Rare, Exotic, and Invisible Higgs Decays at CMS

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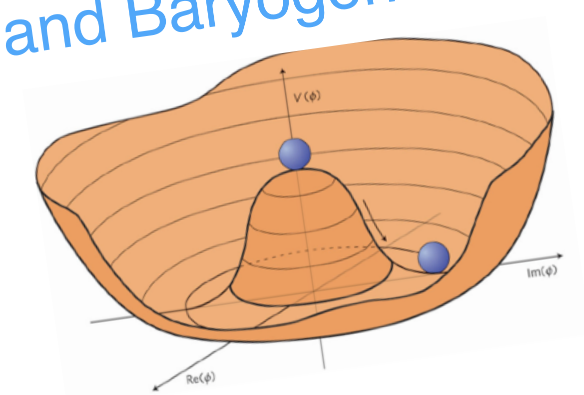
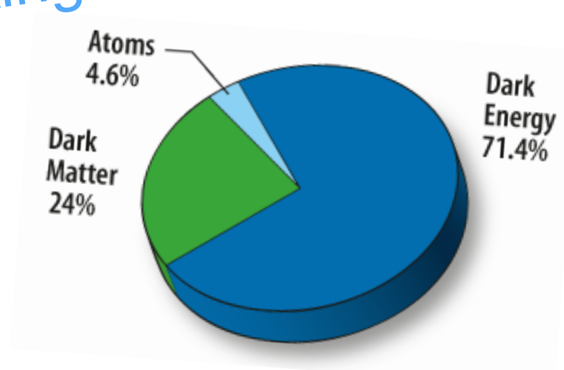
h(125)

- A comprehensive program is underway to characterize the Higgs boson discovered in 2012
  - Mass and width
  - Spin-parity properties
  - Rates and kinematics of production and decay

- The Higgs boson provides a unique and wide ranging probe of Beyond the Standard Model (BSM) physics

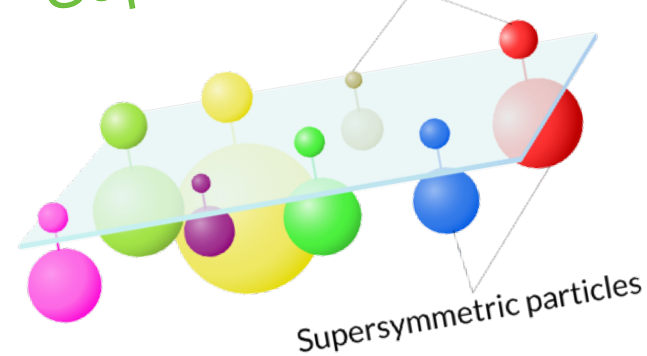
Electroweak Symmetry Breaking and Baryogenesis

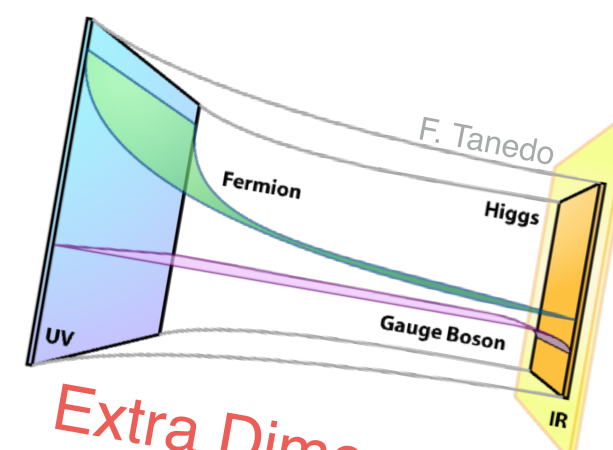




Dark Matter

Supersymmetry



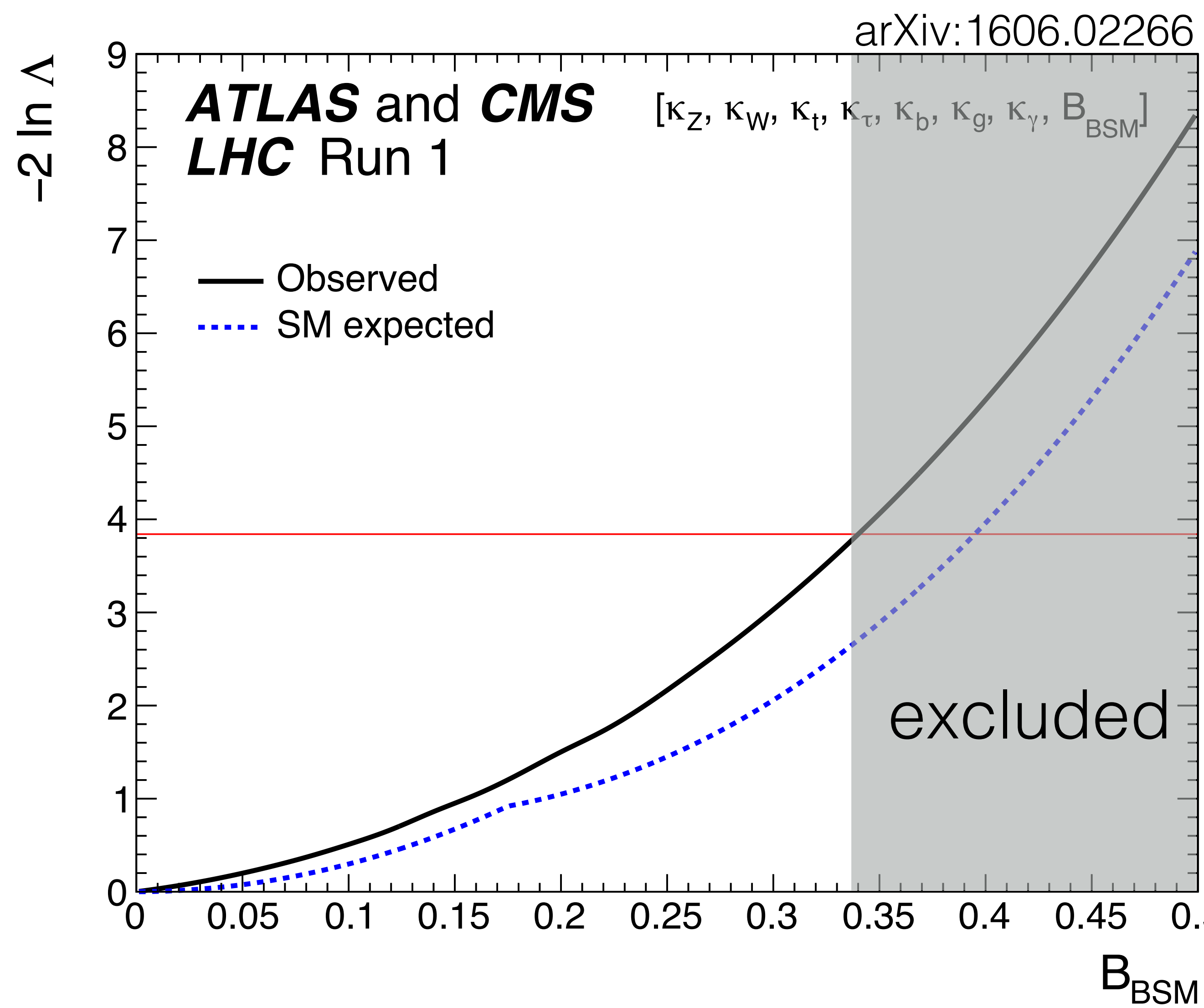


Extra Dimensions

- BSM Higgs boson decays and O(5%) deviations in properties may be the only observable sign of new physics at the LHC.

BSM Higgs Decays

Branching ratio to BSM decays is only constrained to <34% at 95% CL



Places to look:

Rare

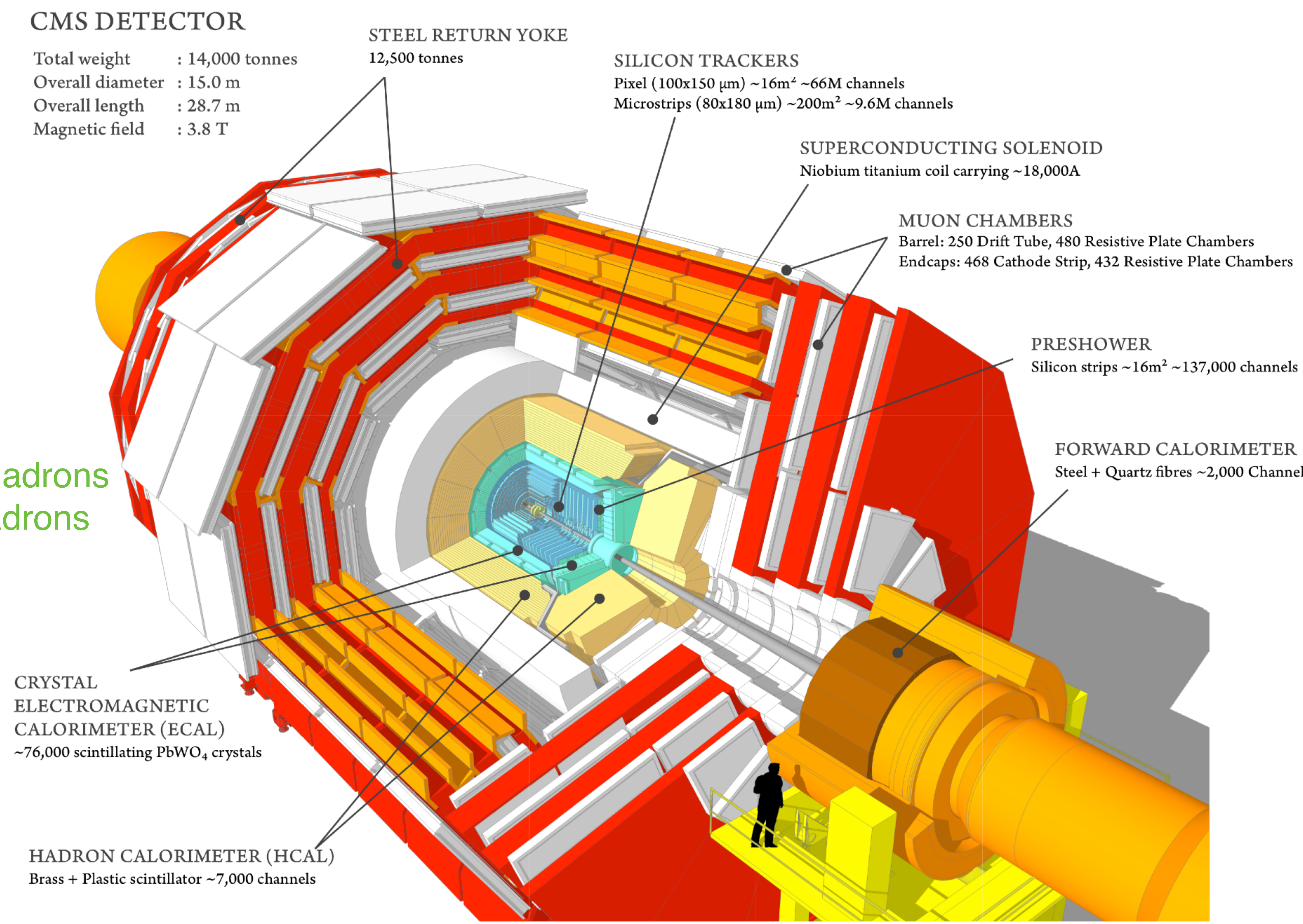
Exotic

Invisible

Invisible

Compact Muon Solenoid

Detects:
photons
electrons
muons
charged hadrons
neutral hadrons

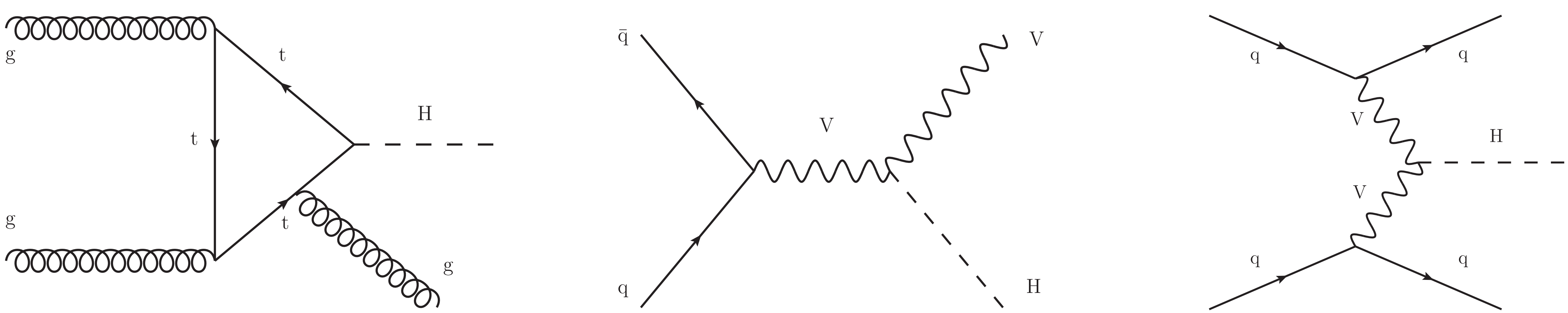


Higgs→$\chi\bar{\chi}$ (invisible)

- Higgs decays to *undetected* dark matter are inferred from the momentum imbalance of *detected* final state particles

$$\overrightarrow{\text{MET}} = \vec{E}_{\mathrm{T}}^{\text{miss}} = -\sum_{\text{detected}} \vec{p}_{\mathrm{T}}$$

- Multiple Higgs production channels



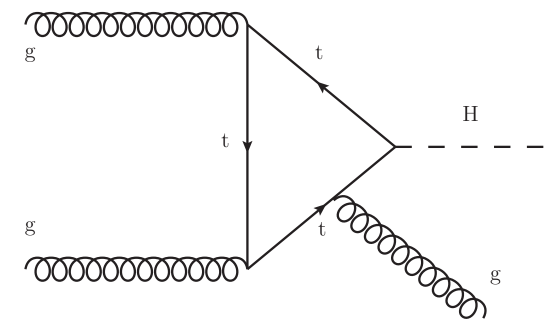
gluon fusion + jet

VH associated
V→merged jets
Z→bb
Z→ll

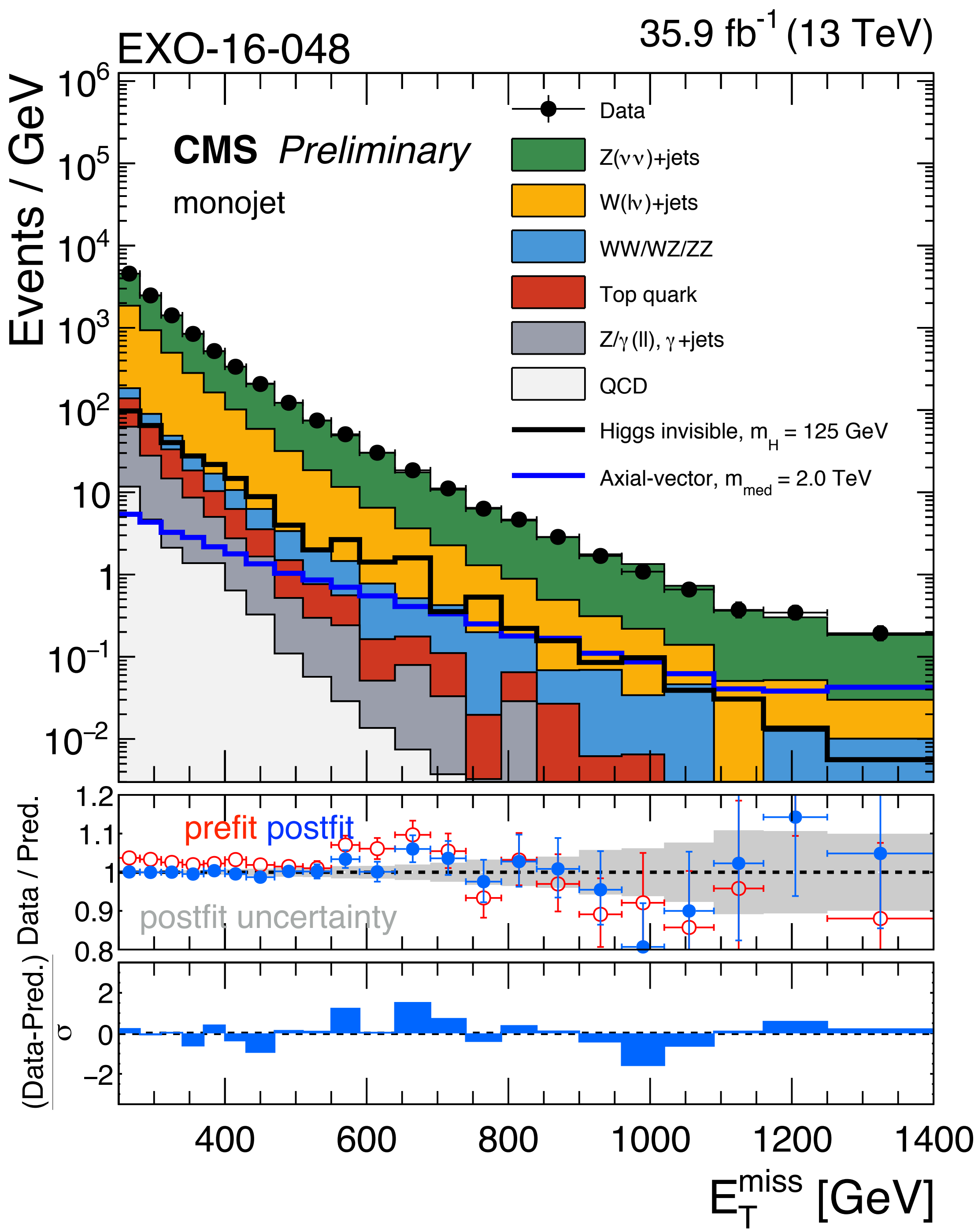
Vector Boson Fusion

Higgs→$\chi\bar{\chi}$ (invisible)

- Understanding MET distributions is crucial



- MET arises in standard model processes from neutrinos
  - e.g. $Z(\nu\bar{\nu})$+jets
  - Modeling is sensitive to high order corrections



- MET also arises from momentum mis-measurement

- Extensive use of data control regions

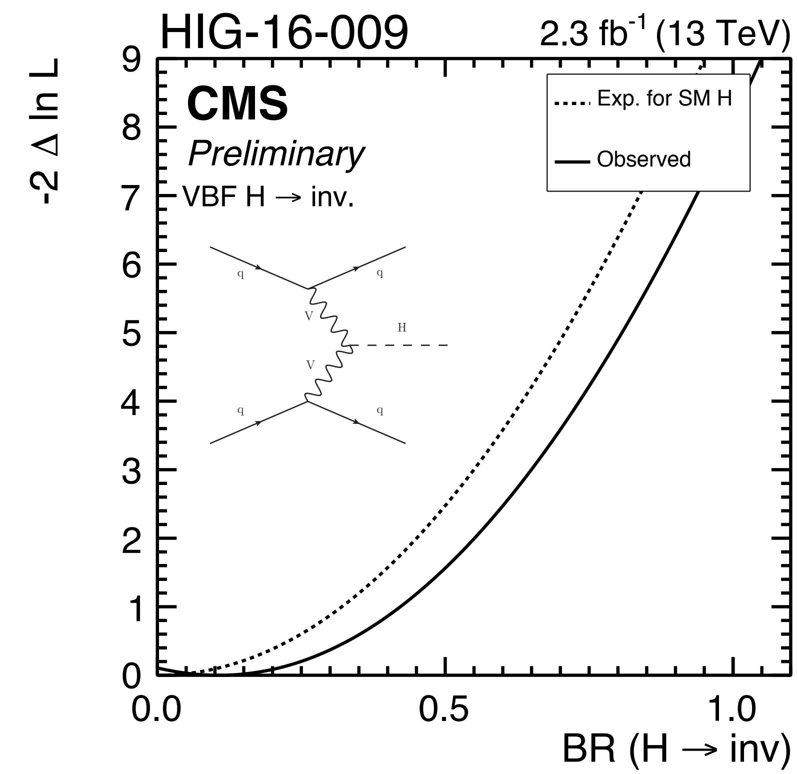
Higgs→$\chi\bar{\chi}$ (invisible) Results

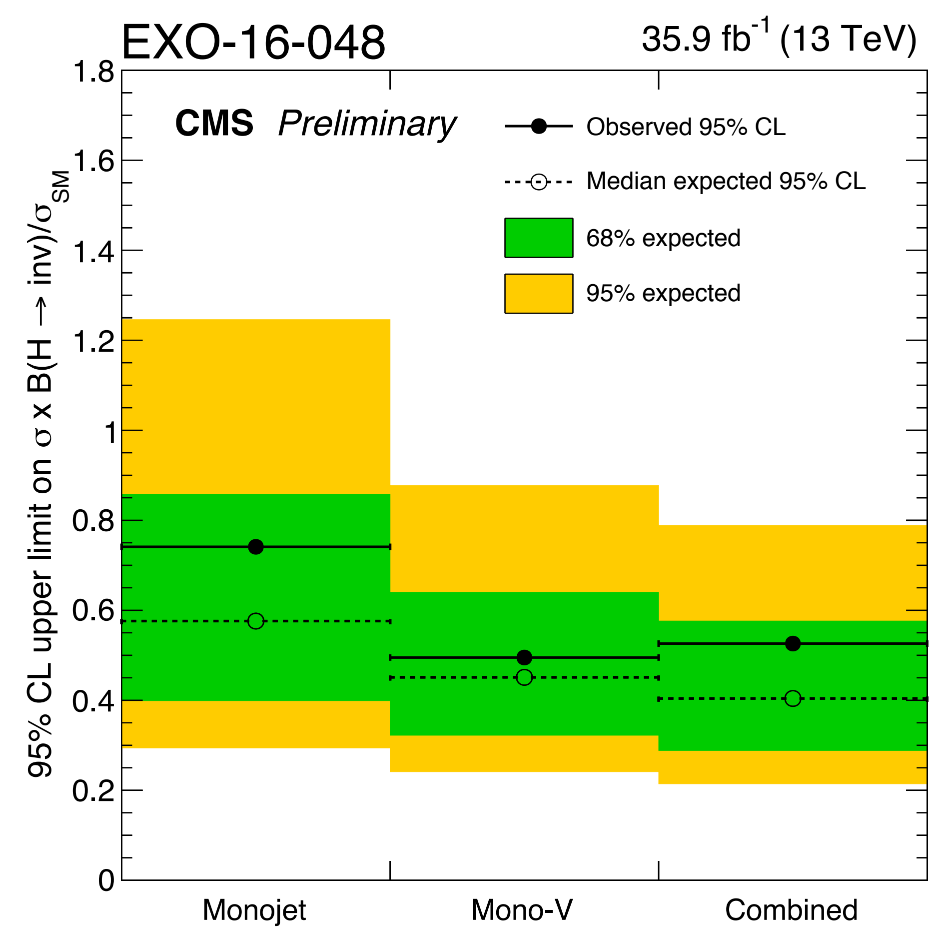
- Observed (expected) 95% CL upper limits on invisible branching ratio from 13 TeV searches

	Data Sample	Observed BR	Expected BR
VBF	2.3 fb^{-1}	< 69%	< 62%
Z(ll)H	36 fb^{-1}	< 40%	< 42%
Mono-jet	36 fb^{-1}	< 74%	< 57%
V(had)H aka Mono-V	36 fb^{-1}	< 49%	< 45%

HIG-16-009, EXO-16-052, EXO-16-048

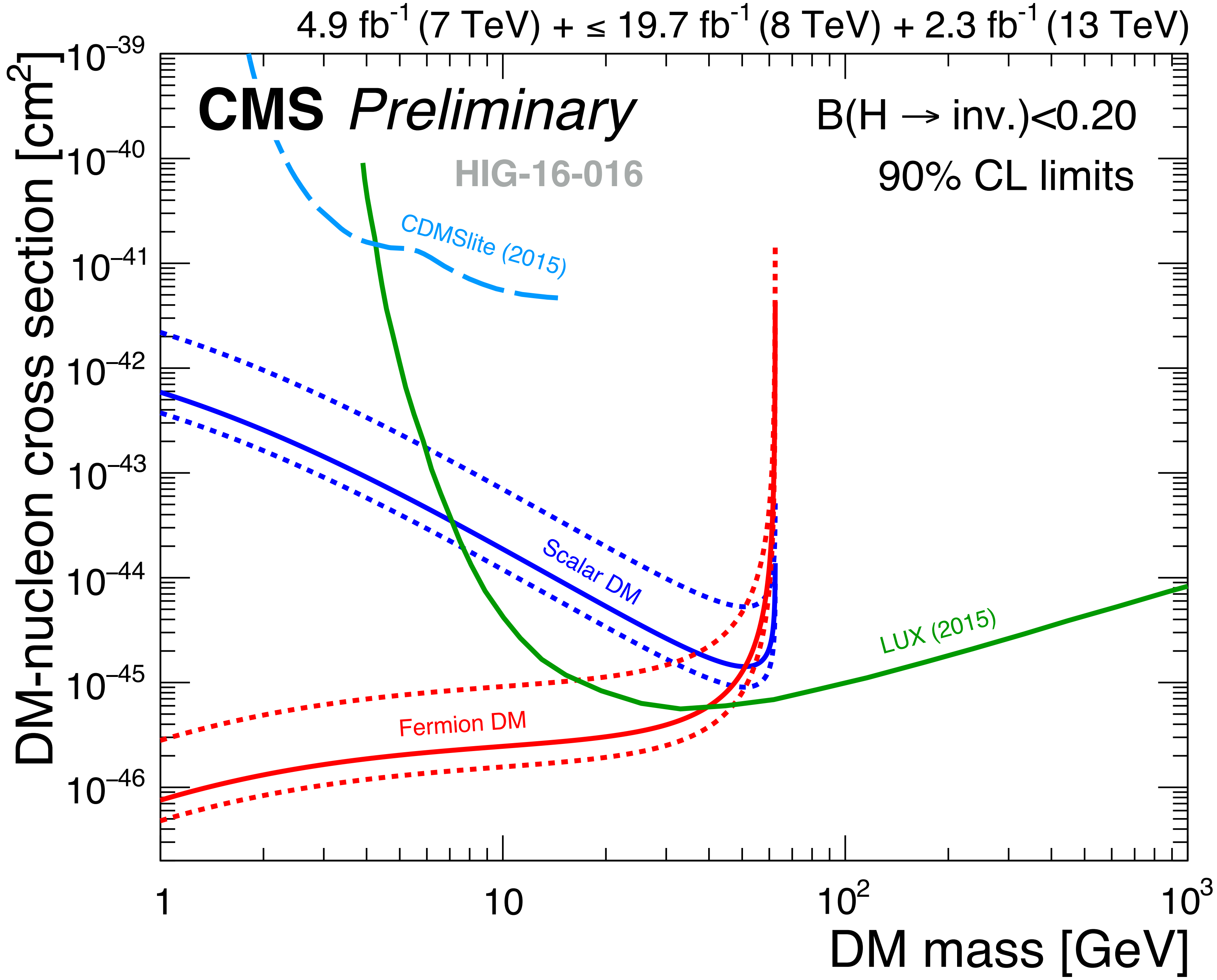
- The searches are statistically independent and are combined to improve sensitivity





Higgs Portal Model

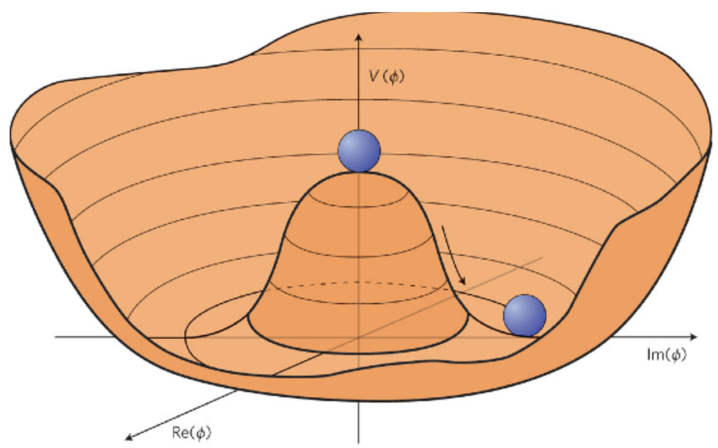
- Interpret in context of Higgs portal model
  - arXiv:0809.2745, arXiv:1212.2131, arXiv:1112.3299, arXiv:1205.3169
- Dark matter interacts with nuclei via Higgs boson exchange



Rare

pp→H*→HH

- The Higgs self coupling is determined by its potential

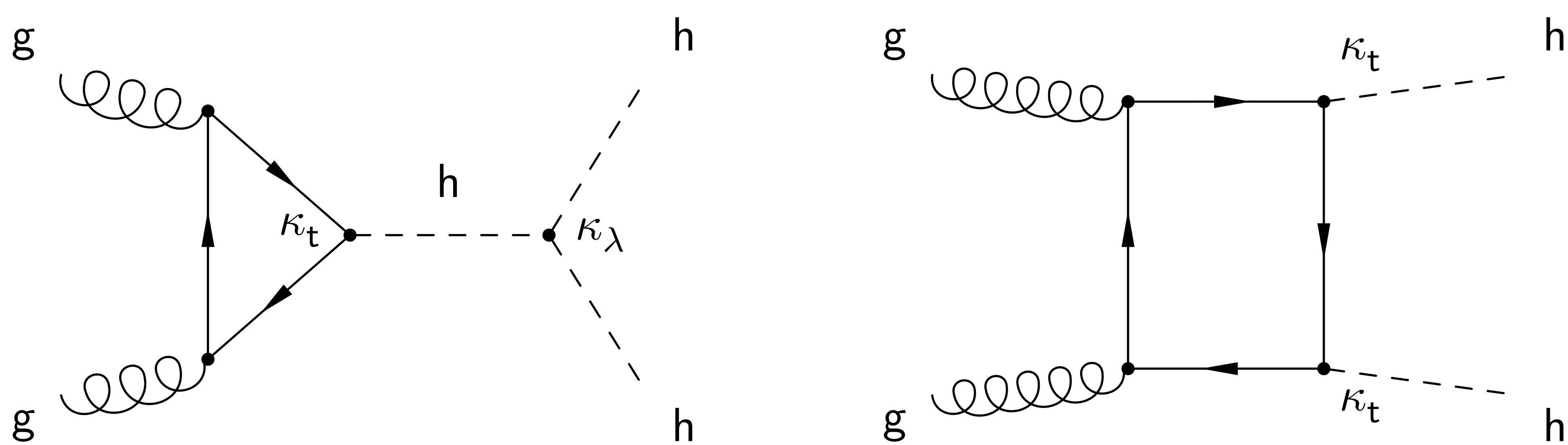


In the standard model,

$$V = \frac{m_h^2}{2}h^2 + \lambda_3 v h^3 + \frac{\lambda_4}{4}h^4$$

where $\lambda_3 = \lambda_4 = m_h^2/(2v^2)$

- We can test λ_3 by studying di-Higgs production
  - Rare in standard model (cross section = 33.5 fb)
  - Constrain the coupling modifiers in these interfering diagrams:



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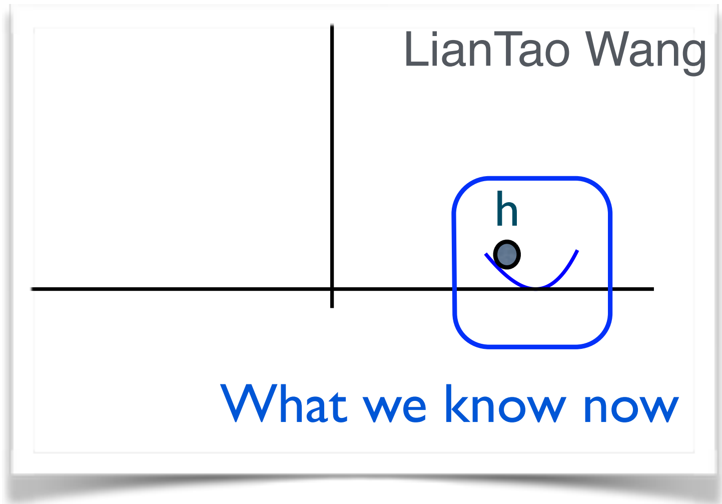

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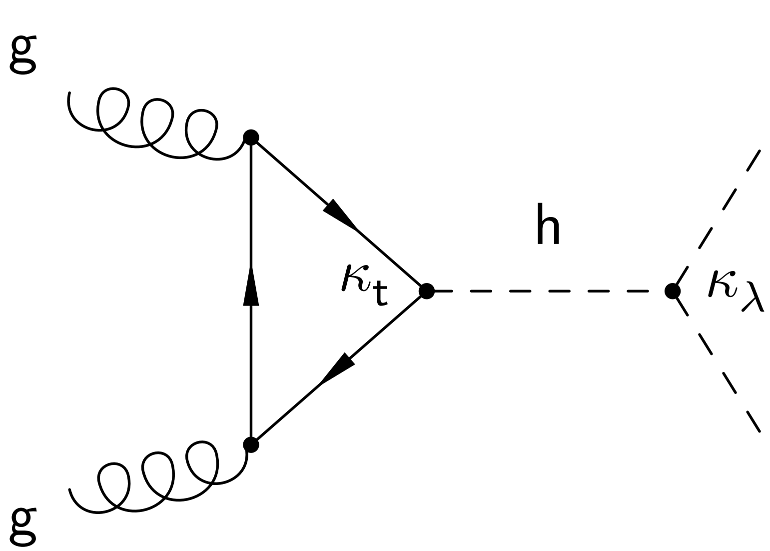
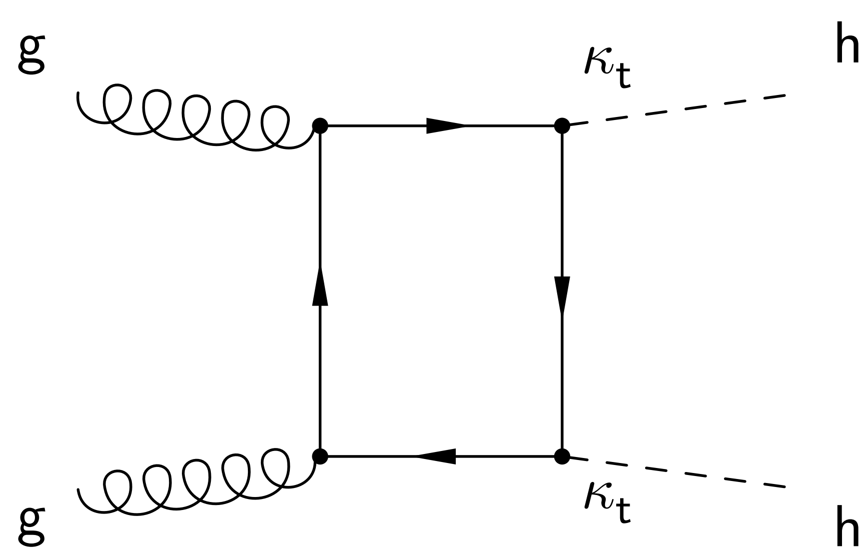
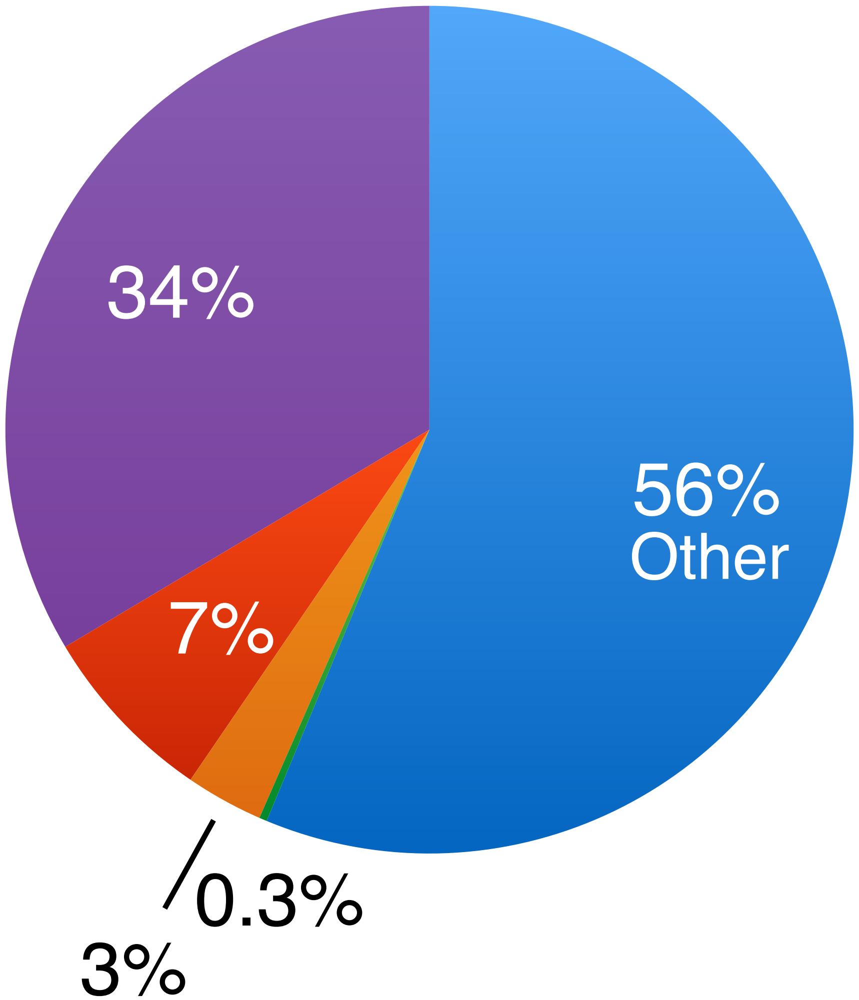




pp→H*→HH

- Multiple final states
  - H(bb)H(bb)
  - H(bb)H(ττ)
  - H(bb)H(VV), leptonic V decays
  - H(bb)H(γγ)
- Analysis sensitivity depends on branching ratios, backgrounds, and experimental resolutions
- The H(bb)H(γγ) channel has the smallest branching ratio, but is the most sensitive to standard model di-Higgs production
  - $\sigma/\sigma_{SM} < 19.2$ at 95% CL

Standard Model HH Branching Ratios



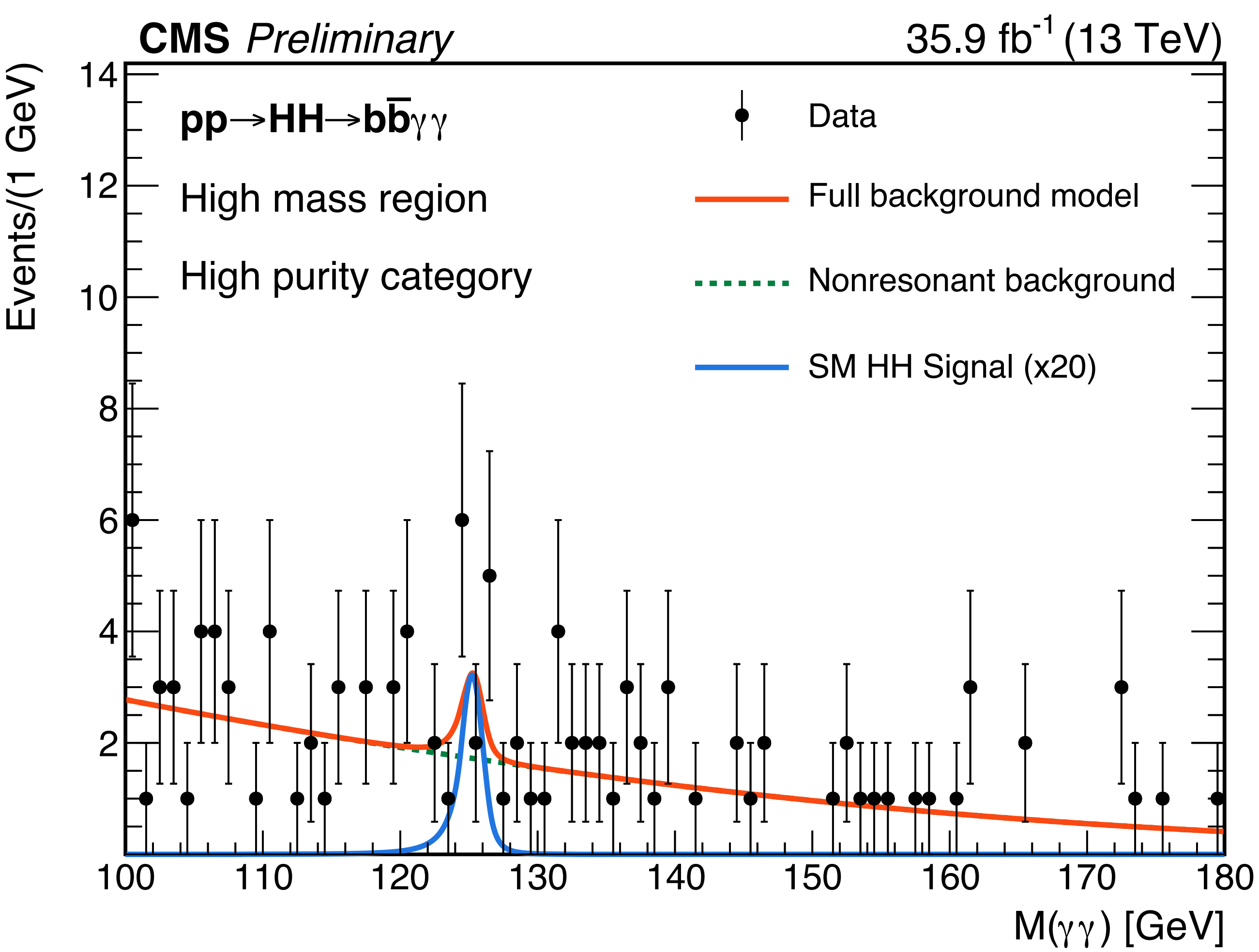
Results:
- HIG-16-026: H(bb)H(bb)
- HIG-17-002: H(bb)H(ττ)
- HIG-17-006: H(bb)H(VV)
- HIG-17-008: H(bb)H(γγ)

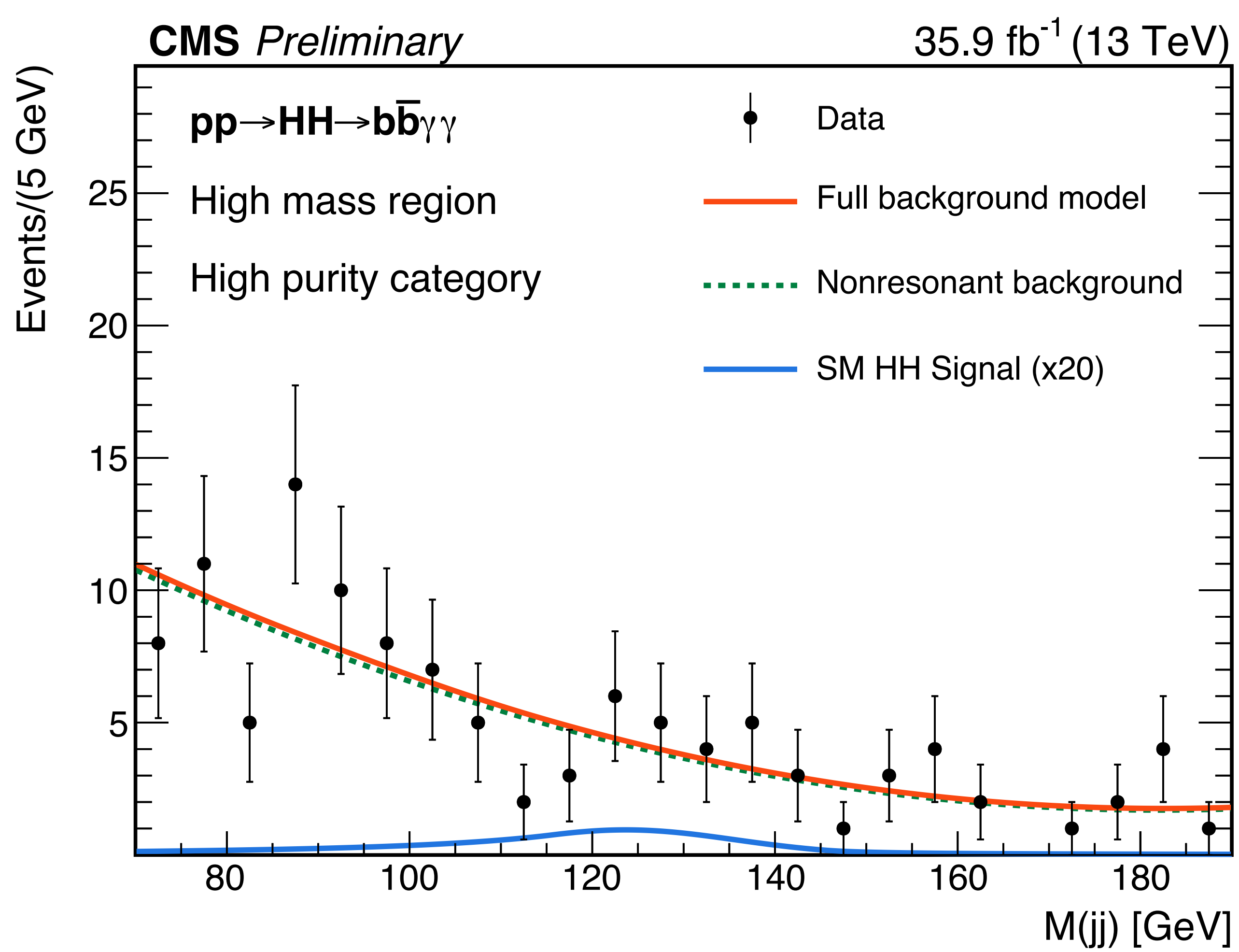
(These also cover BSM resonances decaying to HH)

H(bb)H(γγ)

HIG-17-008

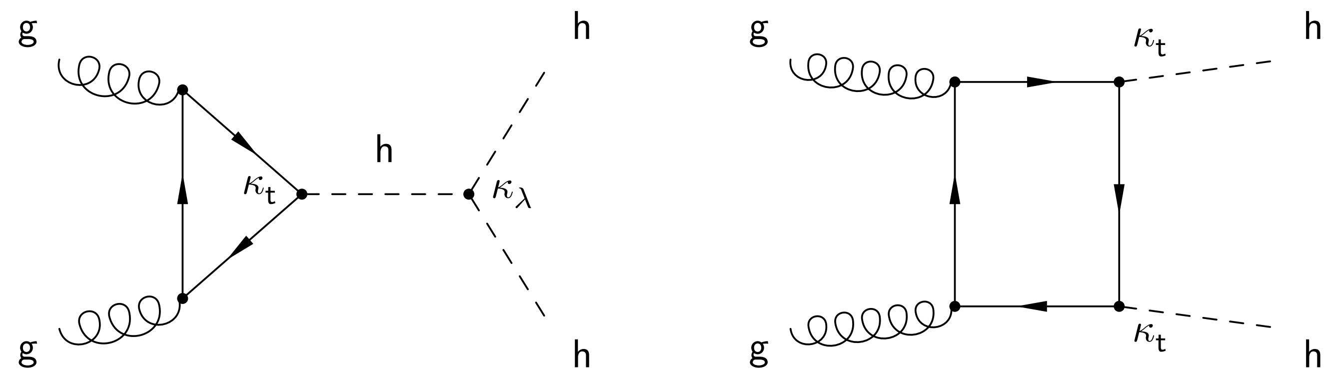
- Excellent di-photon mass resolution
- Fit data in 2D M(γγ)-M(bb) plane



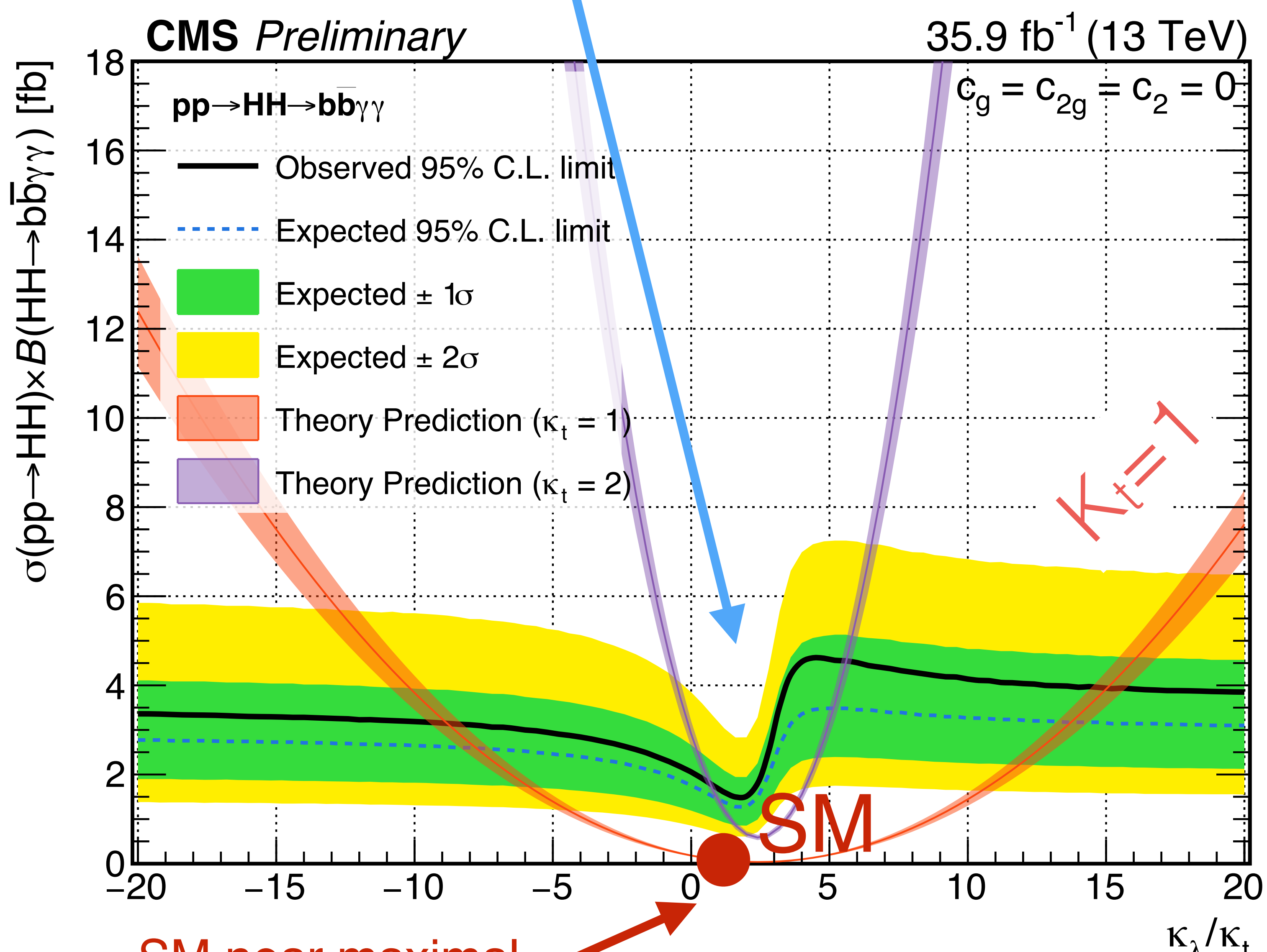


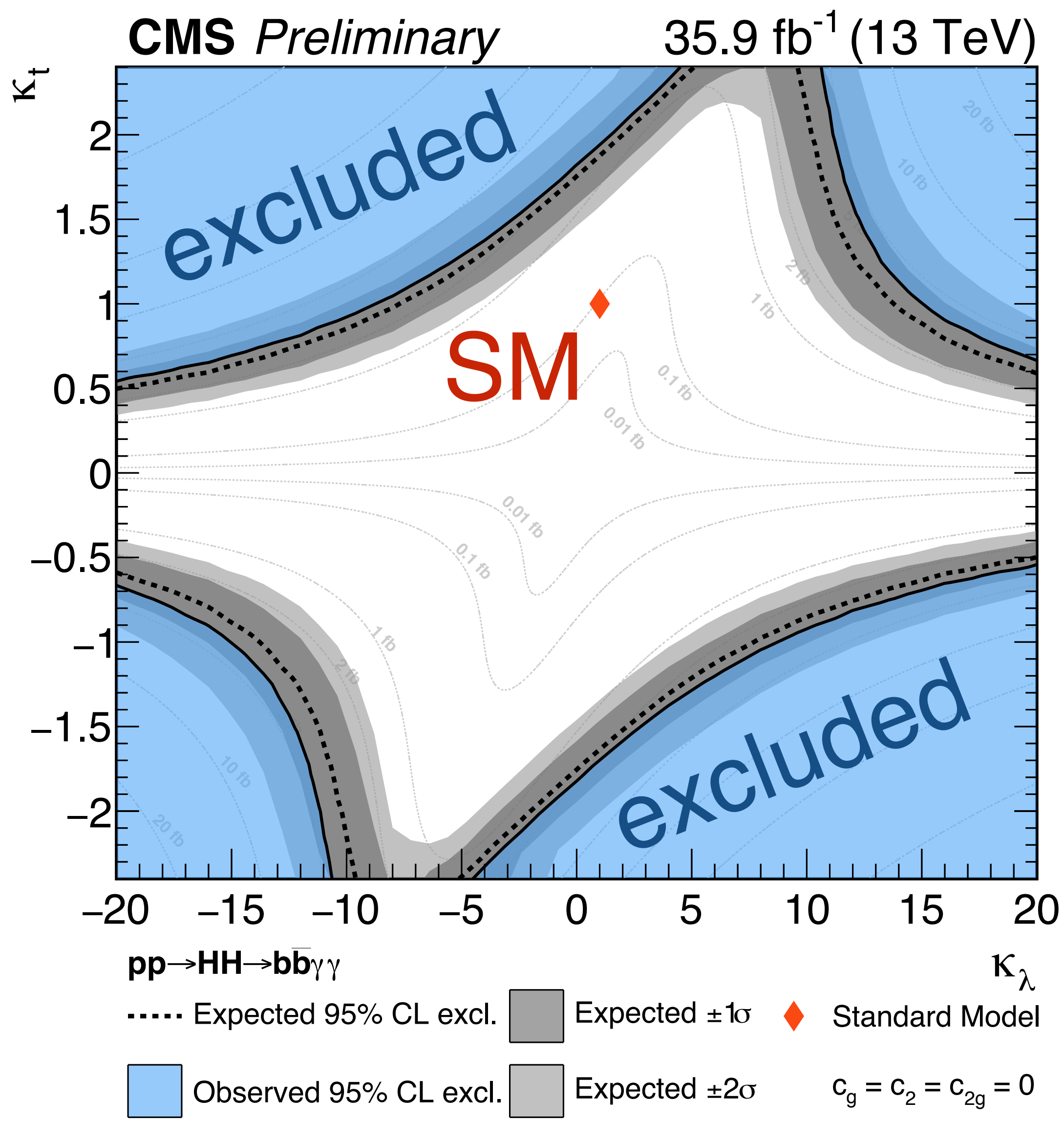
H(bb)H(γγ) Results

HIG-17-008



interfering diagrams changes m_{HH} shape





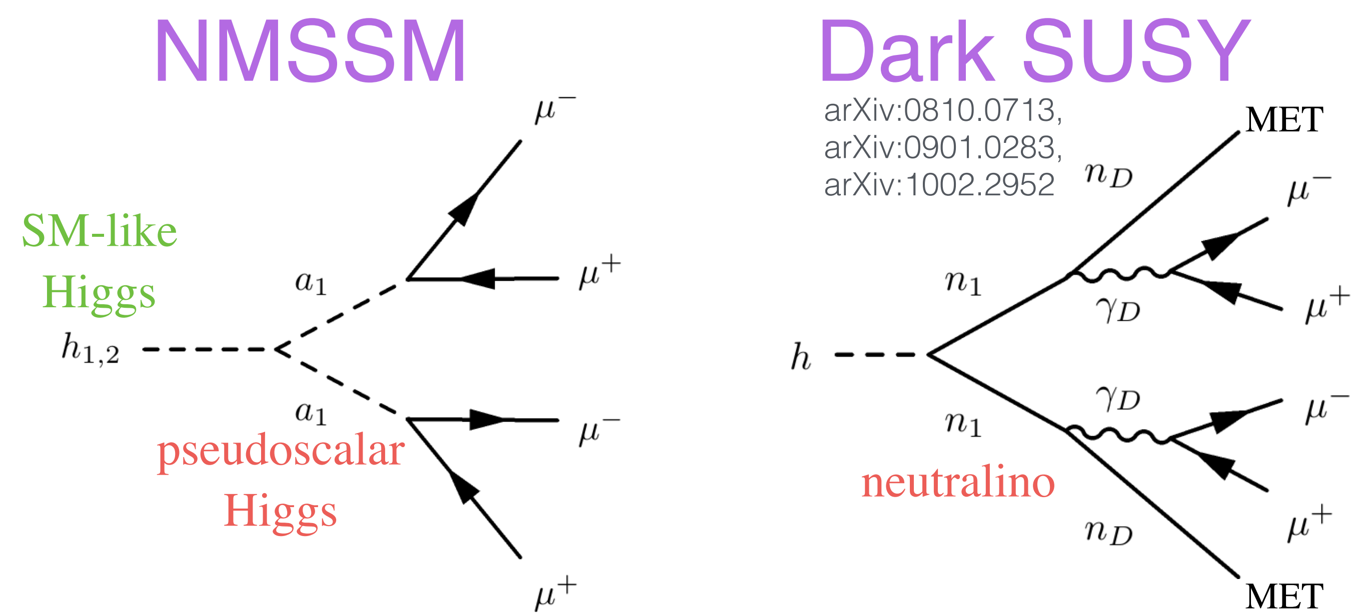
SM near maximal destructive interference

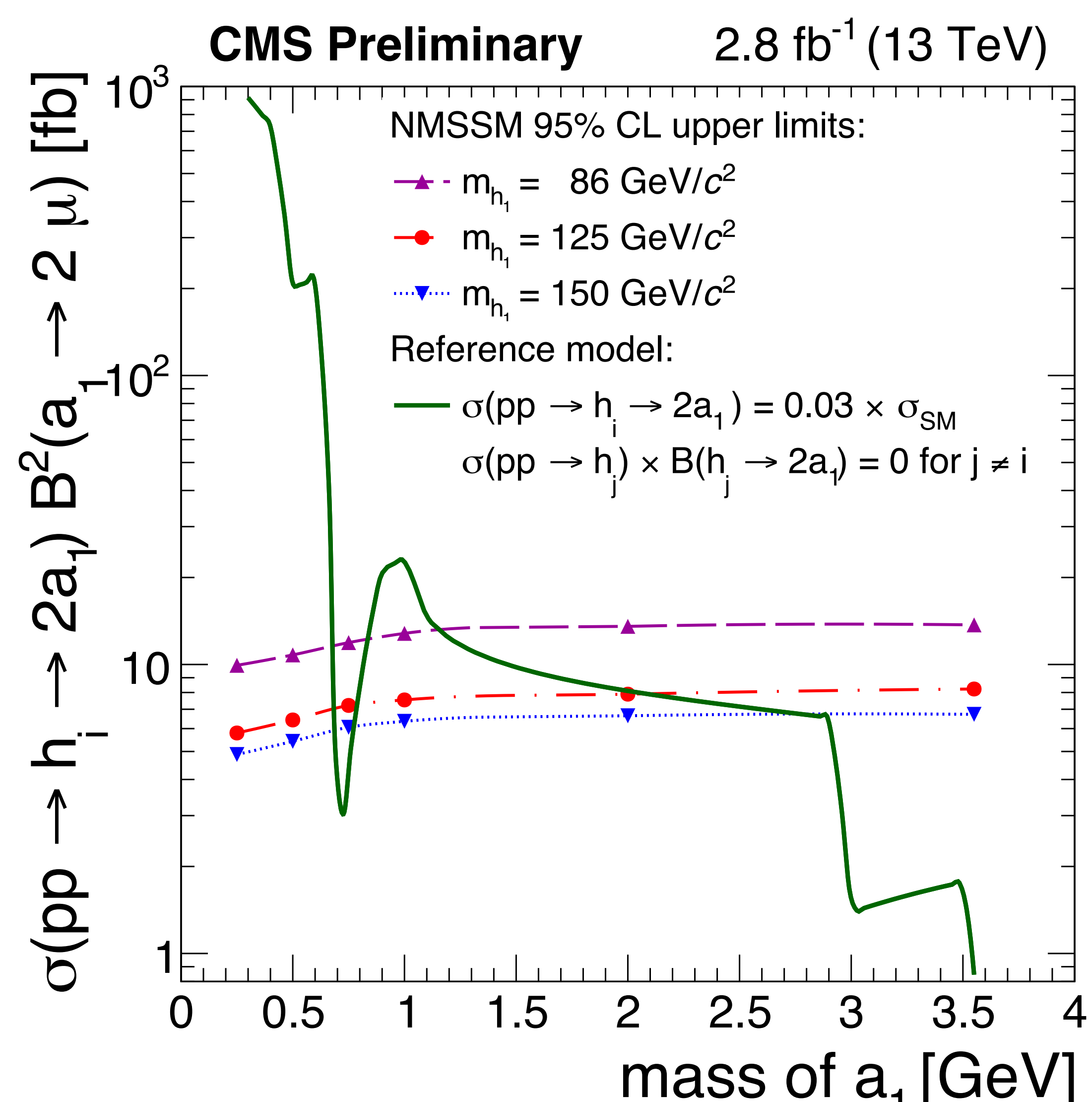
Exotic

H→4μ

HIG-16-035

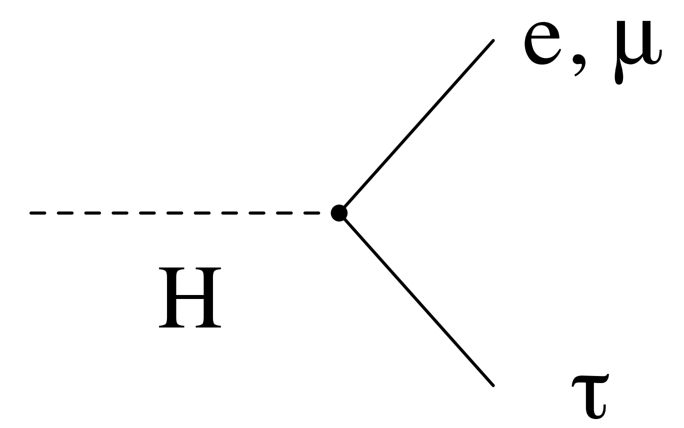
- Arise in supersymmetry
- Reconstruct di-muon pairs with invariant mass < 9 GeV
- Dominant background is $b\bar{b}$
- Model-independent limit
  - $\sigma(pp \to 2a + X) \times \mathcal{B}^2(a \to 2\mu) \times \alpha_{gen}$ < 1.7 fb at 95% CL
- Interpret model benchmarks



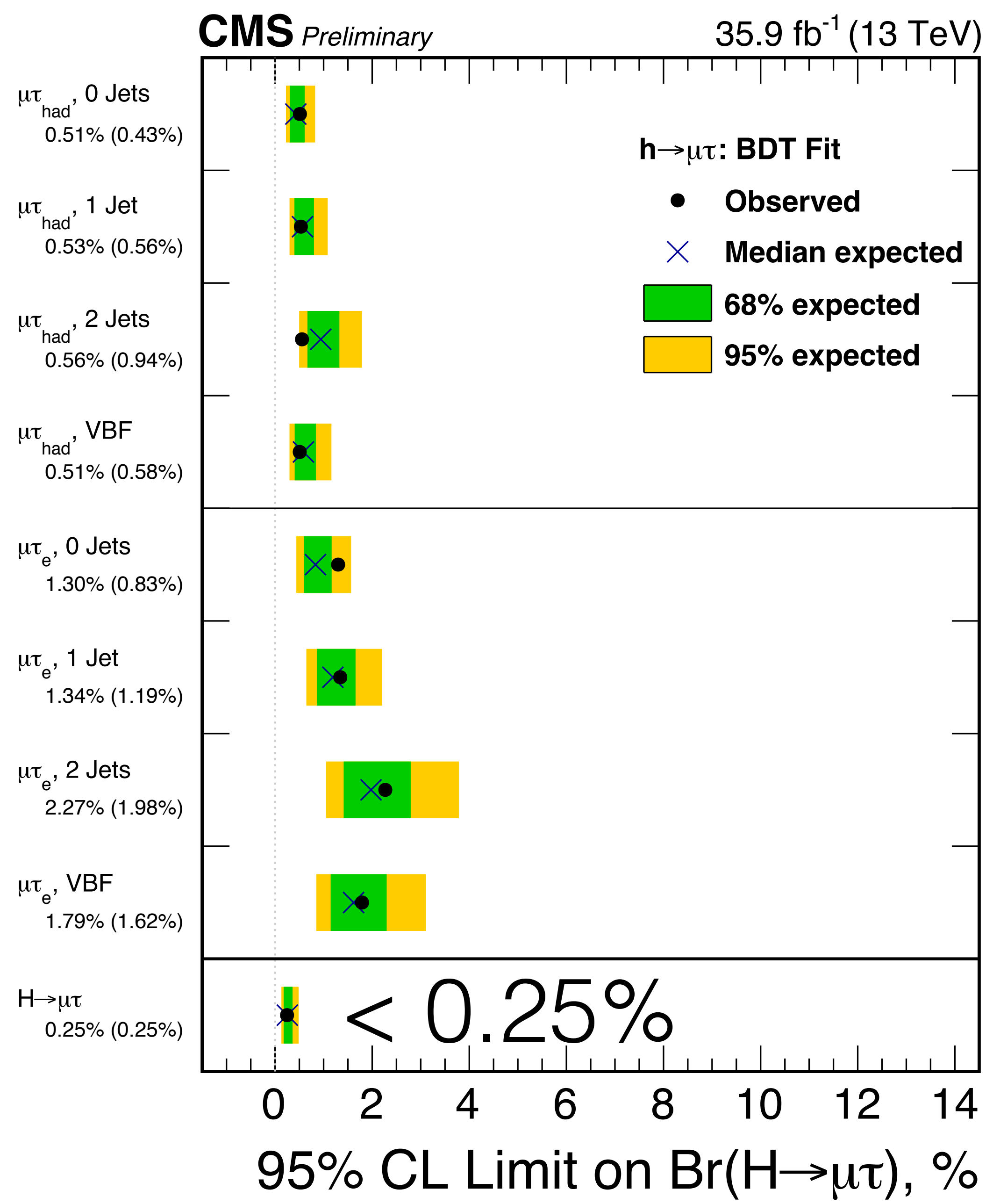


Lepton Flavor Violating Decays HIG-17-001

- Occur in many BSM models, including supersymmetry and Randall-Sundrum models.



- LHC experiments have best sensitivity for H→eτ and H→μτ
  - Exploiting multiple decay channels of the τ (e, μ, hadronic)



- Set upper limits on branching ratios and Yukawa couplings

95% CL upper limit on the Yukawa couplings

	M_{col}-fit	BDT-fit
$\sqrt{\lvert Y_{\mu\tau}\rvert^2 + \lvert Y_{\tau\mu}\rvert^2}$	$< 2.05 \times 10^{-3}$	$< 1.43 \times 10^{-3}$
$\sqrt{\lvert Y_{e\tau}\rvert^2 + \lvert Y_{\tau e}\rvert^2}$	$< 2.45 \times 10^{-3}$	$< 2.26 \times 10^{-3}$

Summary

- A comprehensive program is underway to characterize the 125 GeV Higgs boson

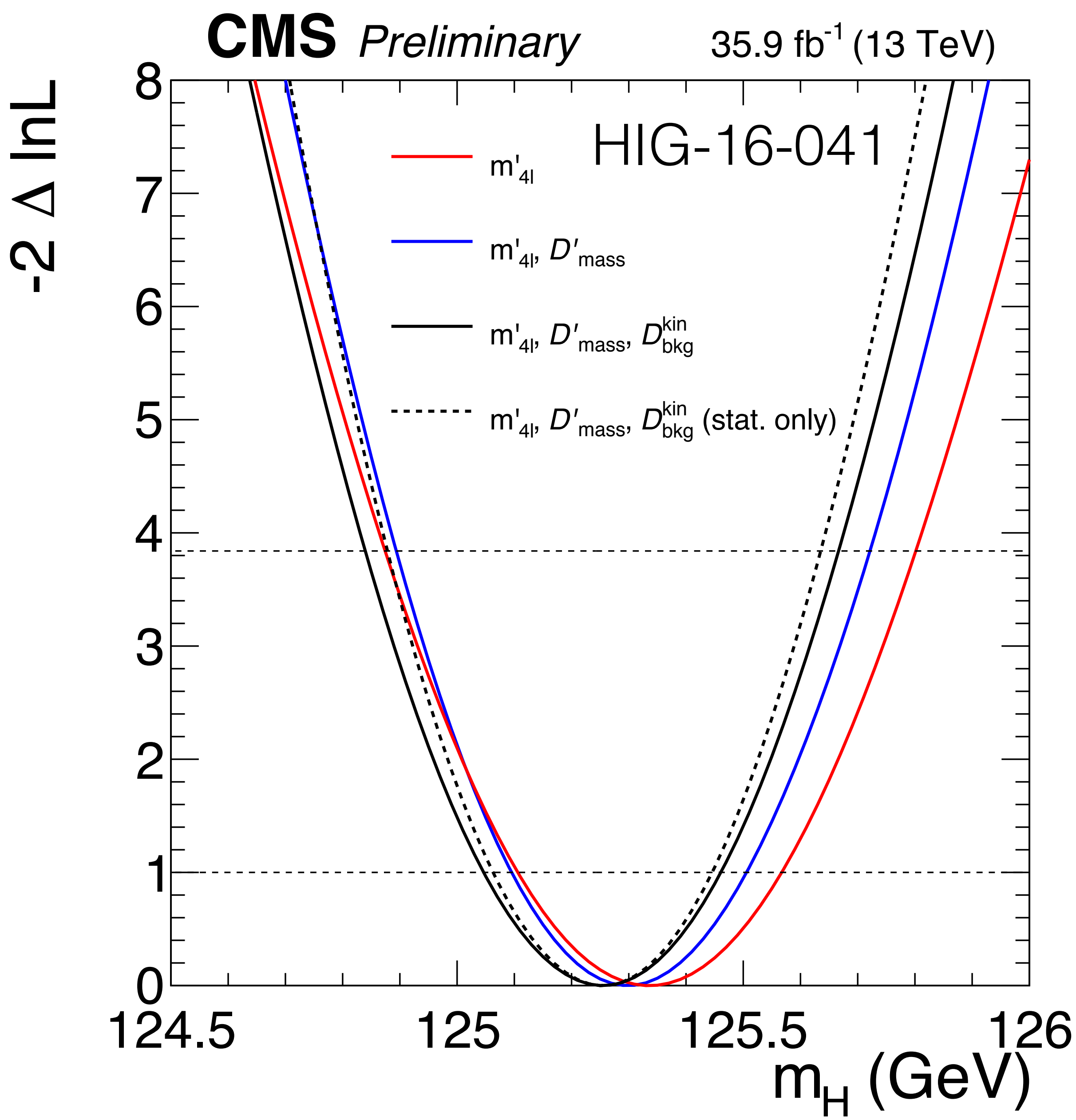
- So far, searches for rare, exotic, and invisible Higgs decays show compatibility with standard model

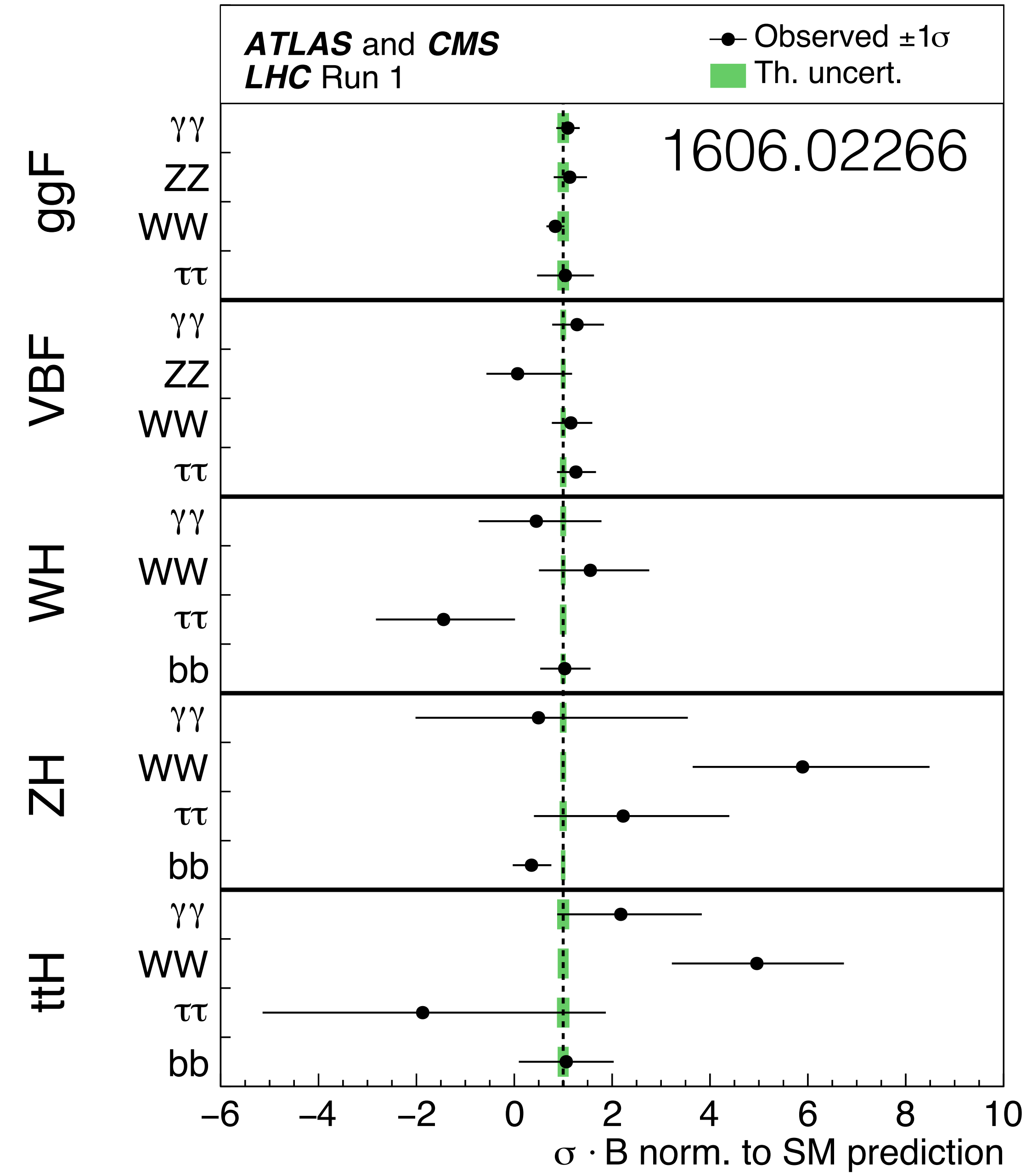
- Recent results on
  - Higgs decays to undetected particles
  - Higgs self coupling
  - Higgs decays to light scalars
  - Lepton flavor violating decays

- Constraints are placed on a wide range of beyond the standard model physics models

Backup

h(125) Properties (examples)

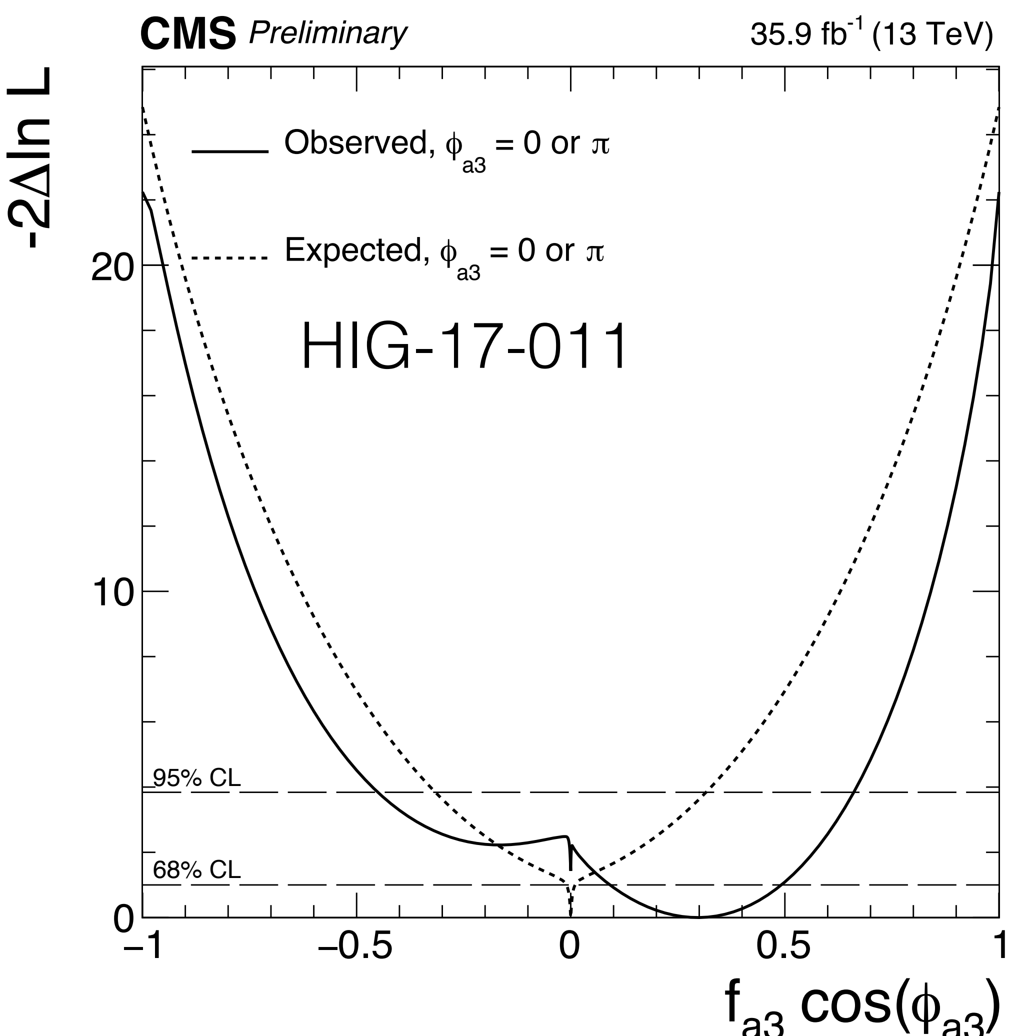




h(125) Properties (examples)

$$\left[a_1^{VV} + \frac{\kappa_1^{VV} q_1^2 + \kappa_2^{VV} q_2^2}{\left(\Lambda_1^{VV}\right)^2} + \frac{\kappa_3^{VV} (q_1 + q_2)^2}{\left(\Lambda_Q^{VV}\right)^2} \right] m_{V1}^2 \epsilon_{V1}^* \epsilon_{V2}^* + a_2^{VV} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3^{VV} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

tree-level scalar (SM) — leading momentum expansion — higher order scalar — pseudoscalar

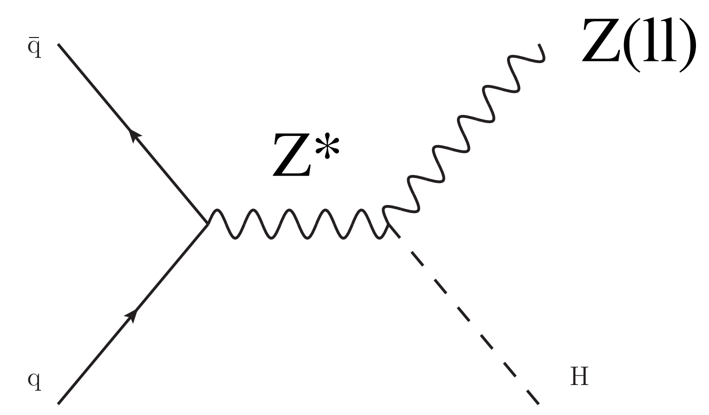


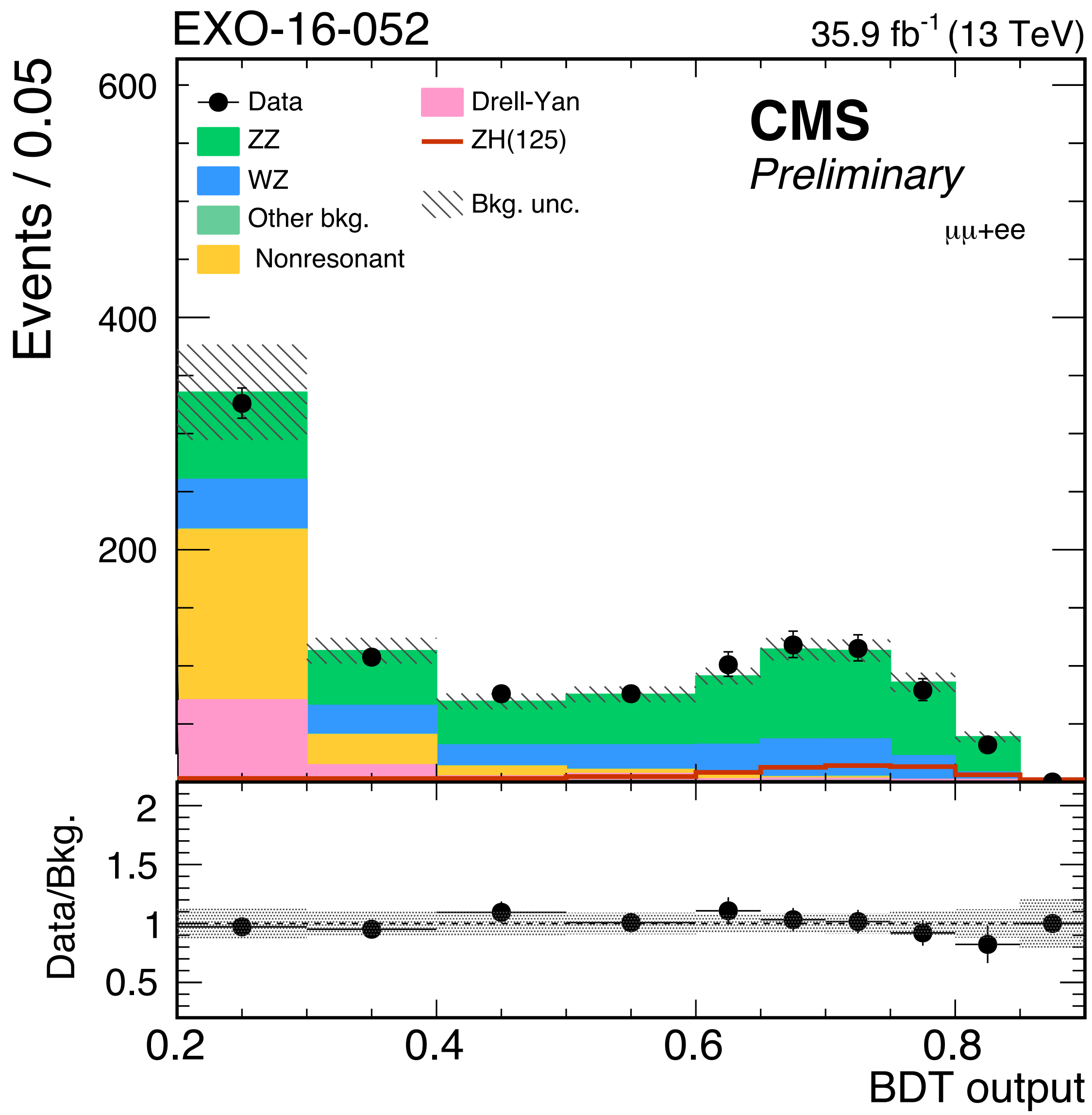
pure pseudoscalar — pure tree-level scalar — pure pseudoscalar

Parameter	Observed	Expected
$f_{a3}\cos(\phi_{a3})$	$0.30^{+0.19}_{-0.21}$ $[-0.45, 0.66]$	$0.000^{+0.017}_{-0.017}$ $[-0.32, 0.32]$
$f_{a2}\cos(\phi_{a2})$	$0.04^{+0.19}_{-0.04}$ $[-0.69, -0.64] \cup [-0.04, 0.64]$	$0.000^{+0.015}_{-0.014}$ $[-0.08, 0.29]$
$f_{\Lambda1}\cos(\phi_{\Lambda1})$	$0.00^{+0.06}_{-0.33}$ $[-0.92, 0.15]$	$0.000^{+0.014}_{-0.014}$ $[-0.79, 0.15]$
$f_{\Lambda1}^{Z\gamma}\cos(\phi_{\Lambda1}^{Z\gamma})$	$0.16^{+0.36}_{-0.25}$ $[-0.43, 0.80]$	$0.000^{+0.020}_{-0.024}$ $[-0.49, 0.80]$

Higgs→χχ̄ (invisible)

- Understanding MET distributions is crucial
  - MET arises in standard model processes from neutrinos
    - e.g. Z(νν̄)+jets
    - Modeling is sensitive to high order corrections
  - MET also arises from momentum mis-measurement
  - Extensive use of data control regions





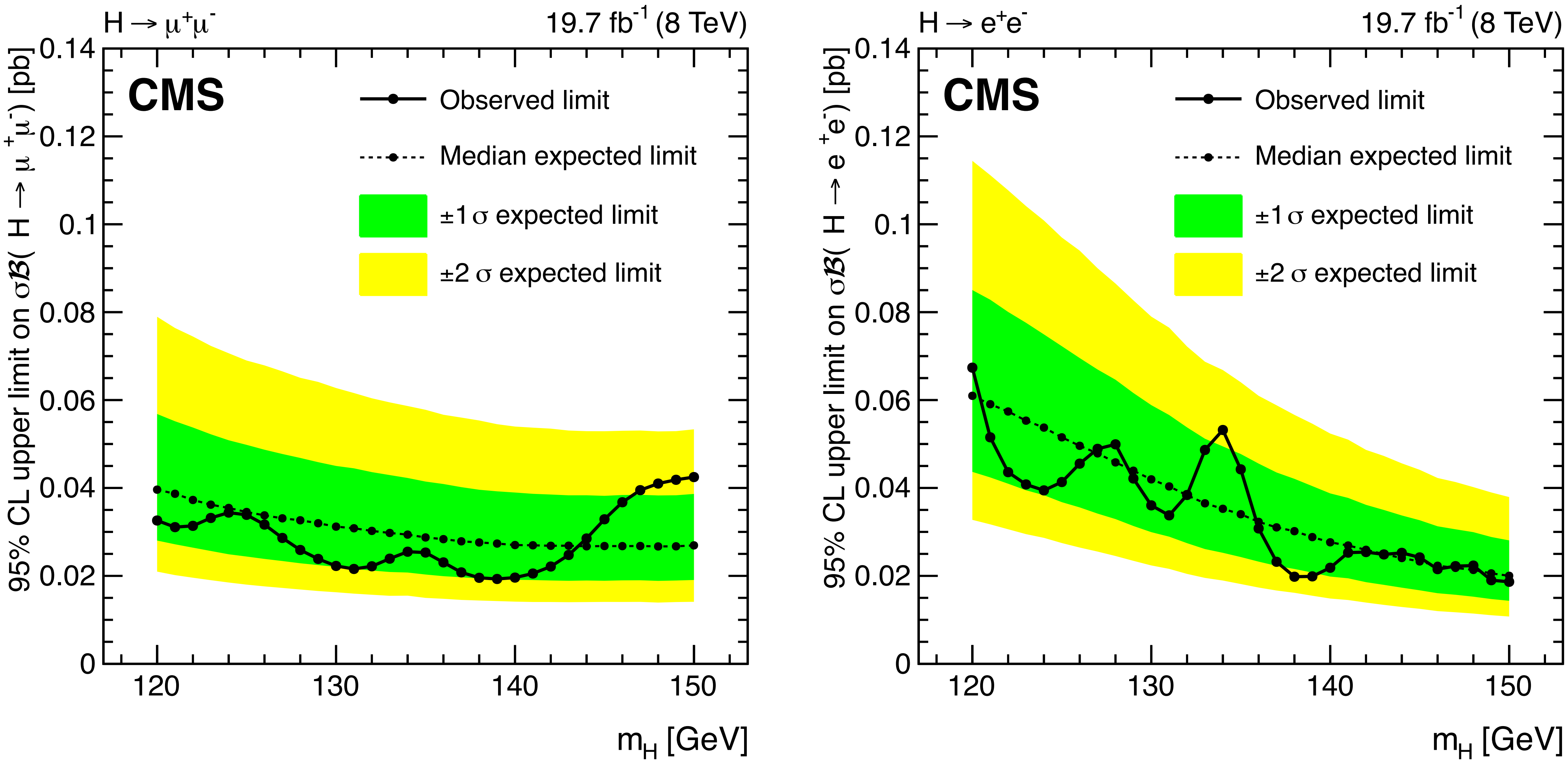
- Multivariate techniques
  - Boosted Decision Tree including MET, lepton kinematics, etc.
  - Improve sensitivity by ~10%

Z(ll)H(inv) Boosted Decision Tree

- $|m_{\ell\ell} - m_{\mathrm{Z}}|$ (dilepton mass);
- $p_{\mathrm{T}}^{\ell 1}$ (leading lepton transverse momentum);
- $p_{\mathrm{T}}^{\ell 2}$ (subleading lepton transverse momentum);
- $p_{\mathrm{T}}^{\ell\ell}$ (dilepton transverse momentum);
- $|\eta^{\ell 1}|$ (leading lepton pseudorapidity);
- $|\eta^{\ell 2}|$ (subleading lepton pseudorapidity);
- $E_{\mathrm{T}}^{\mathrm{miss}}$ (missing transverse energy);
- $m_T(p_{\mathrm{T}}^{\ell 1}, E_{\mathrm{T}}^{\mathrm{miss}})$ (leading lepton transverse mass);
- $m_T(p_{\mathrm{T}}^{\ell 2}, E_{\mathrm{T}}^{\mathrm{miss}})$ (subleading lepton transverse mass);
- $\Delta\phi(\vec{p_{\mathrm{T}}}^{\ell\ell}, \vec{p_{\mathrm{T}}}^{\mathrm{miss}})$ (azimuthal separation between dilepton and missing energy);
- $\Delta R_{\ell\ell}$ (separation between leptons); and
- $|\cos\theta_{\ell 1}^{CS}|$ (cosine of Collins–Soper angle for leading lepton).

$H \rightarrow e^{\pm}e^{\mp}$, $\mu^{\pm}\mu^{\mp}$

HIG-13-007



H→4μ Dark SUSY Limits

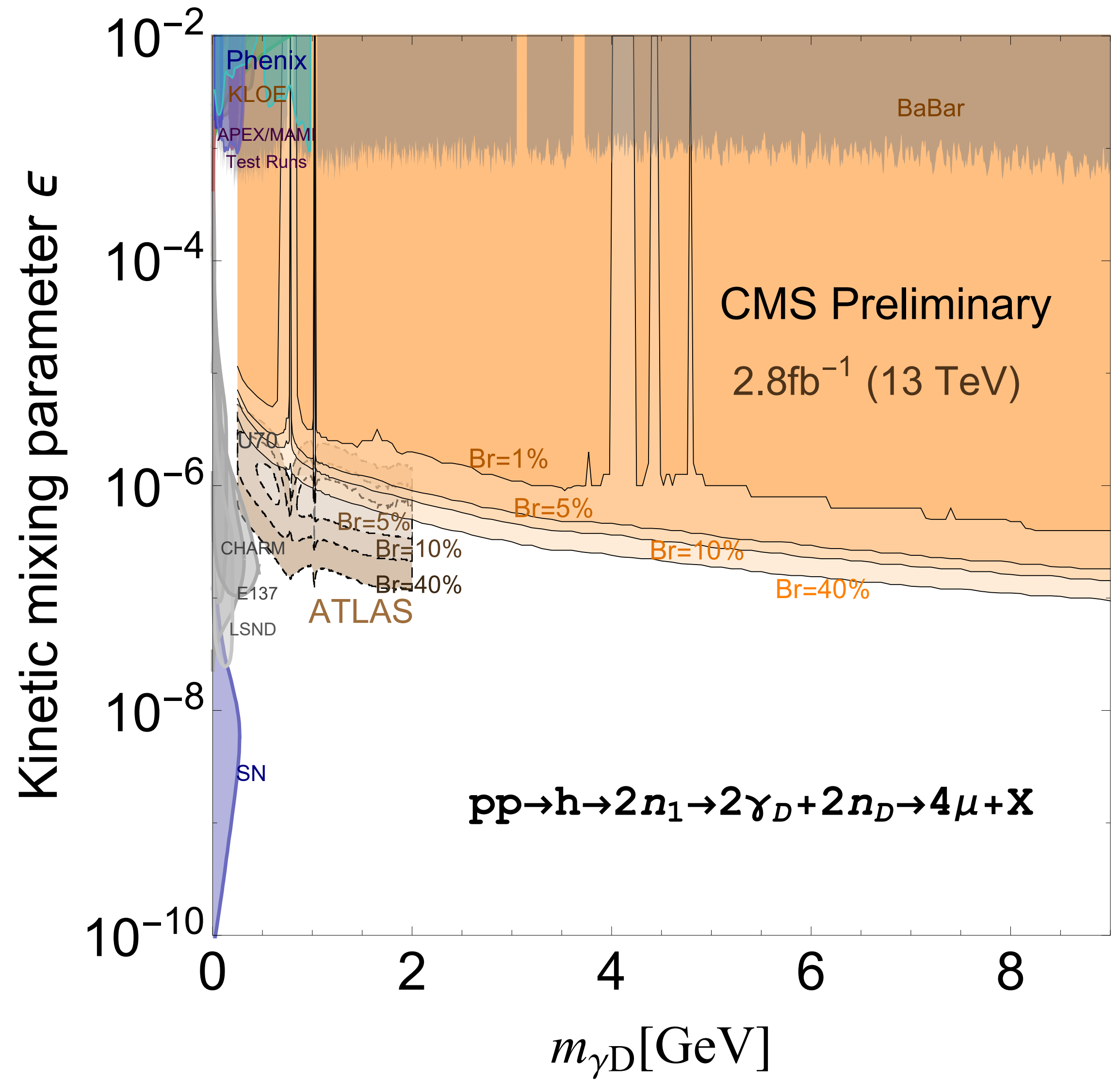


Figure 6: 95% CL upper limits (black solid curves) from this search on $\sigma(\mathrm{pp} \to \mathrm{h} \to 2\gamma_D + X)\,\mathcal{B}(\mathrm{h} \to 2\gamma_D + X)$ (with $m_{n_1} = 10\,\mathrm{GeV}$, $m_{n_D} = 1\,\mathrm{GeV}$) in the plane of two of the parameters (ε and m_{γ_D}) for the dark SUSY scenarios, along with constraints from other experiments. The colored contours represent different values of $\mathcal{B}(\mathrm{h} \to 2\gamma_D + X)$ in the range 1–40%.

Image Credits

- Higgs potential: https://inspirehep.net/record/1252561/plots
- SUSY: https://www.sciencenews.org/article/supersymmetry%E2%80%99s-absence-lhc-puzzles-physicists
- Dark Matter: https://map.gsfc.nasa.gov/universe/uni_matter.html
- Extra Dimensions: https://www.physics.uci.edu/~tanedo/docs.html