CYCU HEP Seminar

CYCU, Taiwan
Feb 26, 2019

Rare Higgs decays and di-Higgs production at CMS

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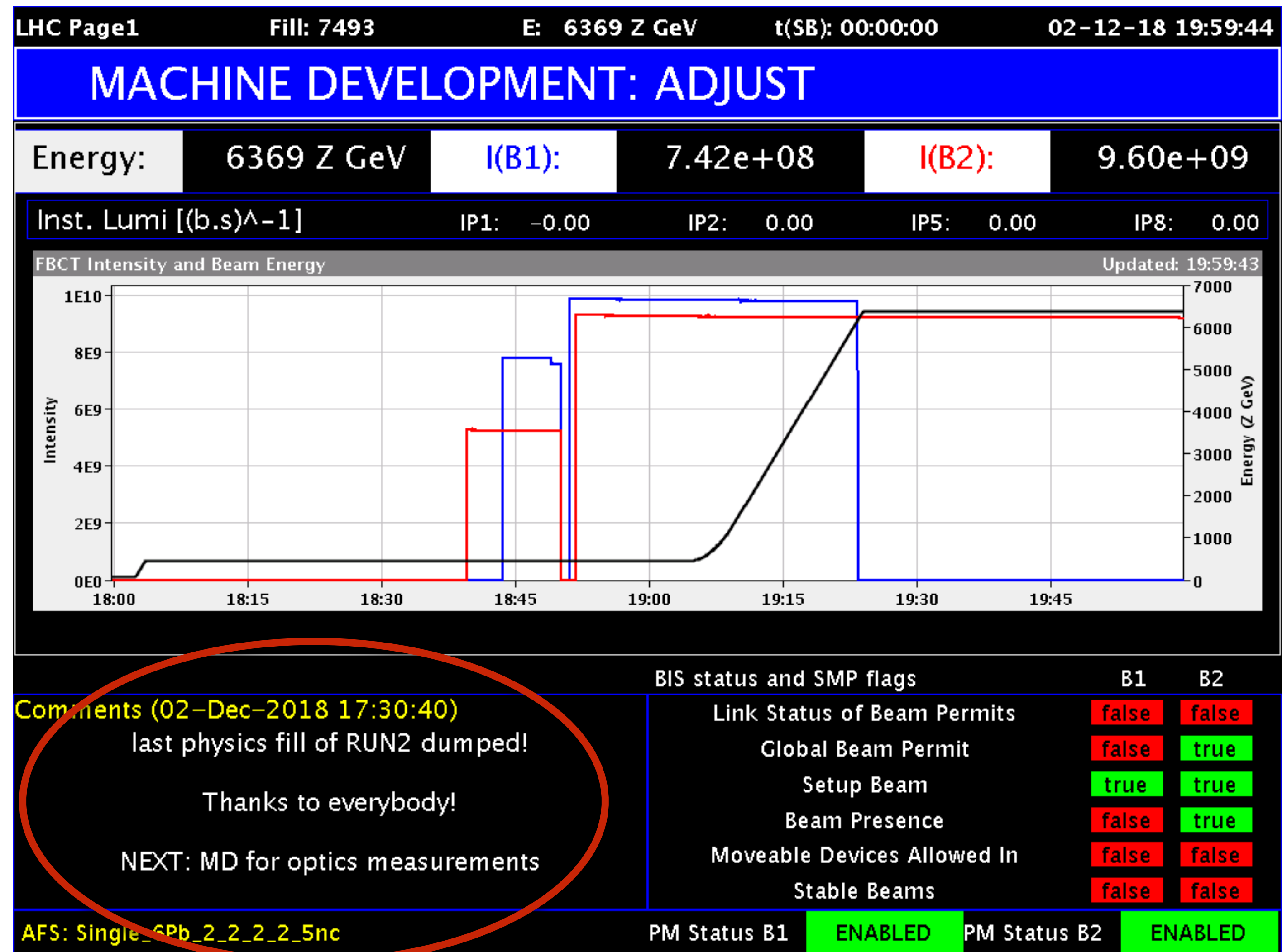
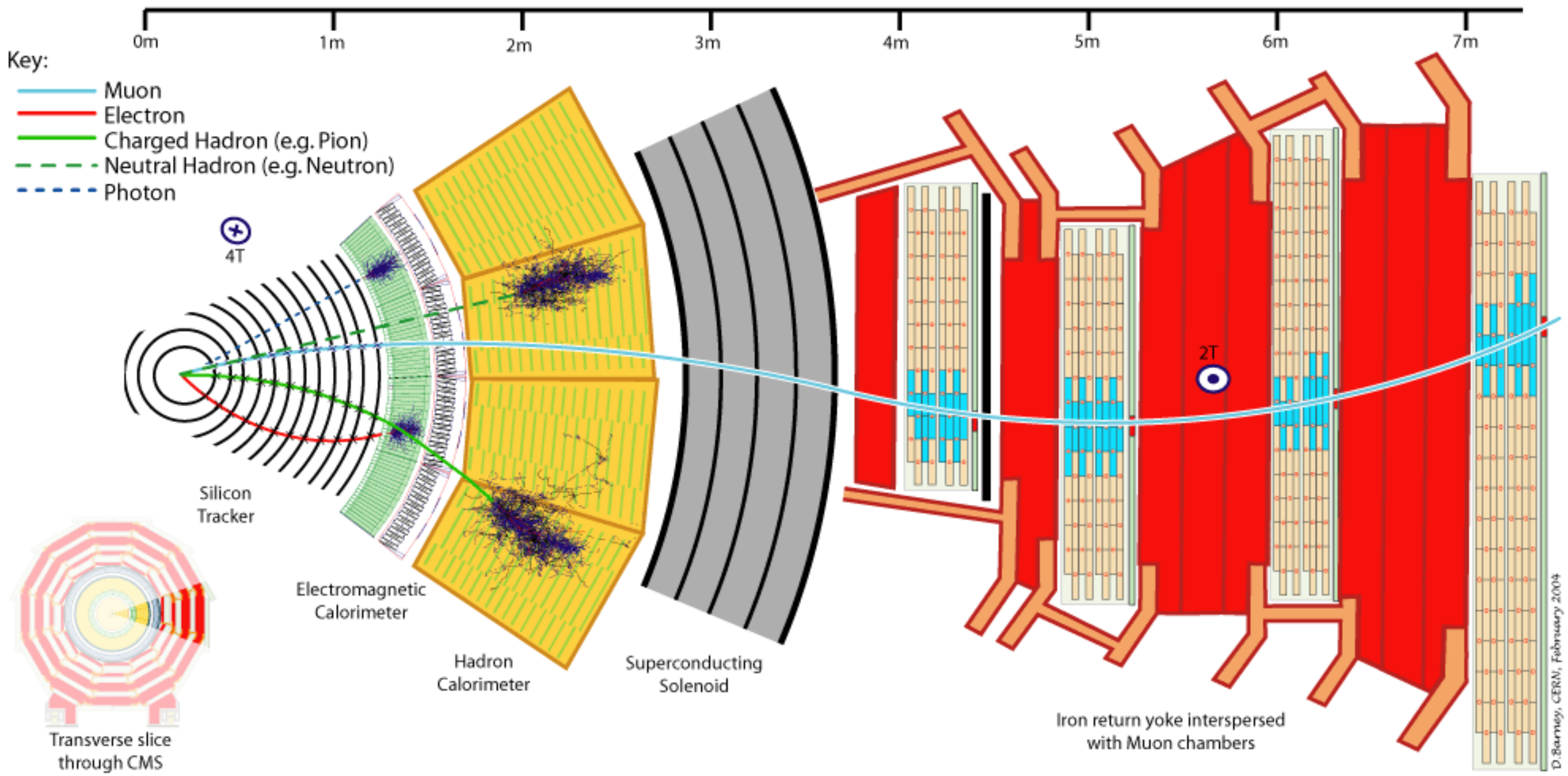
Large Hadron Collider

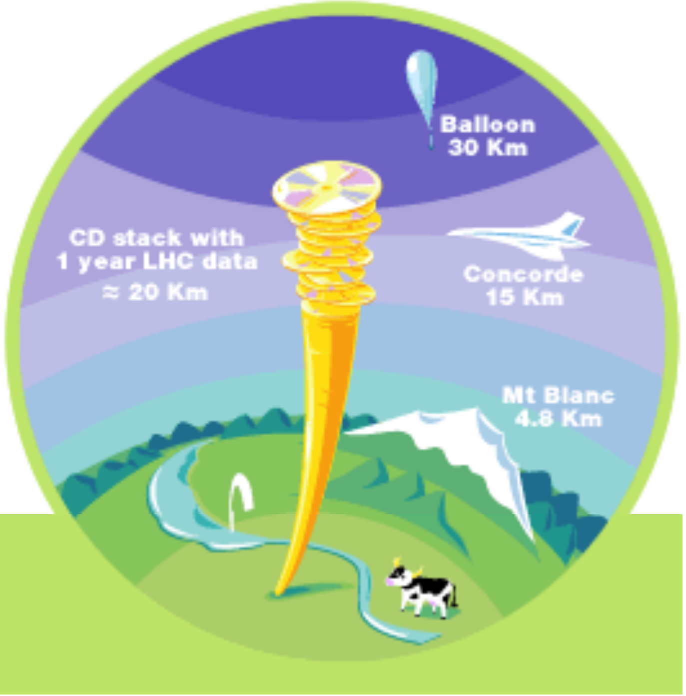


CMS detector



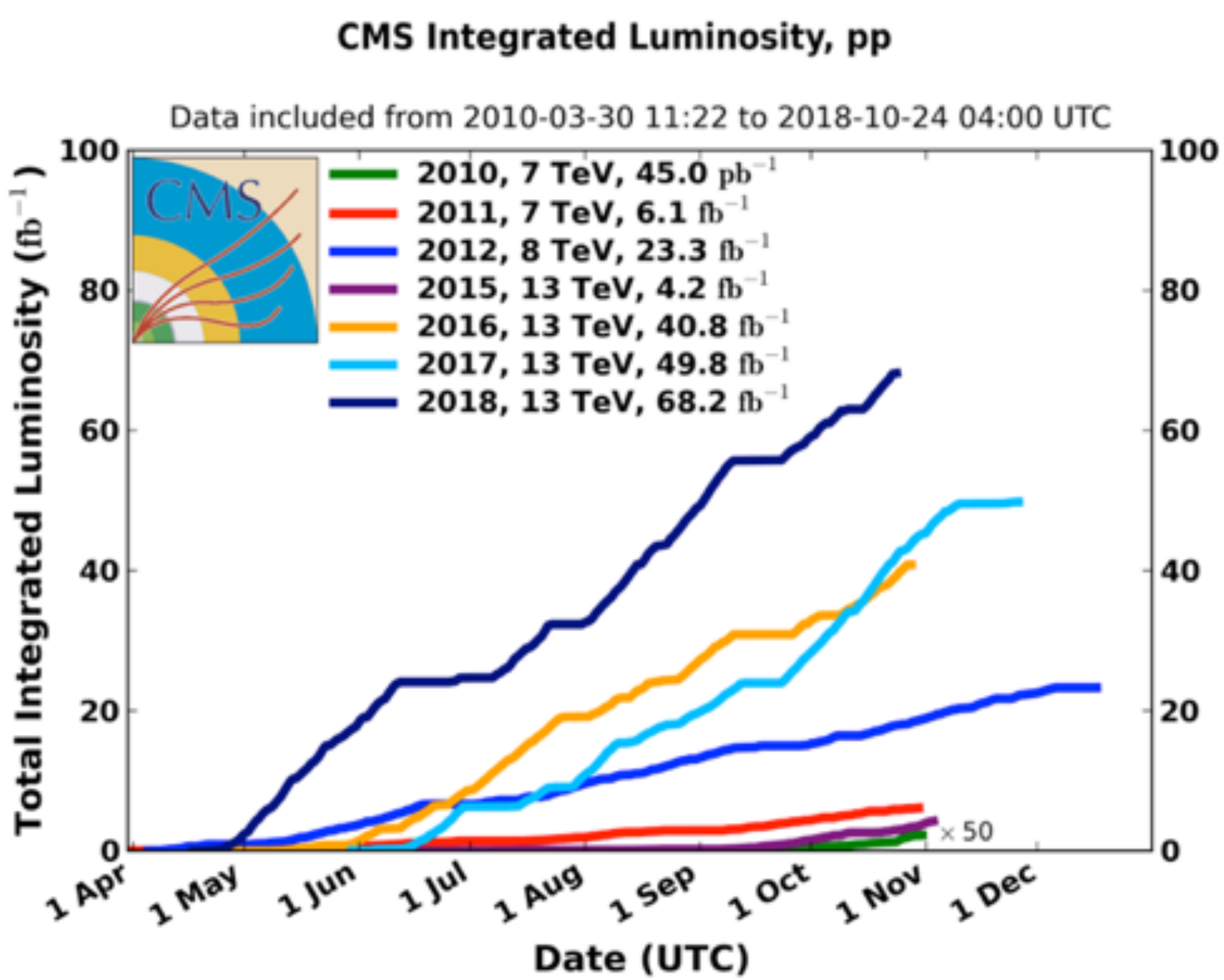
People

Grid computing

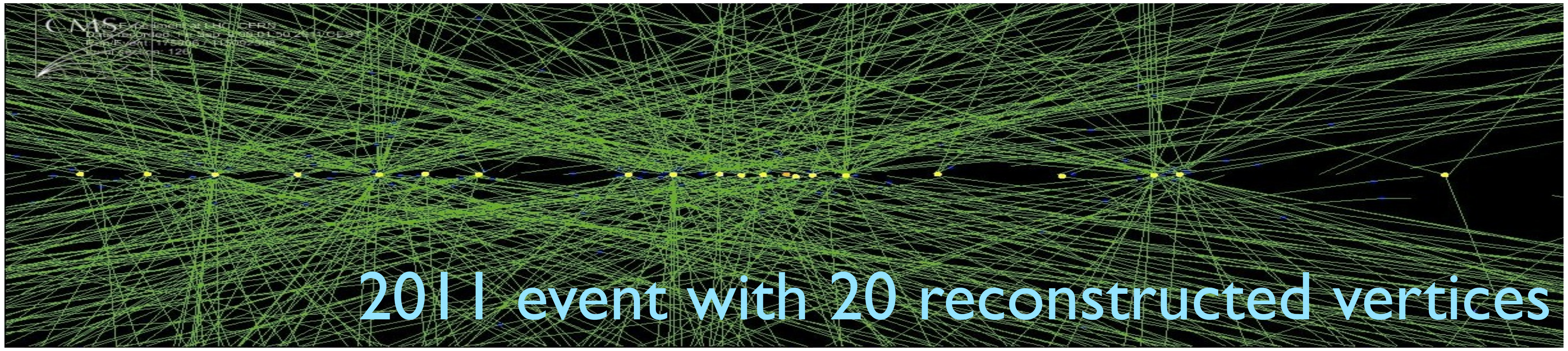


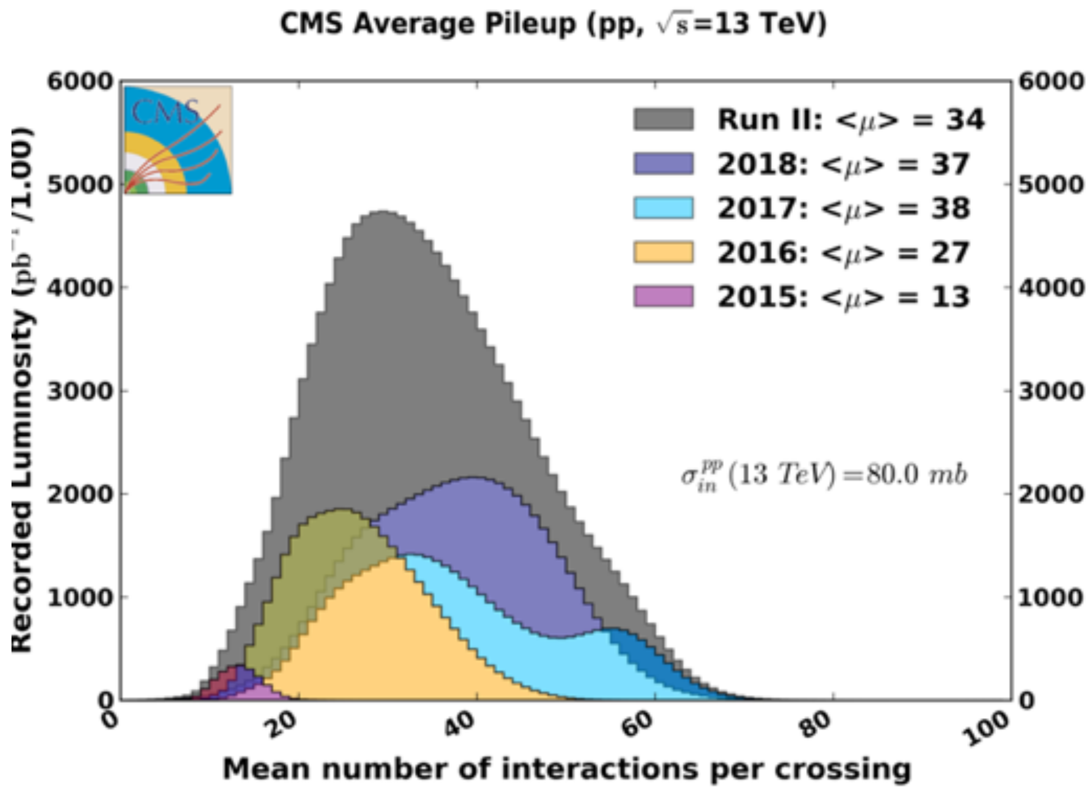
Luminosity from 2010 to 2018

- CMS performance
  - Overall data taking efficiency ~91%
  - Average fraction of operation channel per subsystem > 98.5%



The challenge: pile-up

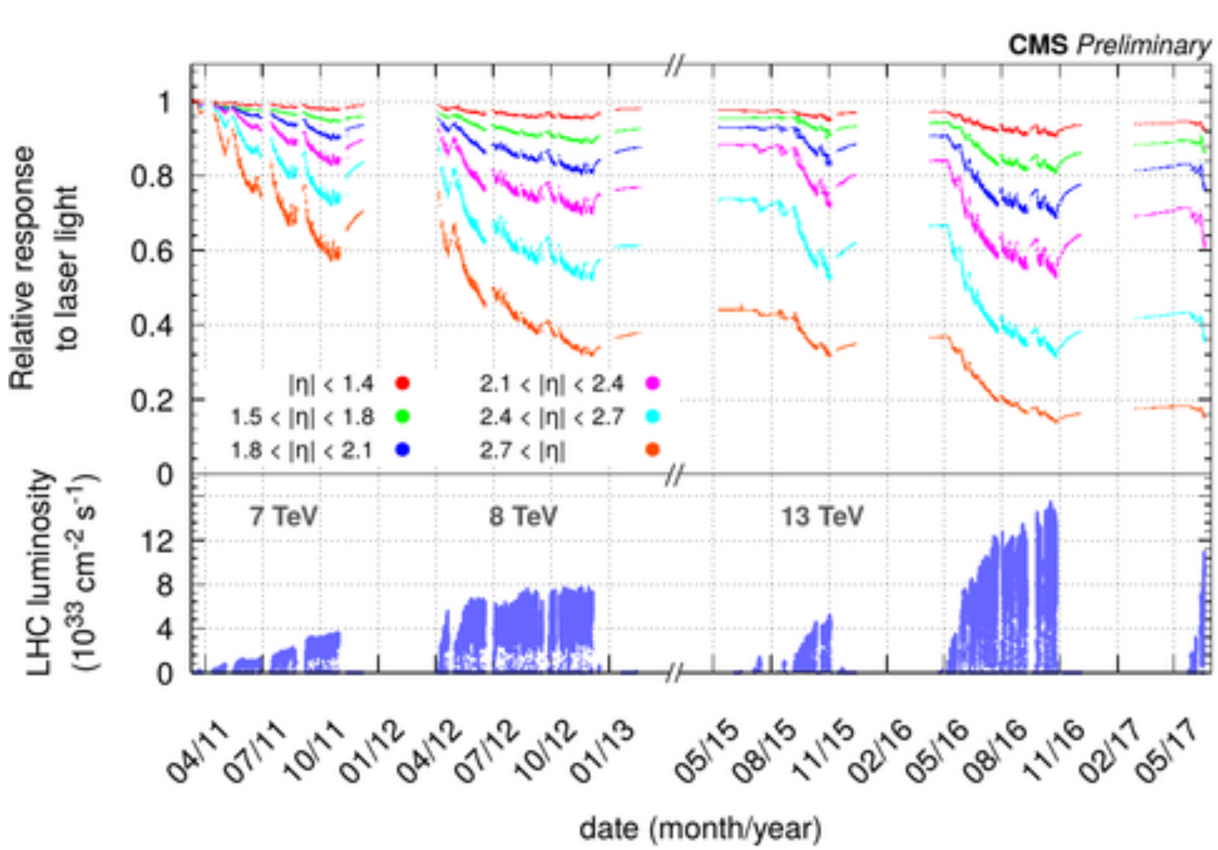


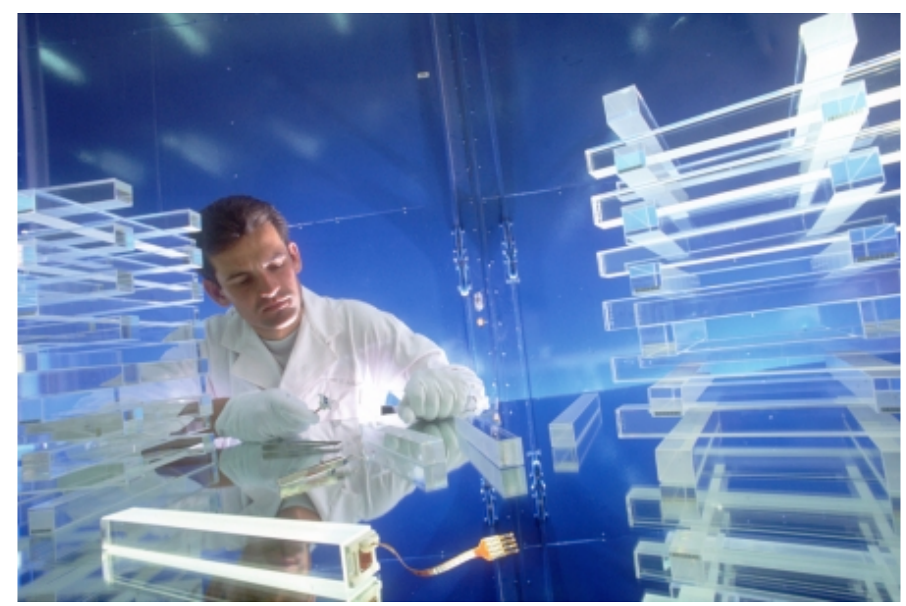


- A ZZ event can be a fake one due to pile-up
- Spoil the "isolation" and MET resolution
- Additional challenge for $H \rightarrow \gamma\gamma$ channel, where the hard-scattering vertex is often not known well
  - picking a wrong vertex would make the mass resolution worse

The challenge: detector calibration (1/2)

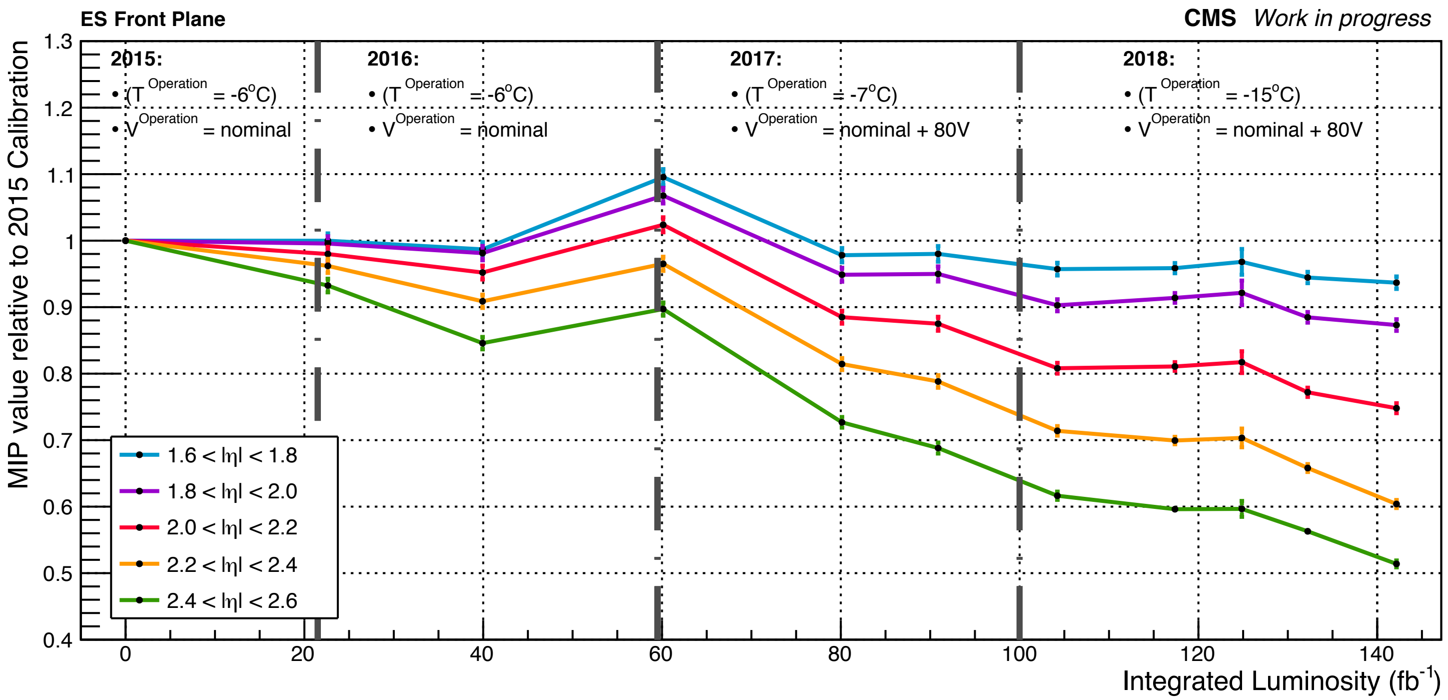
- Discovery potential depends on the di-photon invariant mass resolution
  - excellent performance of the electromagnetic crystal calorimeter needed
- Design energy resolution : ~0.5% for E_{γ} > 100 GeV for unconverted photons in the ECAL barrel
- Crucial aspect: precise calibration
  - in-situ energy calibration using $\pi^{\circ} \to \gamma\gamma$, $\eta \to \gamma\gamma$, $W \to e\nu$ E/p, $Z \to ee$
  - monitoring of transparency losses due to radiation damage with laser system

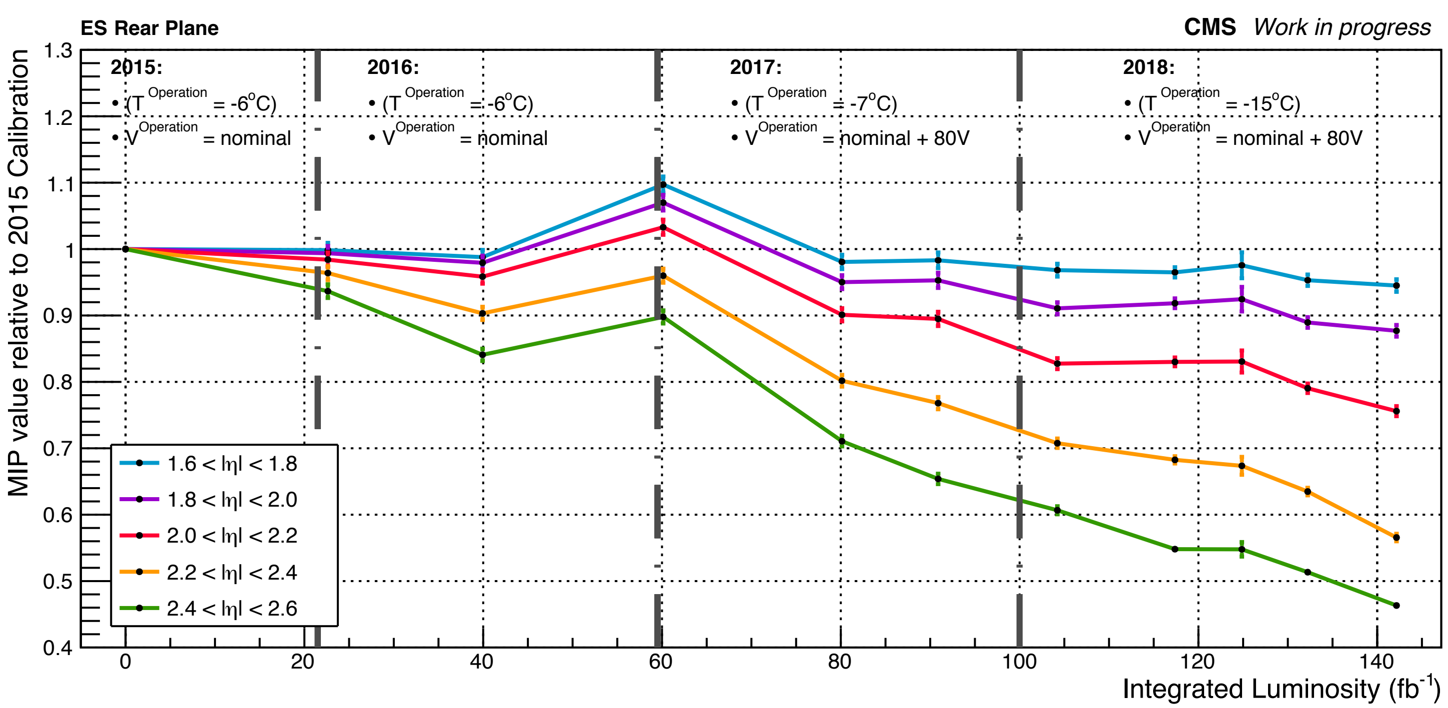


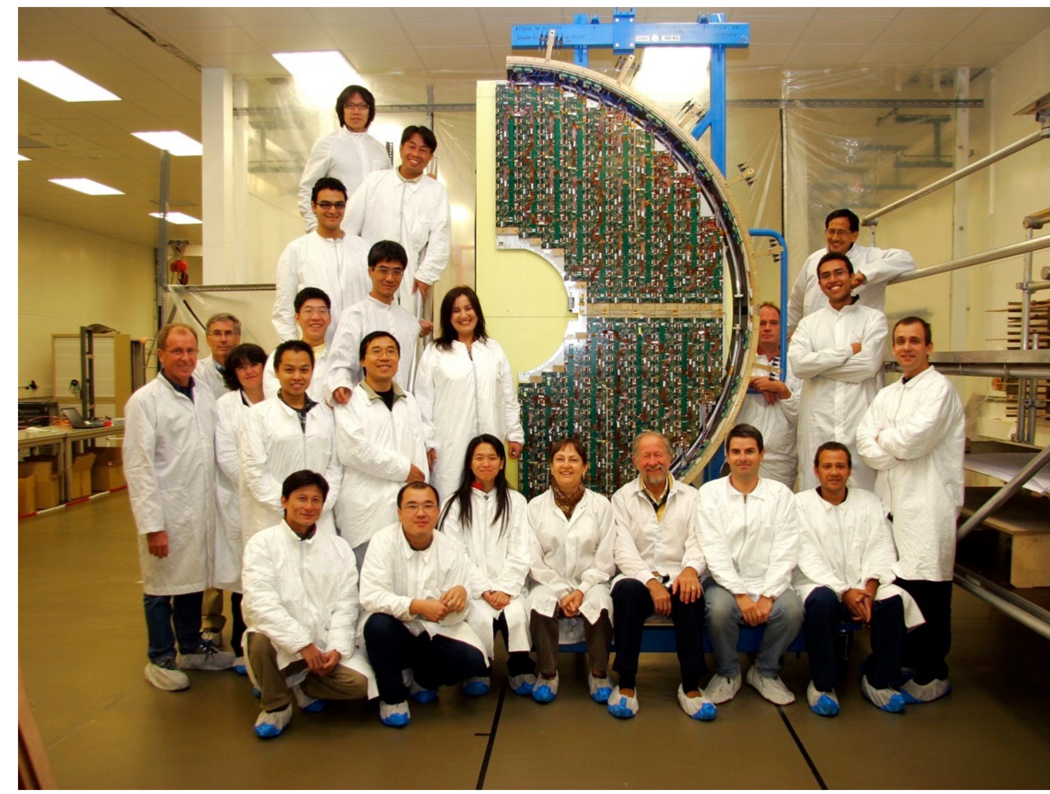


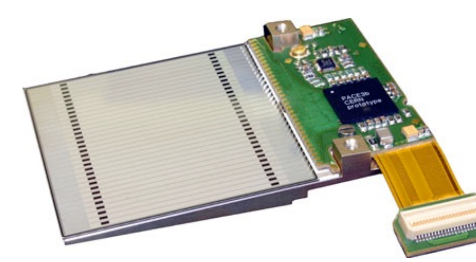
76K $PbWO_4$ crystals organized in barrel (|η| < 1.48) and endcap (1.48 <|η| < 3)
A Pb-Si Preshower in endcap

The challenge: detector calibration (2/2)

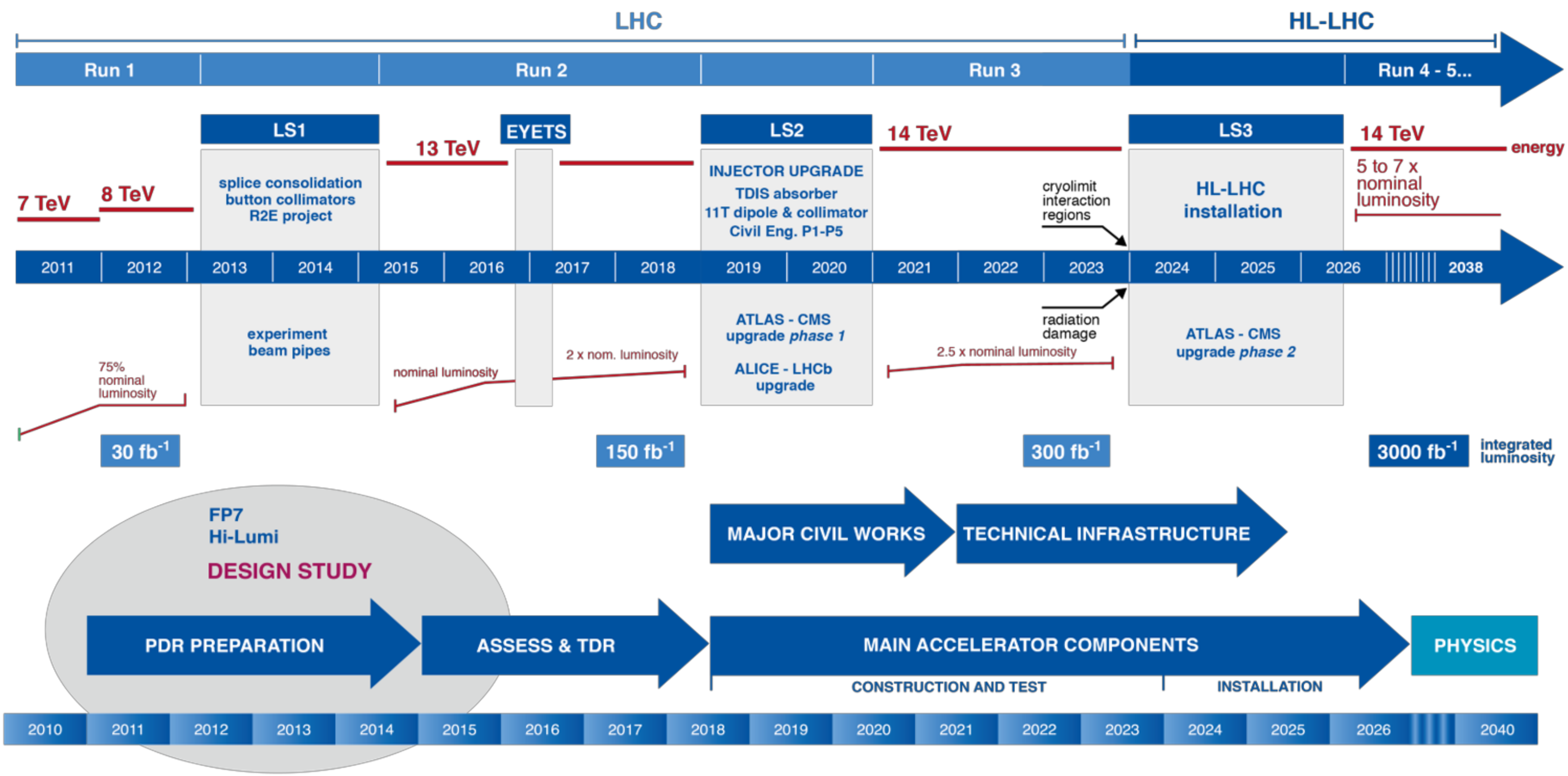






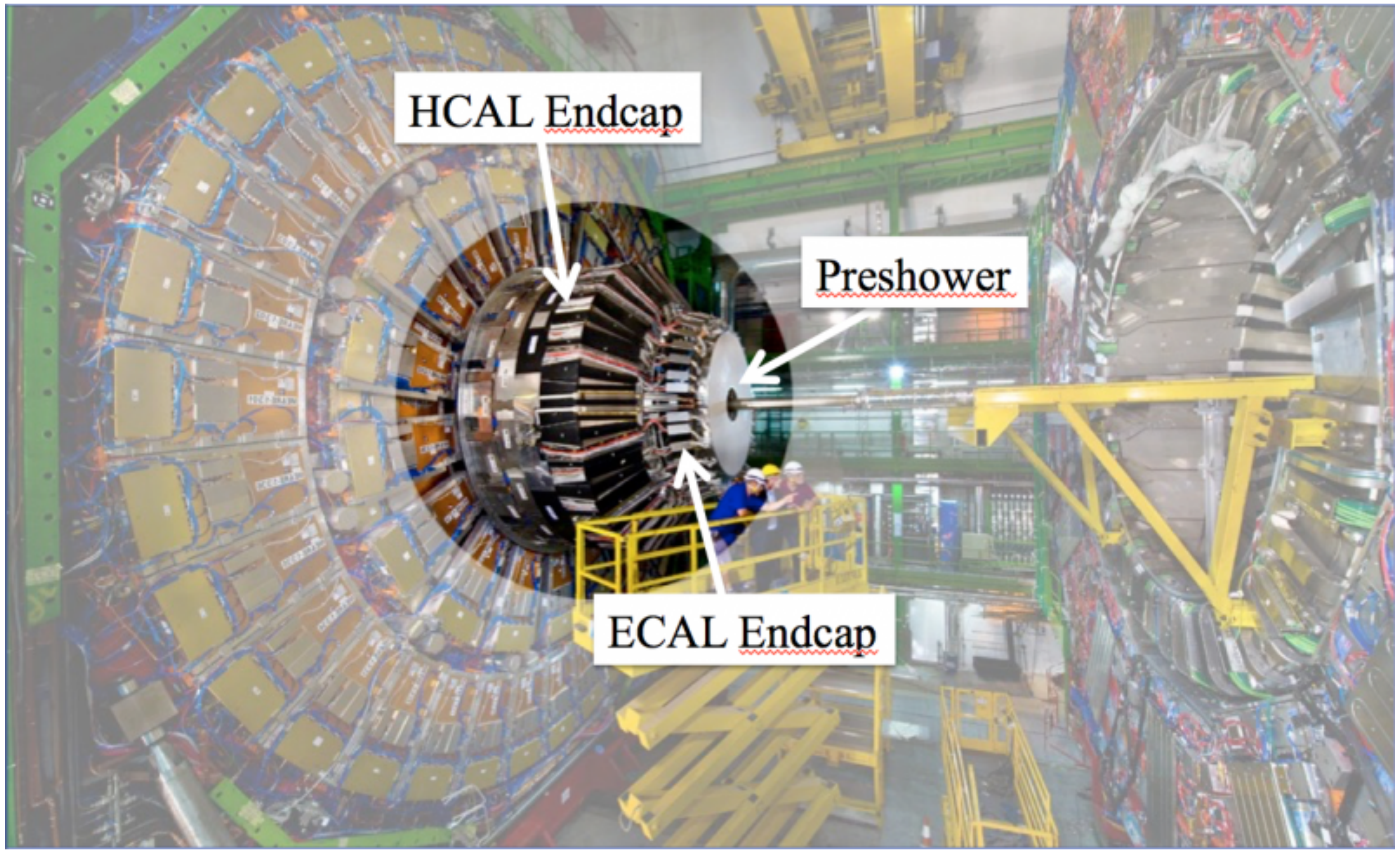


LHC schedule



CMS Phase-2 Upgrade

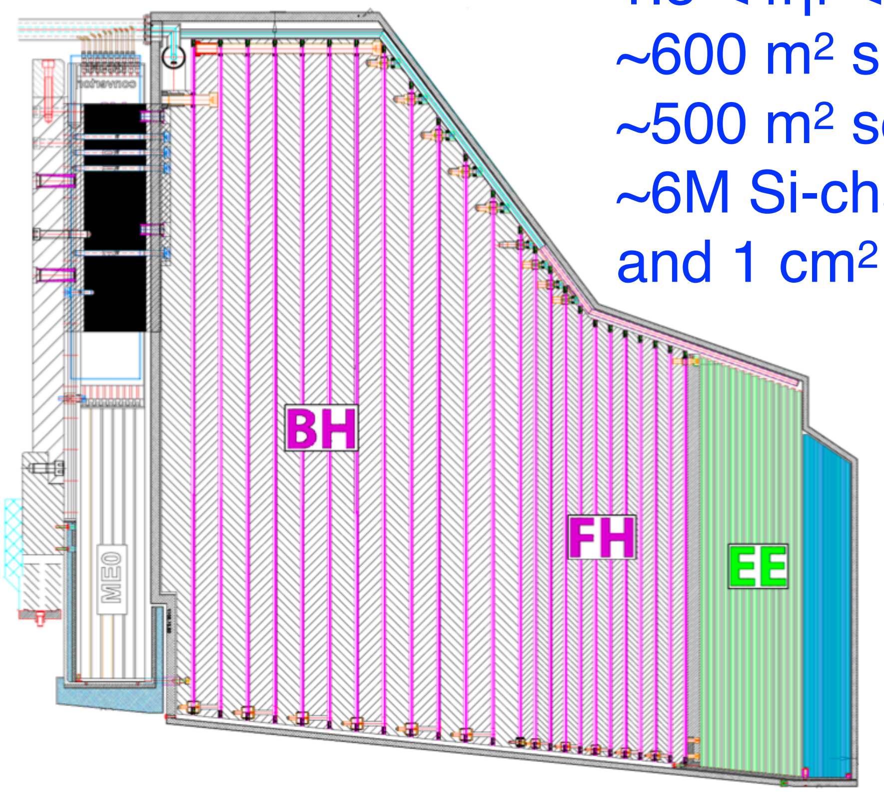
- Current CMS endcap calorimeters designed for radiation does equivalent to 500/fb
  - Replacement of CMS endcap calorimeter during HL-LHC upgrade
- Important role of the forward calorimeter for physics at the HL-LHC
- Detector upgrade important to maintain excellent performance in the harsh HL-LHC

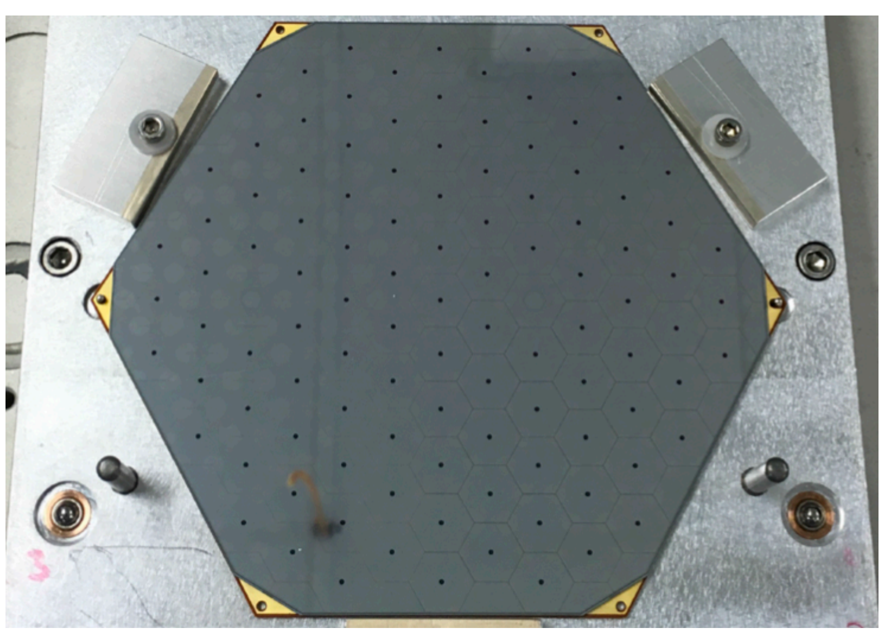


CMS HGCal in a nutshell

Key parameters :

1.5 < lηl < 3.0
~600 m² silicon
~500 m² scintillator
~6M Si-channels, 0.5 and 1 cm² cell-size





	Sensor	Absorbers	Sampling laters and depth
EE (CE-E)	Silicon	Cu, CuW, Pb	28 : 25 X_0, ~1.3λ
FH/BH (CE-H)	Silicon & Scintillator	stainless steel	24 : ~8.5λ

- Active elements :
  - Silicon sensor based hexagonal modules in CE-E and high-radiation regions of CE-H
  - Scintillators with SiPM readout in low-radiation region of CE-H
  - "Cassettes" : Multiple modules mounted on cooling plates with electronics and absorbers

Fine-grained calorimetry was studied before for linear collider detector concepts

Why beam tests ?

- Proof of concept of the baseline design
- Study the calorimeter performance
  - pedestal and noise stability
  - calibration of MIPs
  - response to electrons and hadrons
  - comparison of test beam results with the simulation

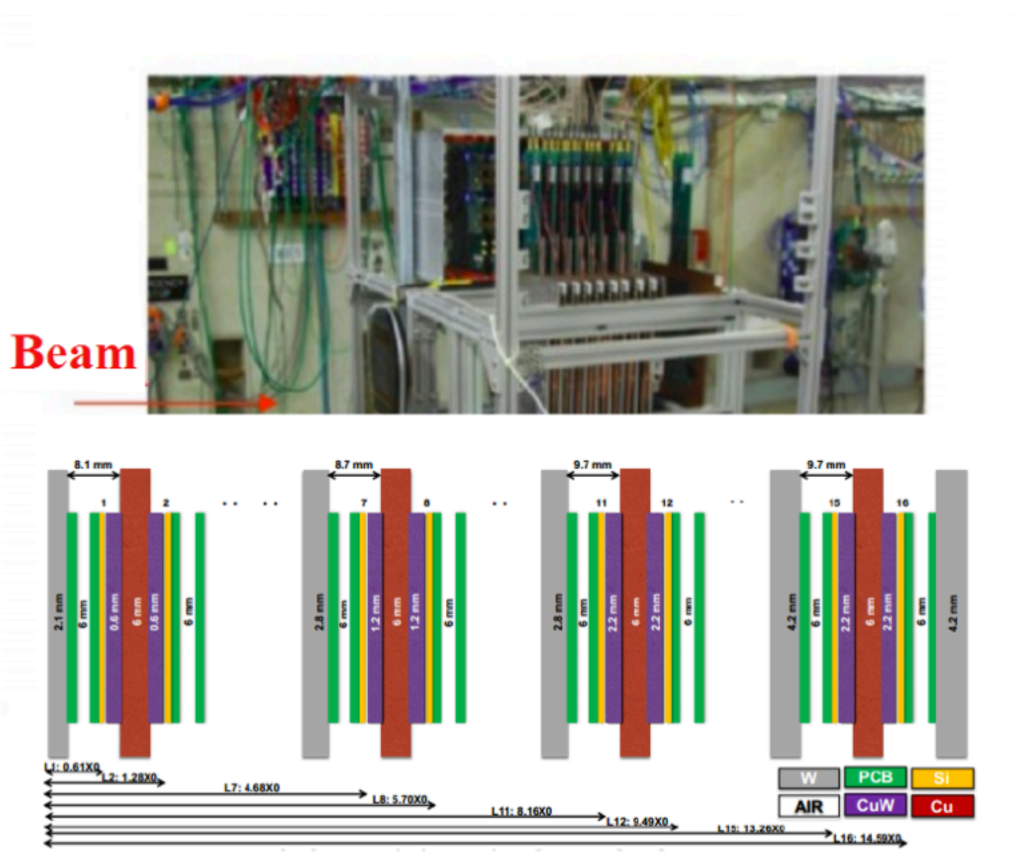
HGCal beam tests @ CERN in 2016 , 2017 and 2018

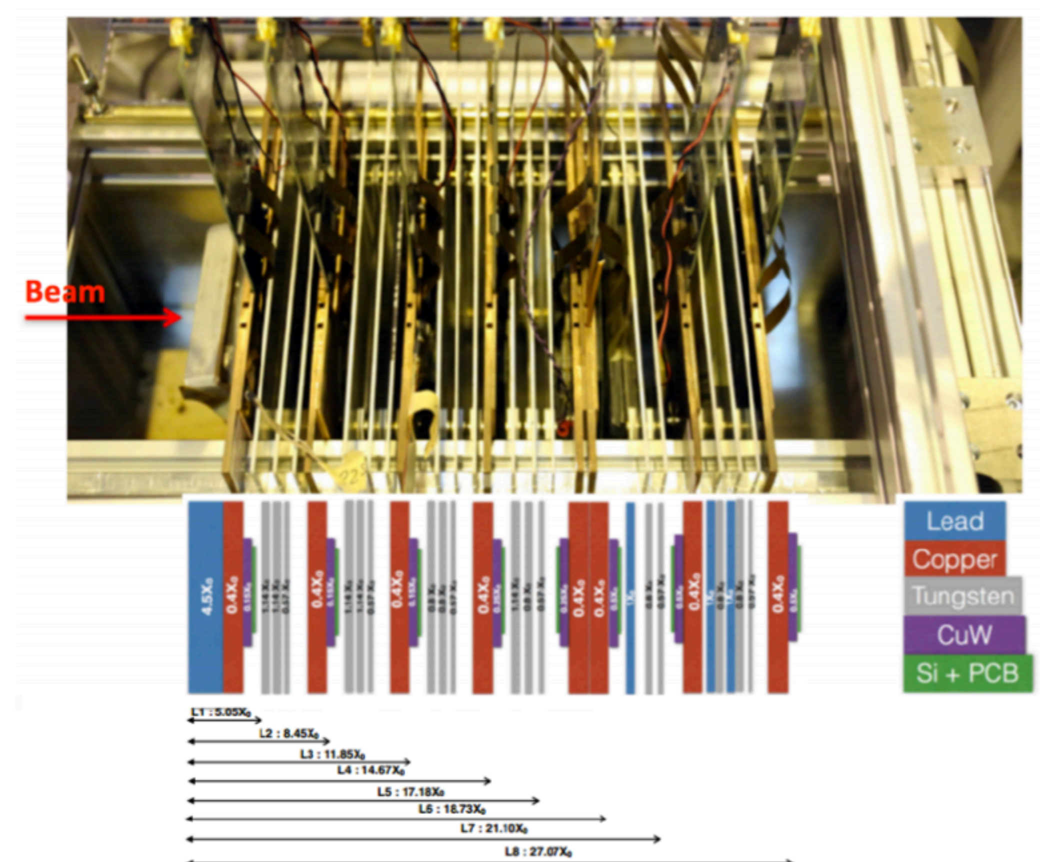
Beam test @ CERN H2

Beam tests in 2016

- FNAL : 16 Si modules, 15 X_0, e beam (4-32 GeV), p beam (120 GeV) for calibration
- CERN : 8 Si modules, 5-27 X_0 and 6-15 X_0, e beam (20-250 GeV), π beam (125 GeV), μ (120 GeV) for calibration

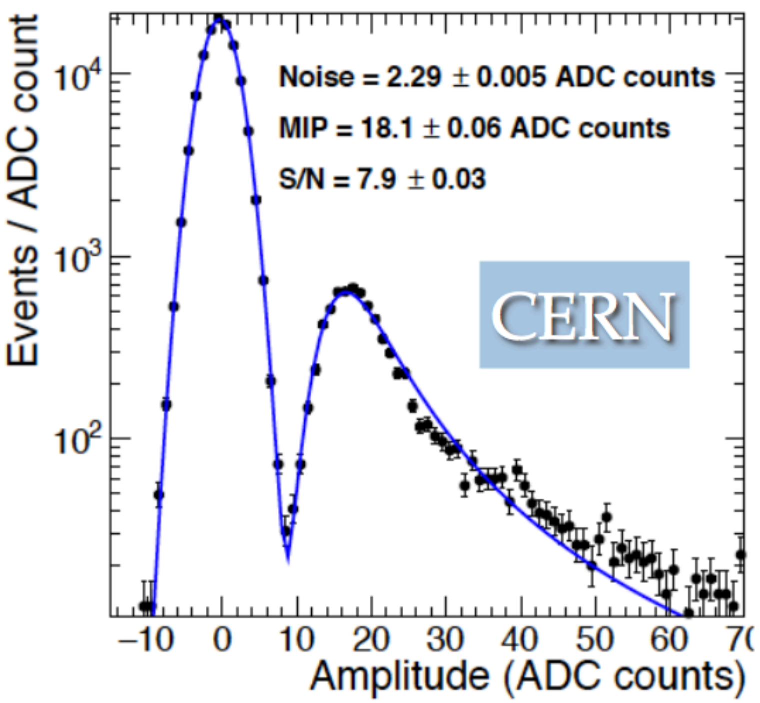
FNAL

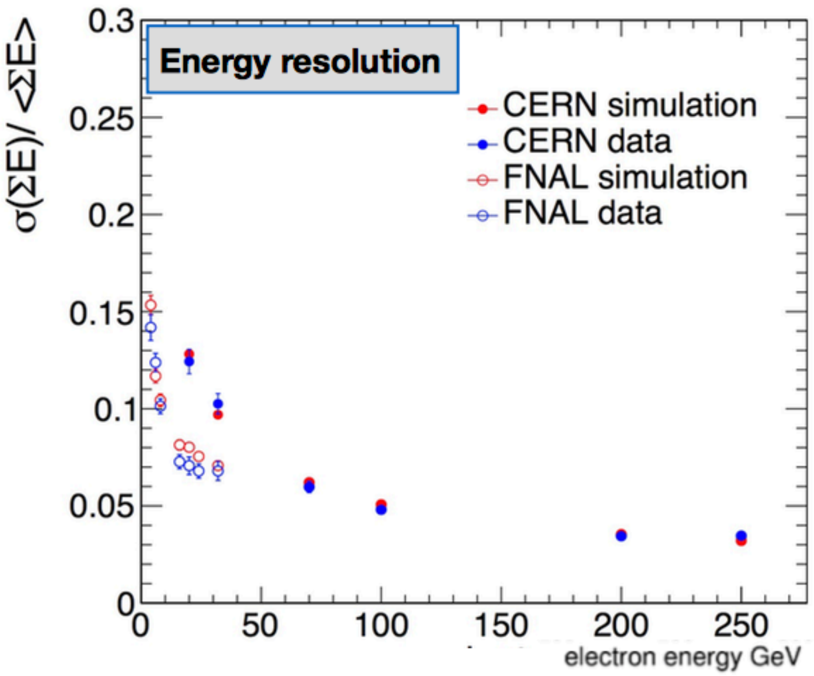


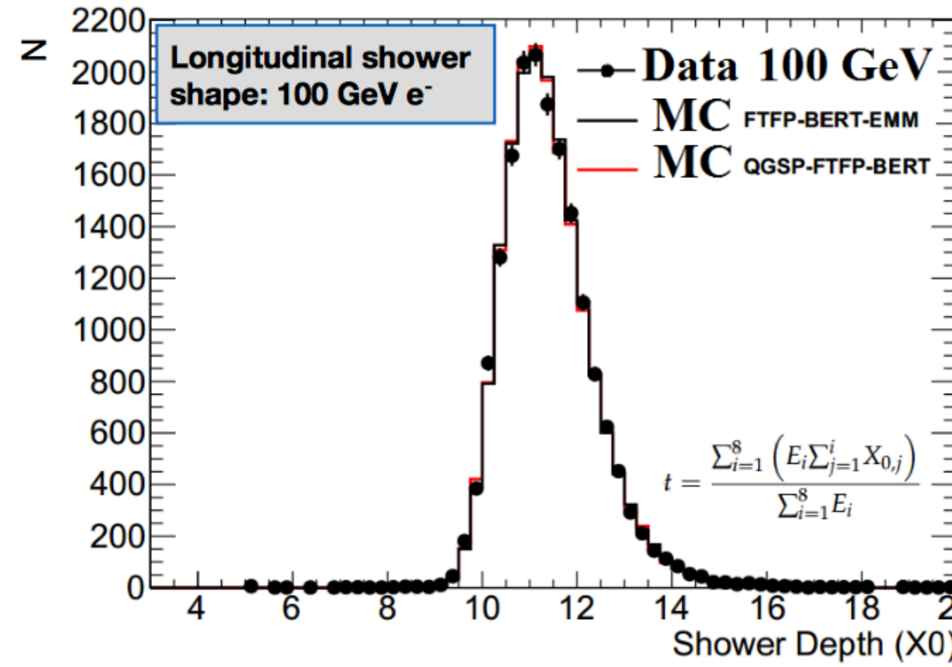


CERN

Results from 2016 beam tests



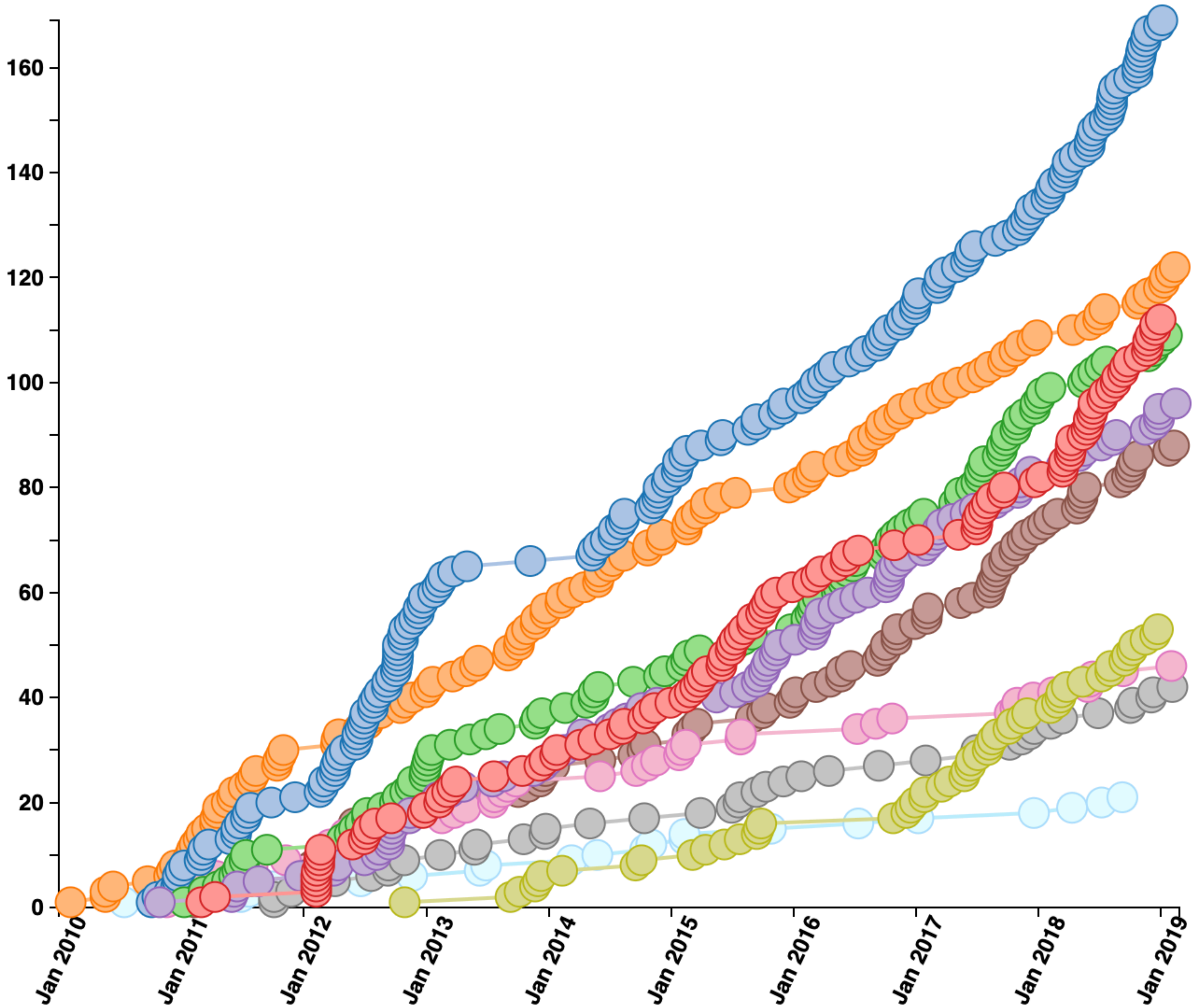




- Overall agreement between dat ana simulation within ~percents
- Main results from 2016 were published in JINST

Number of publications

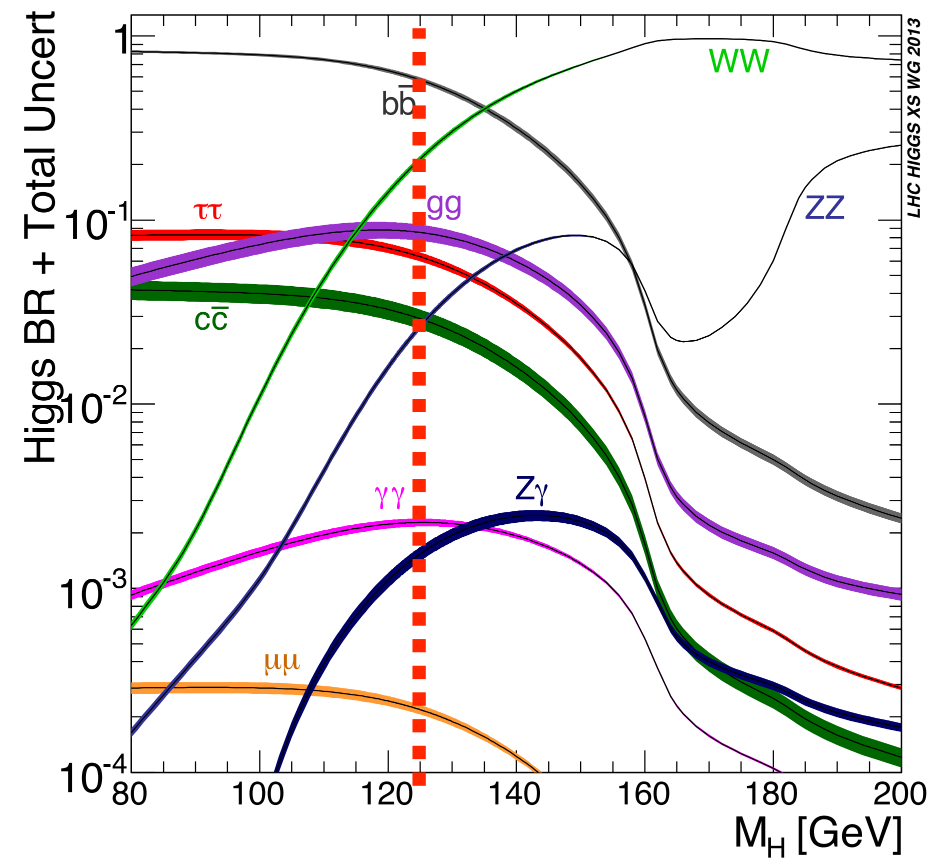
857 collider data papers submitted as of 2019-02-25

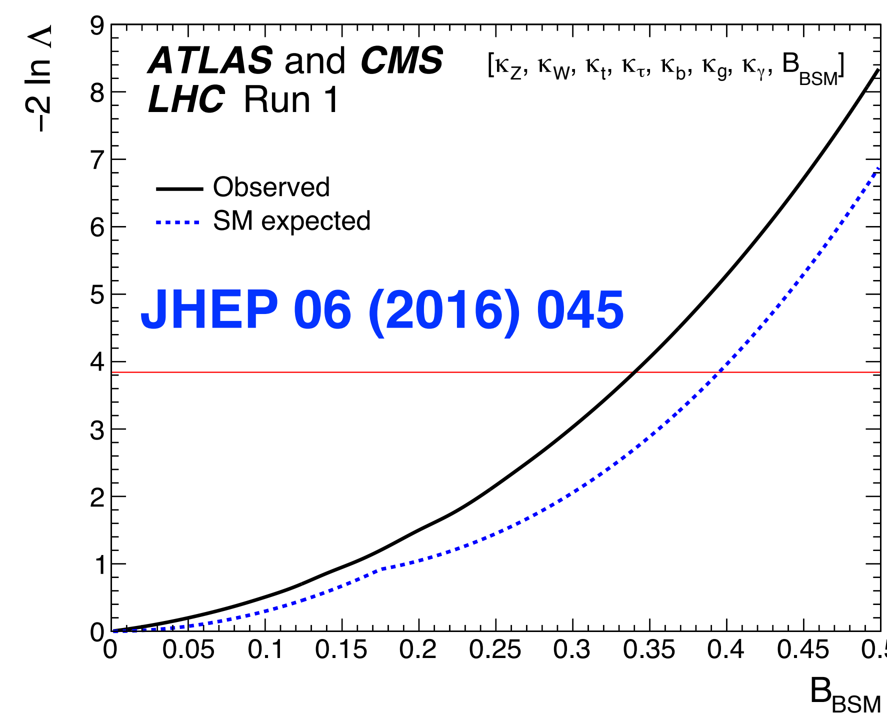


- Rare Higgs decays
    - $H \to ll\gamma$
    - $H \to \mu\mu$
    - $H \to$ invisible

Motivation

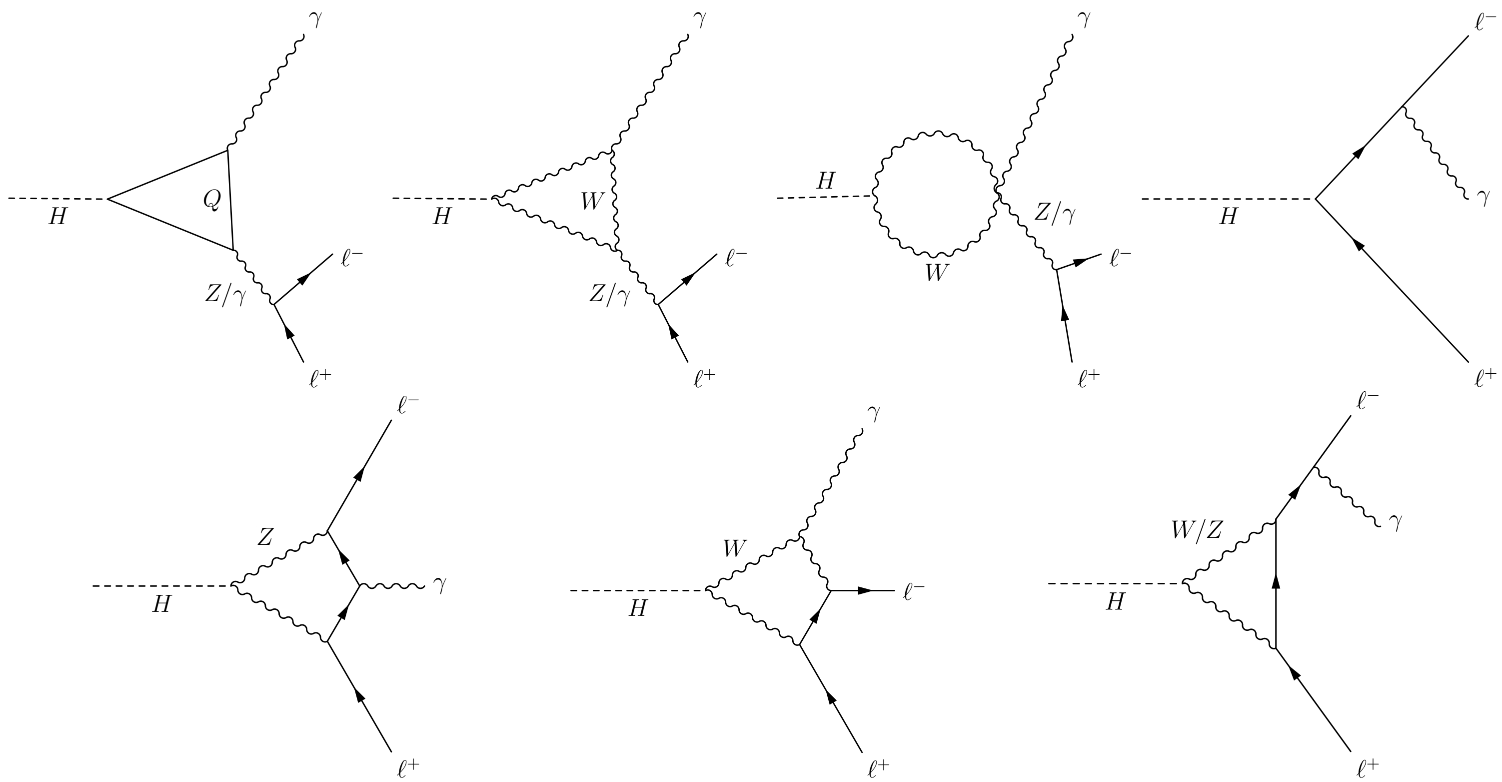
- Higgs boson has been observed in several decay channels
    - current studies of its properties are consistent with the SM predictions
- Several rare decays have not been observed
    - an excess would be a clear indication of new physics
- Several BSM theories predict exotic decays
- potential invisible or undetectable $B_{BSM} < 34\%$ (39% exp.) @ 95% C.L. with Run-I data
    - still allow ample space to look for BSM Higgs decays
- provide an excellent opportunity to look for new physics !





$H \to Z/\gamma^* + \gamma \to ll\gamma$

CMS HIG-17-007

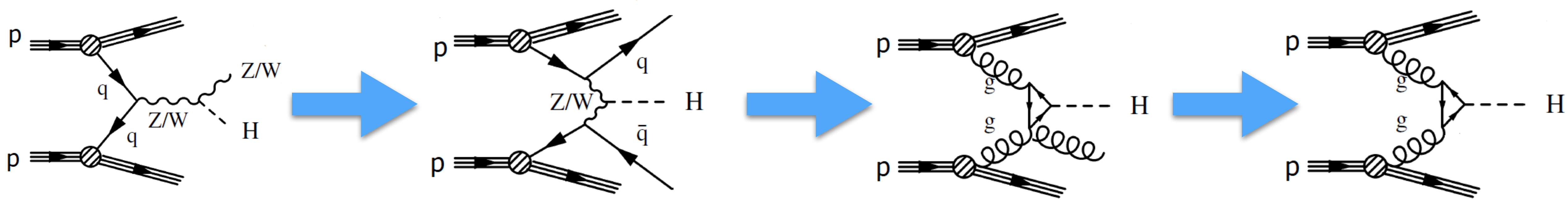


loop induced decay
→ sensitive to physics beyond SM

- Signature: an opposite-sign isolated lepton pair and an isolated photon
  - a clean final-state with good mass resolution
- the threshold, m_{ll} = 50 GeV, is used to separate $H \to Z\gamma$ and $H \to \gamma^*\gamma$
- In SM, $\frac{\Gamma(\mathrm{H} \to \gamma^*\gamma \to \mu\mu\gamma)}{\Gamma(\mathrm{H} \to \gamma\gamma)} = (1.69 \pm 0.10)\%$, $\frac{\Gamma(\mathrm{H} \to Z\gamma \to \ell\ell\gamma)}{\Gamma(\mathrm{H} \to \gamma\gamma)} = (2.27 \pm 0.14)\%$

$H \to Z\gamma \to ll\gamma$ (l = e, μ) CMS HIG-17-007

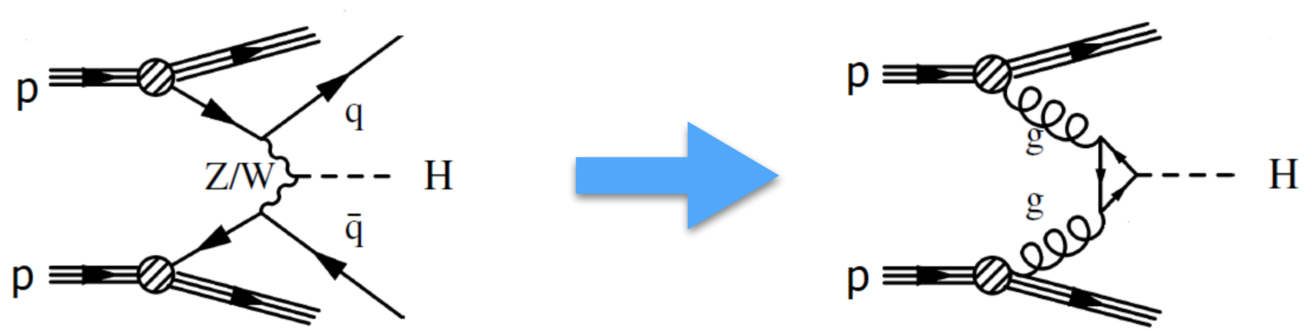
- $BR(H \to Z\gamma) = 1.533 \times 10^{-3}$
- signal yield is similar to $H \to ZZ \to 4l$ but suffers from large background ($Z\gamma$, Z+jets)
- 7 mutually exclusive categories used to differentiate production modes, increase S/B, and enhance the peak resolution
  - sensitivity enhanced by 18%



lepton tag	**di-jet tag**	**boosted tag**	**4 untagged categories**
electron $p_T > 7$ GeV **muon $p_T > 5$ GeV**	**$\Delta\eta_{jj} > 3.5$, $m_{jj} > 500$ GeV** **Zeppenfeld < 2.5** **$\Delta\Phi(ll\gamma, jj) > 2.4$**	**$p_T^{ll\gamma} > 60$ GeV**	**enhance $ll\gamma$ mass resolution and S/B**

$H \to \gamma^*\gamma \to ll\gamma$ ($l = \mu$) CMS HIG-17-007

- $BR(H \to \gamma^*\gamma \to \mu\mu\gamma) = 3.83 \times 10^{-5}$
- unique event topology → two collimated leptons from γ* decay
  - challenge in trigger and identification
  - smaller signal yield but better sensitivity than H→Zγ
- reject J/ψ+γ and Υ+γ with $m_{\mu\mu}$
- 4 mutually exclusive categories used to differentiate production modes, increase S/B, and enhance the peak resolution
  - sensitivity enhanced by 11%



di-jet tag

$\Delta\eta_{jj} > 3.5$, $m_{jj} > 500$ GeV
Zeppenfeld < 2.5
$\Delta\Phi(ll\gamma, jj) > 2.4$

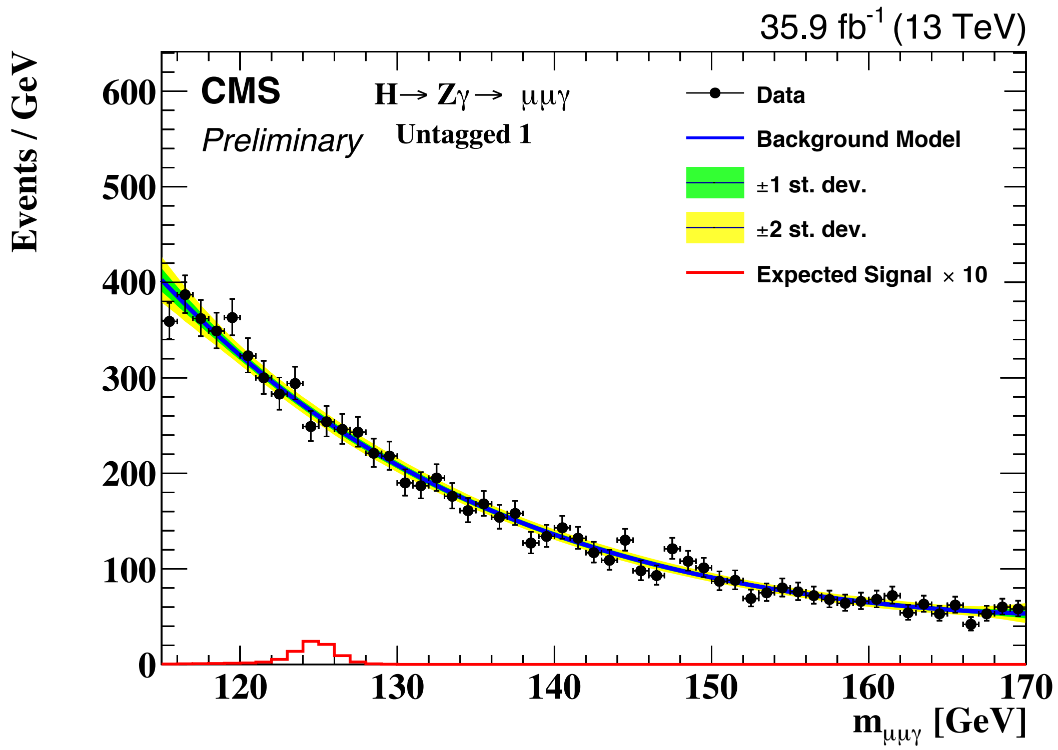
3 untagged categories

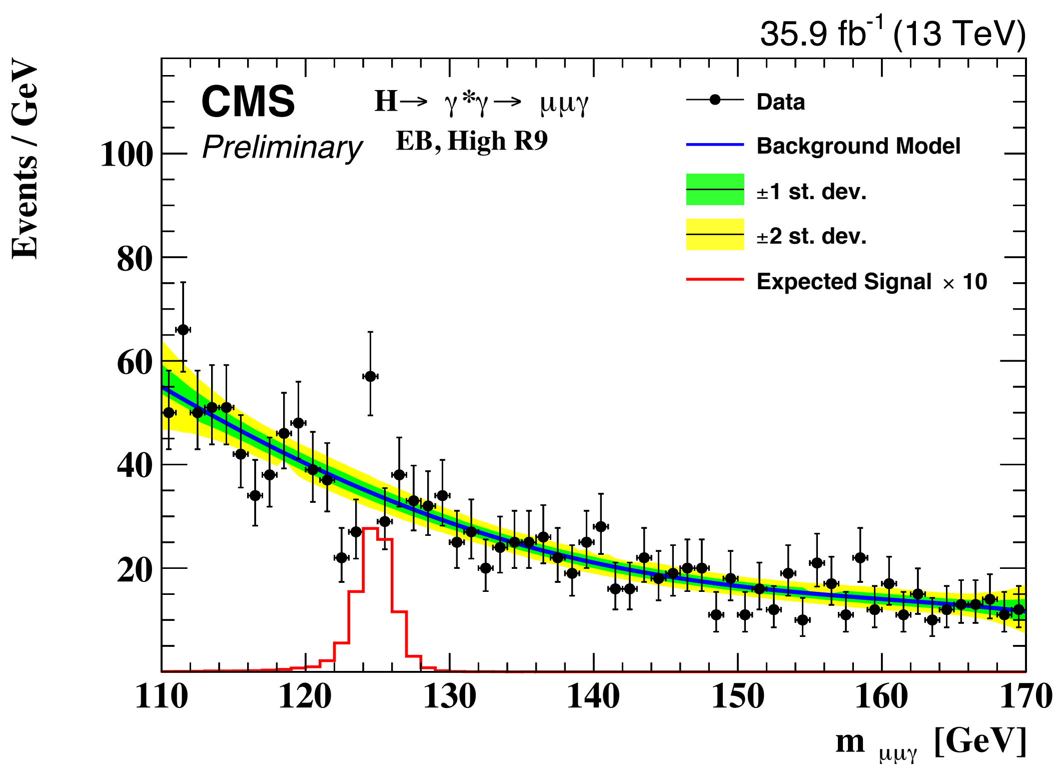
enhance llγ mass resolution and S/B

Signal extraction

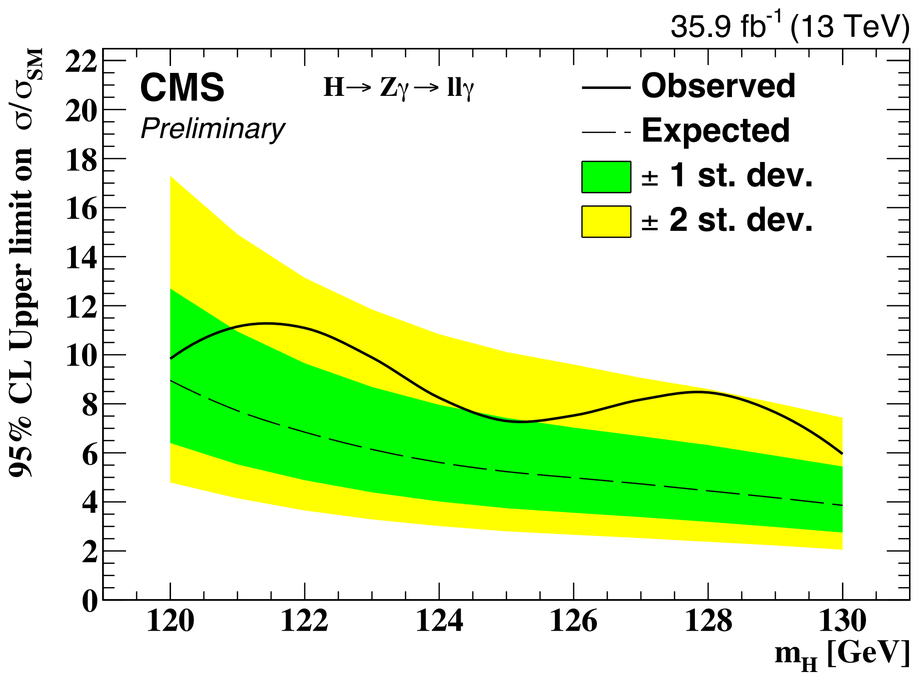
CMS HIG-17-007

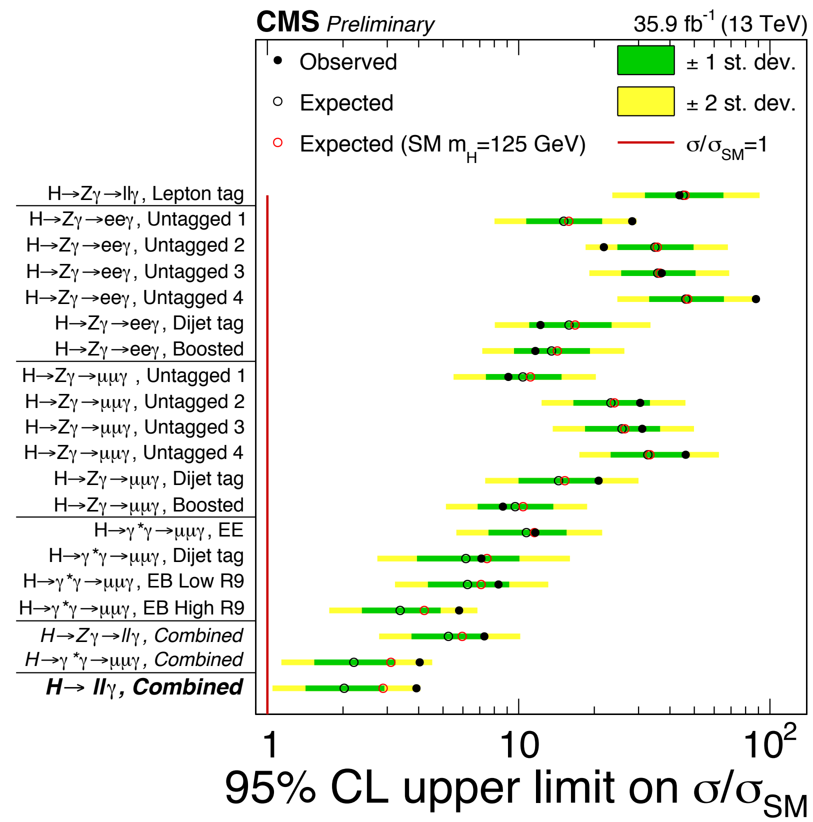
- background fit function minimizes the bias introduced by selected shape
- data are fitted by smoothly falling functions to determine the background
- signal is modeled with a double sided Crystal Ball function and a Crystal Ball function plus an additional Gaussian function for γ*γ and Zγ

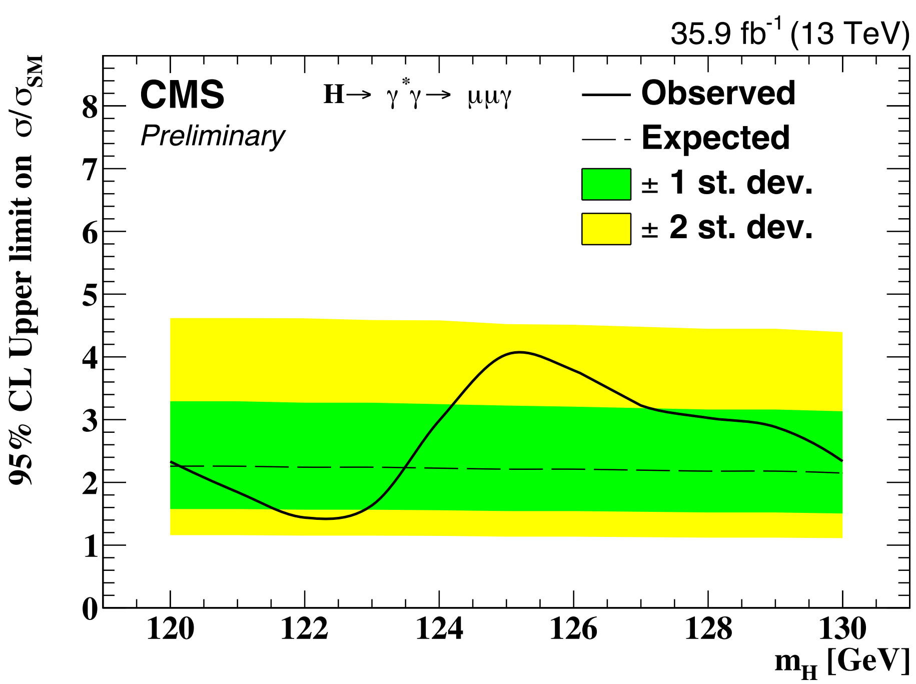


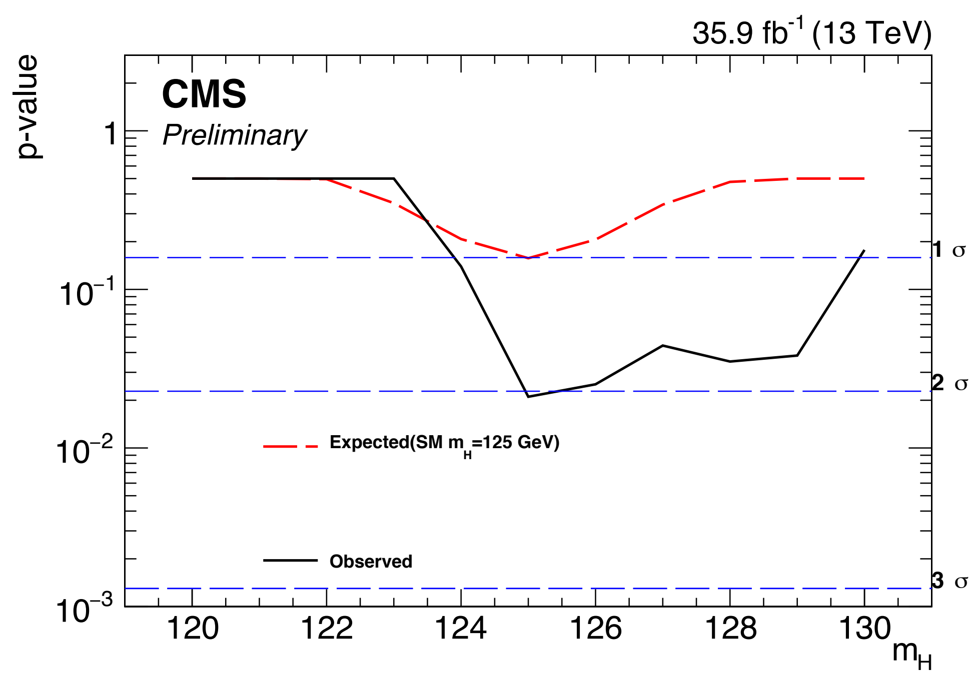


Results of H→Zγ and γ*γ







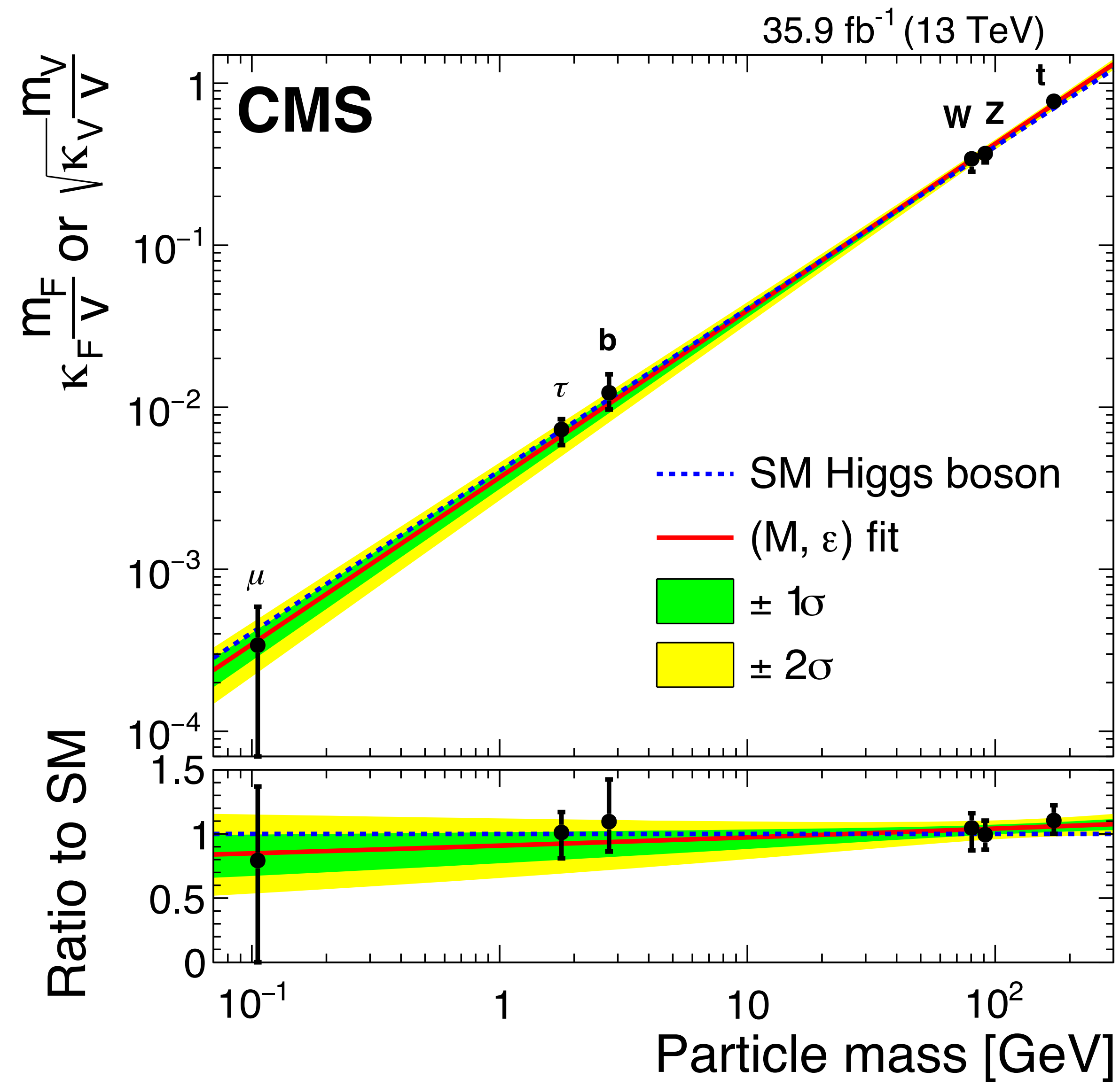


CMS HIG-17-007

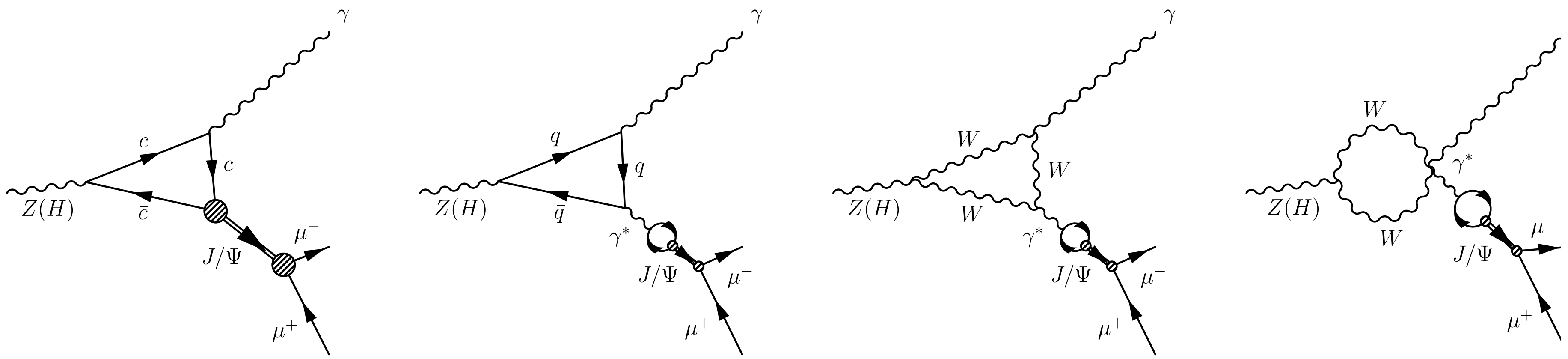
- observed (expected) upper limit for σ/σ_{SM} is 3.9 (2.0)
- corresponding to an observed (expected) p-value of ~2σ (~1σ)

$H \to J/\Psi + \gamma \to \mu\mu\gamma$

- $H \to J/\Psi + \gamma$ is sensitive to the Higgs-charm coupling
  - complementary to the inclusive decay of $H \to cc$
- $BR(H \to J/\Psi + \gamma) = 2.8 \times 10^{-6}$
- In some extensions to the SM, modified Higgs-charm coupling can arise

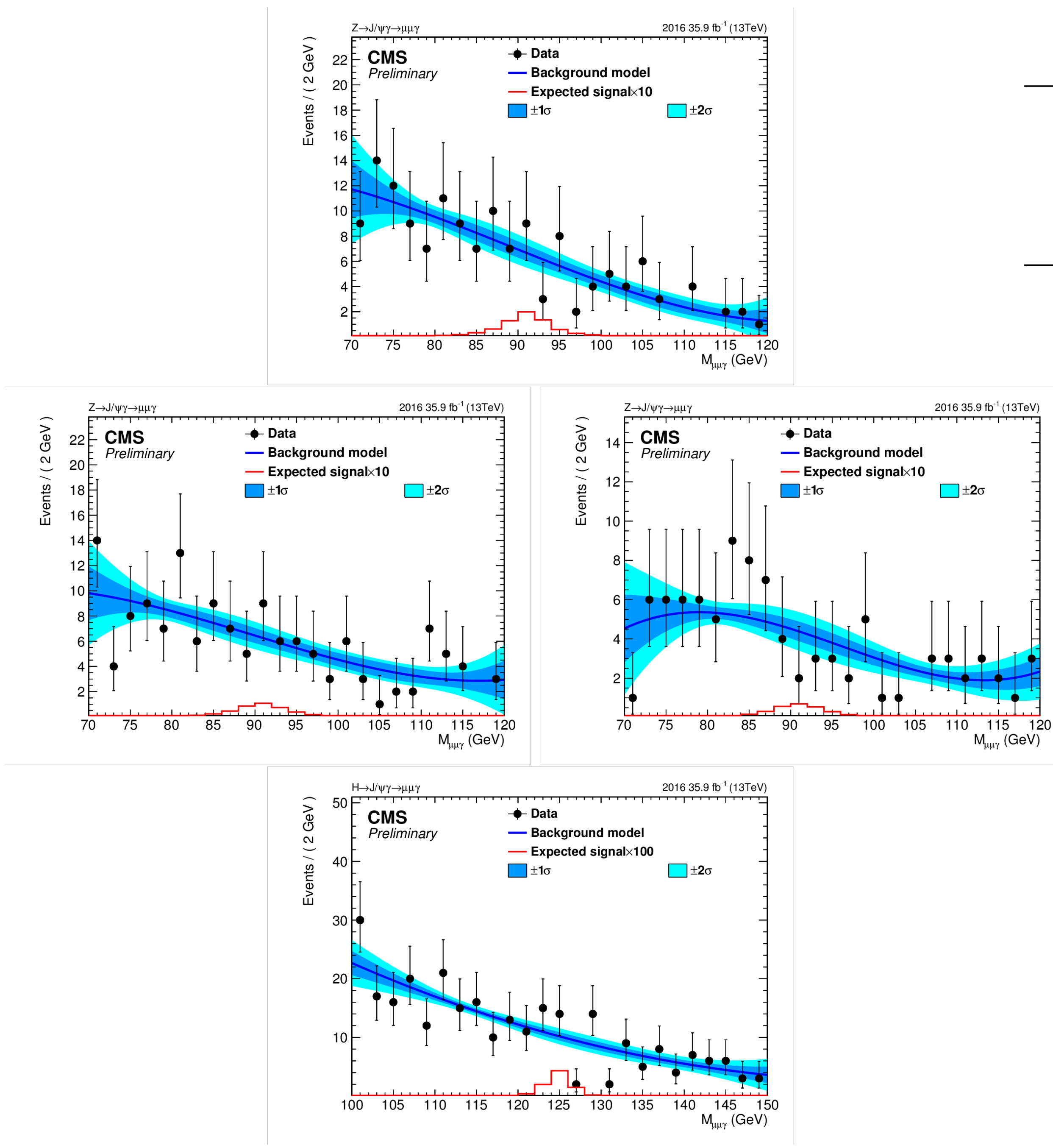


$Z \to J/\Psi + \gamma \to \mu\mu\gamma$



- Larger Z production cross section so that rare Z decays can be probed at much lower rates than for Higgs decays into the same final state
- BR($H \to J/\Psi + \gamma$) = 9.0×10^{-9}
- experimental benchmark for the Higgs boson decay
- test various QCD factorization approaches that are being used in the estimation of branching fractions for hadronic radiative decays of bosons

Results of H/Z→J/Ψ+γ→μμγ



Channel	$\sigma(fb)$ *	$\mathcal{B}(\mathrm{Z(H)} \to \mathrm{J}/\psi\,\gamma)$	$\frac{\mathcal{B}(\mathrm{Z(H)}\to \mathrm{J}/\psi\,\gamma)}{\mathcal{B}_{SM}(\mathrm{Z(H)}\to \mathrm{J}/\psi\,\gamma)}$
$\mathrm{Z} \to \mathrm{J}/\psi\,\gamma$	$4.6\ (5.3^{+2.3}_{-1.6})$	$1.4\ (1.6^{+0.7}_{-0.5}) \times 10^{-6}$	15 (17)
$\mathrm{H} \to \mathrm{J}/\psi\,\gamma$	$2.5\ (1.7^{+0.8}_{-0.5})$	$7.6\ (5.2^{+2.4}_{-1.6}) \times 10^{-4}$	260 (170)

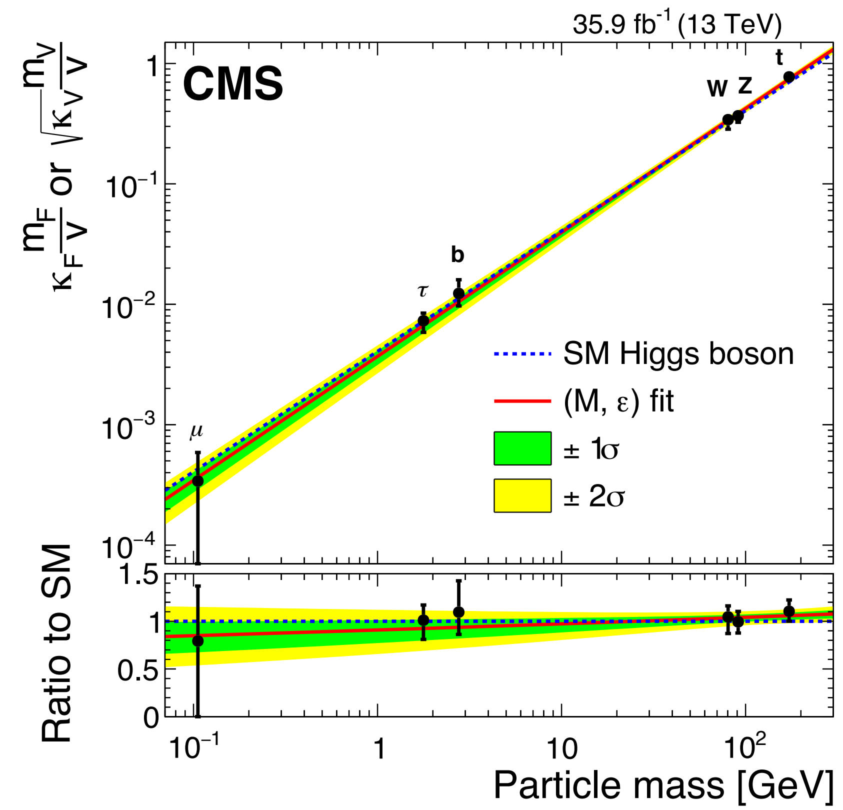
$* :\ \sigma(\mathrm{pp} \to \mathrm{H(Z)} \to (\mathrm{J}/\psi \to \mu\mu)\gamma)\ (fb)$

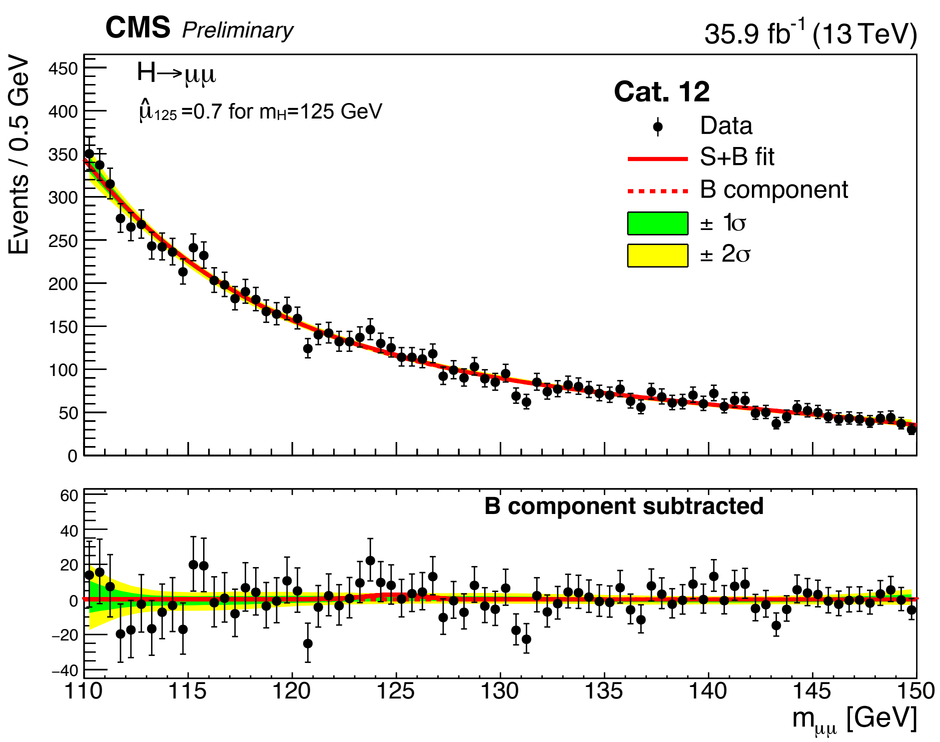
- In the case of Higgs, it's very challenging even for HL-LHC

$H \to \mu\mu$

CMS HIG-17-019

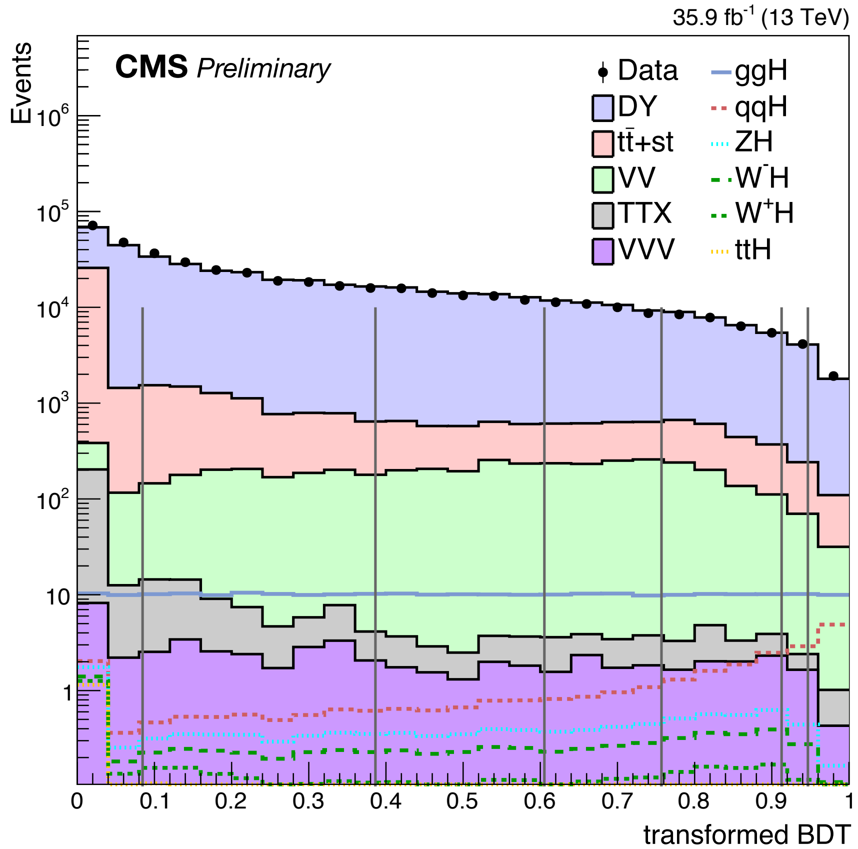
- BR($H \to \mu\mu$) = 2.18×10^{-4}
- only accessible channel to test Higgs couplings to second generation fermions at LHC
- clean fermionic decay
- search for a small peak over a large DY background
- several BSM scenarios predict a higher BR
  - deviation from SM could be a sign for new physics

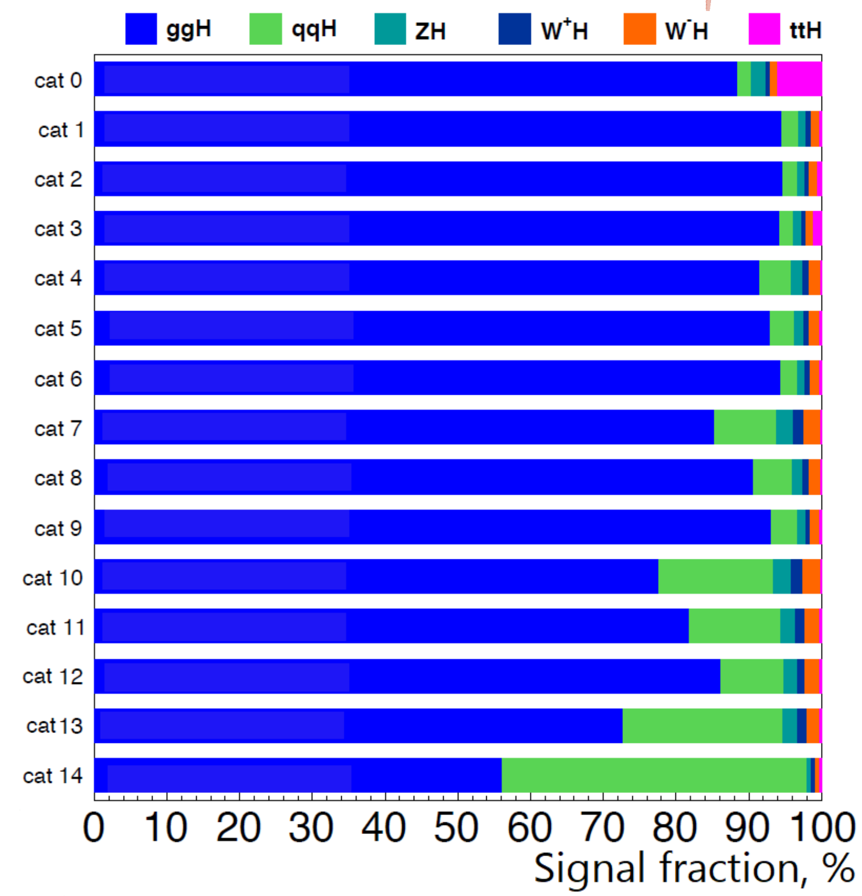




H→μμ analysis

CMS HIG-17-019

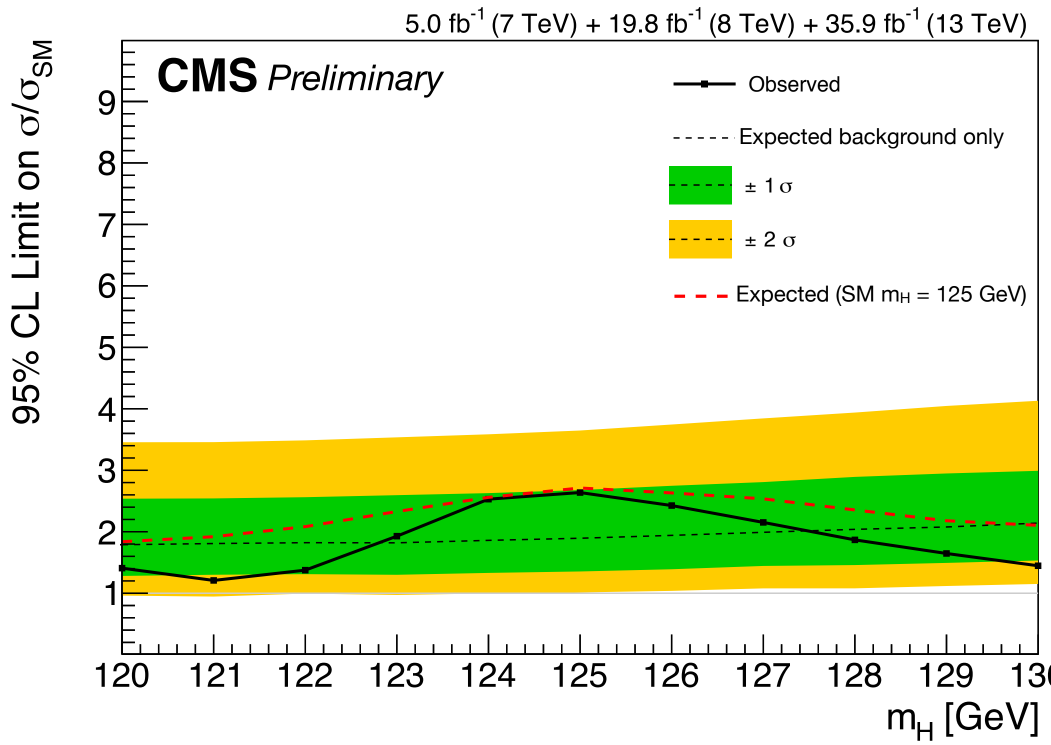


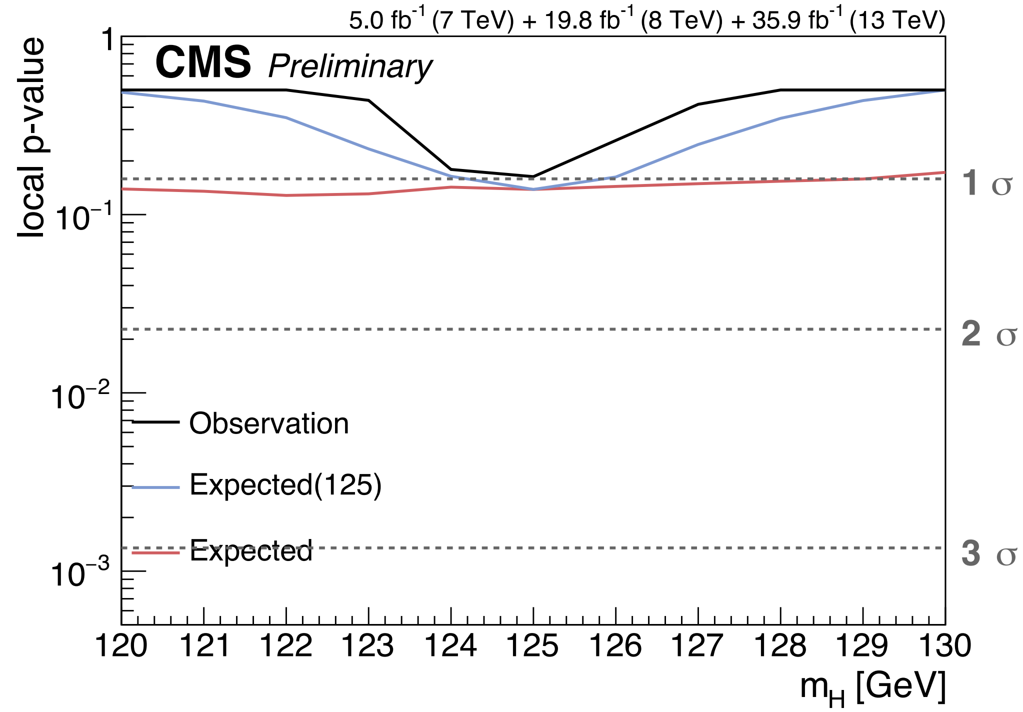


- BDT is used to improve the search sensitivity
- 15 categories are defined based on BDT score and μμ mass resolution
- BDT loosely correlated with VBF

Results of H→μμ

CMS HIG-17-019



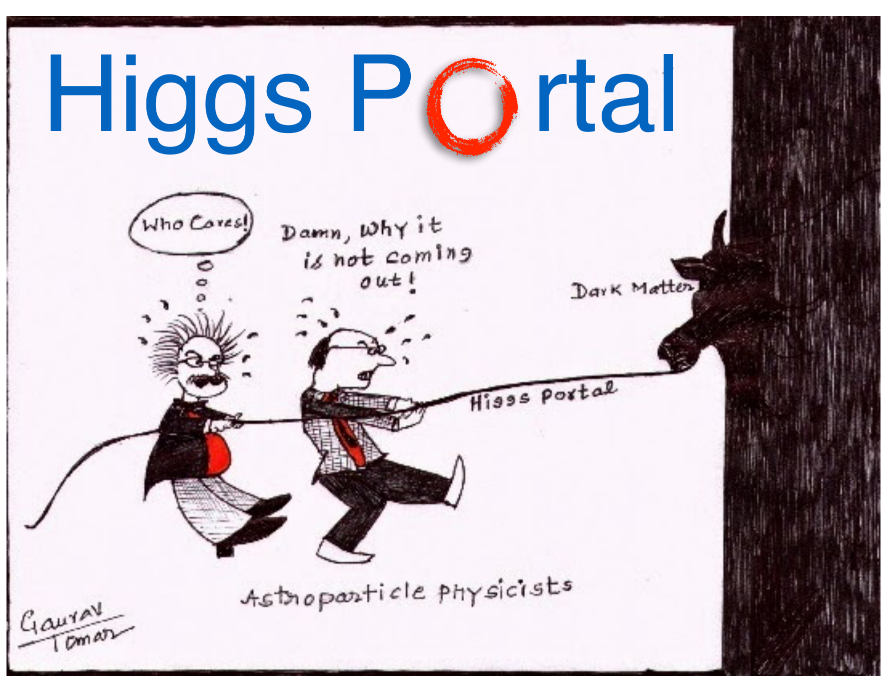


Dataset	95% CL limit on σ/σ_{SM} observed (expected)	Significance observed (expected)
13 TeV (35.9/fb)	2.64 (2.08)	0.74 (0.98)σ
7 TeV + 8 TeV+ 13 TeV	2.64 (1.89)	0.98 (1.09)σ

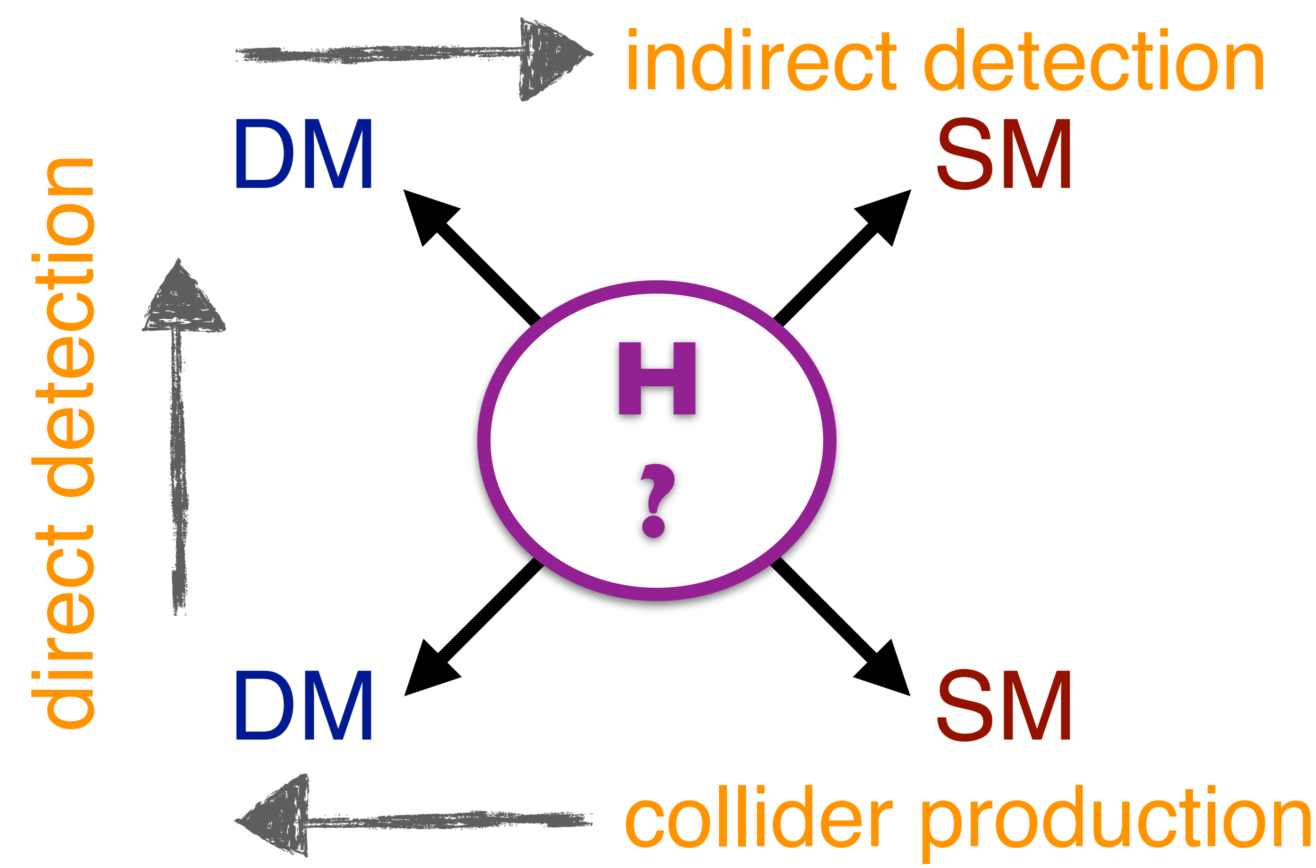
- upper limit on BR(H→μμ) is 5.7×10^{-4}

$H \rightarrow$ *invisible*

- BR($H \rightarrow ZZ \rightarrow 4\nu$) = 0.1% in SM
- a number of BSM models allow for this
  - interactions between the Higgs and dark matter
  - complementary to direct detection
    - dark matter mass < $m_H/2$; $H \rightarrow$ DM kinematically open

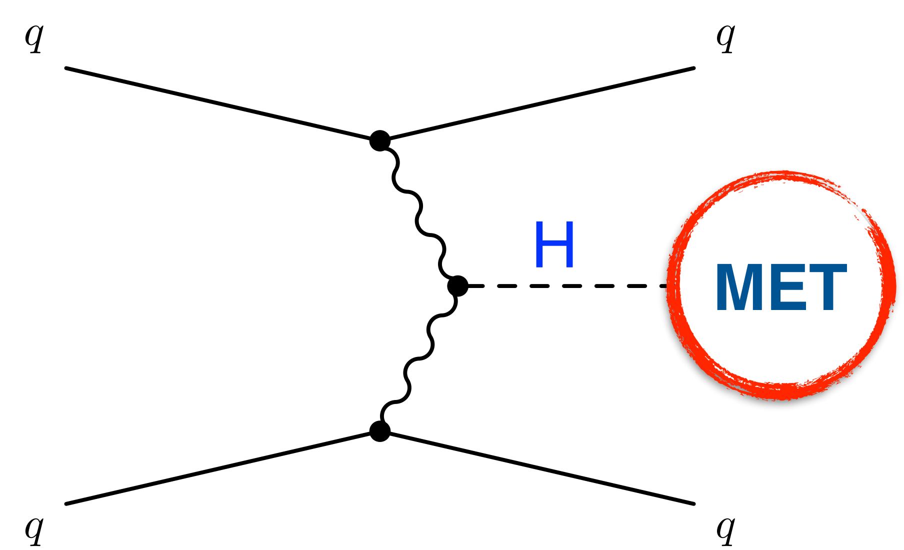


http://rejuvenatte.blogspot.tw

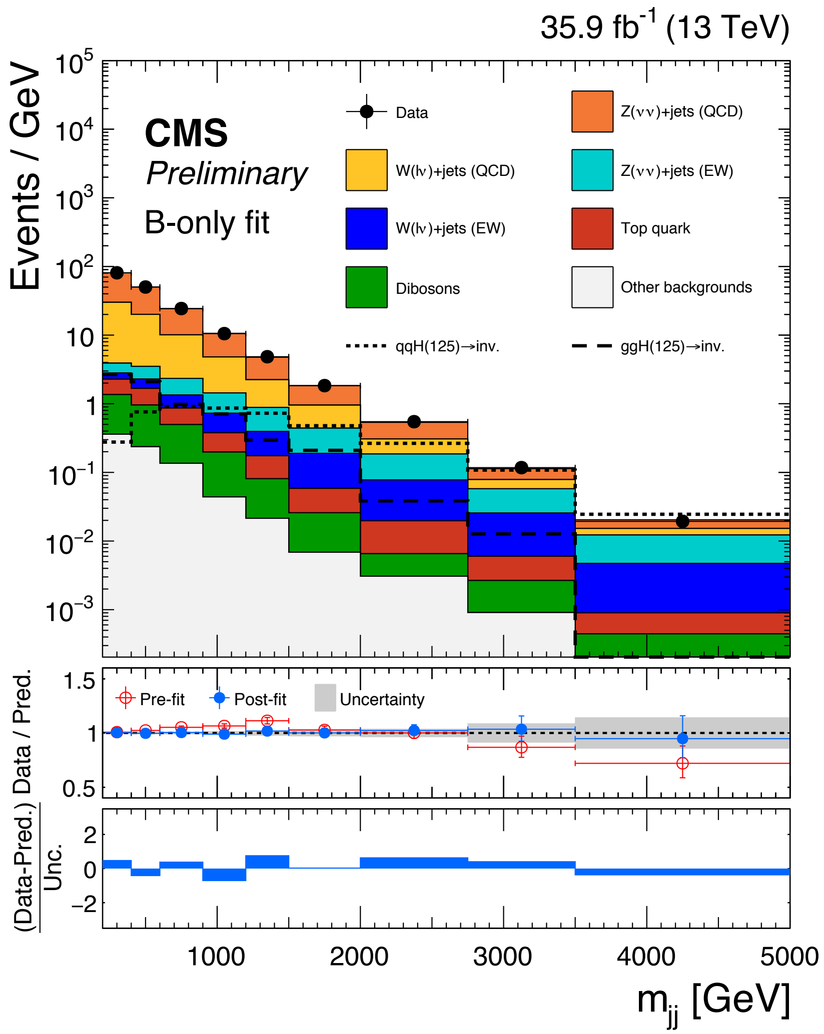


$H \rightarrow$ invisible : VBF tag

CMS HIG-17-023

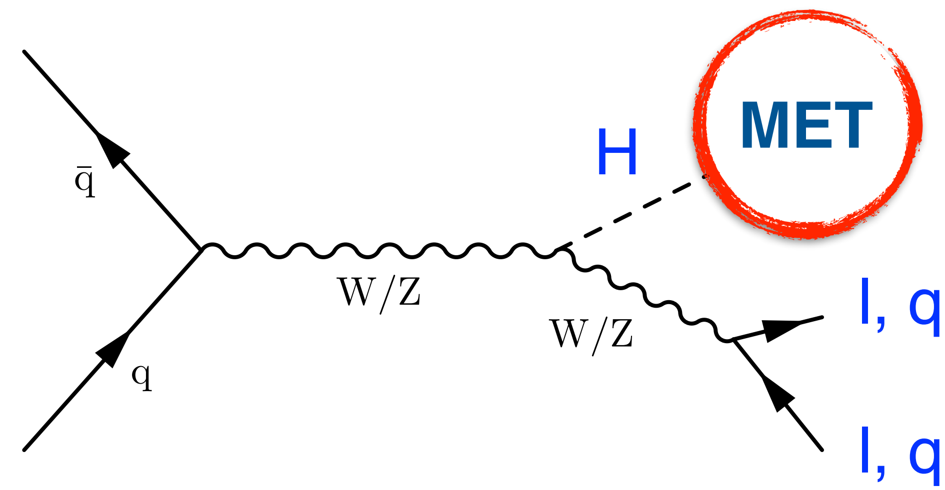


- most sensitive mode due to VBF topology
- reject extra leptons
- two strategies:
  - cut and count
  - shape analysis based on m_{jj}
    - use the full discrimination power of the invariant mass distribution
      - improve the search sensitivity



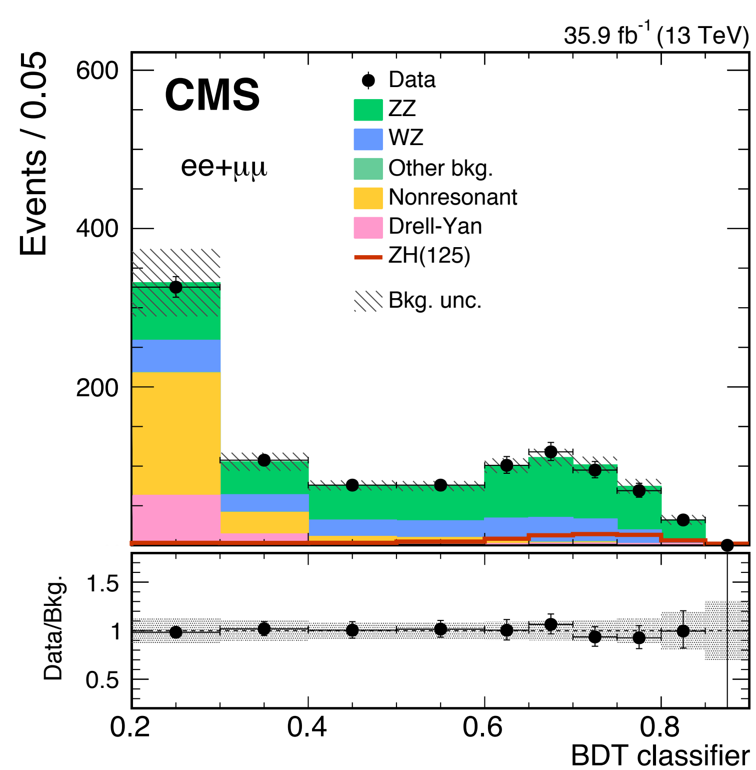
H→invisible：mono-V tag

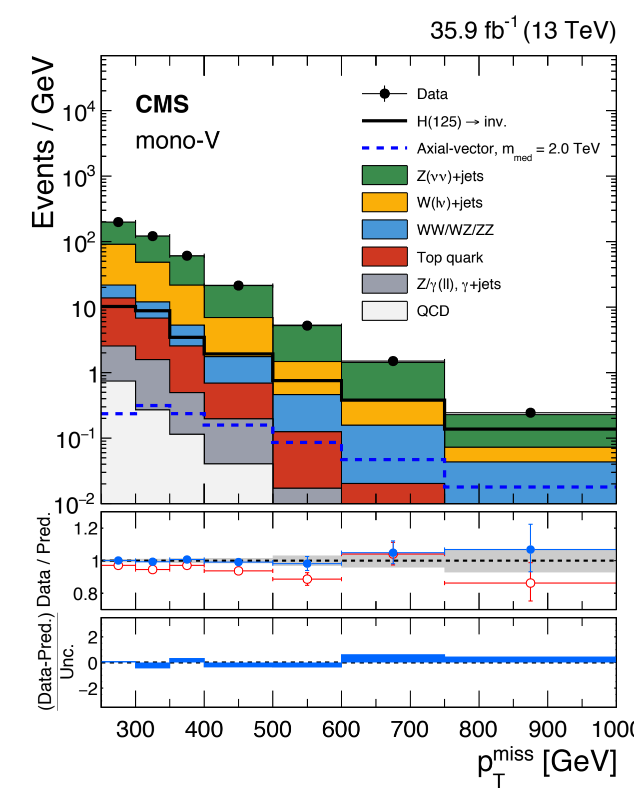
arXiv:1711.00431
arVix:1712.02345



- **Z(→ll)+H**
  - smaller cross section than VBF
  - clean final state with low background
  - the multivariate BDT classifier is used to improve the search sensitivity by 10%

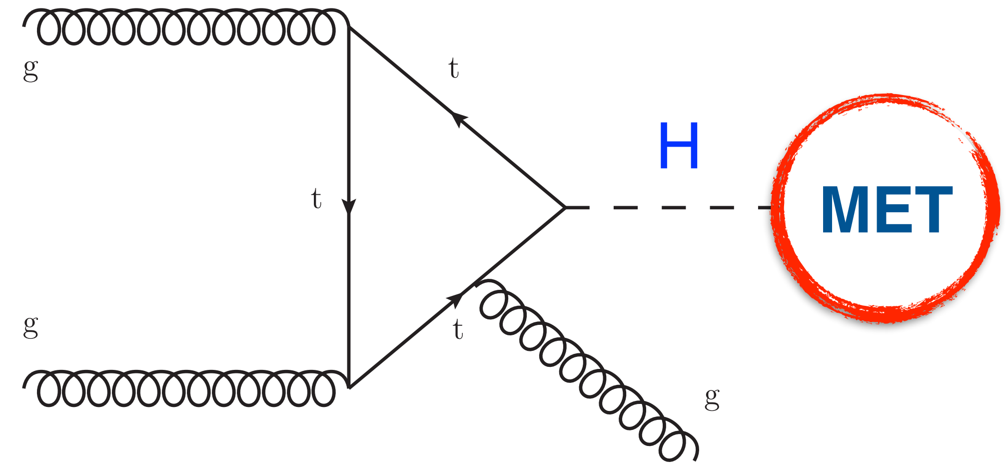
- **V(→qq)+H**
  - large background but relatively larger signal contribution
  - large radius jet (R = 0.8), $p_T > 250$ GeV
  - rely on jet substructure techniques



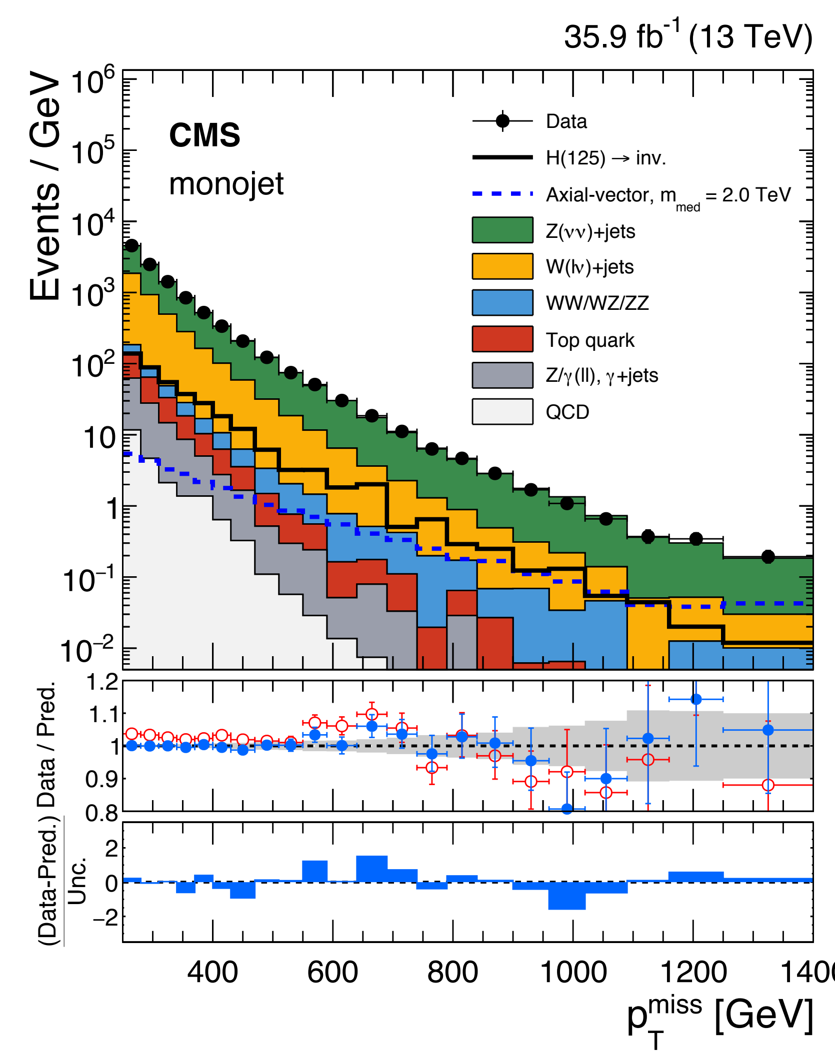


H→invisible：mono-jet tag

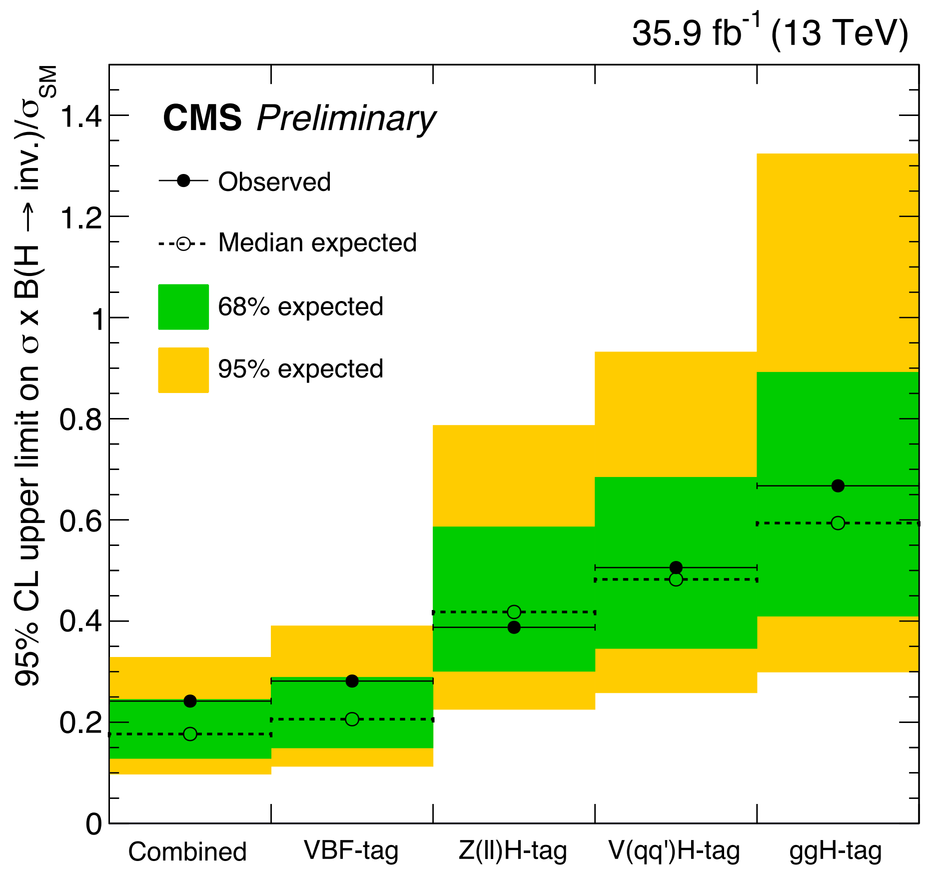
arVix:1712.02345

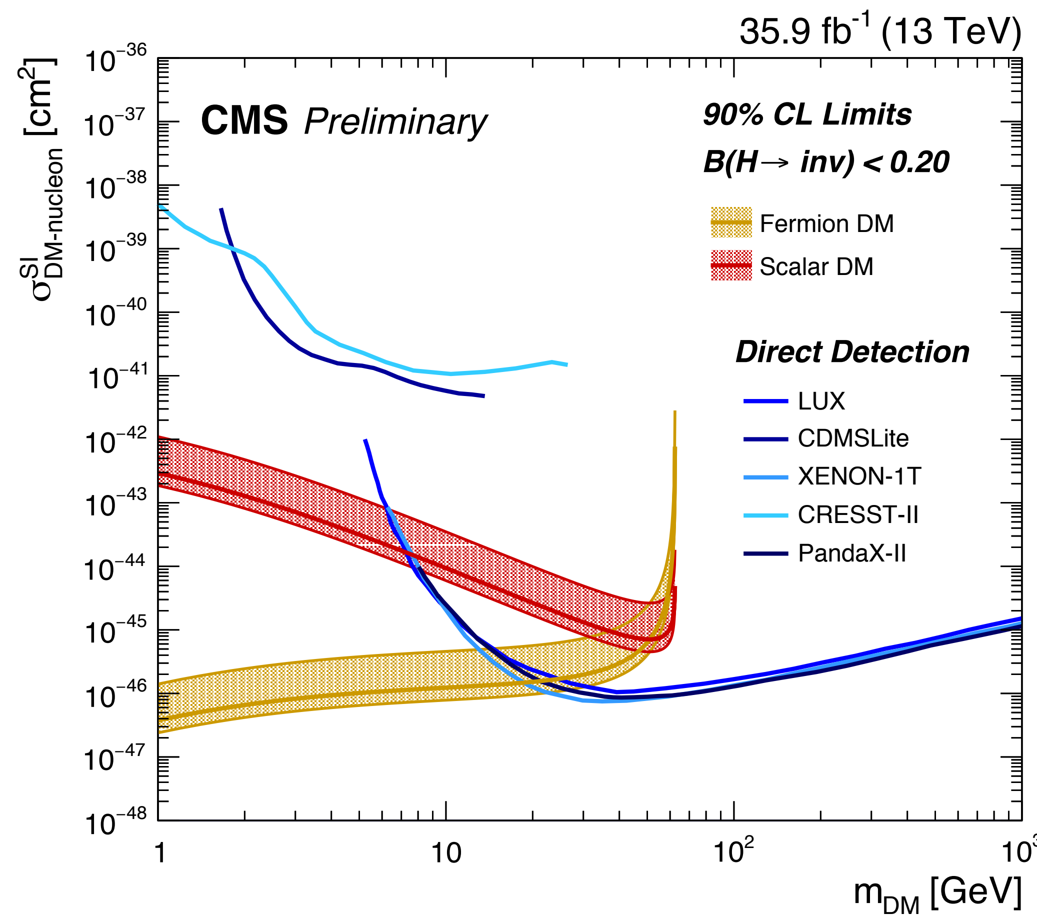


- measure ggH process where the Higgs system is boosted and recoils against a jet
- events failing mono-V tag but satisfying jet p_T > 100 GeV (R = 0.4) are included
- large background
- improve V(jj)H sensitivity by 12.5% after adding this mode



H→invisible：combination





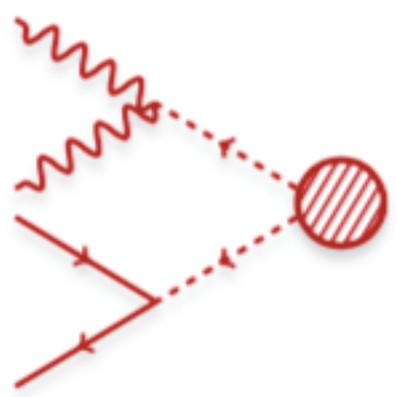
Analysis	Final state	Signal composition	Observed limit	Expected limit
qqH-tagged	VBF-jets + p_T^{miss}	52% qqH, 48% ggH	0.28	0.21
VH-tagged	$Z(\ell\ell) + p_T^{miss}$ [?]	79% qqZH, 21% ggZH	0.40	0.42
	$V(qq') + p_T^{miss}$ [?]	39% ggH, 6% qqH, 33% WH, 22% ZH	0.50	0.48
ggH-tagged	jets + p_T^{miss} [?]	80% ggH, 12% qqH, 5% WH, 3% ZH	0.66	0.59

- No significant deviations from SM expectation are observed in any search mode
- The observed (expected) 95% CL limit on BR(H→inv) assuming SM is 0.24 (0.18)
- The results have been interpreted in Higgs portal model assuming the scalar or fermion nature of the DM
  - excluding the very low DM masses below 20 (fermion) or 7 (scalar) GeV

CMS HIG-17-023

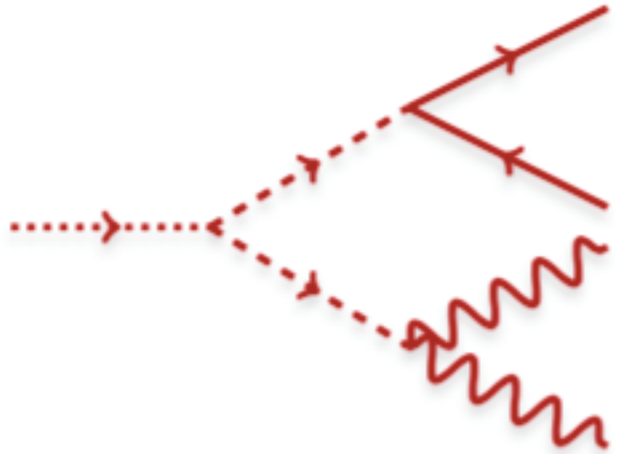
- HH production in γγbb final state

HH production

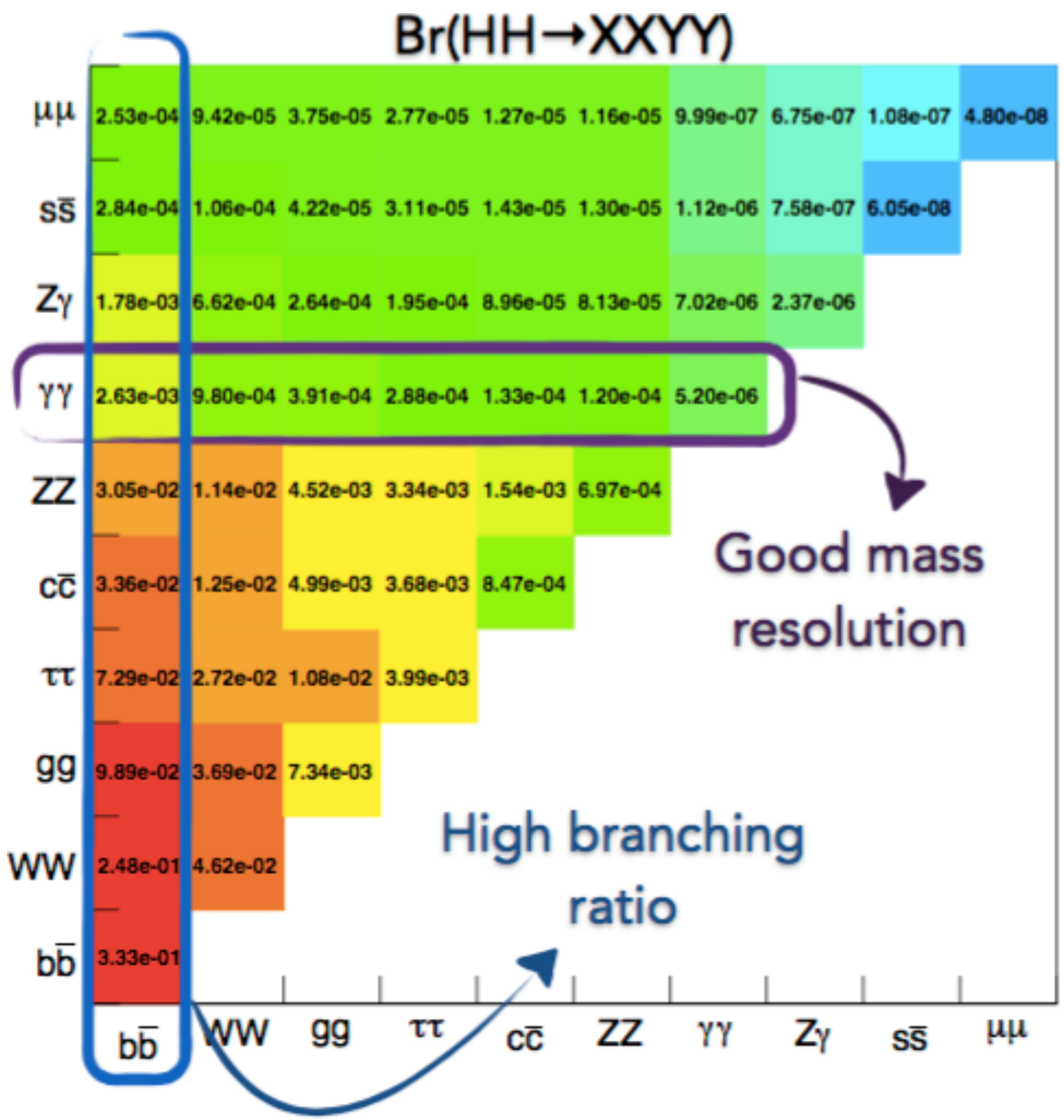


- Non-resonant
  - need to determine the Higgs self-interaction potential responsible for EWSB → requiring a measurement of trilinear and quadrilinear self-coupling of the Higgs particle, as predicted by the SM
  - Quartic coupling out of each of LHC and HL-LHC
  - SM predicts σ(gg→HH) = 34 fb at 13 TeV → not sensitive, but BSM can induce kinematic differences and cross section enhancement

- Resonant
  - Many BSM models predict resonances decaying into two Higgs bosons : WED, MSSM, 2HDM, etc.
  - Model independent search for spin-0 and spin-2 resonances decaying to HH with Mx = [260, 1100] GeV→ non-boosted regime
  - Benchmark model : Warped Extra Dimensions predicts spin-0 (radion) and spin-2 (KK graviton) new particles that couple to the Higgs bosons



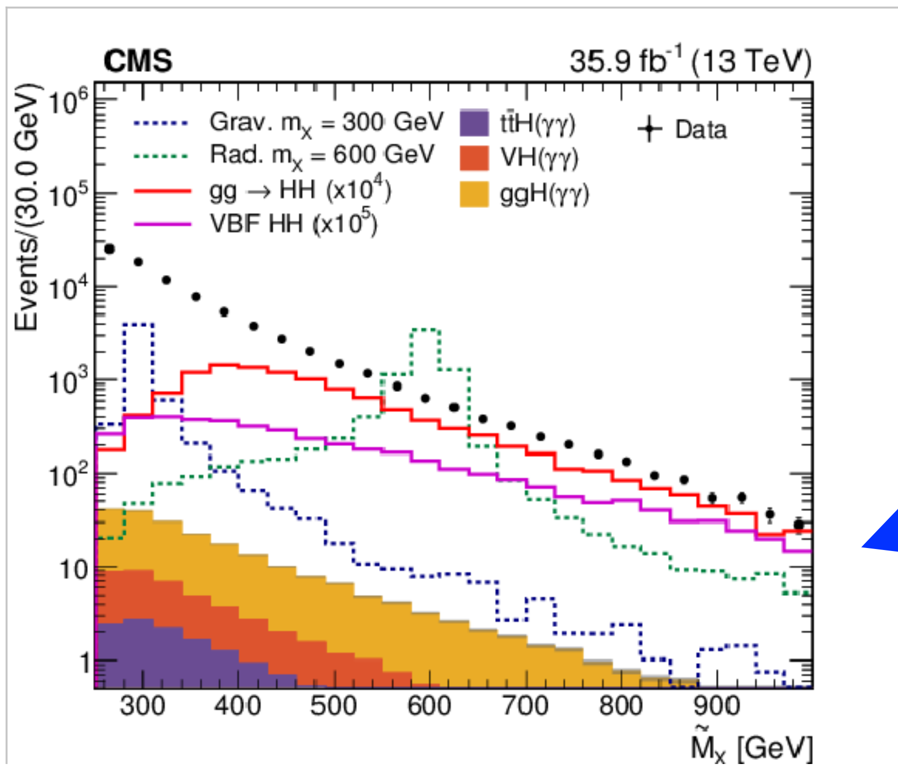
HH→γγbb

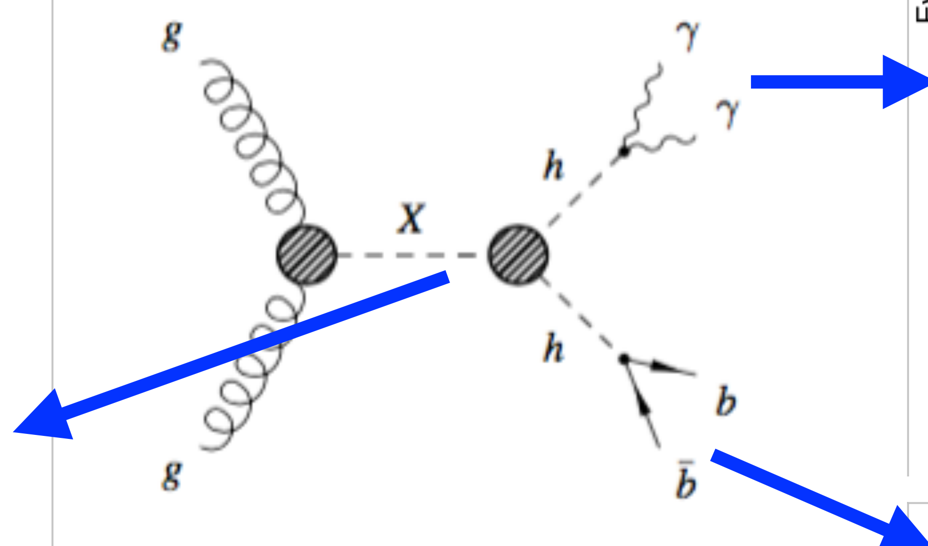


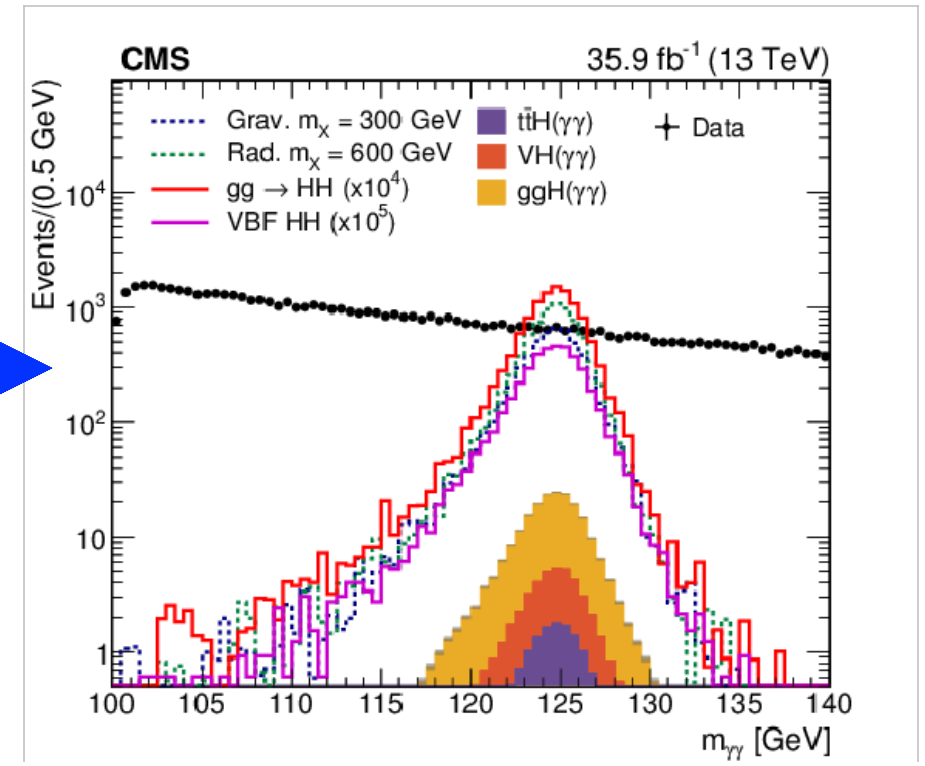
- H→bb
  - high branching ratio
  - tag b-jet to obtain good S/√B
- H→γγ
  - high trigger efficiency and selection
  - good mass resolution
- HH→bbγγ
  - low background

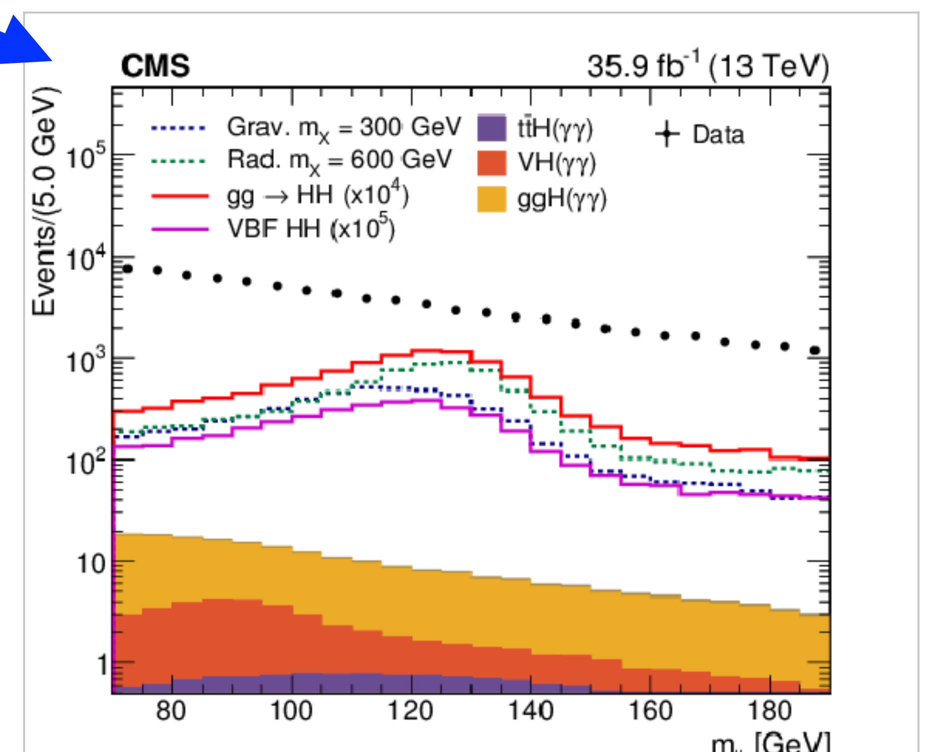
X→HH→bbγγ

CMS HIG-17-008





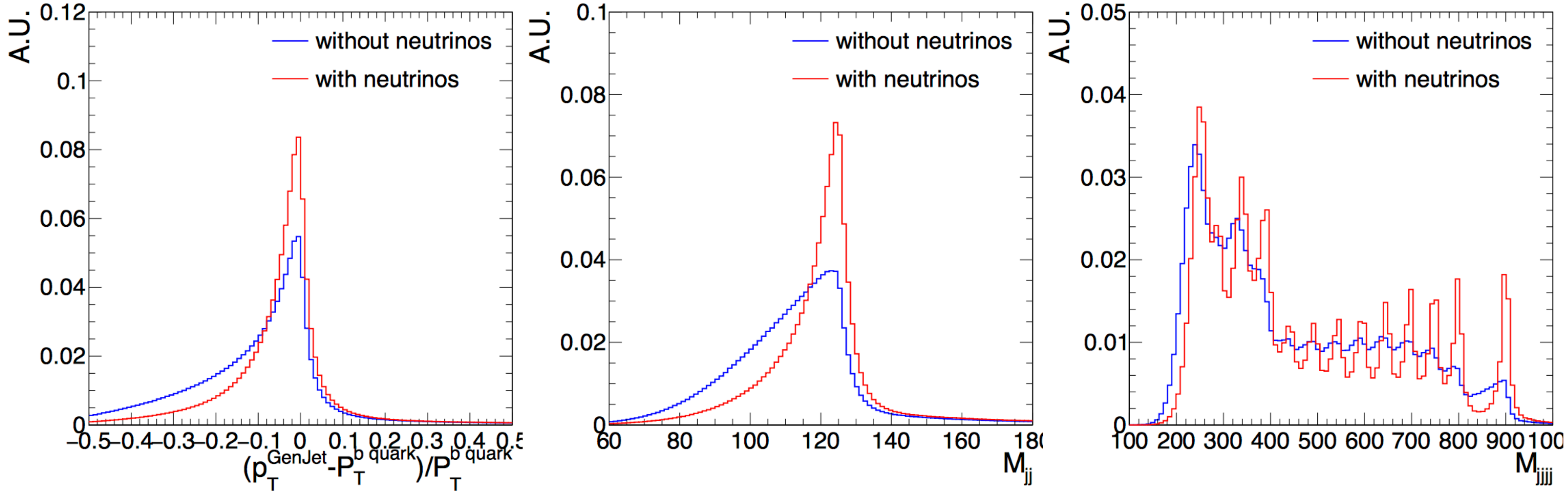




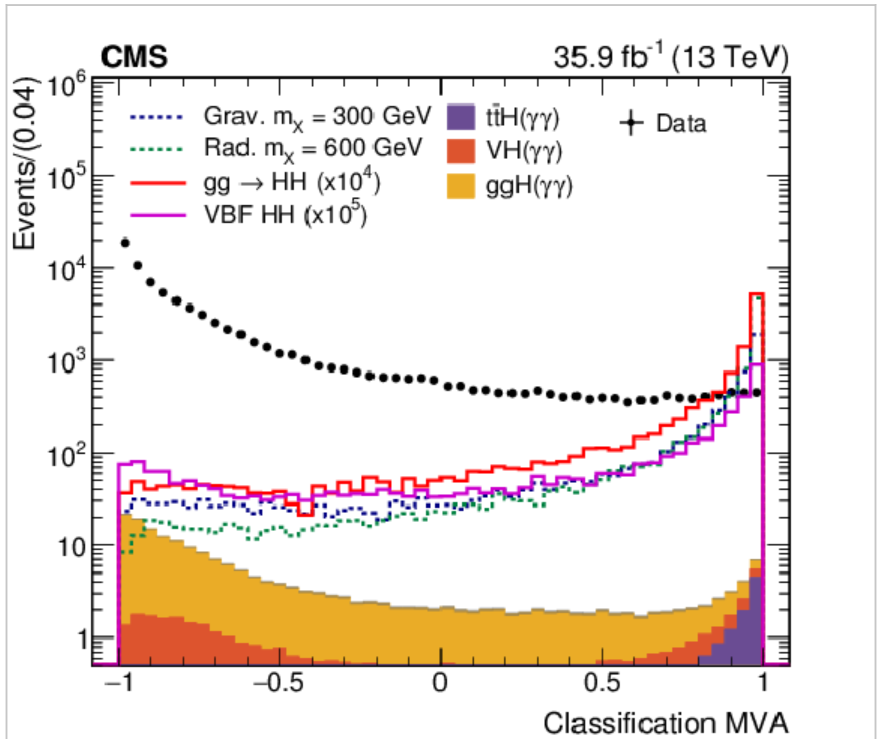
- Main backgrounds:
  - non-resonant QCD: γγbb(>80%) and γjbb/jjbb(<20%)
  - resonant: SM H production - few events but positioned exactly under the γγ peak

Key analysis ingredients

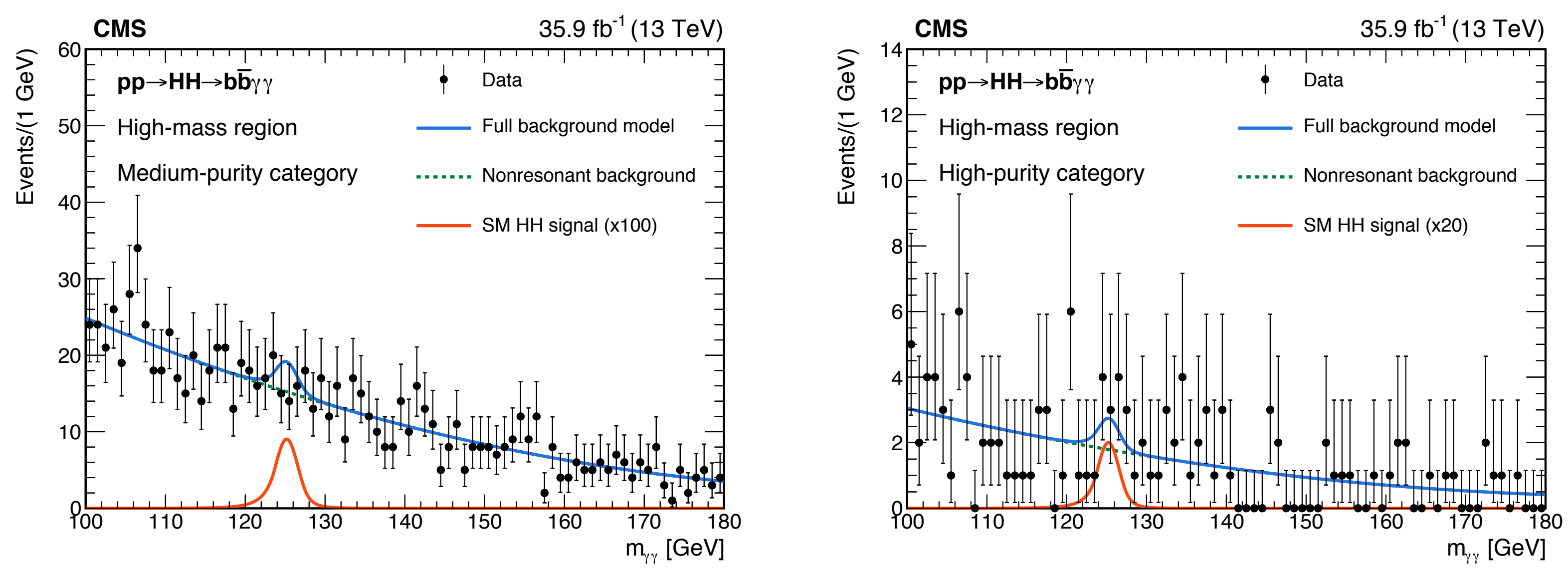
b-jet energy regression



categorization based on MVA

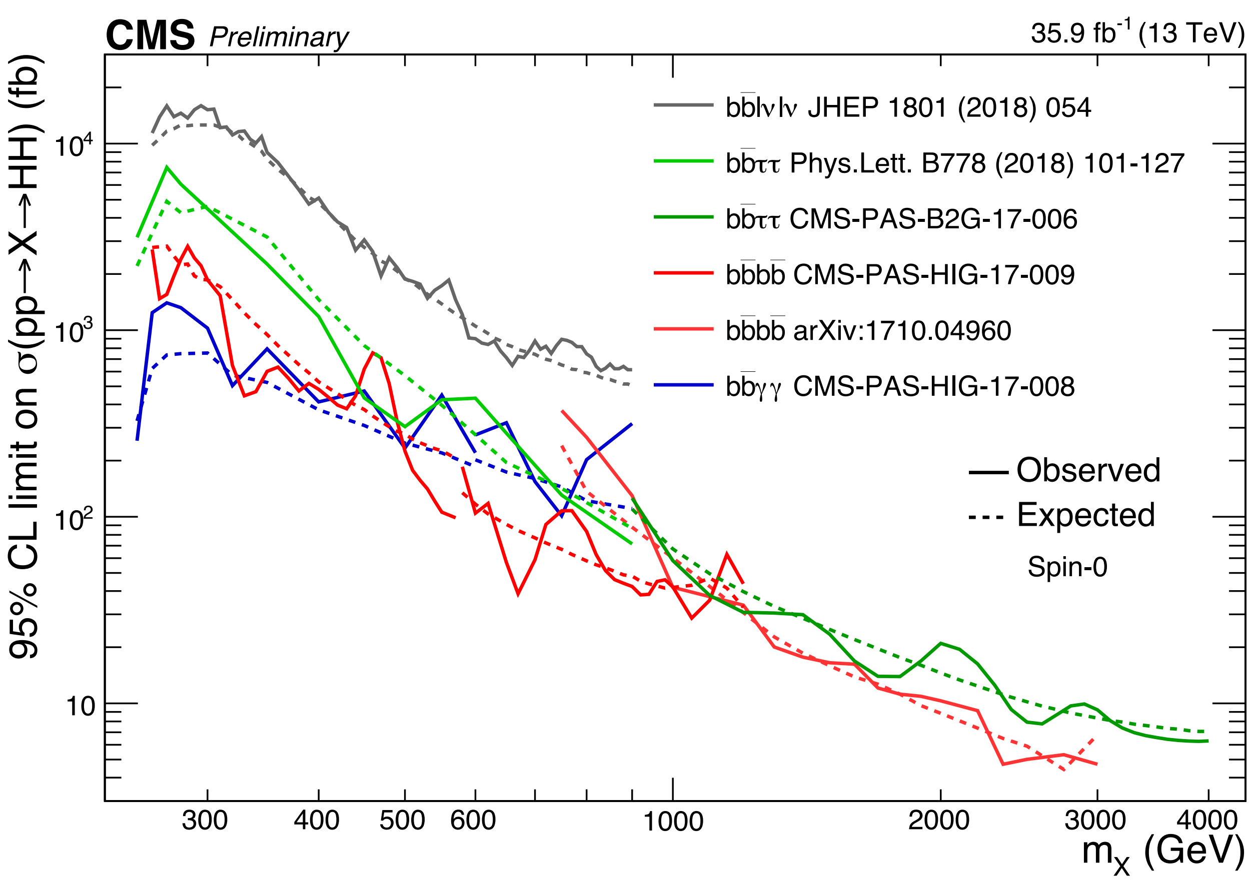


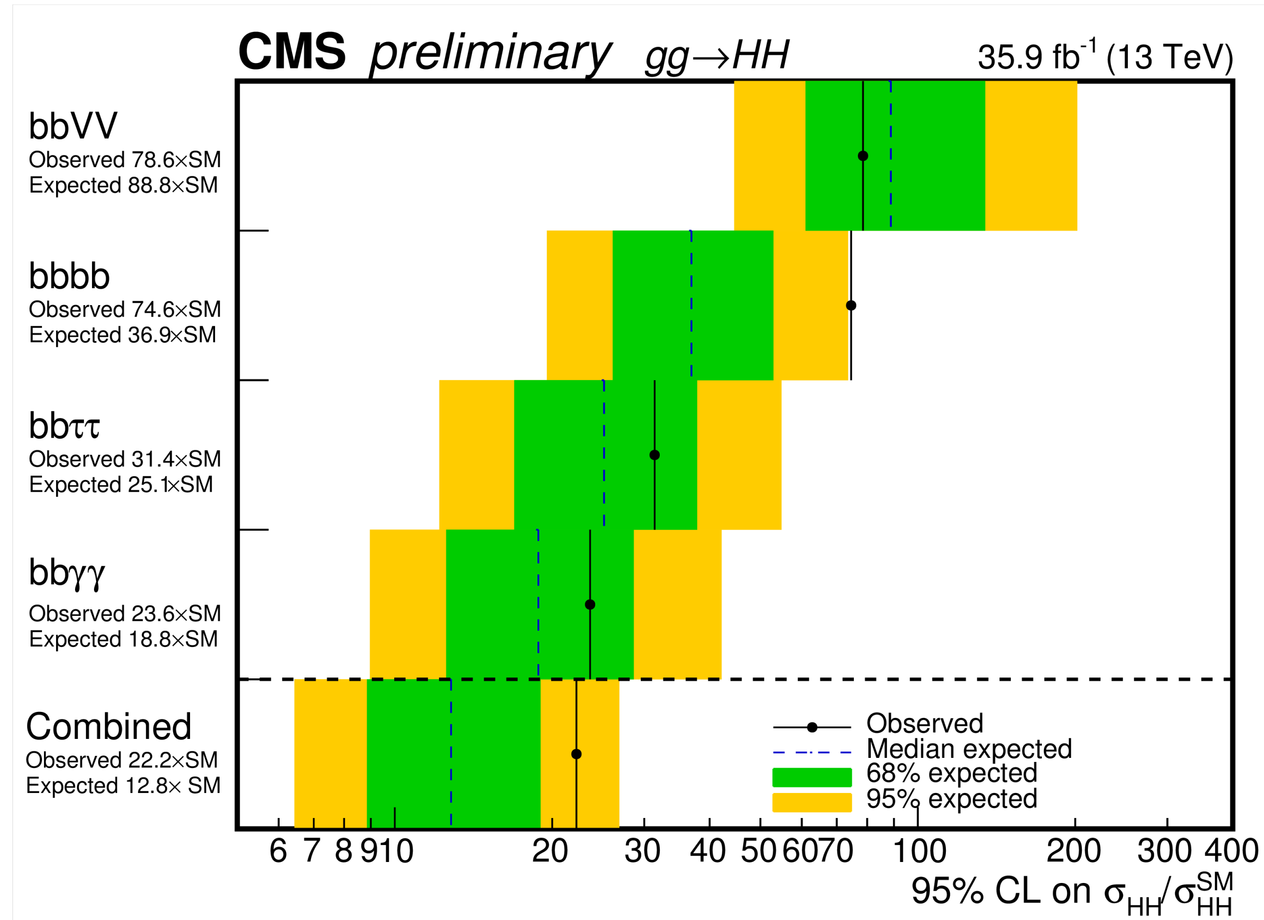
2D analysis



HH results

CMS HIG-17-030





Summary

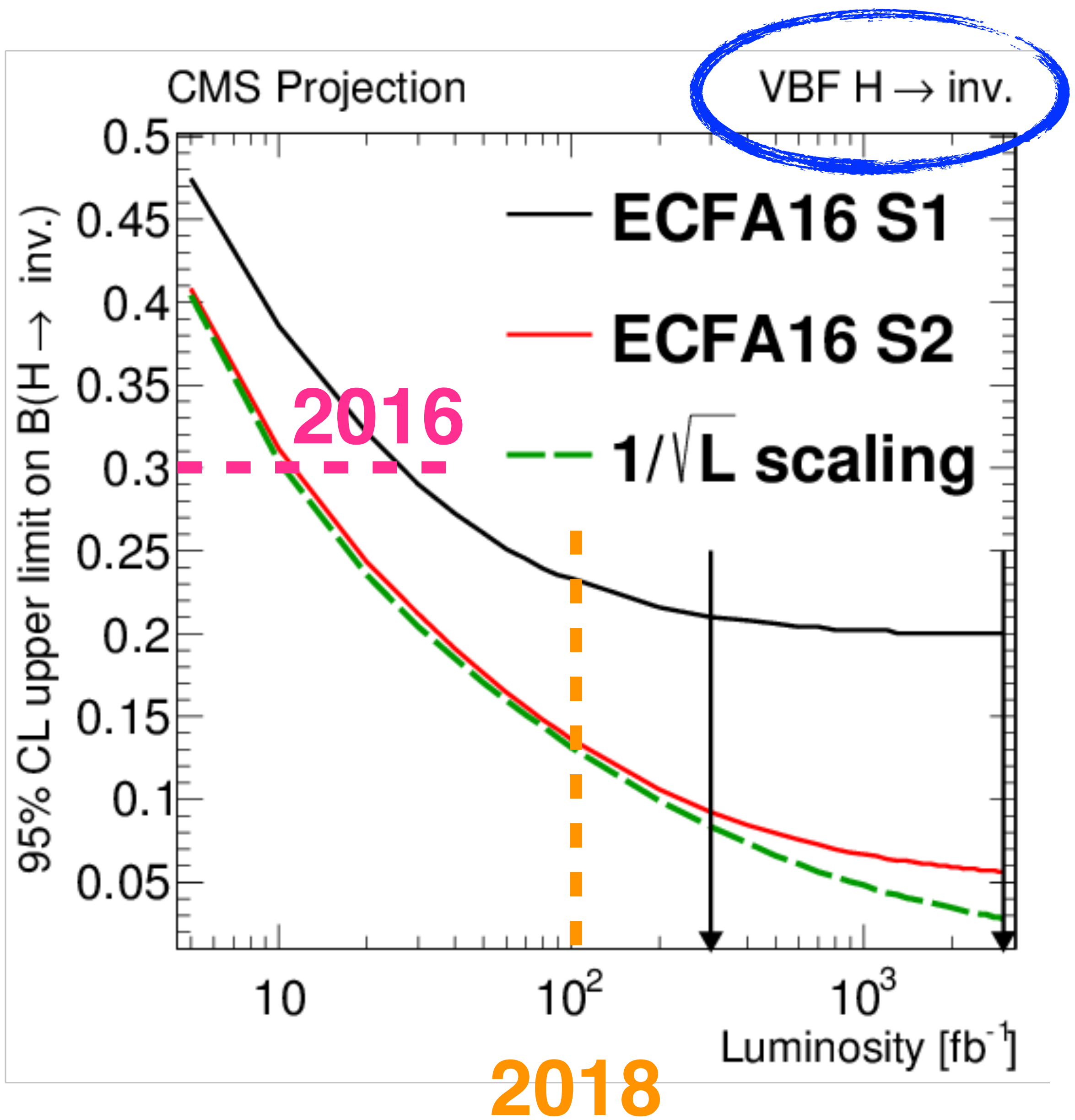
- the discovery of the Higgs boson opens a new opportunity to search for new physics via the rare decays and di-Higgs production!
- a broad program performed by CMS in these fields
- observations are in agreement with SM
- still looking for it …

- Backup

Outlook of H→invisible

CMS DP-2016-064

- SM BR(H→inv.) = 0.001



S1 : all systematic uncertainties are fixed to 2015 values

S2 : experimental systematic uncertainties decrease with L and theoretical ones are scaled by 1/2
→ improved by a factor of 2 by the end of 2018 and 5 at HL-LHC

2HDM+S

- type I: all SM particles couple to the first doublet
- type II: leptons and down-type quarks couple to the second doublet and up-type quarks couple to the first doublet
- type III: leptons couple to the second doublet and quarks to the first one
- type IV: down-type quarks couple to the second doublet, while leptons and up-type quarks couple to the first doublet