CMS Higgs Searches
Measurements in the bb and ττ channels

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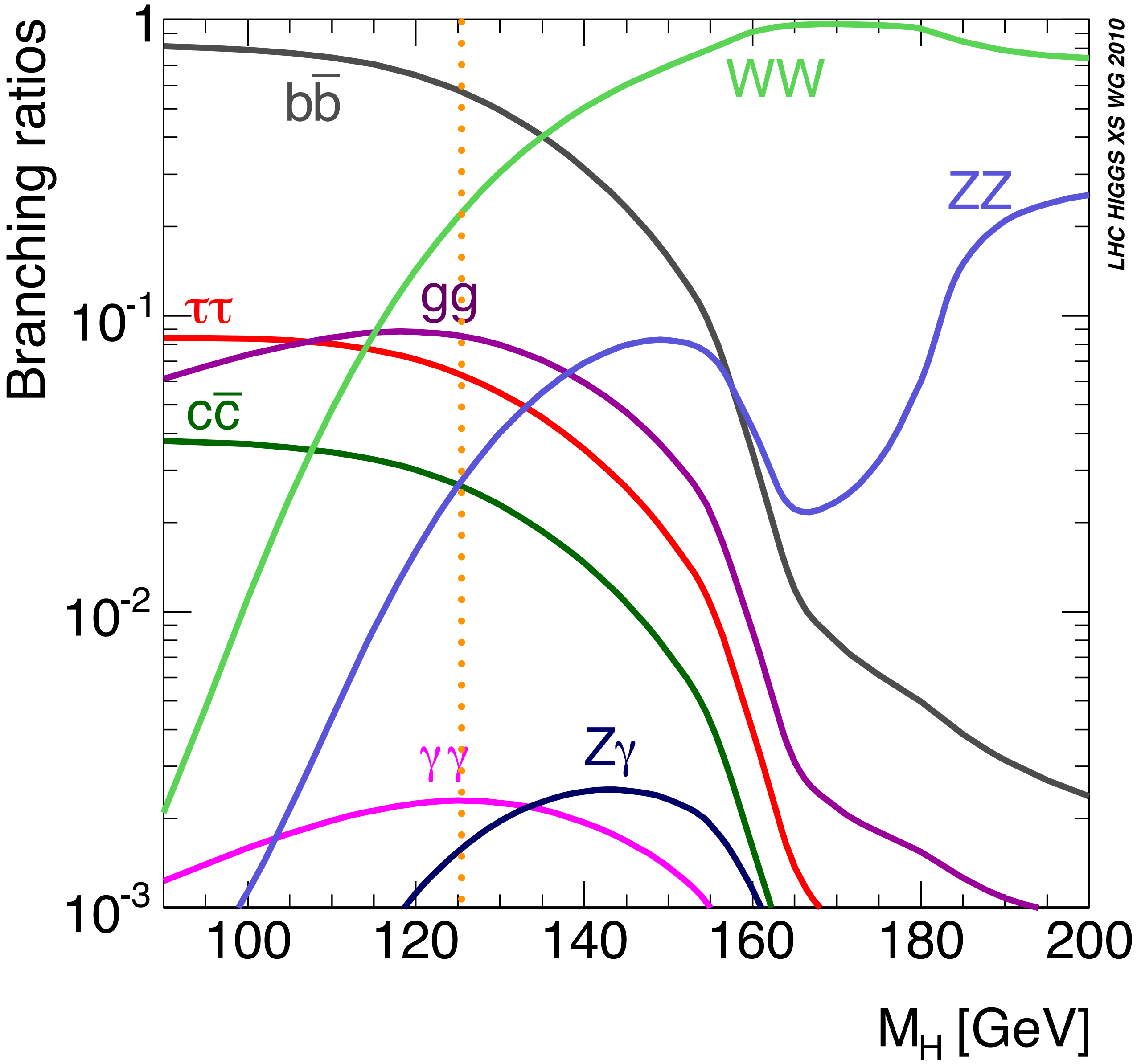
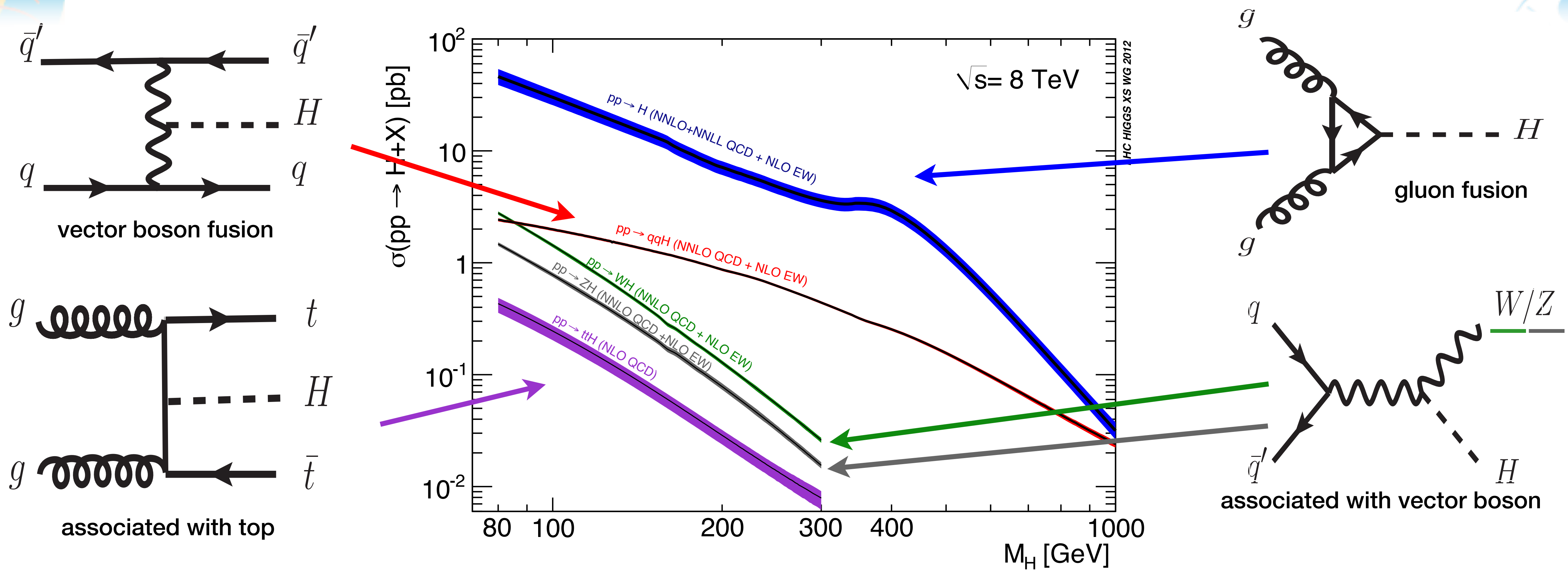
Introduction

- H(125) discovery summer 2012: 5 fb^{-1} (7 TeV) + 5 fb^{-1} (8 TeV).
- Confirmation with full 7+8 TeV datasets: 5 fb^{-1} (7 TeV) + 19.4 fb^{-1} (8 TeV).
- Observation driven by the high-resolution channels γγ and ZZ.
- Does it couple to fermions directly*? How?



* H→γγ gives indirect evidence that H couples to quarks, but not to leptons.

CMS searches for SM Higgs into fermions

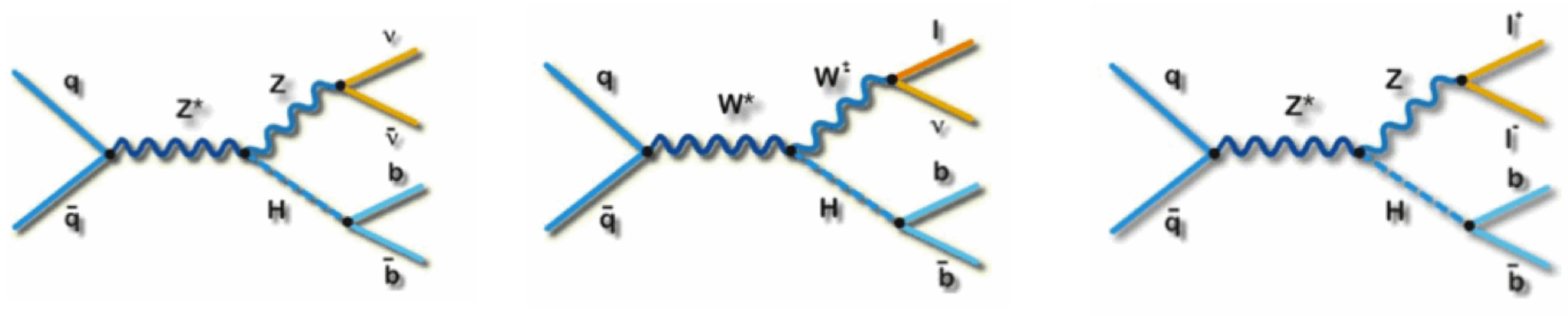


Decay mode	Production	Channels	Luminosity 7 TeV	Luminosity 8 TeV	Documents
bb	VH	13	5 fb^{-1}	12.1 fb^{-1}	CMS PAS HIG-12-044
	ttH	20	5 fb^{-1}	5.1 fb^{-1}	arXiv:1303.0763
ττ	gluon fusion	9 (+8)	4.9 fb^{-1}	19.4 fb^{-1}	CMS PAS HIG-13-004
	VBF	5			
	VH	12	5 fb^{-1}	19.5 fb^{-1}	CMS PAS HIG-12-053

SM H→bb searches

VH, H→bb : Analysis strategy

CMS PAS HIG-12-044



- Search in associated production with W or Z: final states with leptons, MET and b-jets.
- Topologies: Z(νν)H(bb), W(ℓν)H(bb), Z(ℓℓ)H(bb)
  ℓ = e,μ
- General strategy:
  - Boosted vector boson (V) and di-jet (H)
  - b-jet energy regression
  - Boosted decision tree (BDT) shape analysis
- Main backgrounds: V+jets, tt, VV, single top
  - V+jets, tt normalisation estimated from data in control regions

(last updated for HCP 2012)

7 TeV (2011)	8 TeV (2012)
5 fb^{-1}	12 fb^{-1}

VH, H→bb : Event pre-selection and MVA

Event pre-selection

Variable	W(ℓν)H	Z(ℓℓ)H	Z(νν)H
$m_{\ell\ell}$	–	[75 – 105]	–
$p_T(j_1)$	> 30	> 20	> 60
$p_T(j_2)$	> 30	> 20	> 30
$p_T(jj)$	> 120	–	> 130
$m(jj)$	< 250	[80 – 150] (< 250)	< 250
$p_T(V)$	[120 – 170] (> 170)	[50 – 100] (> 100)	–
CSV_{max}	> 0.40	> 0.50 (> 0.244)	> 0.679
CSV_{min}	> 0.40	> 0.244	> 0.244
CSV_{min}^{loose}	– (< 0.40)	–	– (< 0.244)
N_{al}	$= 0$	–	$= 0$
E_T^{miss}	> 45 (elec)	–	[130 – 170] (> 170)
$\Delta\phi(E_T^{miss}, jet)$	–	–	> 0.5
$\Delta\phi(E_T^{miss}, E_T^{miss(trks)})$	–	–	< 0.5
$\Delta\phi(V, H)$	–	–	> 2.0

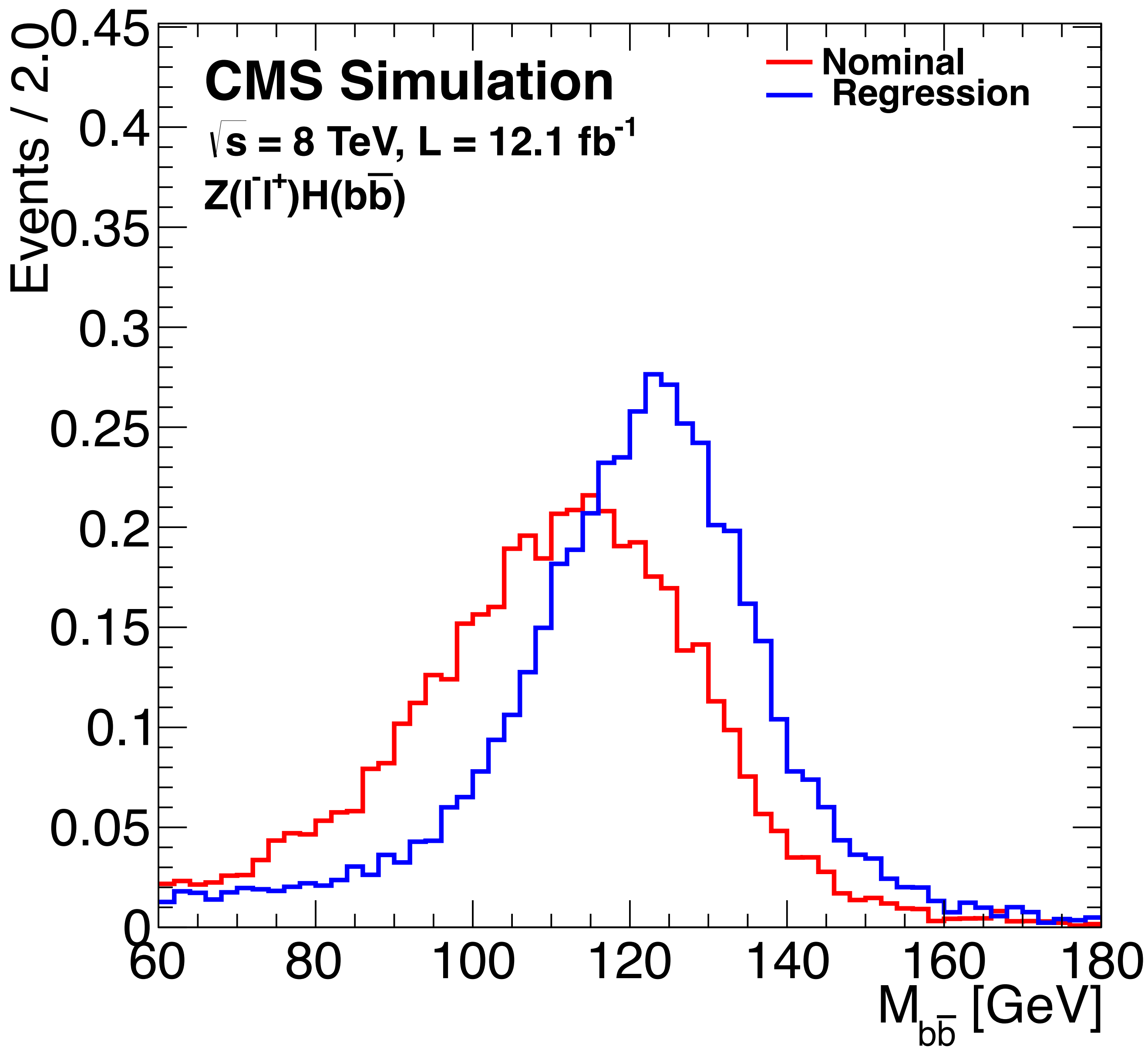
- Pre-selection for the BDT training.
- Categorisation: [low-pT] (high-pT) and (high-pT) with loose b-tag

- BDT inputs →
- Results obtained from fits of the shape of the BDT output.
  - ~20% improvement wrt to cut & count

Variable
p_{Tj}: transverse momentum of each Higgs daughter
$m(jj)$: dijet invariant mass
$p_T(jj)$: dijet transverse momentum
$p_T(V)$: vector boson transverse momentum (or E_T^{miss})
CSV_{max}: value of CSV for the Higgs daughter with largest CSV value
CSV_{min}: value of CSV for the Higgs daughter with second largest CSV value
$\Delta\phi(V, H)$: azimuthal angle between V (or E_T^{miss}) and dijet
$\lvert\Delta\eta(jj)\rvert$: difference in η between Higgs daughters
$\Delta R(jj)$: distance in η–ϕ between Higgs daughters
N_{aj}: number of additional jets
$\Delta\phi(E_T^{miss}, jet)$: azimuthal angle between E_T^{miss} and the closest jet (only for $Z(\nu\nu)H$)
$\Delta\theta_{pull}$: color pull angle [35]

VH, H→bb : b-jet energy regression

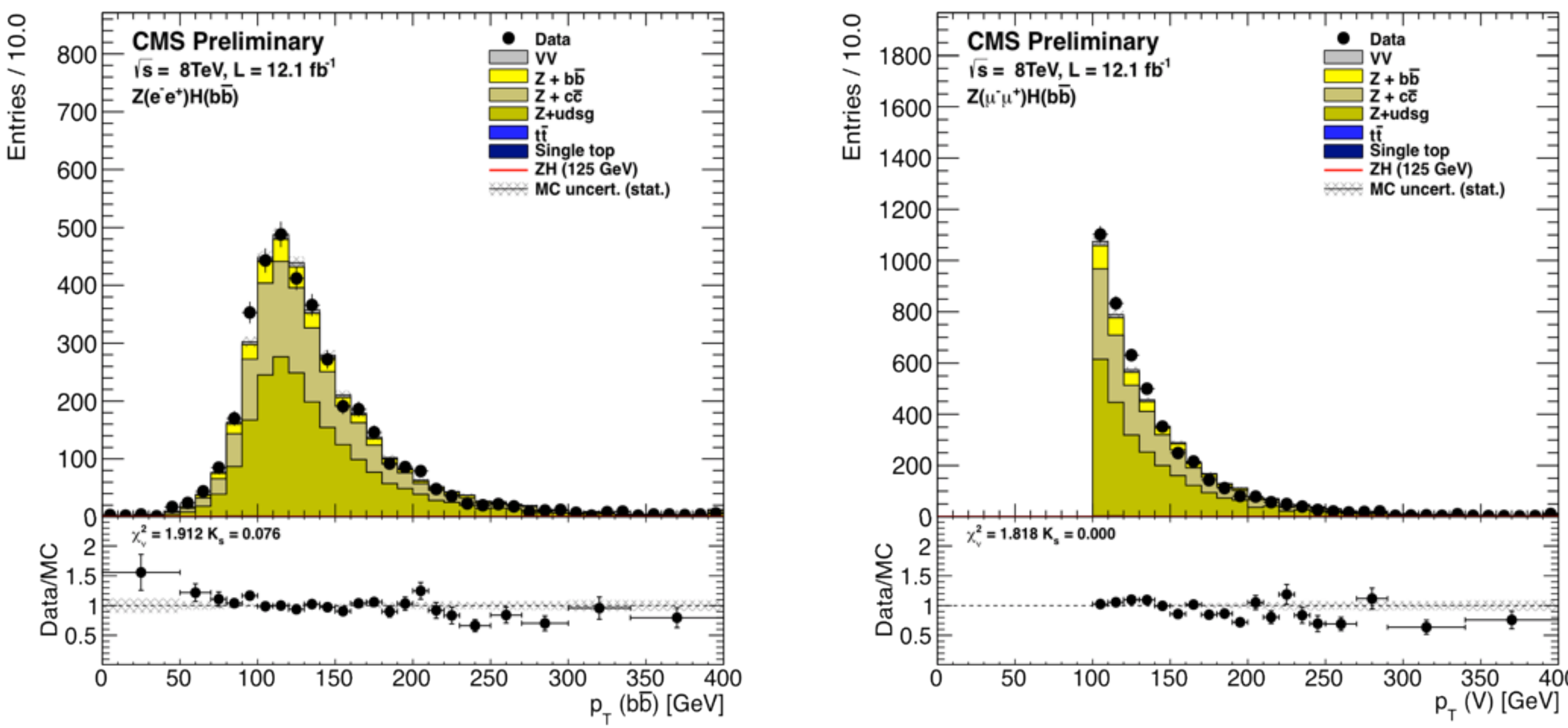
- BDT regression trained on VH signal events using various jet + soft lepton variables.
- Better mass resolution (~15%) → 10-20% improvement in sensitivity.
- Extensive validation on data and MC, e.g., p_T balance in Z(ll)+bb and reconstructed top quark mass



VH, H→bb : Background estimates

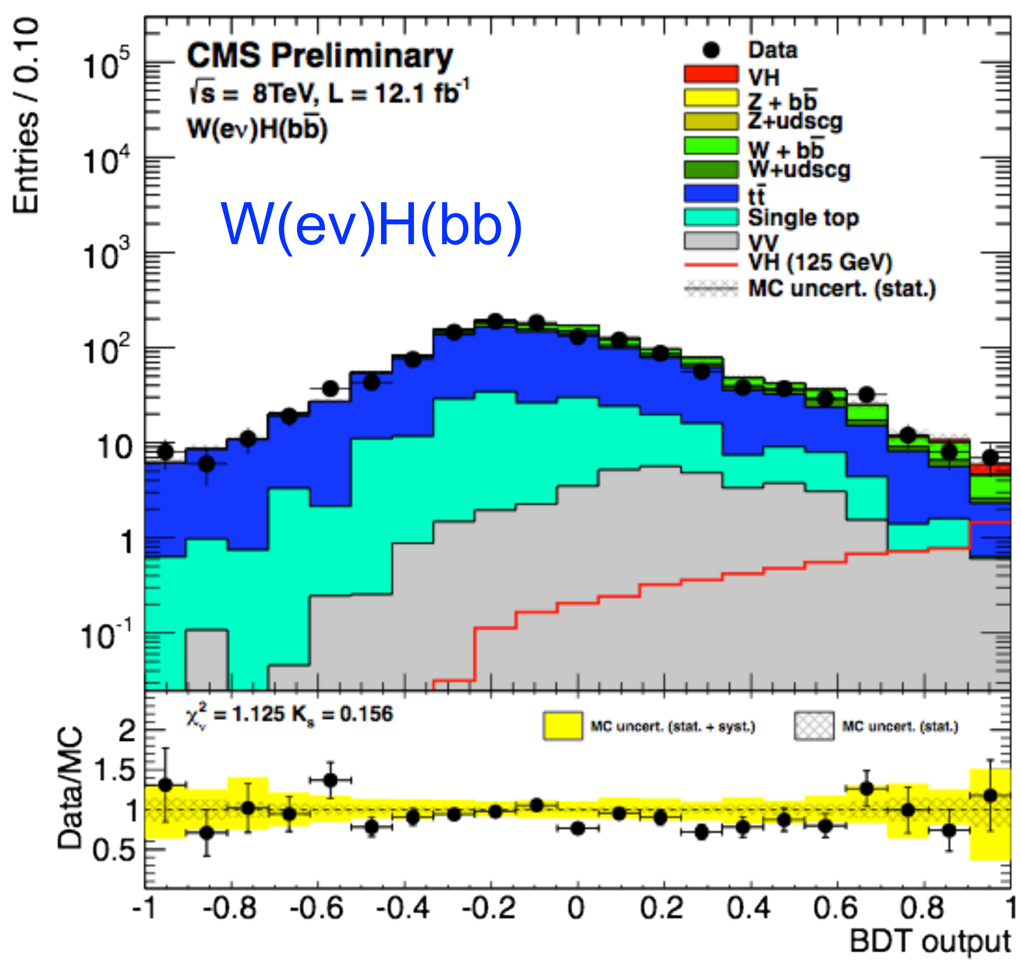
- V+jets and tt Monte Carlo yields corrected by scale factors (SF) from data control regions.
- SF obtained from simultaneous fits to the distributions of discriminating variables.
- Good agreement observed in calibration regions.

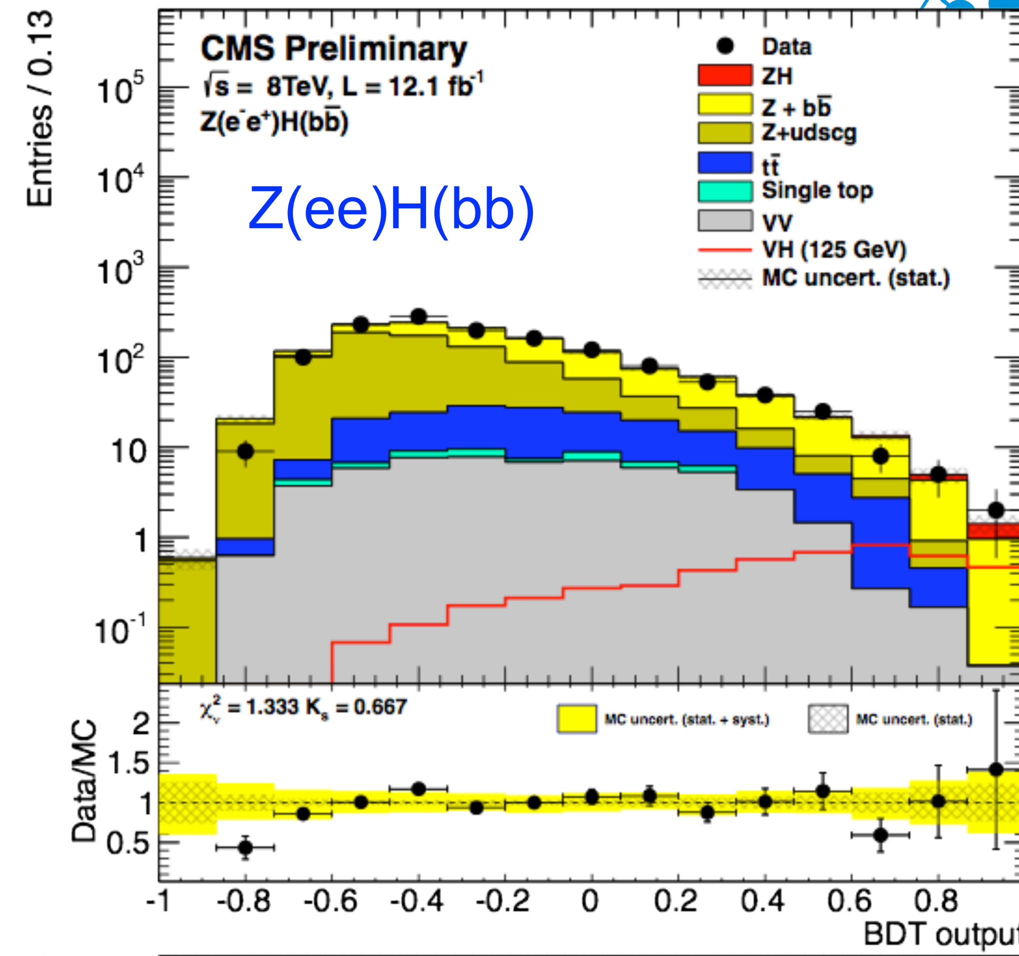
Z+ light jets enriched control region

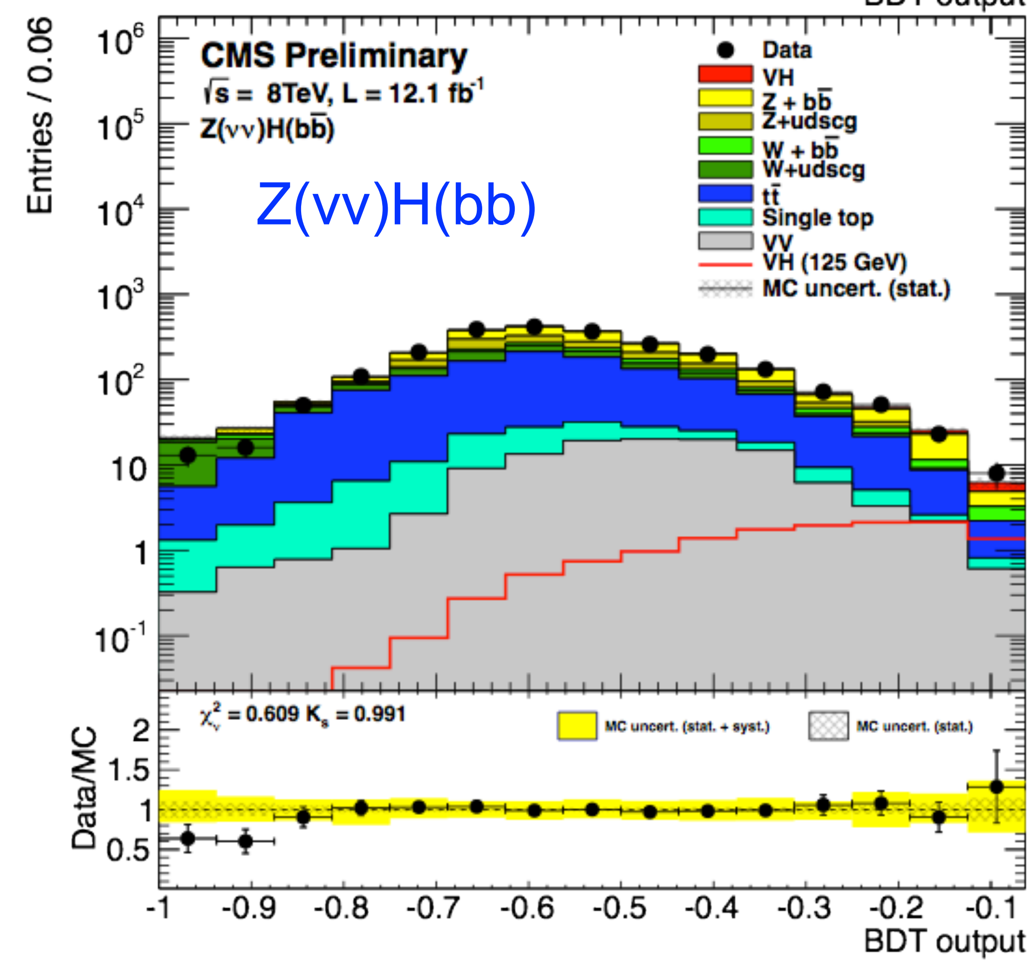


VH, H→bb : BDT analysis

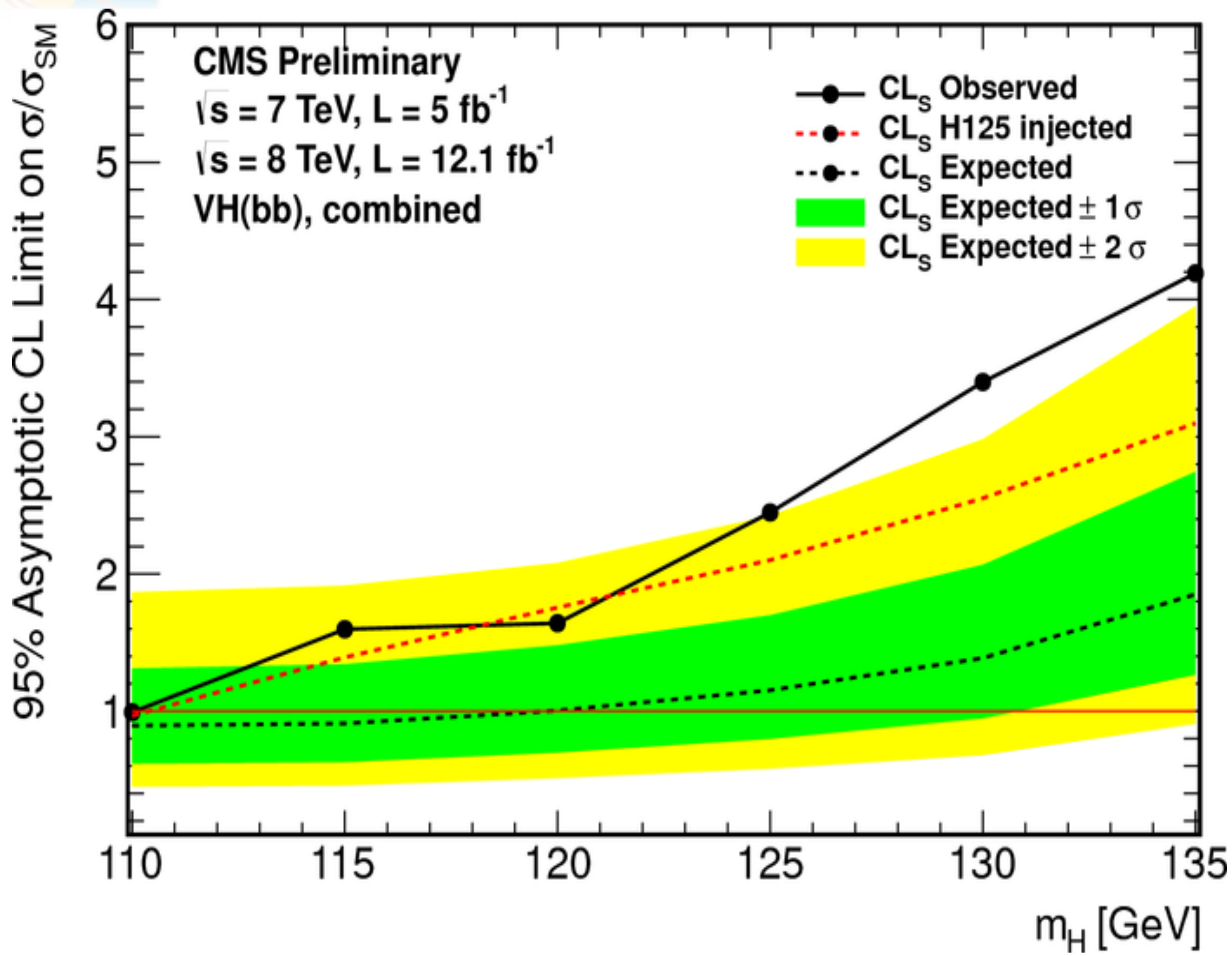
- Examples of final BDT distributions at high $p_T(V)$, 8 TeV
- Excess of events observed for all channels in the BDT fit.

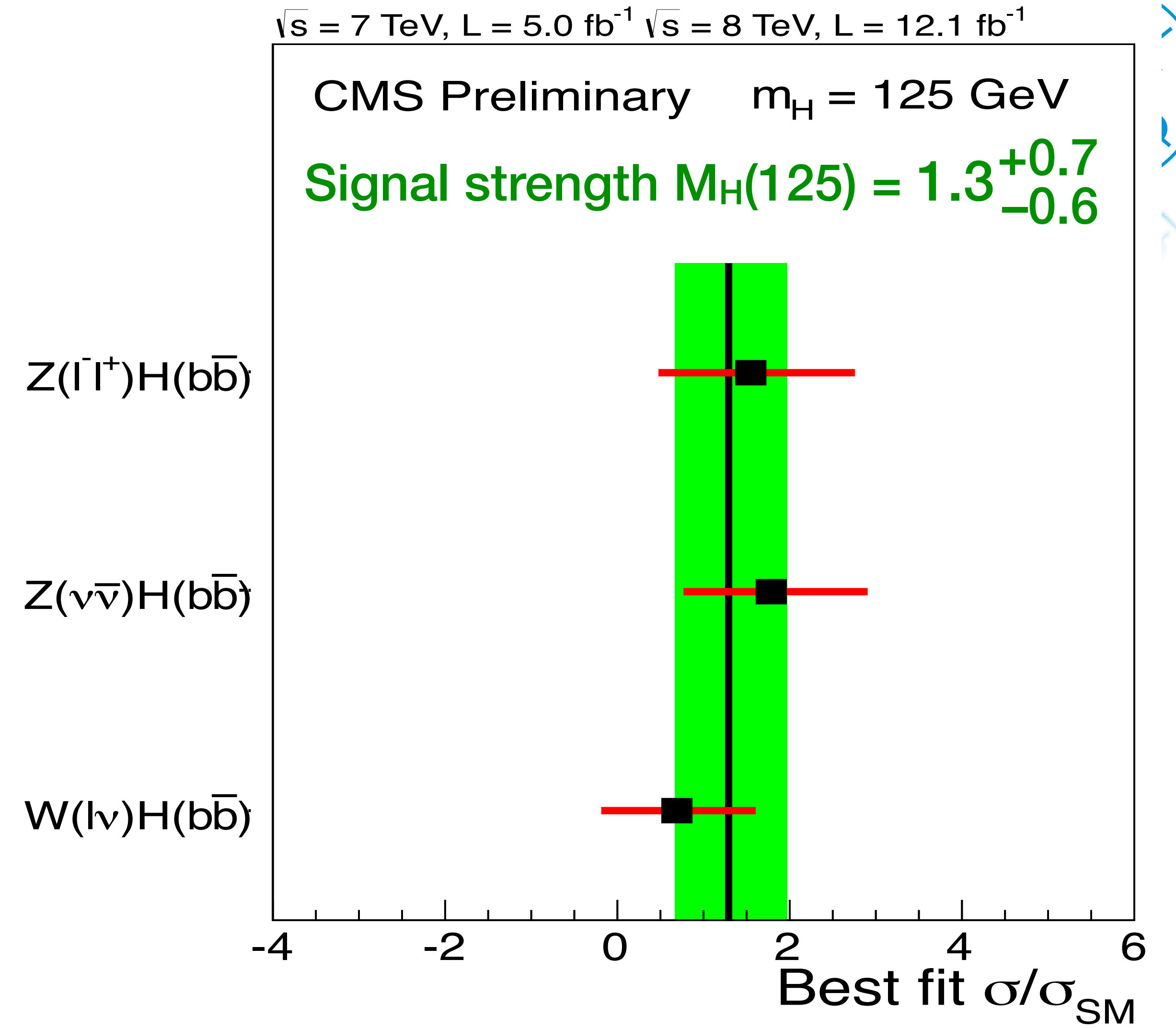


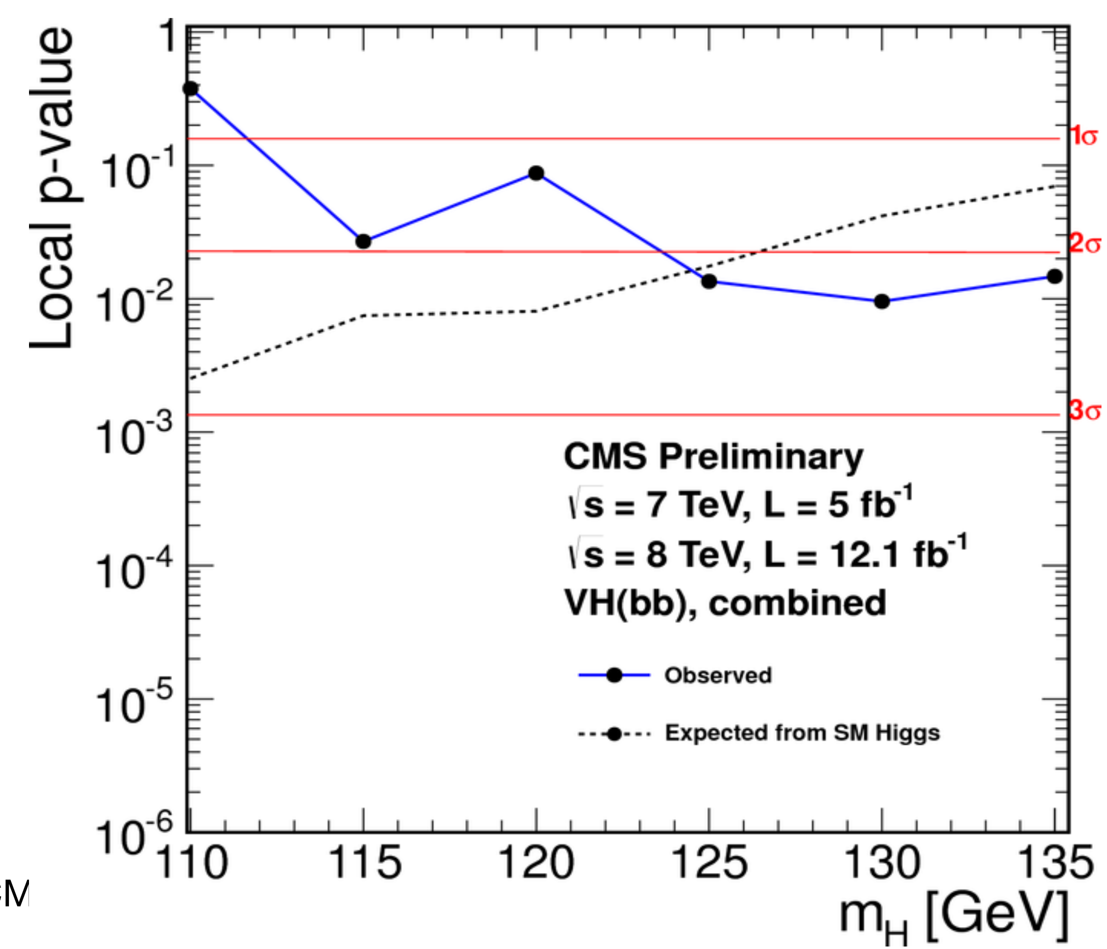




VH, H→bb : Results

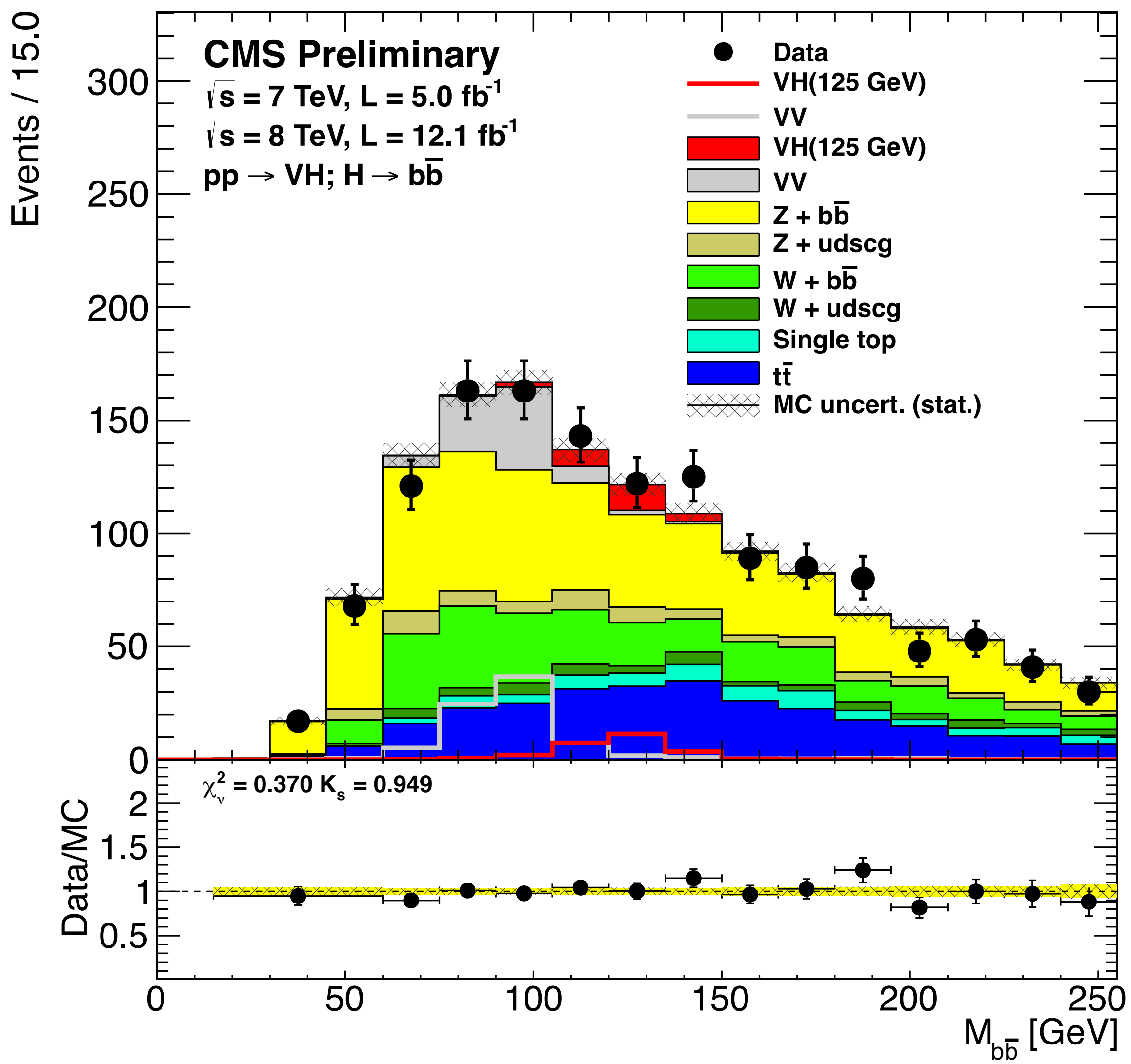


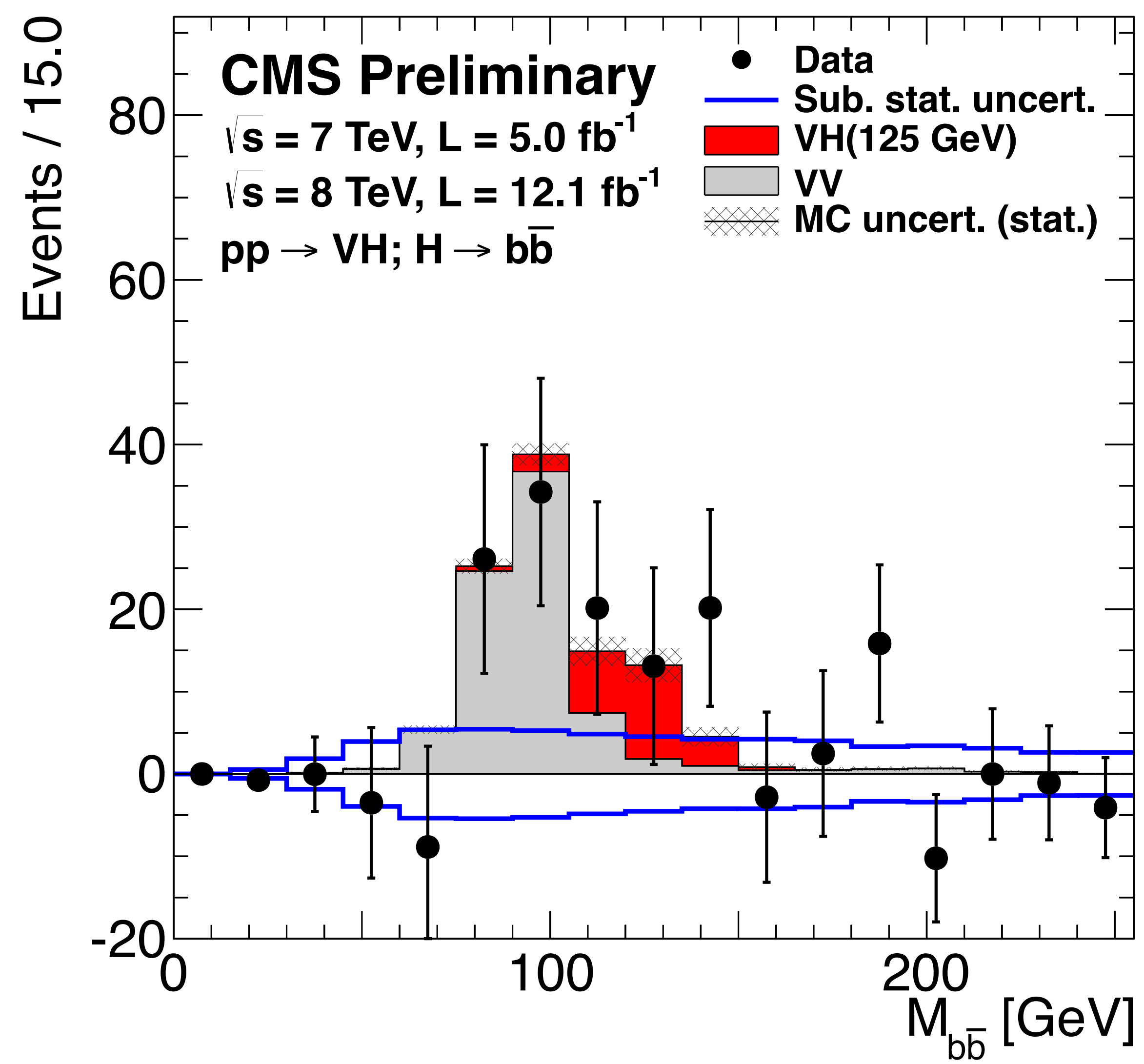




- Reached SM sensitivity < 120 GeV.
- Significance of the excess at m_H = 125 GeV
  - Observed = 2.2σ, Expected = 2.1σ
  - [Tevatron 2.8σ and 1.5σ, respectively]

VH, H→bb : M_{bb} distribution





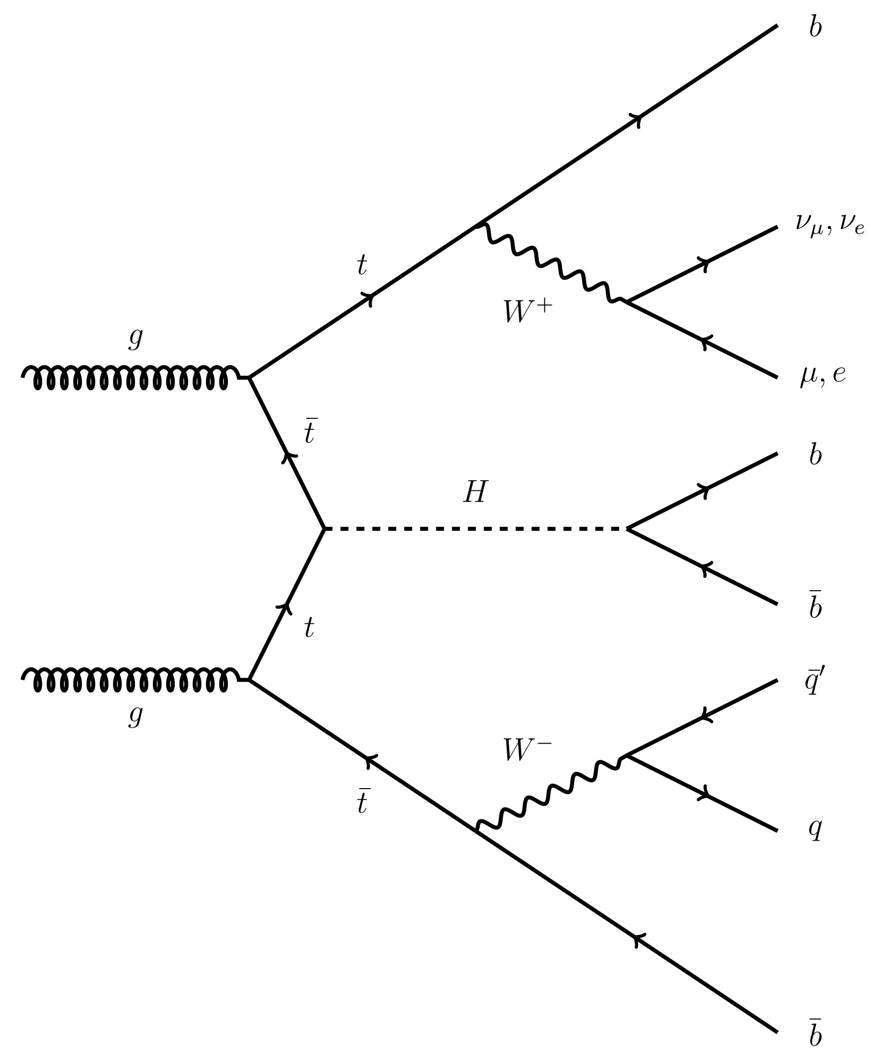
- Tighter cut-based selection for M_{bb}.
- Small excess in the signal region observed in the M_{bb} distribution
- Vector boson pair (VV) is showing up and is well described!

ttH, H→bb analysis

CMS PAS HIG-12-035
arXiv:1303.0763

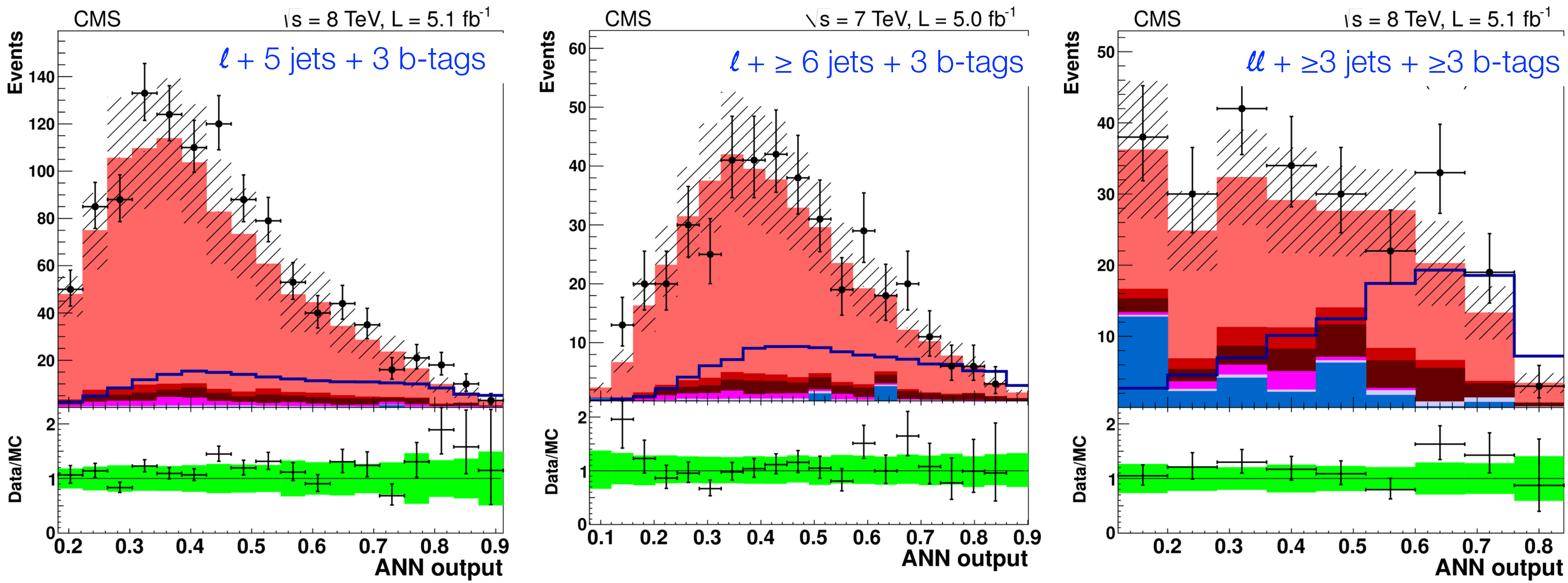
- Main opportunity to directly probe the ttH vertex.
  - Challenging!
- Categorisation
  - di-lepton (ℓℓ) and lepton+jet (ℓ+jets), ℓ = e,μ
  - number of jets (≥2) and b-tags (≥2)
- Data

7 TeV (2011)	8 TeV (2012)
5 fb^{-1}	5.1 fb^{-1}



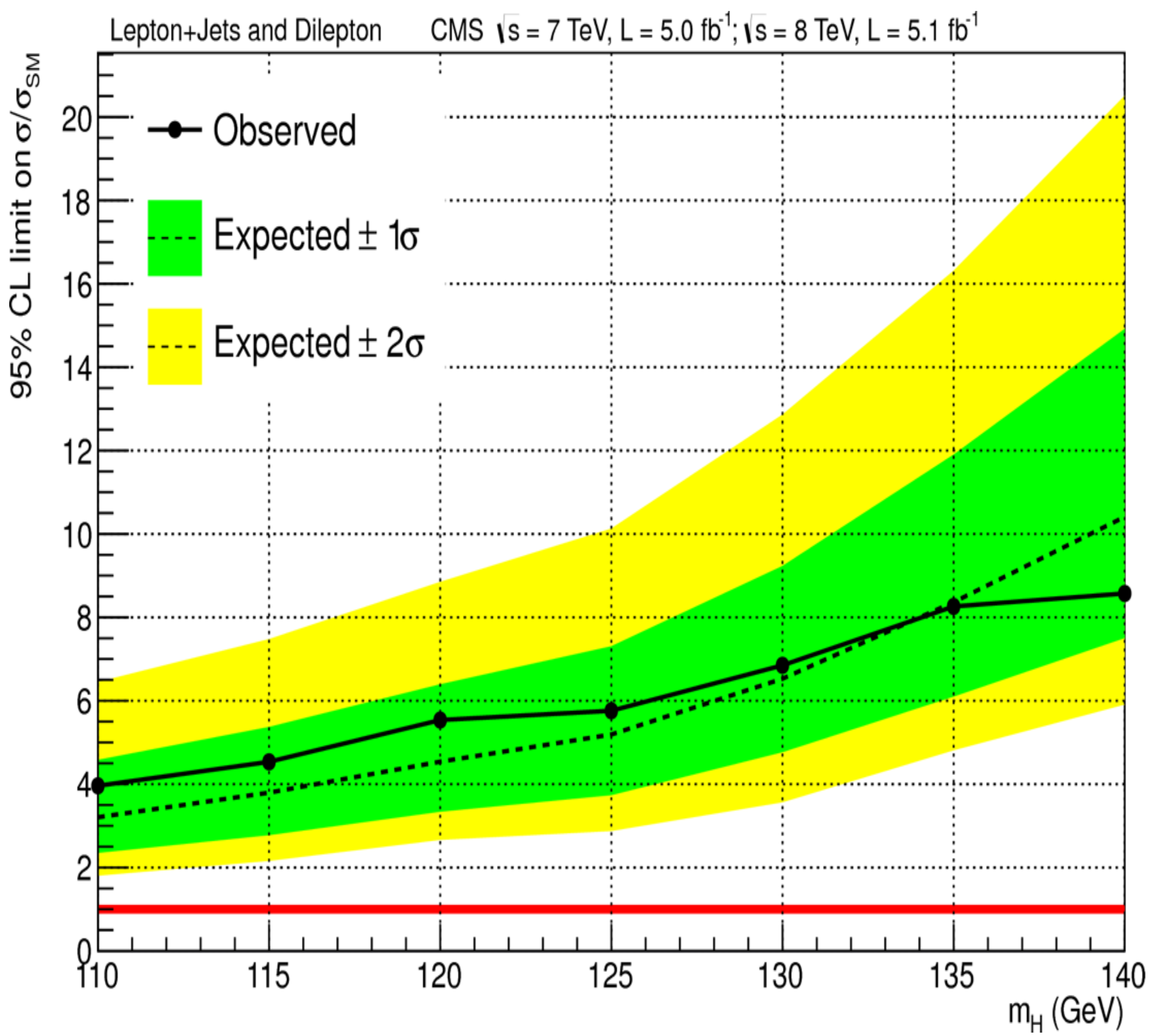
- Main backgrounds from tt+light jets/cc/bb.
- Signal extraction
  - Simultaneous fit of neural network (ANN) shape.
  - Main inputs to ANN: b-tag, kinematic and angular correlations.

ttH, H→bb : ANN analysis



- Good agreement between data and background.

ttH, H→bb : Results

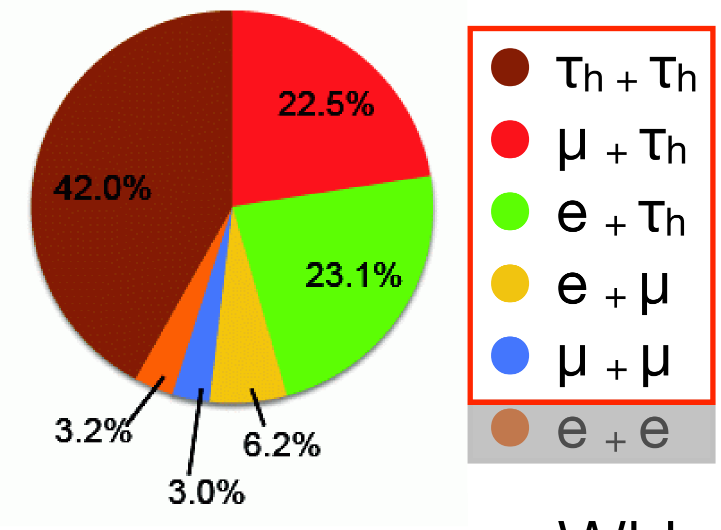


- Lepton+jet channel is the most sensitive, di-lepton improves by 5-10%.
- No evidence of an excess.
- 95% CL upper limits on cross section at mH(125):
  - Expected = 5.2 × σ_{SM}
  - Observed = 5.8 × σ_{SM}

SM $H \rightarrow \tau\tau$ searches

$H \to \tau\tau$: Analysis strategy

- Inclusive $H \to \tau\tau$ decay patterns
  CMS PAS HIG-13-004



→ *included in CMS analysis*

(τ_h : hadronic decay)

- Associated production with vector bosons, VH
  CMS PAS HIG-12-053
  - WH: $\ell\ell\tau_h$, $\tau_h\tau_h\ell$
  - ZH: $\ell\ell\tau\tau$

  $\ell = e,\mu$

- Data

7 TeV (2011)	8 TeV (2012)
5 fb^{-1}	19 fb^{-1}

- Selection (inclusive search)
  - Isolated and well-identified e, μ and τ_h
  - Topological cuts (MVA in μμ channel) to suppress backgrounds
  - Categorisation based on number of jets and $p_T(\tau)$
  - Template fit to $m_{\tau\tau}$ shape ($m_{\tau\tau} \times m_{\mu\mu}$ in the μμ channel)

$H \to \tau\tau$: Event categories

- Event classification according to the number of jets and the p_T of …
  - the visible τ_h ($\mu\tau_h$, $e\tau_h$) or
  - the hardest lepton ($\mu\mu$, $e\mu$)

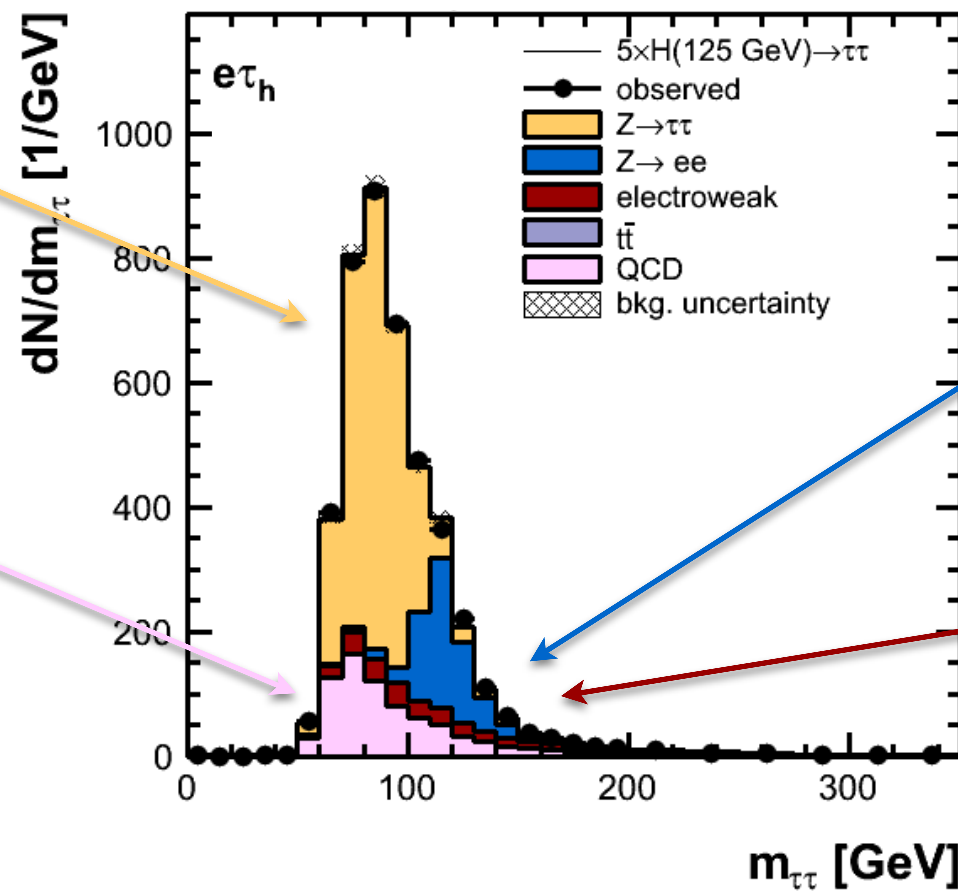
	0 jets	1 jet	2 jets (VBF)
$e\mu$ $\mu\mu$ $\mu\tau_h$ $e\tau_h$	Low p_T • background calibration • no signal extracted	Low p_T • Large statistics	$e\mu$, $\mu\tau_h$, $e\tau_h$: minimum m_{jj} and $\|\Delta\eta_{jj}\|$ requirements, central jet veto $\mu\mu$: MVA selection
	High p_T • background calibration • no signal extracted	High p_T • Better $m_{\tau\tau}$ resolution • Suppressed $Z\to\tau\tau$ background	
$\tau_h\tau_h$	×	Minimum Higgs candidate p_T	Minimum m_{jj} and $\|\Delta\eta_{jj}\|$ requirements. Minimum Higgs candidate p_T

H→ττ : Background estimation

Z→ττ: Embedding, replace μ in Z→μμ events by simulated τ decays; normalised by Z→μμ events.

QCD: Normalisation and shape from SS/OS

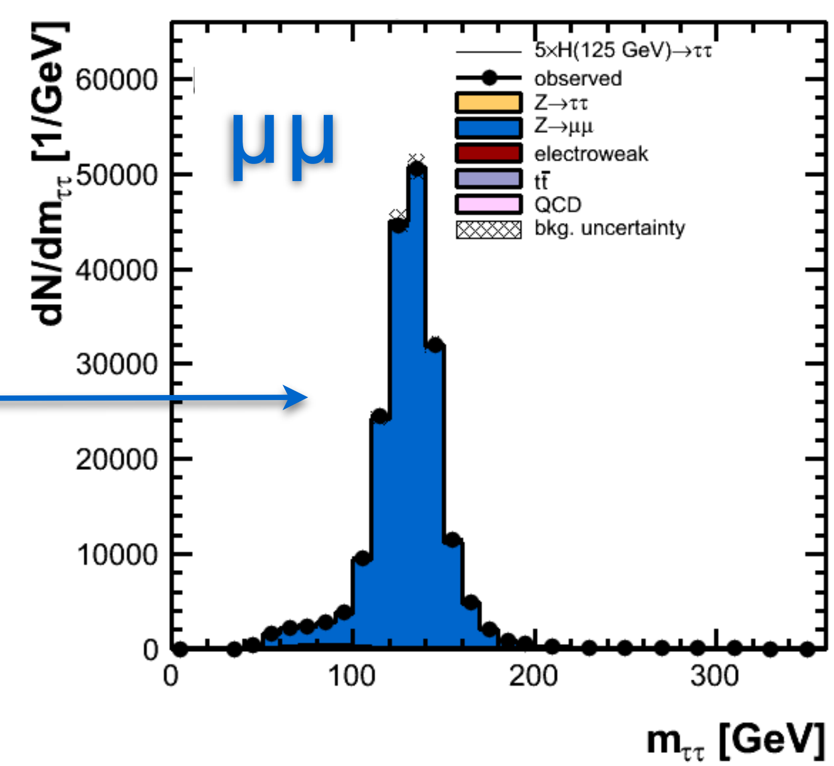
ttbar: shape from simulation; normalisation from sideband

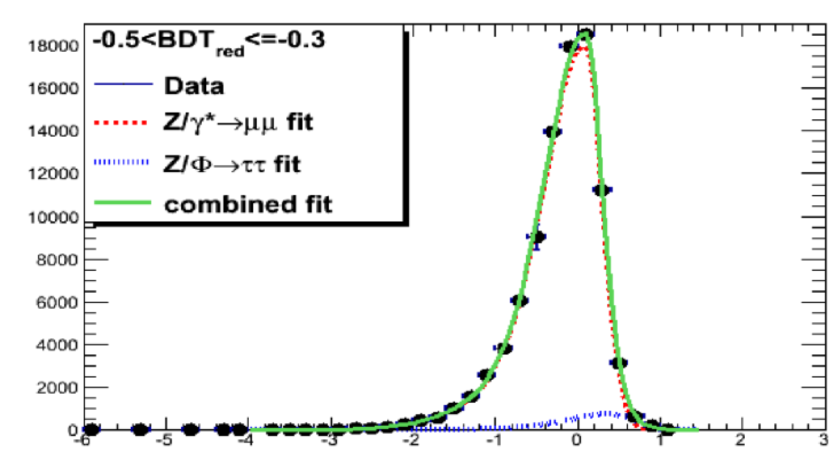


Z→ee/μμ: from simulation, corrected for jet→τ, e/μ→τ fake rate

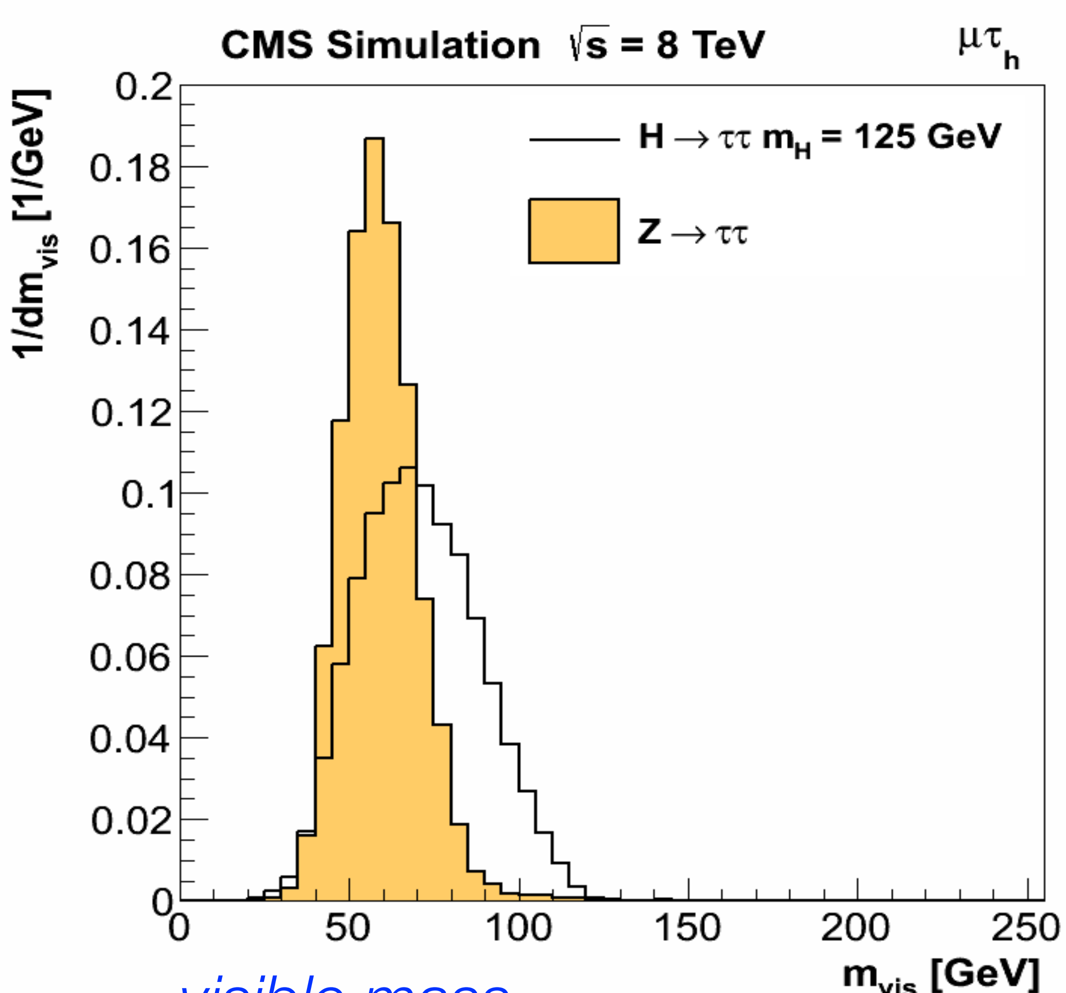
Di-boson/W+jets: shape from simulation; normalisation from sideband

Z→μμ for the μμ channel: shape from MC; normalisation from template fits to DCA significance

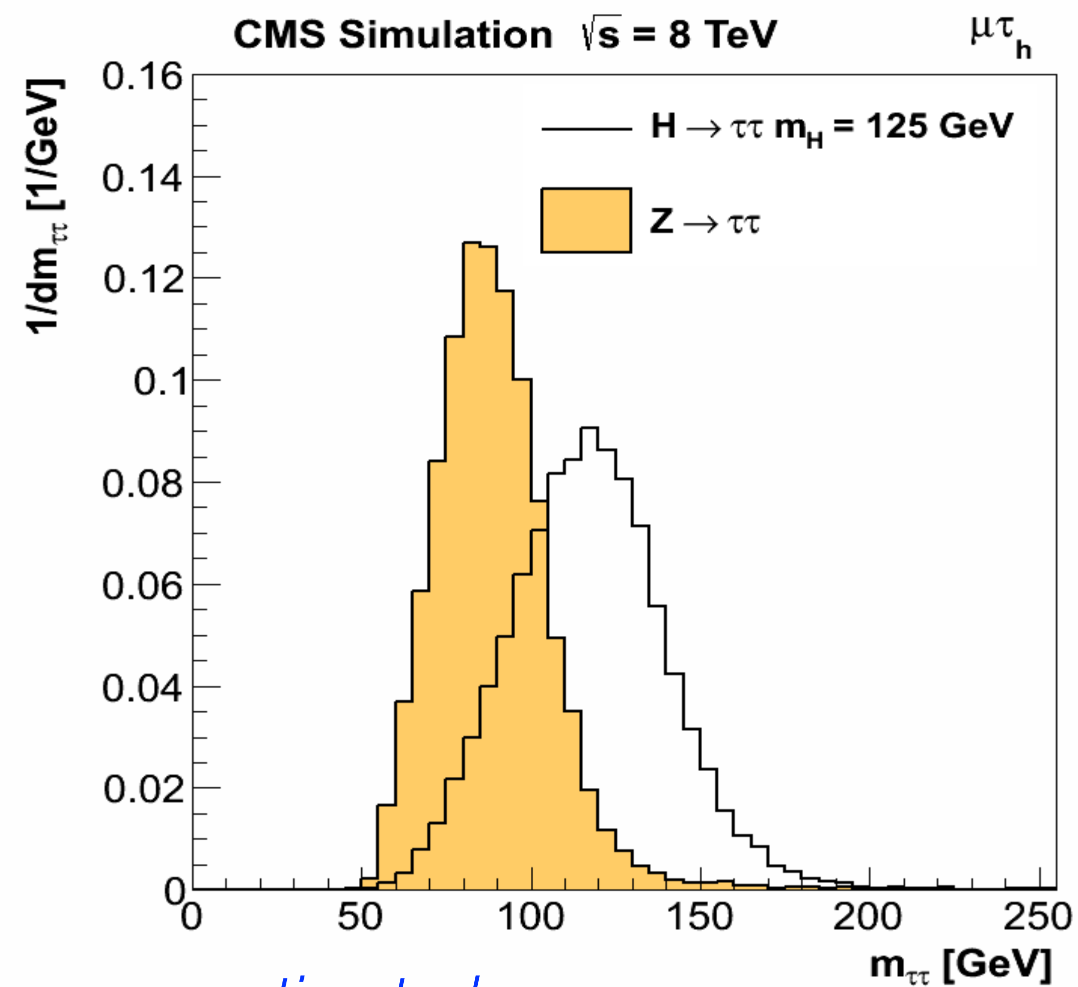




H → ττ : Reconstruction of τ-pair mass

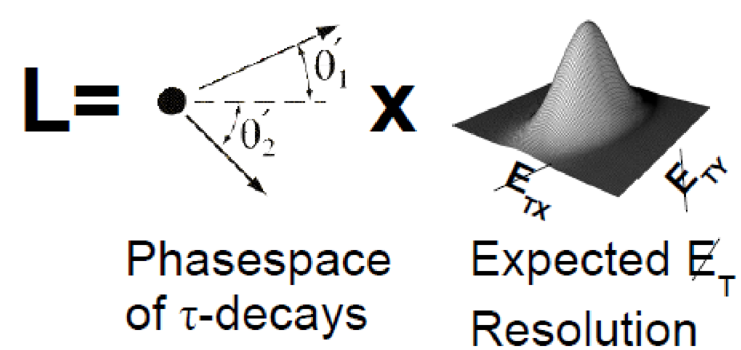


visible mass



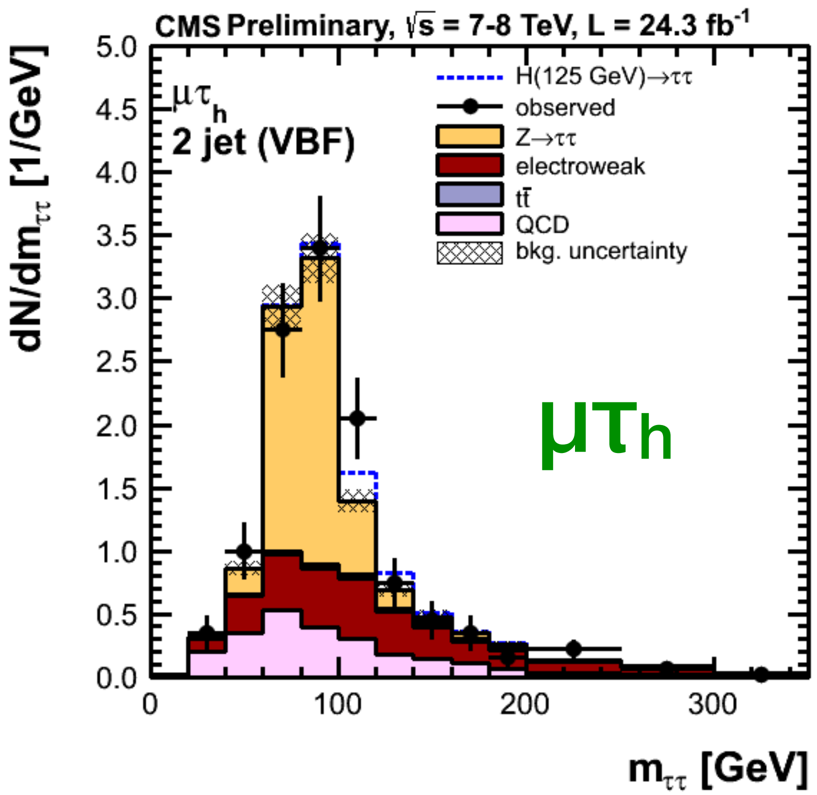
estimated mass

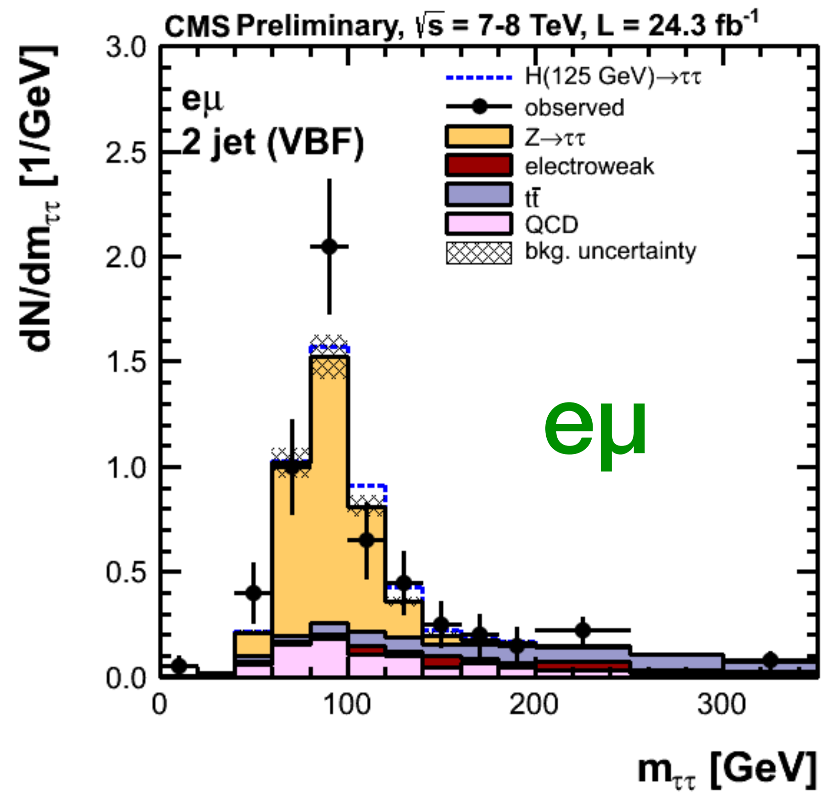
- Invariant mass of ττ determined using a maximum likelihood fit.
- Estimated on event-by-event basis using four-momenta of visible decay products, E_x^{miss}, E_y^{miss}, expected E_T^{miss} resolution

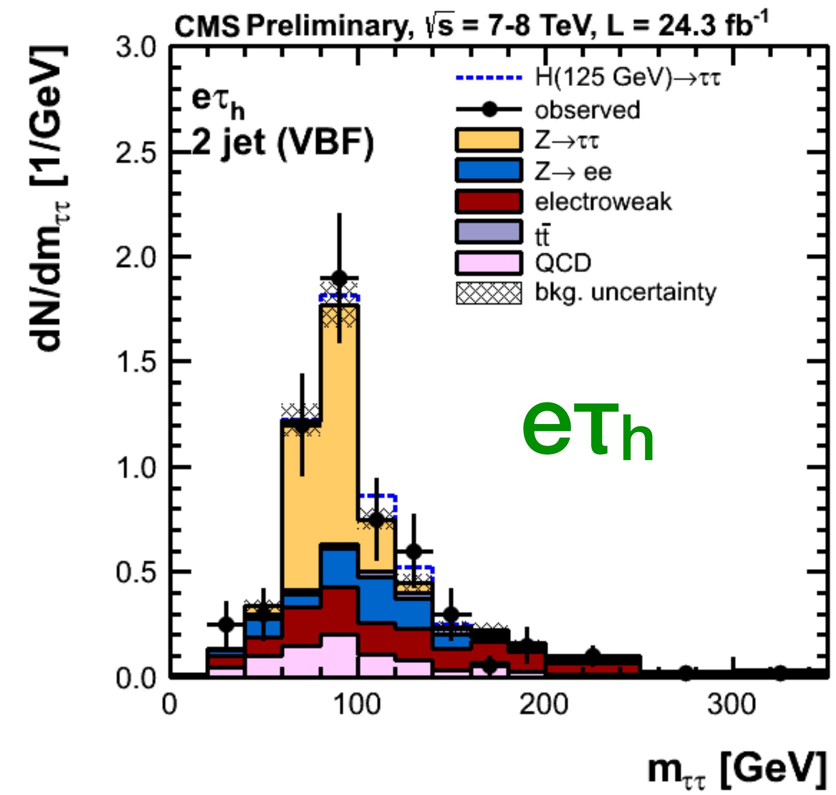


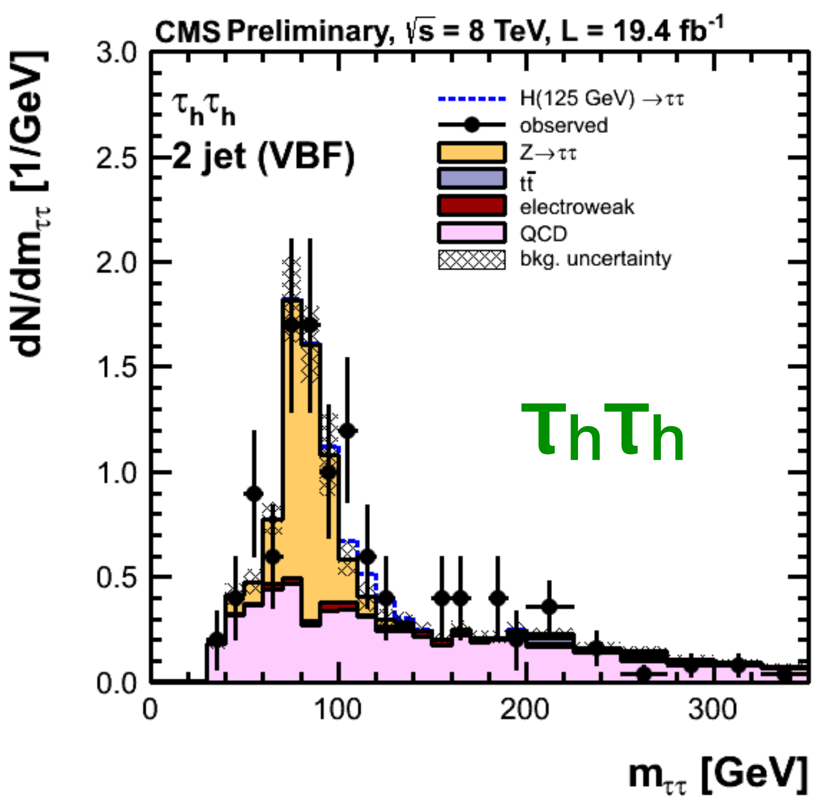
$H \rightarrow \tau\tau$: $m_{\tau\tau}$ distributions

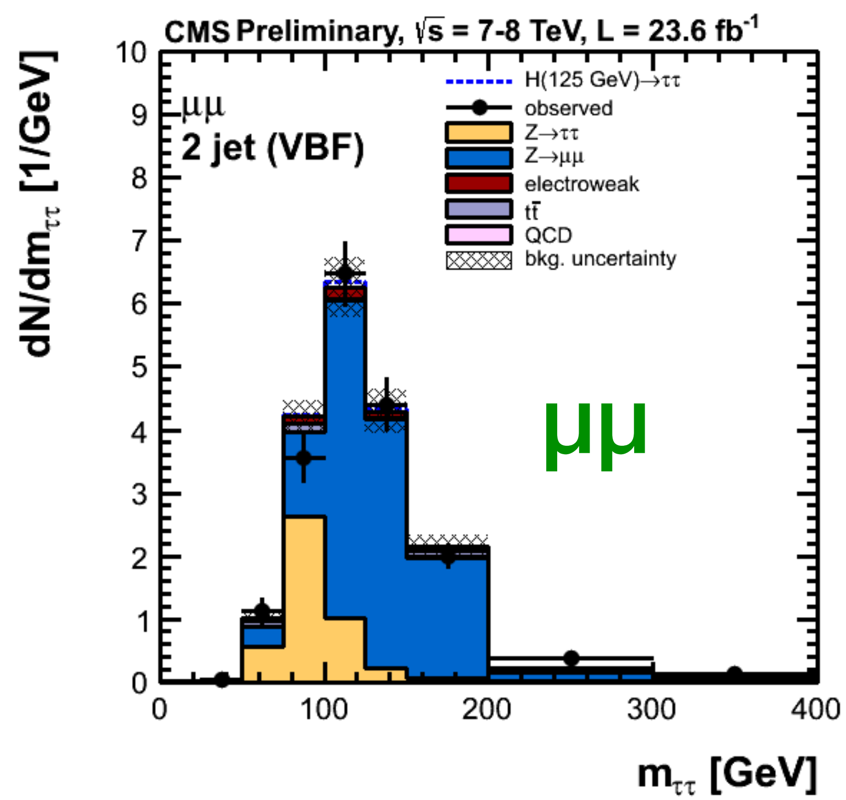
2-Jet (VBF) category





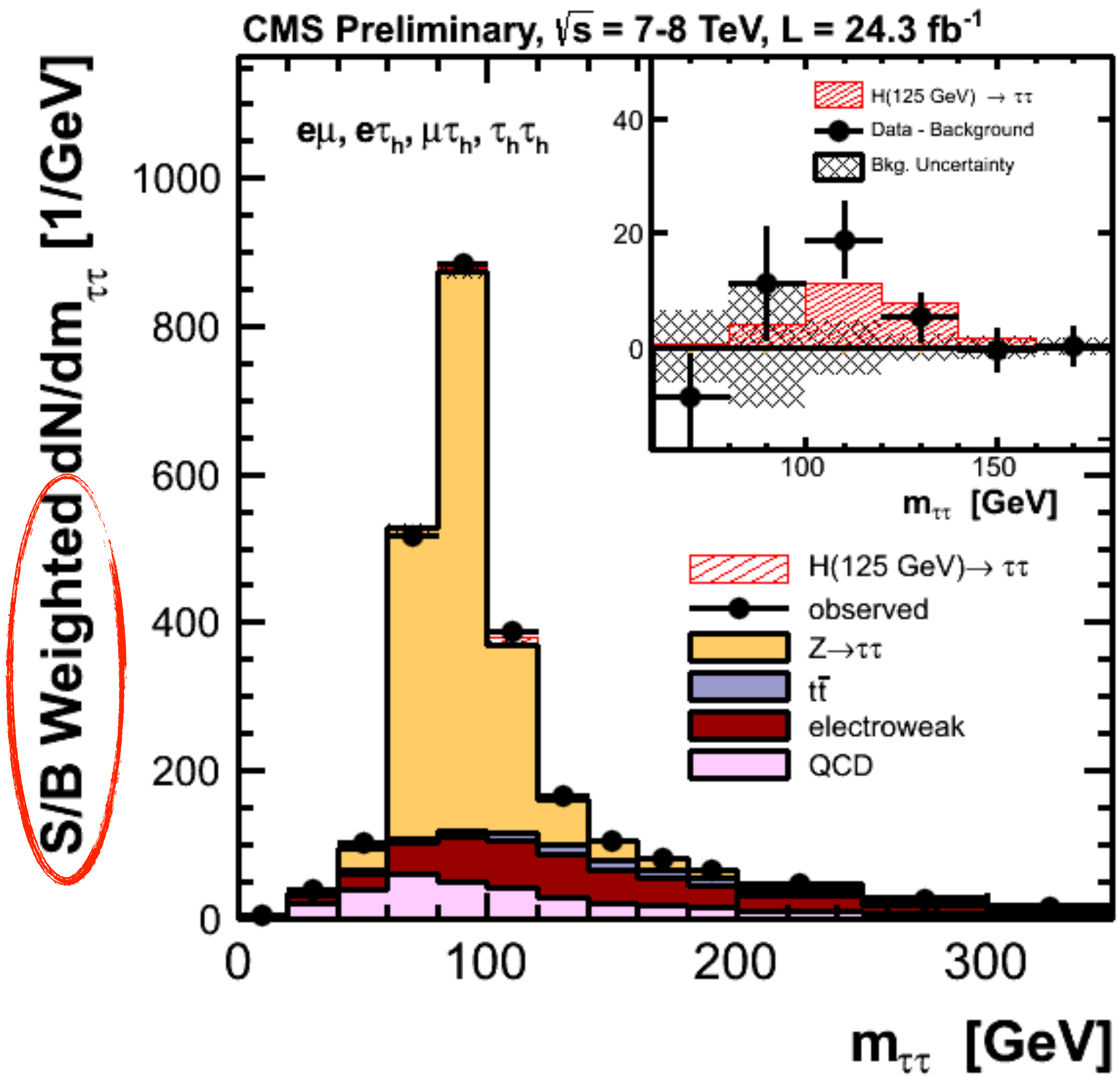






- In the μμ final state, results from statistical inference on the 2D distribution of the $m_{\tau\tau}$ and m_{vis}.

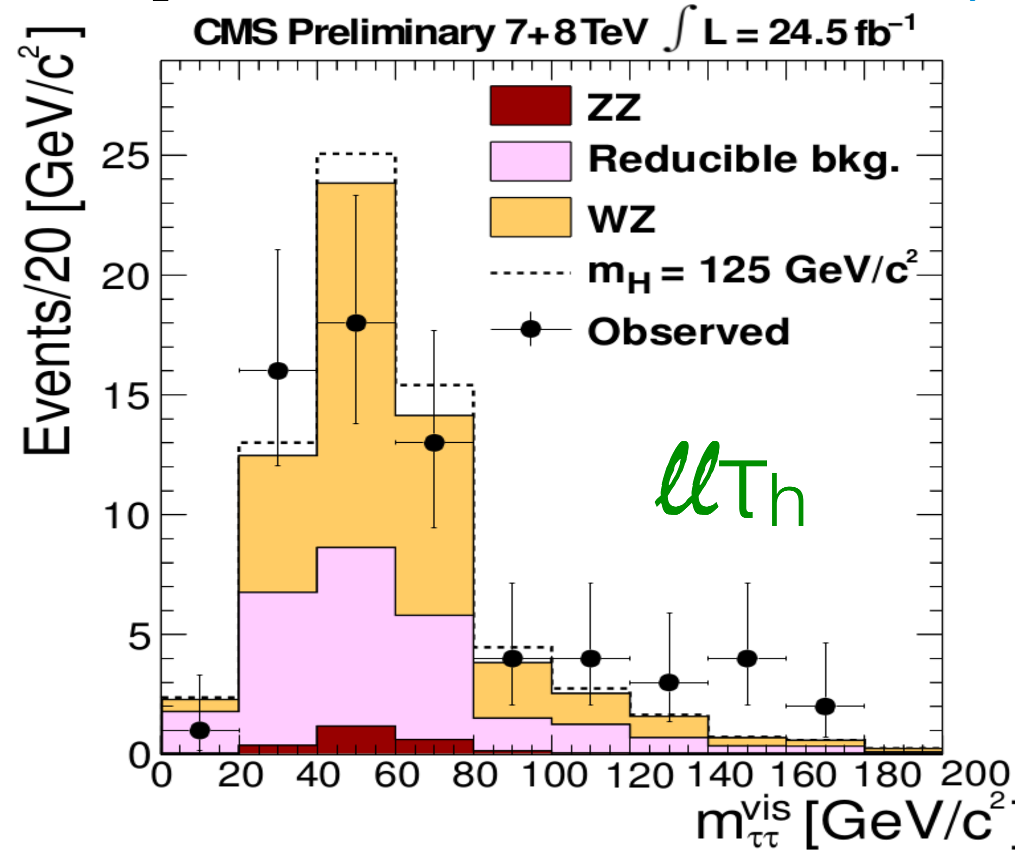
H → ττ : combined $m_{\tau\tau}$ distribution

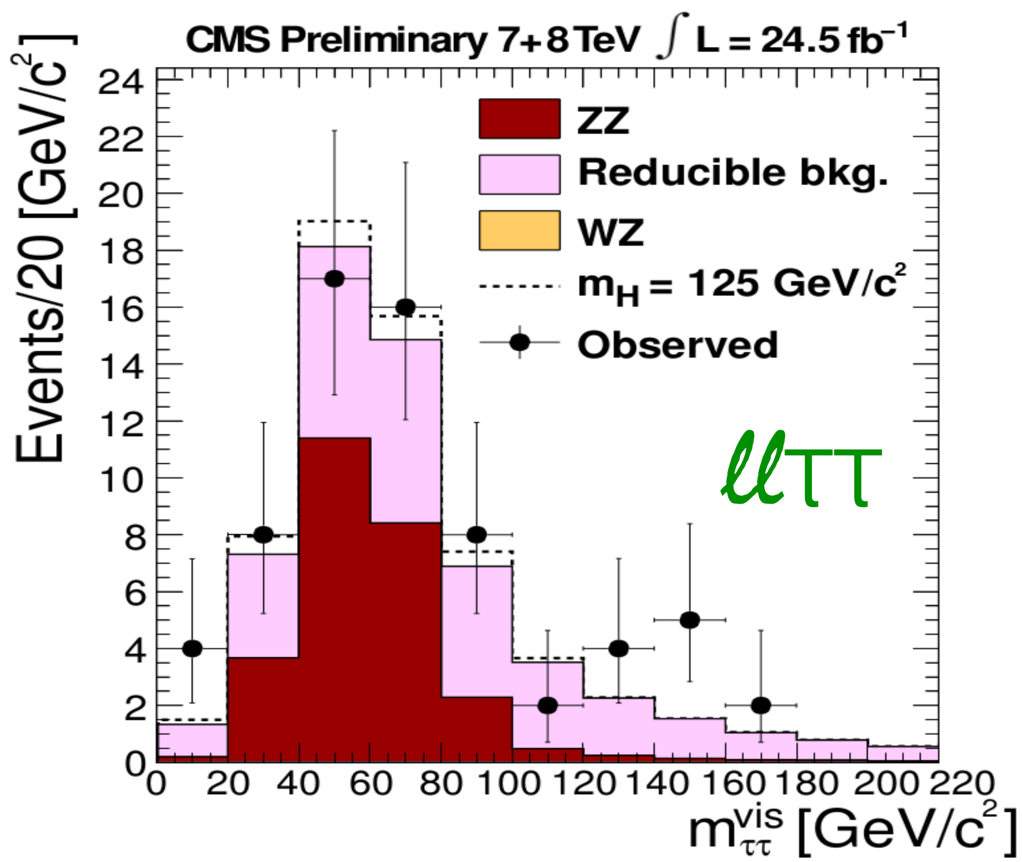


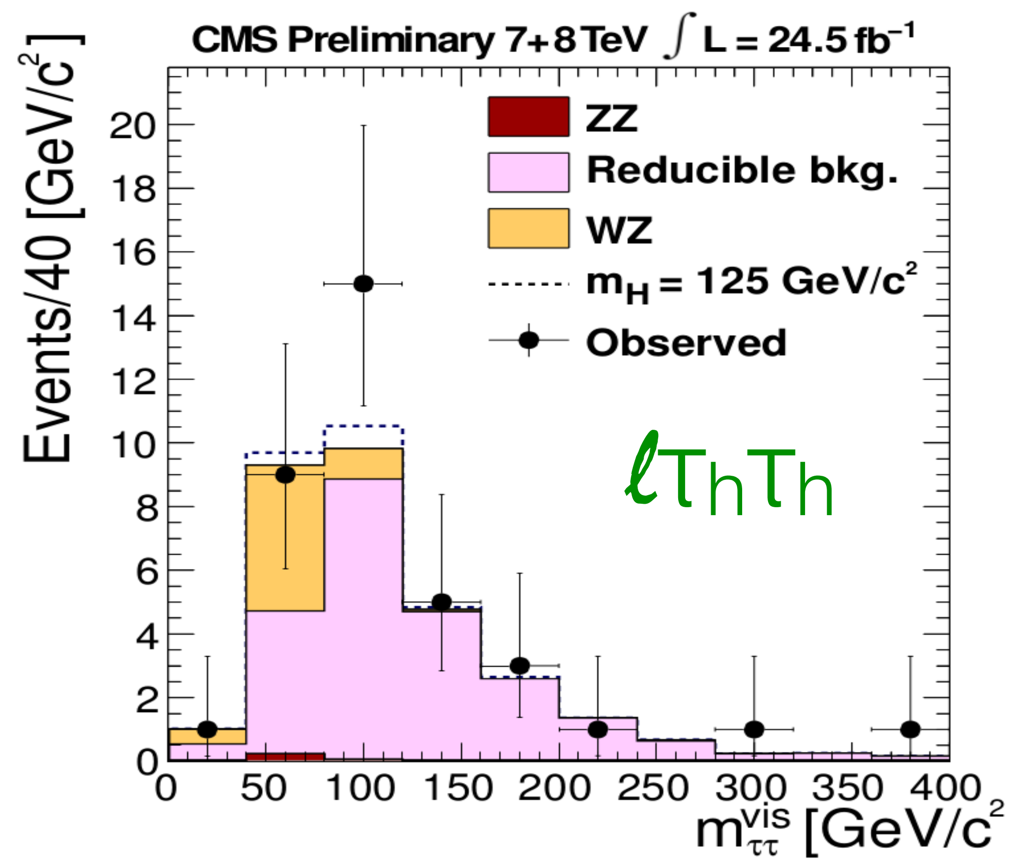
- Signal-like excess seen!
- Compatible with H(125)!
- Inset: background subtracted.

H → ττ : VH analysis

- Small background compared to inclusive H→ττ.
- Channels: $\ell\ell\tau_h$, $\tau_h\tau_h\ell$, $\ell\ell\tau\tau$ (l=e,μ; τ→e,μ,τ_h)
- Signal extracted from mass of visible decay products.

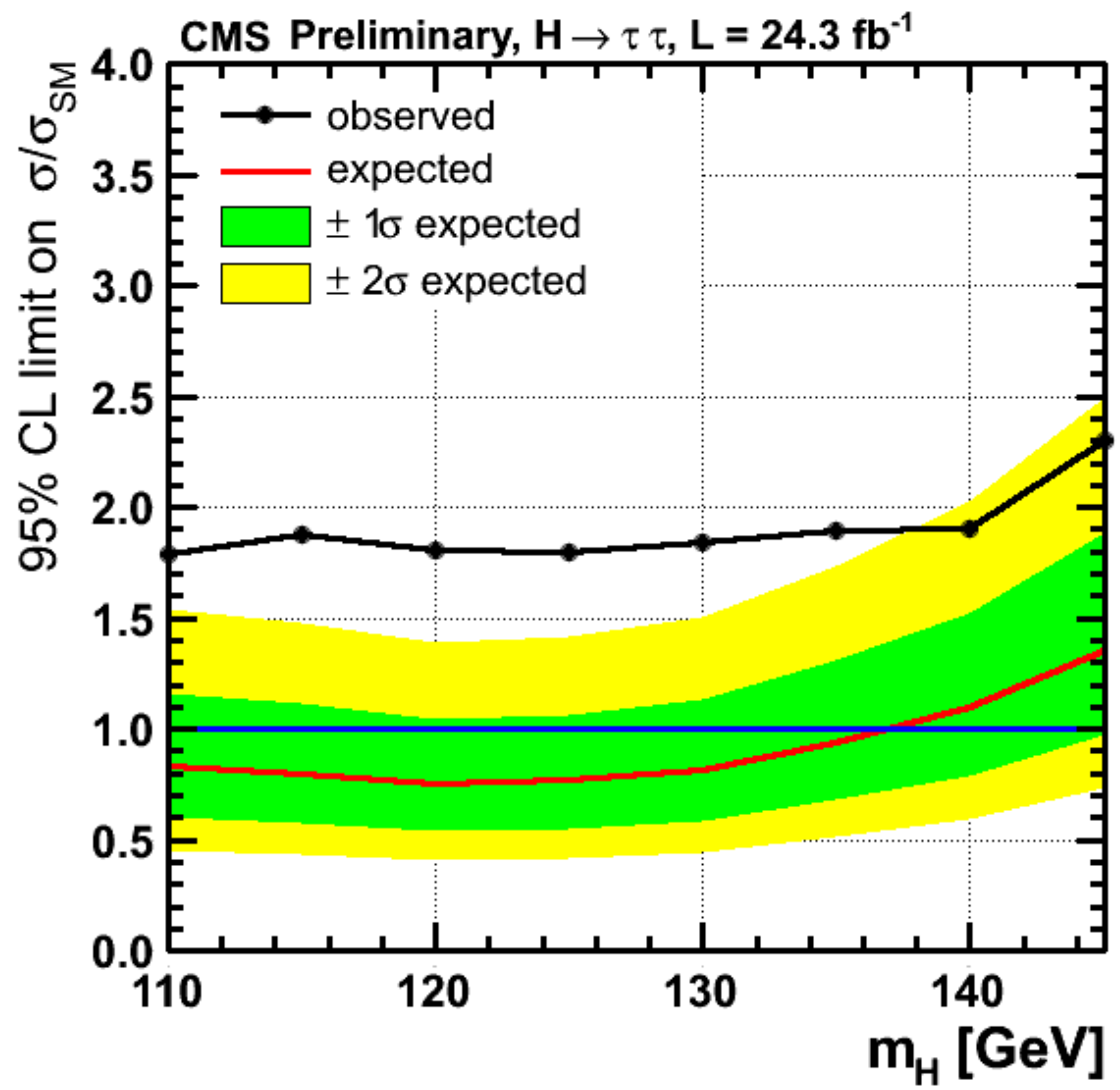


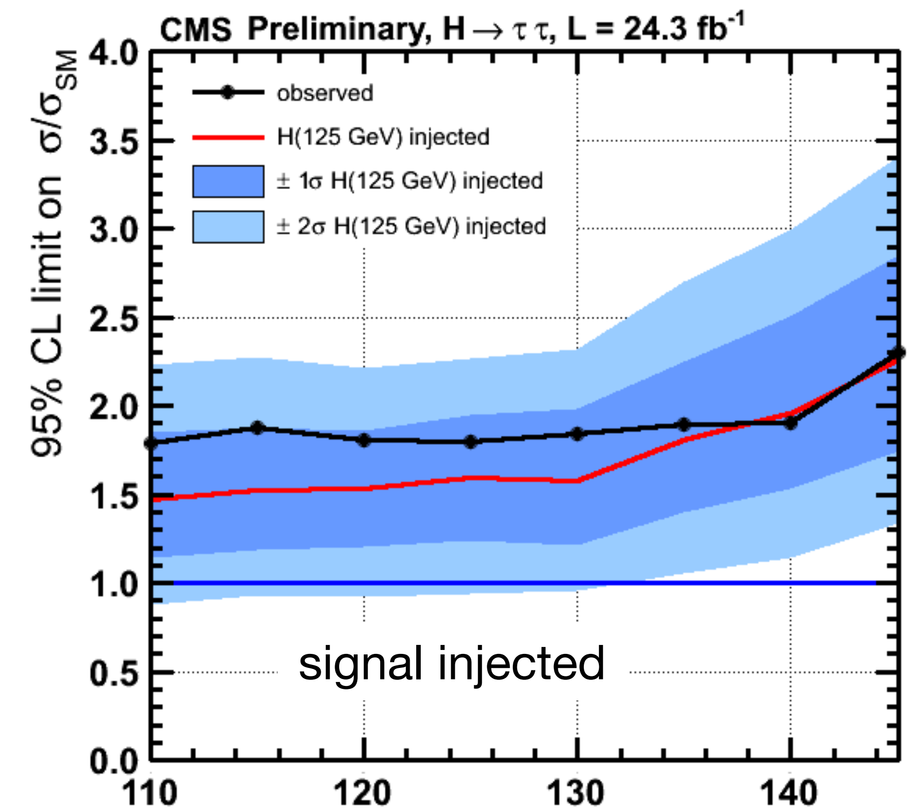


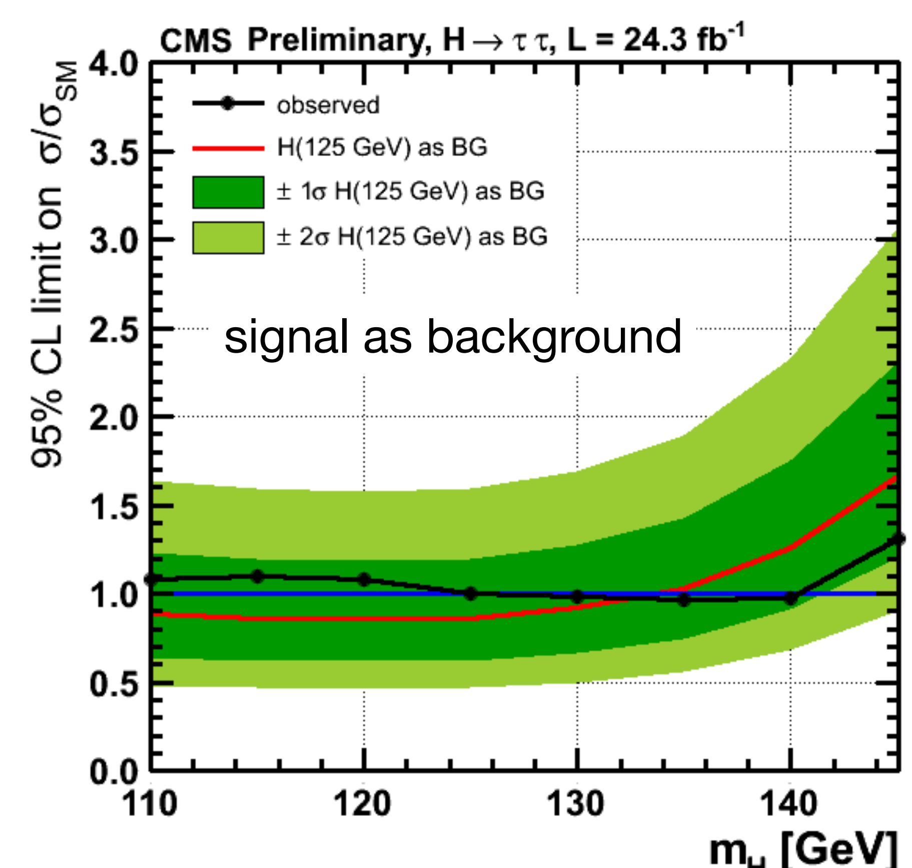


H→ττ : 95% CL upper limits on σ/σ$_{SM}$

Include VH, H→ττ

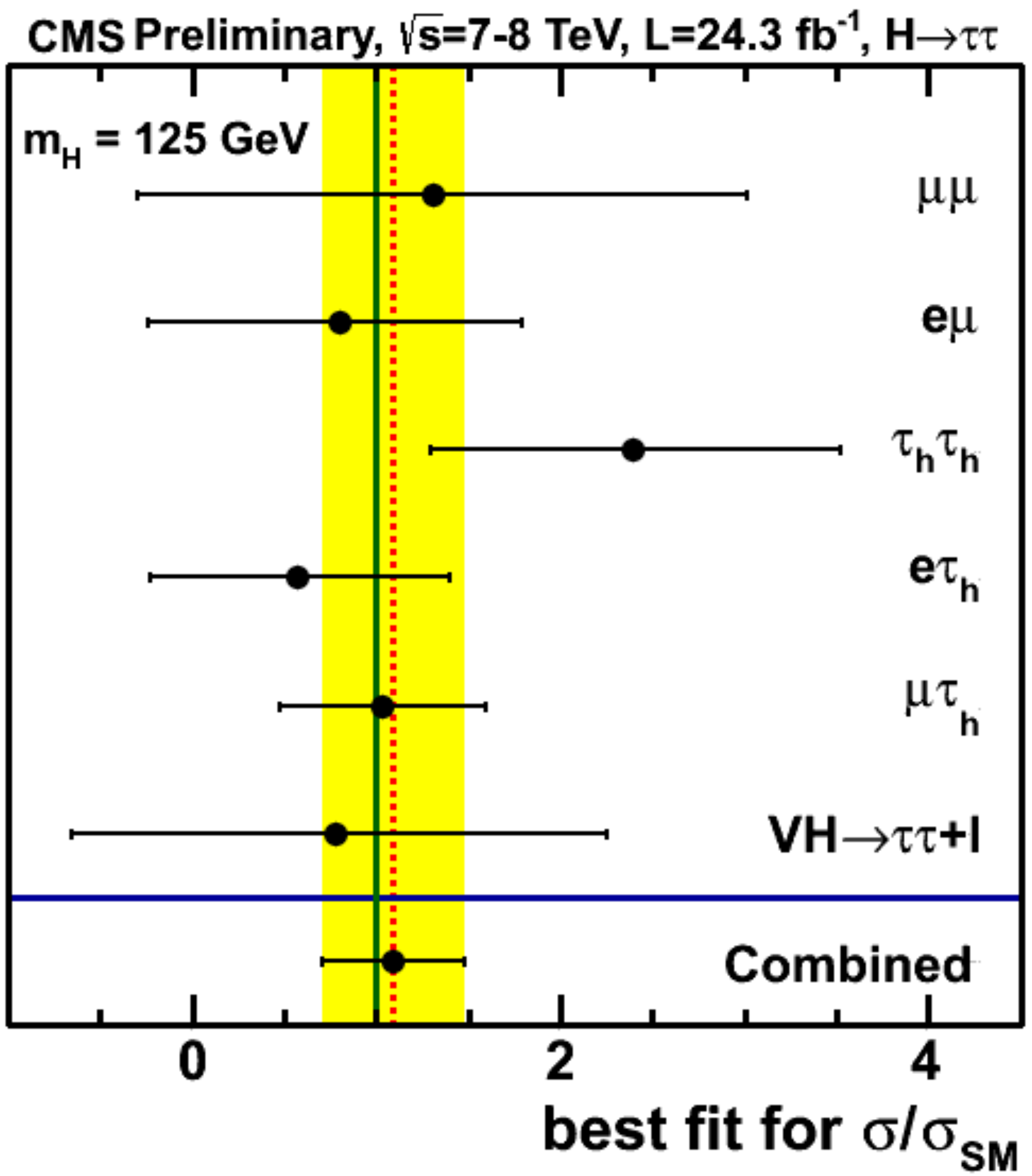


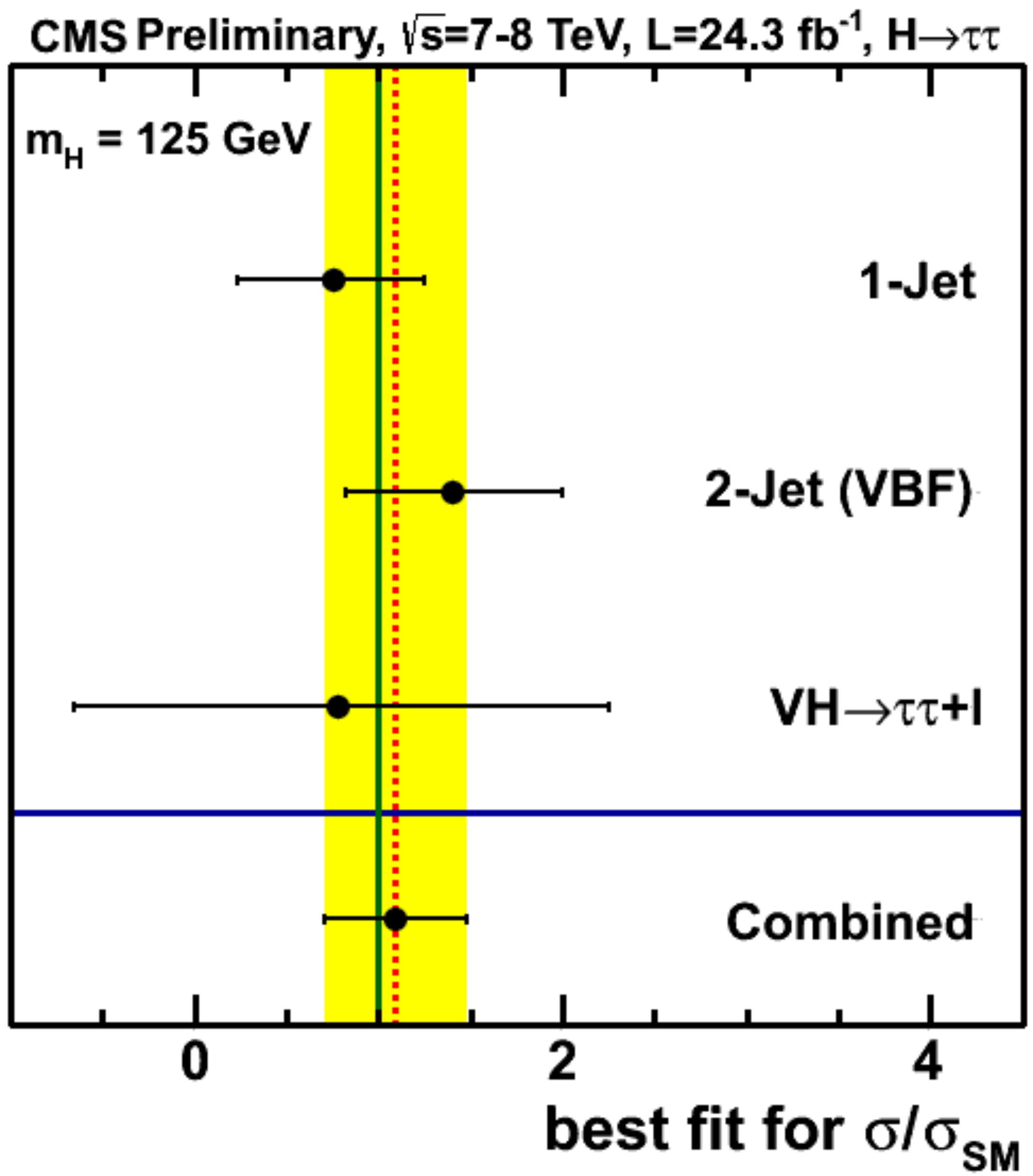




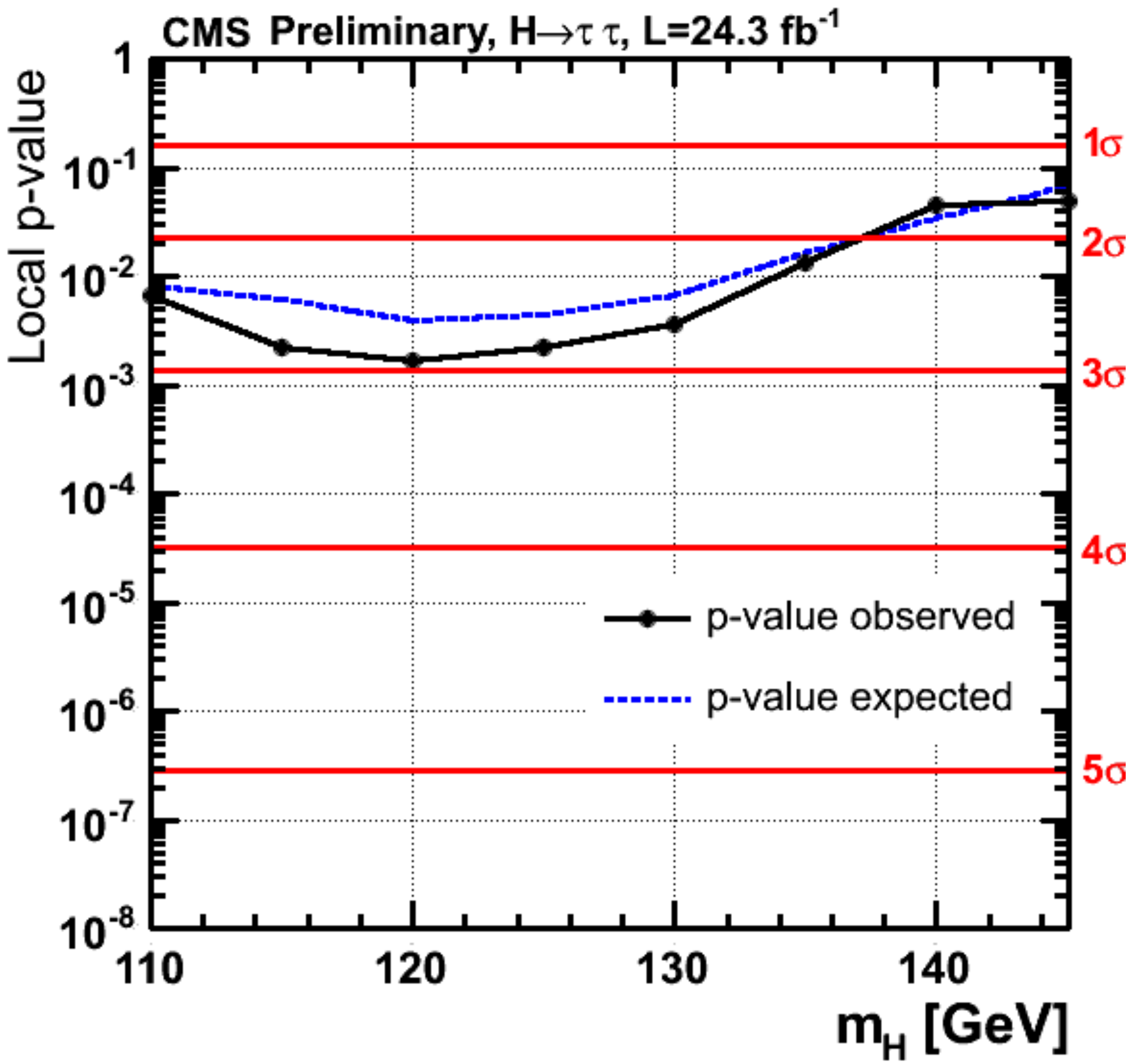
- Broad excess observed compatible with SM Higgs with m_H = 125 GeV.
- 95% CL upper limits on cross section at m_H(125)
    - Expected = 0.77 × σ$_{SM}$
    - Observed = 1.80 × σ$_{SM}$

$H \rightarrow \tau\tau$: Signal strength





- All channels combined: $\hat{\mu} = 1.1 \pm 0.4$ at m_H = 125 GeV.
- Compatible with the SM expectations.
- Consistent across channels and categories.



- Expected (observed) significance at m_H = 125 GeV: 2.62 σ (2.85 σ)
- Minimum p-value (2.93 σ) at m_H=120 GeV

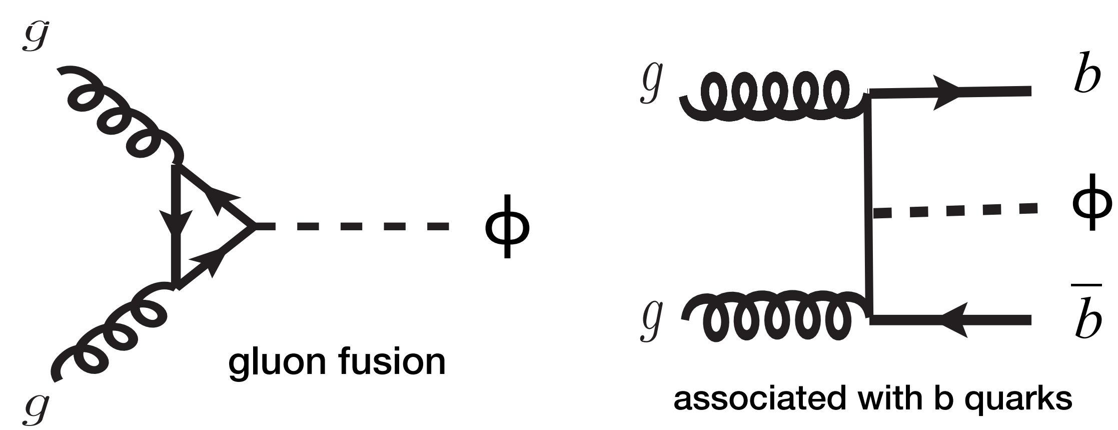
Evidence of direct coupling of Higgs to taus!

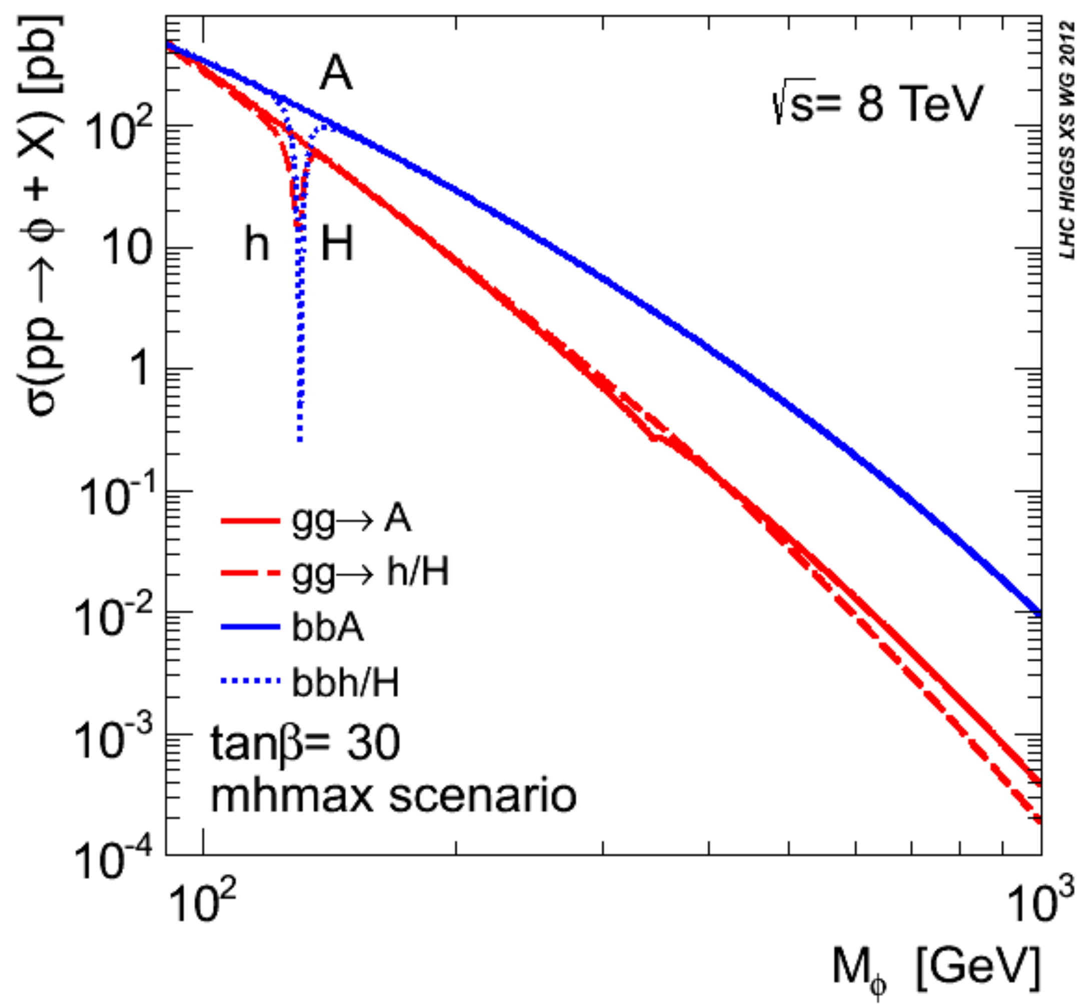
Higgs searches in the context of the Minimal Supersymmetric Model

MSSM Higgs bosons

- The MSSM features two Higgs doublets.
- Symmetry spontaneously broken twice
- Higgs sector: Five Higgs particles
  - Three neutral: ϕ = h, H, A
  - Two charged: $H^{\pm}$
  - Observed 126 GeV state often identified as the lightest Higgs (h)
- At tree level, two independent parameters:
  - m_A
  - tan β (ratio of v.e.v. of the two Higgs doublets)
- The mass of the CP-odd Higgs boson A is usually ~degenerate with one of the CP-even bosons

Neutral Higgs bosons production





MSSM Higgs searches in CMS

Mode	Production	Channels	Luminosity 7 TeV	Luminosity 8 TeV	Documents
$\phi \to bb$	$bb\phi$	2	$4.8\ fb^{-1}$	–	CMS PAS HIG-12-033
$\phi \to \tau\tau$	$gg \to \phi$	4	$4.9\ fb^{-1}$	$12.1\ fb^{-1}$	CMS PAS HIG-12-050
	$bb\phi$	4			
* $\phi \to \mu\mu$	$gg \to \phi$	1	$4.9\ fb^{-1}$	–	CMS PAS HIG-12-011
	$bb\phi$	2			
* $H^{\pm} \to \tau^{\pm}\nu$	$t \to H^{+}b$	1	$4.9\ fb^{-1}$	–	CMS PAS HIG-12-052

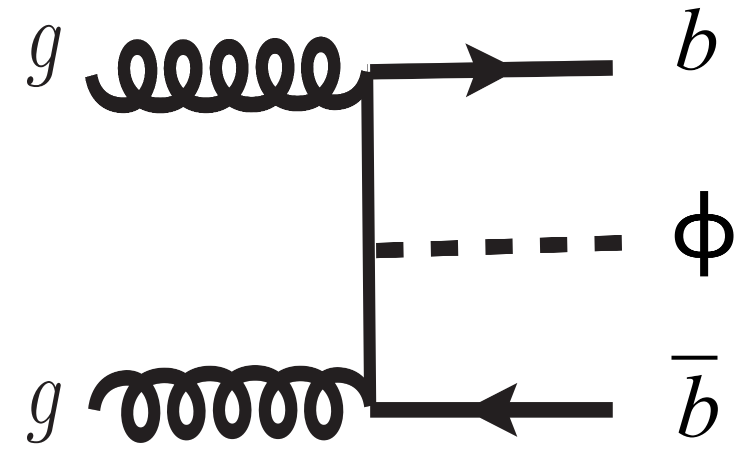
* Not discussed in this presentation

MSSM $\phi \rightarrow bb$ searches

MSSM φ → bb searches

Yes, we can!

- MSSM neutral Higgs boson decaying to b quakrs and produced in association with b quark(s)
  - Enhancement wrt SM for tan β > 1
  - Large BR(φ→bb) even at large masses
- Only b-jets (and radiation) in the final state:
  - Challenging triggers at the LHC



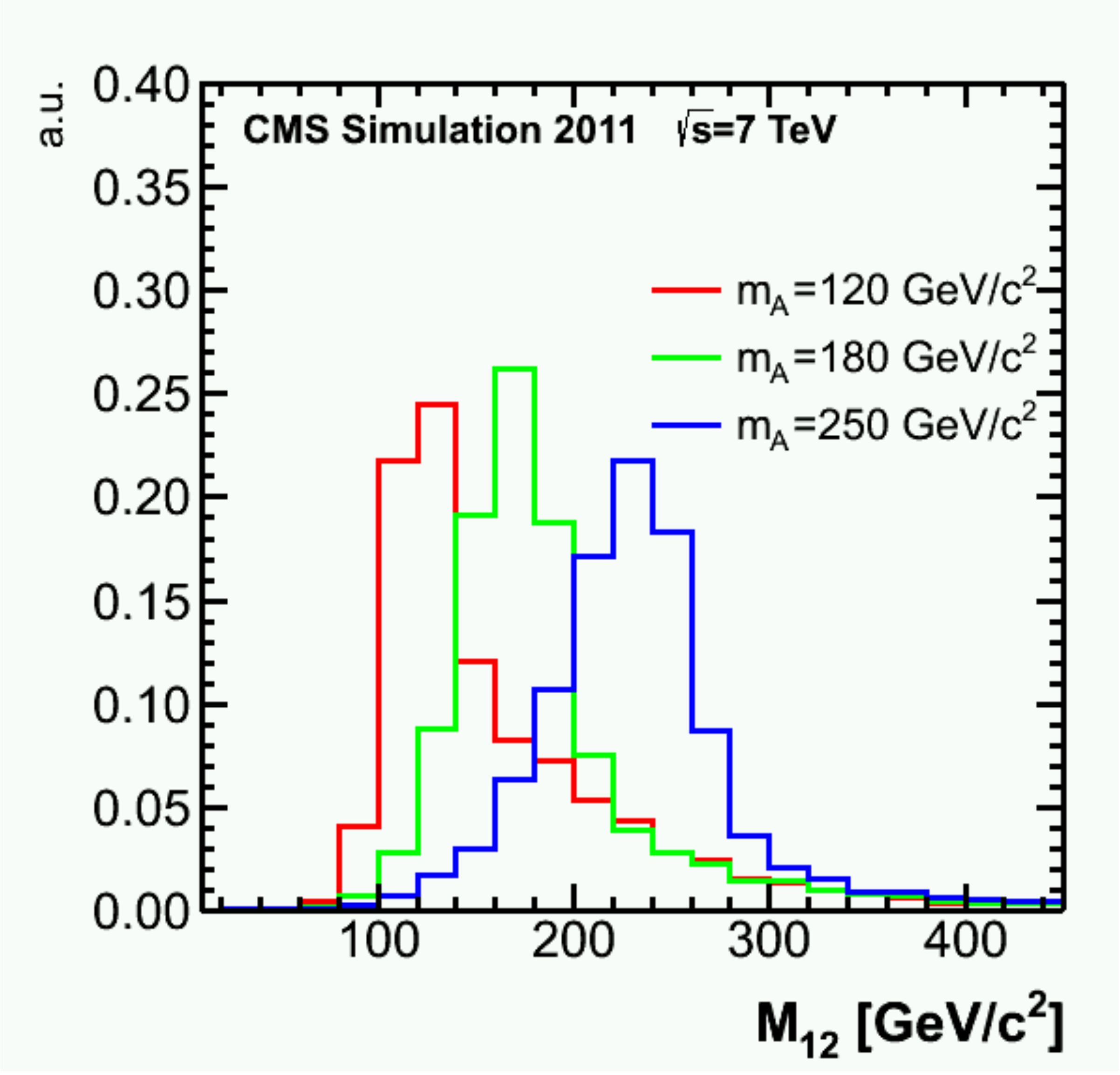
associated with b quarks

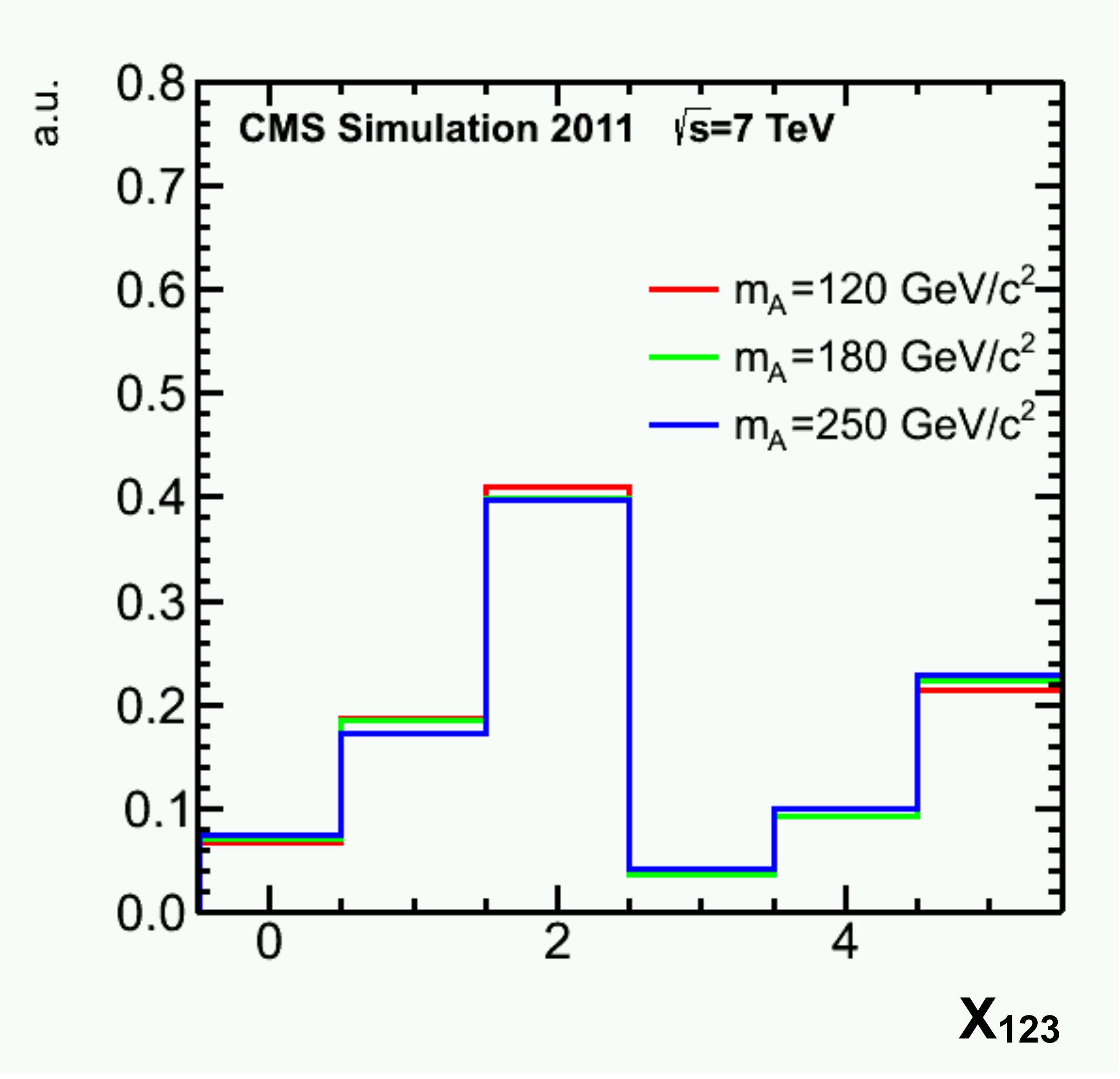
- Two complementary approaches:
  - "All-hadronic" trigger: requiring up to 3 jets; ≥ 2 b-tags (3 offline b-tags)
  - "Semileptonic" trigger: requiring 2 jets; ≥ 1 or 2 b-tags (3 offline b-tags); ≥ 1 muon from B-hadron decay
  - Almost independent samples (2–3% overlap)
- Data: 2.7 fb^{-1} – 4.8 fb^{-1} at 7 TeV (2011)
- Background: heavy flavour multi-jet, derived from the data.
- Signal would appear as a peak in the di-jet mass distribution in triple-btag sample.

MSSM $\phi \to bb$: Signal templates

(all-hadronic)

- Pythia in the 4-flavour scheme.
- Invariant mass M_{12} of the two leading jets.
- Variable X_{123} computed from the secondary vertex mass of the three leading jets, reflects the b-tag content of the event → further signal / background separation.

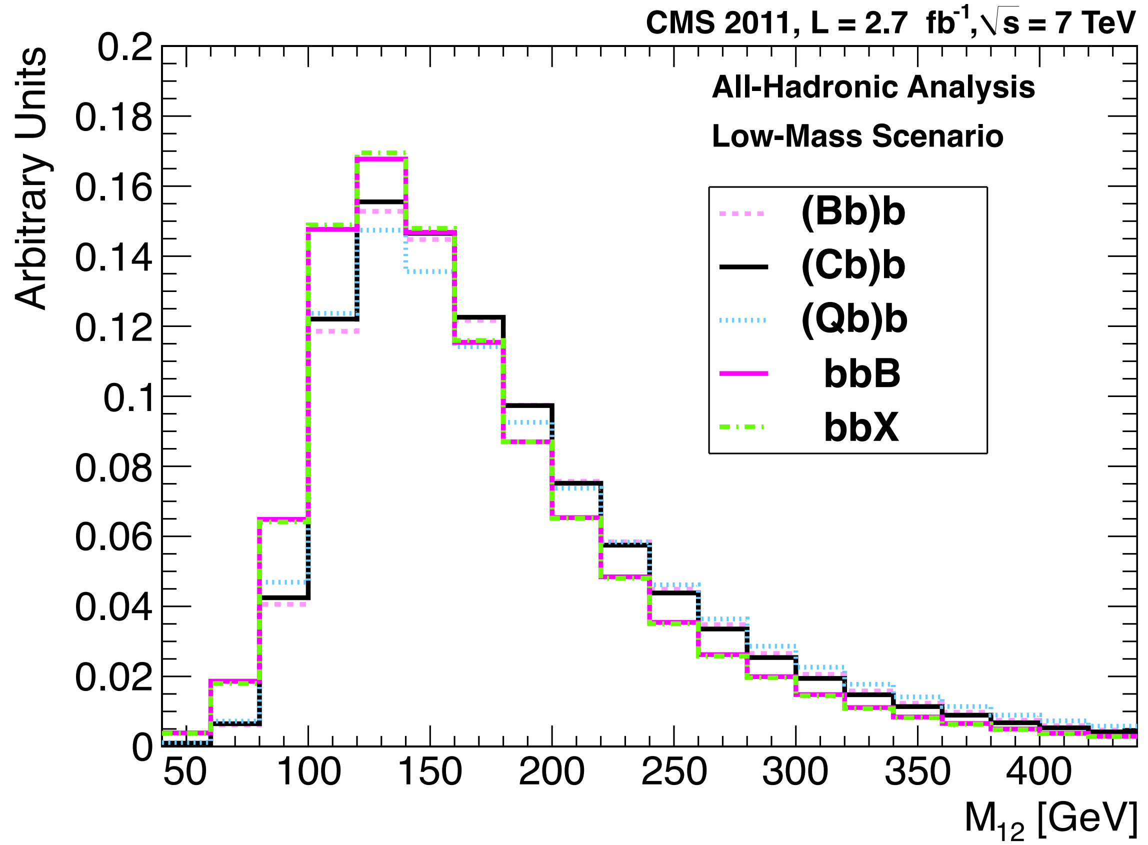


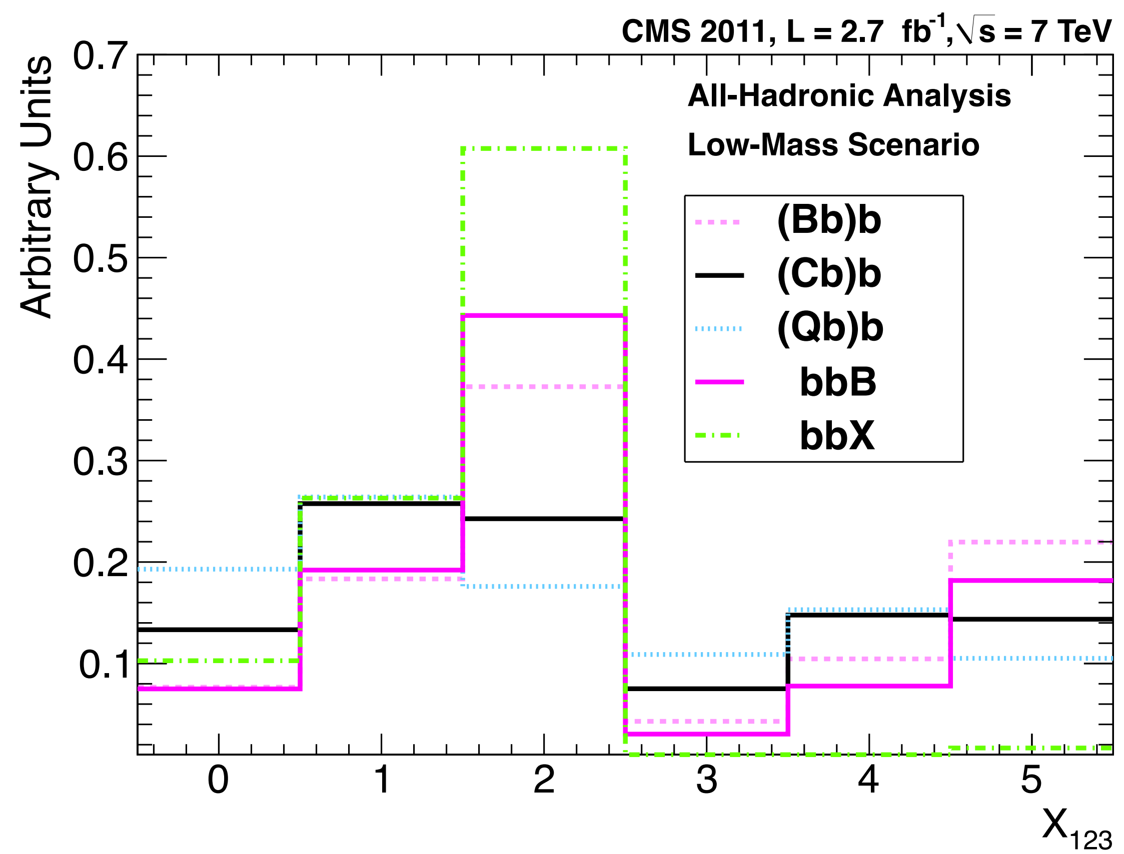


MSSM ϕ → bb : Background model

(all-hadronic)

- Data-driven background modelling from double b-tag sample.
- Untagged jet is weighted according to the b-tag probability and the corresponding SV mass index probability of assumed flavour.
- Almost identical templates merged
  - bbX = bbC + bbQ
  - (Fb)b = Fbb+bFb, where F=B,C,Q
- X_{123} gives further distinction between different flavour compositions.
- Five 2D templates: M_{12} vs. X_{123}
- Normalisation from fit to data spectrum.

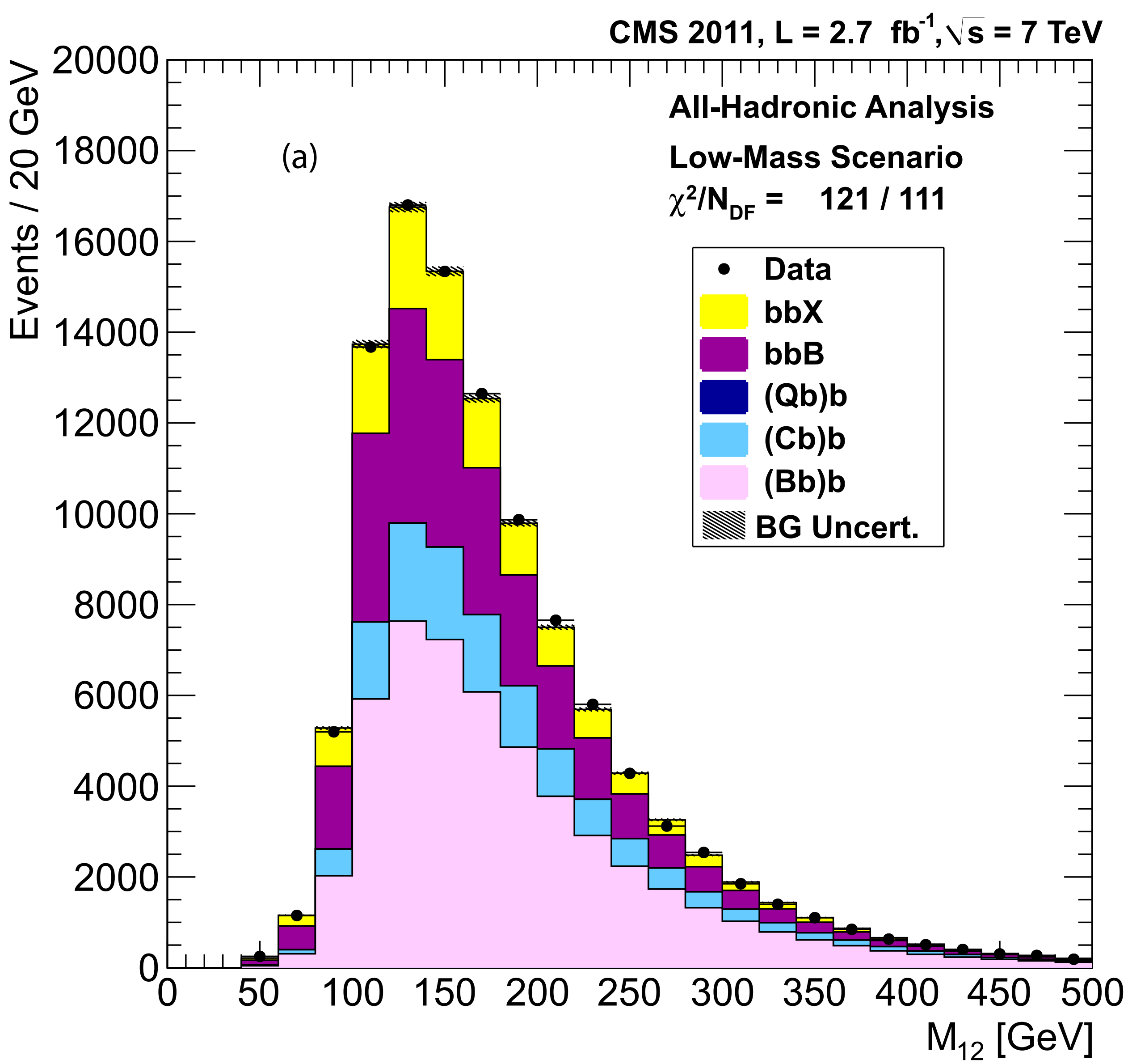


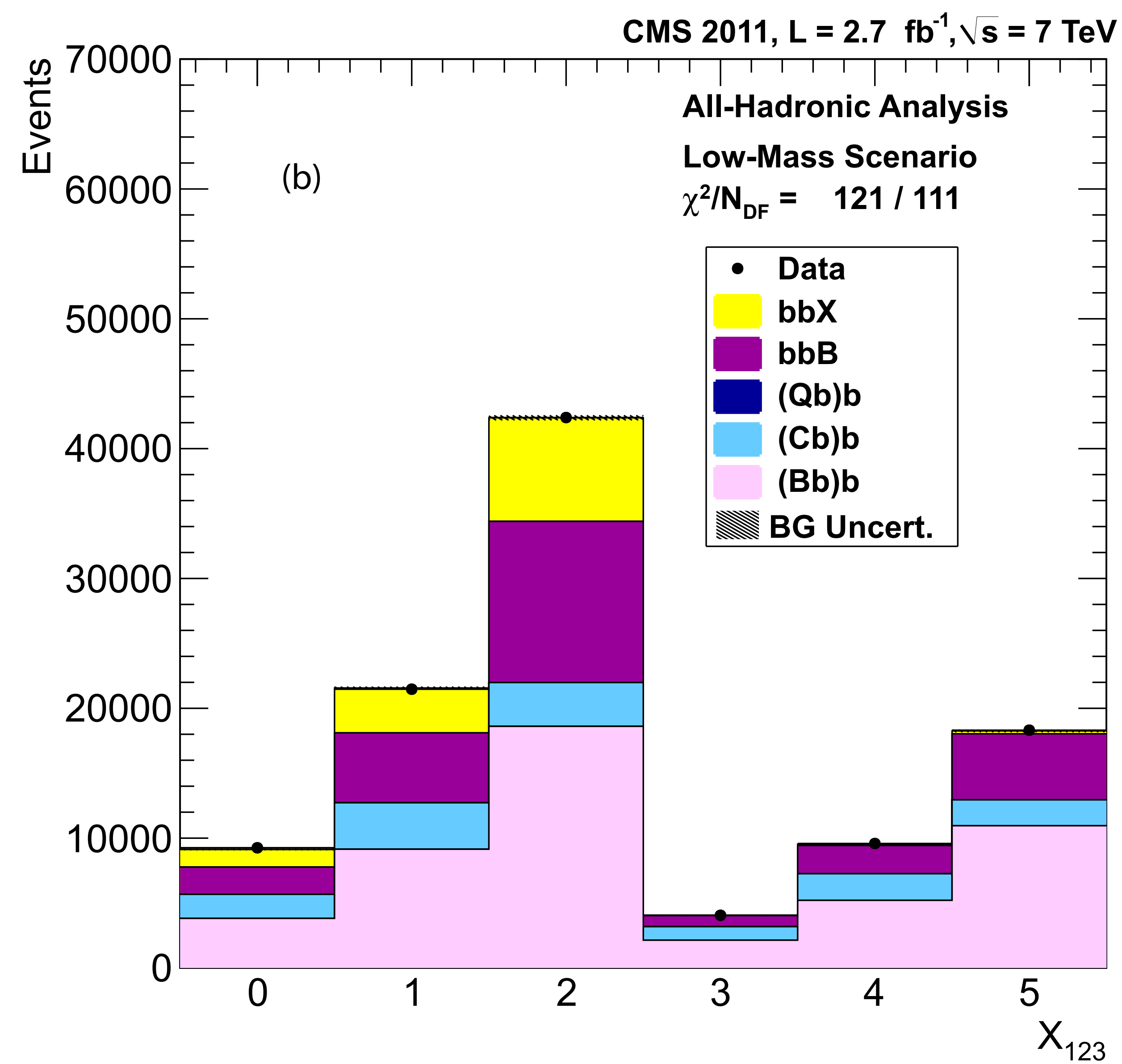


MSSM Φ → bb : Fit to data

(all-hadronic)

- Fit with background only templates with shapes obtained with double b-tag sample.
- About 73% contribution of real triple b jets.
- Excellent agreement with triple b-tag data

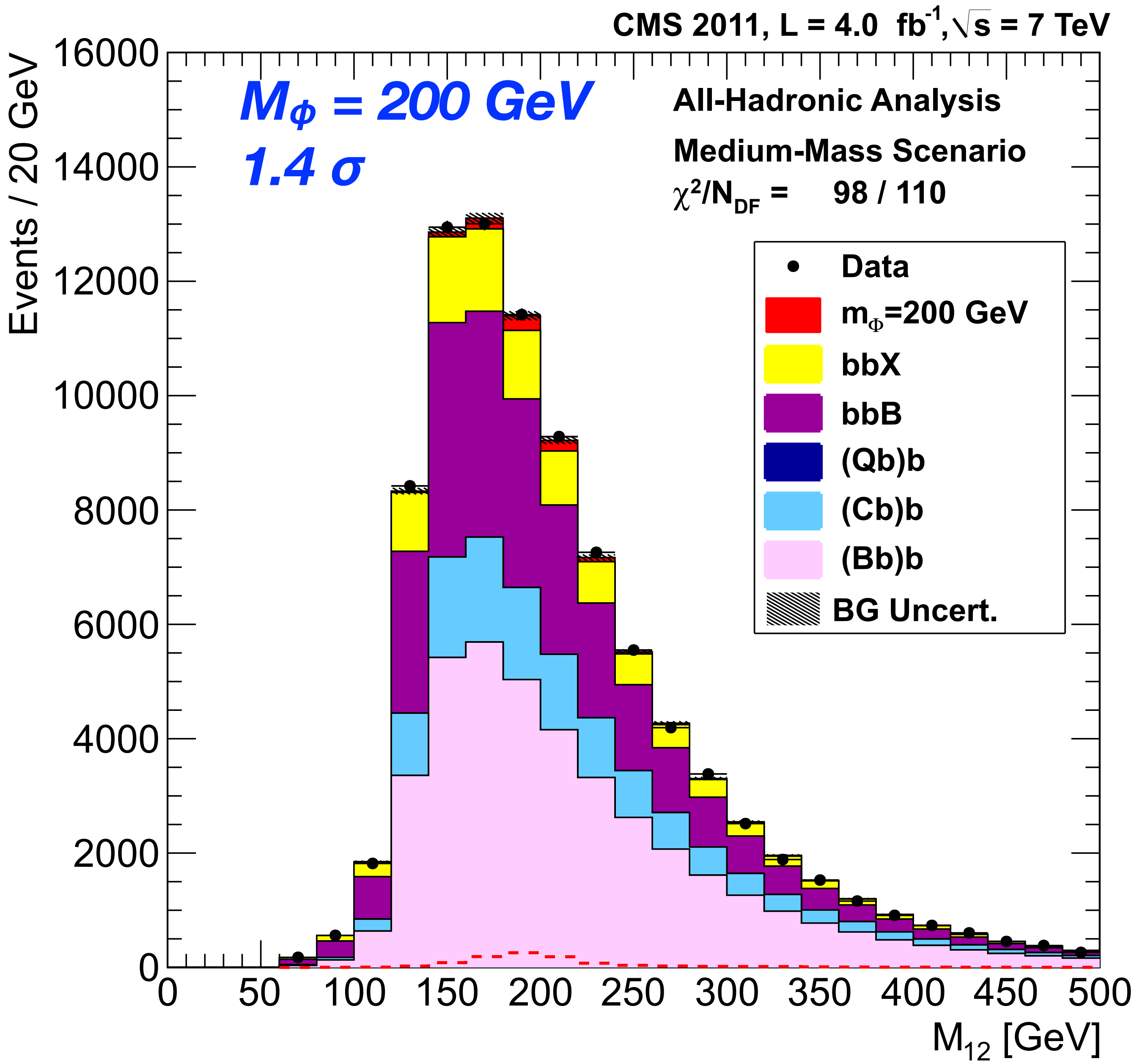




MSSM Φ → bb : Fit to data

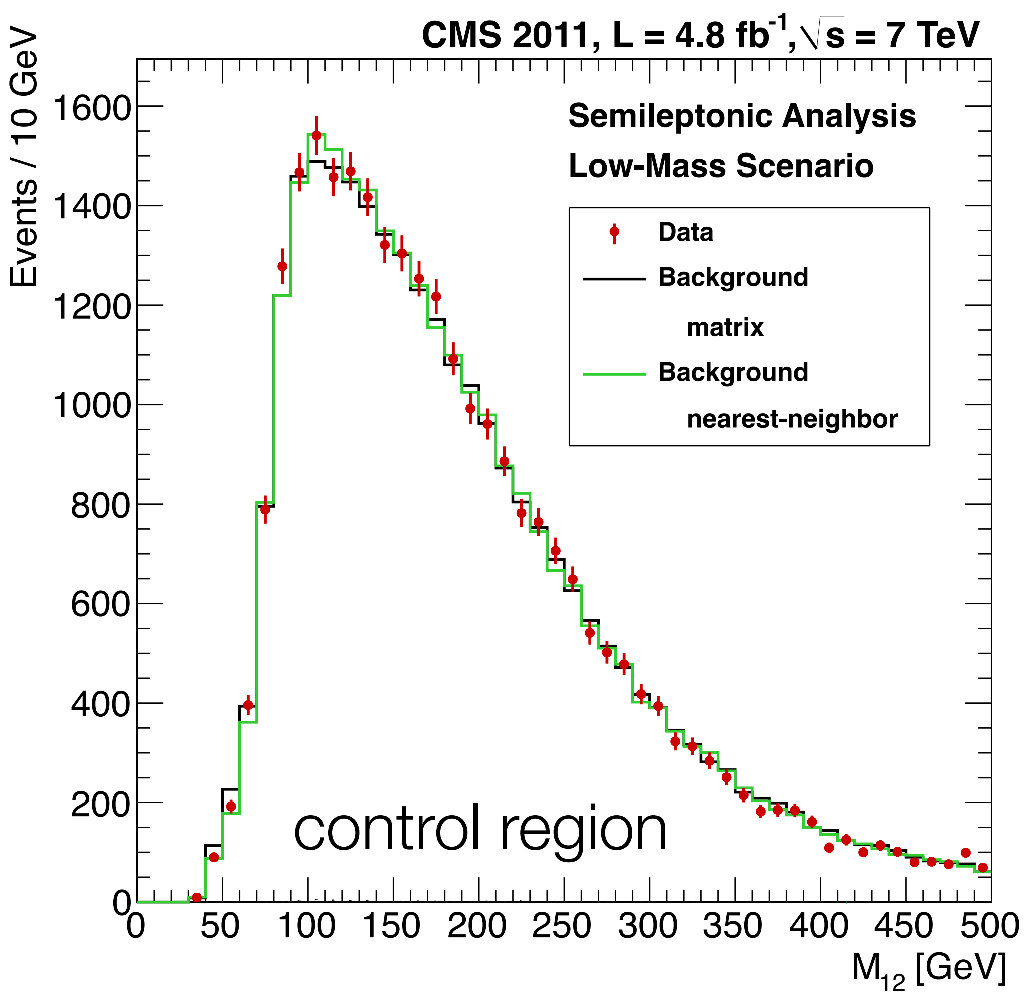
(all-hadronic)

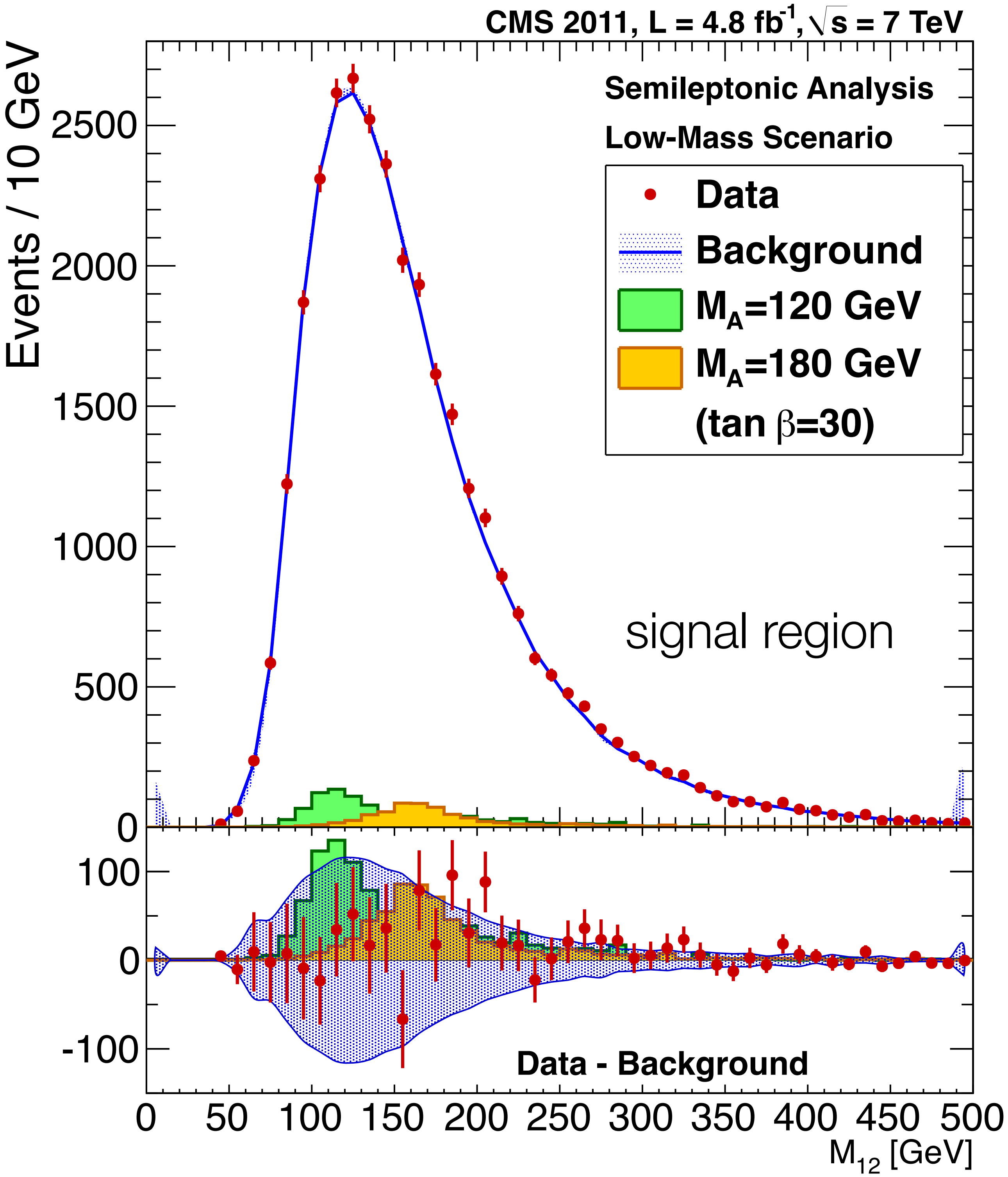
- Signal + background templates fits
  - Mass range 90 – 350 GeV
  - No significant excess observed at any mass



MSSM Φ → bb : Semileptonic analysis

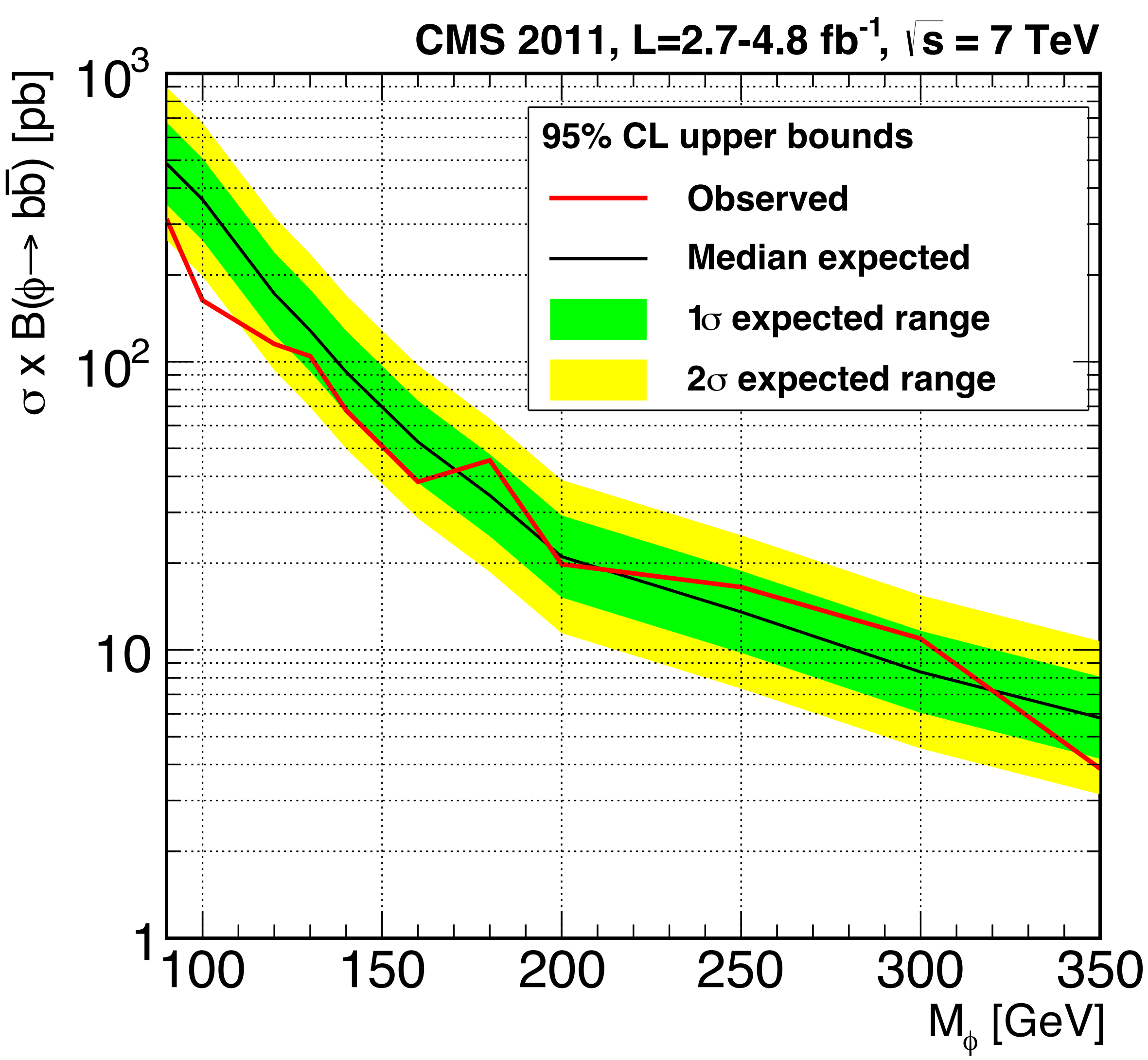
- Background normalisation and shape obtained from data in control regions.
  - Two independent methods using single and double b-tag data samples.
- Mass range 90 – 350 GeV.
- No significant excess observed at any mass.

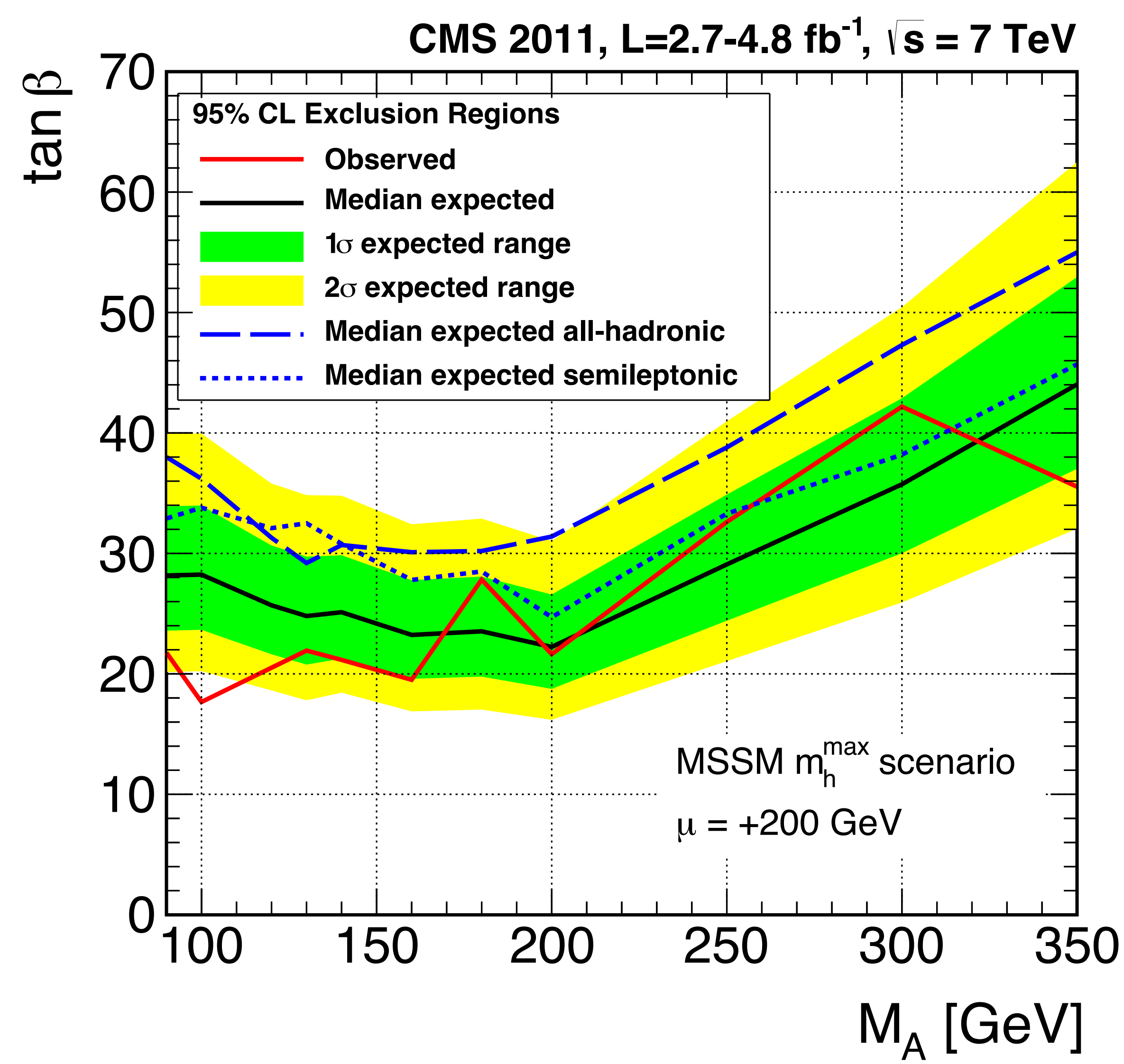




MSSM Φ → bb : Limits

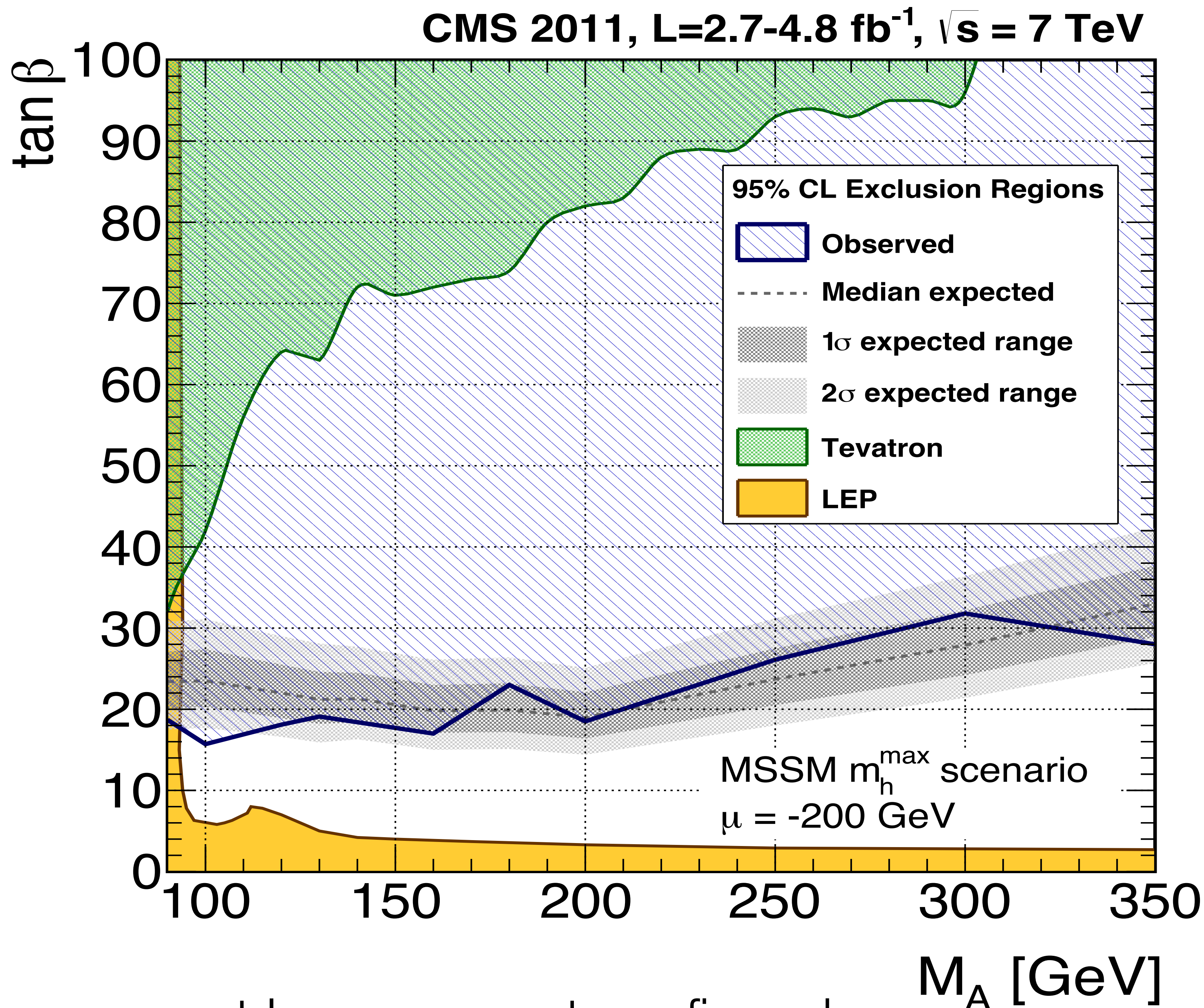
- All-hadronic and semileptonic analysis are almost orthogonal, 2-3% overlap (removed from all-hadronic dataset)
- Upper limits for σ×BR and tanβ vs m_A (NNLO 5-flavour scheme cross sections - Higgs XS WG)
- CMS convention: SUSY parameter μ = + 200 GeV





- For comparison with Tevatron, we also give results for μ = –200 GeV (nex

MSSM ϕ → bb : Comparison with Tevatron

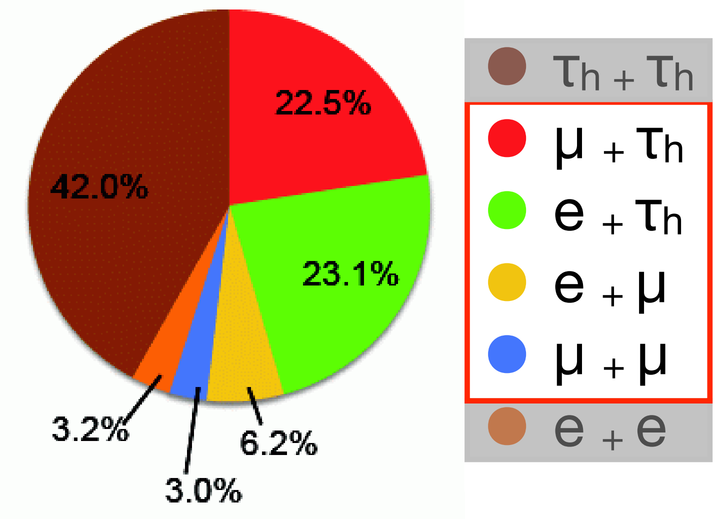


- CDF–D0 +2σ excess at low mass not confirmed.
- First time done at the LHC!
- World's best sensitivity in the bb channel, with 2011 data alone.

MSSM $\phi \rightarrow \tau\tau$ searches

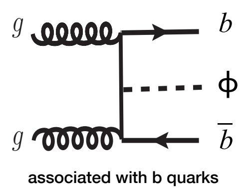
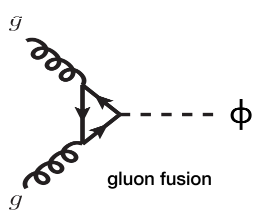
ϕ → ττ : Analysis strategy

- Good compromise between relatively large BR also at high masses and manageable backgrounds.



included in CMS MSSM analysis

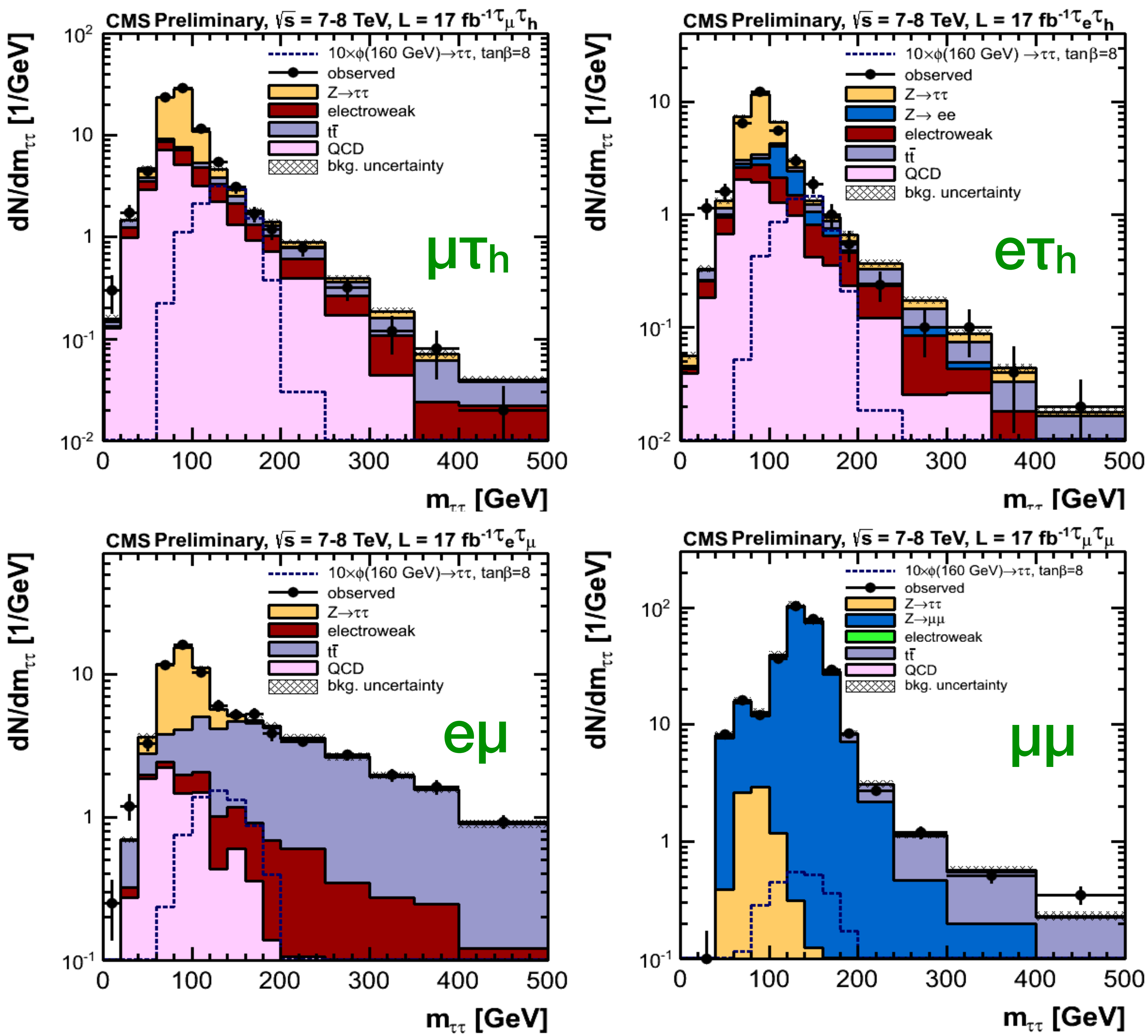
Production mechanisms & event categories

	b-tag category	≥ 1 b-tagged jet with p_T > 20 GeV ≤ 1 jet with p_T < 30 GeV
	no b-tag category	NO b-tagged jet with p_T > 20 GeV

- Triggers, lepton selection, τ mass reconstruction, background treatment: same as in the SM H→ττ searches

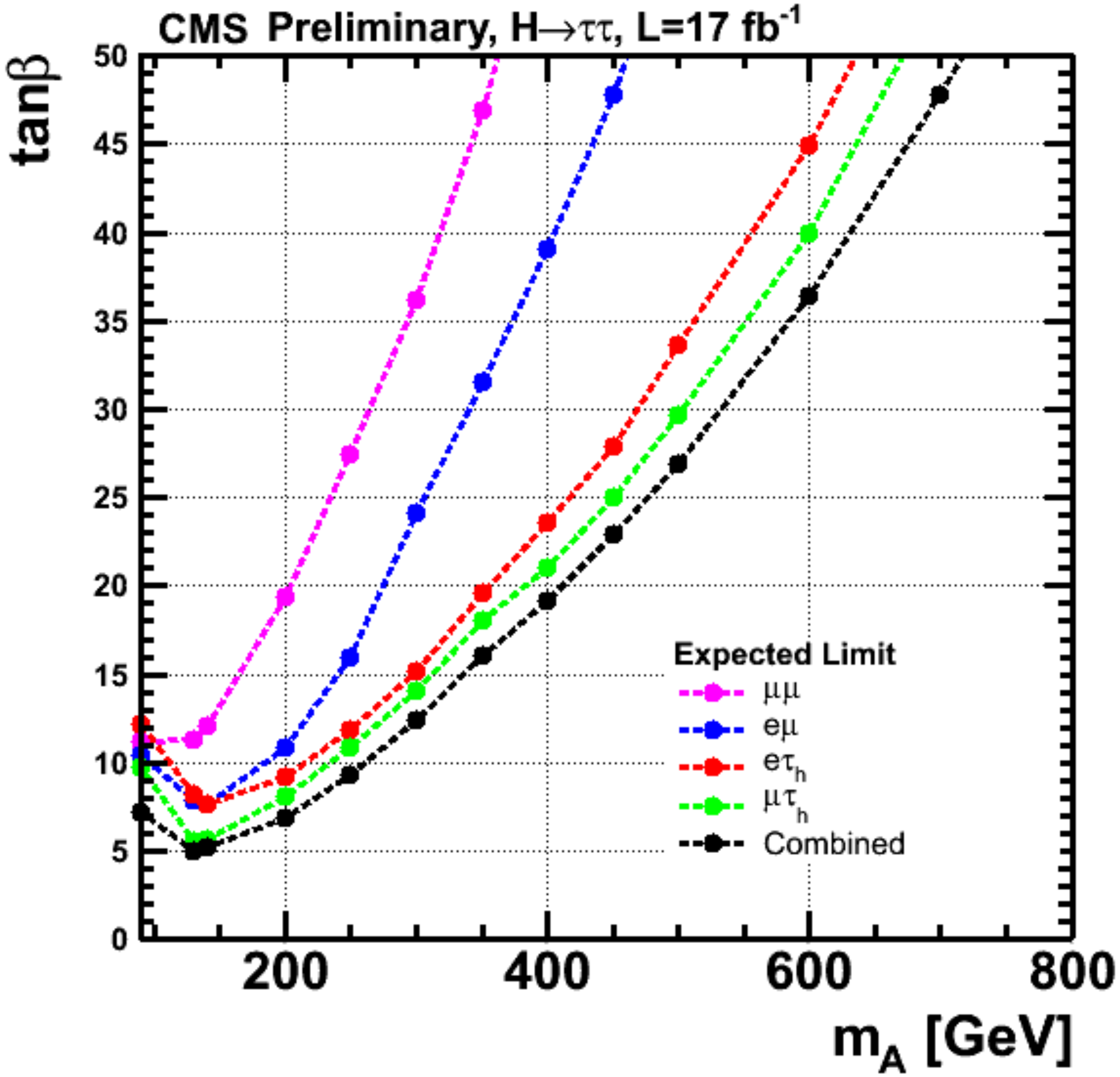
$\phi \rightarrow \tau\tau$: $m_{\tau\tau}$ distributions

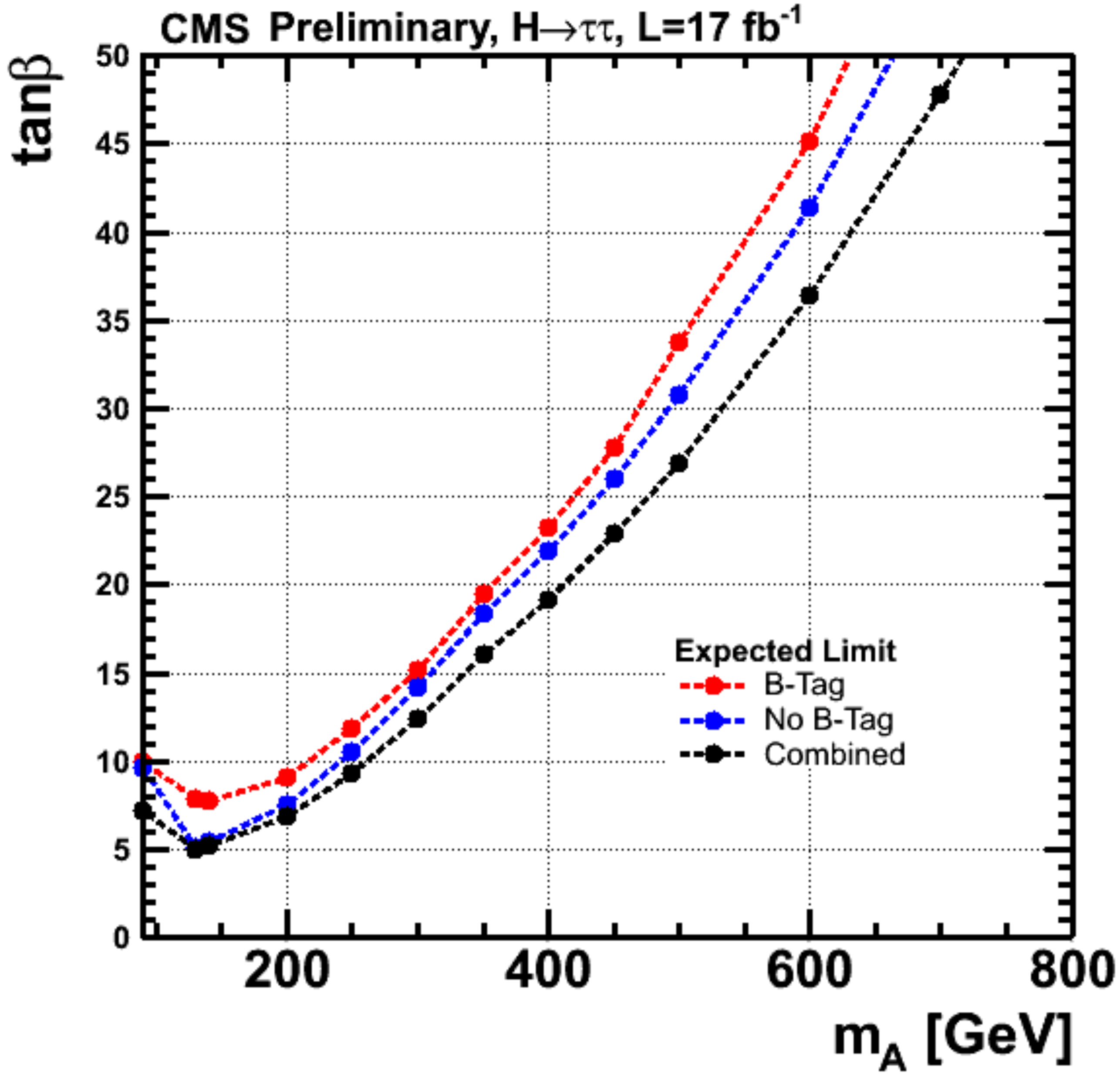
b-tag category



- No excess observed.
- All distributions well described by background-only hypothesis.

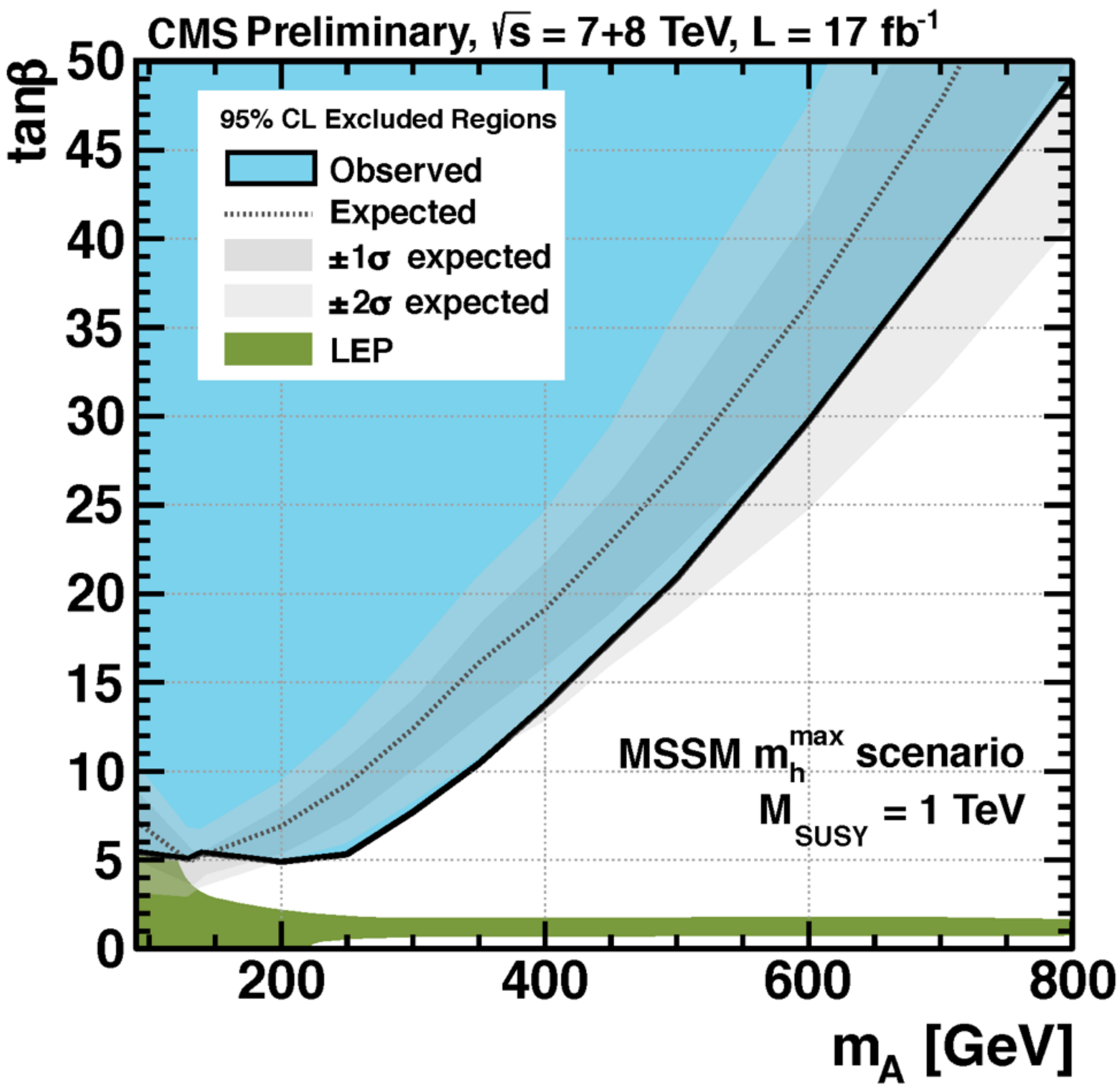
MSSM $\phi \to \tau\tau$ channels sensitivity





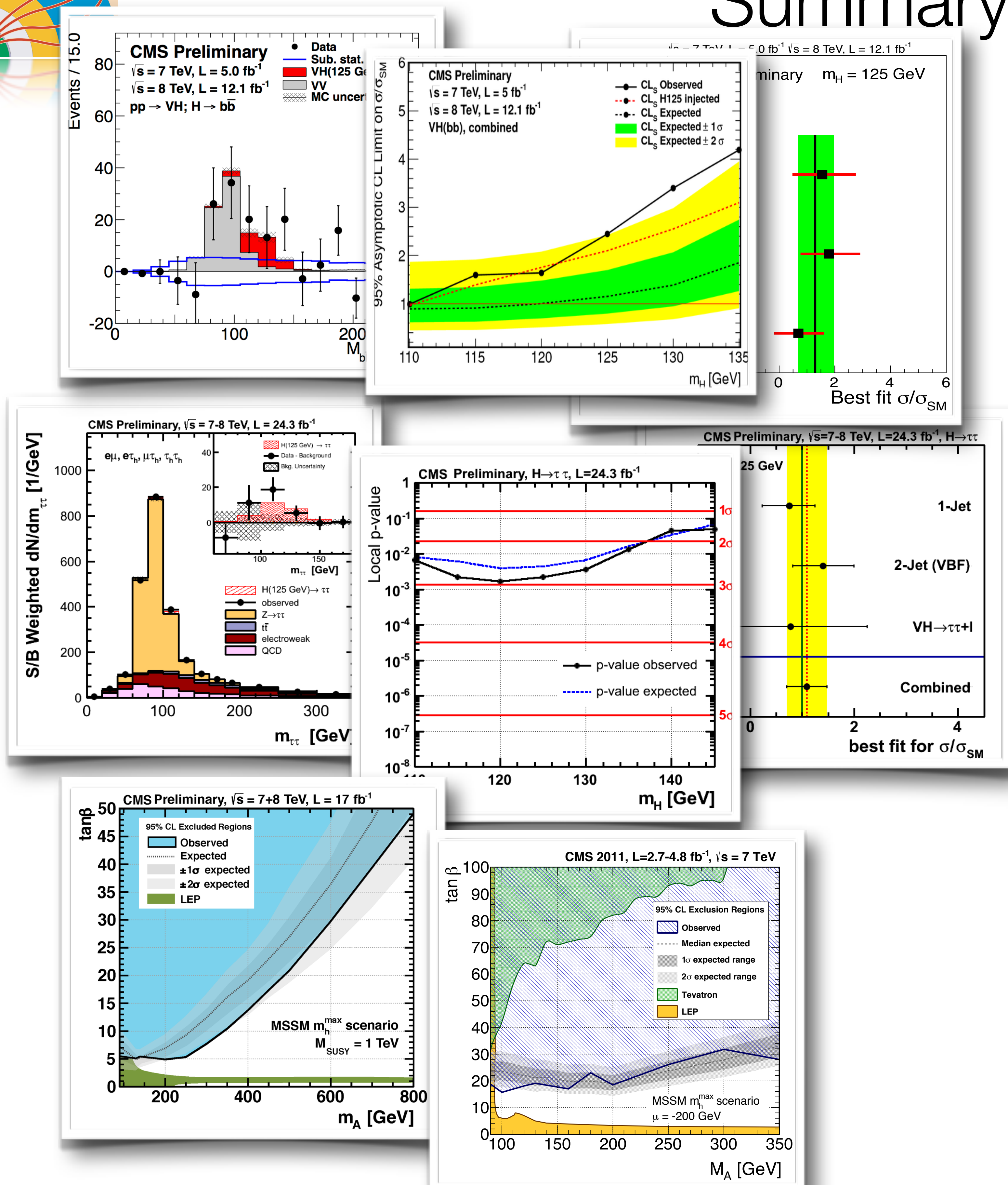
- Sensitivity driven by
  - single lepton channel
  - No b-tag category

$\phi \to \tau\tau$: MSSM limits



- Interpretation in the m_h^{max} scenario
- 95% CL exclusion limit in m_A–tanβ parameter space
  - tanβ < 5 for mA ≤ 250 GeV
  - Touching LEP constraint at low m_A

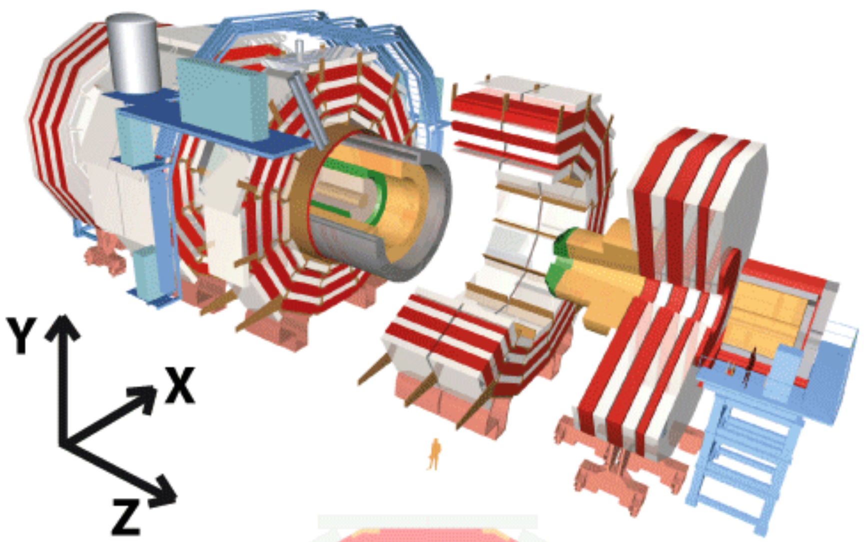
Summary

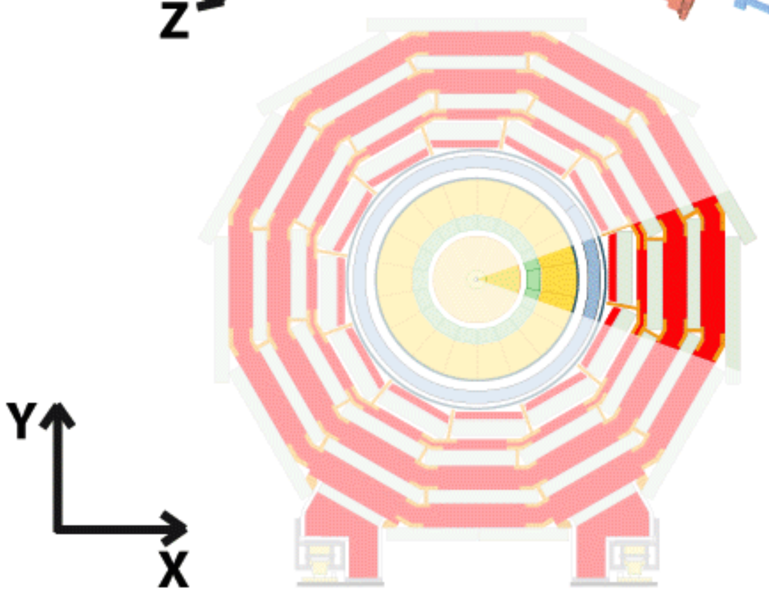


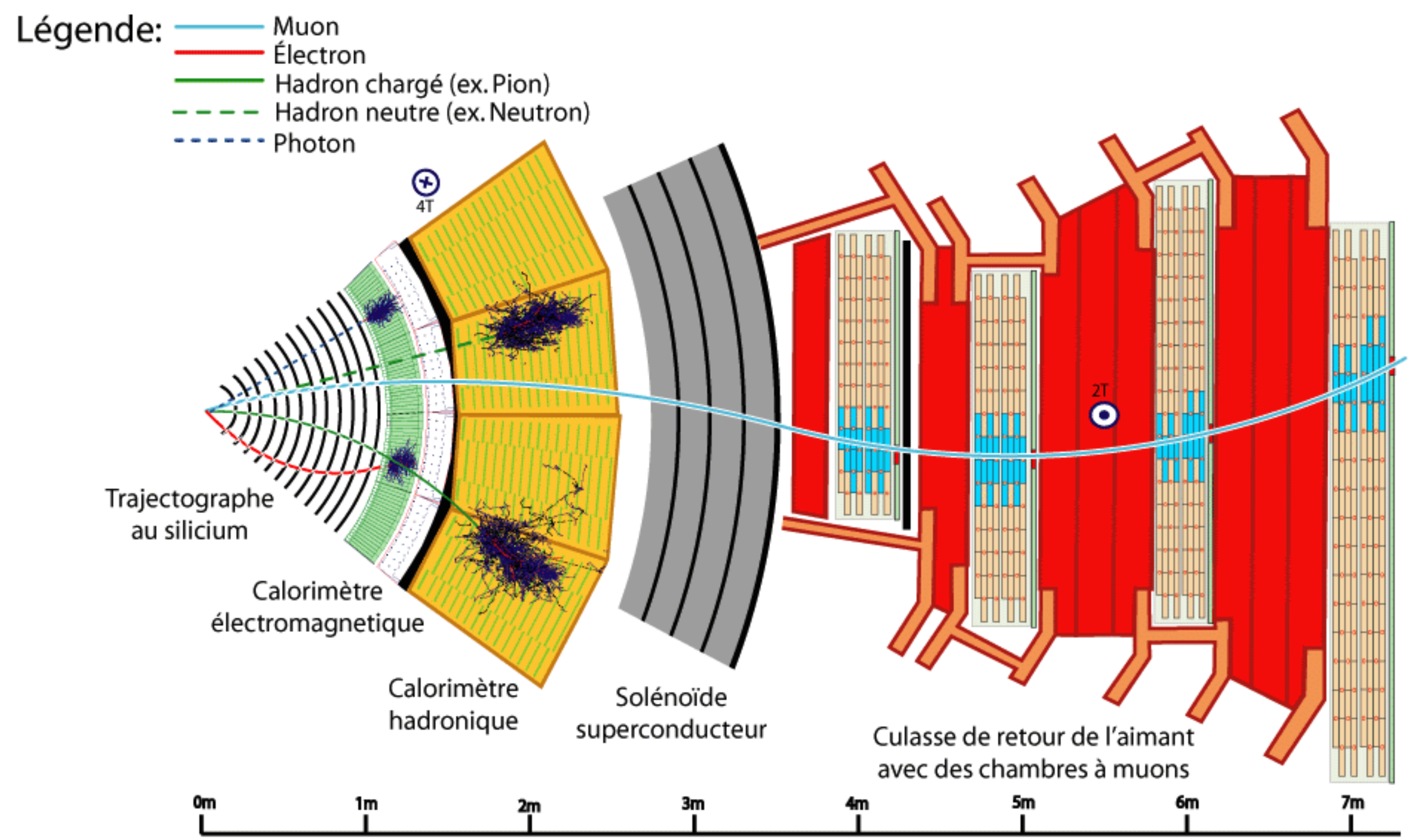
- Evidence of new 125 GeV particle direct coupling to fermions: τ leptons and b quarks.
- No excess observed in MSSM Higgs searches.
- Most analyses still to add the full 2012 dataset.
- Further improvements in the analyses are possible.
- Stay tuned!

additional material

How CMS detects particles





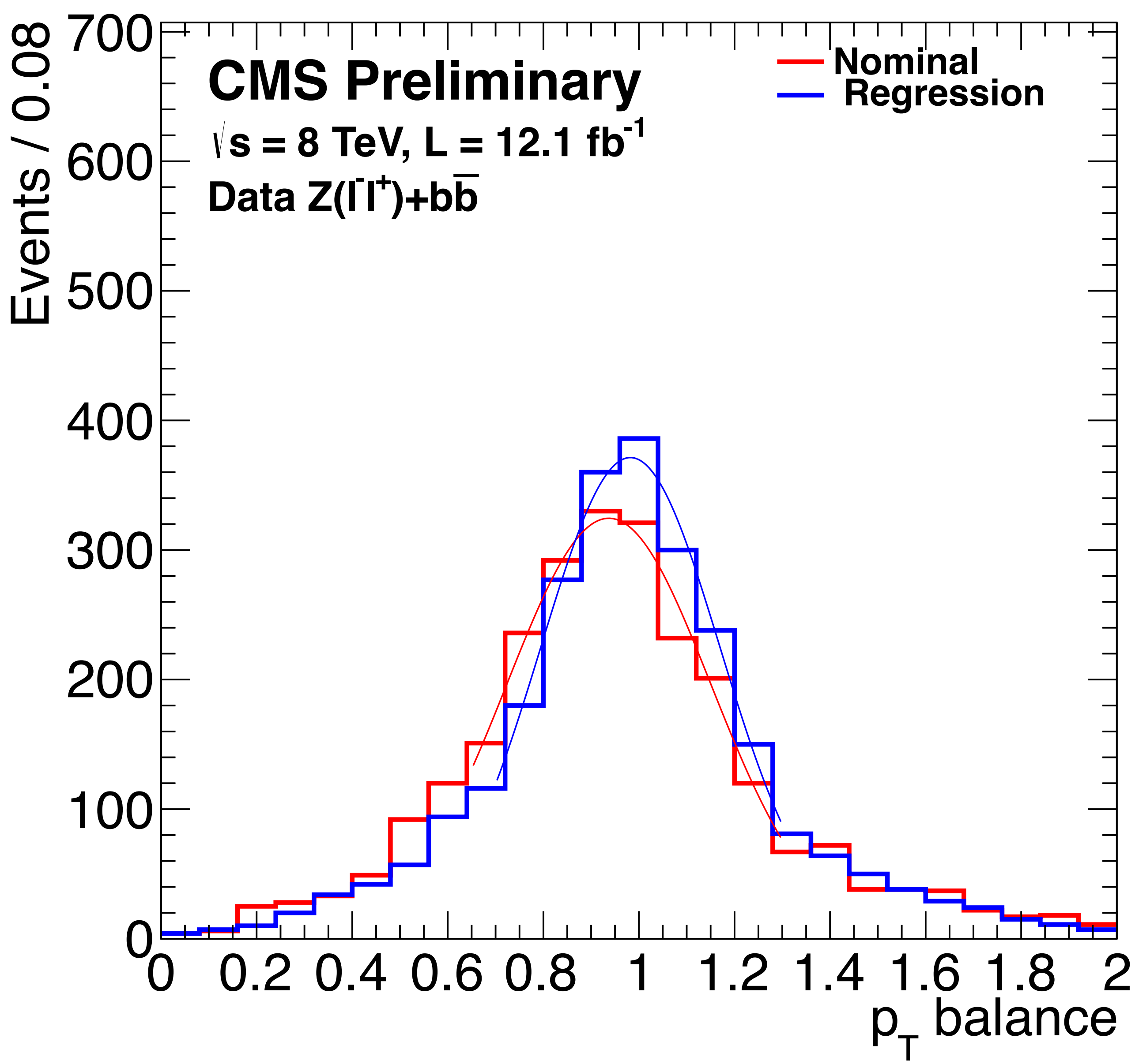


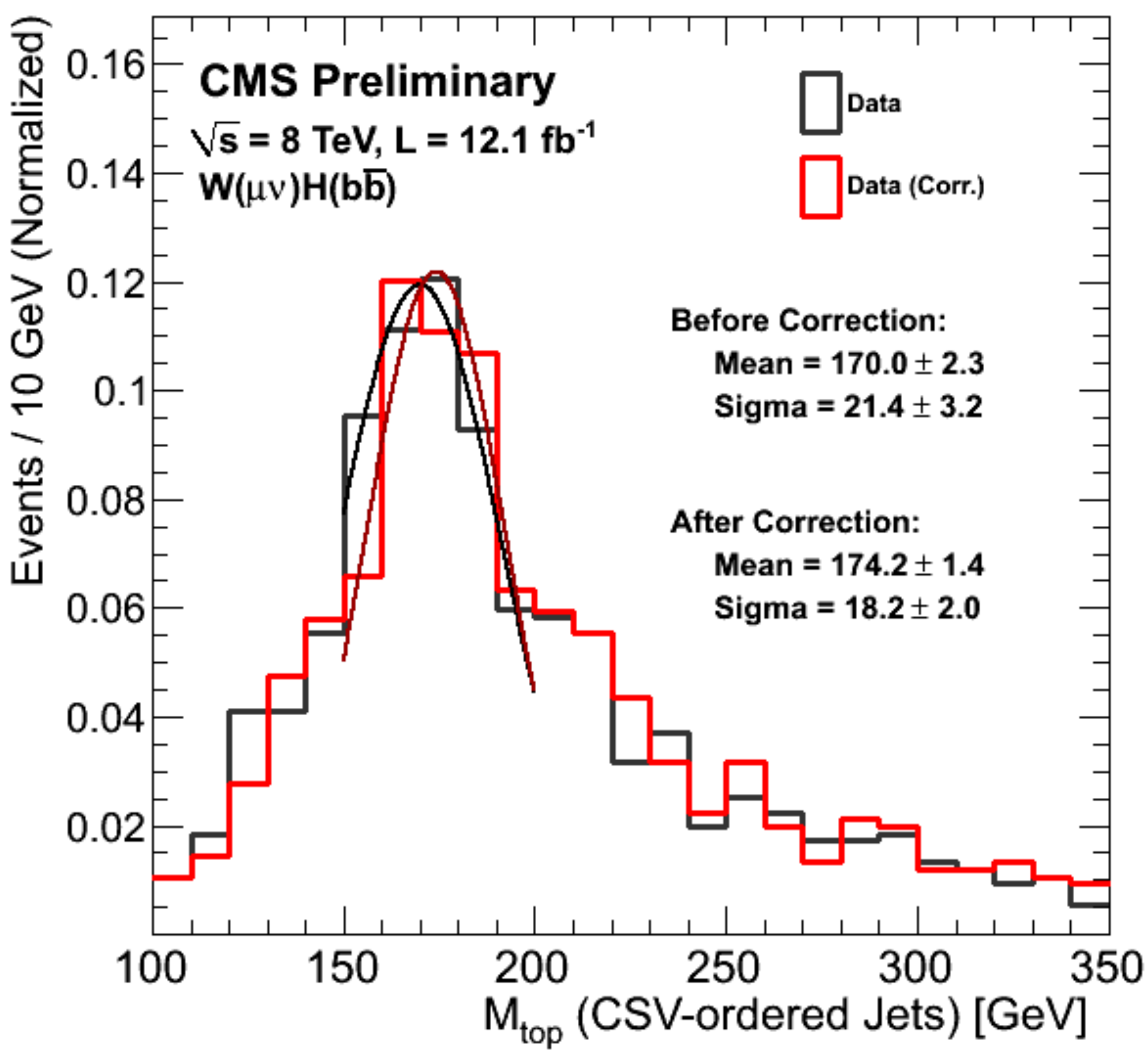
VH, H→bb trigger

Triggers	7 TeV (2011)	8 TeV (2012)
W(μν)H Z(μμ)H	≥ 1 (isolated) muon p_T^{μ} > 17–40 GeV/c	≥ 1 (isolated) muon p_T^{μ} > 24–40 GeV/c
W(eν)H	≥ 1 isolated electron p_T^{e} > 17–30 GeV/c (≥ 2 jets for lower threshold)	≥ 1 isolated electron p_T^{e} > 27 GeV/c
Z(ee)H	≥ 2 isolated electrons $p_T^{e,1st}$ > 17 GeV/c $p_T^{e,2nd}$ > 8 GeV/c	≥ 2 isolated electrons $p_T^{e,1st}$ > 17 GeV/c $p_T^{e,2nd}$ > 8 GeV/c
Z(νν)H	MET > 150 GeV OR ≥ 2 central jets pT > 20 GeV MET > 80-100 GeV	MET > 150 GeV OR ≥ 2 central jets pT > 30 GeV, MET > 80 GeV

VH, H→bb regression validation

- Extensive validation on data and MC
- E.g., pT balance in Z(ll)+bb and reconstructed top quark mass





VH, H→bb Systematics

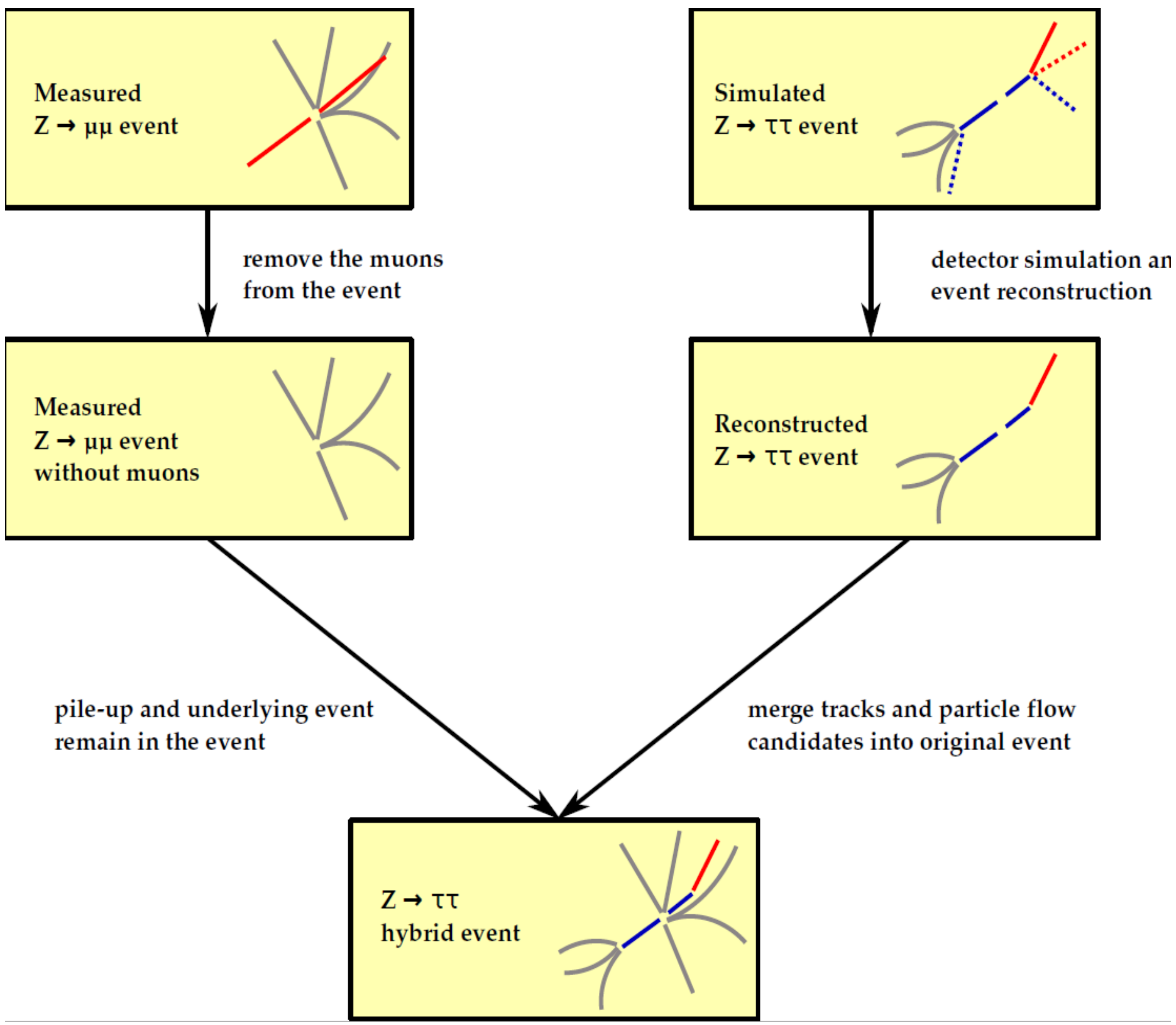
Source	Range
Luminosity	2.2-4.4%
Lepton efficiency and trigger (per lepton)	3%
$Z(\nu\nu)H$ triggers	3%
Jet energy scale	2–3%
Jet energy resolution	3–6%
Missing transverse energy	3%
b-tagging	3–15%
Signal cross section (scale and PDF)	4%
Signal cross section (p_T boost, EWK/QCD)	5–10% / 10%
Signal Monte Carlo statistics	1-5%
Backgrounds (data estimate)	$\approx$ 10%
Single-top (simulation estimate)	15–30%
Dibosons (simulation estimate)	30%

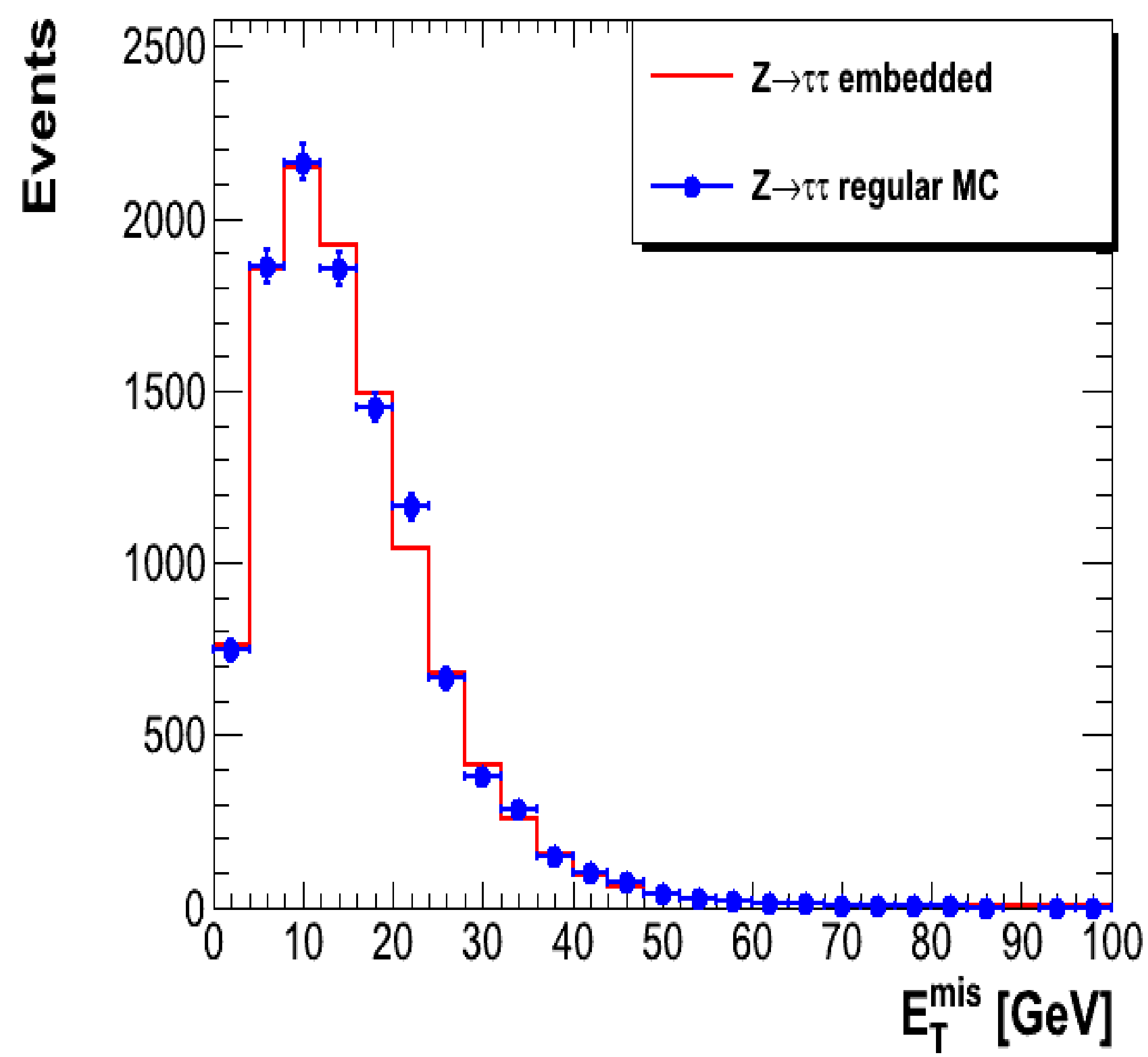
$t\bar{t}H$, H→bb Systematics

Source	Rate Uncertainty	Shape	Remarks
Luminosity (7 TeV)	2.2%	No	All signal and backgrounds
Luminosity (8 TeV)	4.4%	No	All signal and backgrounds
Lepton ID/Trig	4%	No	All signal and backgrounds
Pileup	1%	No	All signal and backgrounds
Additional Pileup Corr.	–	Yes	All signal and backgrounds
Jet Energy Resolution	1.5%	No	All signal and backgrounds
Jet Energy Scale	0–60%	Yes	All signal and backgrounds
b-Tag SF (b/c)	0–33.6%	Yes	All signal and backgrounds
b-Tag SF (mistag)	0–23.5%	Yes	All signal and backgrounds
MC Statistics	–	Yes	All backgrounds
PDF (gg)	9%	No	For gg initiated processes ($t\bar{t}$, $t\bar{t}Z$, $t\bar{t}H$)
PDF ($q\bar{q}$)	4.2–7%	No	For $q\bar{q}$ initiated processes ($t\bar{t}W$, W, Z).
PDF (qg)	4.6%	No	For qg initiated processes (single top)
QCD Scale ($t\bar{t}H$)	15%	No	For NLO $t\bar{t}H$ prediction
QCD Scale ($t\bar{t}$)	2–12%	No	For NLO $t\bar{t}$ and single top predictions
QCD Scale (V)	1.2–1.3%	No	For NNLO W and Z prediction
QCD Scale (VV)	3.5%	No	For NLO diboson prediction
Madgraph Scale ($t\bar{t}$)	0–20%	Yes	$t\bar{t}$ + jets/$b\bar{b}$/$c\bar{c}$ uncorrelated. Varies by jet bin.
Madgraph Scale (V)	20–60%	No	Varies by jet bin.
$t\bar{t} + b\bar{b}$	50%	No	Only $t\bar{t} + b\bar{b}$.

H→ττ : Embedding

- Z→ττ is the main irreducible background.
- Estimated from embedded sample: μ in Z→μμ events replaced by simulated τ.
- Normalised from Z→μμ events.



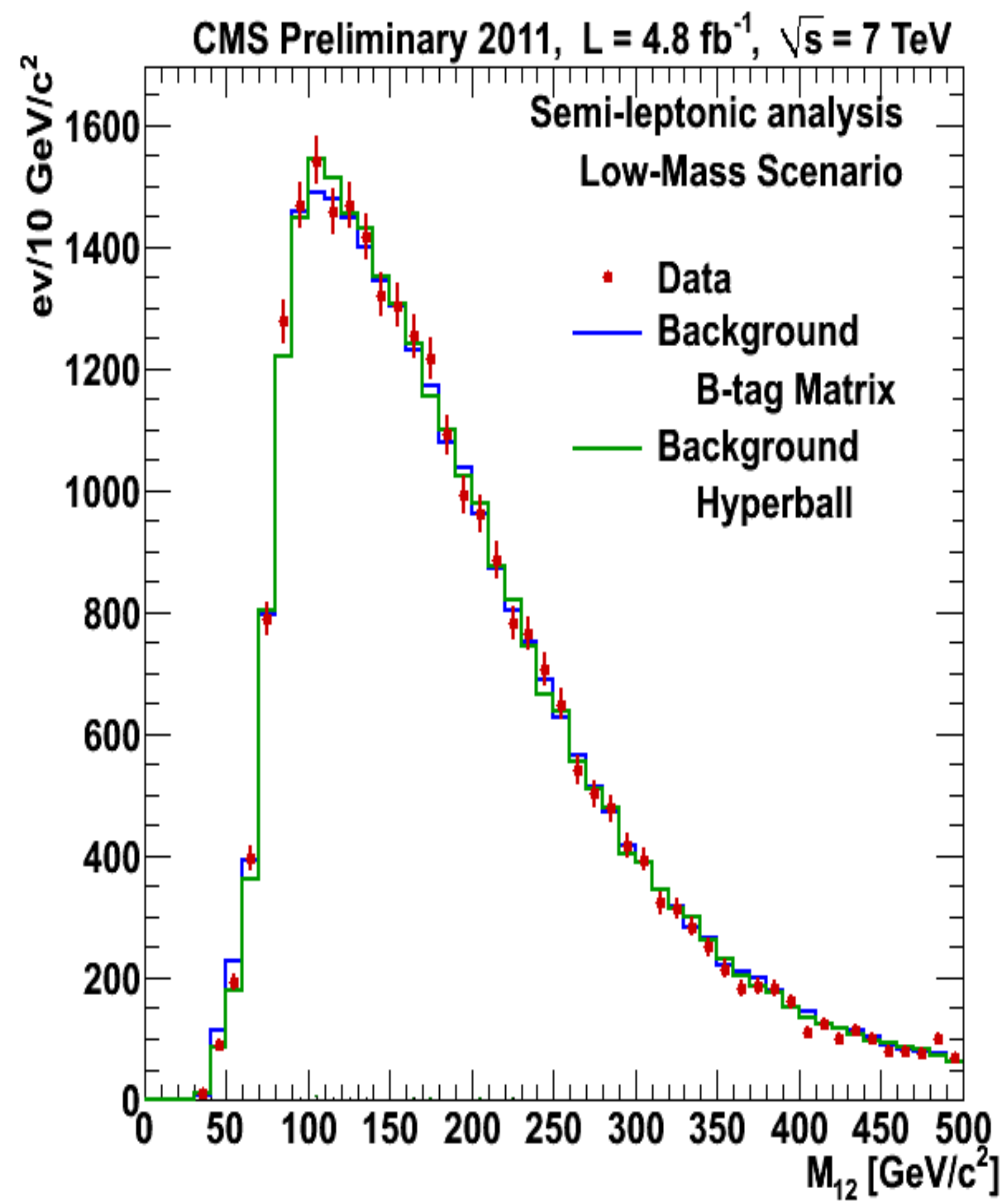


MSSM Φ → bb

Event selection	All-hadronic	Semi-leptonic
Triggers	≥ 2 or 3 Jets ≥ 2 b-tagged Jets	≥ 1 Muon ≥ 1 or 2 Jets ≥ 1 or 2 b-tagged Jets
Jets	≥ 3 Jets p_T^{1st} > 46 (60) GeV p_T^{2nd} > 38 (53) GeV p_T^{3rd} > 20 GeV 3 leading Jets b-tagged	≥ 3 Jets $p_T^{1st,2nd}$ > 30 GeV p_T^{3rd} > 20 GeV 3 leading Jets b-tagged
Muon	–	≥ 1 Muon, p_T > 15 GeV

MSSM Φ → bb (semileptonic)

- Background estimation – semi-leptonic
- BTagMatrix
  - B-tag probability matrices (*bbj* sample).
  - B-tag eff from MC, flavour fractions from data
  - $F(x;bbb) = F(x;bbj) \otimes P^{3^{rd}jet}_{b-tag}(\ldots)$
- Hyperball (nearest neighbour)
  - Sample *bjj* (excl *bbj* sample)
  - Compute the fraction *f* of similar events passing full selection.
  - $F(x;bbb) = F(x;bjj) \otimes f$
- The two methods are combined
  - Use bin-per-bin weighted average of B-tag Matrix and Hyperball prediction to get background shape.



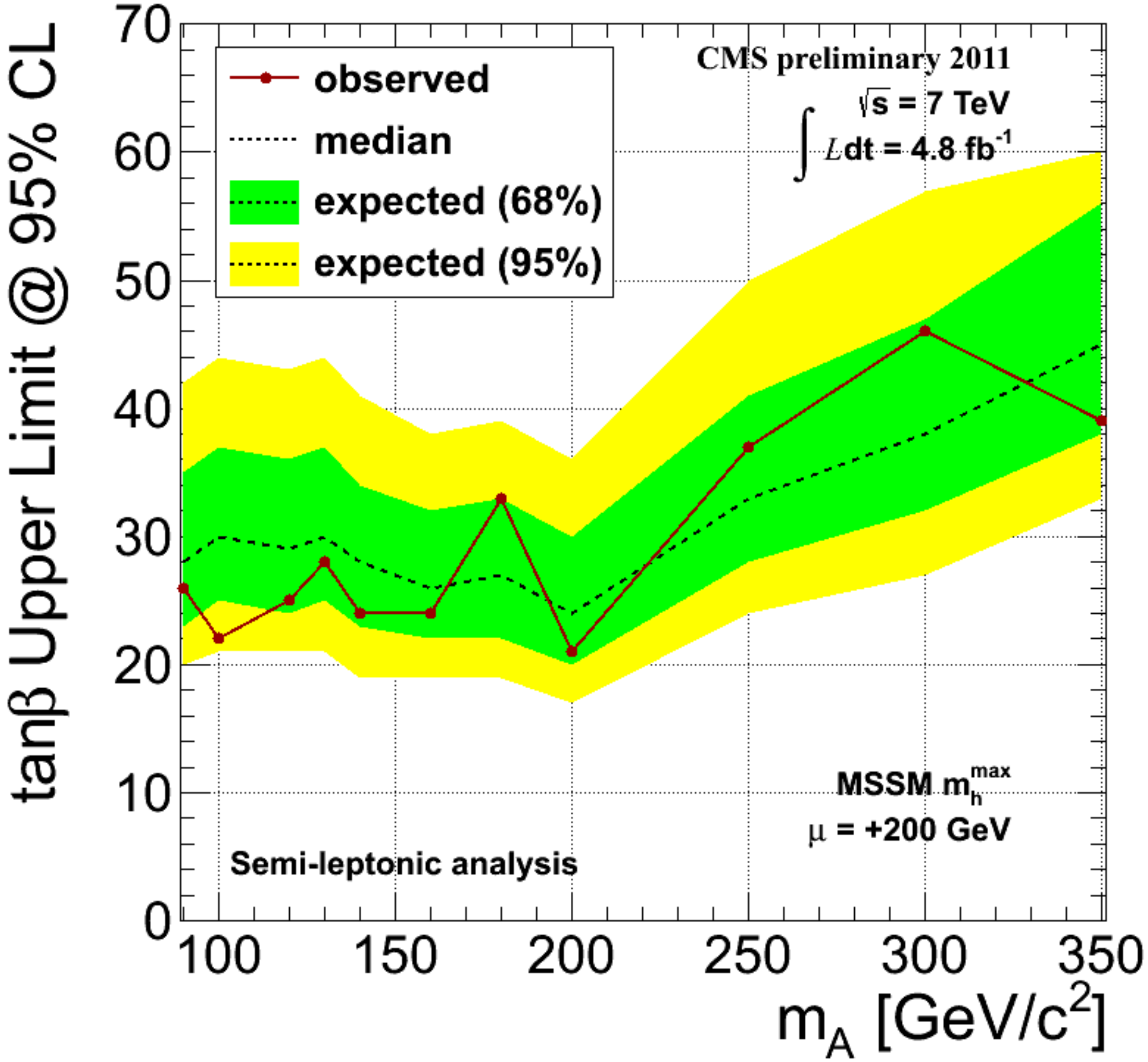
MSSM ϕ → bb Systematics

- Systematic uncertainties on the signal yield

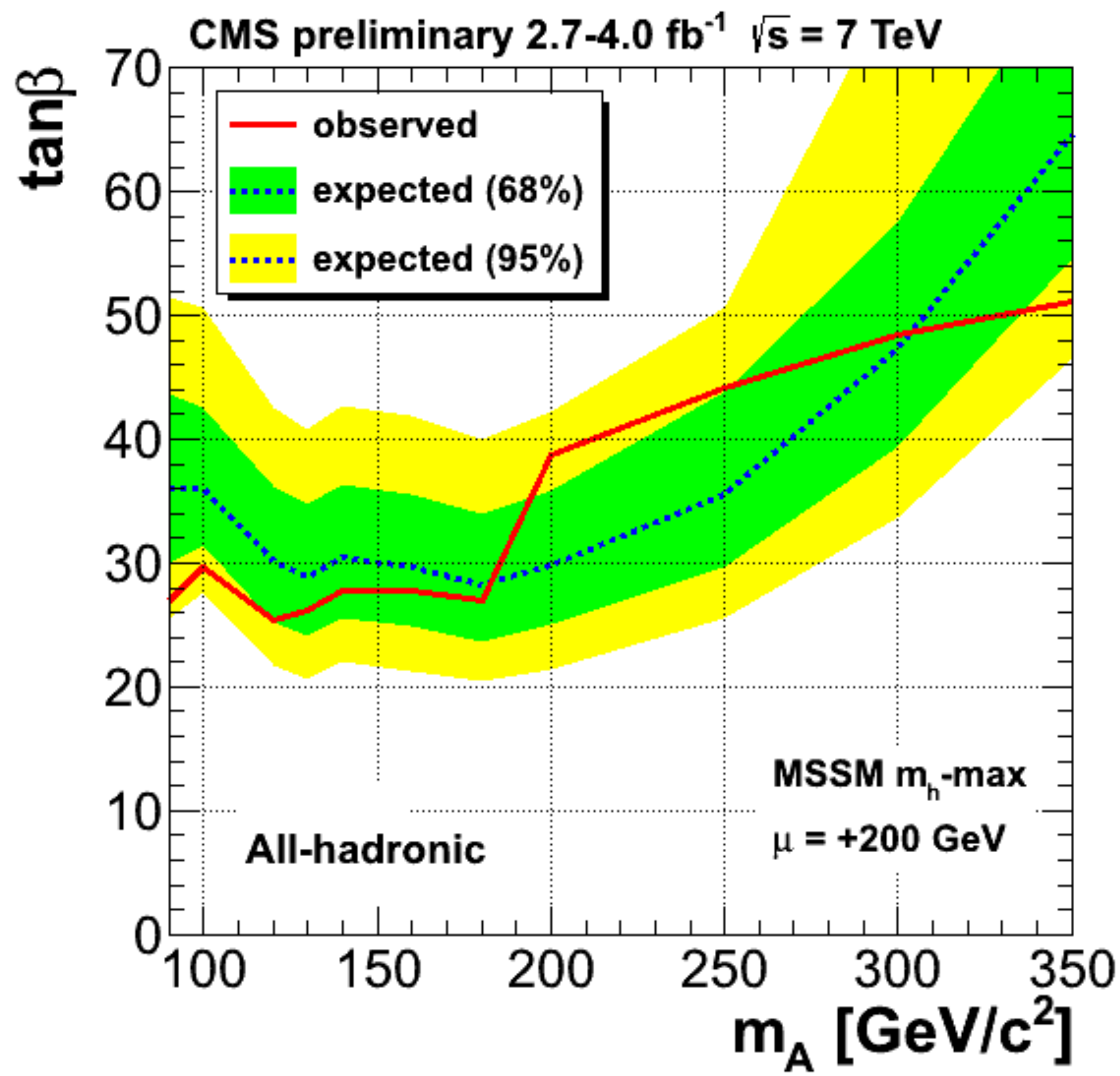
Source	All-hadronic	Semileptonic	Type
Trigger efficiency	10%	3 – 5%	rate
Online b-tagging efficiency	32%	–	rate
Offline b-tagging efficiency	10–13%†	12%	shape/rate
b-tagging efficiency dependence on topology	6%	–	rate
Jet energy scale	1.4–6.8%	3.1%	shape/rate
Jet energy resolution	0.6–1.3%	1.9%	shape/rate
Muon momentum scale and resolution	–	1%	rate
Signal Monte Carlo statistics	1.1–2.6%		rate
Integrated luminosity	2.2%		rate
PDF and α_s uncertainties	3–6%⋆	2.7–4.7%⋆	rate
Factorization and renormalization QCD scale	6–28%⋆		rate
Underlying event and parton showering	4%⋆		rate

MSSM $\phi \rightarrow bb$ Limits

Semileptonic



All-hadronic



$\phi \to$ bb Tevatron