SM Higgs boson interaction with the Yukawa sector in CMS

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on behalf of CMS collaboration

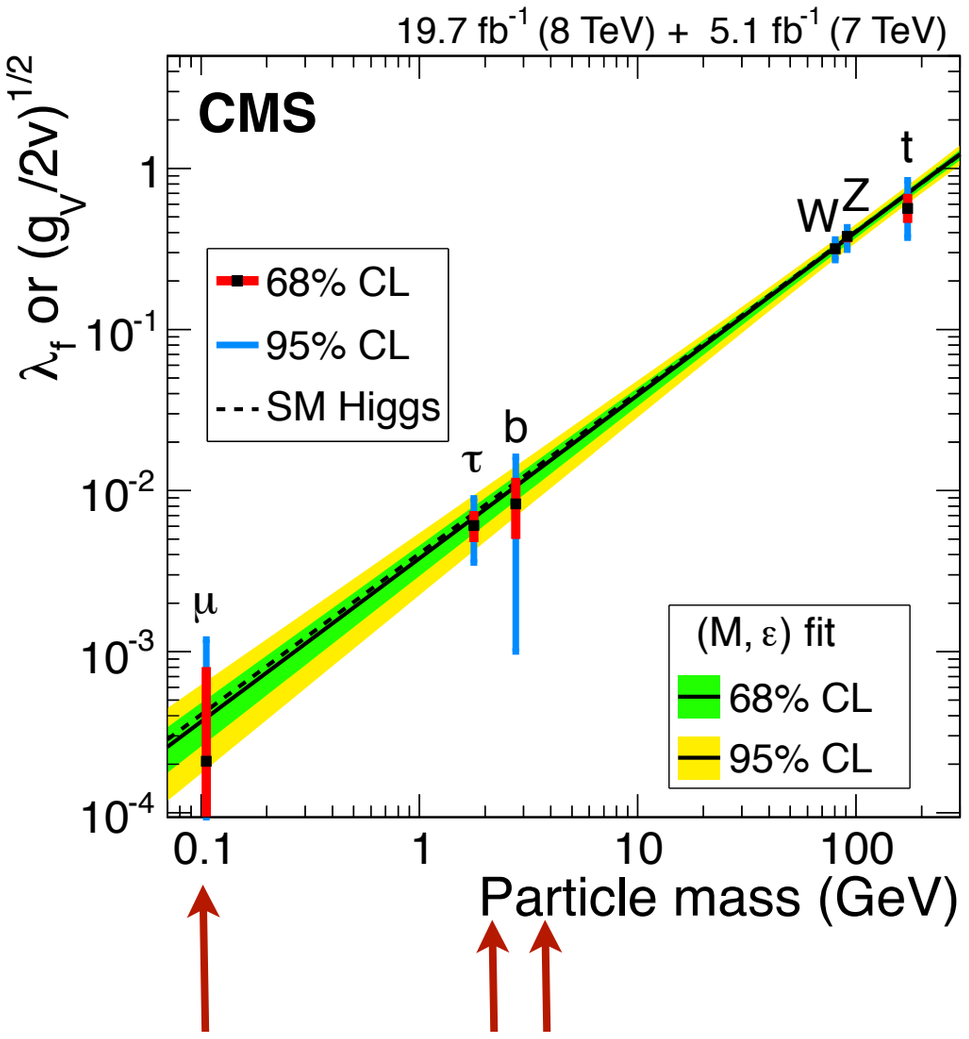
HC15, Durham (UK) 12-15 Oct 2015

Outline

- Higgs coupling to fermions in CMS from LHC run1
  - H->bb
  - H->ττ
  - H->μμ
    - production modes considered

Decay/Production	ggF	VBF	VH	ttH
H->ττ	✓	✓	✓	✓
H->bb		✓	✓	✓
H->μμ	✓	✓		

- Prospects for Run2 and future
  - N.B this talk will concentrate on SM searches and do not concentrate too much on ttH. BSM and ttH results will be presented in other talks

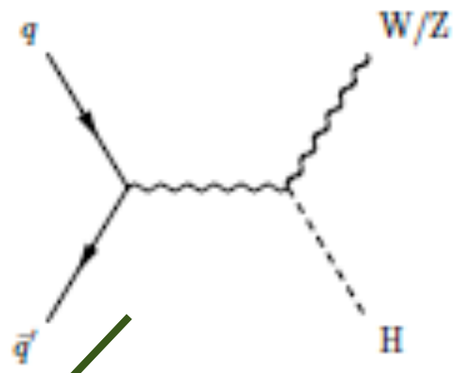


Decay channel	Branching ratio [%]
$H \to b\bar{b}$	57.5 ± 1.9
$H \to WW$	21.6 ± 0.9
$H \to gg$	8.56 ± 0.86
$H \to \tau\tau$	6.30 ± 0.36
$H \to c\bar{c}$	2.90 ± 0.35
$H \to ZZ$	2.67 ± 0.11
$H \to \gamma\gamma$	0.228 ± 0.011
$H \to Z\gamma$	0.155 ± 0.014
$H \to \mu\mu$	0.022 ± 0.001

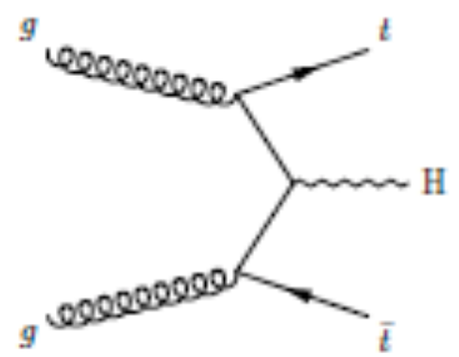
H->bb

- H->bb has the largest branching fraction @ 125 GeV: 58%
- Large QCD-induced bb backgrounds (overwhelming for ggH)
  - VH and ttH: (semi)leptonic decay channels
    - lower cross section, but pure QCD background is not dominant
  - VBF: 2q2b final state
    - higher cross section, but QCD background irreducible

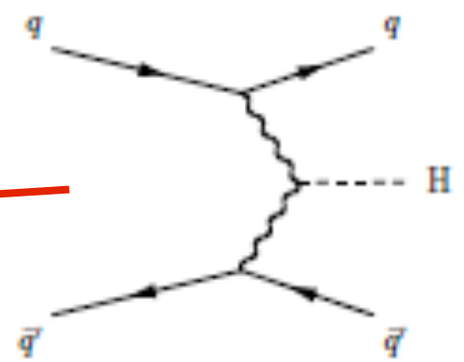
    approach with dedicated triggers
- Perform combination of all run1 H->bb channels results



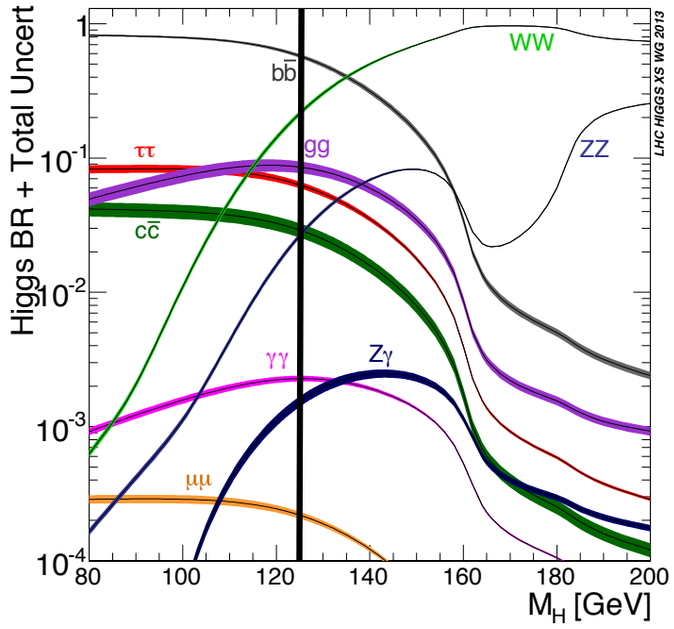
VH

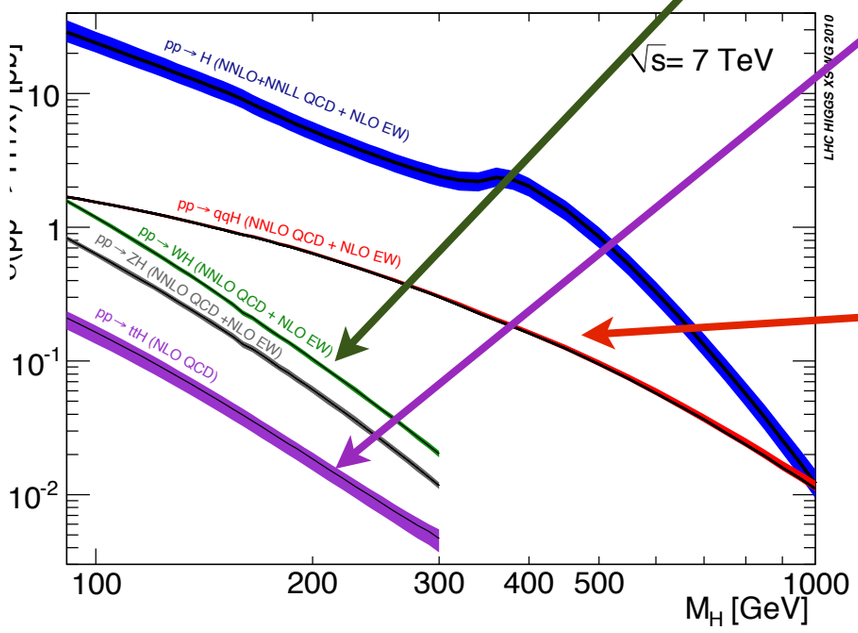


ttH



VBF





H->bb : VHbb(1)

CMS-HIG-13-012
PRD 89 (2014) 012003

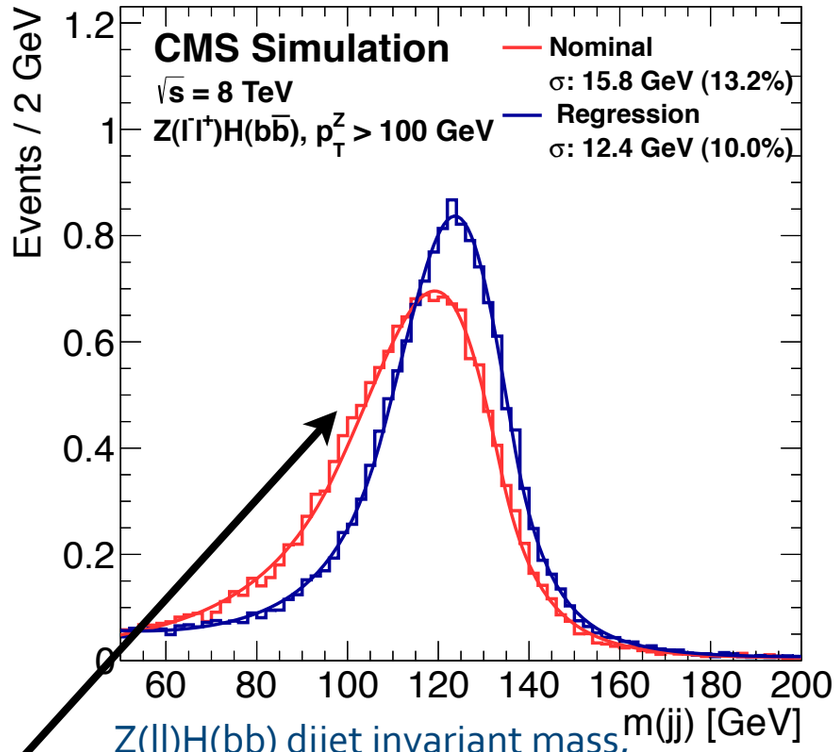
- Search in 6 decay channels: W(e,μ,τ)H, Z(ee/μμ)H, Z(νν)H
  - Backgrounds: W/Z + jets, ttbar, diboson, QCD

Analysis strategy

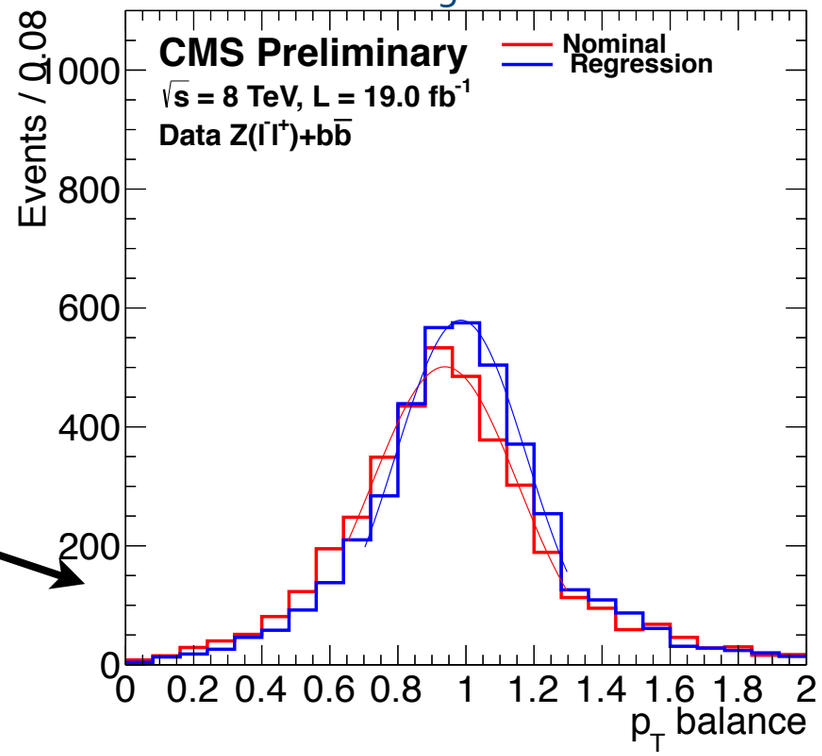
- High boosted vector boson and dijet,
- 2 b-tagged jets
- back-to-back V & H
- Reconstruct m_{bb}
- Build a multivariate discriminant using the reconstructed bb invariant mass, b-tag values, kinematic variables, . . .
- Fit the discriminant shape and extract limits combining pT(V) boost categories

Optimization

- Multivariate regression to derive jet energy correction on top of the average CMS one !
  - H->bb invariant mass resolution improves 15%
- Background calibration in control regions:
  - tt, W/Z+jets (light flavour, b or bb enriched)
  - shape and normalization in signal region better constrained



Z(ll)H(bb) dijet invariant mass, before and after regression



dijet pt/ Z pt before and after regression, in b-enriched data

H->bb : VHbb(2)

CMS-HIG-13-012
PRD 89 (2014) 012003

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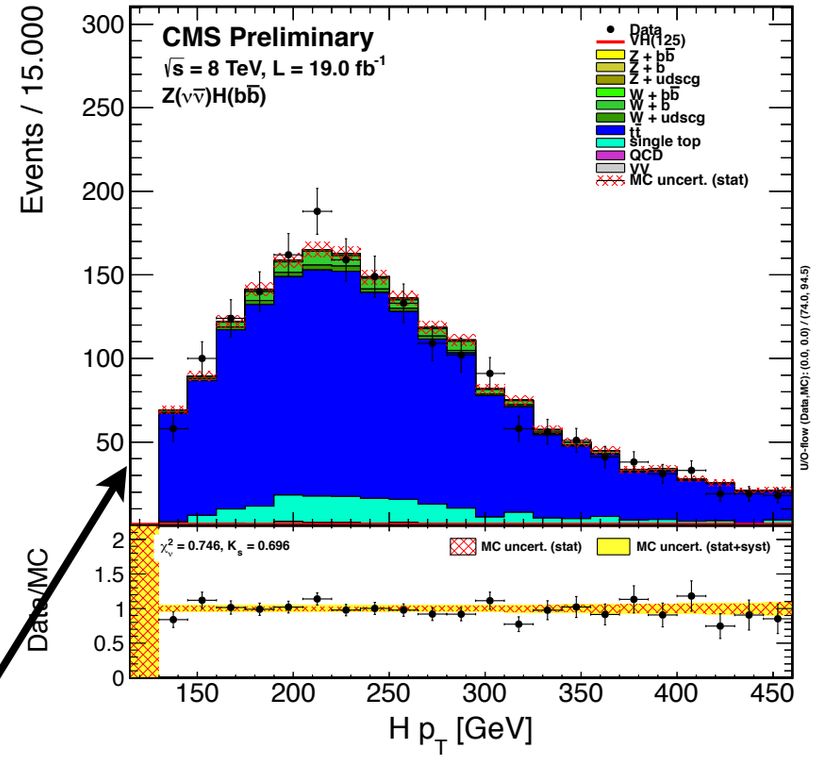
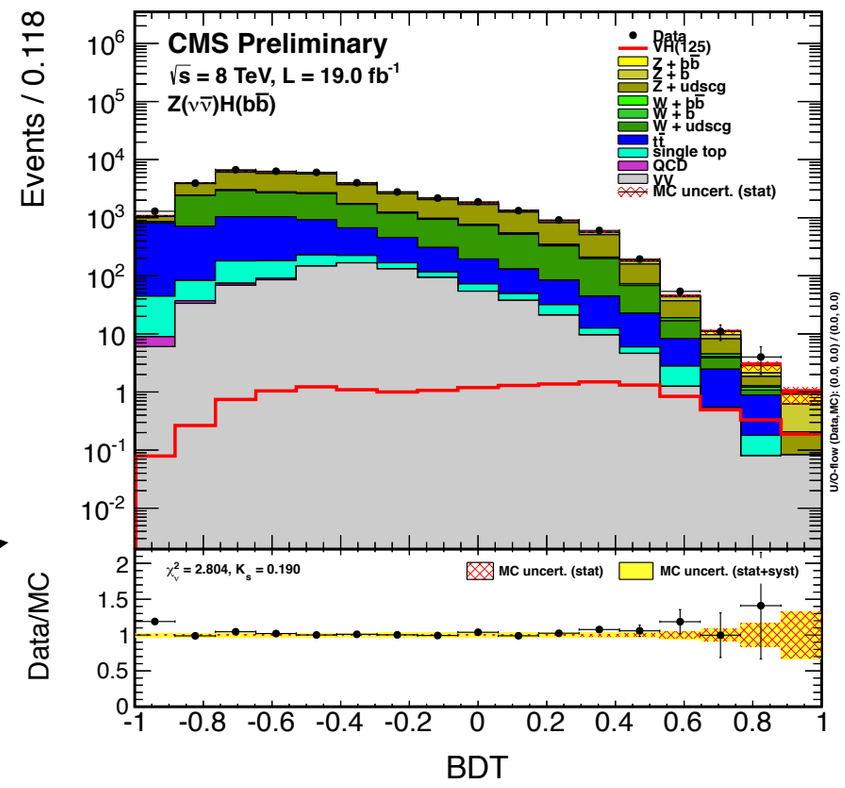


Z(nunu)H(bb) dijet pt in ttbar region

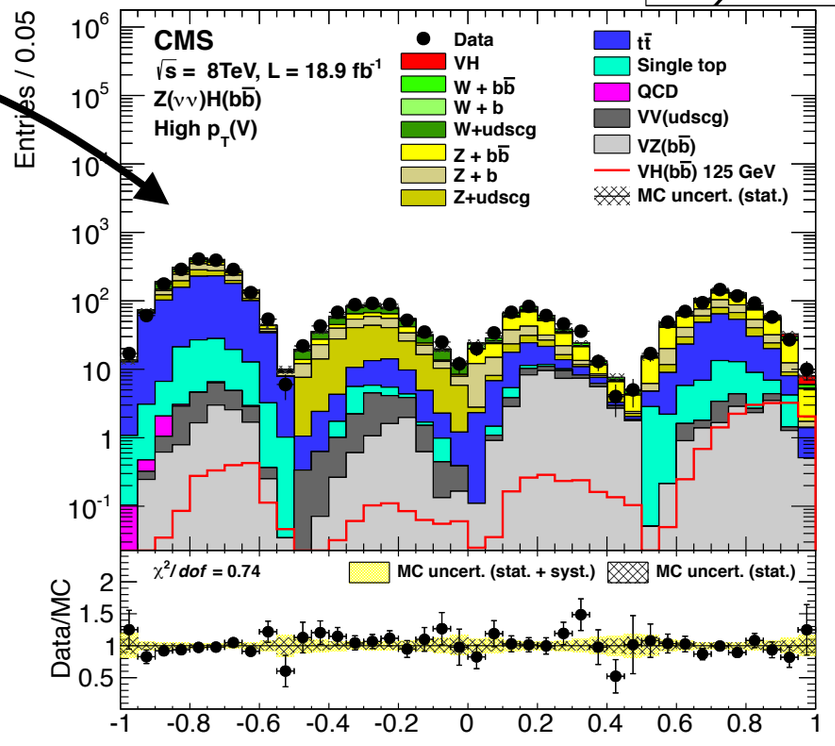


Z(nunu)H(bb) BDT in Z+udscg region

H->bb : VHbb(3)

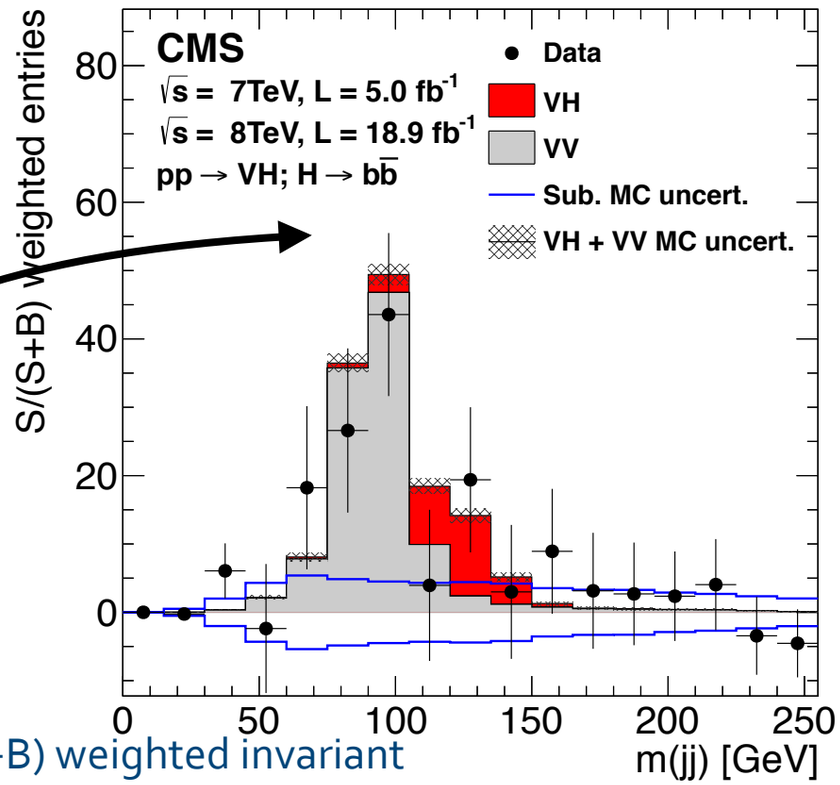
x3 (pT region)
x6 (channel)

- Multivariate discrimination
  - Several background-specific BDTs are trained to separate individual backgrounds from signal (tt, V+jets and VV).
  - Events are classified according to these specific BDTs before being run through the final BDT (per mass and per channel)
  - A fit is performed to the shape of the final BDT output distribution, composed of four subsets of events (simultaneously in all channel)



final BDT output in Z(nn)H channel, high pT(V) region

- Results *(updated including ggZH contribution in HIG-14-009!)*
  - ggZH gives ~15% contribution at high pt
  - An excess is observed, compatible with the SM expectation.
  - 95% CLs limitobserved (expected) limit 1.68 (0.85) at m= 125 GeV
  - significance 2.1 σ (expected 2.5 σ)
  - best-fitted μ= 0.89 +- 0.43



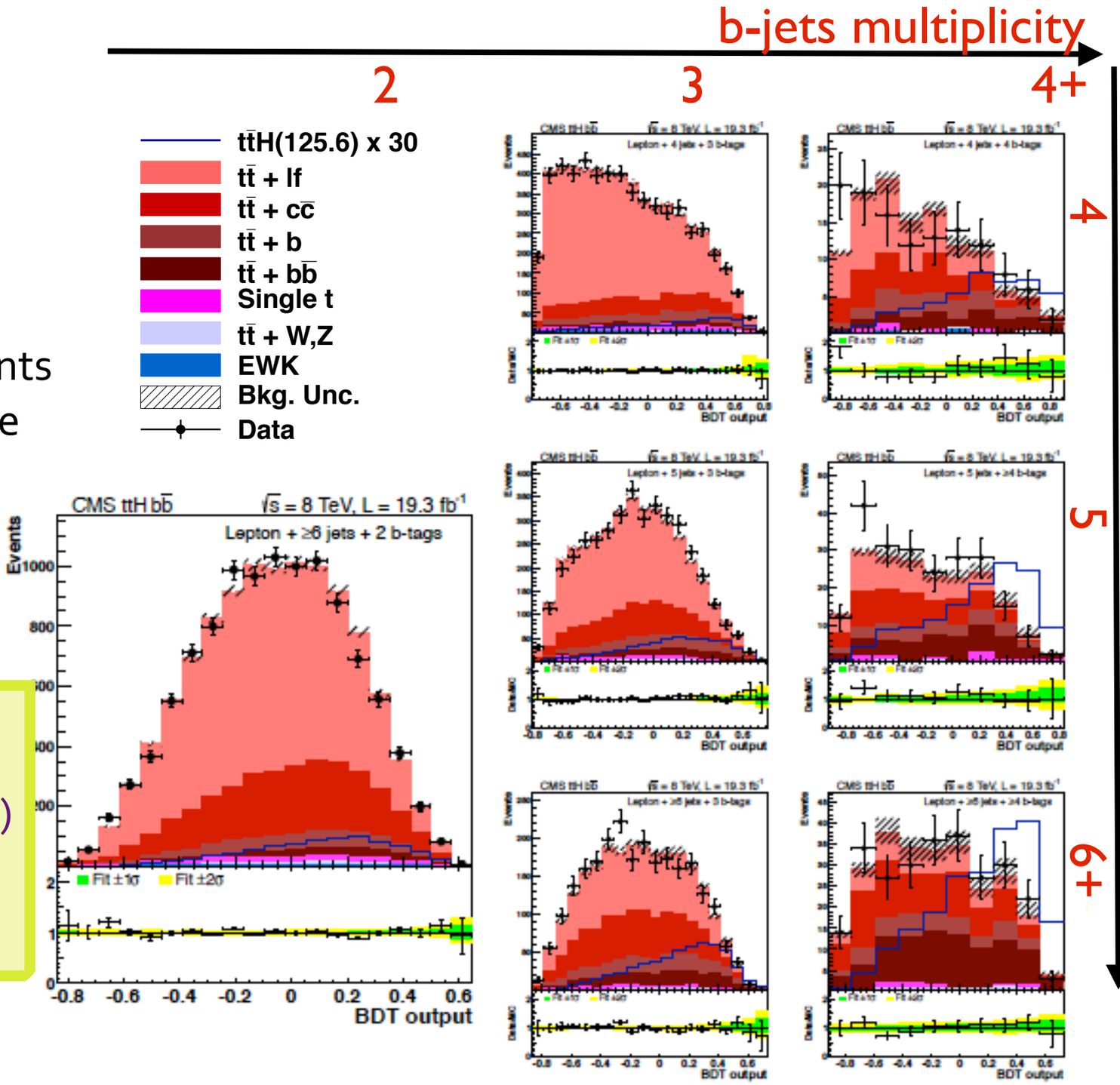
S/(S+B) weighted invariant mass distribution, all bkg expect VV substucted

- Mbb analysis cross check in signal region and VZbb peak

H->bb: ttHbb BDTs

CMS-HIG-13-029
JHEP 09 (2014) 087

- Search in leptons+jets and dilepton channel
  - Main backgrounds: tt + (bb /cc/light quarks/b/t), tt + V, W/Z + jets, diboson & QCD
- Analysis strategy
  - Look for high jet multiplicity and many b tags
  - Classify events in Njet and Nbjets bins
  - Build multivariate discriminants using event kinematics, shape and b-tag variables
  - Fit the discriminant shape a extract limits



Results

- observed (expected) limit 4.1 (3.5)
- significance 0.4 σ (0.6expected)
- best-fitted μ= 0.7 +- 1.9

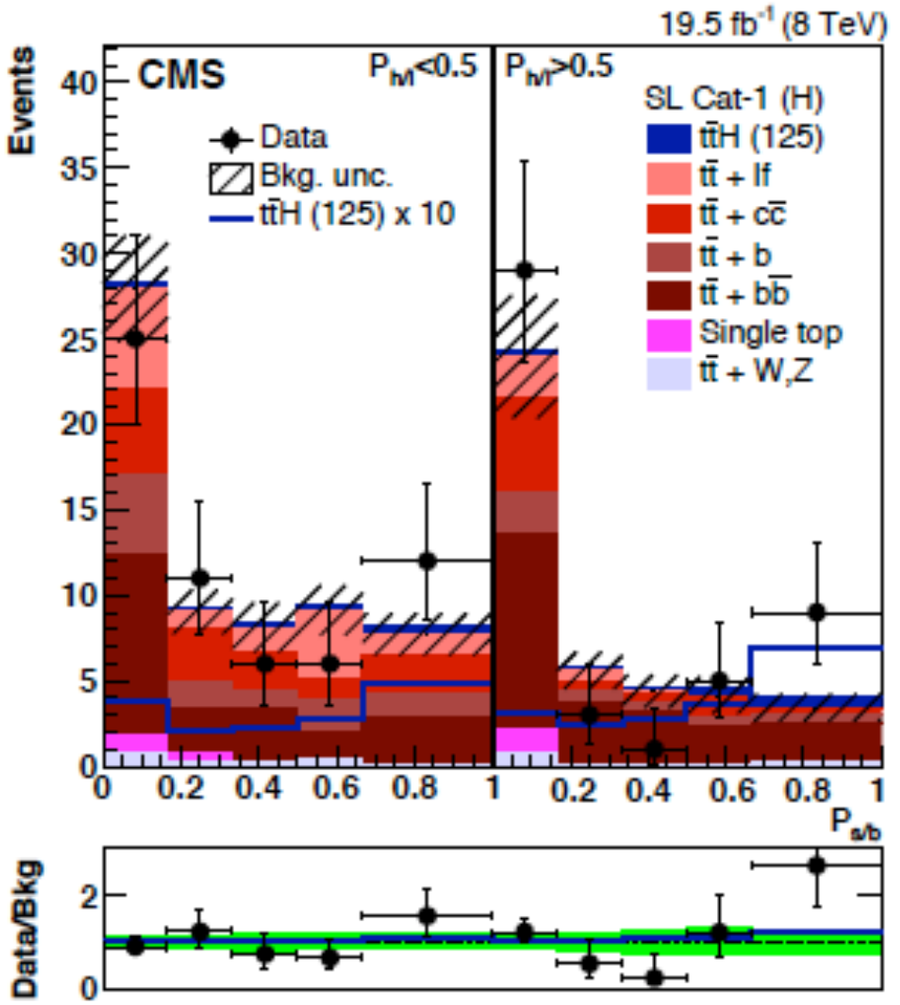
H->bb: ttHbb MEM

CMS-HIG-14-010
EPJC 75 (2015) 251

- Analysis strategy
  - Alternative approach using a matrix element method
    - increased sensitivity over the BDT analysis.
    - Define two likelihood ratios based on LO matrix elements,
      - discriminate between ttH (sig) and tt+ bb/lf (bkg)

$$P_{s/b} = \frac{w(\vec{y}|t\bar{t}H)}{w(\vec{y}|t\bar{t}H)+k_{s/b}w(\vec{y}|t\bar{t}+b\bar{b})} \qquad P_{h/l} = \frac{f(\vec{\xi}|t\bar{t}+hf)}{f(\vec{\xi}|t\bar{t}+hf)+f(\vec{\xi}|t\bar{t}+lf)}$$

      - classify event in one dileptonic and 3 semileptonic categories based on b-jet multiplicity
      - perform 2D fit of the ratios to extract limits



Distribution of the $P_{s/b}$ discriminant, in two $P_{h/l}$ bins

- ME good for dealing with
  - combinatorics
  - small S/B ratios

Results

- observed (expected) limit 4.2 (3.3)
- best-fitted μ= 1.2 +- 1.6

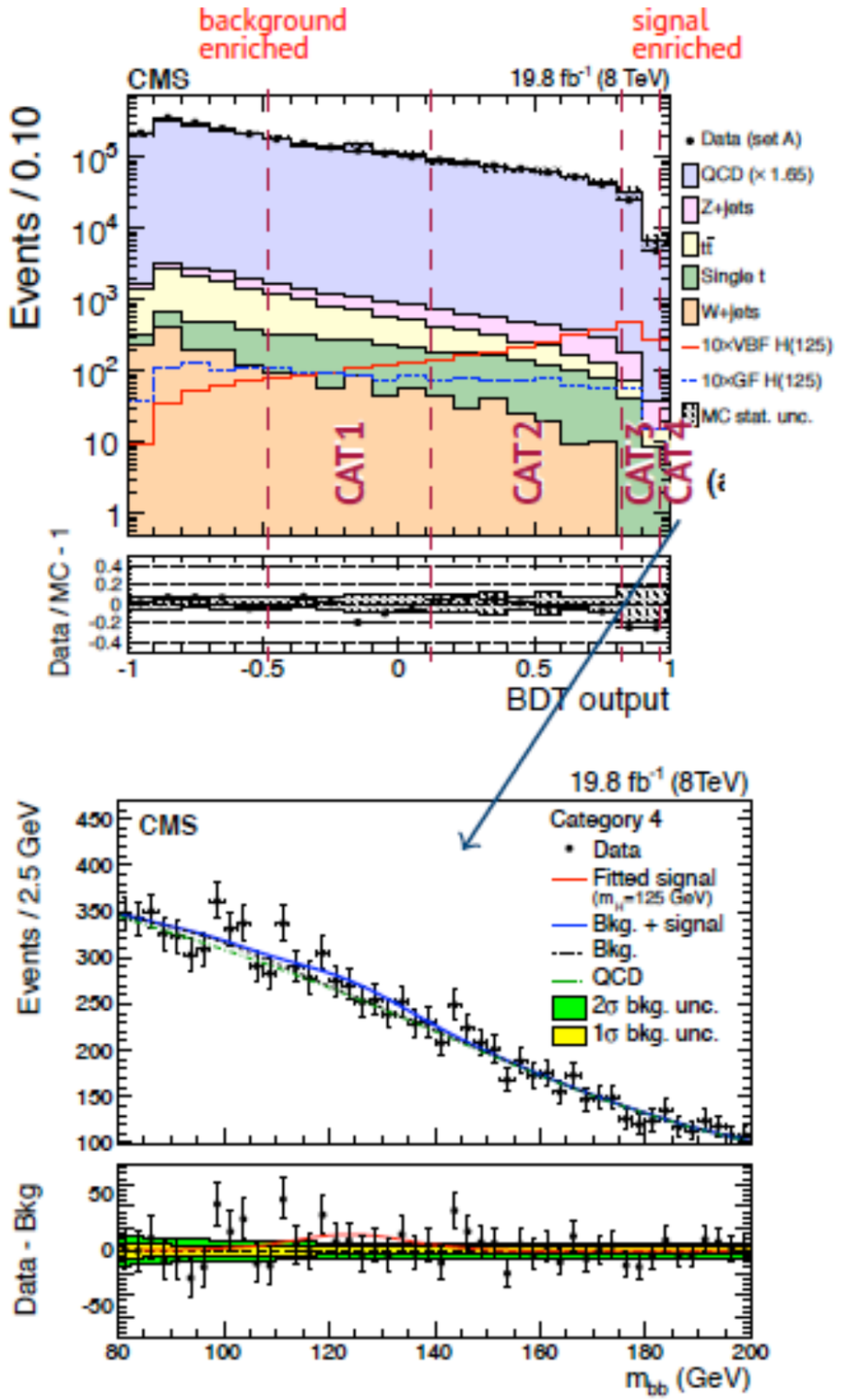
Hbb: VBFbb (new in 2015!)

CMS-HIG-14-004
10.1103/PhysRevD.92.032088

- Search for 4 jets final states: qqbb
  - Main bkgs: QCD!, Wjets, tt, single-t
- Analysis strategy
  - dedicated triggers
  - event selections: fwd light jets and central b-jets
  - Multivariate discriminator using kinematics, b-tagging and quark-gluon discriminator
    - m_{bb} unbiased
  - classify events in 4 categories based on BDT output
  - Fit simultaneous of Mbb in all categories
  - Fit strategy validated fitting Zbb resonance

Results

- observed (expected) limit 5.5(2.2)
- significance 2.2 σ (0.8expected)
- best-fitted μ= 2.8 +- 1.6



Fit of the invariant mass distribution in CAT4

H->bb combo (new in 2015)

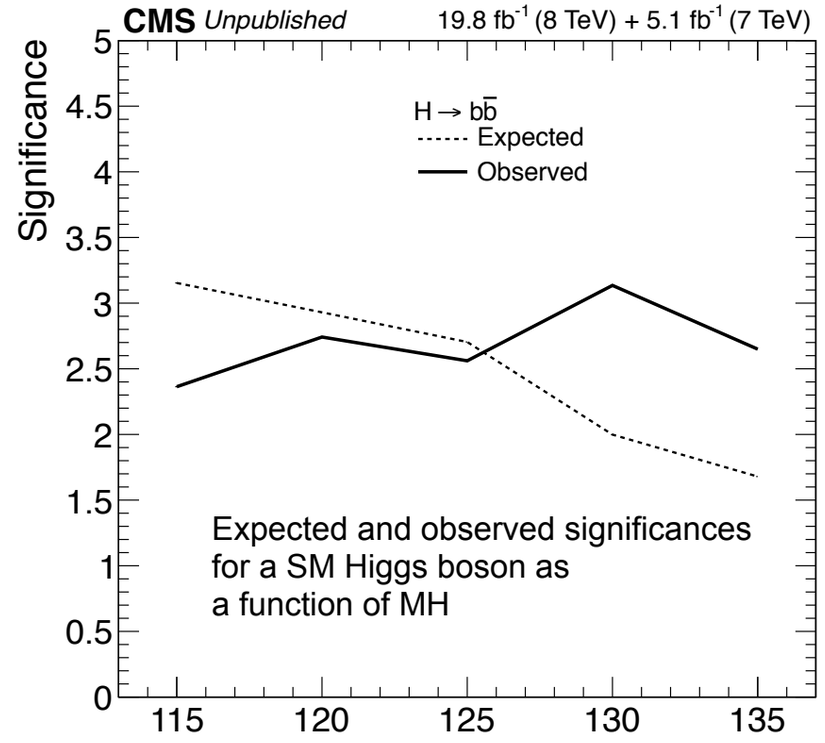
CMS-HIG-14-004
10.1103/PhysRevD.92.032088

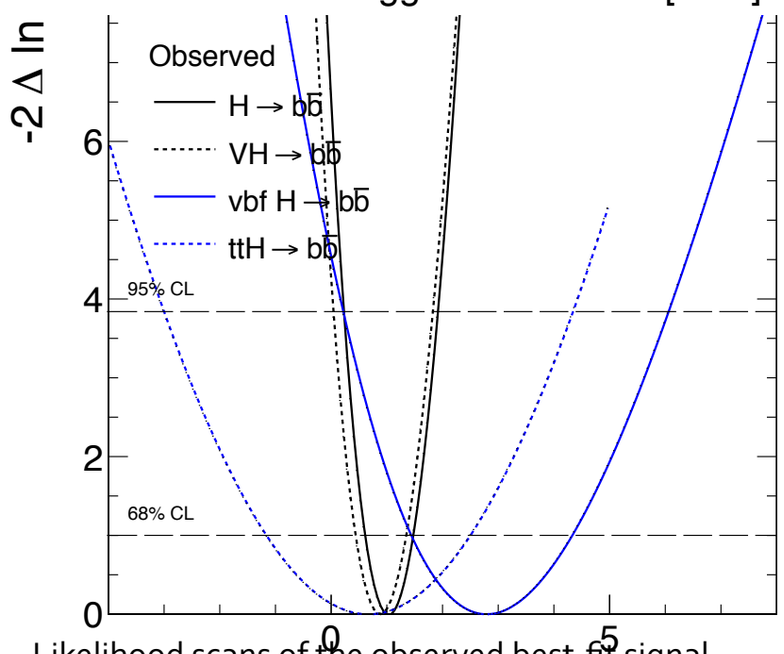
- The three public CMS Hbb results have been combined
  - VHbb updated results
  - ttHbb BDT analysis
  - VBFbb

$H \to b\bar{b}$ Channel	Best fit (68% CL) Observed	Upper limits (95% CL) Observed	Upper limits (95% CL) Expected	Signal significance Observed	Signal significance Expected
VH	0.89 ± 0.43	1.68	0.85	2.08	2.52
$t\bar{t}H$	0.7 ± 1.8	4.1	3.5	0.37	0.58
VBF	$2.8^{+1.6}_{-1.4}$	5.5	2.5	2.20	0.83
Combined	$1.03^{+0.44}_{-0.42}$	1.77	0.78	2.56	2.70

Results

- significance 2.6 σ (2.7expected)
- best-fitted μ= 1.03 +- 0.43





Likelihood scans of the observed best-fit signal strength
$\mu=\sigma/\sigma$ SM for VH, VBF and ttH

H->ττ (1)

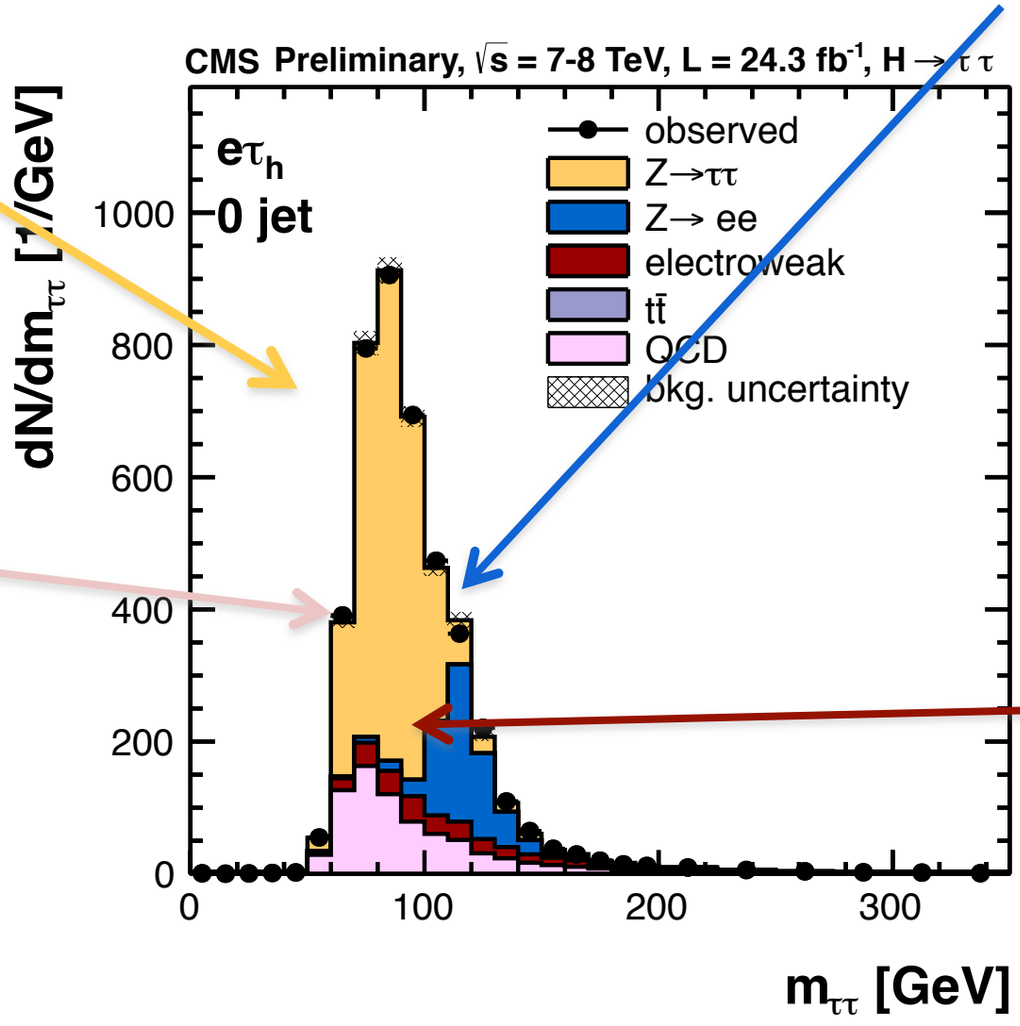
CMS-HIG-13-004
J. High Energy Phys. 05 (2014) 104

- Includes all 4 main production modes!
  - events categorized in
    - τ decay modes (e, μ, τhad)
    - number of jets
    - boost of Higgs candidates, and topology (VBF, ggH, etc.)
- Background form data as much of possible

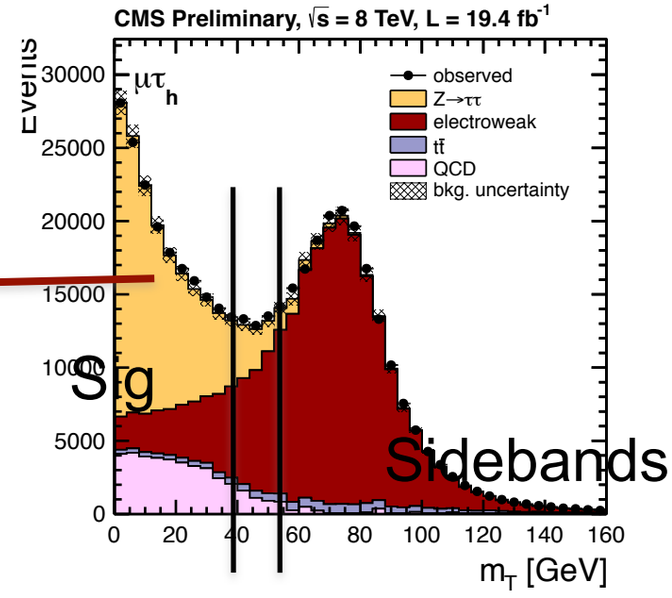
DY→ll – from MC but correcting the l→ τ fake rate

Z→ττ
Embedding: Z→μμ data, replace μ with simulated τ decay
Normalization from Z→μμ data

QCD - estimated from same sign data, corrected for SS/OS ratio

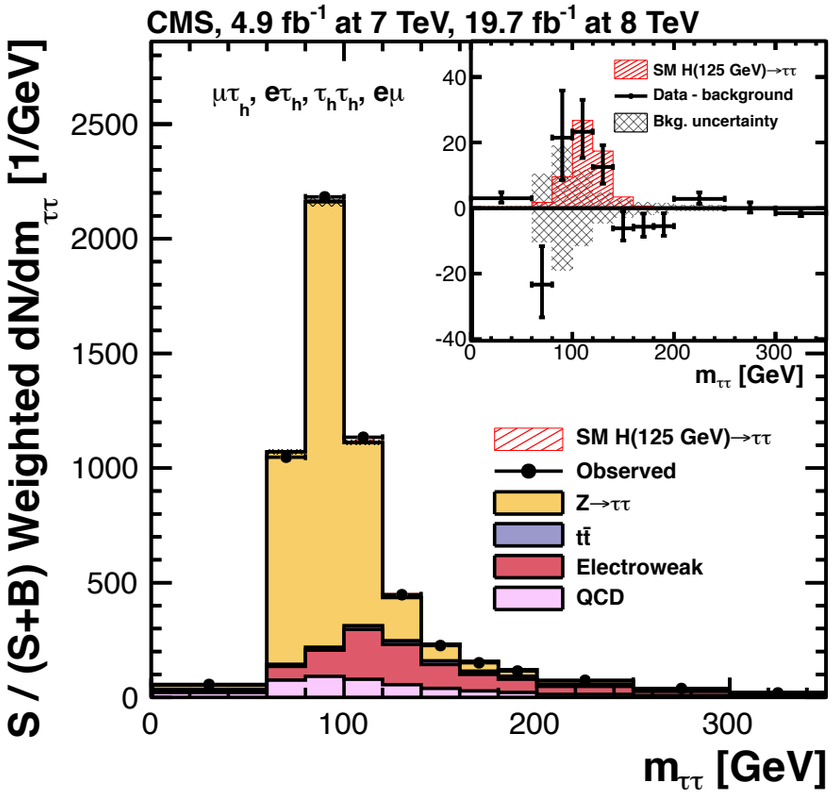


EWK – mostly W+jets: using M_T sidebands and angles between MET and τs, so MET reconstruction is critical!

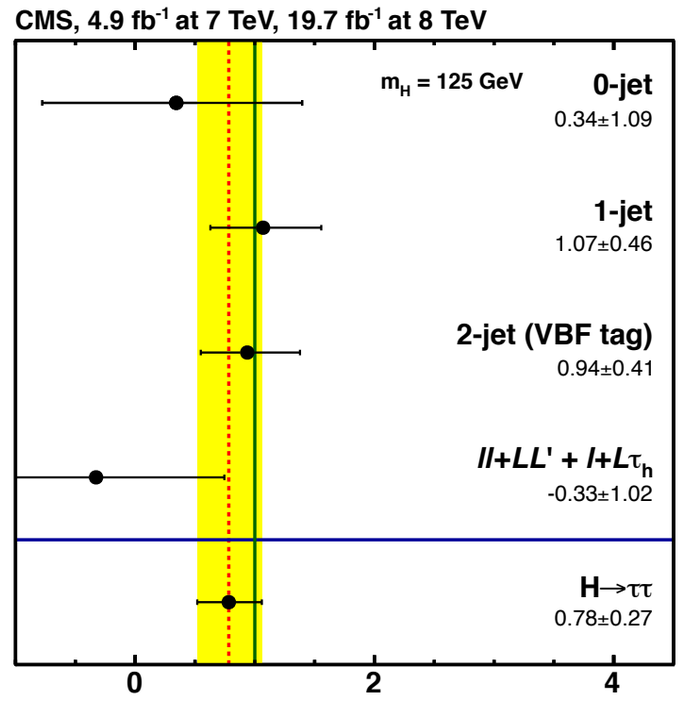


H->ττ (2)

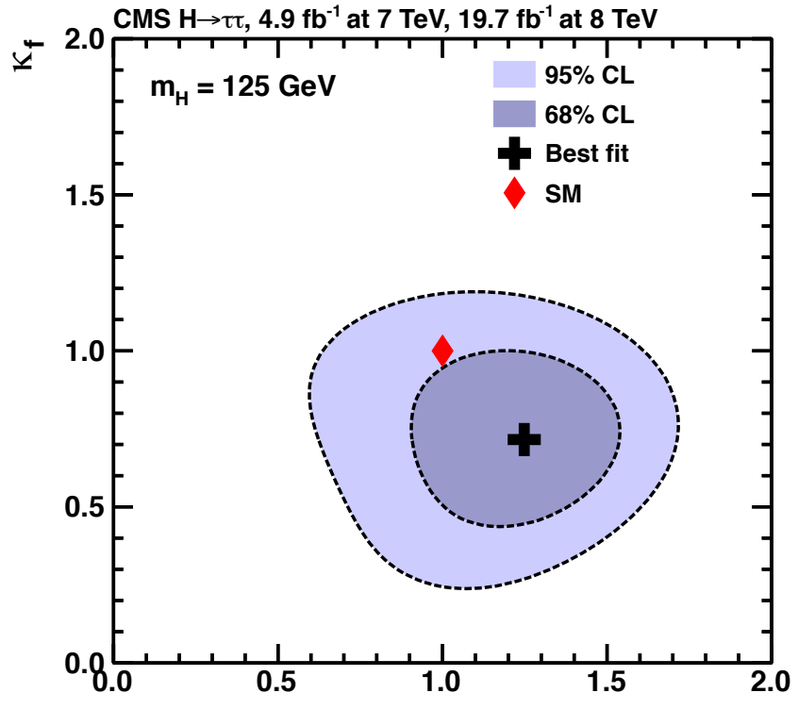
- Signal extraction
  - simultaneous fit of mττ in all categories



all combined categories



Best-fit signal strength values, for independent categories, and combined



Likelihood scan as a function of κV and κf

Results: evidence of H->ττ

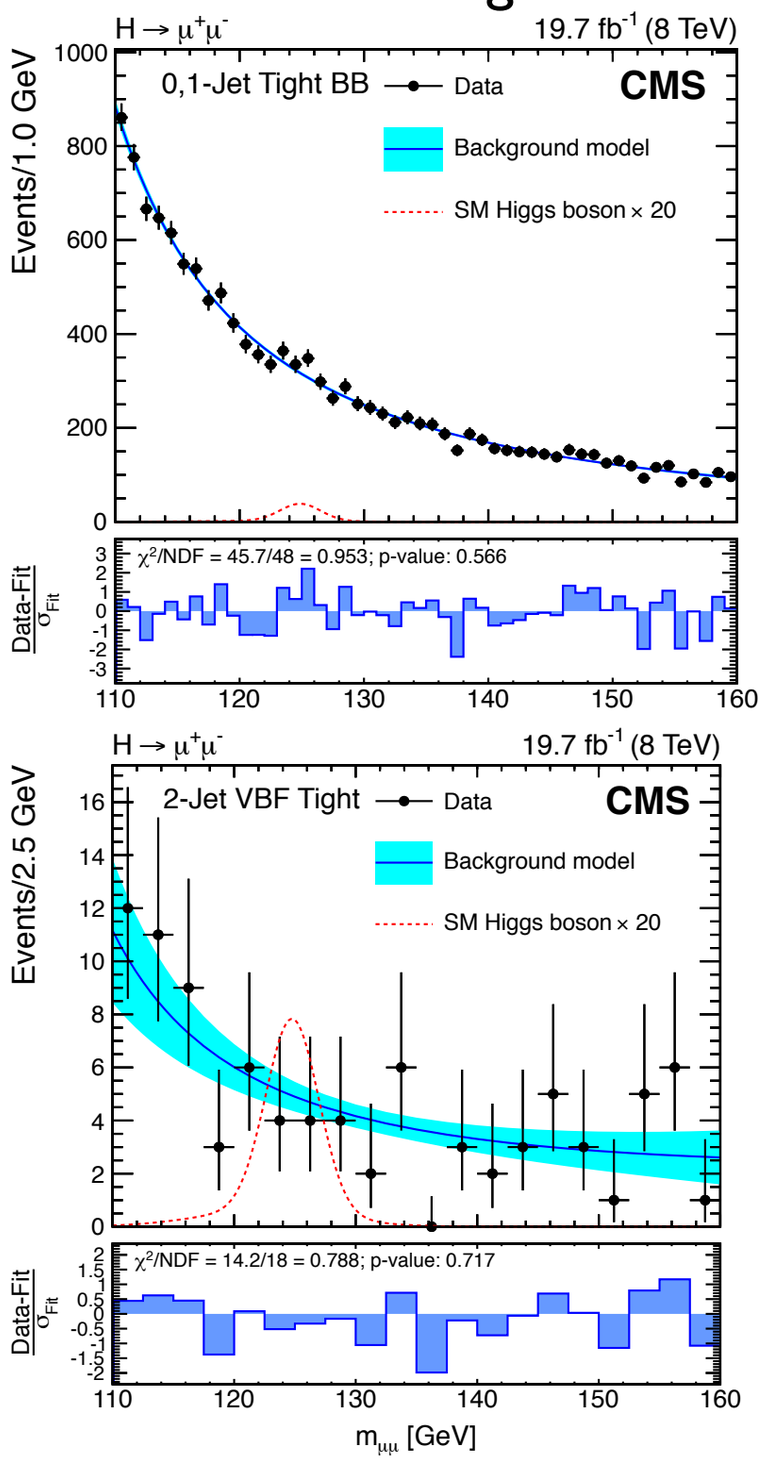
- significance 3.2 (expected 3.7)
- best-fitted μ= 0.78 +- 0.27

H->μμ, ee

CMS-HIG-13-007
Phys. Lett. B 744 (2015) 184

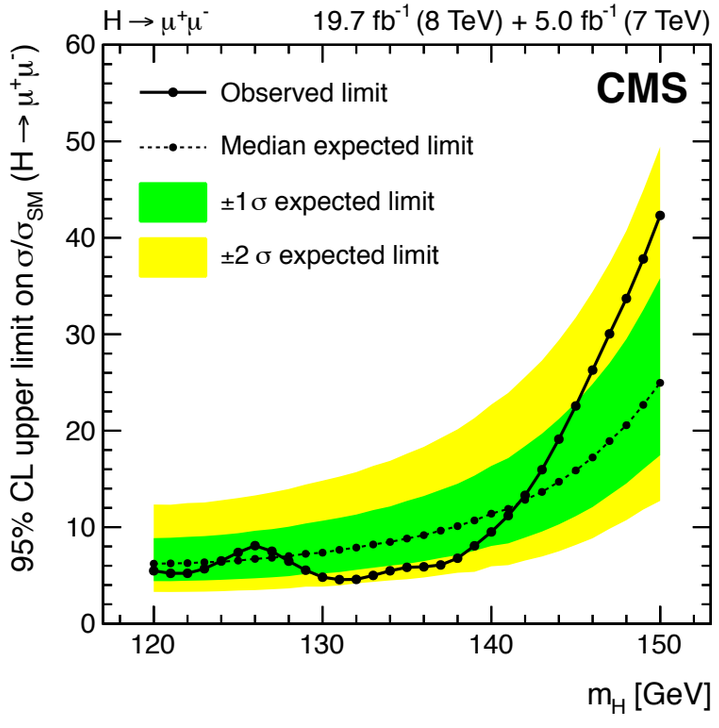
- High mass resolution 1.6 - 2.5 GeV FWHM @ 125 GeV
  - Analysis divided in categories based on
    - Higgs mass resolution
    - Production mechanism (ggH & VBF)
  - Signal extraction
    - parametric fit of the muon/electron invariant mass

2 examples for a total of 15 categories



Results

σ x BR (H -> μμ) < 3.4*10⁻²pb
σ/σSM < 7.4 (6.9 expected)
σ x BR (H->ee) < 3.8*10⁻²pb
assuming SM production
BR(H->μμ) < 0.0016
BR(H -> ee) < 0.0019

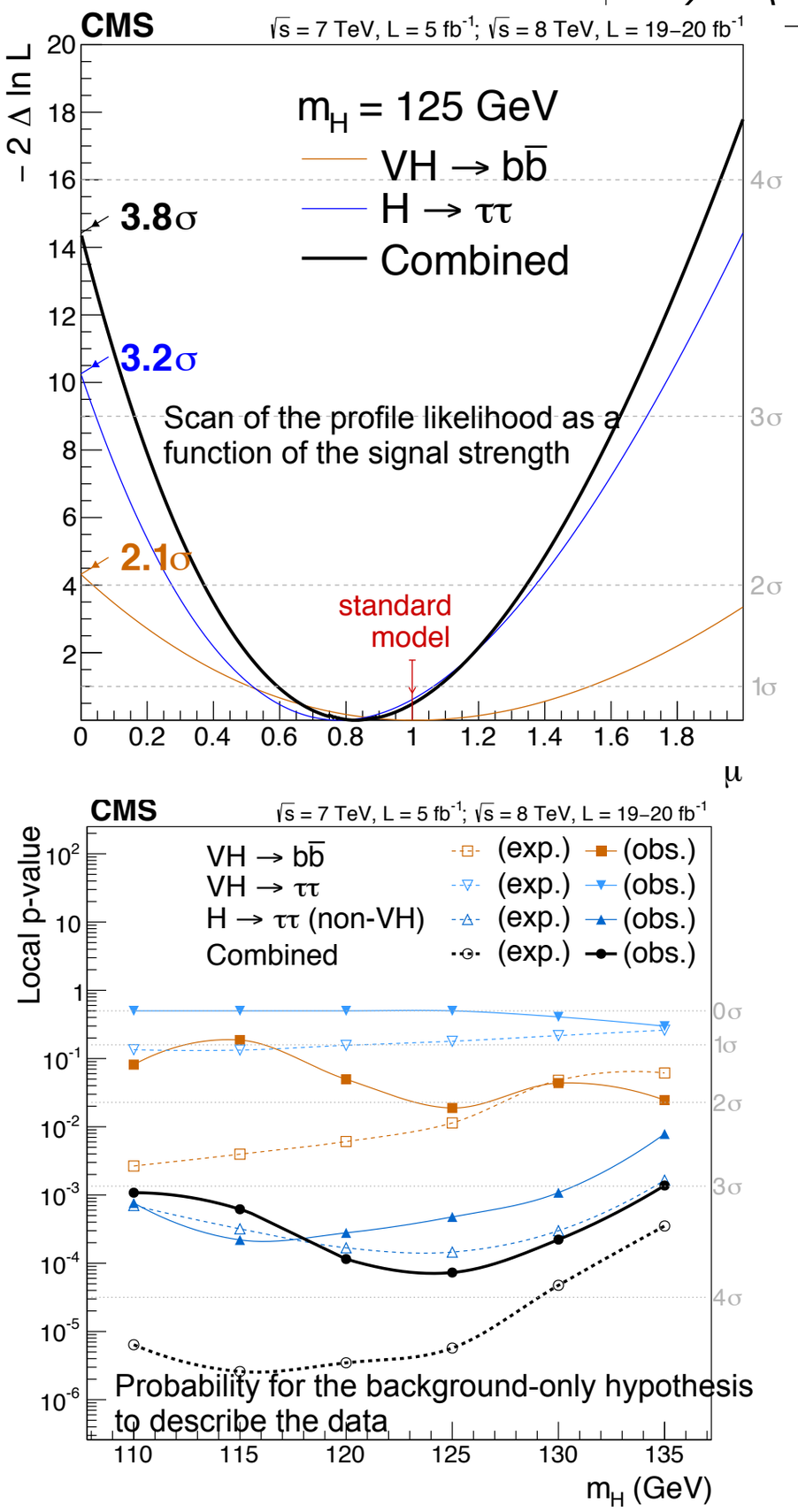


CMS H->fermions

CMS-HIG-13-033
Nature Phys. 10 (2014) 557-560

- Evidence to down-type fermions
  - current measurement mainly constraint the coupling to up-type top quark
    - combine only VHbb and Hττ
    - driven by Hττ evidence

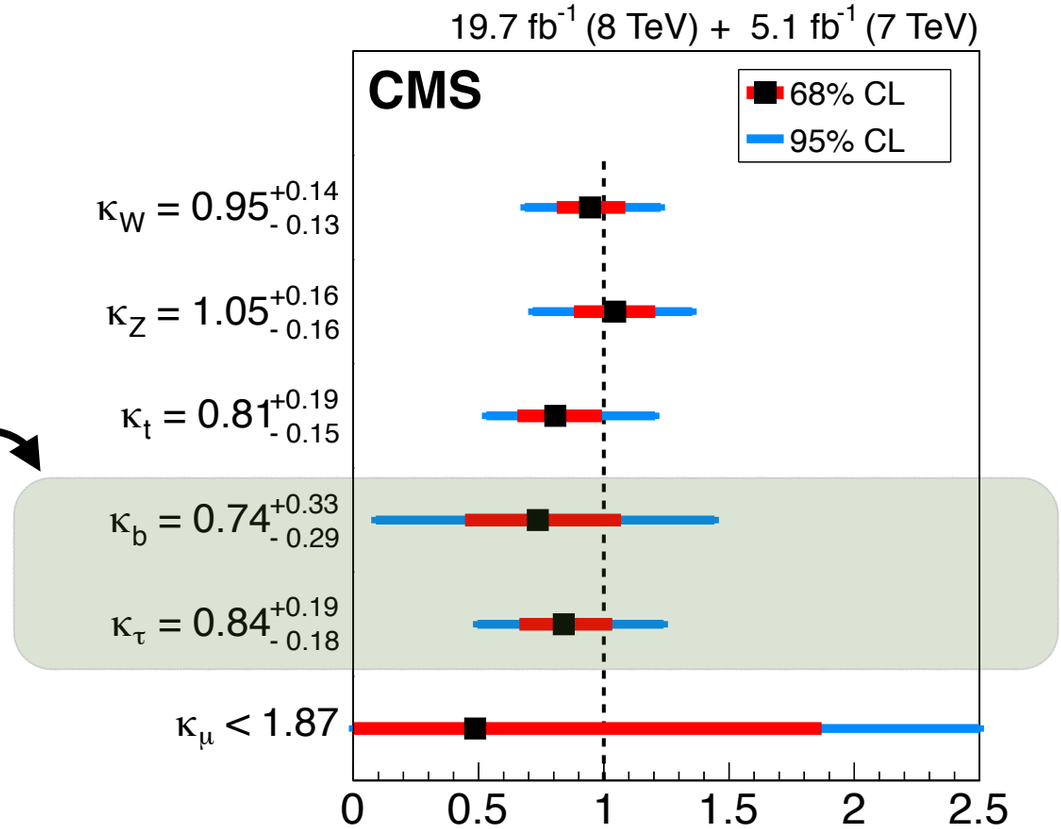
Channel ($m_H = 125$ GeV)	Significance (σ)		Best-fit
	Expected	Observed	μ
Combined	4.4	3.8	0.83 ± 0.24

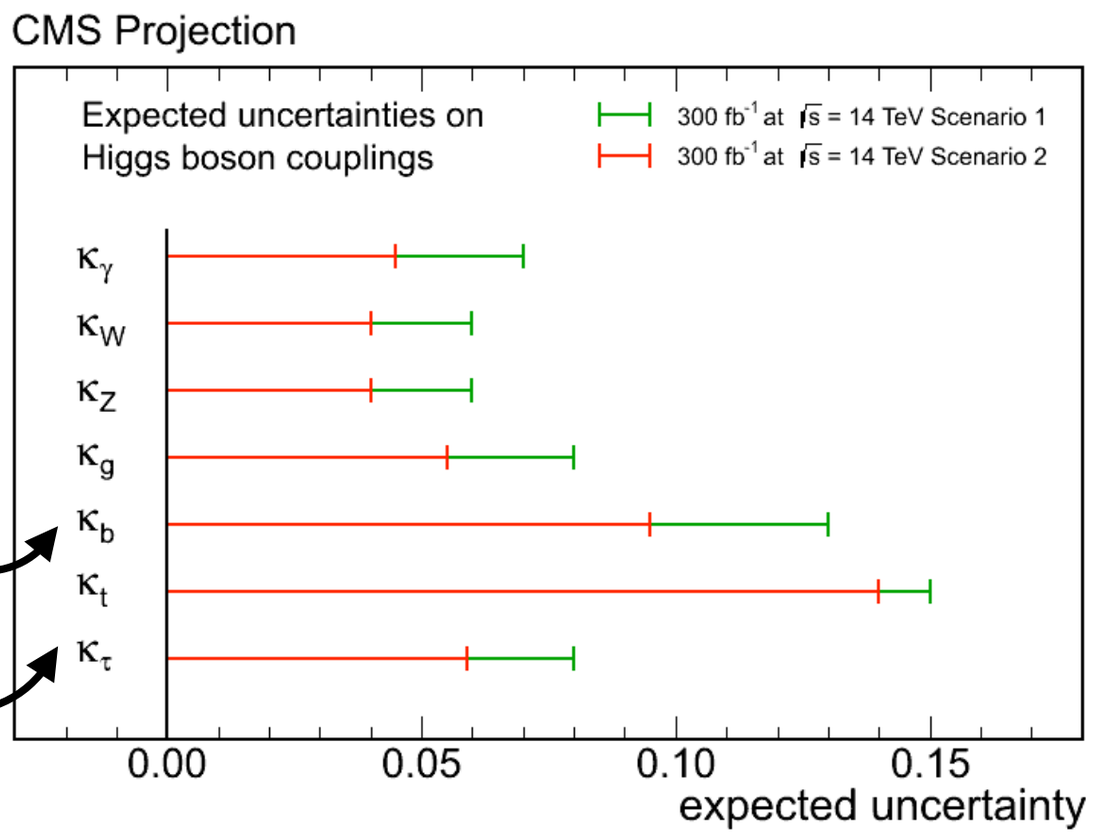


yes, the Higgs boson interacts with matter!

Conclusions and prospects

- legacy from LHC run1
  - evidence of Higgs coupling to τ and fermions
  - excess in H->bb channel of 2.6 σ
  - all suggests Higgs boson is the SM Higgs
  - introduction and validation of new techniques (regression, MEM, τ embedding, etc.)
- From CMS run2
  - conclusive evidence of Hbb at 13TeV
  - reduce measured uncertainties (stat and syst!) on signal strengths
- From full CMS phase1 300 fb^{-1})
  - reduce uncertainty to k_b to ~15%
  - reduce uncertainty to k_τ ~8%
  - evidence of H->μμ



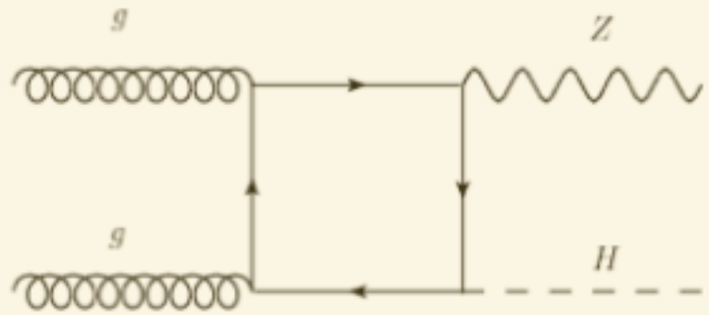


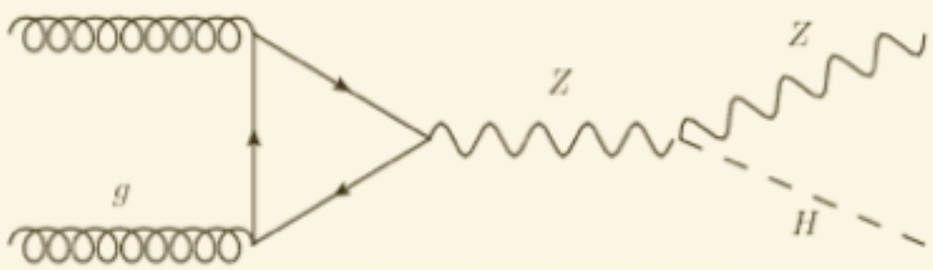
BACK UP

ggZH

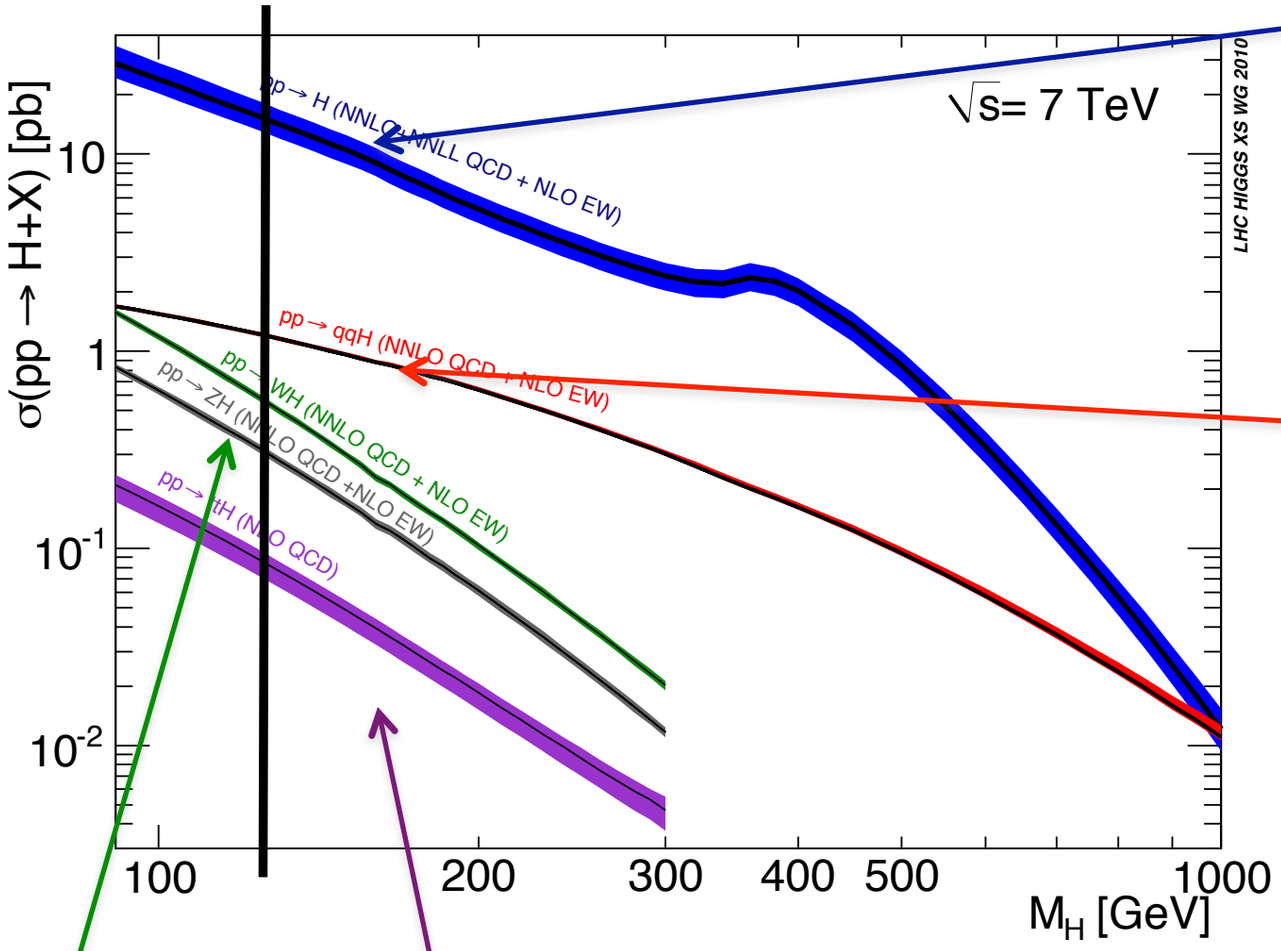
Updated new results including **ggZH process in signal**

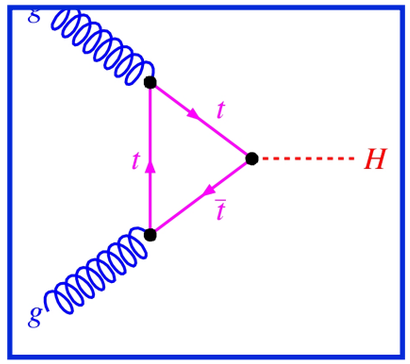
- ggZH gives **sizeable** contribution in **high p_T regions**
- updated results (CERN-PH-EP-2014-288):
  - best-fit $\mu = 0.89 \pm 0.43$
  - $\sigma/\sigma_{SM} < 1.68$ (0.85 expected)
  - significance: 2.08σ (2.52σ expected)



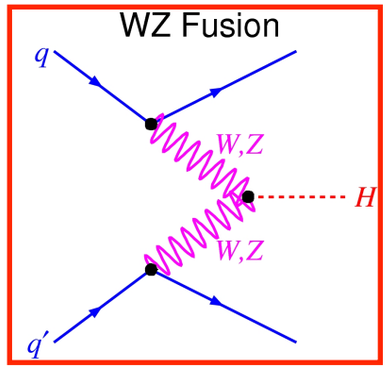


func(Xsection * BR, eff, bkgs)





g-g fusion



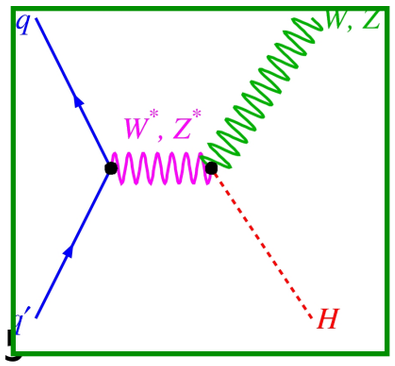
Vector boson fusion

H→ττ

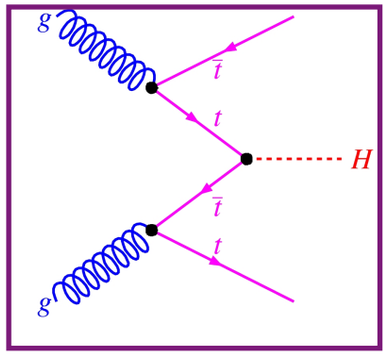
- gluon fusion difficult but possible(can use association with jets or go to high pt regime)
- VBF cleaner
- VH and ttH also added

very important for study Higgs properties!

Association with Z/W



Association with tt^bar



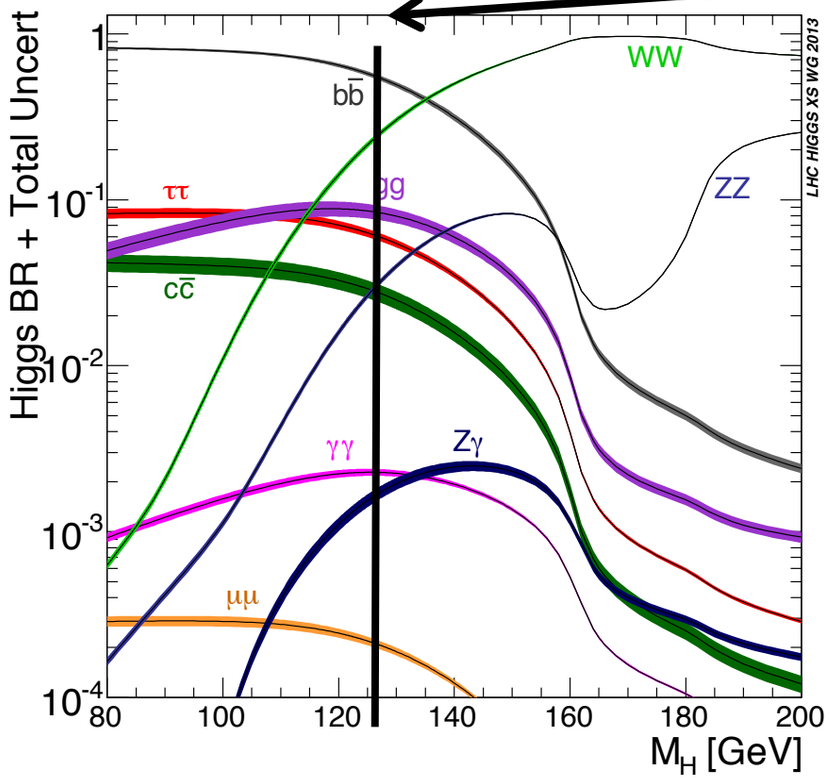
H→bb

overwhelming QCD: need to go with associated production,

- VH - can use lepton/MET and topology
- ttH - even less rate, look at topology, but ttbar bkg well understood
- VBF recently added

Region of interest

m_H=125.09 GeV



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$H \to c\bar{c}$	2.90 ± 0.35
$H \to ZZ$	2.67 ± 0.11
$H \to \gamma\gamma$	0.228 ± 0.011
$H \to Z\gamma$	0.155 ± 0.014
$H \to \mu\mu$	0.022 ± 0.001

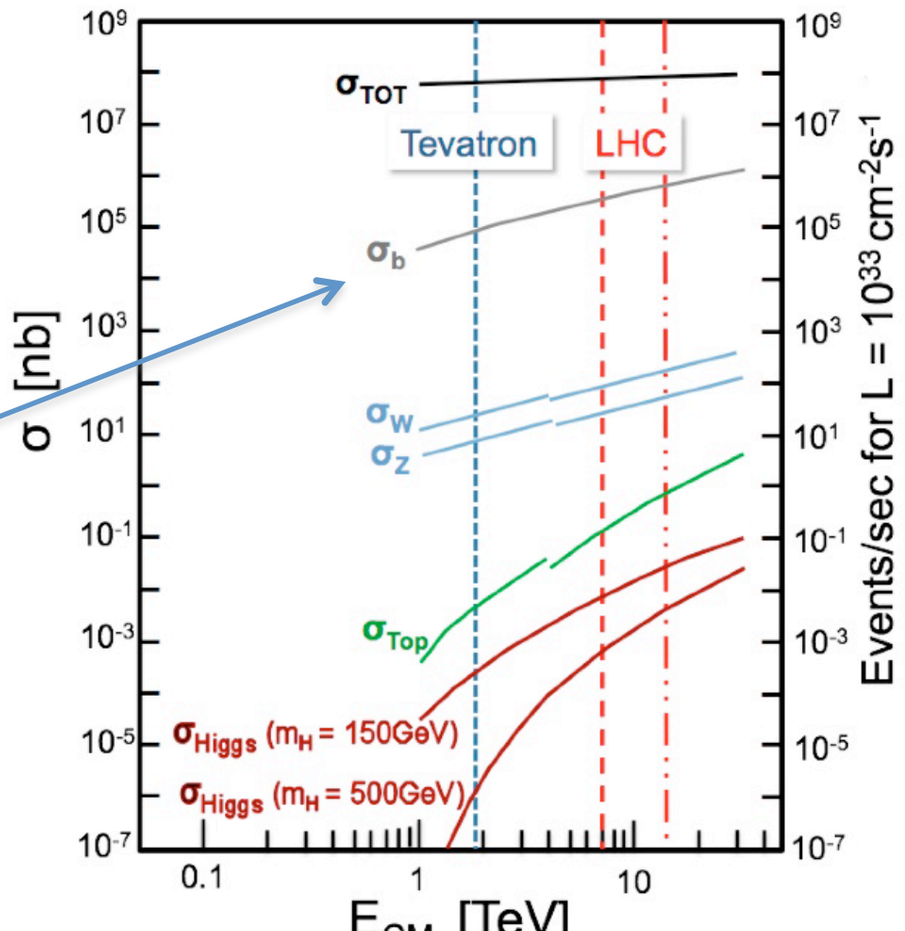
SM BR theory uncertainties
2-5% for most important or

But σ_{bb}(QCD) ~ 10^7
σxBR(H→bb)!

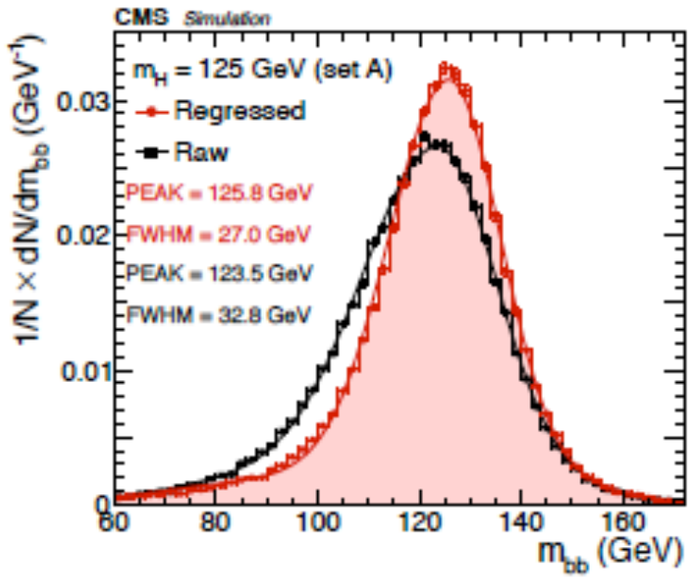
b's and tau's ← test the Higgs couplings to fermions vs bosons

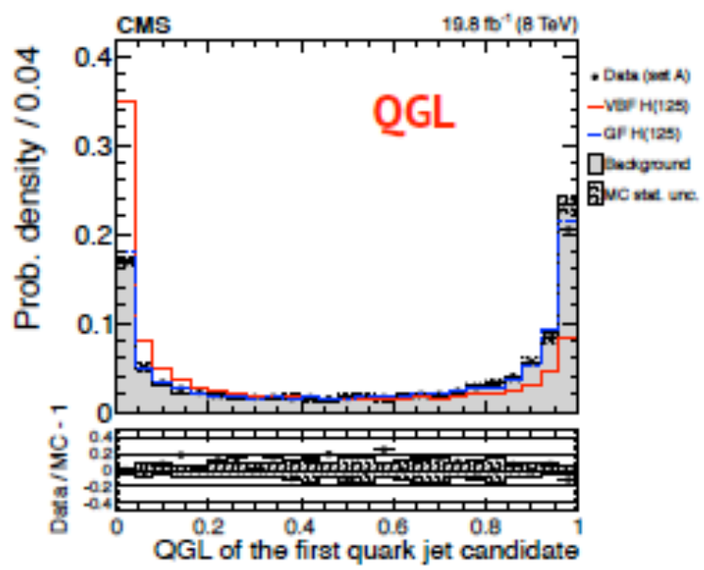
Vital part of the Higgs identification and Higgs property studies

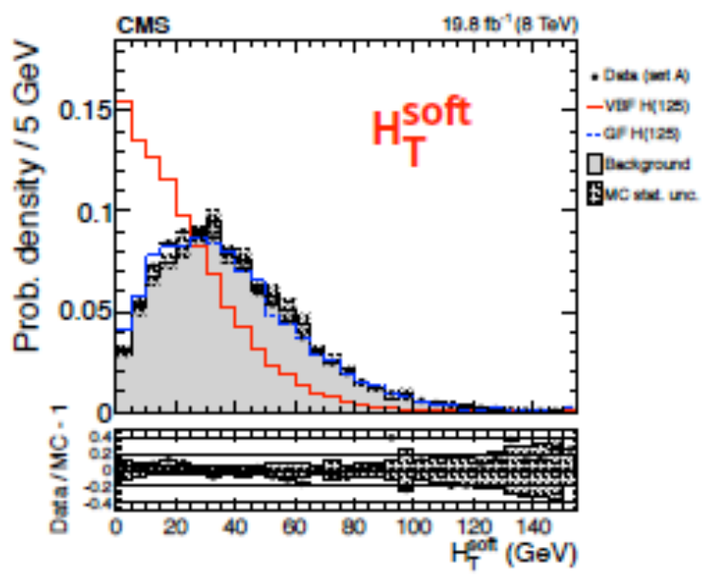
But life is hard…



VBF addendum







Optimization

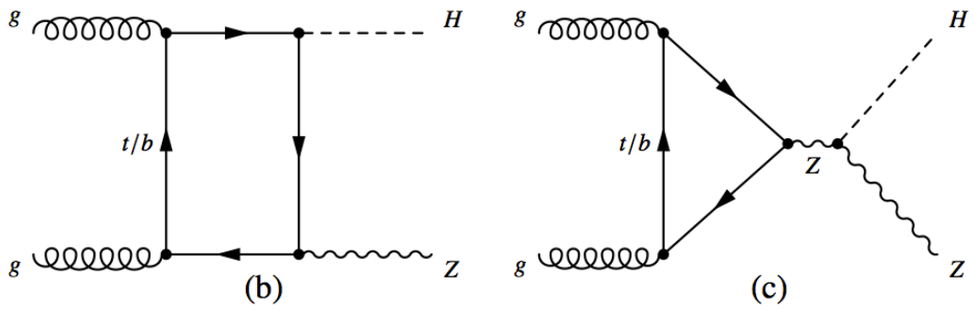
- **jet $p_\perp$ regression** similar to VH analysis
  → *improved $m_{b\bar{b}}$ resolution*
- **quark/gluon discrimination** using jet shape properties (CMS-PAS-JME-13-002)
- no colour flow in rapidity gap between VBF jets
  → *discriminating variable **soft H_T***
- improved event interpretation
  → ***b jet identification** using BDT*
- **QCD template derivation** in bkg enriched categories (CAT1 & CAT5) + transfer to other ones with 1st/2nd order polynomial multiplicative functions

Results

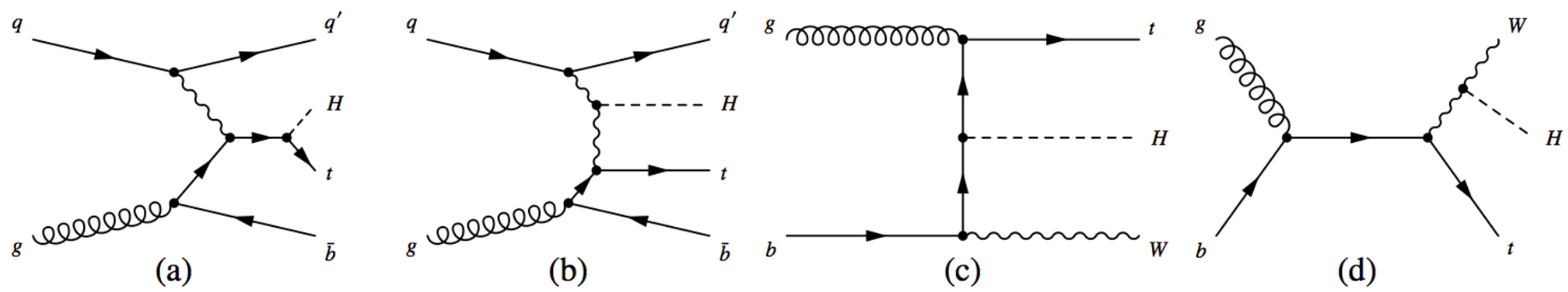
- observed (expected) limit 5.5 (2.5) at $m_H = 125$ GeV
- significance 2.2σ (0.8σ)
- best-fitted $\mu = 2.8^{+1.6}_{-1.4}$

other ptoduction mechanisms

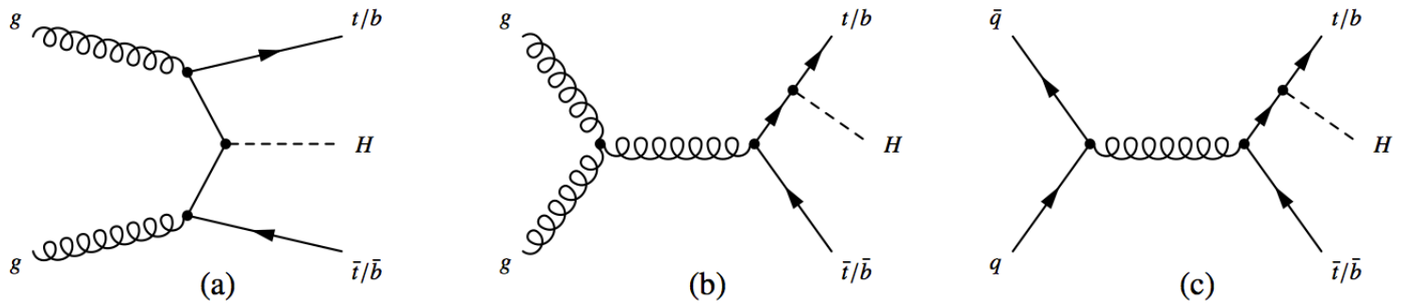
- ggZH:
  - O(10%) effect on VHbb in SM, higher p_T than qqZH



- tHq + tHW
  - Not really sensitive but has larger effects for negative couplings



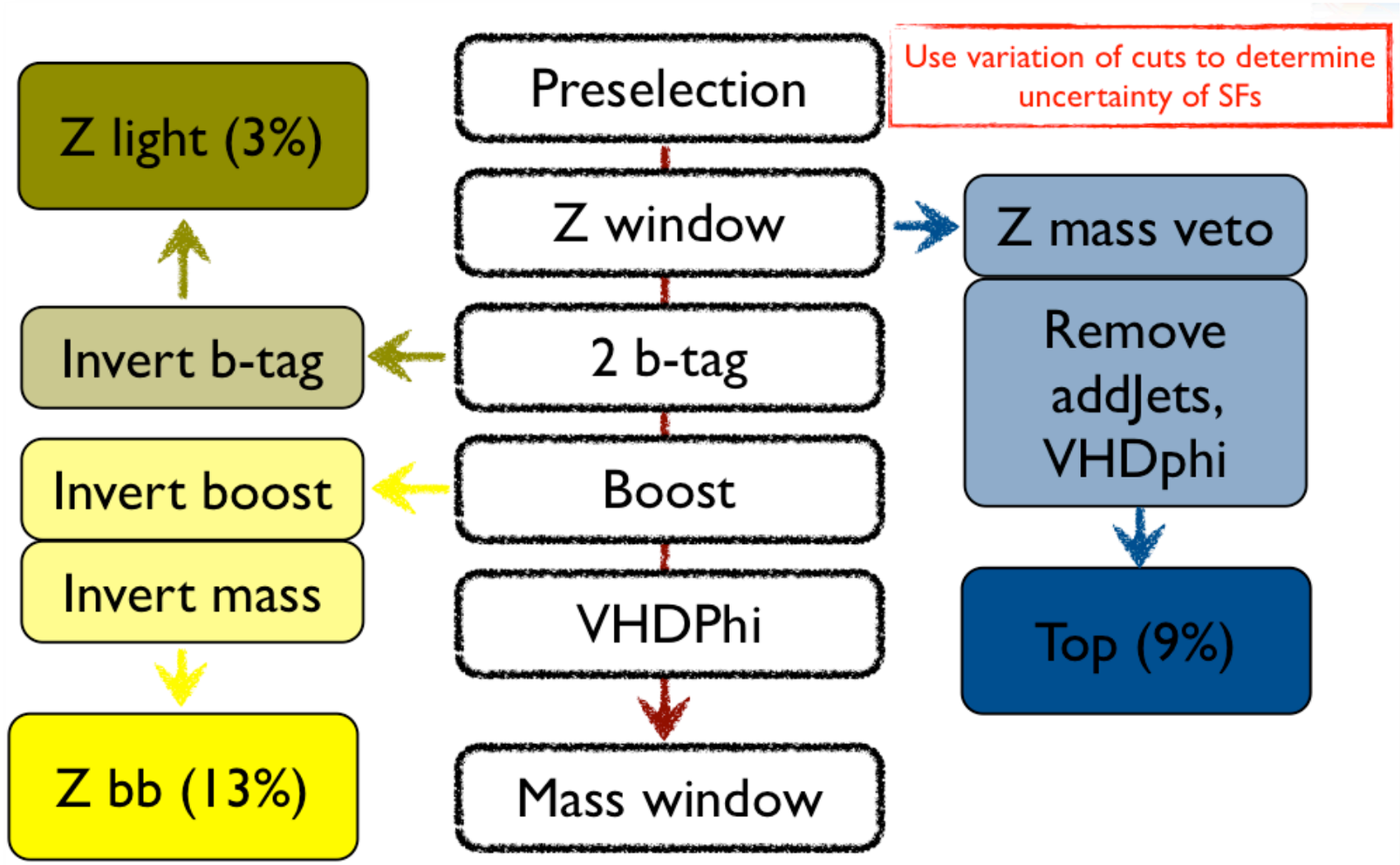
- bbH
  - Similar to ttH but not really distinguishable from ggF



VHbb: Bkg Control Regions

Definition of Control Regions (CR) crucial element of the analysis

Example: Zee control region definition



Define several CR enriched in different background components:

Control regions cuts as close as possible to the signal region

Renormalize MC simulation yields and extrapolate to signal region

Account for associated stat. and syst. uncertainties

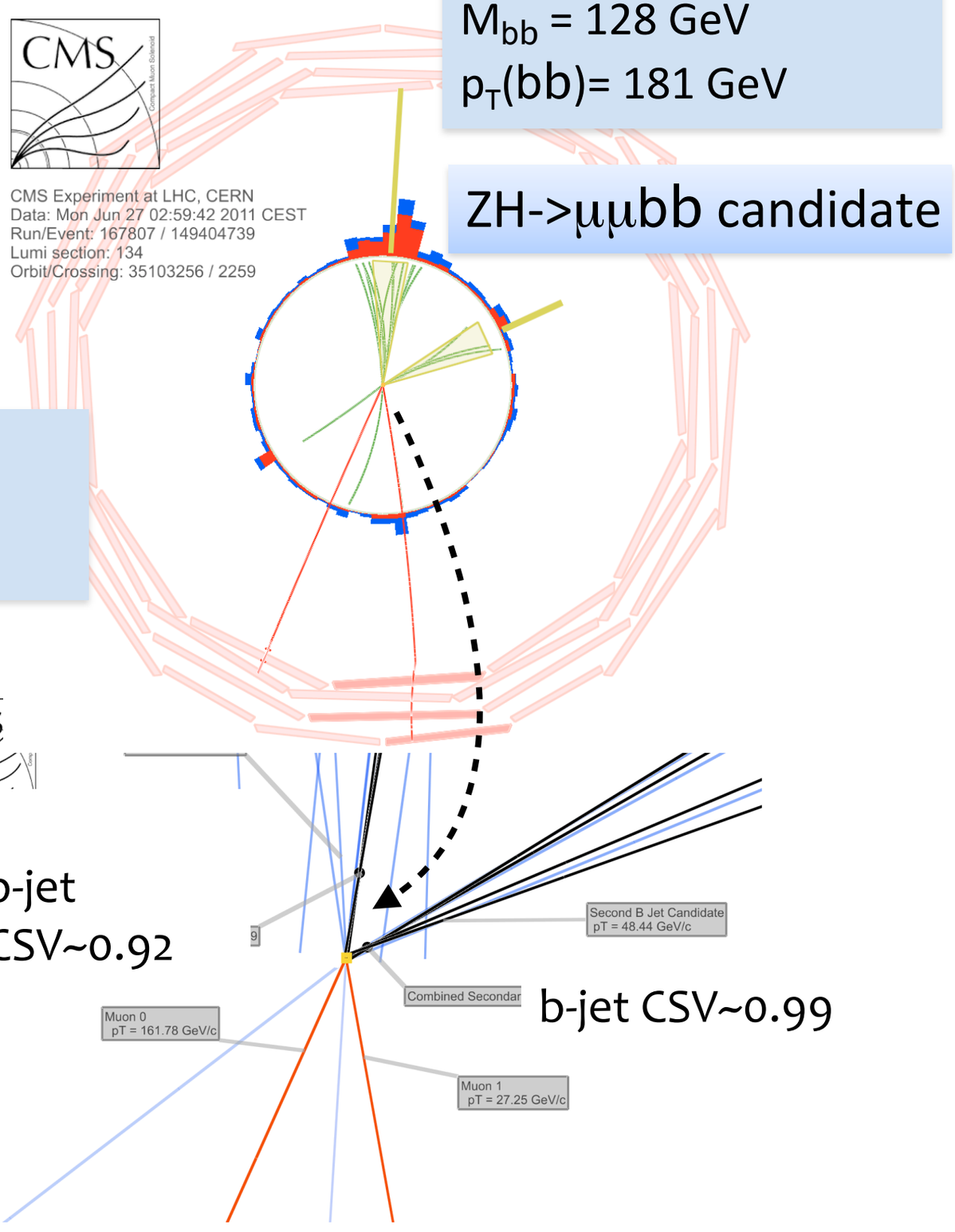
(%)= uncertainty

H -> bb VHbb strategy

First CMS VHbb 2011 analysis
Phys. Lett. B 710(2012) 284-306

- 5 channels:
  - Z(ll)Hbb
  - Z(νν)Hbb
  - W(lν)Hbb

Associated Production
→ final states with leptons, MET and b-jets

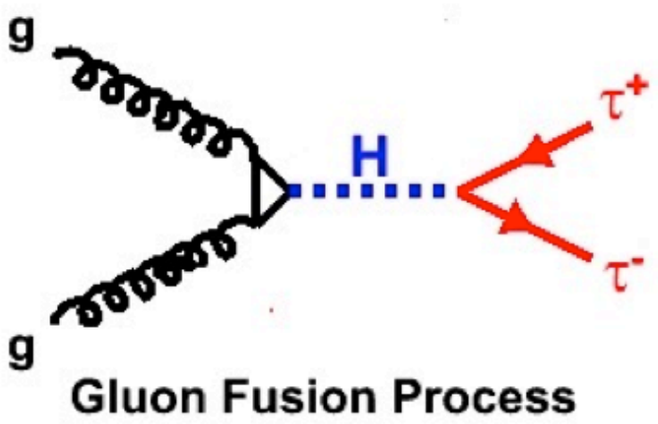


General strategy:

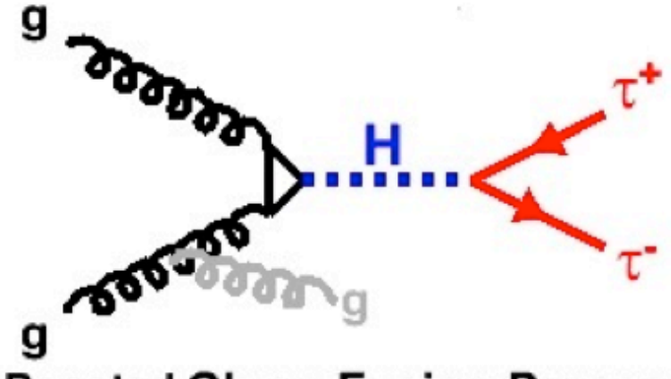
(a) High boosted vector boson and dijet,
(b) 2 b-tagged jets,
(c) back-to-back V & H
(d) Reconstruct m_{bb}

$H \rightarrow \tau\tau \rightarrow \mu\tau_h, e\tau_h, e\mu, \mu\mu$

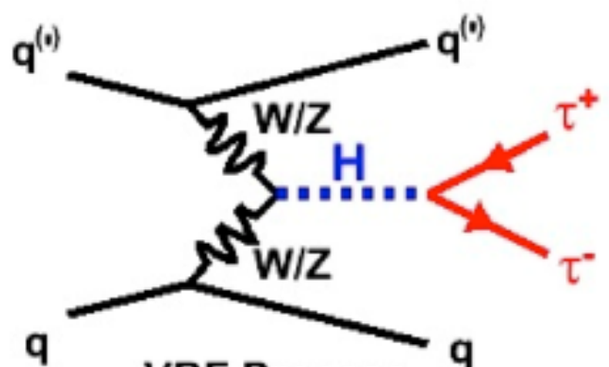
- Sensitive to all production modes
- Probes coupling to leptons
- Enhanced σ x BR in MSSM



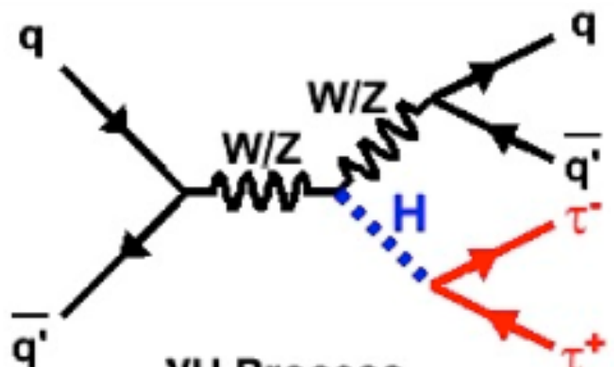
Gluon Fusion Process



Boosted Gluon Fusion Process



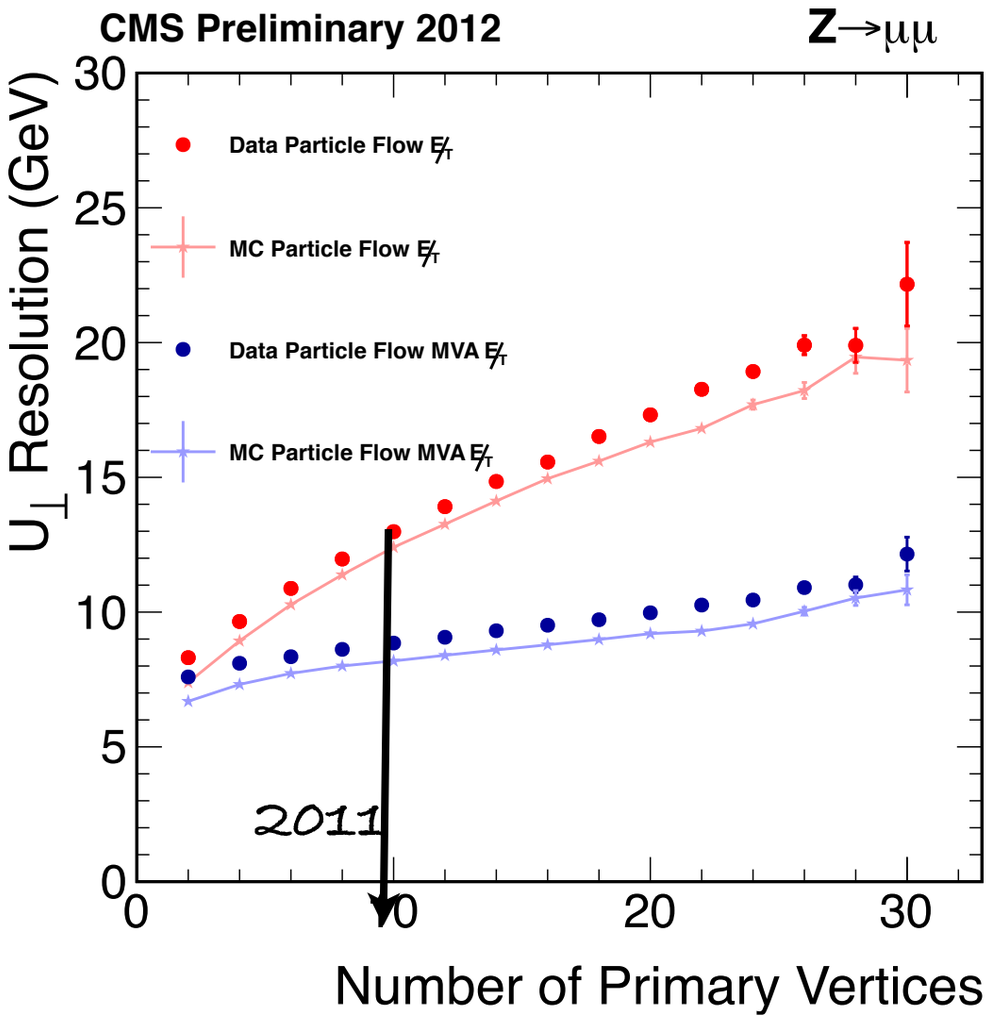
VBF Process

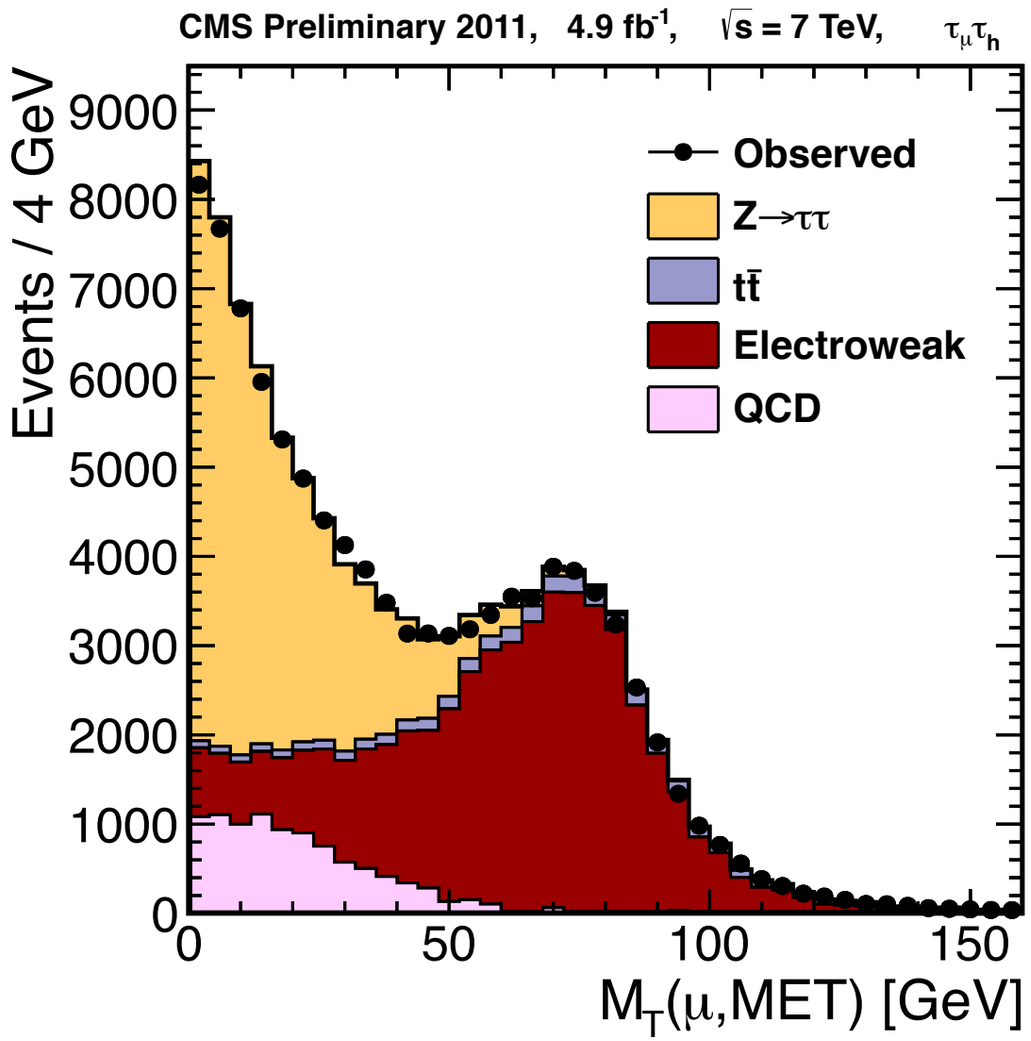


VH Process

H -> ττ MVA MET regression

$$m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}} E_{\mathrm{T}}^{\mathrm{miss}} (1 - \cos(\Delta\phi))}$$

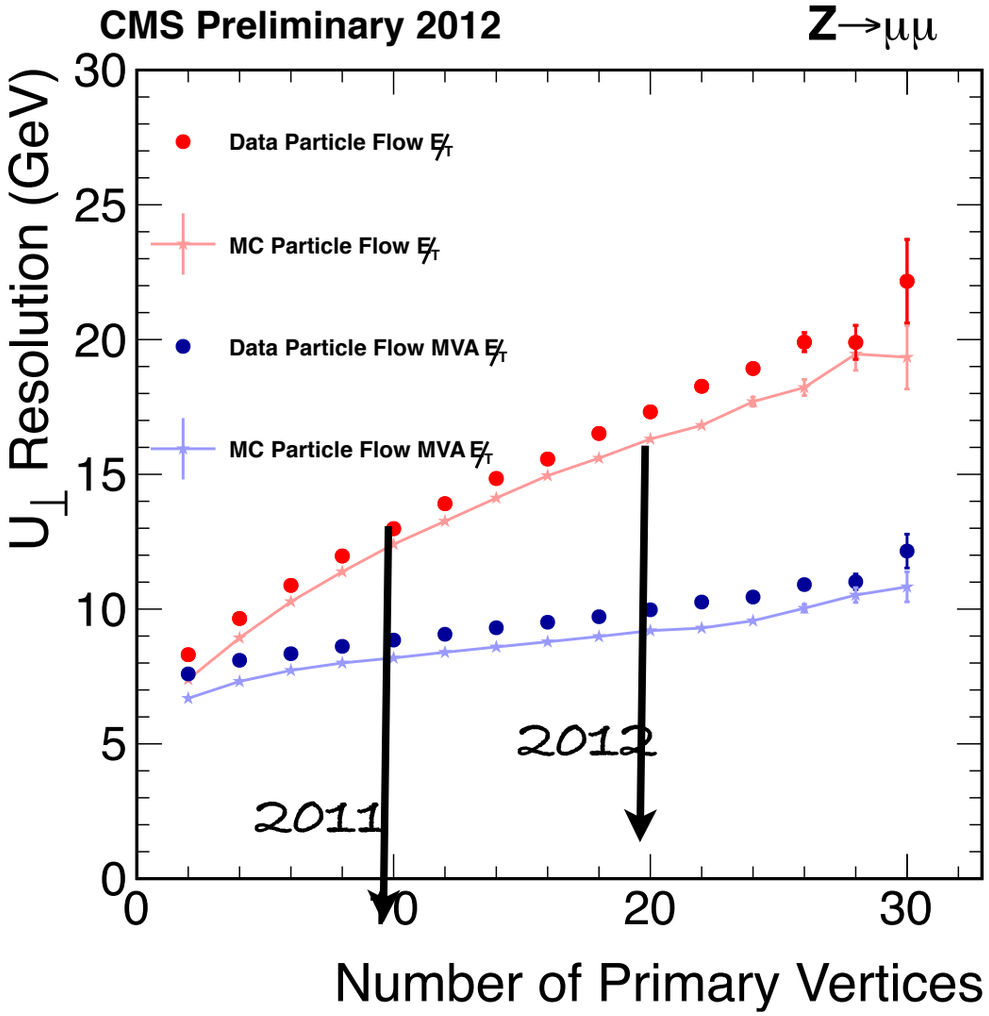


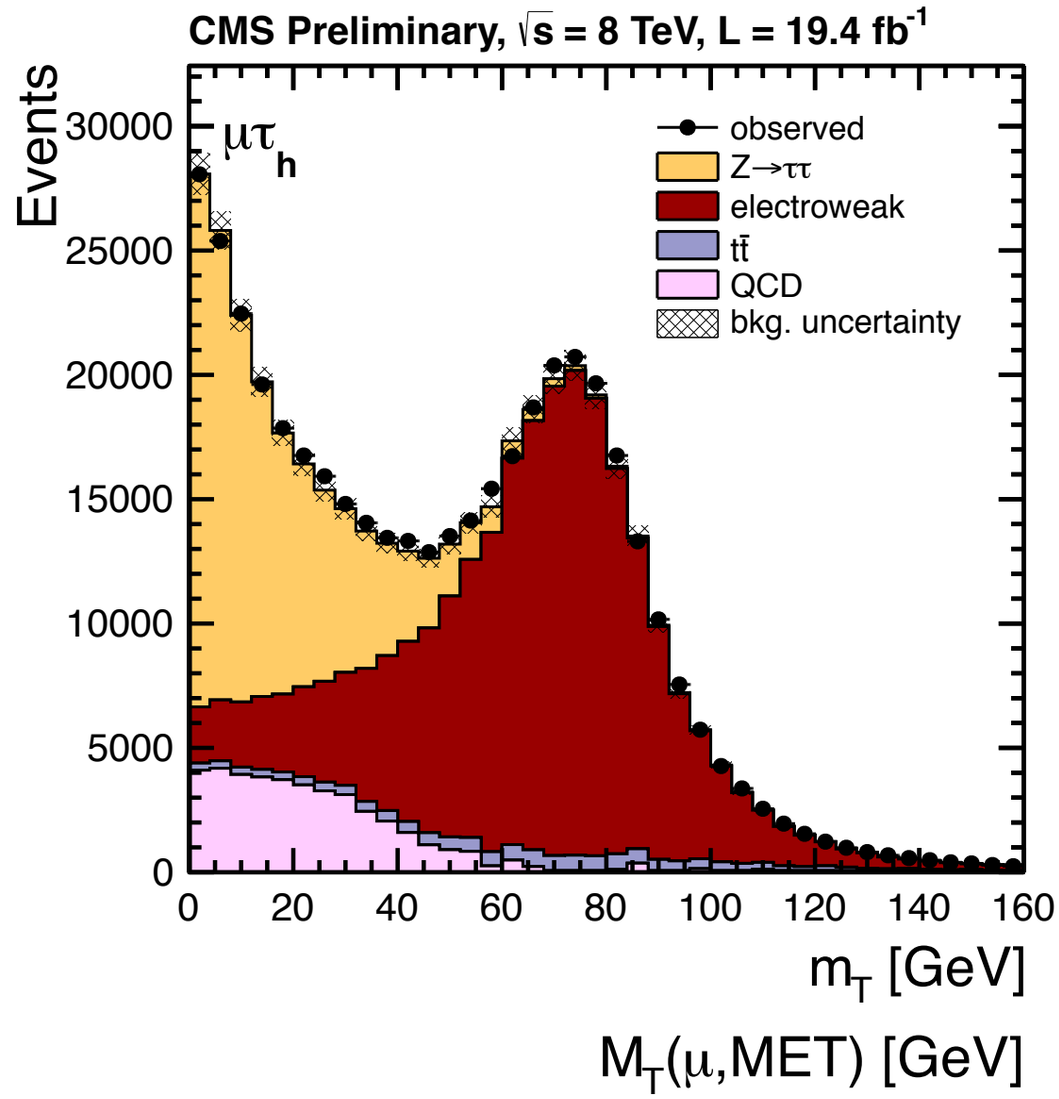


- significant improvement in resolution and pileup dependence
- crucial for H->ττ: best separation of signal from W+jets

H -> ττ MVA MET regression

$$m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}} E_{\mathrm{T}}^{\mathrm{miss}} (1 - \cos(\Delta\phi))}$$





- significant improvement in resolution and pileup dependence
- crucial for H->ττ: best separation of signal from W+jets

H -> ττ Analysis strategy

UF

number of jets (p_T>30)

$\mu\tau_h$, $e\tau_h$, $e\mu$, $\mu\mu$

τ p_T

0 Jet, Low p_T
High background

1 Jet, Low p_T
Enhancement from jet requirement

0 Jet, High pT
Lepton p_T spectrum harder from H

1 Jet, High p_T
Enhancement from p_T and jet requirement

VBF
2 jets, no jets in rapidity gap
mjj>500

$\tau_h\tau_h$ **1 Jet**
high p_T(H) requirement

$\tau_h\tau_h$ **2 Jet (VBF)**
high p_T(H) requirement
mjj>250

- Search performed in 5 tau-pair final states: $\mu\tau_h$, $e\tau_h$, $e\mu$, $\mu\mu$, $\tau_h\tau_h$
- Select isolated, well-identified leptons, τ_h + topological cuts (e.g. m_T in $l\tau_h$) to suppress backgrounds
- Categorize events based on number of jets, τ p_T
- Template fit to $m_{\tau\tau}$ shape

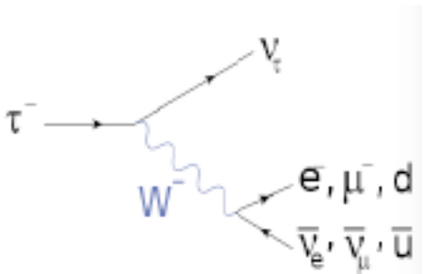
Michele de Gruttola

H -> ττ

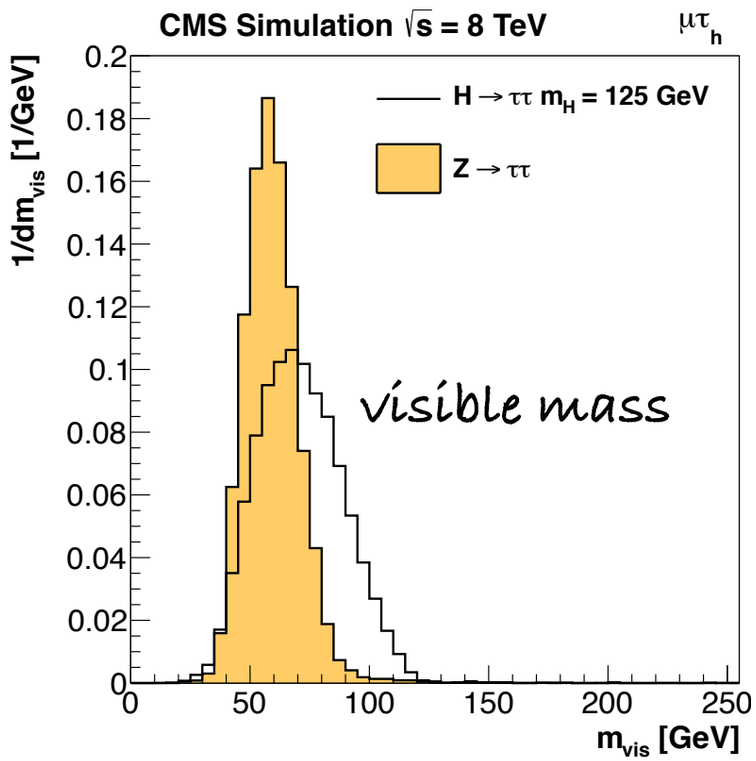
Mττ resolution

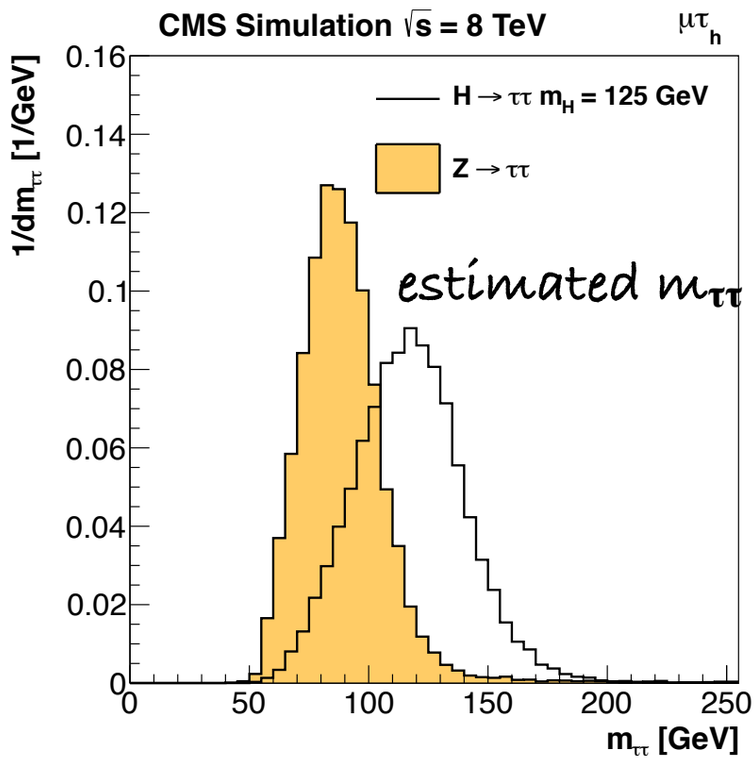
2011 analysis in PLB: Phys. Lett. B 713(2012) 68-90

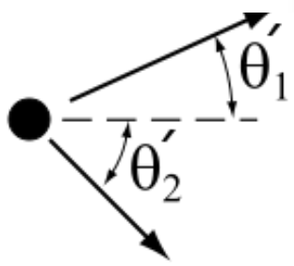
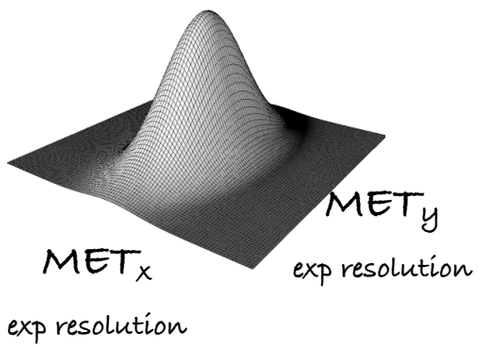
- also new 2012
  - Improved tau ID new mass reconstructions better mass resolution)



H/Z separation





$\mathcal{L} =$  $\times$ 

- Event-by-event estimator of true m(ττ) likelihood using momenta of visible decay products, angles and MET directions and expected resolution