Higgs results from CMS

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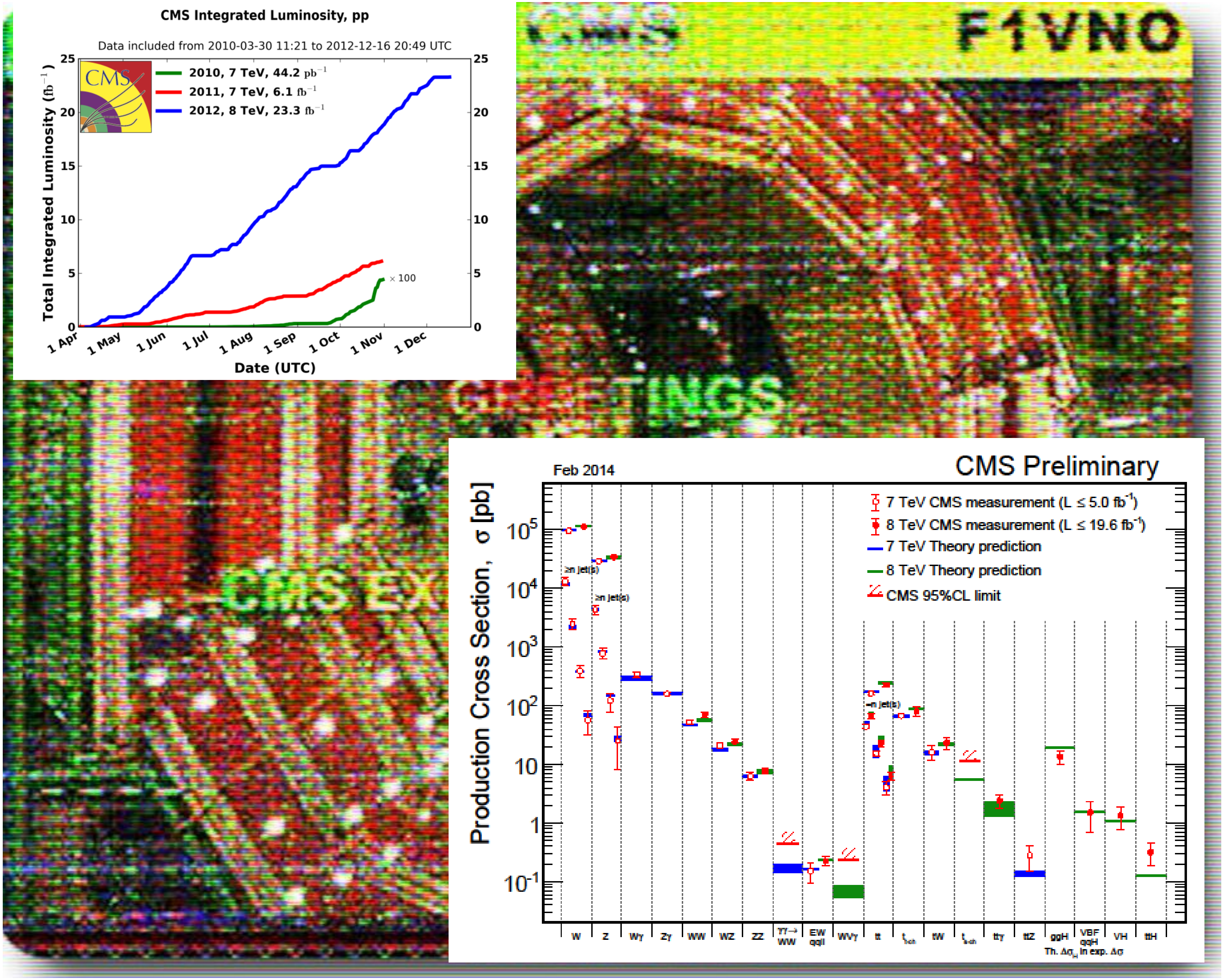
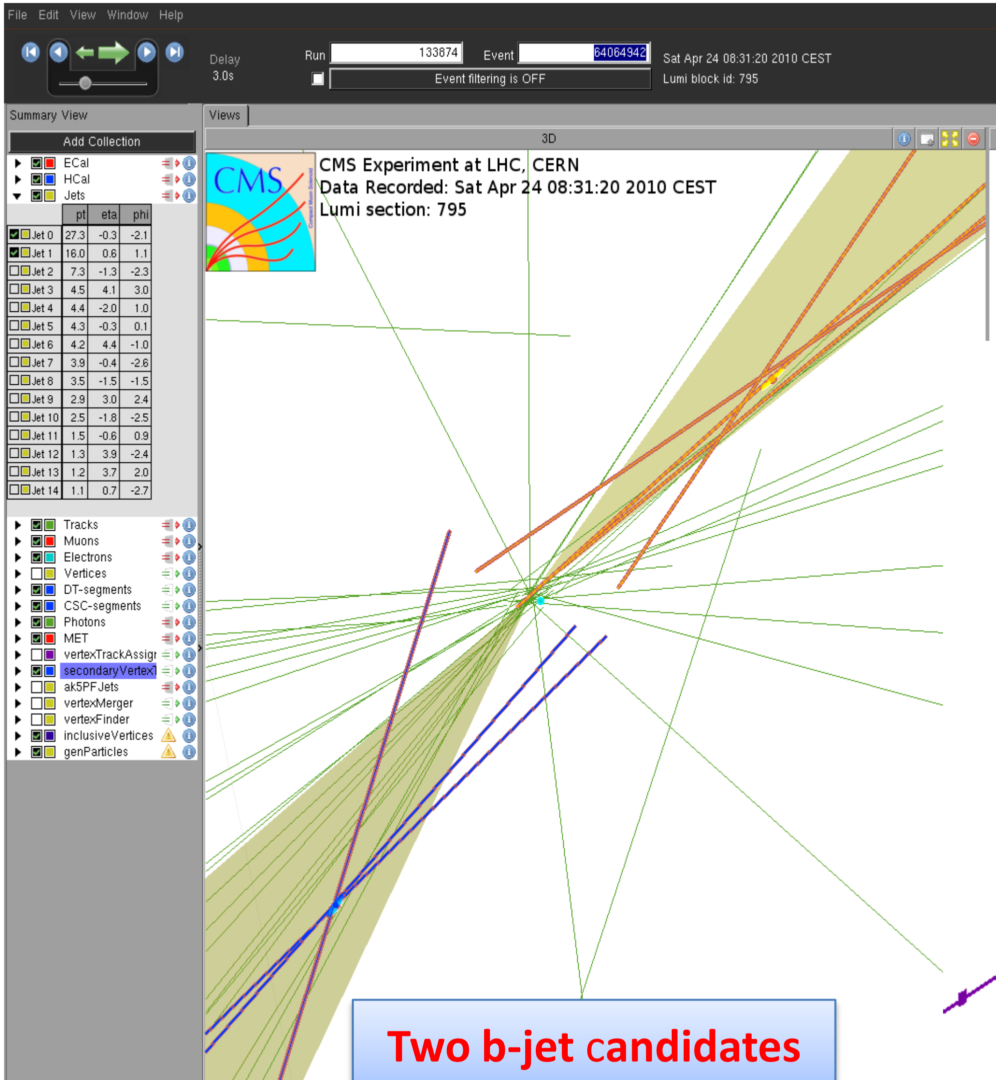
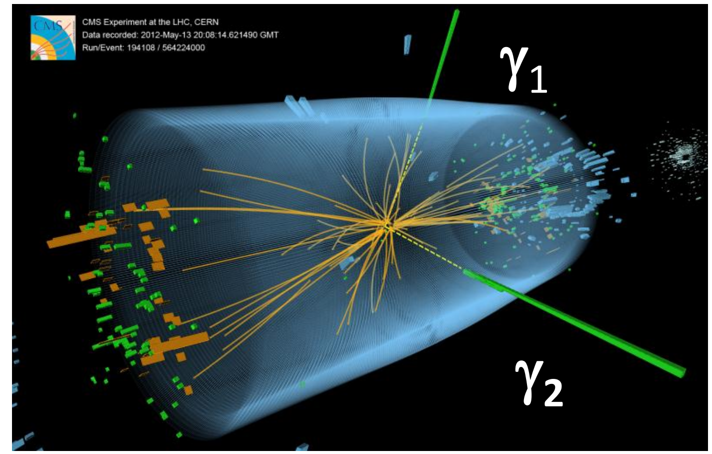
SUSY 2014, 22 July.

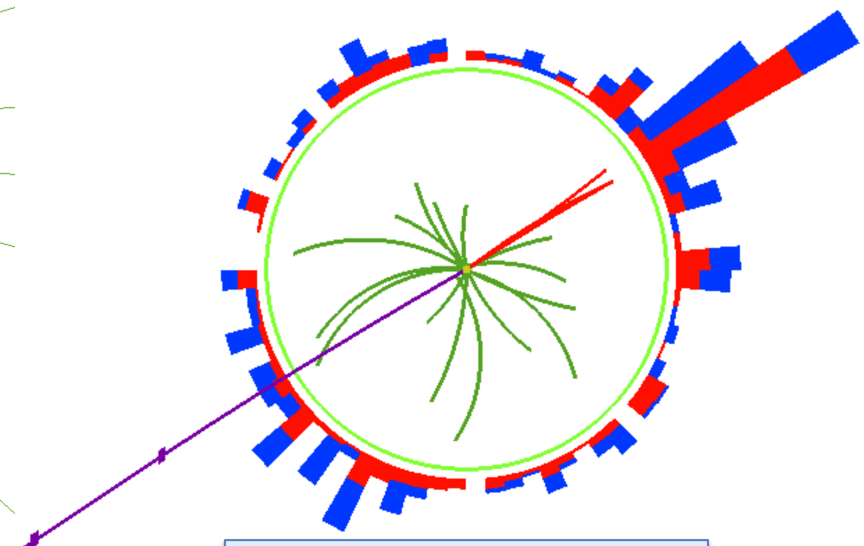

CMS
F1VNO
GREETINGS
CMS EX
CMS Integrated Luminosity, pp
Data included from 2010-03-30 11:21 to 2012-12-16 20:49 UTC
2010, 7 TeV, 44.2 pb⁻¹
2011, 7 TeV, 6.1 fb⁻¹
2012, 8 TeV, 23.3 fb⁻¹
× 100
Total Integrated Luminosity (fb⁻¹)
Date (UTC)
1 Apr
1 May
1 Jun
1 Jul
1 Aug
1 Sep
1 Oct
1 Nov
1 Dec
Feb 2014
CMS Preliminary
7 TeV CMS measurement (L ≤ 5.0 fb⁻¹)
8 TeV CMS measurement (L ≤ 19.6 fb⁻¹)
7 TeV Theory prediction
8 TeV Theory prediction
CMS 95%CL limit
Production Cross Section, σ [pb]
≥n jet(s)
W
Z
Wγ
Zγ
WW
WZ
ZZ
γγ→WW
EW qqll
WVγ
tt
t t-ch
tW
t s-ch
ttγ
ttZ
ggH
VBF qqH
VH
ttH
Th. Δσ_H in exp. Δσ

Few words about CMS reconstruction



Two b-jet candidates

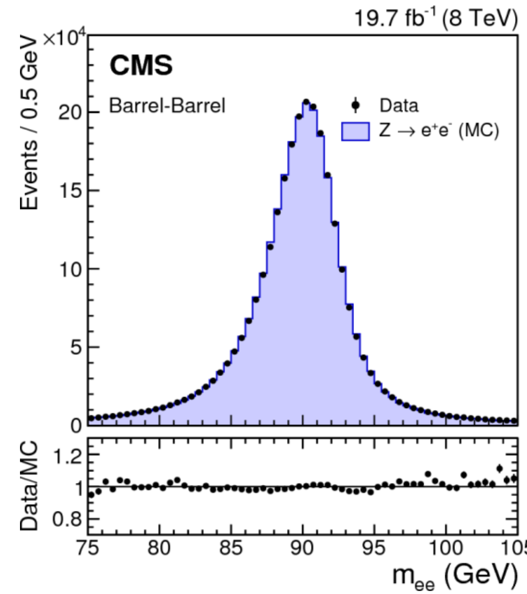


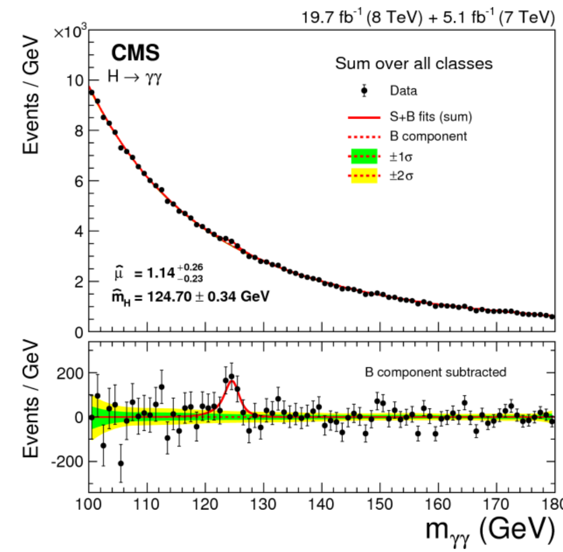


Z->ττ->$\tau_\mu\tau_h$

Reconstruction: *photons*

- **variation of crystal transparency is monitored every 40 min with laser system**
- **energy scale is obtained with MC photons using multivariate regression technique**
  - **input: cluster shape variables, E/H, (η,ϕ), Nvtx, PU density**
- **Finally, reconstructing e's as γ's in $Z \rightarrow ee$ events obtain:**
  - **corrections of energy in data to reproduce MC m_{ee} peak position**
  - **smearing of MC energy to reproduce m_{ee} resolution**
  - **take into account imperfect modelling of e/γ difference in MC:**
    - **Imperfect description of tracker material**
    - **Non uniformity of light collection**
    - **G4 model**

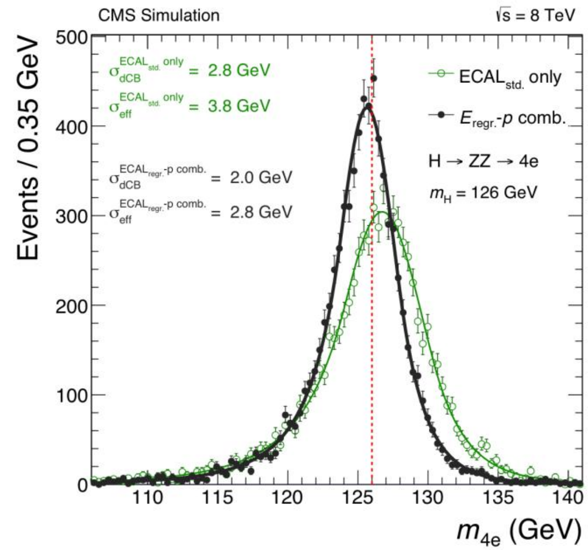


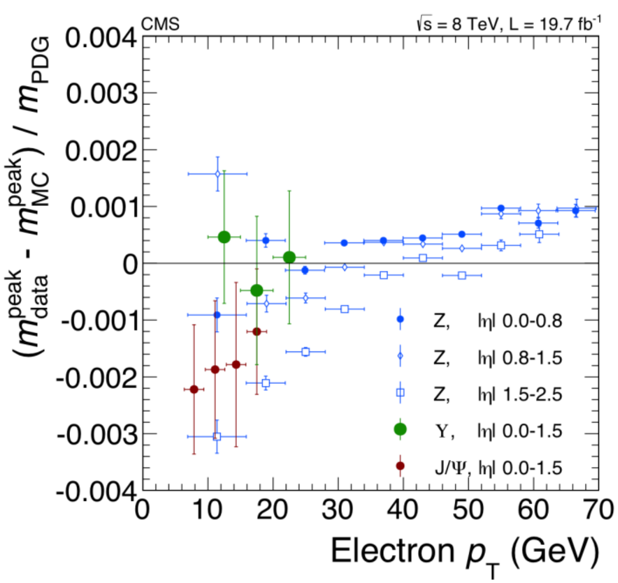


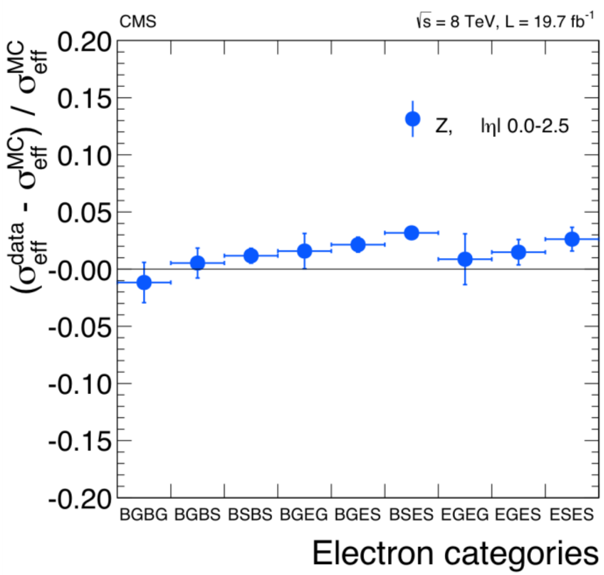
$\sigma_{eff}(m_{\gamma\gamma}) = [1.0\text{-}2.6]$ GeV

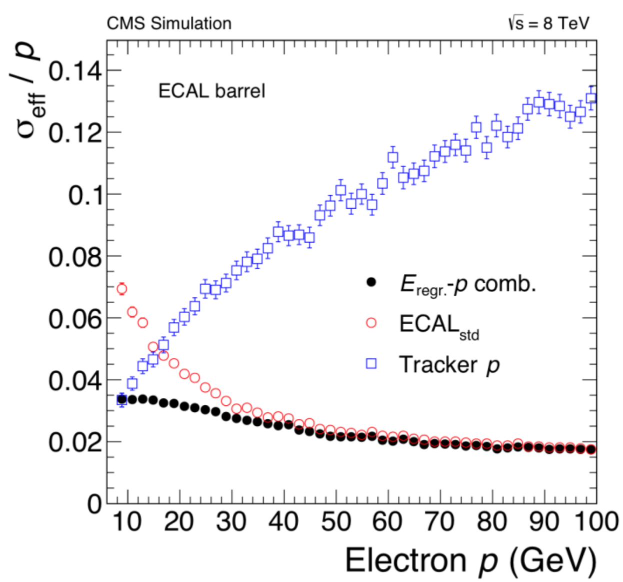
Reconstruction: *electrons*

- **Momentum scale is obtained with MC electrons:**
  - **combined ECAL + tracker information using MVA regression technique**
- **Correct discrepancy between data and simulation on the momentum scale and resolution using Z→ee events**
  - **dominant sources of discrepancy**
    - **residual tracker misalignment**
    - **imperfect corrections of the crystal transparency loss**
- **Validate with J/ψ, Υ(1S)->ee for e's p_T < 20 GeV**





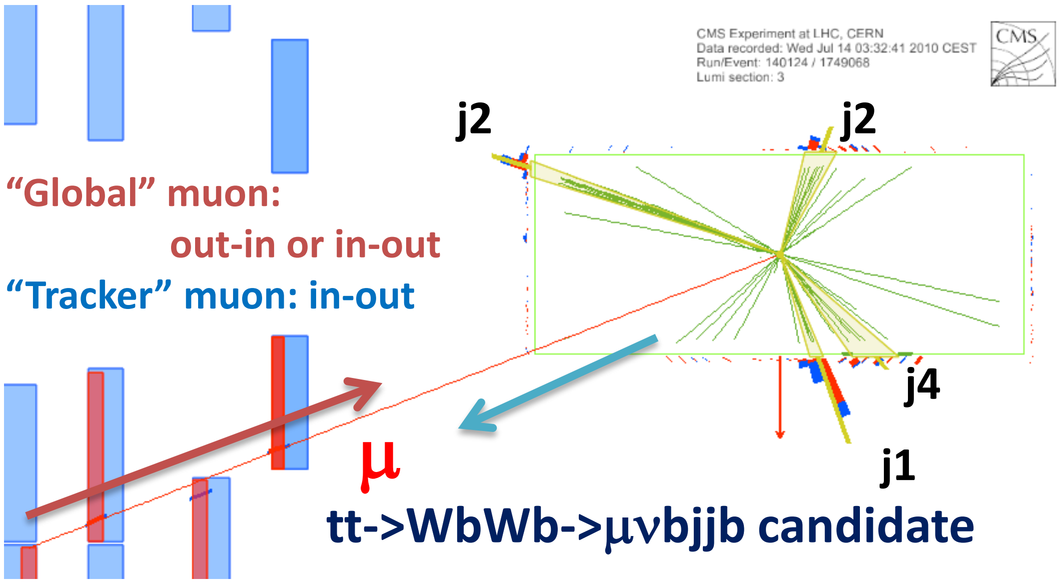




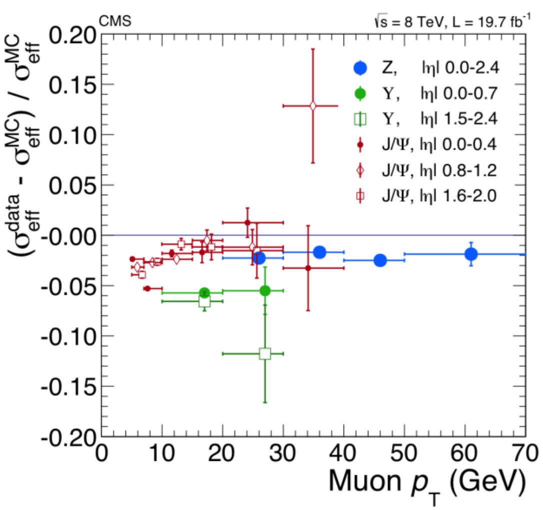
Reconstruction: muons

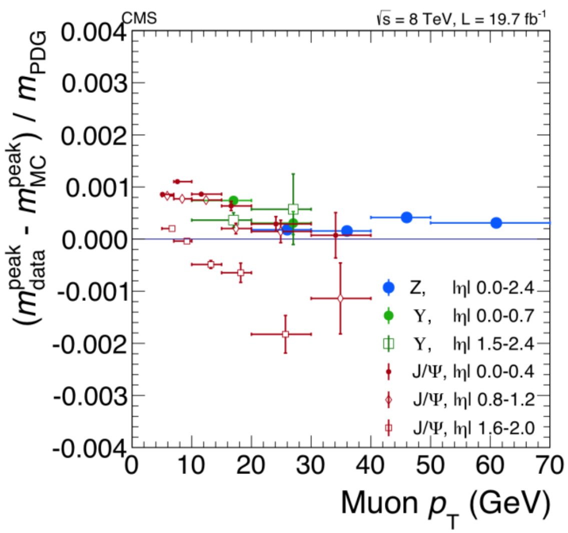
- **Absolute scale and resolution is obtained with $Z \rightarrow \mu\mu$ and low mass di-muon resonances**
  - **main source of data-MC disagreement is residual tracker misalignment**

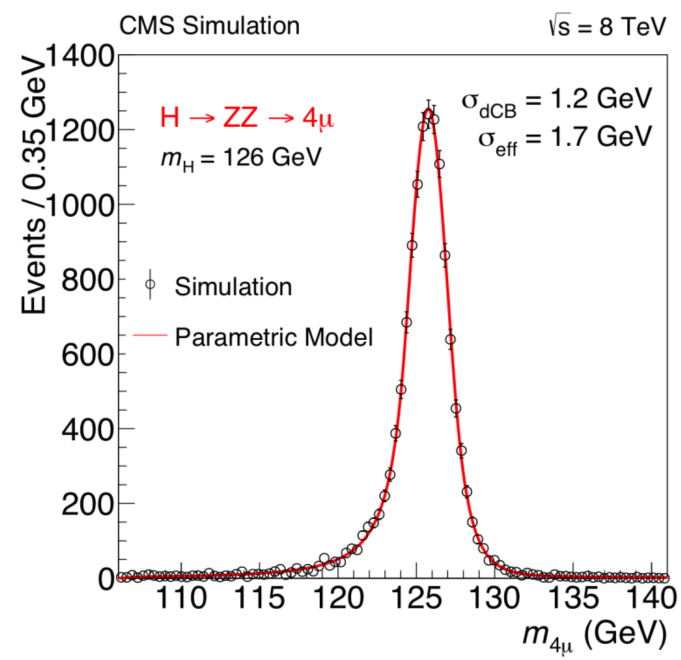
p_T resolution in the momentum range relevant for $H \rightarrow ZZ \rightarrow 4\ell$ analysis:
- **1.3-2.0 % barrel**
- **6 % endcap**



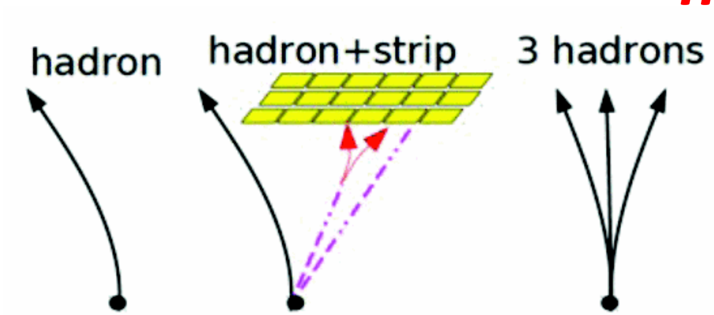
tt->WbWb->μνbjjb candidate

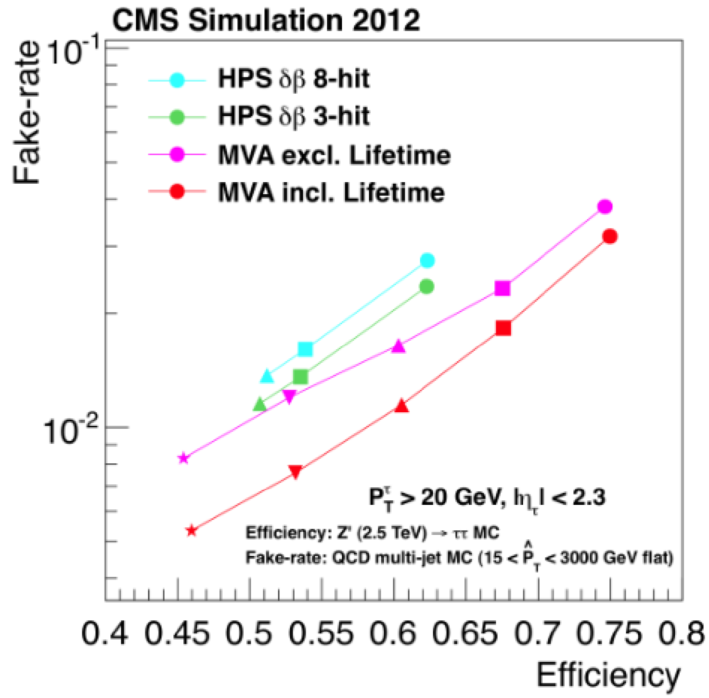




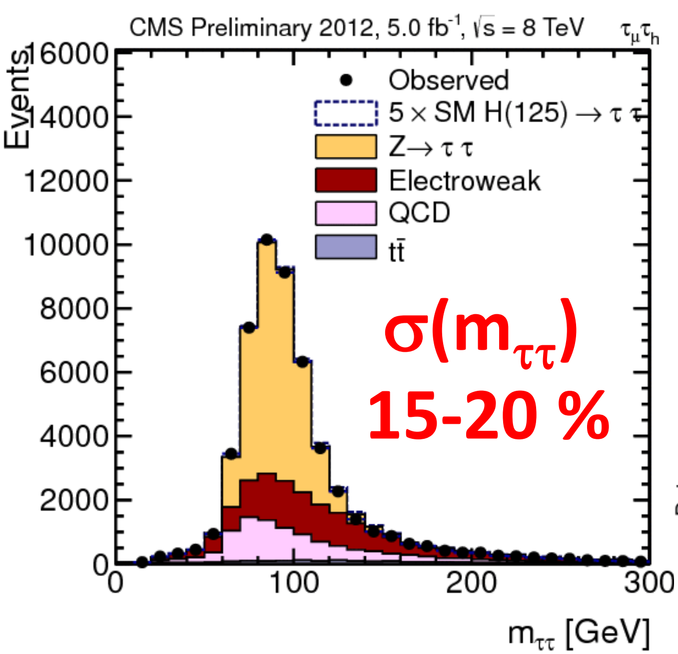


Reconstructions: $\tau \rightarrow$ *hadrons* (τ_h)

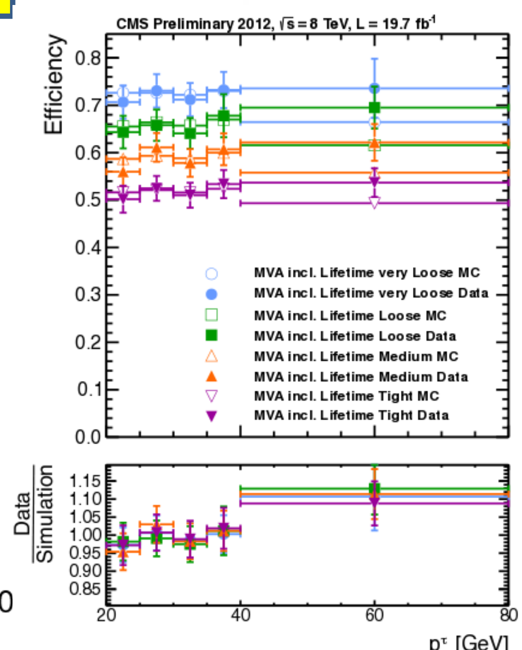


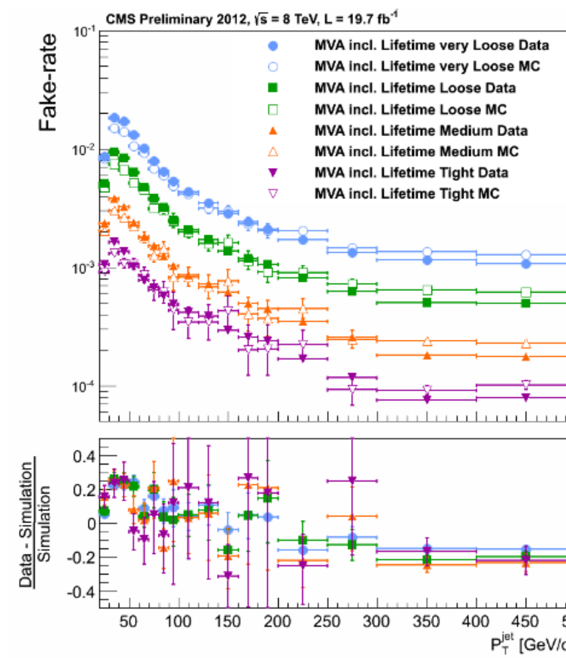


τ ID uncertainty – 7 %
τ JES uncertainty < 3 %



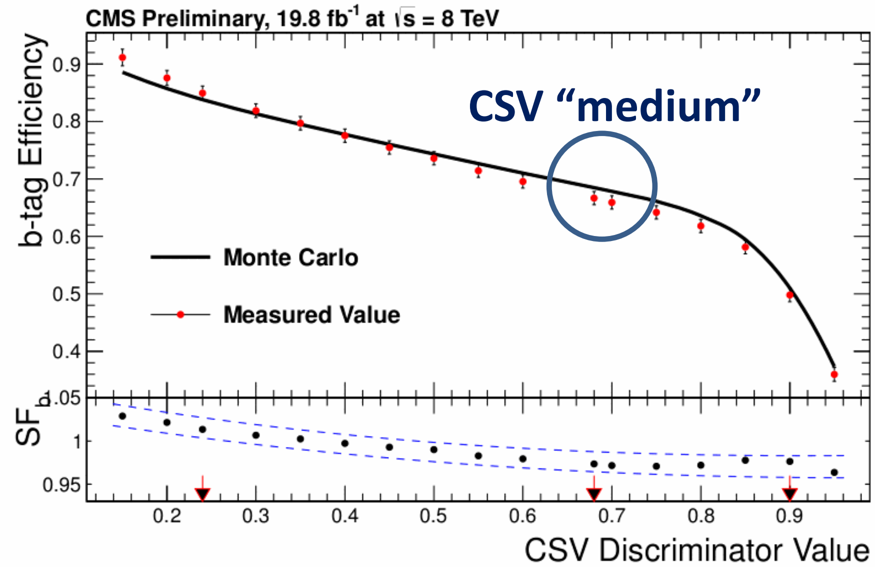
$\sigma(m_{\tau\tau})$
15-20 %





• Reconstruction: *b-jets*

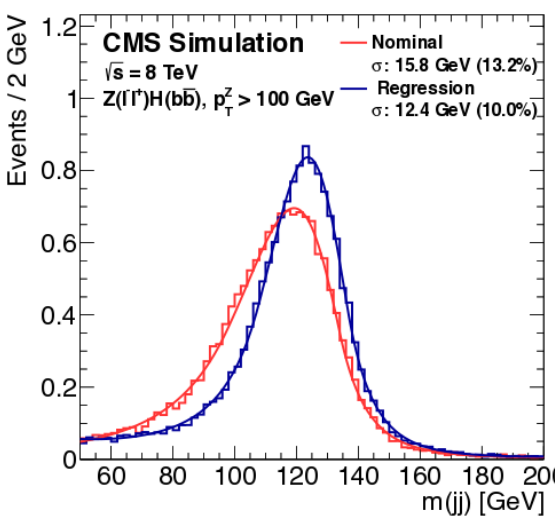
three operational points for b-tagging with Combined Secondary Vertex algorithm

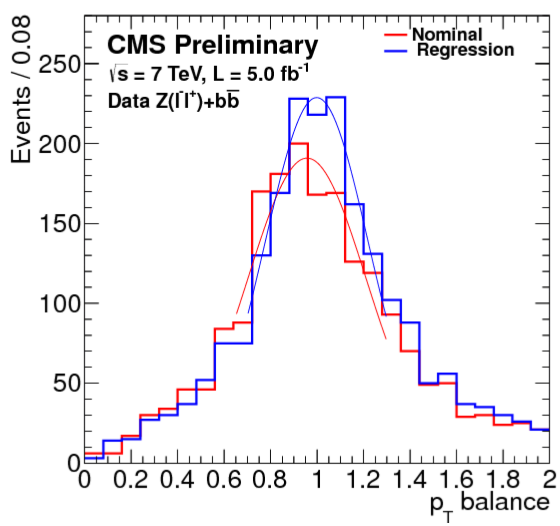


Fake rate: for $80 < p_T^j < 120$ GeV, $|\eta| < 2.4$

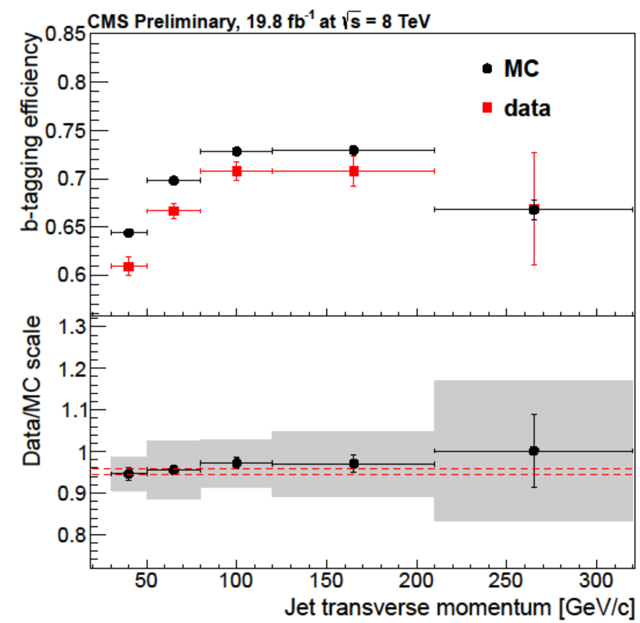
b tagger	misidentification probability	SF_{light}
JPL	0.0944 ± 0.0004	$1.03 \pm 0.01 \pm 0.07$
CSVL	0.0990 ± 0.0004	$1.10 \pm 0.01 \pm 0.05$
JPM	0.0105 ± 0.0002	$1.10 \pm 0.02 \pm 0.20$
CSVM	0.0142 ± 0.0002	$1.17 \pm 0.02 \pm 0.15$
TCHPT	0.0026 ± 0.0001	$1.27 \pm 0.06 \pm 0.27$
JPT	0.0013 ± 0.0001	$1.11 \pm 0.07 \pm 0.31$
CSVT	0.0016 ± 0.0001	$1.26 \pm 0.07 \pm 0.28$

m_{bb} resolution ~ 10 %



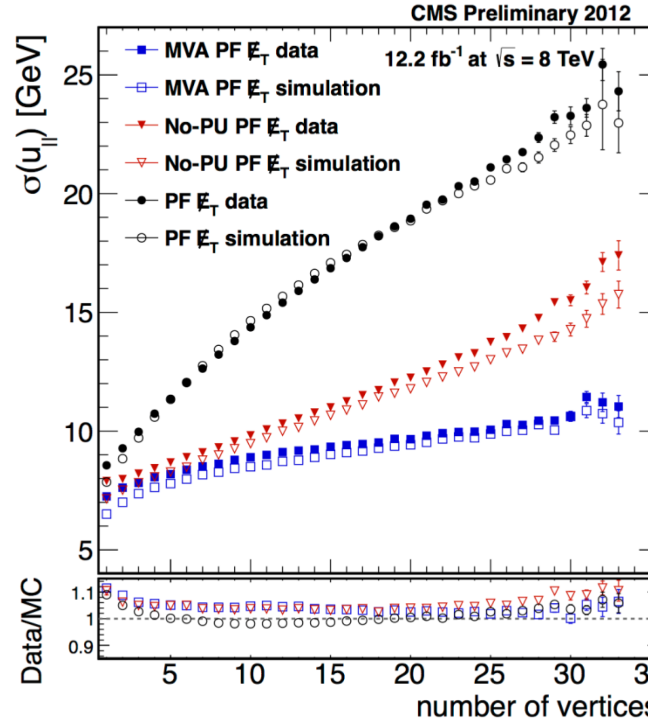


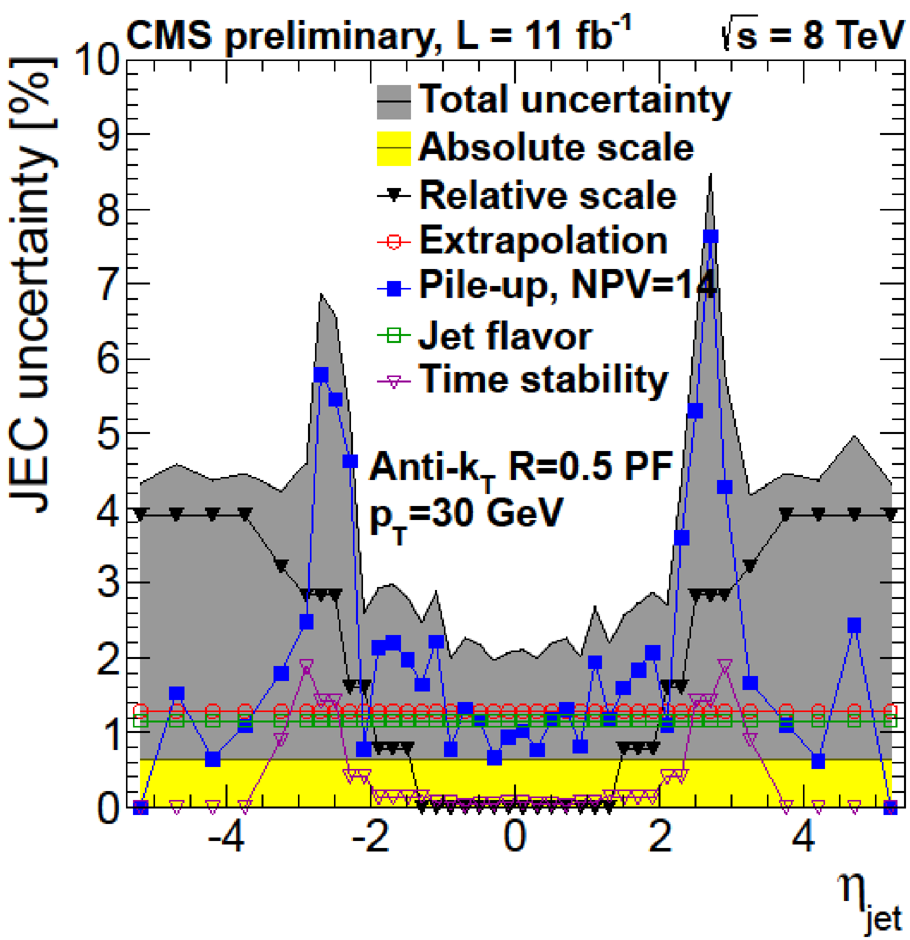
CSVM efficiency vs p_T of b-jets

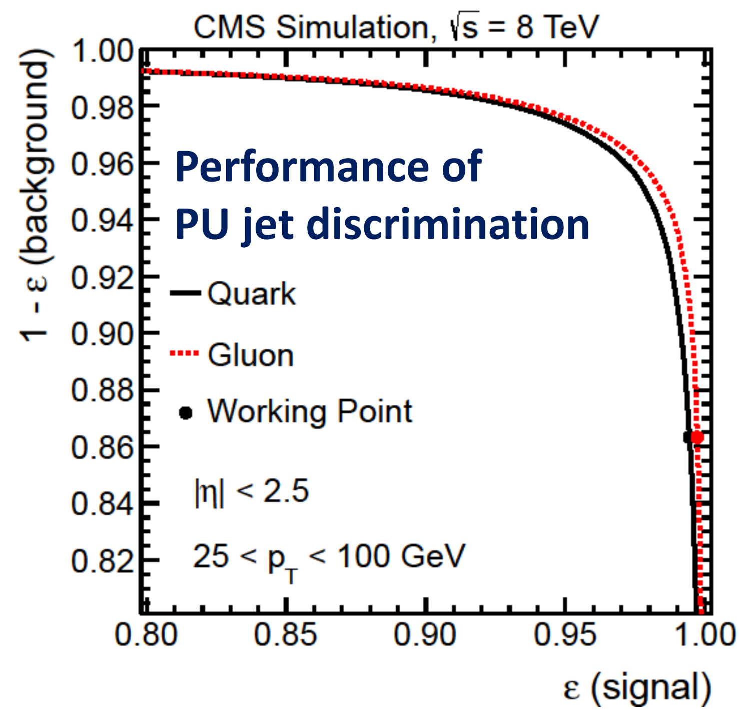


Reconstruction: jets, E_T^{miss}

- PF (+JPT, Trk, Calo) jets - anti-k_T R=0.5
- PU jet reductions
  - most useful within the tracker acceptance
- PU mitigation algos for E_T^{miss}





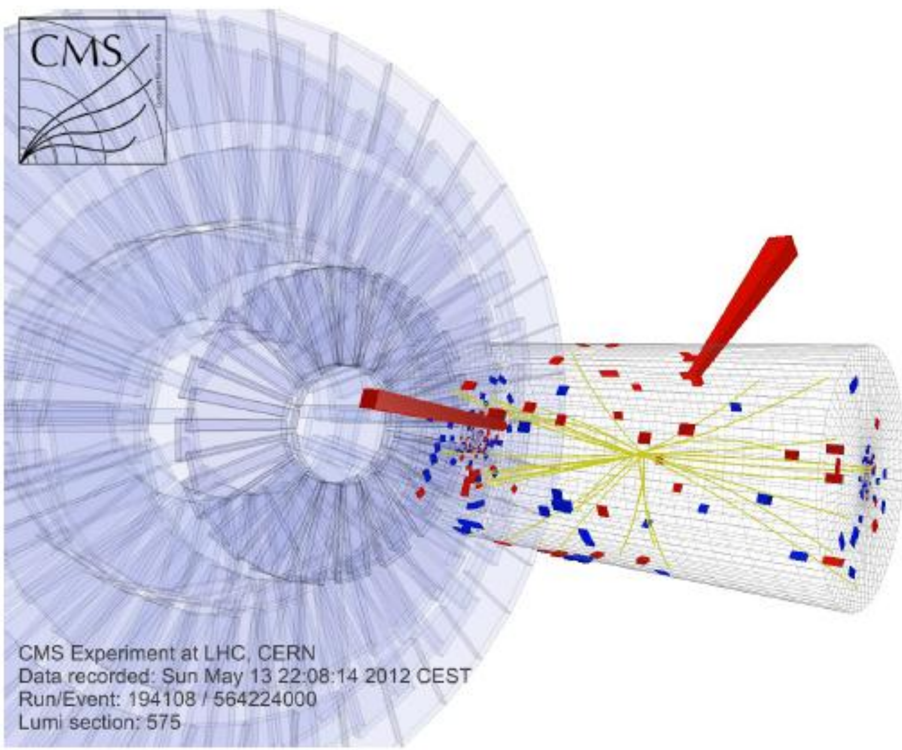


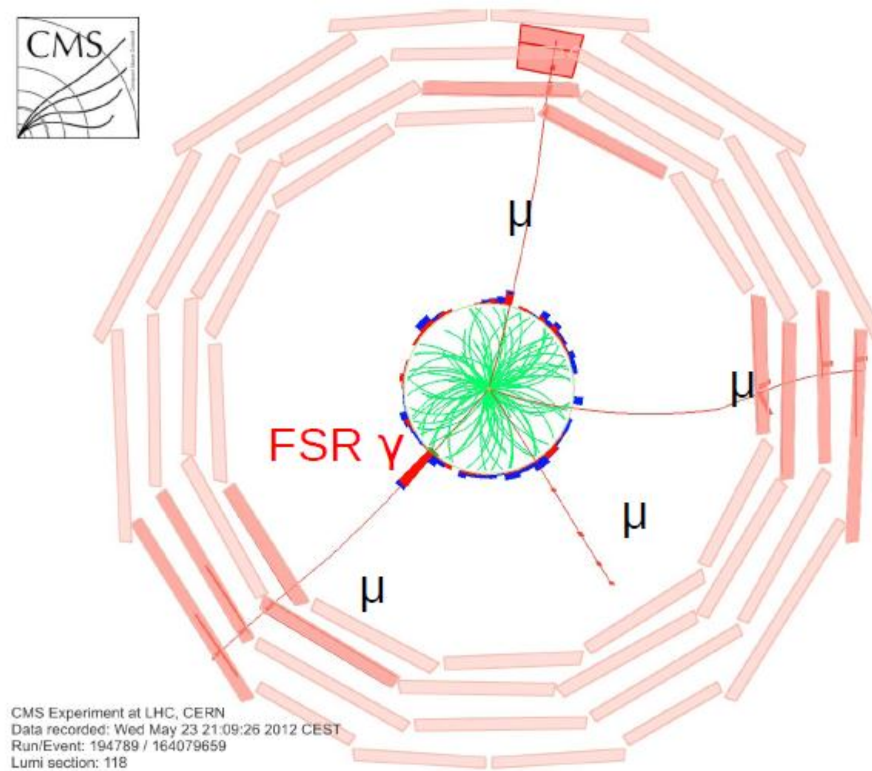
Layout for
Higgs result presentation

- measurements of h properties
  - mass, width, spin/CP
  - consistency with SM couplings to bosons and fermions
- Searches for BSM Higgs boson(s)
  - non-SM h decays
  - other Higgs bosons
- Rare SM h decays

References to CMS publications are in backup slides

Measurement of h properties





How mass, spin/CP are measured in h→ZZ→4ℓ and h→γγ analyses

- **h→ZZ→4ℓ**
  - mass: fit with 3D likelihood

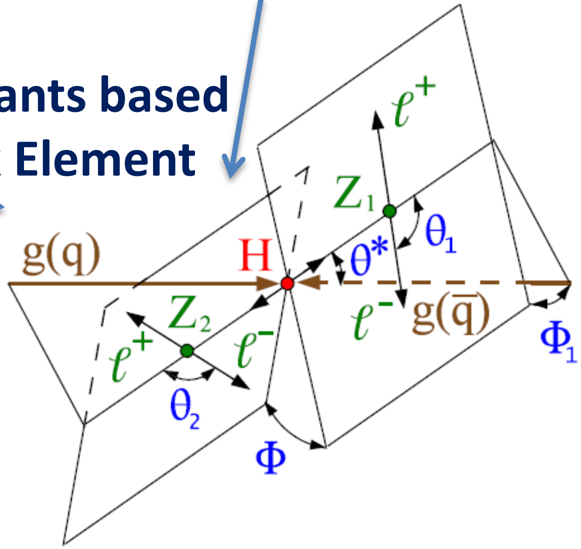
$$\mathcal{L}_{3D}^{m,\Gamma} \equiv \mathcal{L}_{3D}^{m,\Gamma}(m_{4\ell}, \mathcal{D}_{\rm m}, \mathcal{D}_{\rm bkg}^{\rm kin}) = \mathcal{P}(m_{4\ell}|m_{\rm H}, \Gamma, \mathcal{D}_{\rm m})\mathcal{P}(\mathcal{D}_{\rm m}|m_{4\ell}) \times \mathcal{P}(\mathcal{D}_{\rm bkg}^{\rm kin}|m_{4\ell}).$$

per-event mass uncertainty

  - spin/CP; CL_S using 2D likelihood ratio

$$\mathcal{L}_{2D}^{J^P} \equiv \mathcal{L}_{2D}^{J^P}(\mathcal{D}_{\rm bkg}, \mathcal{D}_{J^P})$$

Discriminants based on Matrix Element



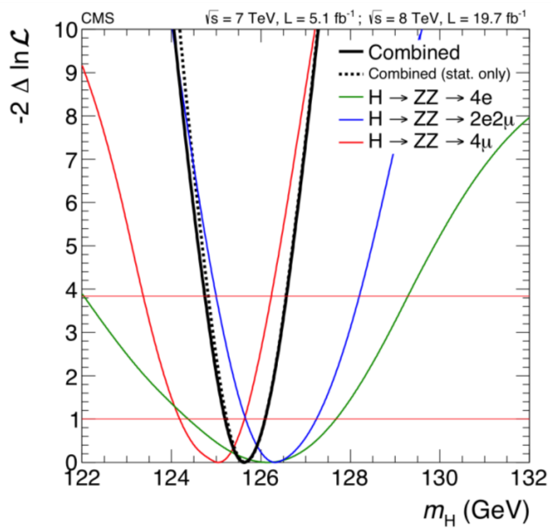
- **h→γγ**
  - mass: fit $m_{\gamma\gamma}$ floating $\mu_{\gamma\gamma}$
  - spin/CP: CL_S with ratio of likelihoods using $\cos(\theta_{CS})$ to discriminate between hypotheses

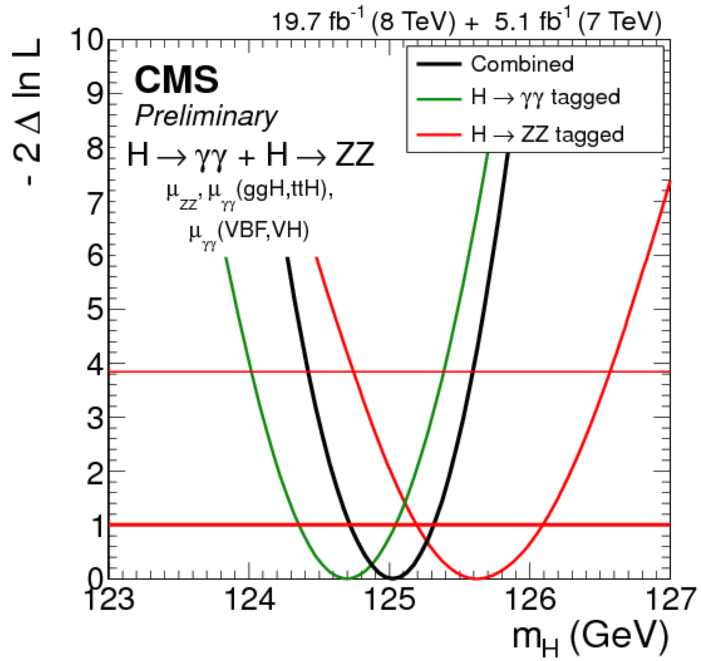
$$\cos(\theta^*_{\rm CS}) = 2 \times \frac{E_2 p_{z1} - E_1 p_{z2}}{m_{\gamma\gamma}\sqrt{m^2_{\gamma\gamma} + (p_{\rm T}^{\gamma\gamma})^2}}$$

For spin/CP HJU generator is used in both γγ and ZZ->4ℓ modes

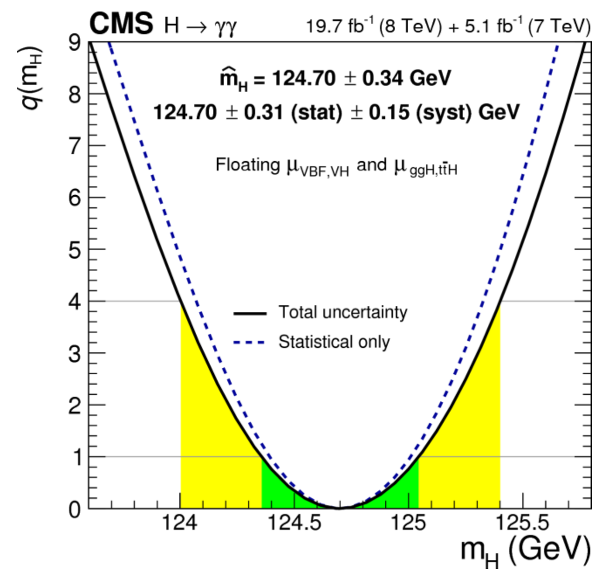
h boson mass

- $h \rightarrow ZZ \rightarrow 4\ell$





- $h \rightarrow \gamma\gamma$

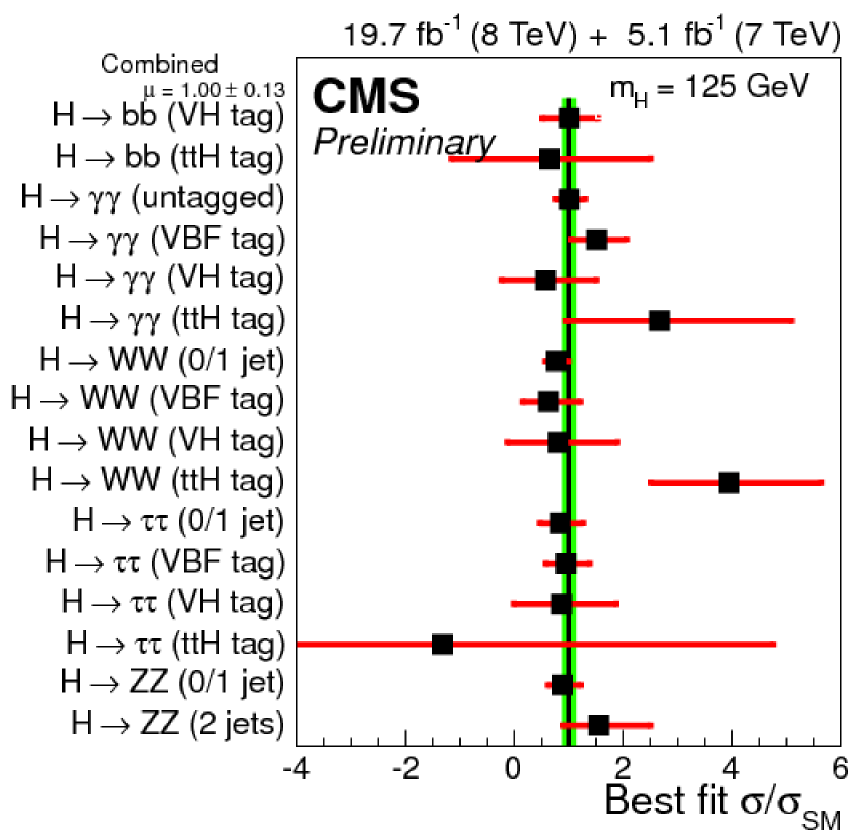


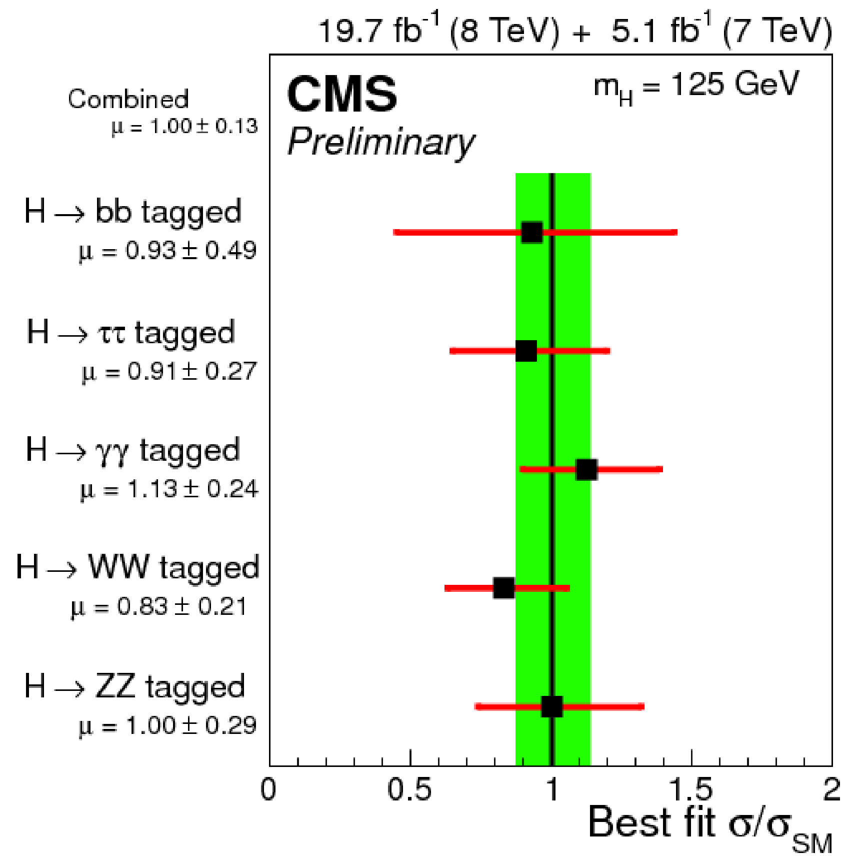
m^{ZZ}_h = 125.6±0.4(stat.)±0.2(syst.)
μ =0.94$\pm^{0.26}_{0.23}$(stat.)$\pm^{0.13}_{0.09}$(syst.)

$m^{\gamma\gamma}_h$ = 124.72±0.31(stat.)±0.15(syst.)
μ =1.14$\pm^{0.26}_{0.23}$

Combined m_h = 125.0±0.30 GeV

h signal strength at best fit mass





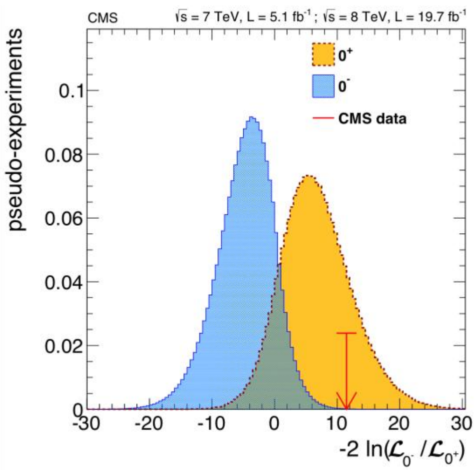
- **$\mu = 1.00 \pm 0.13$**

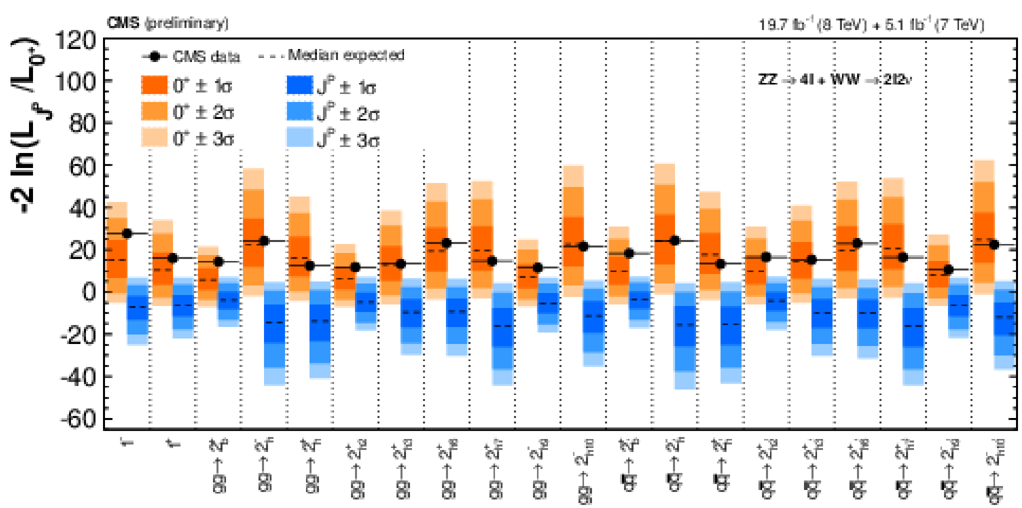
h spin/CP

CP even vs CP odd; spin 0 vs spin 1 or spin 2

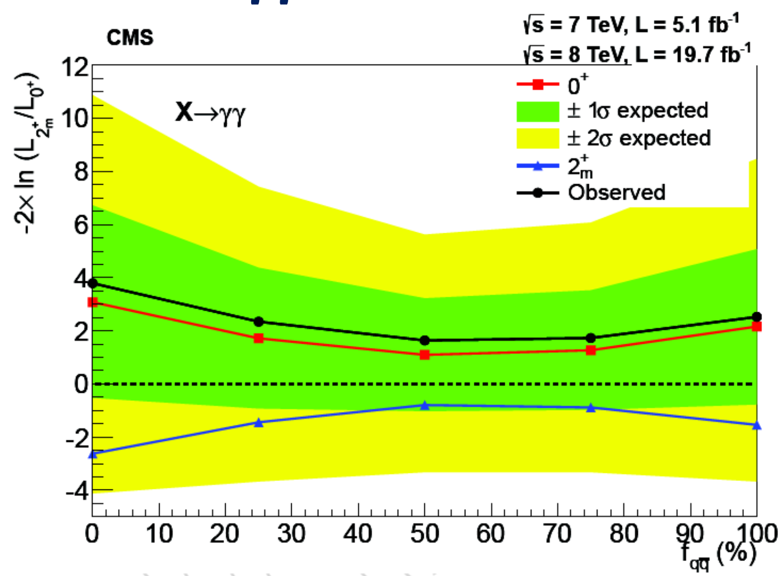
- **h→ZZ→4ℓ + H→WW→ℓνℓν**

Pseudoscalar boson, spin-one and spin-two hypotheses are excluded at 99.9% C.L. or higher





- **h→γγ: 0^+ vs 2^+**

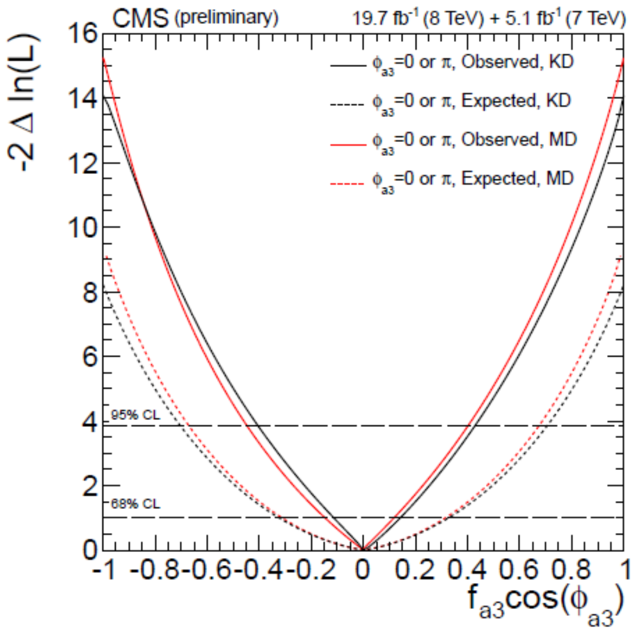


$f_{q\bar{q}}$	$1 - CL_S$ expected	$1 - CL_S$ observed
0	0.92	0.94
0.25	0.78	0.83
0.50	0.64	0.71
0.75	0.69	0.75
1	0.83	0.85

Measuring CP-odd fraction with $h \to ZZ \to 4\ell$ (I)

$$A(X_{J=0} \to V_1 V_2) \sim v^{-1} \left(\left[a_1 - e^{i\phi_{\Lambda_1}} \frac{q_{Z_1}^2 + q_{Z_2}^2}{(\Lambda_1)^2} \right] m_Z^2 \epsilon_{Z_1}^* \epsilon_{Z_2}^* + a_2 f_{\mu\nu}^{*(Z_1)} f^{*(Z_2),\mu\nu} + a_3 f_{\mu\nu}^{*(Z_1)} \tilde{f}^{*(Z_2),\mu\nu} + a_2^{Z\gamma} f_{\mu\nu}^{*(Z)} f^{*(\gamma),\mu\nu} + a_3^{Z\gamma} f_{\mu\nu}^{*(Z)} \tilde{f}^{*(\gamma),\mu\nu} + a_2^{\gamma\gamma} f_{\mu\nu}^{*(\gamma_1)} f^{*(\gamma_2),\mu\nu} + a_3^{\gamma\gamma} f_{\mu\nu}^{*(\gamma_1)} \tilde{f}^{*(\gamma_2),\mu\nu} \right)$$

a_1, a_2 - CP-even couplings
a_3 – CP-odd couplings
Λ_1 – scale of new physics



fraction of CP-odd contribution:

$$f_{a3} = \frac{|a_3|^2\sigma_3}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda_1} / (\Lambda_1)^4}$$

$$\frac{|a_i|}{|a_1|} = \sqrt{\frac{f_{ai}}{f_{a1}}} \times \sqrt{\frac{\sigma_1}{\sigma_i}}$$

σ_1/σ_3=6.36

- **assuming a_3 to be constant**
- **a_2=0 (no CP-even high dim.)**

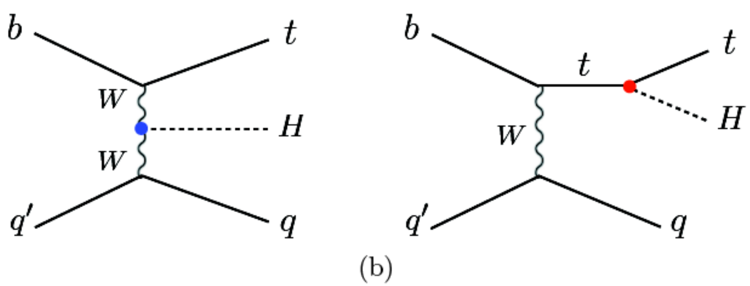
a_3/a_1 = [-2.05,2.19] observed

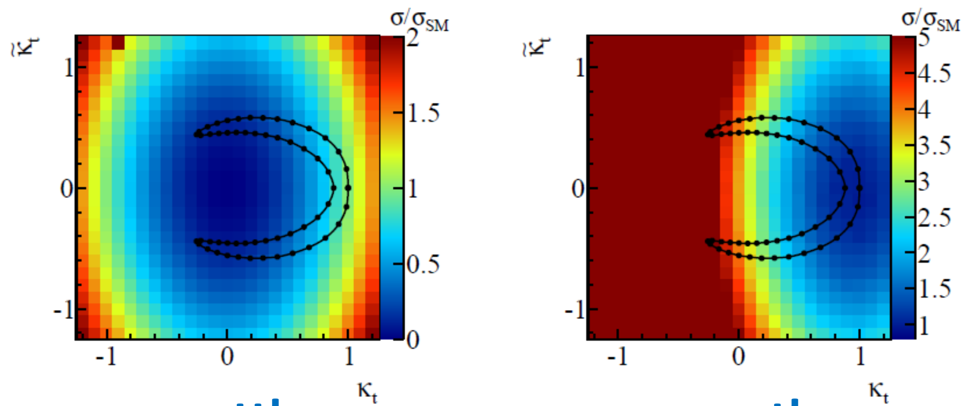
Measuring CP-odd fraction with $h \to ZZ \to 4\ell$ (II)

- Small f_{a3} does not necessary mean small CP-odd admixture
  - observables involving the Higgs-gauge couplings project on the CP-even component
  - better to look into observables with Higgs-fermion couplings

Single top+h, h→γγ analysis

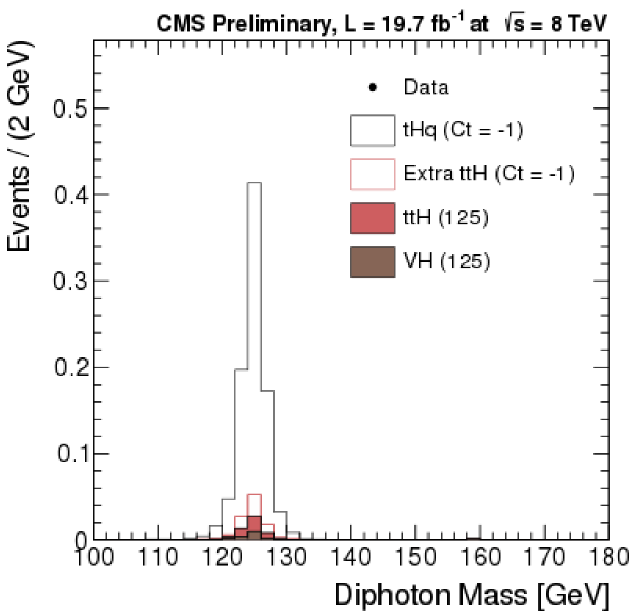
J. Ellis, D.S.Hwang, M. Takeuchi arXiv:1312.5736





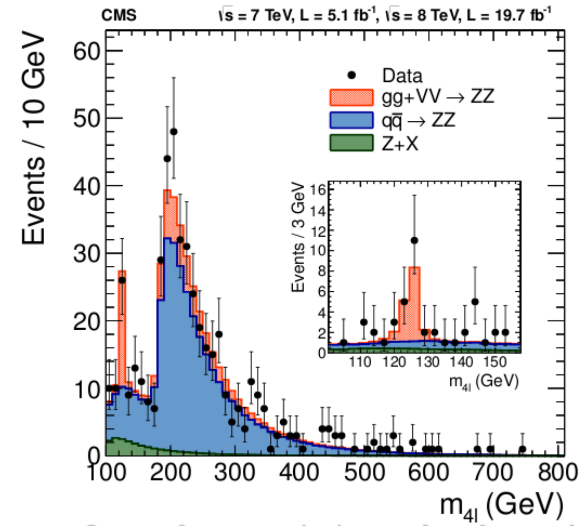
- **Due to interference pp→tqh process is sensitive to both magnitude and sign of y_{tth}**
- **tth and th can be used to measure scalar and pseudo-scalar h-top couplings**

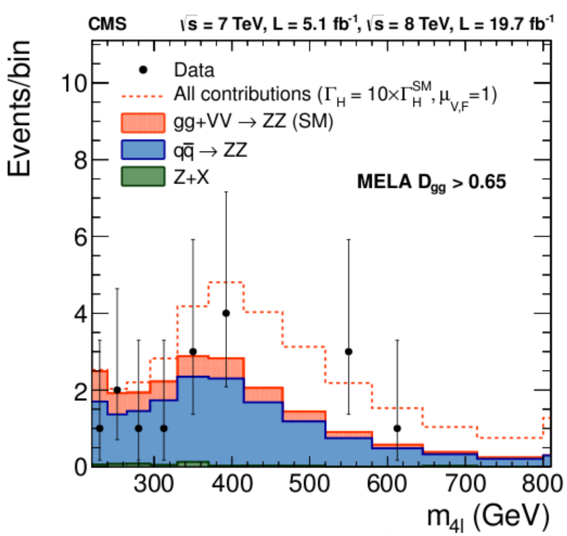
Upper limit = 4.1 x expected cross-section with k_t=-1.

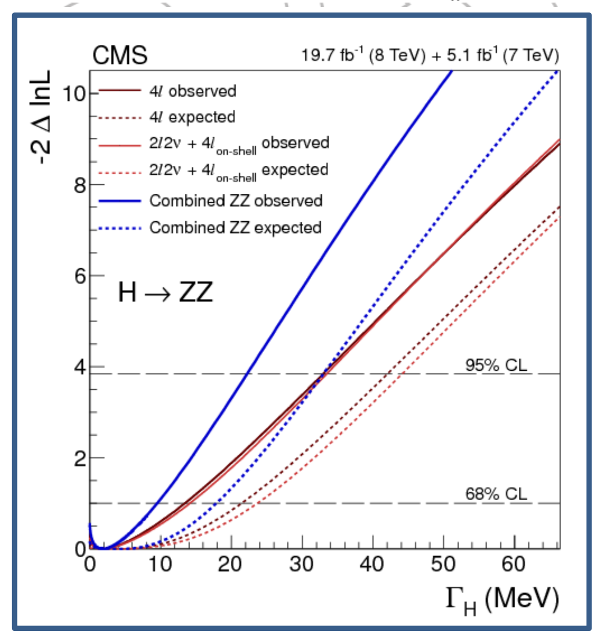


Width of h(125) boson using off-shell H production and ZZ decay

- $\sigma_{i\text{->}h(\text{on-shell})\text{->}f} \sim g_i^2 g_f^2 / \Gamma_h$
- $\sigma_{i\text{->}h(\text{off-shell})\text{->}f} \sim g_i^2 g_f^2$
- $\sigma_{h\text{-}gg\text{->}ZZ\ \text{interference}} \sim g_i g_f$
- **Fit on- and off-shell mass region**
  - varying $g_i^2 g_f^2$ and Γ_h
  - assuming SM off/on-shell yield ratio







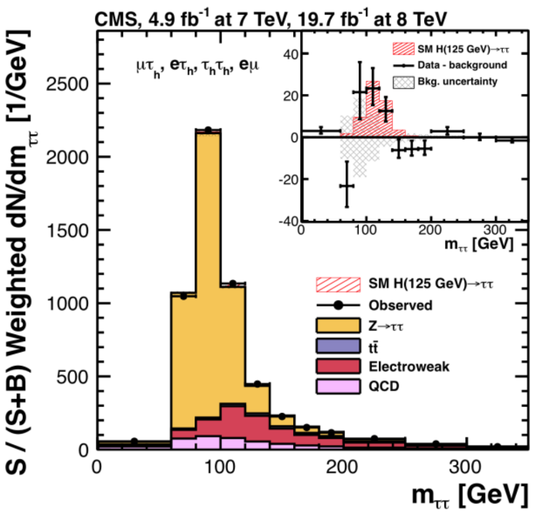
Higgs boson couplings at LHC

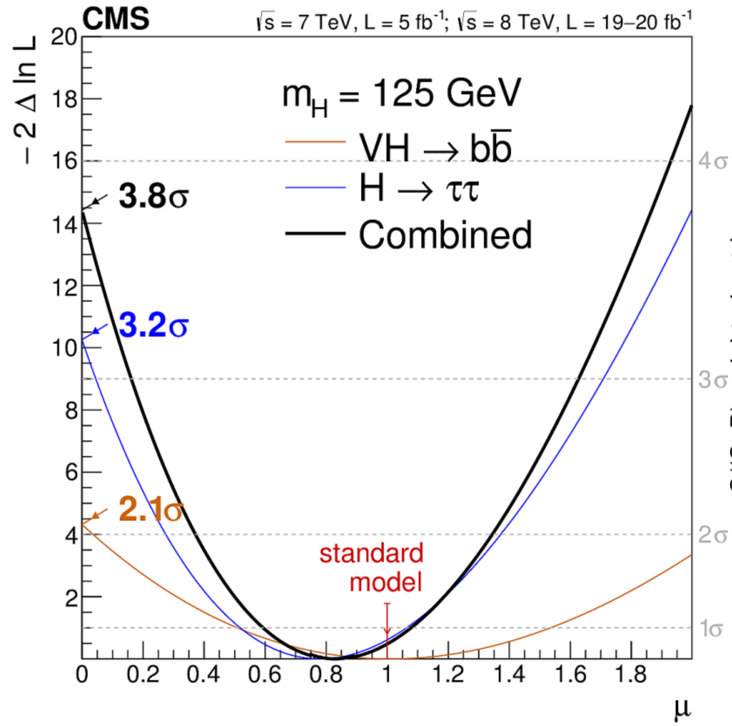
- **determination of total width impossible without further assumptions**
- **not all final states are accessible**
- **what is done so far:**
  - **perform fits to coupling strength modifiers to check consistency with SM**
    - ***LHC HXSWG Recommendations, benchmark models***

October 2013 – January 2014 :

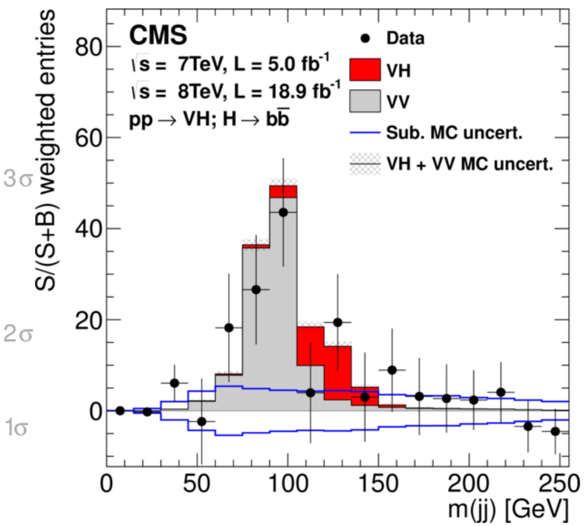
h(125) boson couples to τ and b

h→ττ





Vh, h→bb

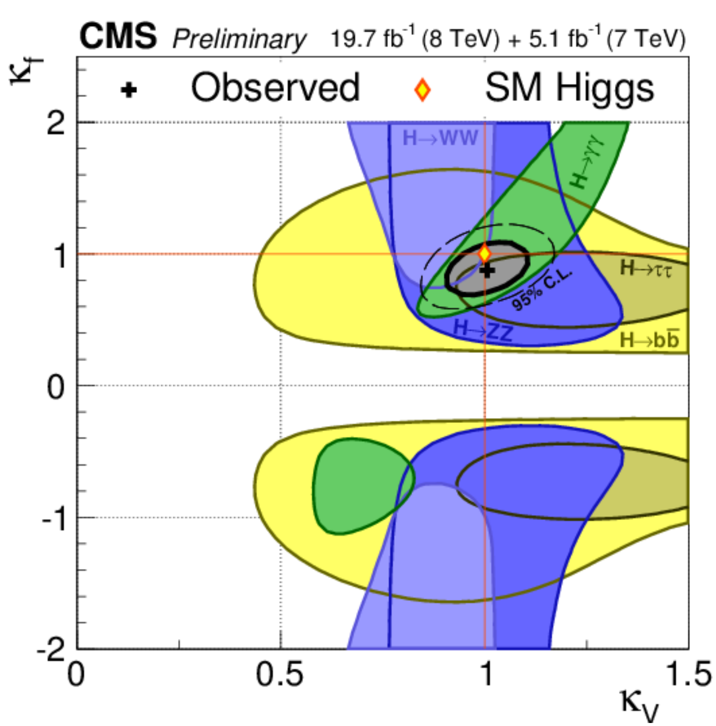


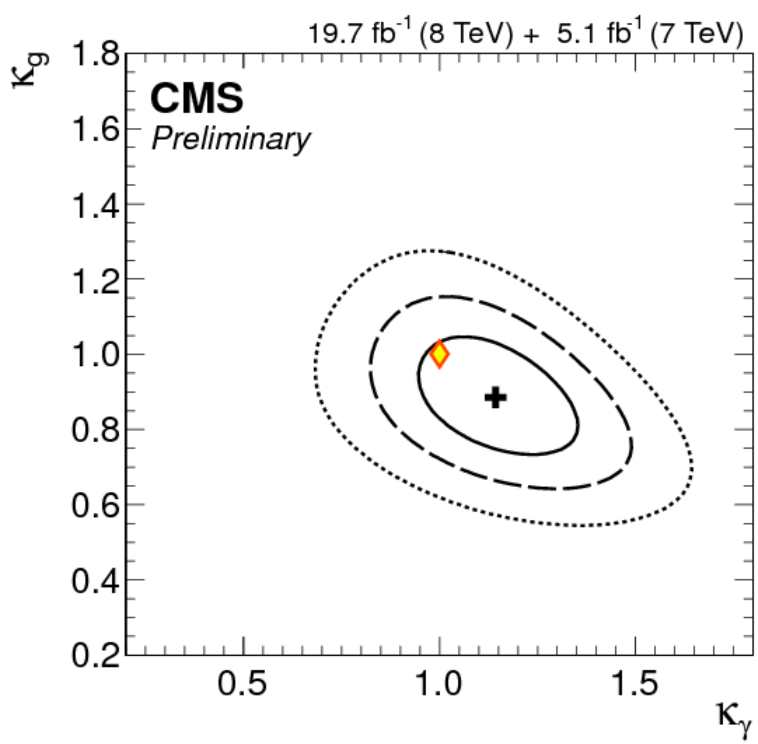
Channel	Significance (σ)		Best-fit
($m_H = 125\,\mathrm{GeV}$)	Expected	Observed	μ
$\mathrm{VH} \to \mathrm{b\bar{b}}$	2.3	2.1	1.0 ± 0.5
$\mathrm{H} \to \tau\tau$	3.7	3.2	0.78 ± 0.27
Combined	4.4	3.8	0.83 ± 0.24

Some benchmark parameterizations of Higgs boson couplings

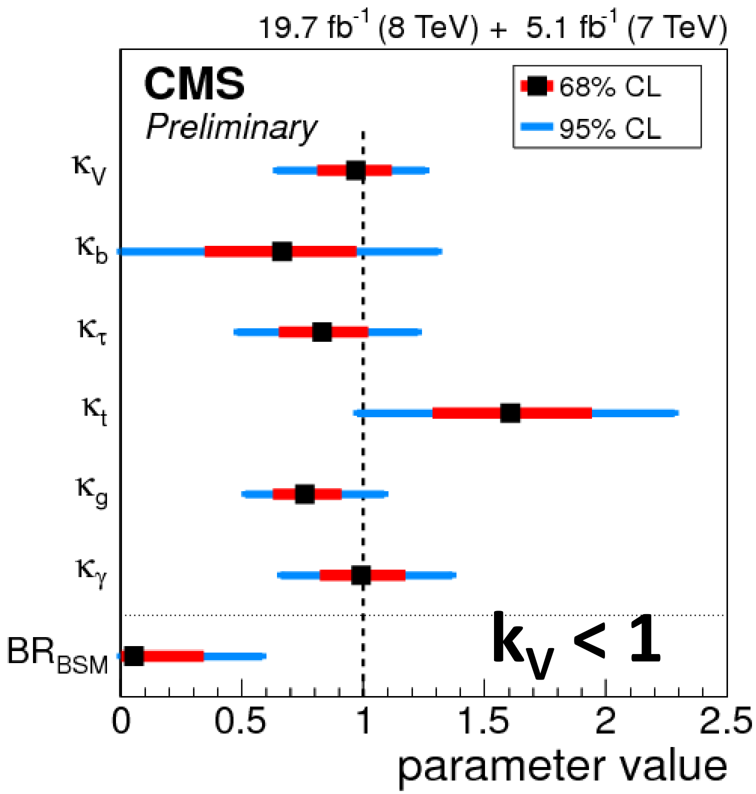
- k_V – common scale factor for vector boson couplings
- k_f – common scale factor for fermion couplings
- assuming no invisible and undetectable widths

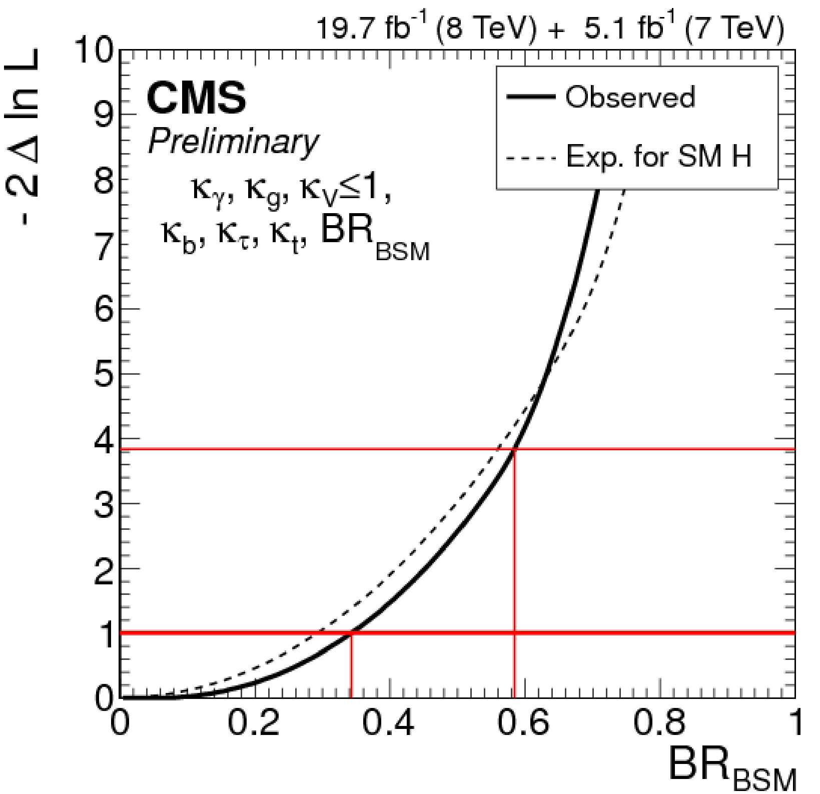
- k_γ, k_g – probing loop structure assuming no invisible or undetectable width





Constraining h→BSM with "visible" modes

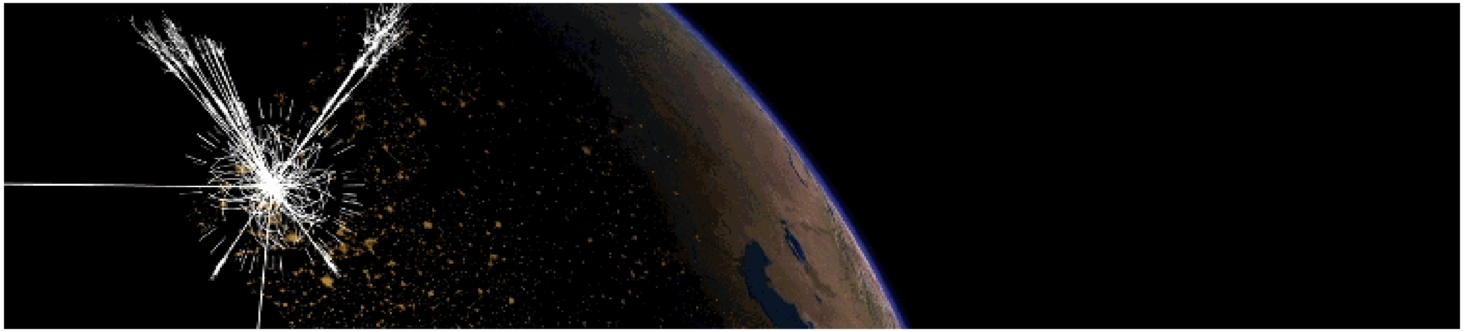




BR_{BSM} < 0.58 at 95% CL

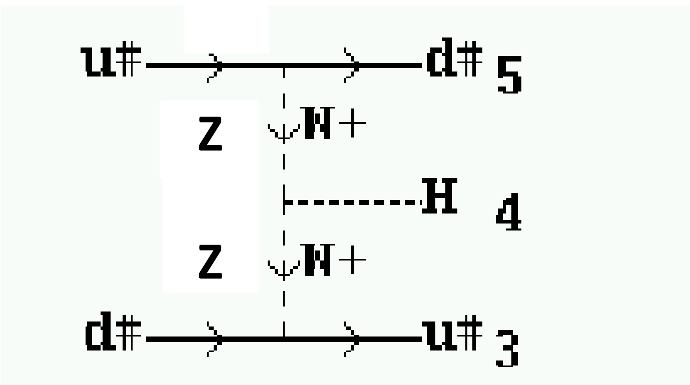
Non-SM h decays:

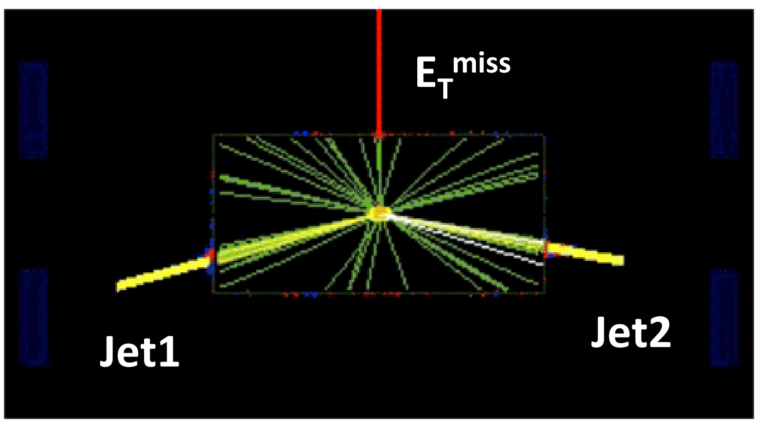
searches for $h \rightarrow$invisible with VBF h, Zh (Z->$\ell\ell$,bb)



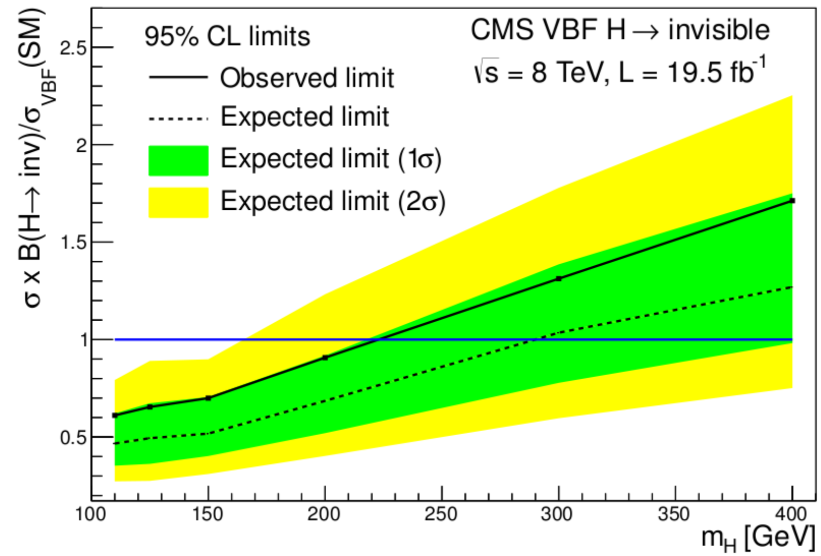
Detection of Dark Matter

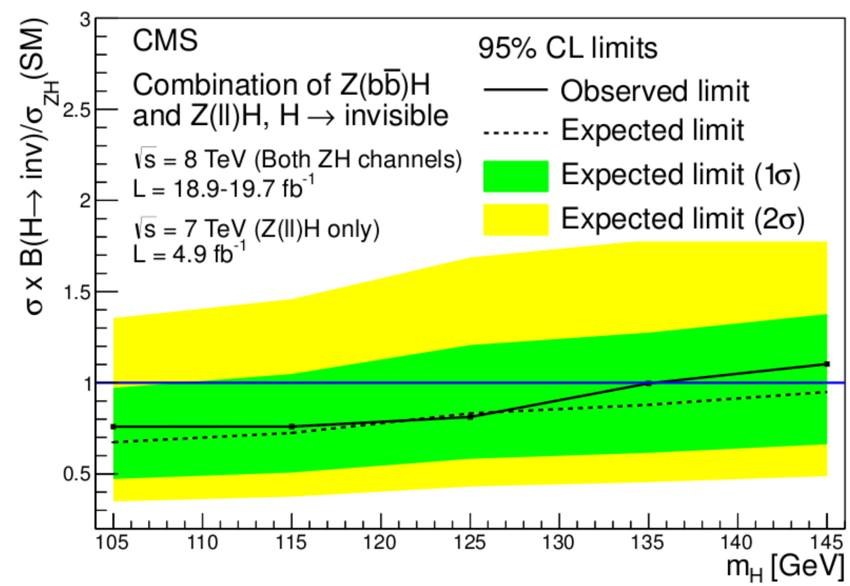
most sensitive mode qq'→qq'h (VBF h)





Event 191202:51:82701983

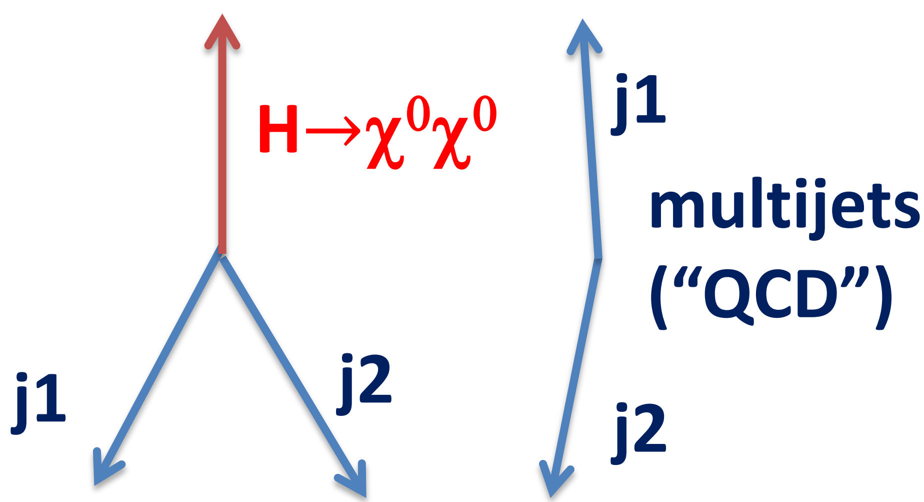


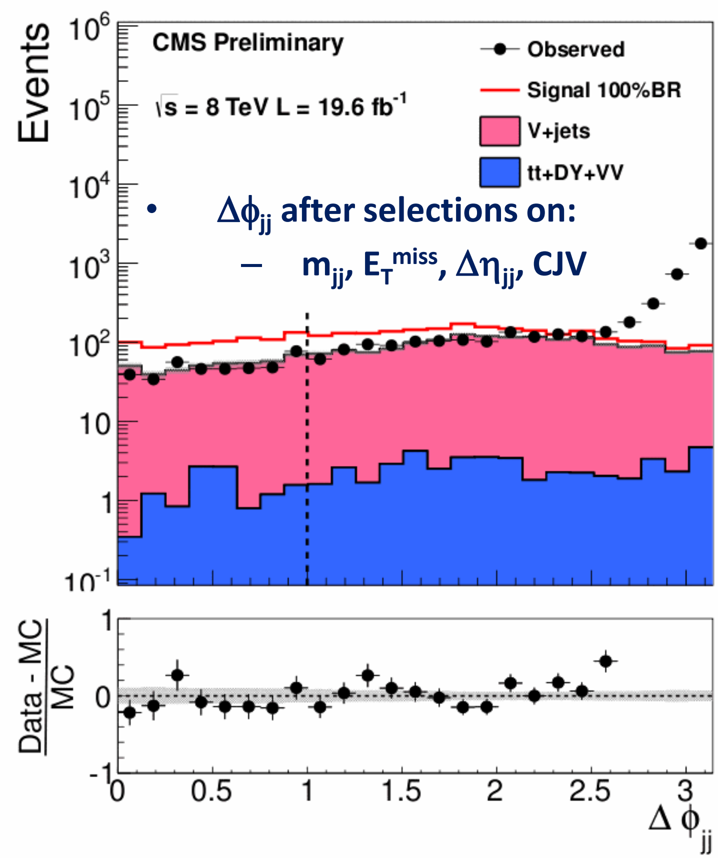


VBF h→invisible: offline signal selections and topology

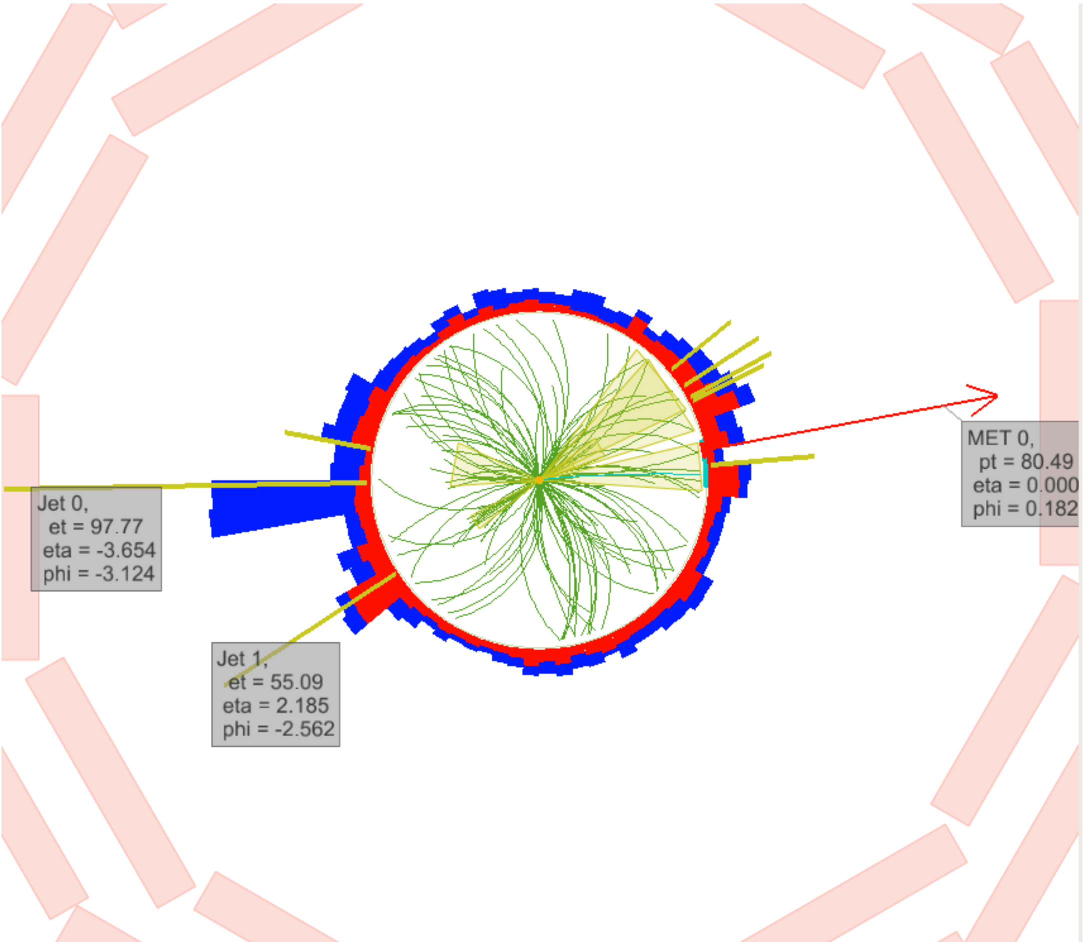
- two jets p_T>50 GeV, $|\eta|$<4.7
- m_{jj} > 1100 GeV
- $\Delta\eta_{jj}$ > 4.2
- E_T^{miss} > 130 GeV
- $\Delta\phi_{jj}$ < 1.0
- Central Jet Veto (CJV)

Signal: small $\Delta\phi_{jj}$
QCD: large $\Delta\phi_{jj}$



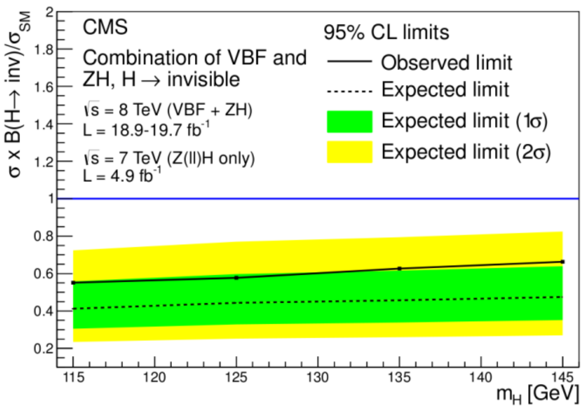


Signal region, with CJV (x,y view)



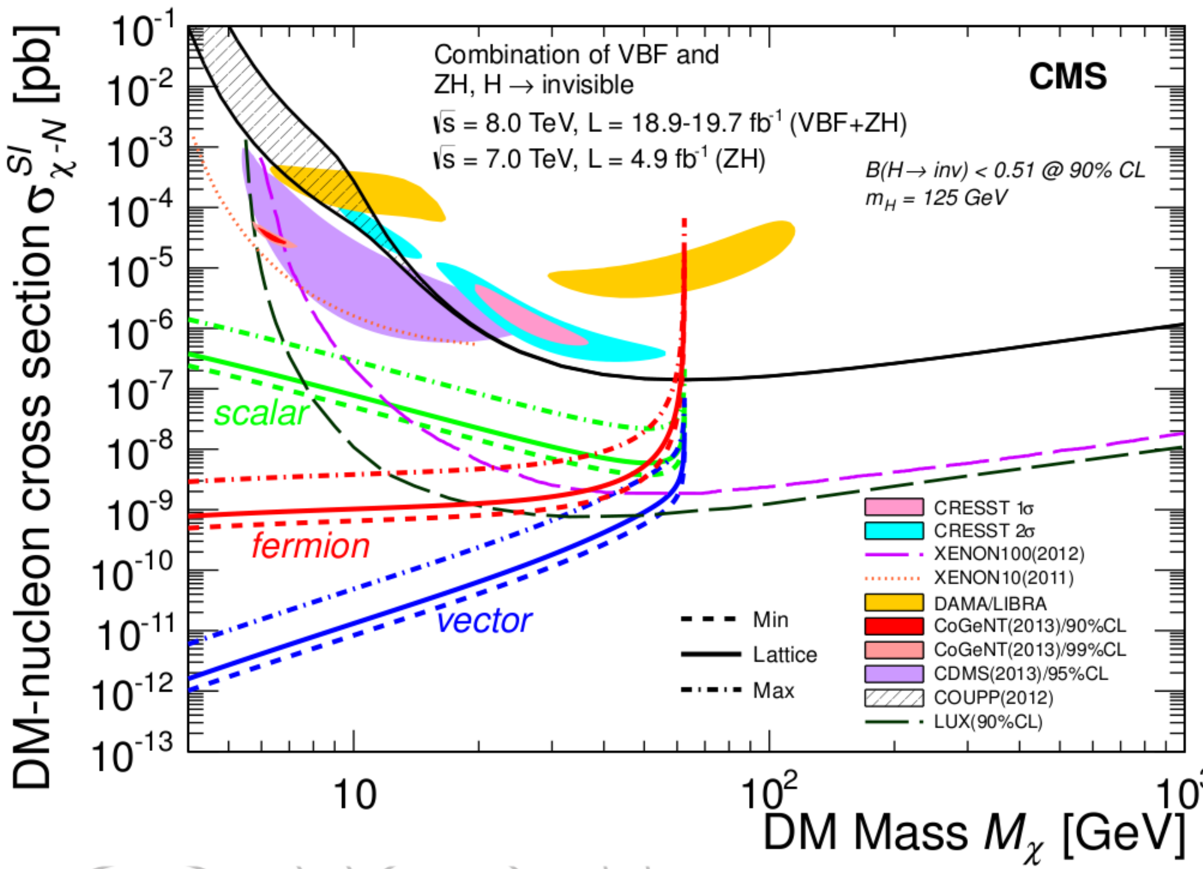
	▽pT	eta	phi
0	97.8	-3.654	-3.124
1	55.1	2.185	-2.562
2	27.0	-0.200	0.084
3	24.8	2.286	0.502
4	23.4	-2.044	2.958
5	23.0	0.359	0.575
6	21.6	-2.901	0.472
7	20.4	1.349	0.691

Interpretation of H->invisible direct search in Higgs-portal Dark Matter models



BR($h_{125\ GeV}$→inv) < 0.58 at 95 % CL (expected < 0.44)

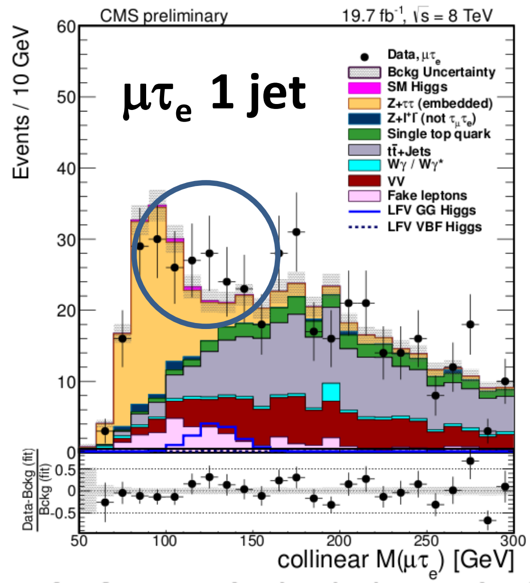
combining VBF and ZH modes

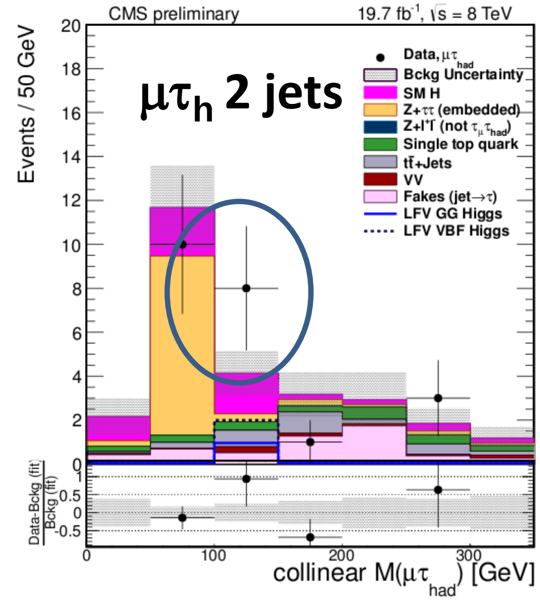


Non-SM h decays:

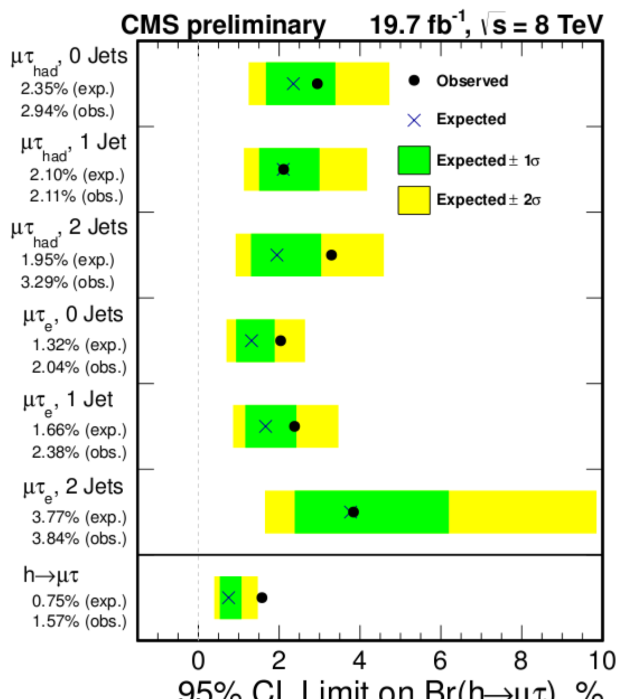
LFV with h→μτ

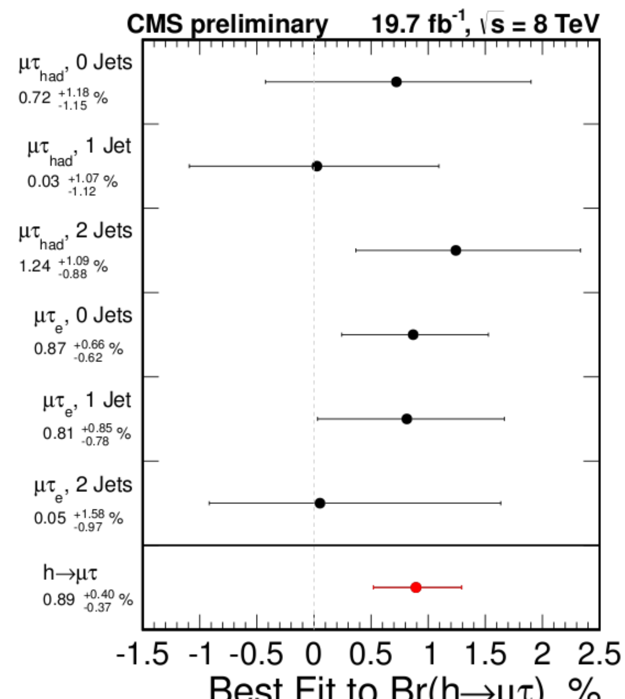
- Events are subdivided on 0, 1, 2 jet categories
- $\mu\tau_e$, $\mu\tau_h$ topologies
- m_h is reconstructed in collinear approximation





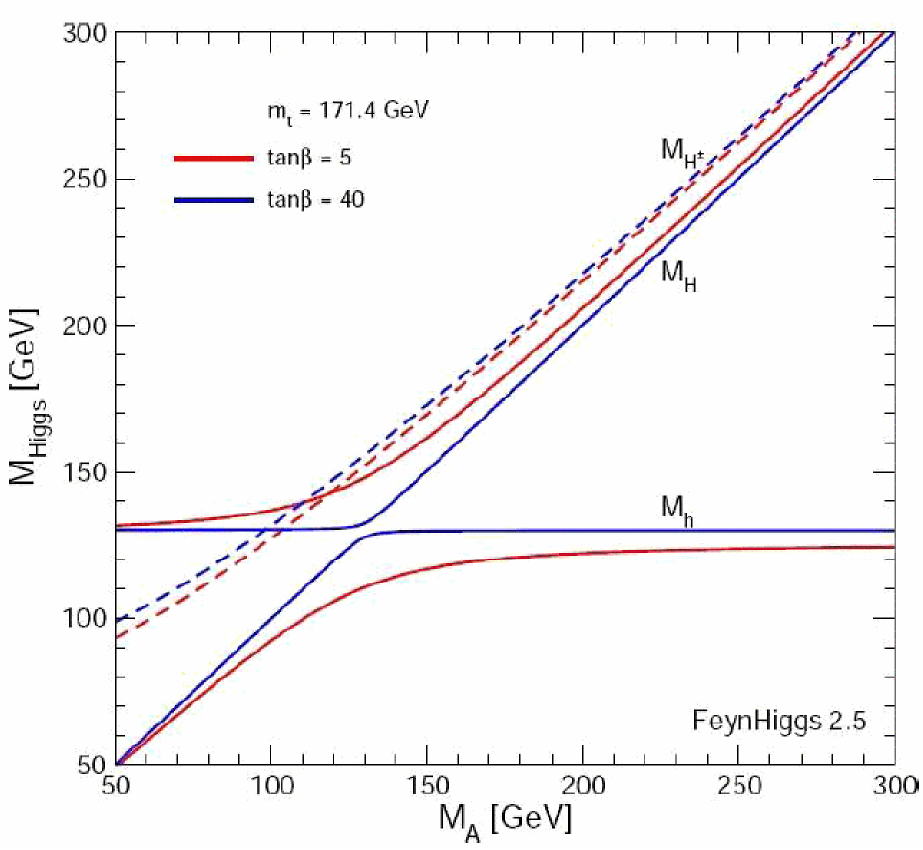
- **Upper limit:**
  - BR < 1.57 %
- **~ 2.5 σ access**





Searches for other Higgs bosons

MSSM Higgs bosons

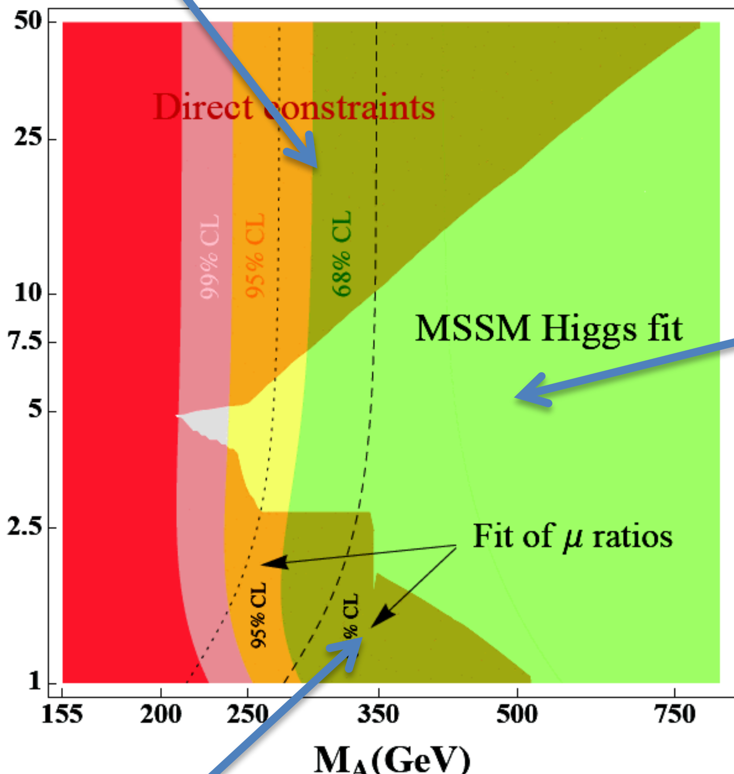


- **five Higgs bosons in MSSM:**
  - **two CP-even h, H; one CP-odd A, two charged $H^{+/-}$**
  - ***what is discovered as state of 125 GeV, h or H ?***

Landscape of BSM Higgs channels in MSSM

- ***High tanβ*:** $\phi \to \tau\tau$, $\phi \to \mu\mu$; $H^+ \to \tau\nu$, tb

A. Djouadi et.al. arXiv:1307.5205

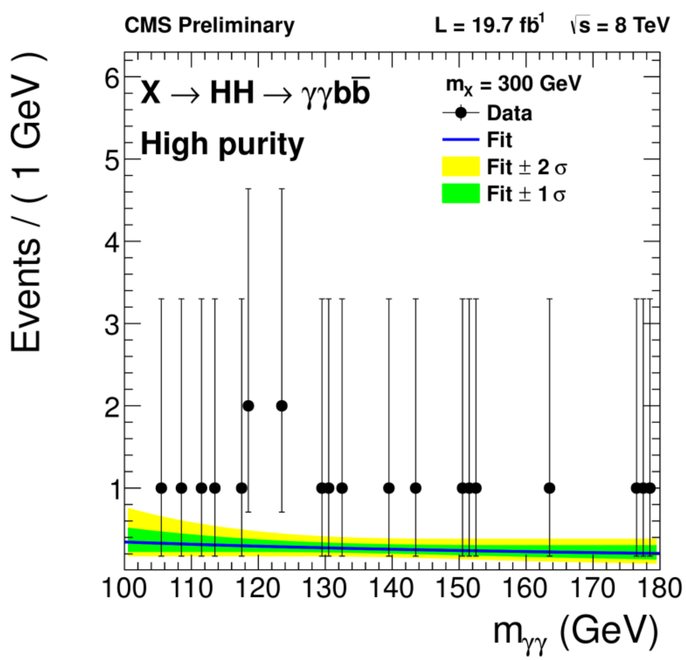


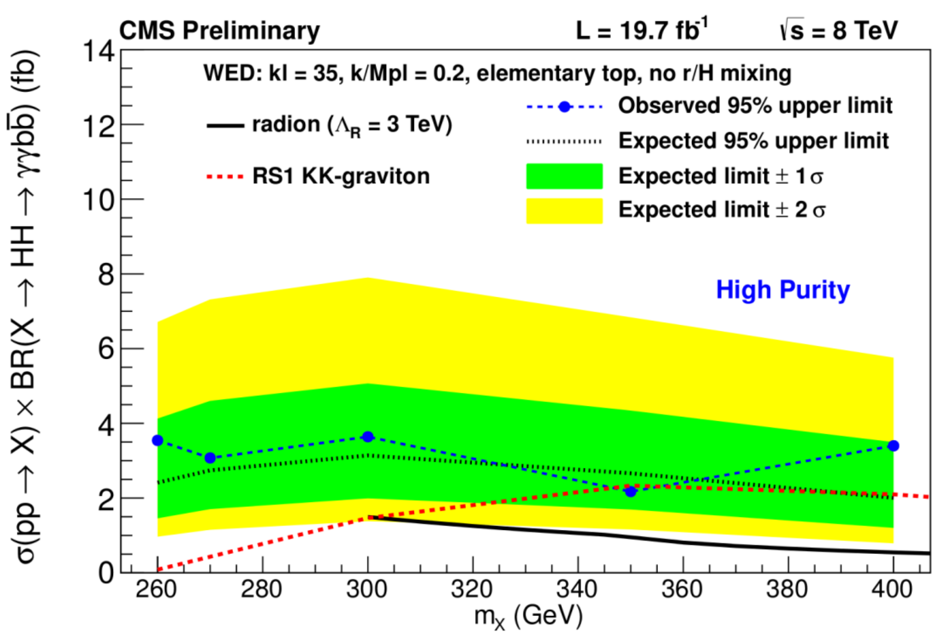
- ***Intermediate tanβ*:**
  - $H/A \to \chi_i^0 \chi_j^0$, $\chi_i^+ \chi_j^-$
  - $H^+ \to \chi_i^+ \chi_j^0$

- ***Low tanβ*:** $A \to Zh$; $H \to hh$, tt; $H^+ \to cs$, cb, $\tau\nu$, tb, Wh

$H \to hh \to \gamma\gamma bb$

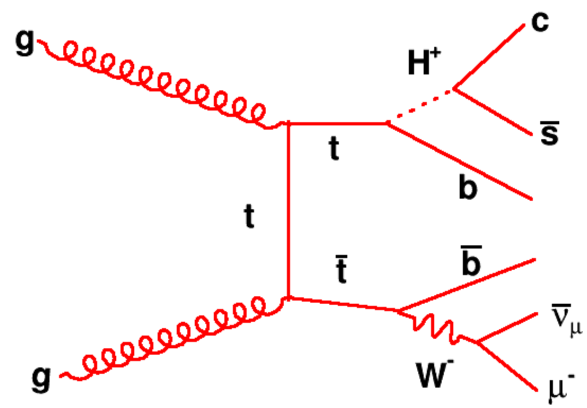
- **Search strategy:**
  - looking for signal in $m_{\gamma\gamma}$ distribution for $\gamma\gamma bb$ events selected within m_{bb} and $m_{\gamma\gamma bb}$ mass windows
- **In hMSSM** (A. Djouadi et.al. arXiv:1307.5205):
  - $\sigma(gg \to H)xBR(H \to hh \to \gamma\gamma bb)$=2.9 fb for m_A=300 GeV, $\tan\beta$=2
    - close to observed limit !

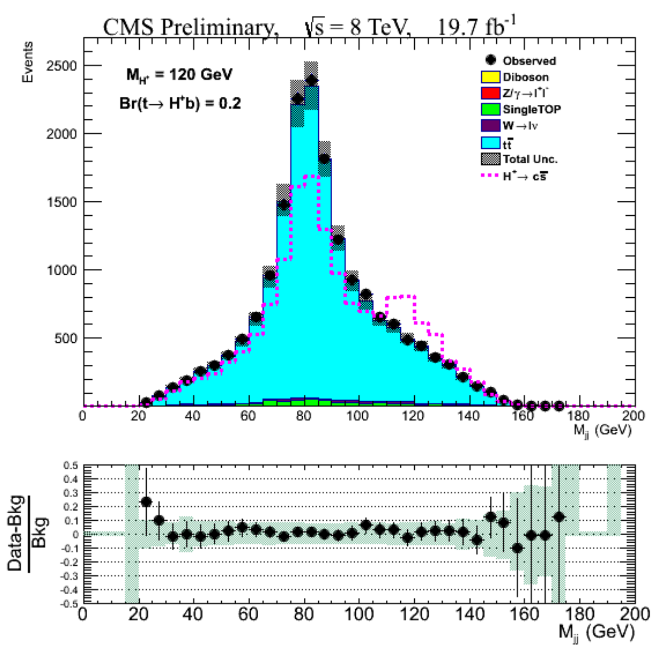


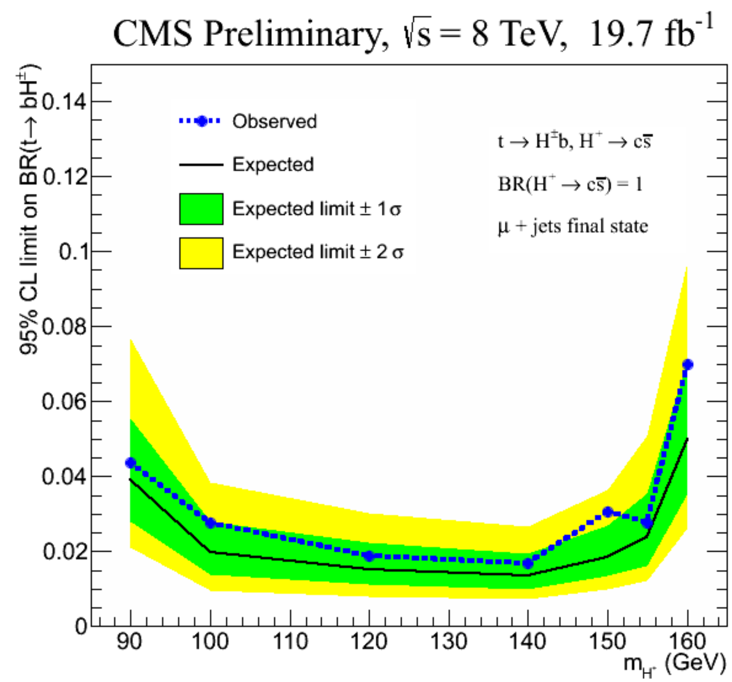


$t\bar{t} \rightarrow bWbH^+$, $H^+ \rightarrow cs$, $m_{H+} < m_t$

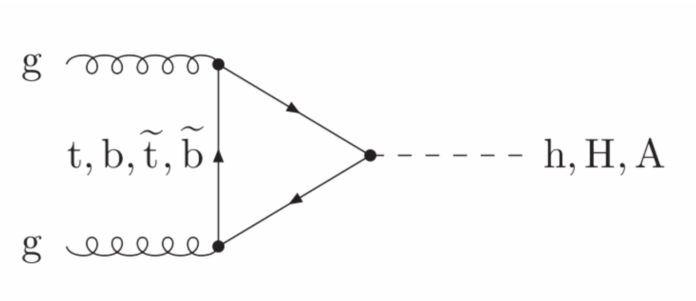
- **Search strategy:**
  - trigger with muon from t->Wb->μνb decay
  - search for bump in di-jet mass distribution for jets from 2nd top decay
  - kinematic fit with top mass constraint

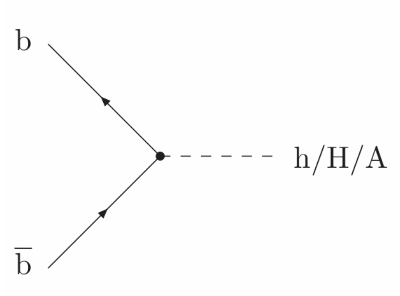


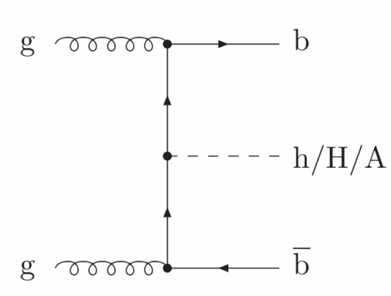




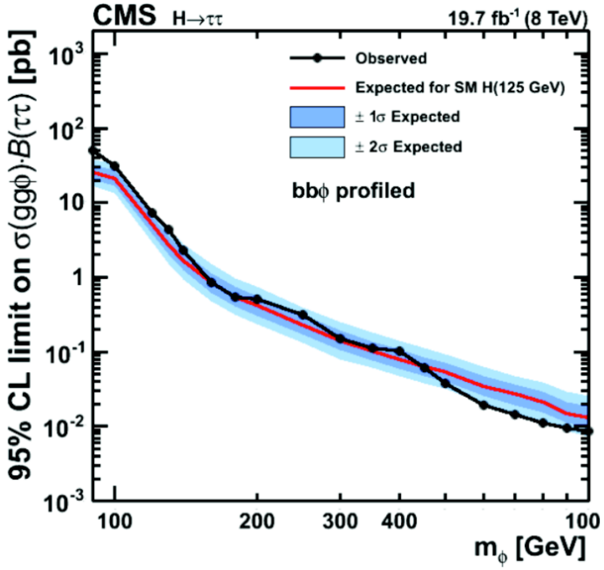
h,H,A→ττ

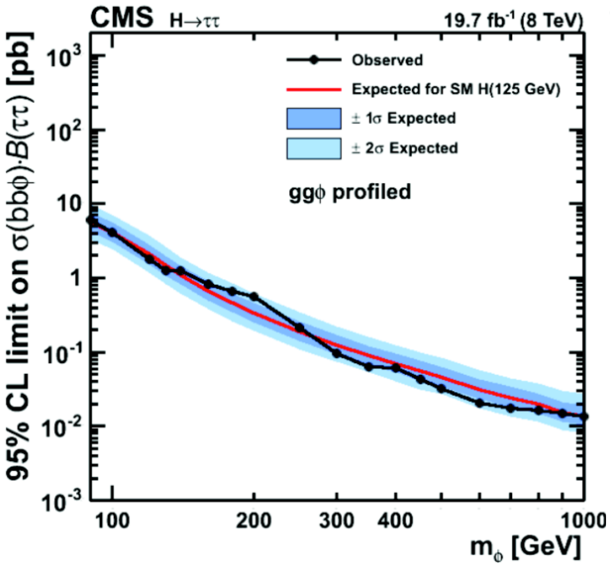


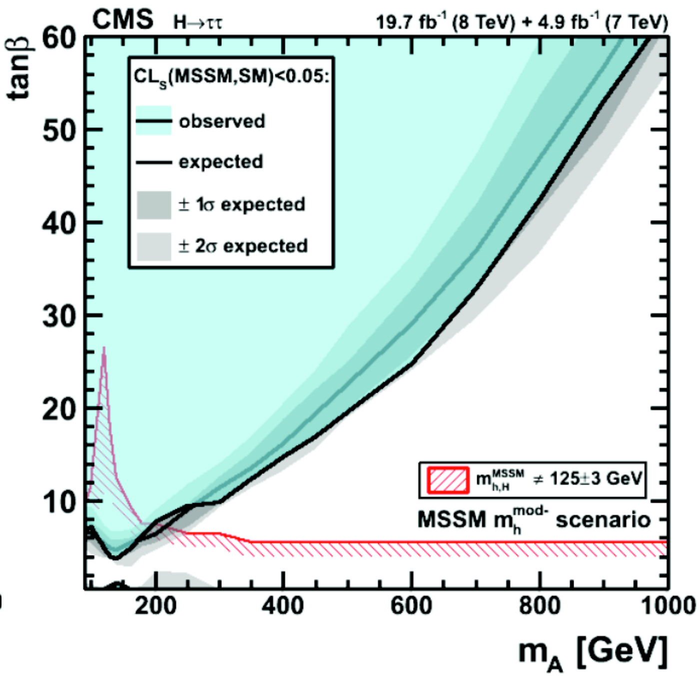




- split events into b-tag and no-b-tag categories
- consider $\tau_\mu\tau_h$, $\tau_e\tau_h$, $\tau_h\tau_h$, $\tau_e\tau_\mu$, $\tau_\mu\tau_\mu$ final states







- model independent limits
- m_A-tanβ exclusions in new benchmark scenarios (M.Carena at al. arXiv:1302.7033)

Searches for heavy H decays into ZZ and WW

Interpretation in the Additional EW singlet model (h, H):

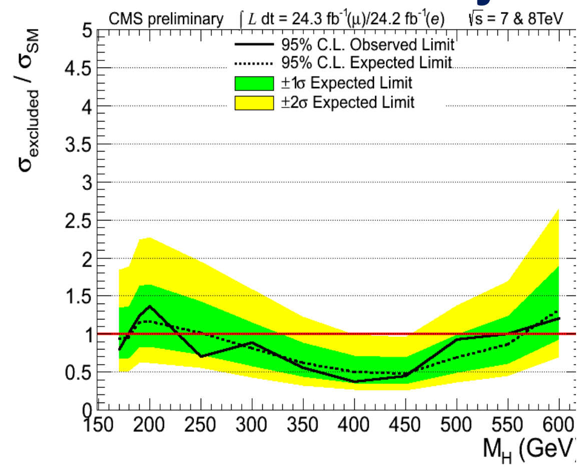
$\sigma_h = c \times \sigma_{h,SM}$
$\Gamma_h = c \times \Gamma_{h,SM}$
$BR_{h,i} = BR_{h,SM,i}$

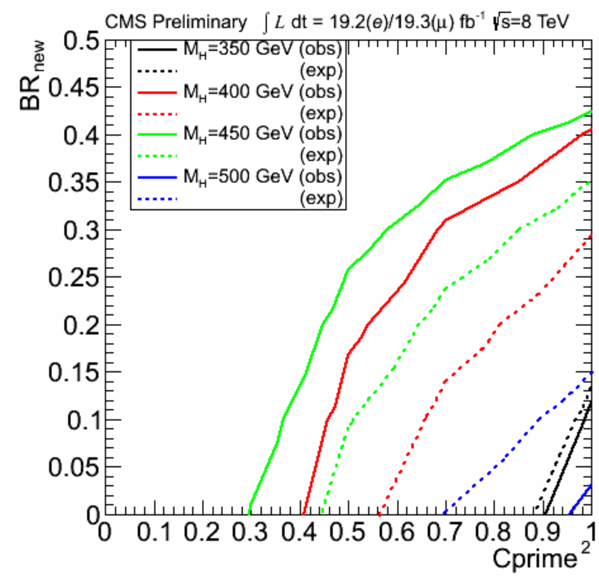
$\sigma_H = c' \times \sigma_{H,SM}$
$\Gamma_H = c' / [1 - BR_{H,new}]\ \Gamma_{H,SM}$
$BR_{H,i} = [1 - BR_{H,new}]\ BR_{H,SM,I}$

$c^2 + c'^2 = 1$

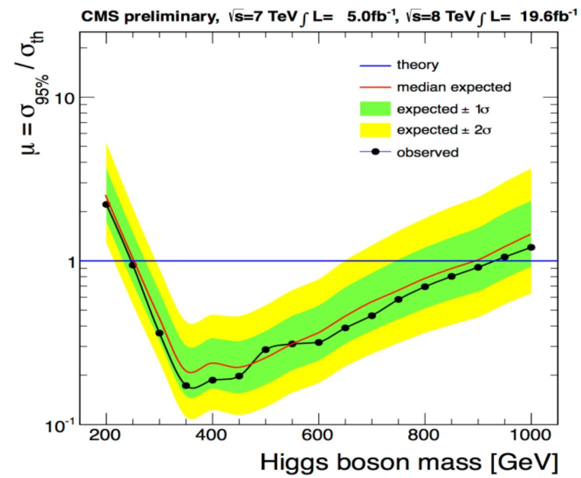
$c'^2 = 1 - \mu_h$
$\mu_H = c'^2 [1 - BR_{H,new}]$

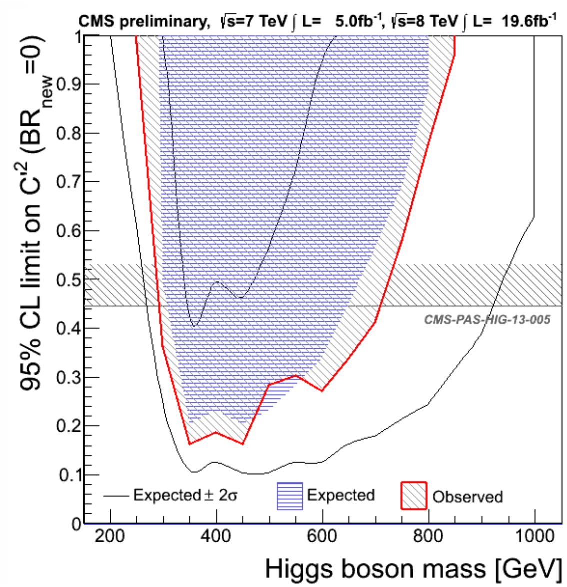
H->WW->2ℓ2j





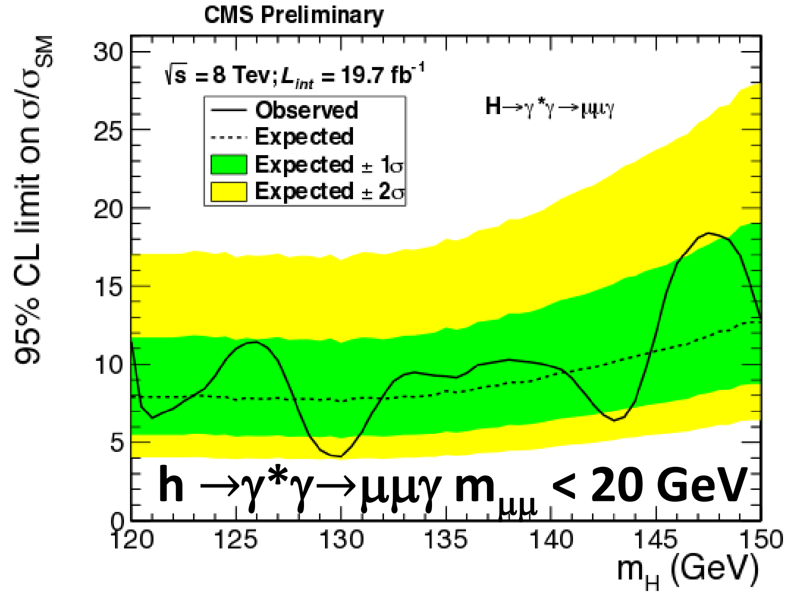
H->ZZ->2ℓ2ν

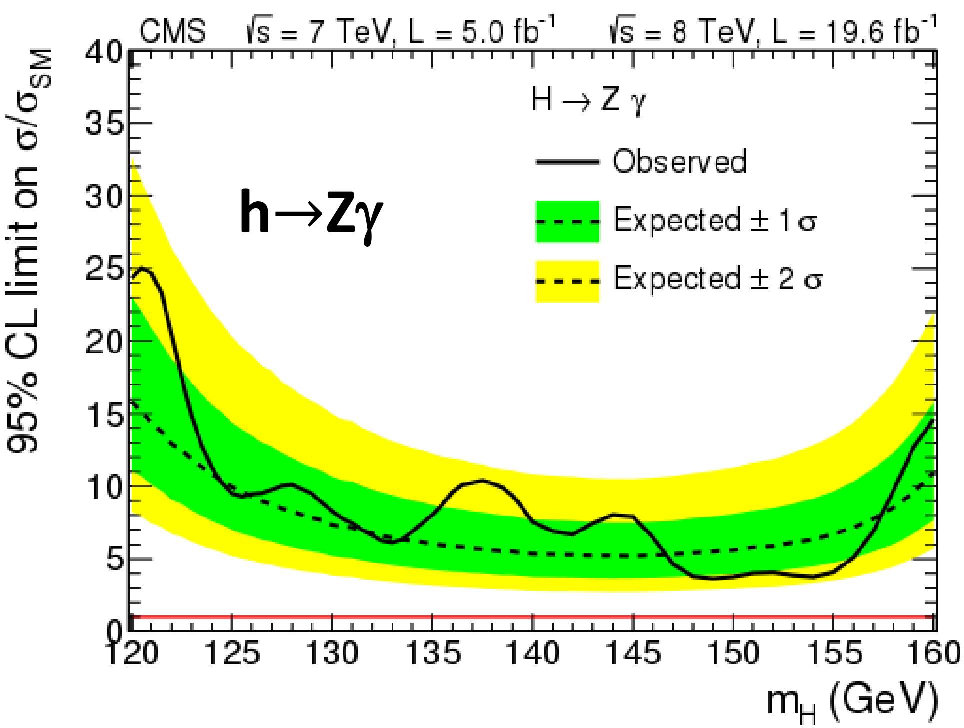


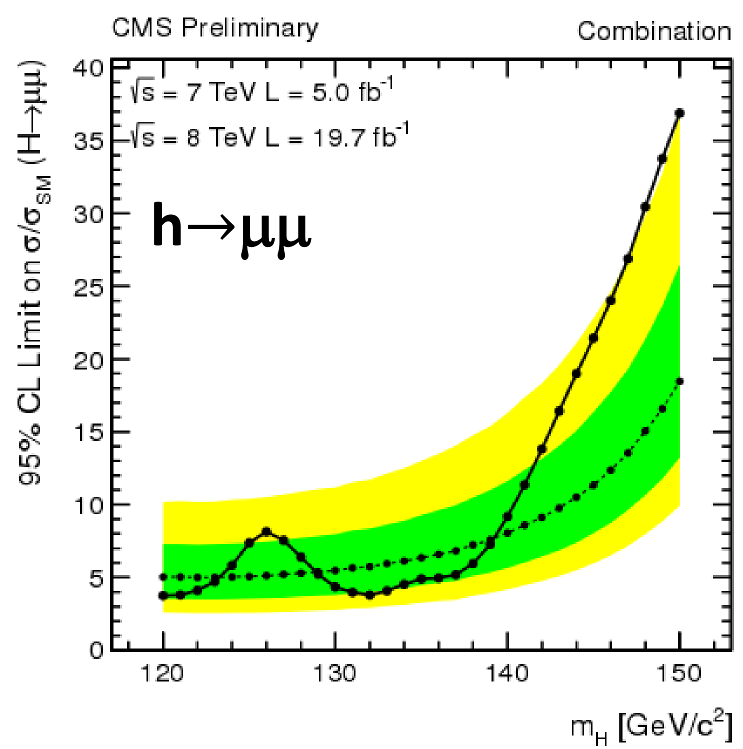


Rare SM h decay

Decay mode	limit σ / σ_{SM}
$h \to \gamma^* \gamma \to \mu\mu\gamma$	~ 10
$h \to Z\gamma$	~10
$h \to \mu\mu$	7.4

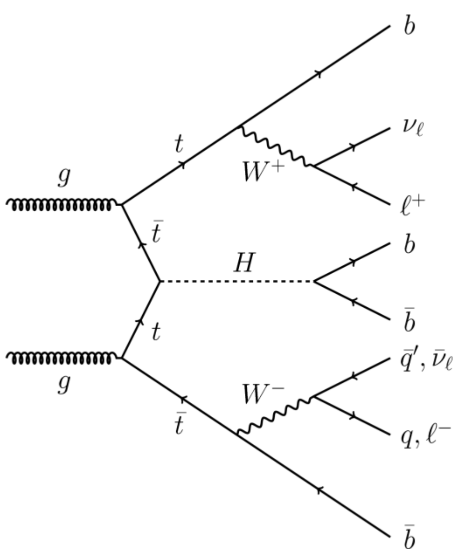


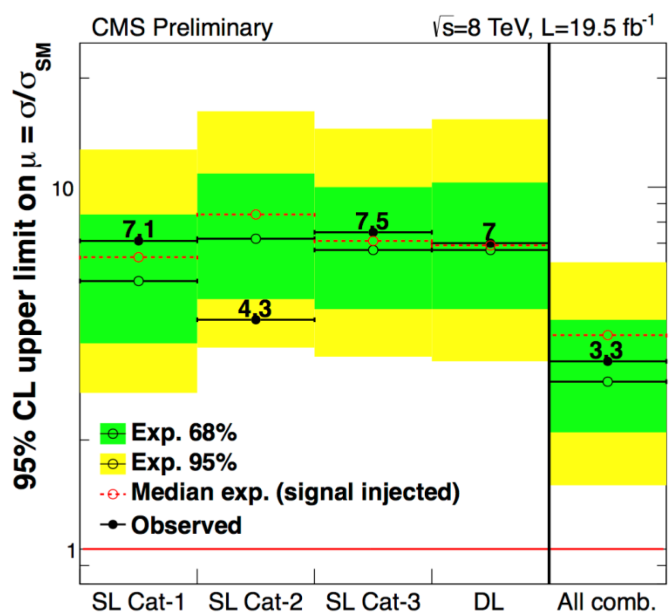


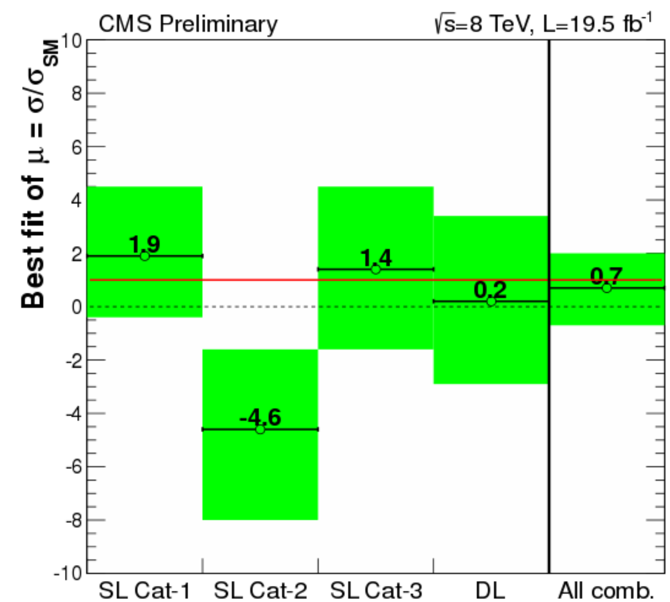


Resent result on tth, h->bb: limit 3.3 σ_{SM} at 95 % C.L.

- **Not rare, but difficult and very important channel**
  - supposed to be the hot subject with 13 TeV data
- **$1\ell + \geq 5$ jets or $2\ell + \geq 4$ jets with ≥ 2 b-tagged jets**
- **ME method based on LO MadGraph**
  - must use NLO generation in Run2 analyses !







Conclusions

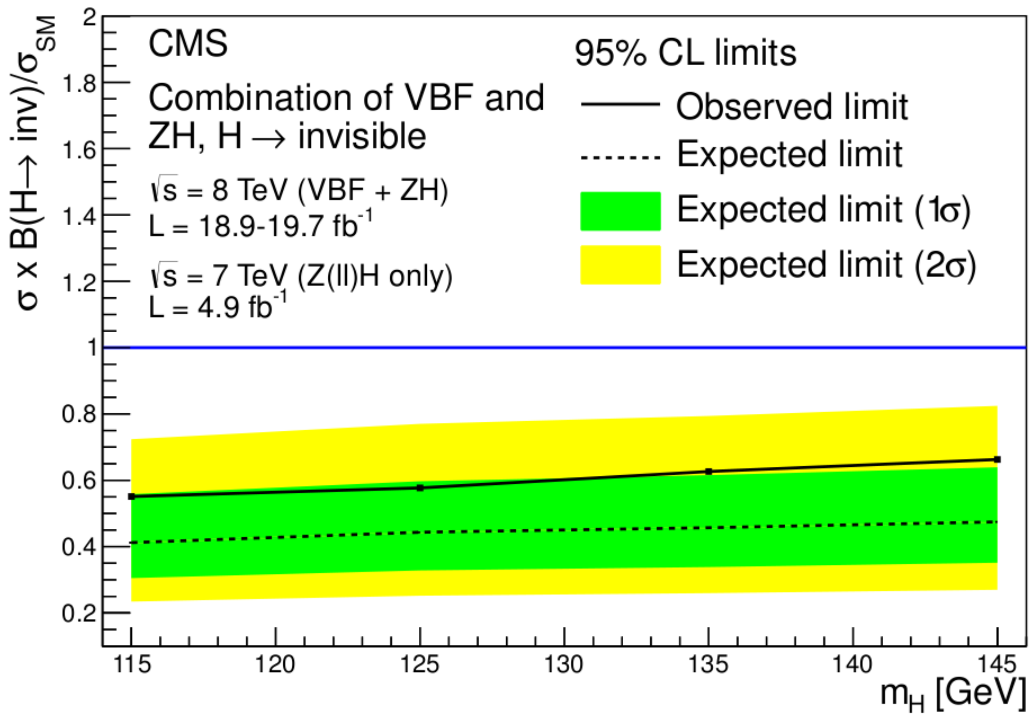
- Very reach physics program for BSM Higgs boson searches and h(125) boson measurements at LHC
- We expect to have another discovery in the Higgs sector during LHC or HL-LHC operation

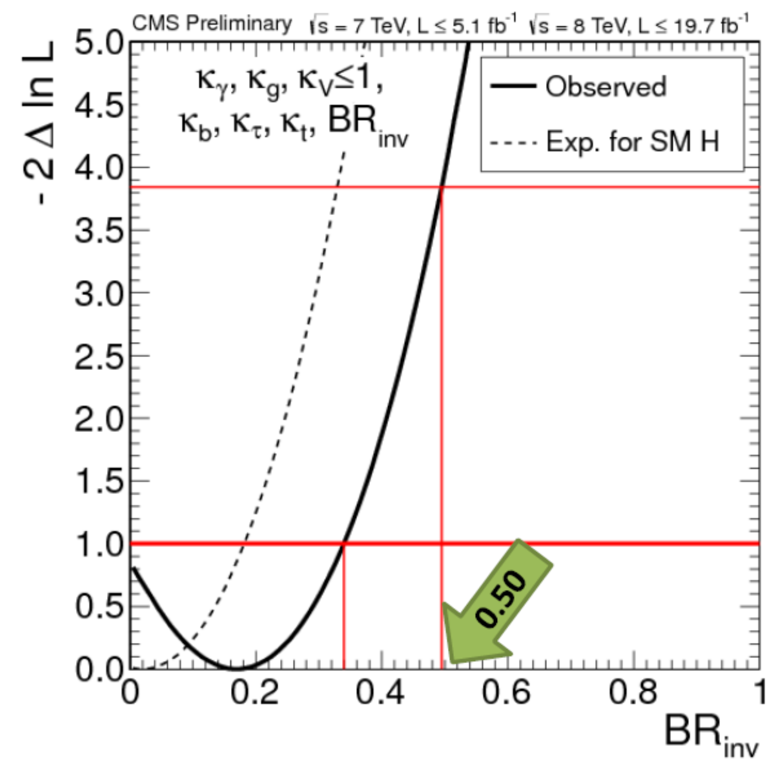
BACK UP

References to CMS results shown

- h->ZZ->4l, arXiv:1312.5353 Phys. Rev. D 89 (092007) , width: PAS-14-002
- Tensor structure from H->WW and combined with H->ZZ; HIG-14-012, HIG-14-014
- h->$\gamma\gamma$, (p)
- h->WW, arXiv:1312.1129, JHEP 01 (2014) 096
- Combination for h decays to fermions, HIG-13-033, arXiv:1401.6527
  - h->$\tau\tau$, arXiv:1401.5041, JHEP 05 (2014) 104
  - Vh, h->bb , arXiv:1310.3687, Phys. Rev. D 89, 012003 (2014)
- tth combination, HIG-13-029 (to be paper), ttH with ME HIG-14-010
- pp->qth, h->$\gamma\gamma$ HIG-14-001, h->bb HIG-14-015
- h->Zγ/$\gamma^*\gamma$->$\ell\ell\gamma$, h->$\mu\mu$, ee, arXiv:1307.5515, HIG-14-003, HIG-13-007
- h->invisible, arXiv:1404.1344
- h->$\mu\tau$, HIG-14-005
- ϕ->$\tau\tau$, $\mu\mu$ HIG-13-021, HIG-13-024
- H->hh->$\gamma\gamma$bb, HIG-13-032
- H->hh, A->Zh with multi-leptons and di-γs, HIG-13-025
- Heavy X->$\gamma\gamma$, HIG-14-006
- H^+->$\tau\nu$ with τ_h, no CADI line yet
- H^+->tb, $\tau\nu$ (with τ_ℓ), HIG-13-026
- H^+->cs, HIG-13-035
- H->WW,ZZ, heavy Higgs combination HIG-13-031,
  - heavy Higgs HIG-14-007 (ZZ->2l2q),14-008 (WW->lnuJ) , HIG-13-027(jj)/008 (J) (WW->lnujj), HIG-13-014 (H-ZZ->2ℓ2ν)
- Couplings from combination, HIG-14-009

Constraining BR(h→inv) using direct h→inv searches AND "visible" modes



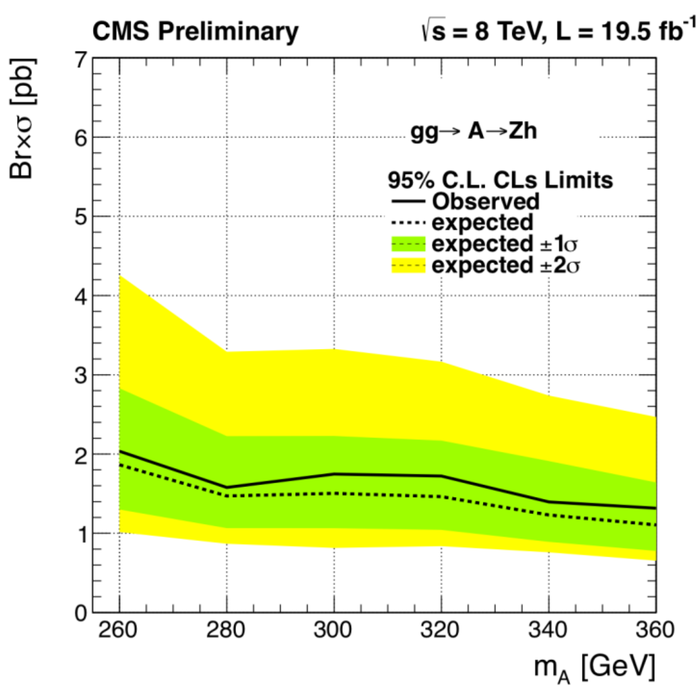


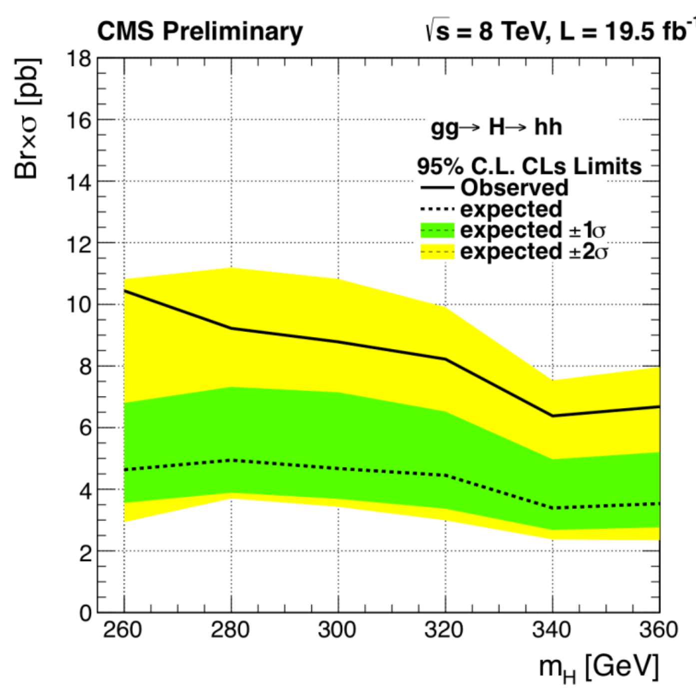
$BR_{invisible}$ < 0.50 at 95% CL

("invisible" - any decay mode that goes into "non-interacting" particles)

Low tanβ: H->hh and A->Zh with multi-lepton and di-photon final states

- **Limits on σxBr for gg->H->hh (gg->A->Zh) are given assuming SM BRs for h and no contribution from gg->A->Zh (gg->H->hh)**
- **In hMSSM (A. Djouadi et.al. arXiv:1307.5205):**
  - **σ(gg->A)BR(A->Zh)=1.7 pb for m_A=300 GeV, tanβ=2.0 - close to observed limit !**
  - **σ(gg->H)BR(H->hh)=3.9 pb for m_A=300 GeV, tanβ=1.0 – lower than observed limit**

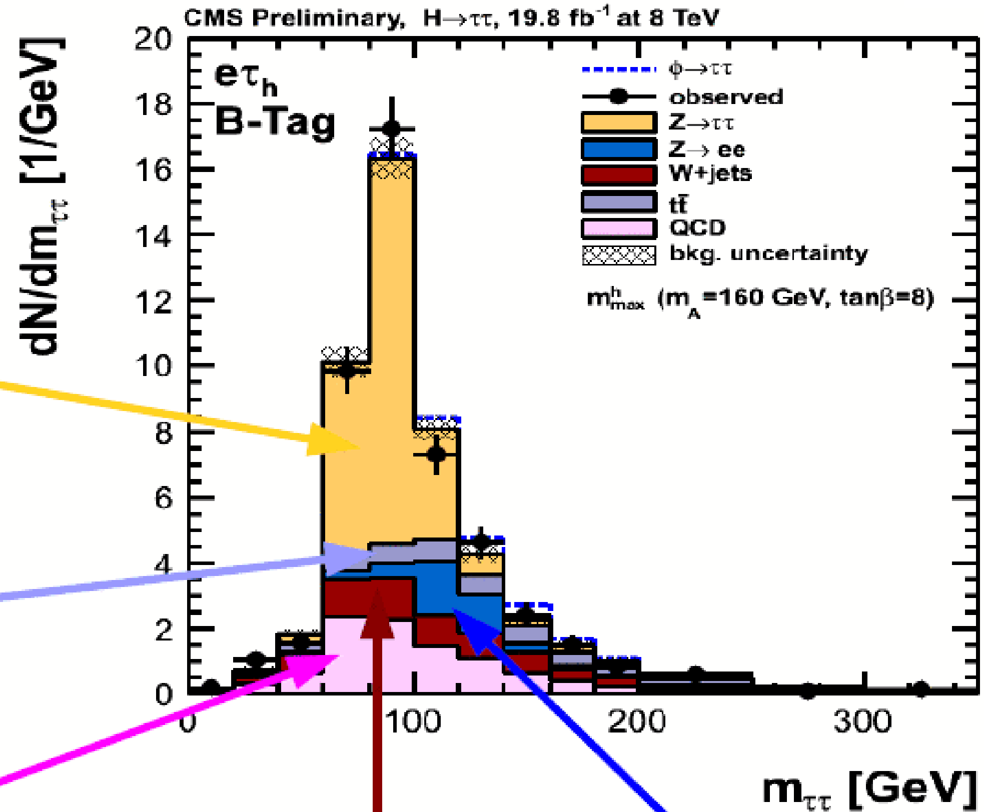




Background estimation in $\Phi \rightarrow \tau\tau$

$Z/\gamma^* \rightarrow \tau\tau$:
- Embedding: in $Z \rightarrow \mu\mu$, replace μ by sim. τ decay
- Normalized from $Z \rightarrow \mu\mu$ events

ttbar:
- From simulation
- Normalization from sideband

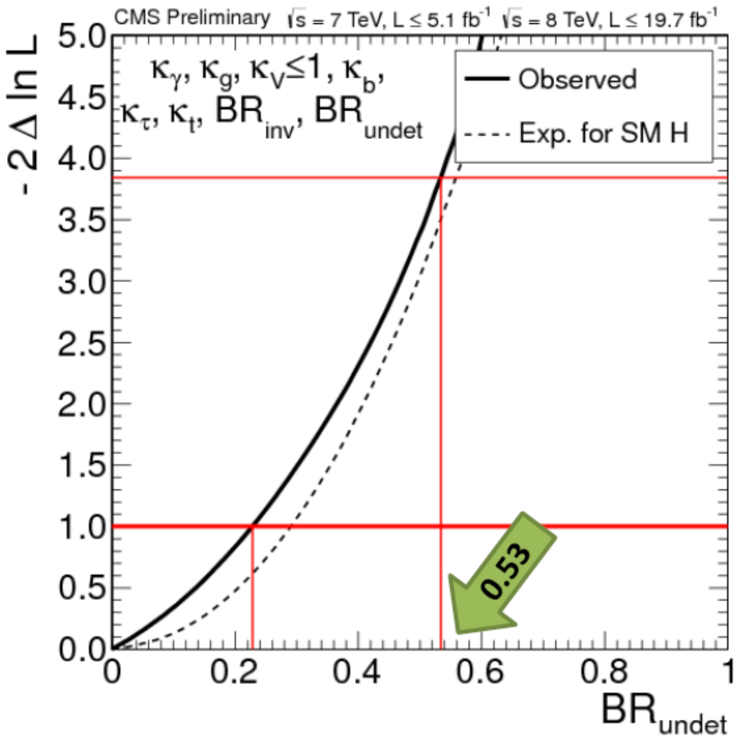


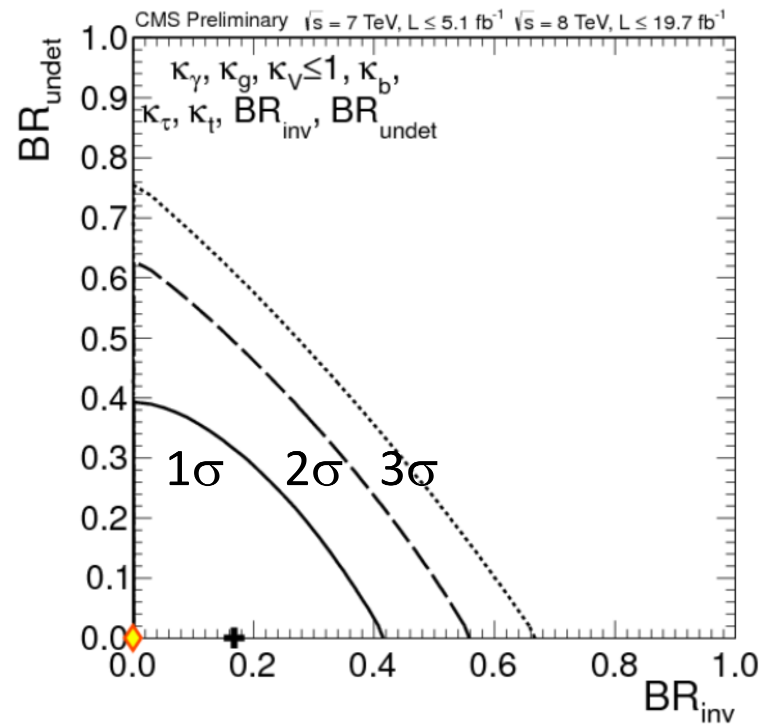
QCD:
- Normalization & shape taken from SS/OS or fakerate

Di-boson/W+jets:
- From simulation or data
- Normalization from sideband

$Z/\gamma^* \rightarrow ee\ (\mu\mu)$:
- From simulation or data
- Corrected for jet $\rightarrow \tau$, $e/\mu \rightarrow \tau$ fakerate

Constraining "invisible" and "undetectable" modes using direct h->inv searches AND "visible" modes





BR_{undet} < 0.53 at 95% CL

("undetectable" - any mode, SM or BSM, that can't be seen, e.g. due. to bkg or other reasons)