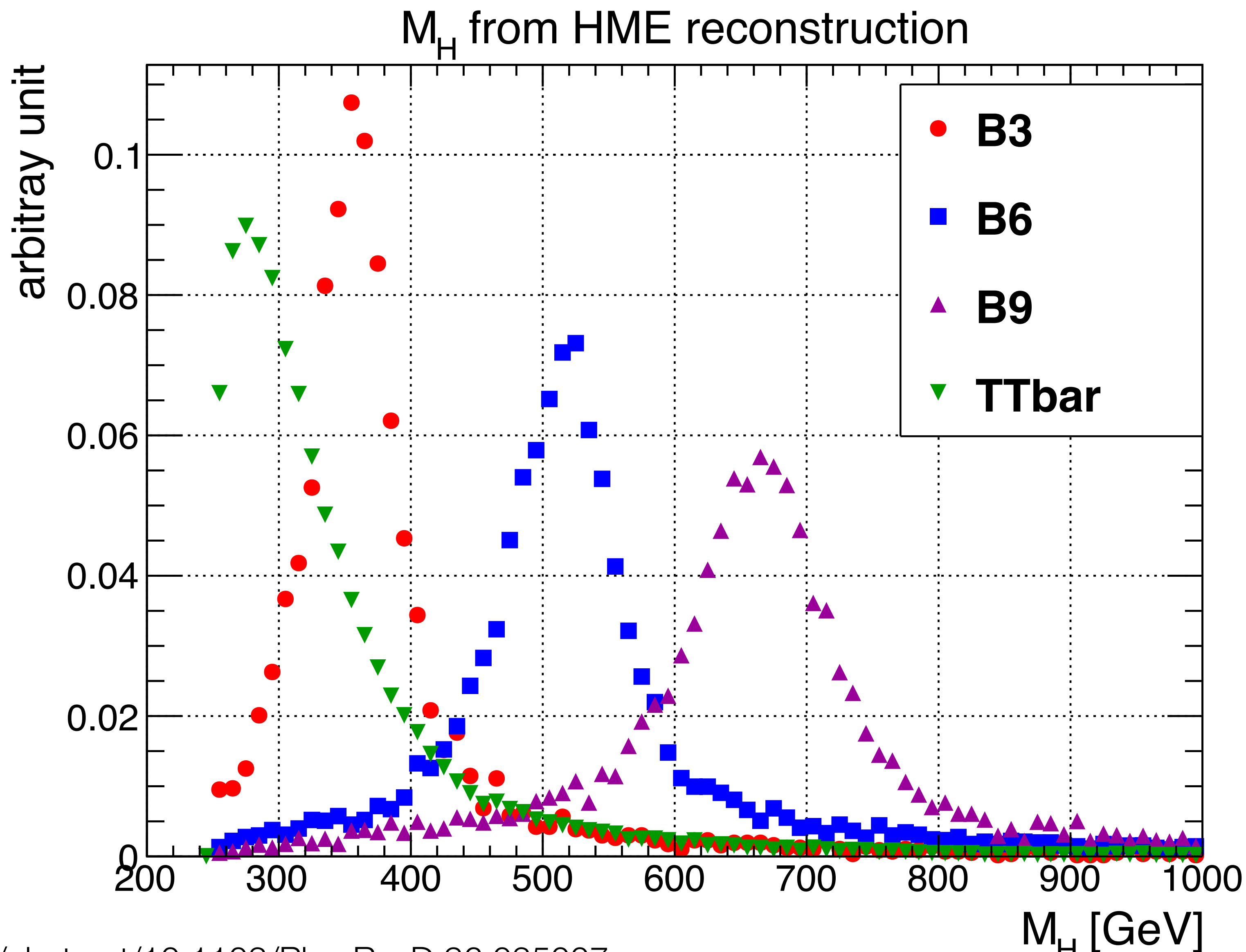
Bonus: Heavy Mass Estimator

- The maximum of the MMC likelihood if the MMC value fore each event

- The final MMC distribution has a resolution that depends on the mass point

- In the case of tt MMC impose unnatural kinematic condition:
  → Equations have no solution
  → MMC value peak below tt mass

- MMC mass in the final discriminating variable we use to derive limits



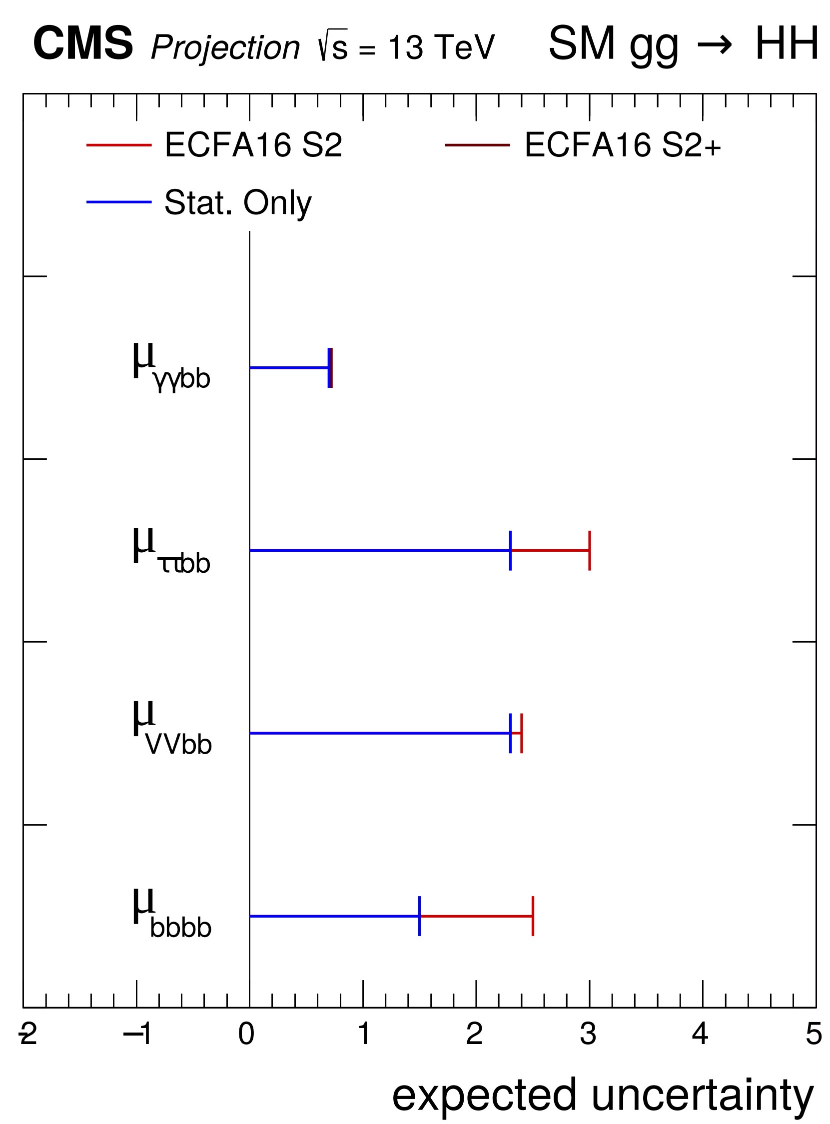
https://journals.aps.org/prd/abstract/10.1103/PhysRevD.96.035007

Conclusions

- Program of dedicated searches for non-standard decays of the Higgs boson ongoing
  → Room for BSM Higgs boson decays
  → Signatures motivated by broad range of phenomenology

- Fundamental to provide a simple way to reinterpret CMS results (e.g. model independent limits)

- HH crucial during High Luminosity:
  → Right: projection fo the sensitivity to gg → HH with 3 ab^{-1} assuming theory syst. reduced by 2 (based on 2015 results)



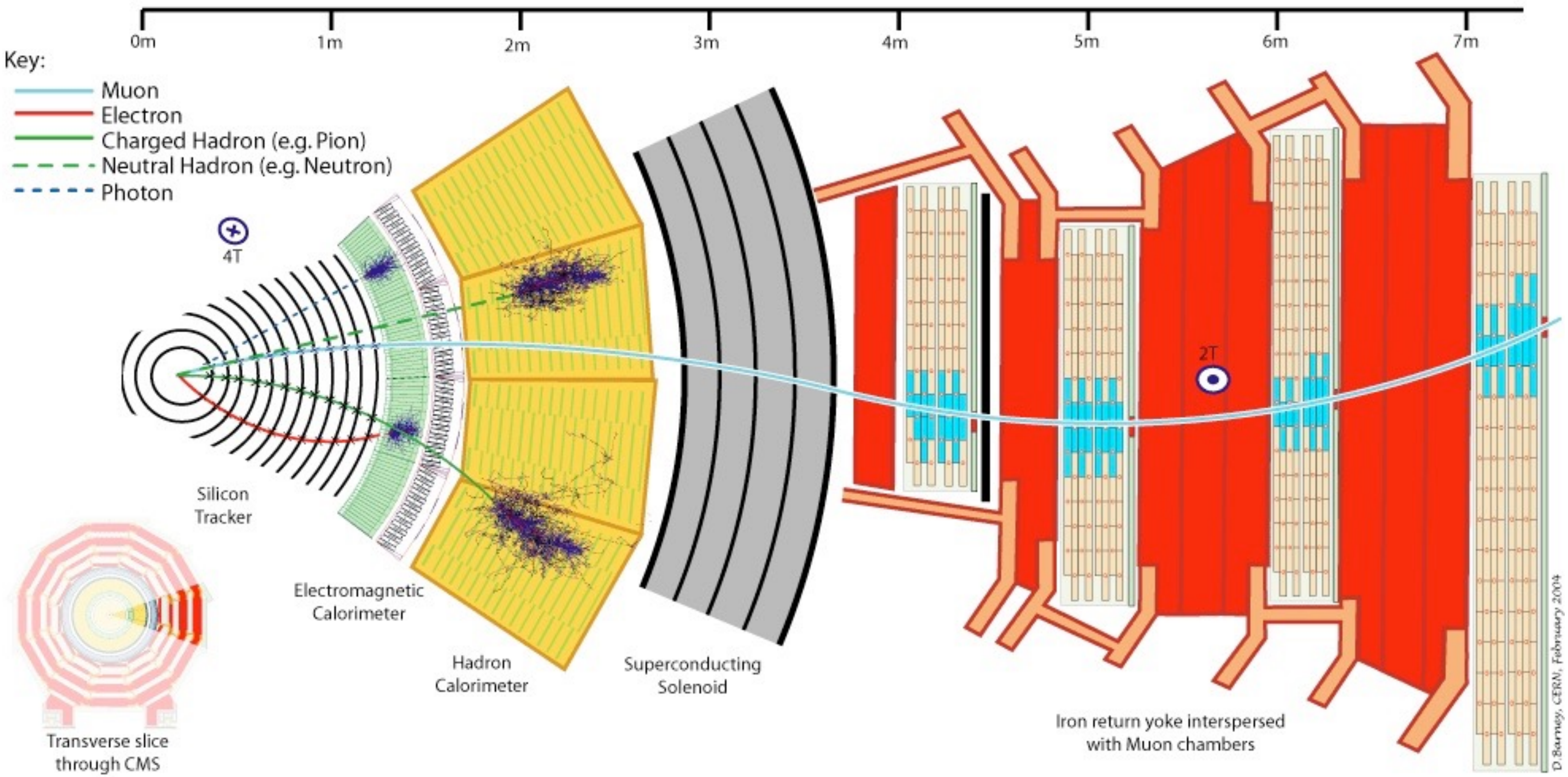
https://cds.cern.ch/record/2266165?ln=en

- It is NOT just redoing analysis with more statistic!
  → Carefully explore all phase space (resolved, boosted, semi-boosted…)
  → Novel techniques application (parametric learning, HME…)

- Exciting times ahead of us!

Backup

The Compact Muon Solenoid



Extending the Higgs sector

❖ Higgs sector could be extended in many ways.

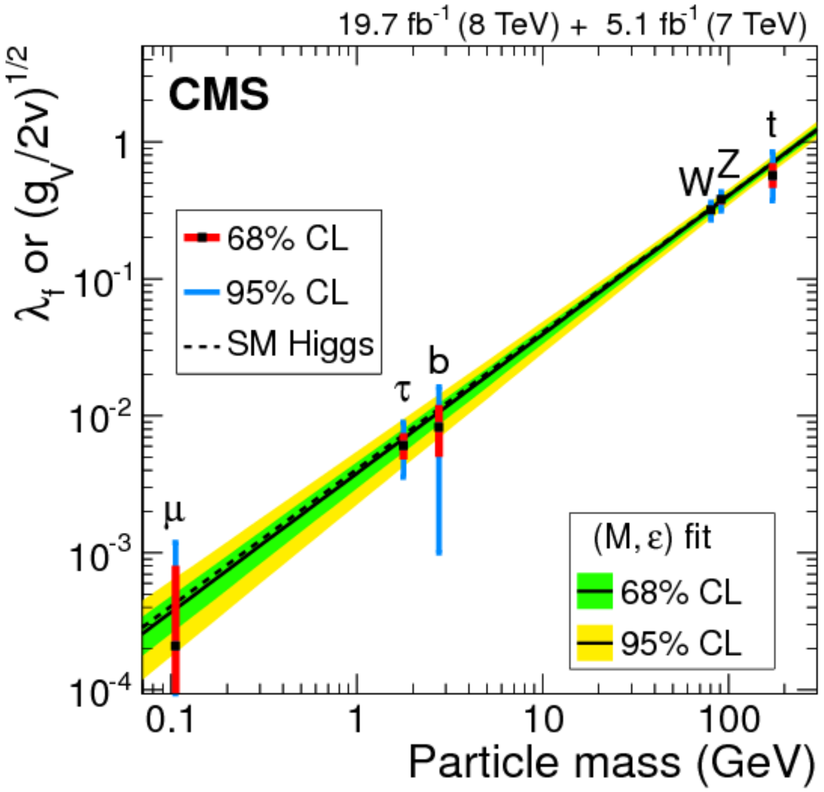
Model	Description	Higgs bosons
SM (one doublet of complex scalar fields)	3 d.o.f. give mass to $W^{\pm}$ and Z, Yukawa couplings generate fermion mass	h
SM + real singlet	Used in the context of EWK baryogenesis, DM…	h, H
2HDM (contains a second doublet)	Prerequisite for SUSY, natural in GUT, DM originating from 2HDM	h, H, A, $H^{\pm}$
2HDM + complex singlet (e.g. NMSSM)	Solve the mu-problem in MSSM (where H(125) is unnaturally heavy)	h_1, h_2, h_3, a_1, a_2, $H^{\pm}$
SM + triplet	Natural explanation for small neutrino masses	h, H, A, $H^{\pm}$, $H^{\pm\pm}$

❖ Plus: many other exotic models…

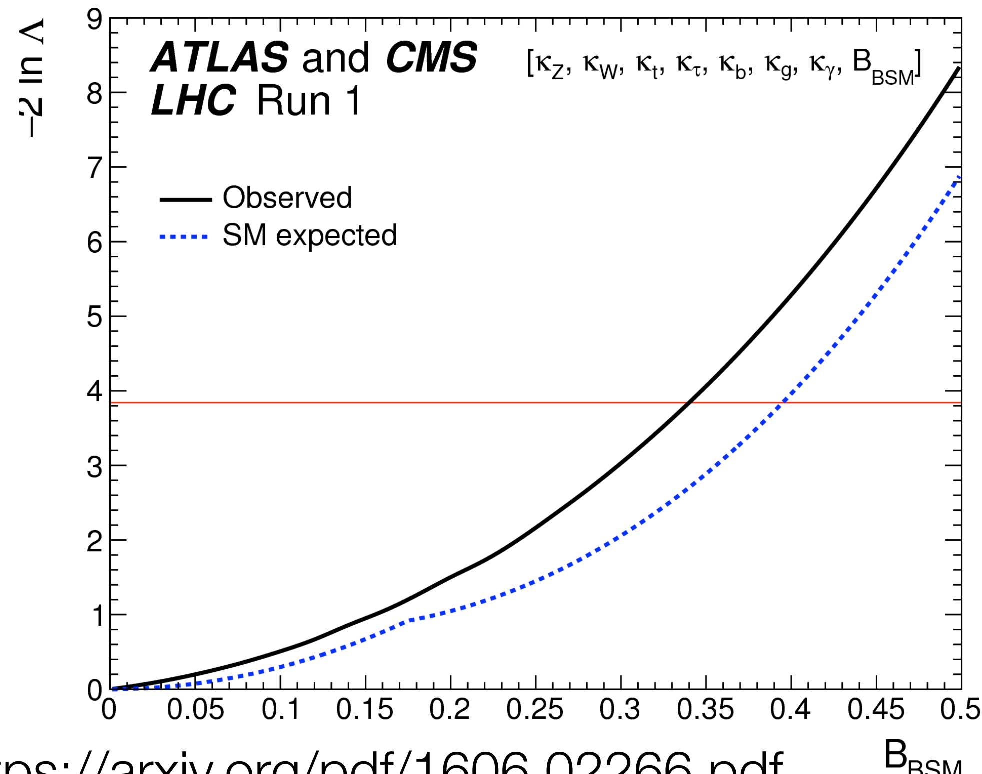
What do we know about SM Higgs?

- Higgs-like particle has been observed:
  - → $m_H = 125.09 \pm 0.21(\text{stat}) \pm 0.11(\text{syst})$
  - → $\Gamma_H < 26$ MeV (for $f_{\Lambda Q}=0$ at the 95% CL.)
  - → $J^{PC} = 0^{++}$

  (https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG)

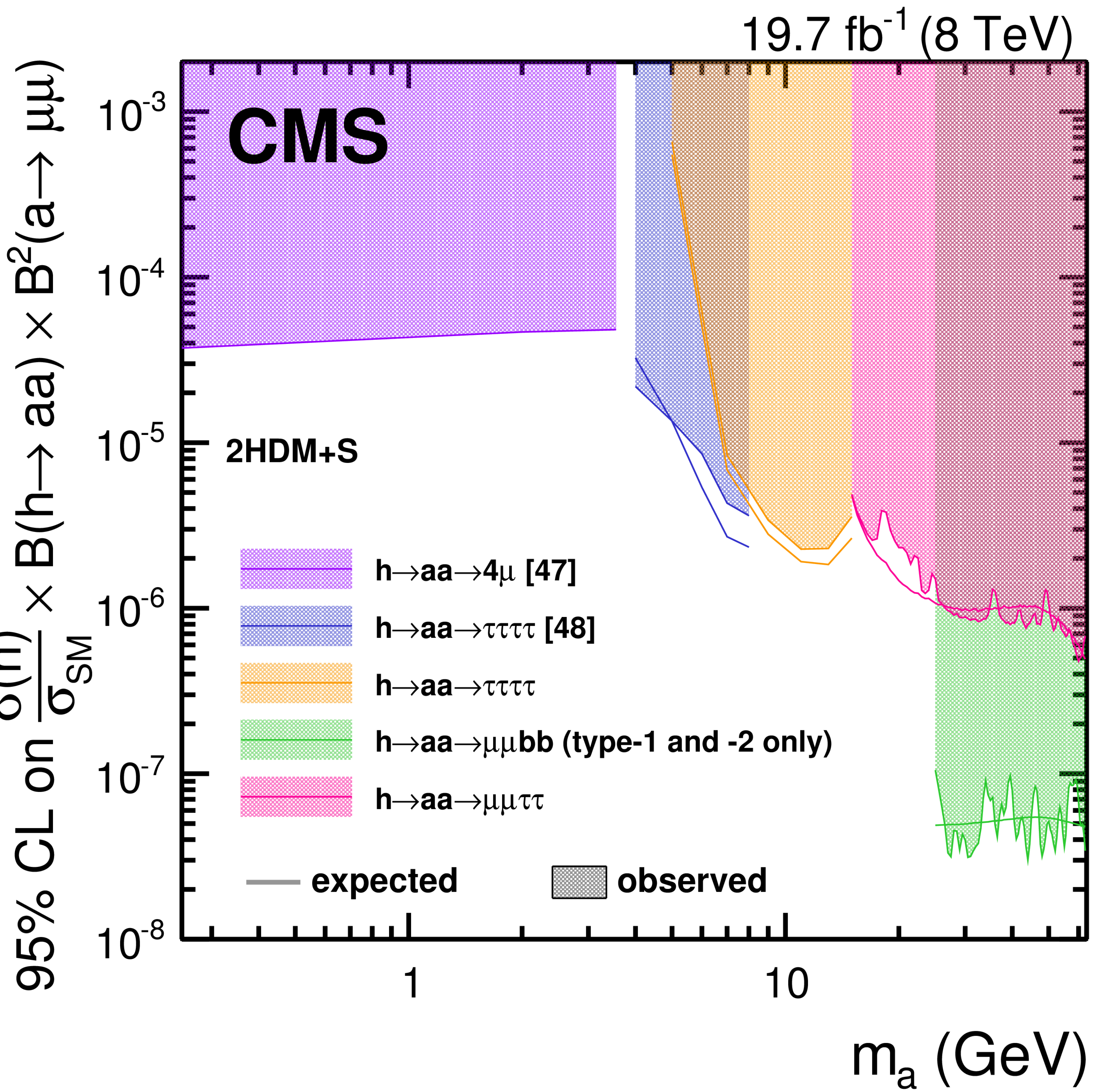


- No SUSY has been discovered so far, but:
  - → Still good to focus in naturalness
  - → General interest on sparticles with influence on quadratic term in Higgs potential
  - → See if newly found resonance is part of an extended Higgs sector is of primary importance!

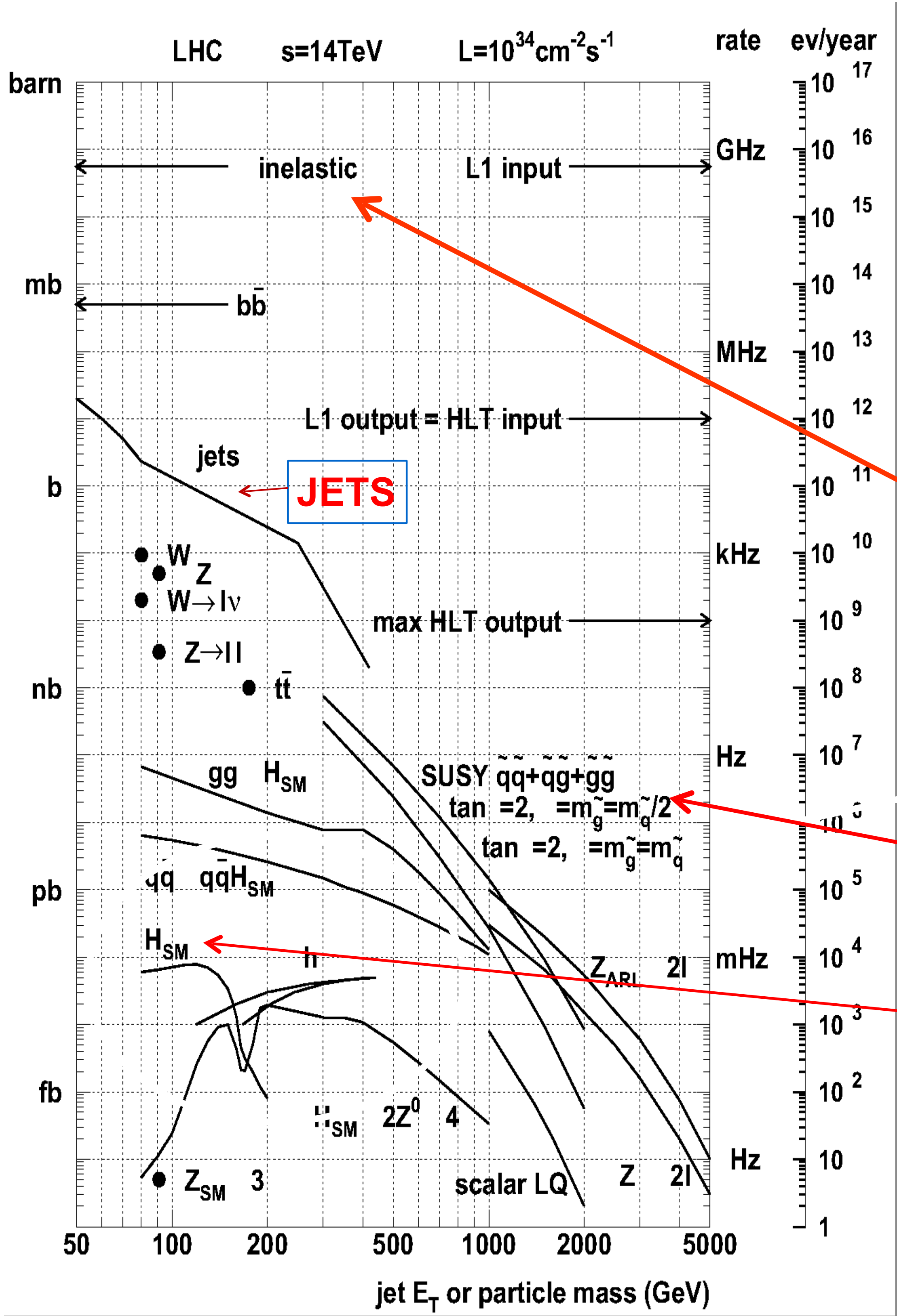


- Still room for BSM decay of Higgs boson:
  - → BR (h→BSM) < 34% at 95% CL

https://arxiv.org/pdf/1606.02266.pdf



19.7 fb-1 (8 TeV)
CMS
2HDM+S
95% CL on σ(h)/σSM × B(h→ aa) × B2(a→ μμ)
10-3
10-4
10-5
10-6
10-7
10-8
1
10
ma (GeV)
h→aa→4μ [47]
h→aa→ττττ [48]
h→aa→ττττ
h→aa→μμbb (type-1 and -2 only)
h→aa→μμττ
expected
observed



- Cross sections and background estimates (measured, calculated/predicted) tell us what minimum energy and luminosity we need from the colliding beams and therefore what rates the detector must be able to handle
- Production dynamics determine the range of energies and angles we need to measure

Inelastic "background" events produced at a rate of 1 GHz.

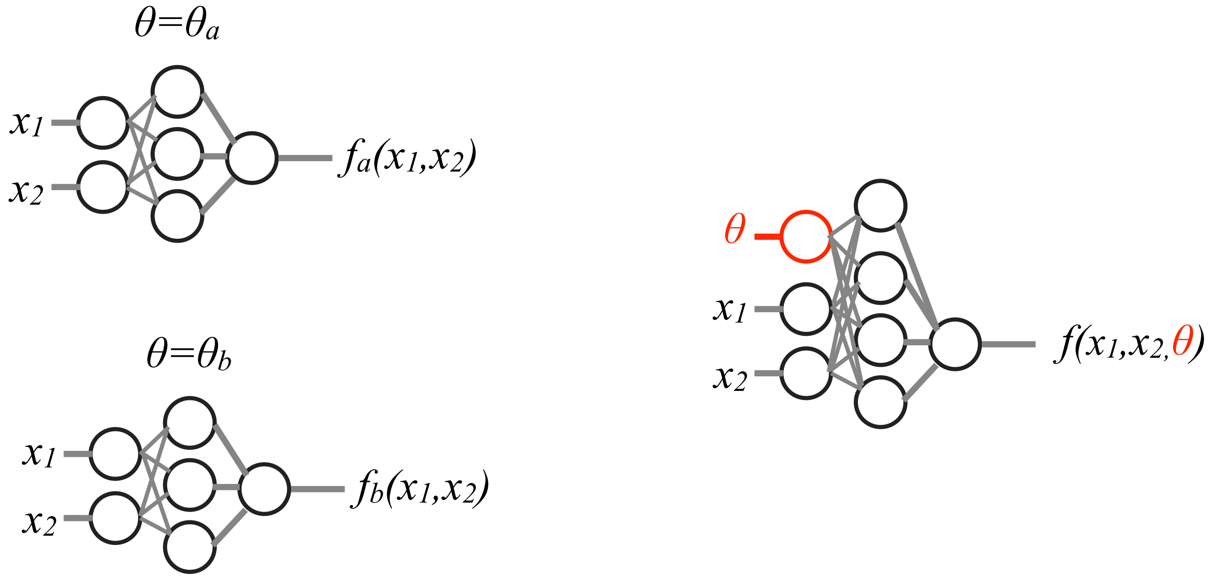
Supersymmetry ~ 1Hz

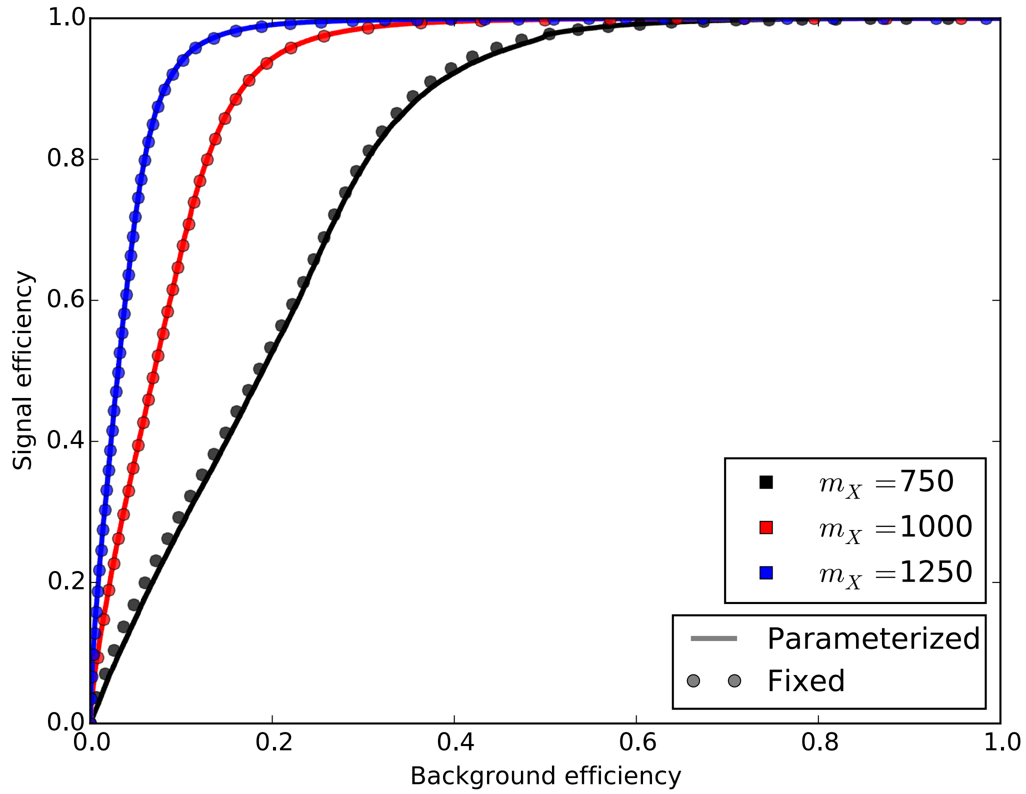
Detectable Higgs production ~ 1 milliHz

DNN: a novel approach

* https://link.springer.com/article/10.1007%2FJHEP01%282018%29054

- ❖ Parametric training of a Deep Neutral Network
  - → Used in CMS-PAS-HIG-17-006*
- ❖ Solve several common issue:
  - → Train a single mass point and apply DNN to all masses
  - → Train a mix of unlabelled mass points
  - → Train different DNNs using few mass points
- ❖ Plus allow:
  - → Smooth interpolation
  - → Optimal continuous performances
- ❖ Ongoing: adding HME (whole shape!) to DNN





Parameterized Machine Learning for High-Energy Physics, Pierre Baldi, Kyle Cranmer et all. arXiv:1601.07913v1 [hep-ex] 28 Jan 2016