Search for (pseudo-)scalar boson(s) in the ττ final state at CMS

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Introduction and outline

SM-like Higgs boson discovered at the LHC!

(Excess observed in the **$H \to \tau\tau$** channel with 3.2σ at 125 GeV)

But, is it really the SM Higgs boson or just one of multiple Higgs bosons existing?

Two ways to answer to this question...

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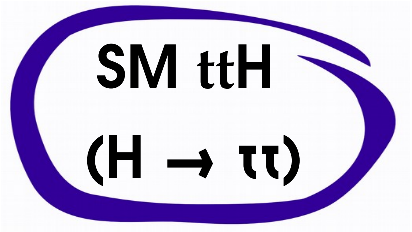
- Precision measurements of the new particle properties
  - → Search for not-yet observed SM production mechanisms



Crucial for direct measurement of top Yukawa coupling

- $\sigma_{SM}(pp \to ttH) = 130$ fb @ $m_H = 125$ GeV (NLO)
- $BR(H \to ff) \sim |Y_t|^2$

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SM ttH
(H → ττ)

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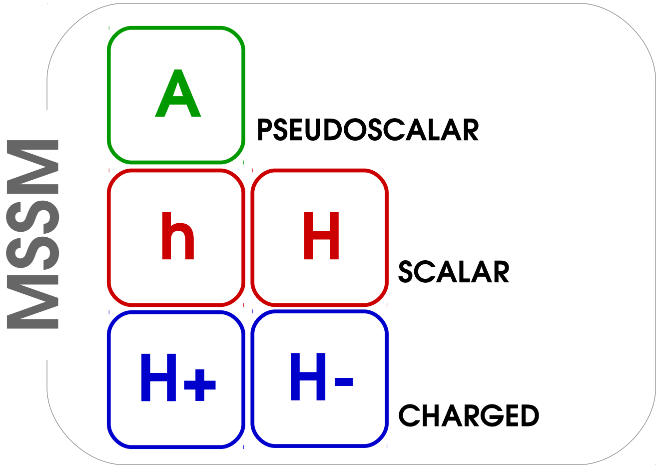
- $BR(H \to f\bar{f}) \sim |Y_f|^2$

- Find more Higgs bosons!



MSSM H → ττ

Hadronic τ reconstruction in CMS

τ decays predominantly into hadrons: ~65%

Hadron Plus Strips (HPS) algorithm

allows τ_h reconstruction in different decay modes

Decay mode	Resonance	Mass (MeV/c^2)	Branching fraction (%)
$\tau^- \to h^- \nu_\tau$			11.6%
$\tau^- \to h^- \pi^0 \nu_\tau$	ρ^-	770	26.0%
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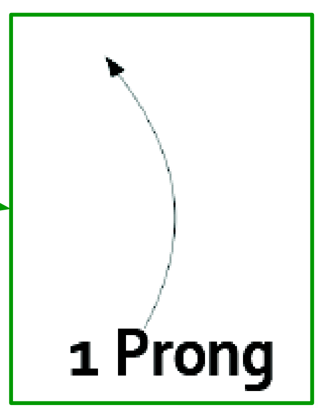

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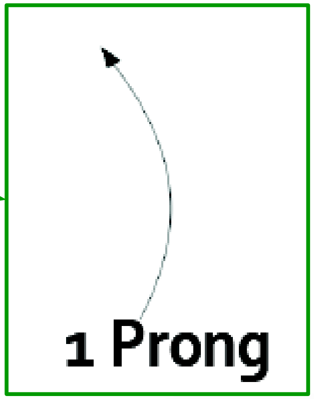

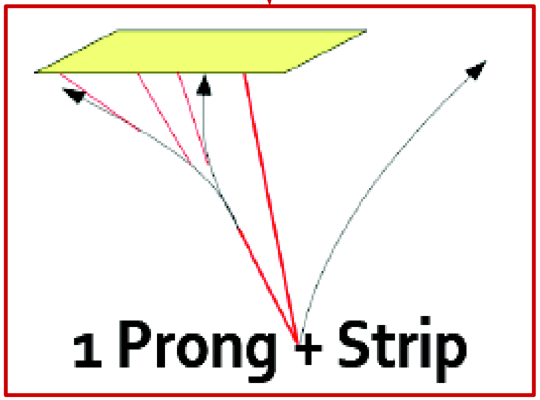

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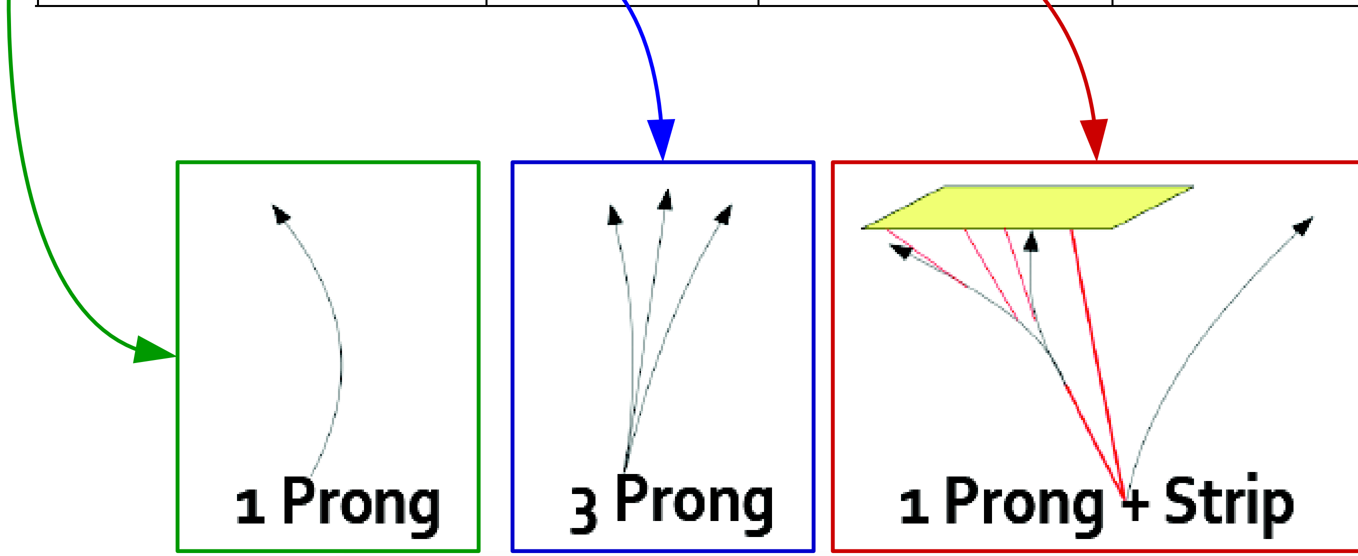
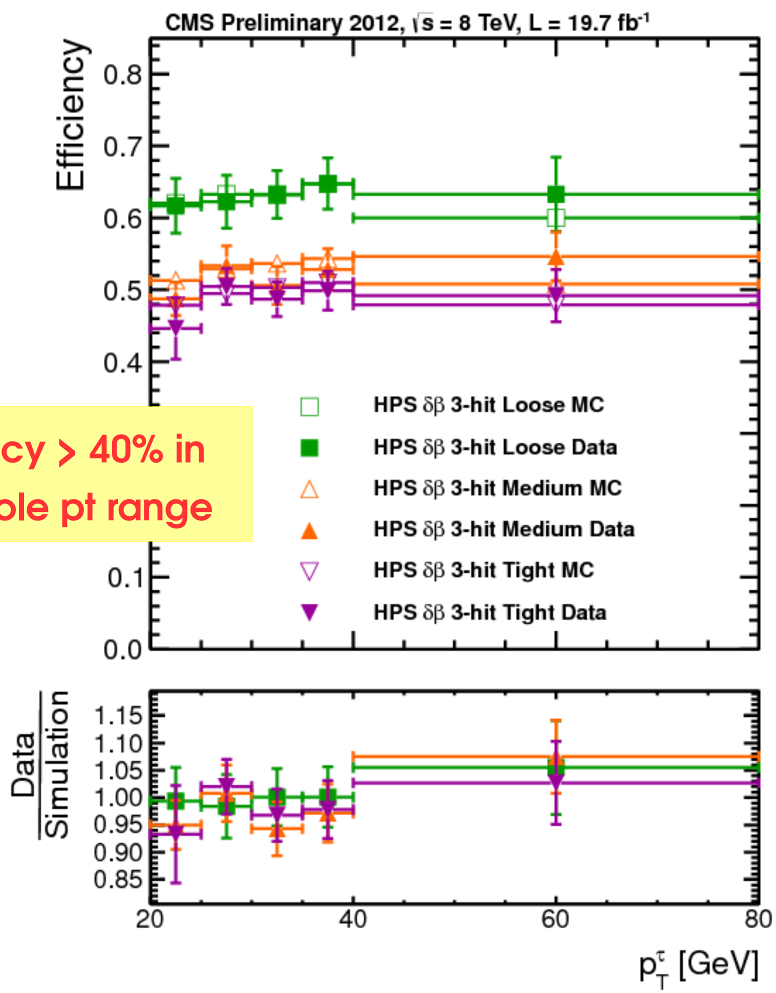


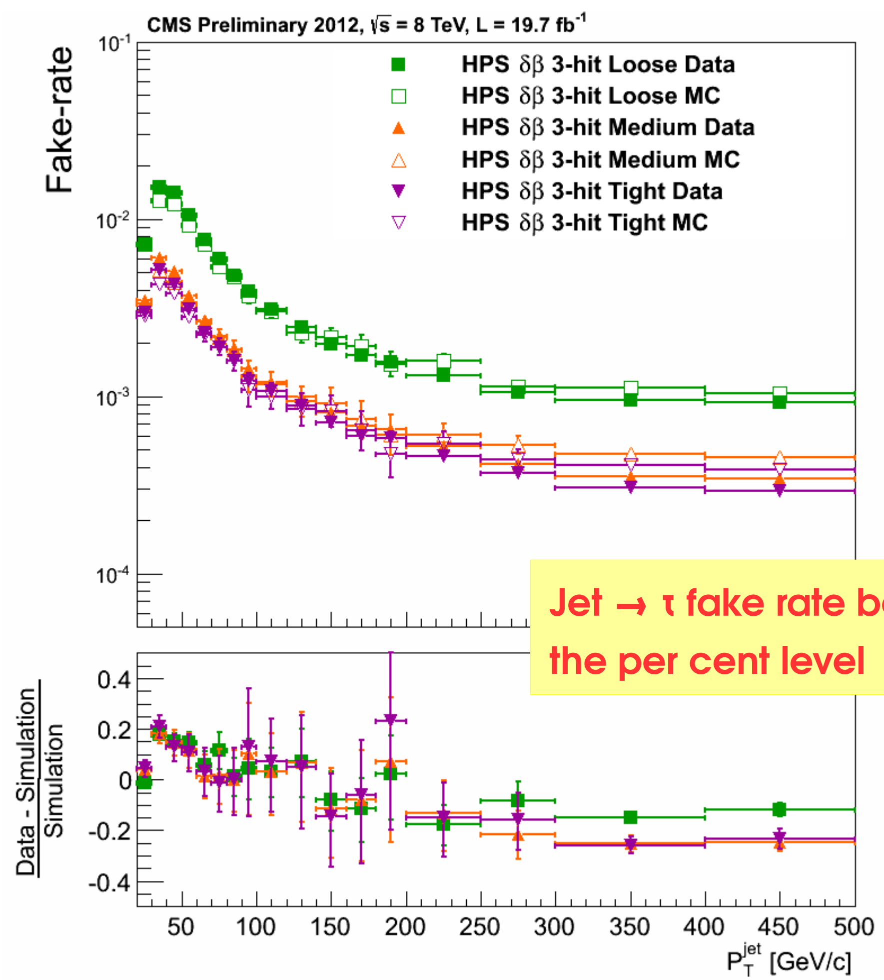
Hadronic τ reconstruction in CMS

Run1 Tau ID performance (CMS-DP-2014-015)

ID = τ_h decay mode reconstruction + isolation



Efficiency > 40% in the whole pt range



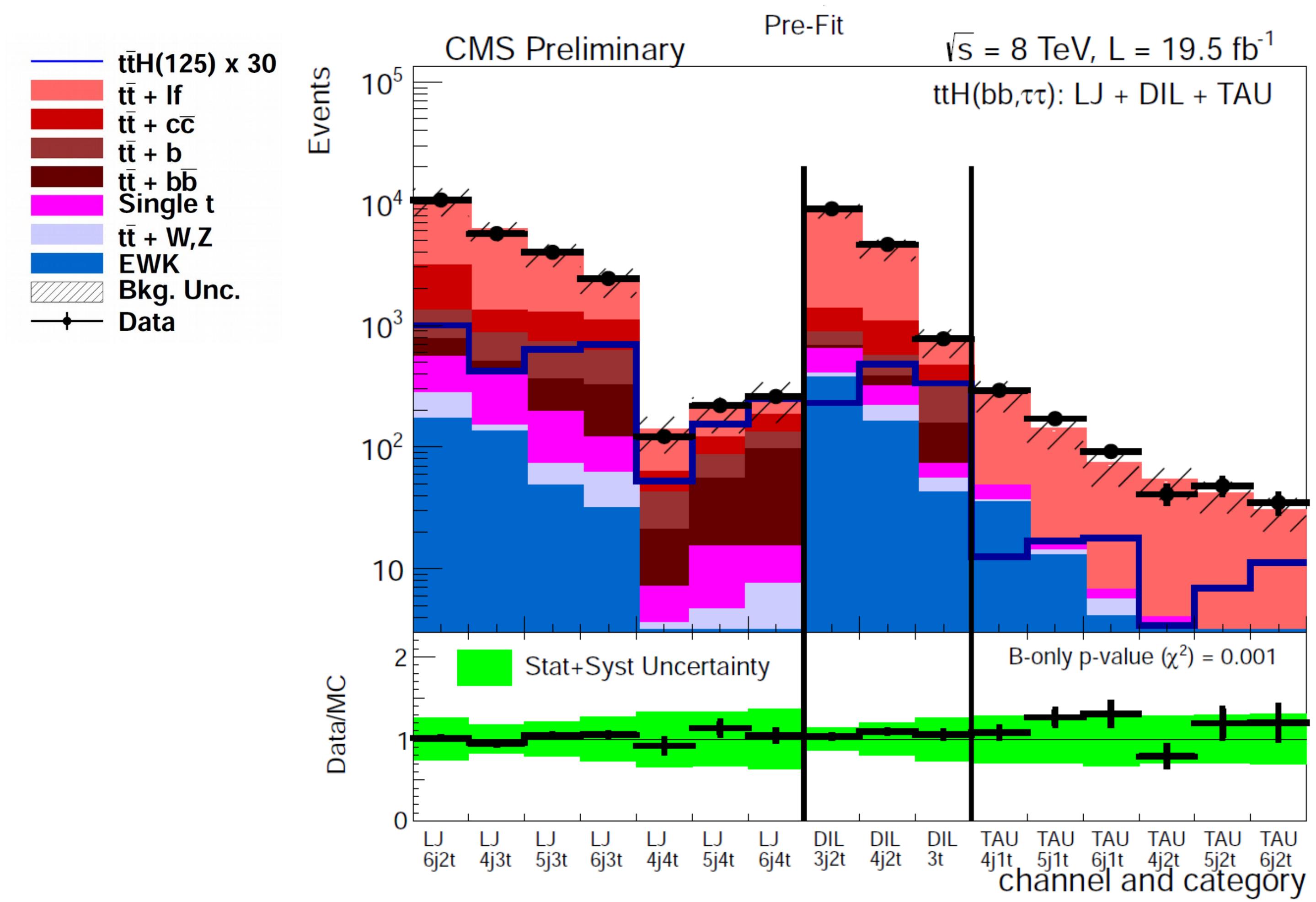
Jet → τ fake rate below the per cent level

Data well modeled by MC simulation!

SM ttH
$H \rightarrow \tau\tau$

- **H → hadrons** (HIG-13-019): both τ decaying hadronically
  8 TeV, 19.5 fb^{-1}
- **H → leptons** (HIG-13-020): at least one τ decaying leptonically
  8 TeV, 19.6 fb^{-1}
- **Combined ttH results** (HIG-14-009)
  7+8 TeV, 5.1+19.7 fb^{-1}

H → hadrons: analysis overview



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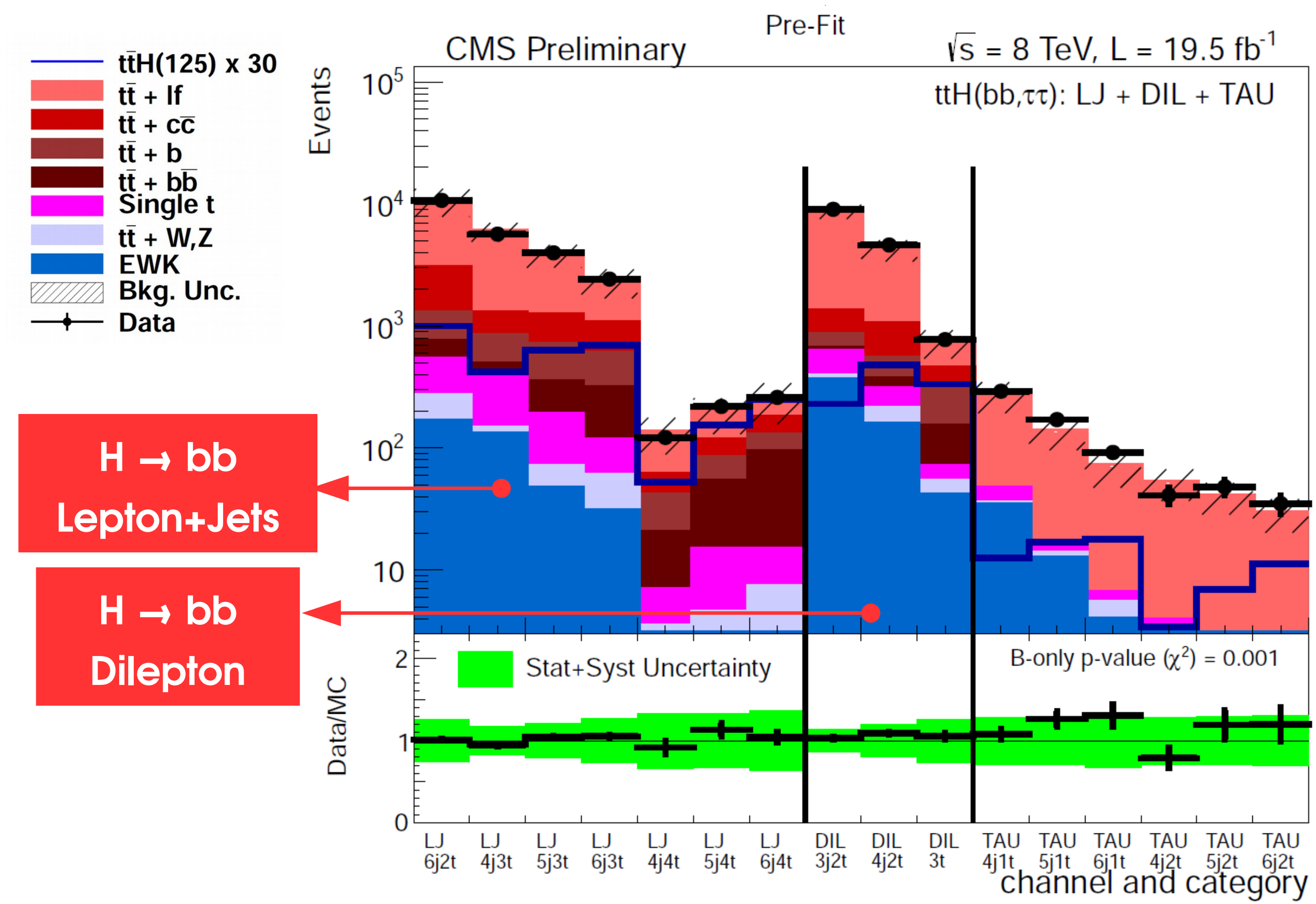
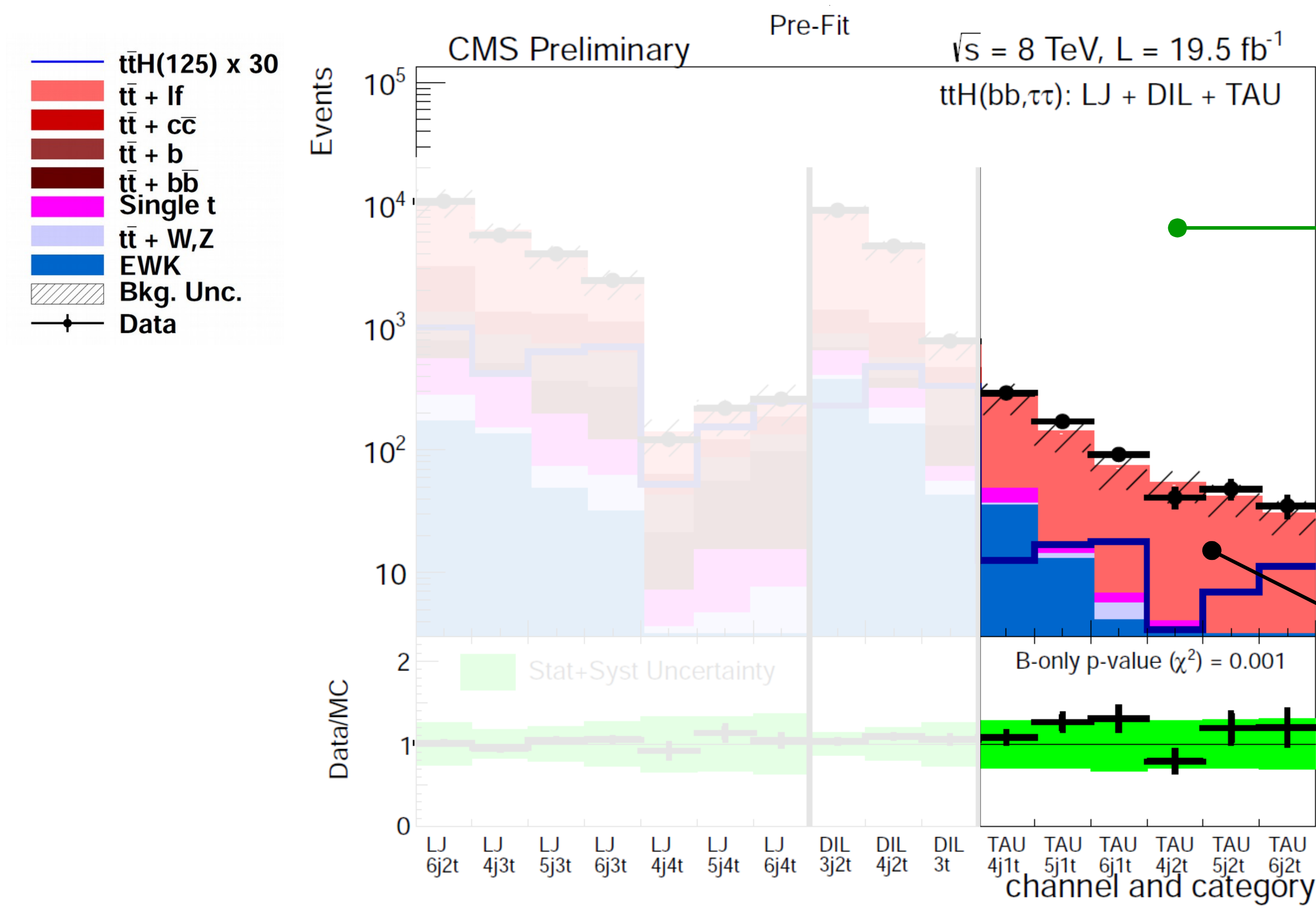


H → hadrons: analysis overview



TAU

tt → ℓνjjbb

H → ττ

- 1 e/μ
- 2, 3 or ≥4 jets
- 1 or 2 b-tagged jets
- 2 τ-tagged jets

Main background

tt+jets estimated from MC

<u>Strategy:</u> exclusive categorization in #jets and #b-jets

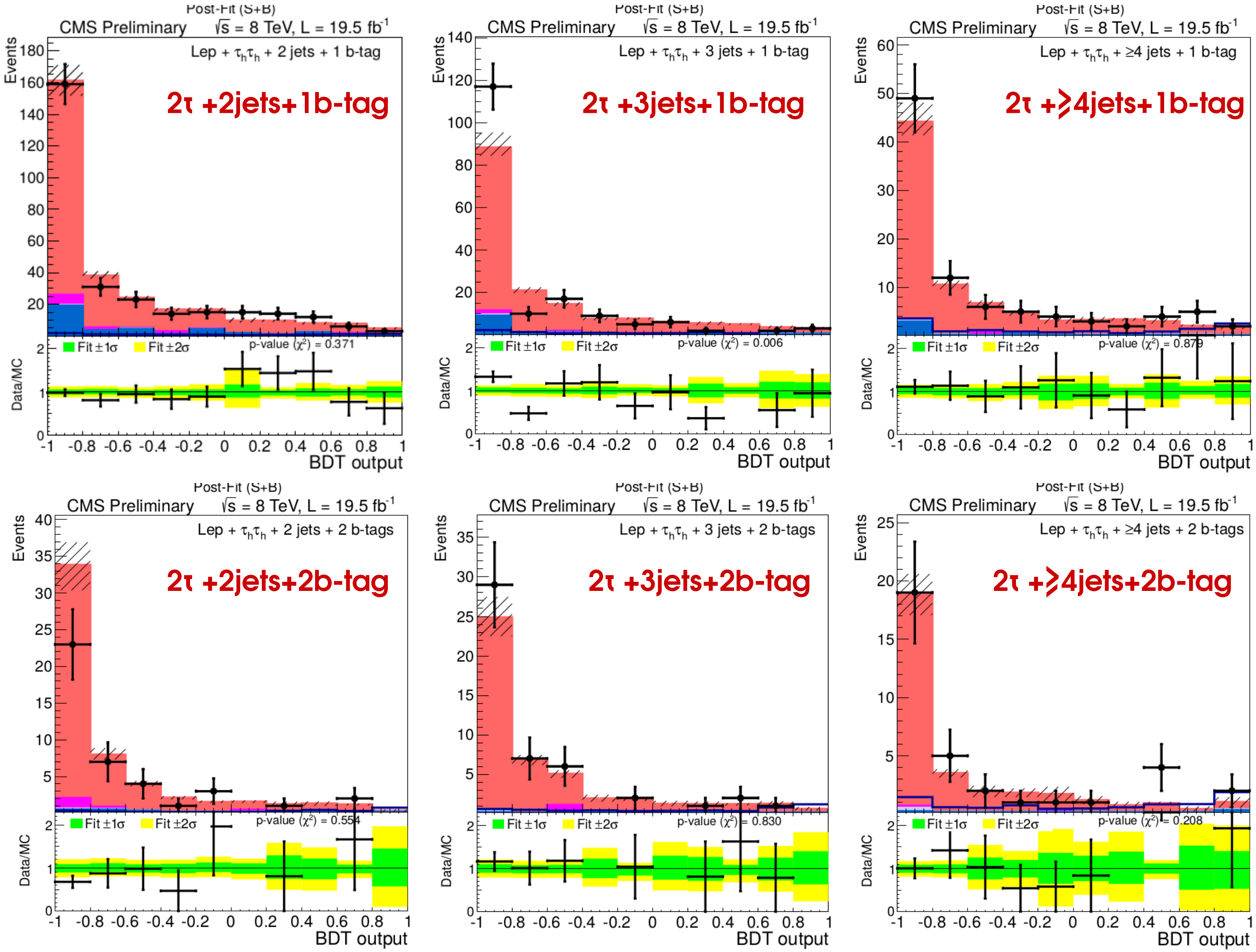
→ Better S/B at large values of #jet and/or #b-jets

→ Improve S/B using ***Boosted Decsion Trees***

- Variables used for the TAU channel: isolation, kinematics, decay mode reconstruction, di-tau visible mass shape

TAU channel final distributions

Signal extraction done fitting BDT outputs



All combined

→ **#S≈2**

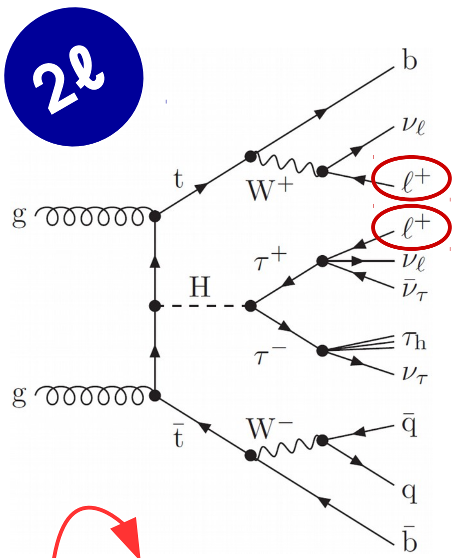
→ **S/B≈0.003**

→ Background normalized using the best fit value of all the nuisance parameters

→ Post-fit nuisance parameter uncertainties

HIG-13-020

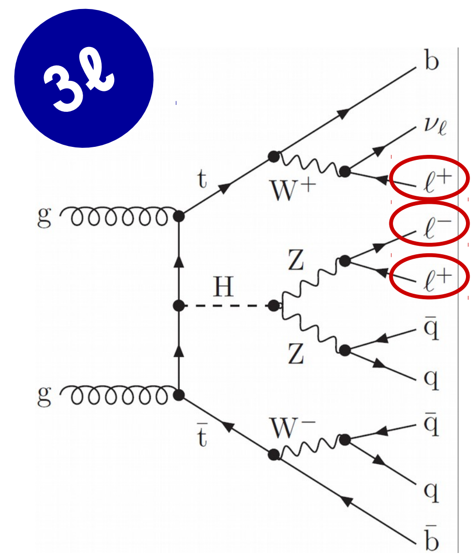
H → leptons: analysis overview



no overlap with Dilepton ttH

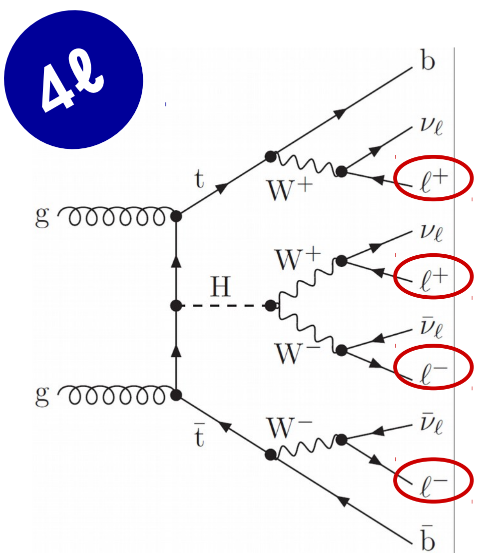
= 2ℓ (SS)	⩾ 4 jets	⩾ 1 b-jet

→ #S≈2
→ S/B≈0.02
ττ



= 3ℓ	⩾ 2 jets	⩾ 1 b-jet

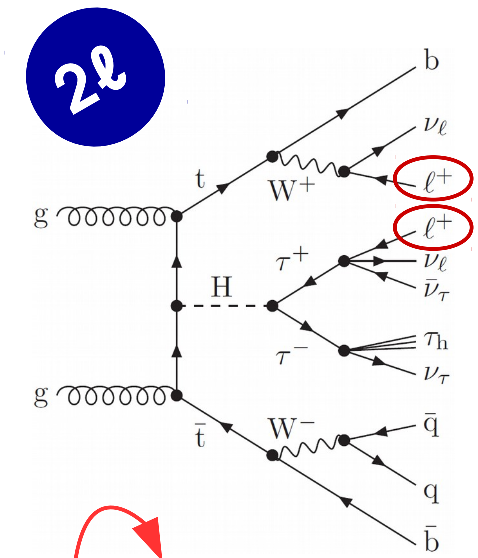
→ #S≈1
→ S/B≈0.01
ττ

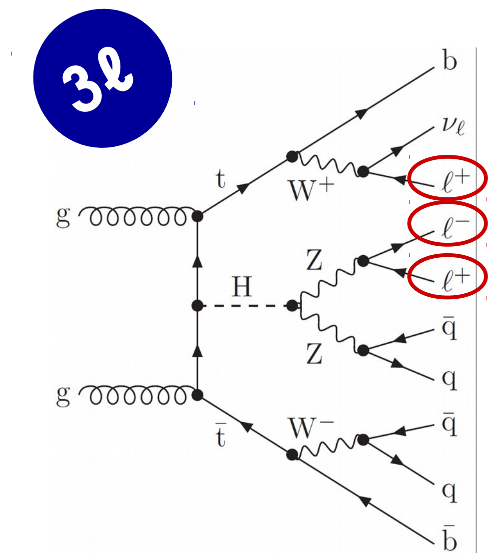


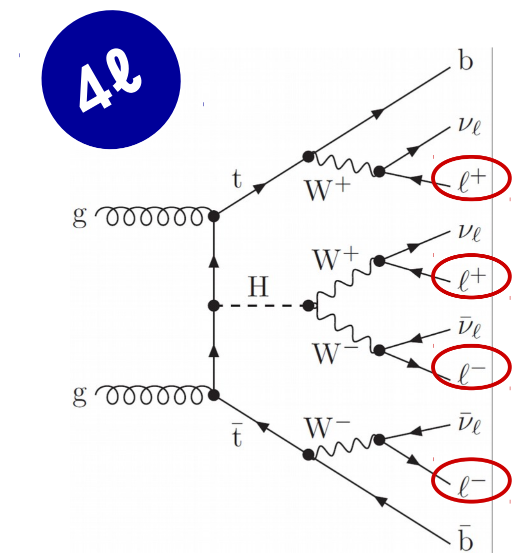
= 4ℓ	⩾ 2 jets	⩾ 1 b-jet

→ #S≈0.2
→ S/B≈0.8
ττ

H → leptons: analysis overview







no overlap with Dilepton tt̄H

= 2ℓ (SS)	≥ 4 jets	≥ 1 b-jet

→ **#S≈2**
→ **S/B≈0.02**
tt

= 3ℓ	≥ 2 jets	≥ 1 b-jet

→ **#S≈1**
→ **S/B≈0.01**
tt

= 4ℓ	≥ 2 jets	≥ 1 b-jet

→ **#S≈0.2**
→ **S/B≈0.8**
tt

S/B separation strategy

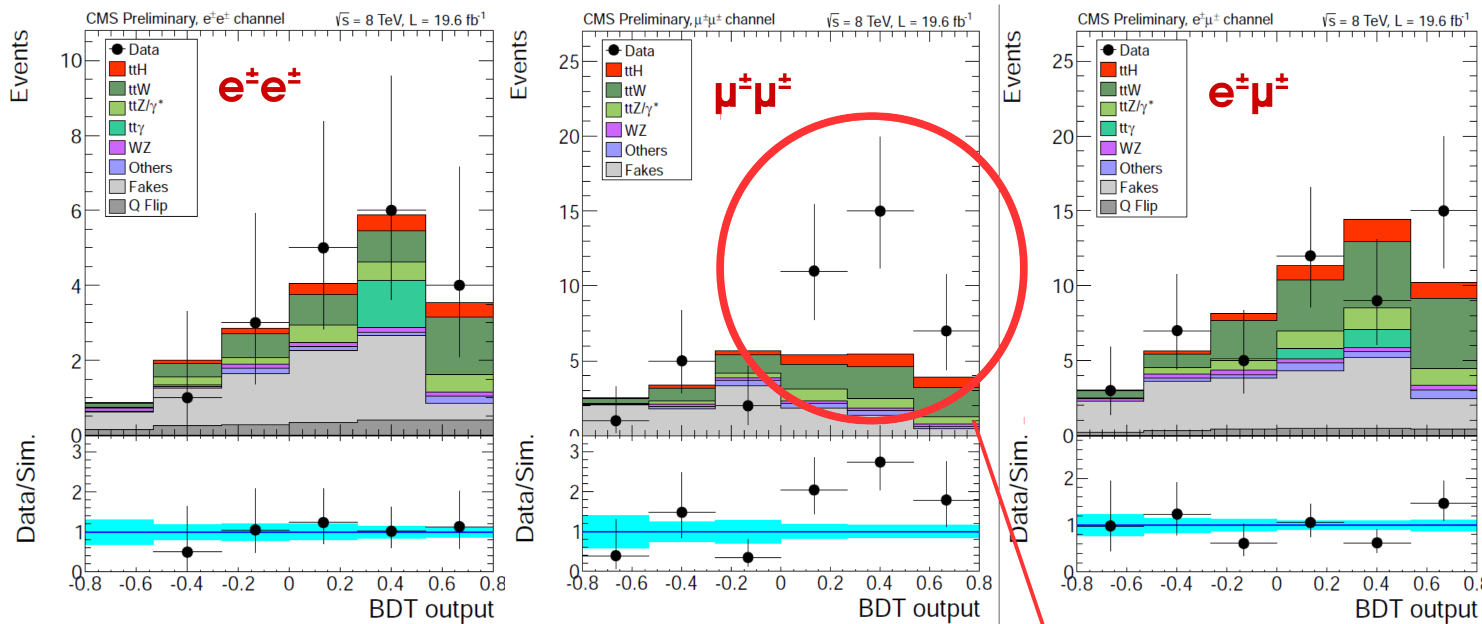
→ #jet most discriminating variable
→ **2ℓ, 3ℓ:** categorize events in positive and negative total lepton charge (ttW, WZ, W+jets asymmetric)
→ signal extracted with ***Boosted Decision Trees***
- Kinematic variables for 2ℓ and 3ℓ
- #jet only for 4ℓ

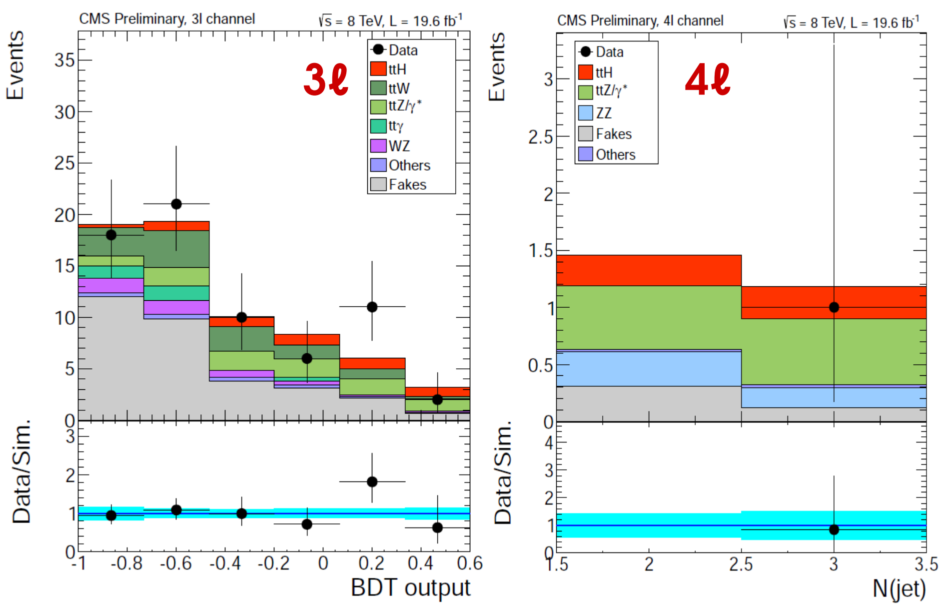
Backgrounds

→ tt+fake leptons
- (data driven estimate)

→ tt+Z/W,VV+jets
- (MC estimate only)

Final distributions





SIGNAL LIKE EXCESS!

- Unlikely from underestimated bkg. (data/MC agreement in ee and eμ).
- Excess confirmed by cross-check analysis

→ Background yields from combined fit to the final discriminant at μ=1

→ Post-fit nuisance parameter uncertainties assuming μ=1

Combined ttH results

7+8 TeV

Channel	$\mu=\sigma/\sigma_{SM}$	$\Delta\mu$
ttH, H → bb	0.65	-1.81/+1.85
ttH H → $\tau_h\tau_h$	-1.32	-3.60/+6.08
ttH H → leptons	3.94	-1.43/+1.70
ttH H → γγ	2.67	-1.73/+2.41
ttH combined	**2.76**	**-0.92/+1.05**

Contributing to the H→hadrons analysis (ttH, H → bb; ttH H → $\tau_h\tau_h$)

SS di-muon excess contribution (ttH H → leptons)

→ **Compatible with the SM expectation (μ=1) within 2σ**

→ Direct access to the Y_t coupling measurement

→ Excess mainly driven by the SS di-muon excess in the H → lepton channel and H →γγ

MSSM
$\Phi \rightarrow \tau\tau$

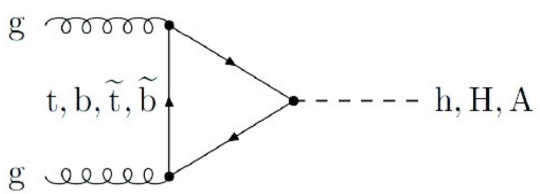
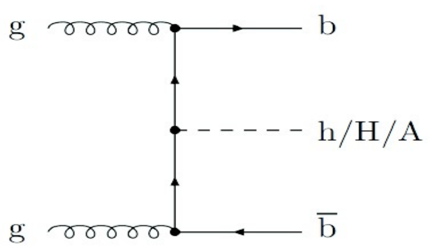
Φ generic label for any one of the neutral MSSM Higgs bosons h, H or A

- **HIG-13-021**

  7+8 TeV, 4.9+19.7 fb^{-1}

(old analysis for 7 TeV not discussed but included in the final results)

Analysis overview

Production mode	Category	Parameter space (m_A,tanβ)	Channels
 gluon-gluon fusion pp→Φ	**No b-tag** More sensitive to pp→Φ Events without b-jets	Dominates for small tanβ values.	**μμ**: 3.0% **eμ**: 6.2% **μτ_h**: 22.6% **eτ_h**: 23.1% **$\tau_h\tau_h$**: 42.0%
 b-associated production pp→Φb	**B-tag** More sensitive to pp→Φb Events with ≥1b-jets	Dominates for large tanβ values. ○ **σ(pp→Φb)*BR(Φ→ττ) highly favoured in the MSSM w.r.t. SM** because of the enhanced bottom Yukawa coupling	

Analysis overview

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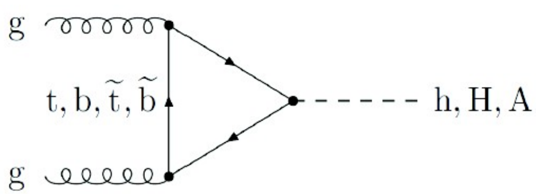
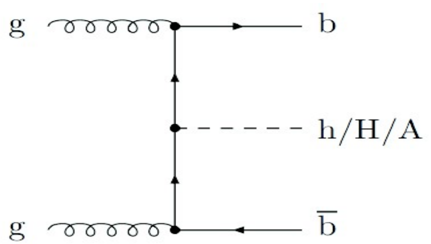
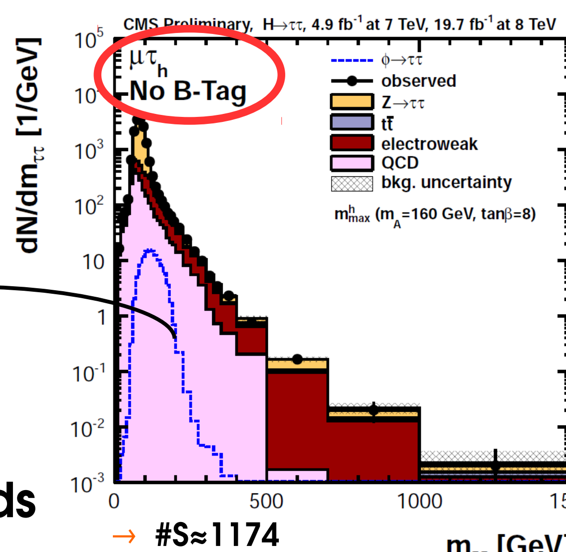
 gluon-gluon fusion pp→Φ	**No b-tag** More sensitive to pp→Φ Events without b-jets	Dominates for small tanβ values.	μμ: 3.0% eμ: 6.2% μτh: 22.6% eτh: 23.1% τhτh: 42.0%
 b-associated production pp→Φb	**B-tag** More sensitive to pp→Φb Events with ≥1b-jets	Dominates for large tanβ values. ○ **σ(pp→Φb)*BR(Φ→ττ) highly favoured in the MSSM w.r.t. SM** because of the enhanced bottom Yukawa coupling	

<u>Strategy:</u> search for peak in di-τ mass distribution

→ $m_{\tau\tau}$ reconstructed with a <u>likelihood-based method</u> **(SVFit)**

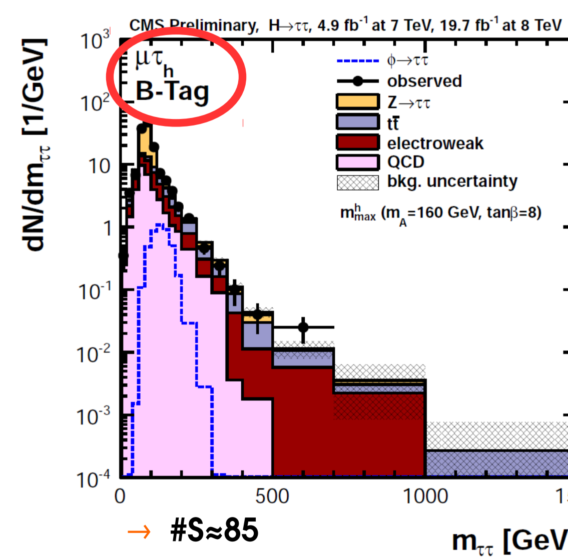
Main backgrounds

Z → ττ, QCD and electroweak



→ #S≈1174

→ S/B≈0.01



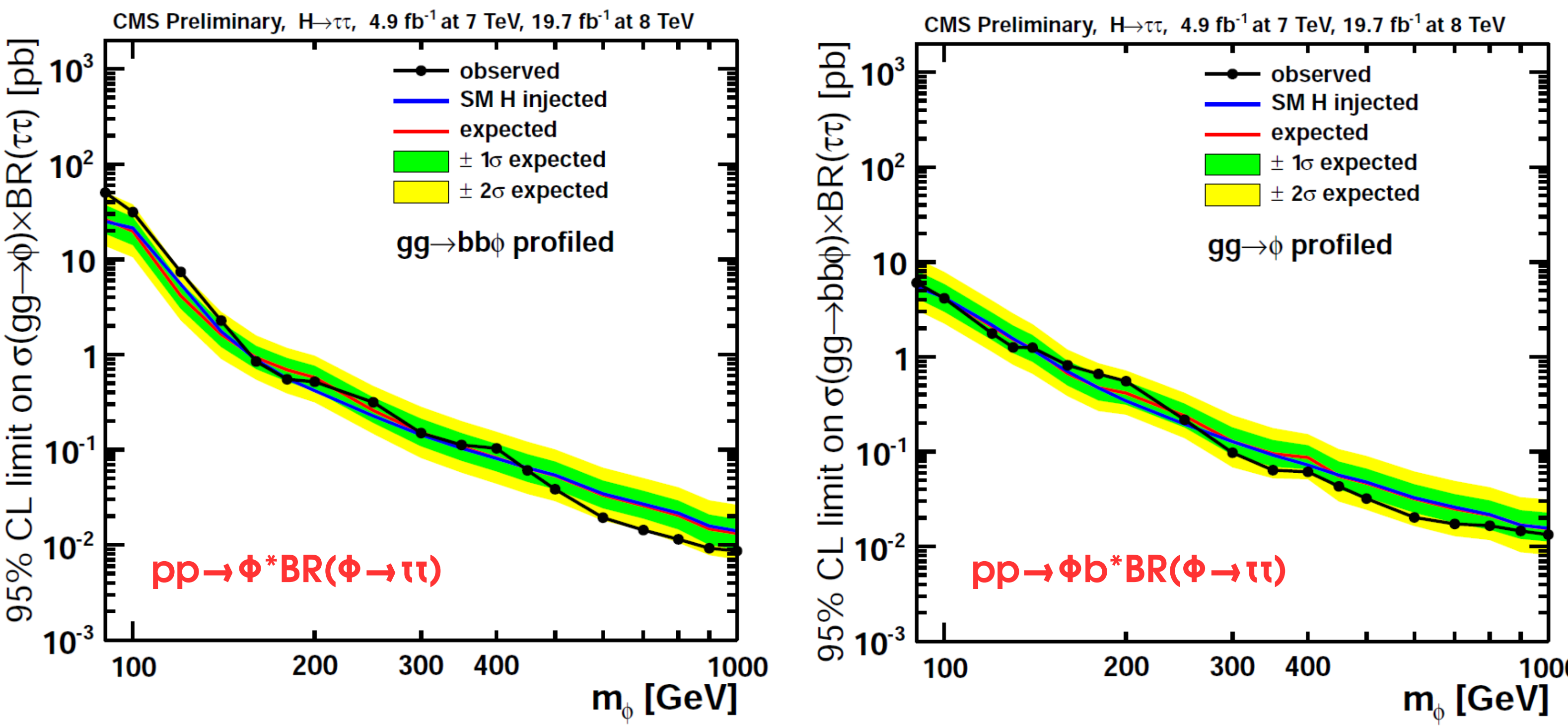
→ #S≈85

→ S/B≈0.03

Model independent limits

Invariant mass spectra show no evidence for a MSSM signal

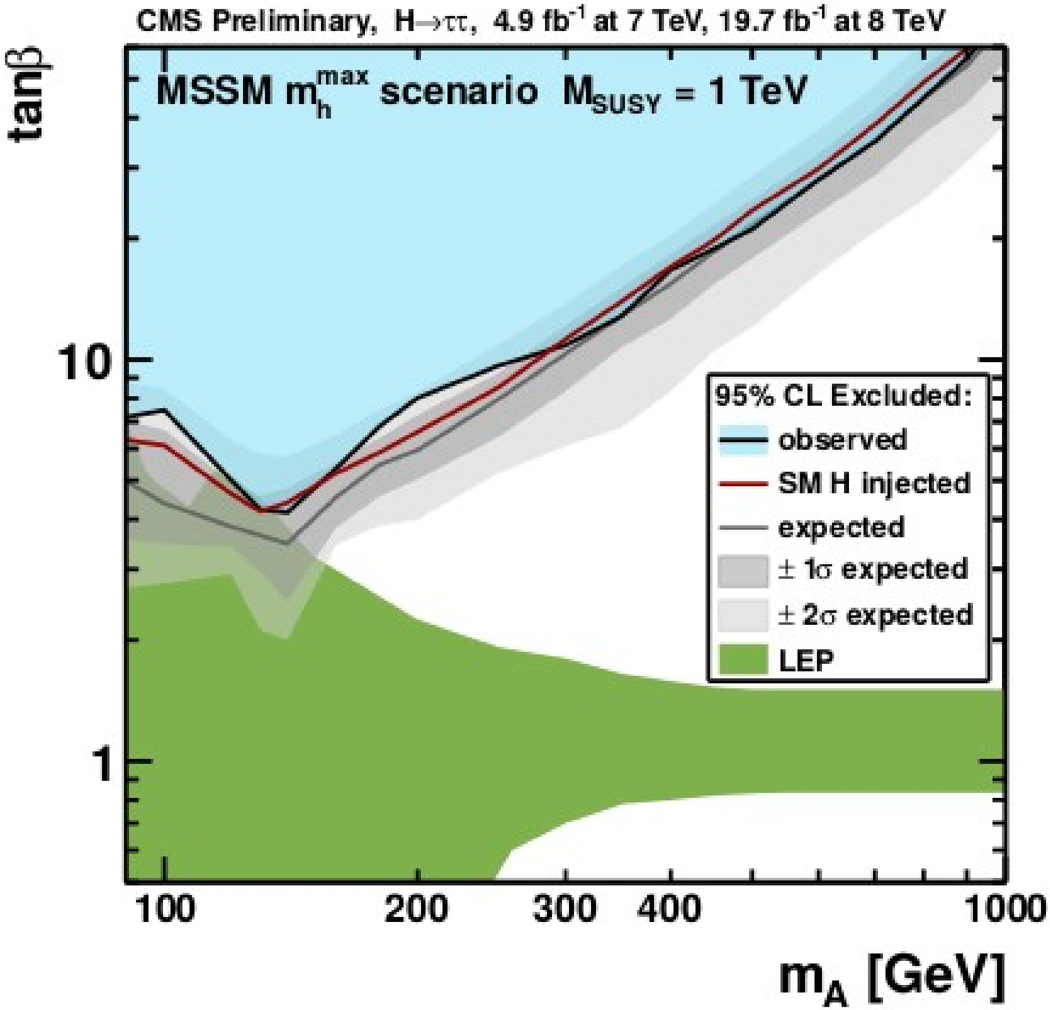
Model independent 95%CL limit on **σ*BR for ggH** and **bbH** processes



Observed results compatible with no H → ττ signal
(red) and with SM signal only (blue) hypotheses

Interpretation in the m_h^{max} scenario

Exclusion contour at 95%CL in m_A-tan(β) plane for a MSSM benchmark scenario



RED: Only SM H→ττ signal injected

GREY: No H→ττ signal (neither MSSM nor SM)

Summary and outlook

SM and MSSM CMS analyses presented focusing on the search for (pseudo-)scalar boson(s) in the ττ decay channel

SM ttH

→ μ from combined fit (H→hadrons/H→leptons/H →γγ) is compatible with the SM expectation at 2σ level

→ excess driven by the SS di-muon channel

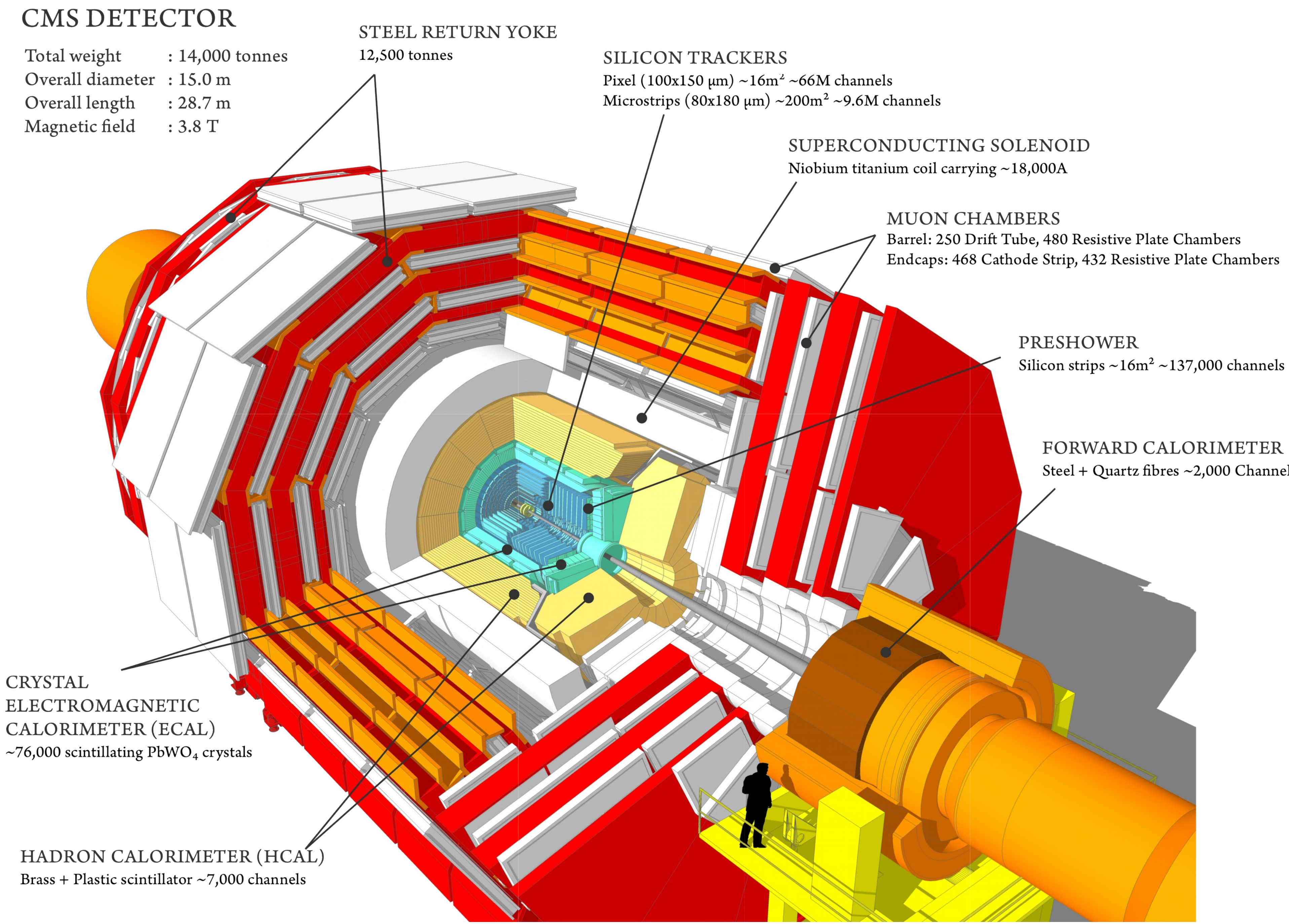
MSSM Φ→ττ

→ No evidence for a MSSM Higgs signal observed in CMS data so far

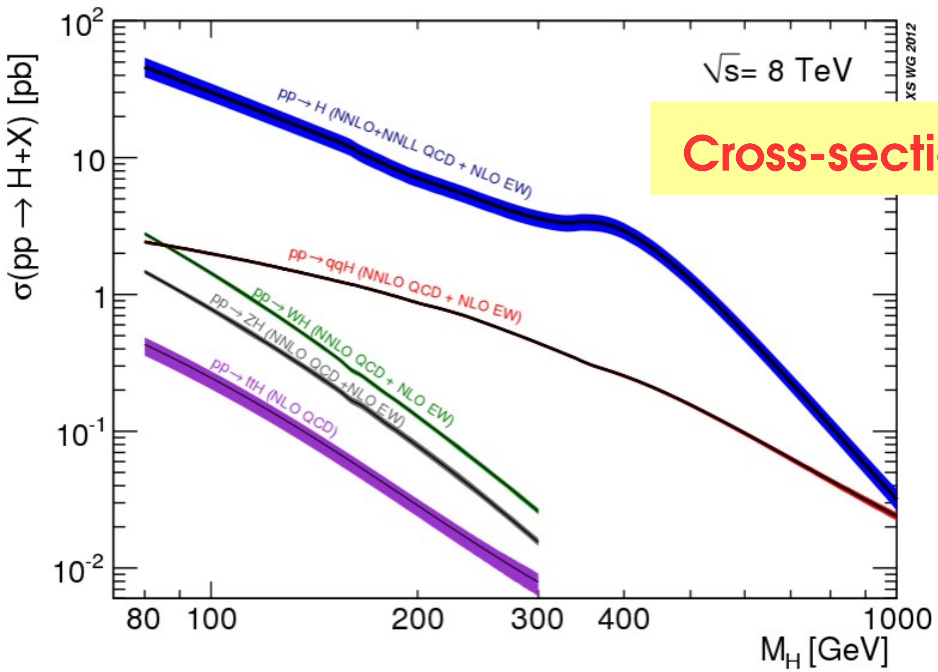
- Additional and promising BSM Higgs analyses ongoing in the ττ final state
- Expected enhanced sensitivity with higher center-of-mass energy and luminosity
- **<u>Run2 is coming...stay tuned!</u>**

Backup

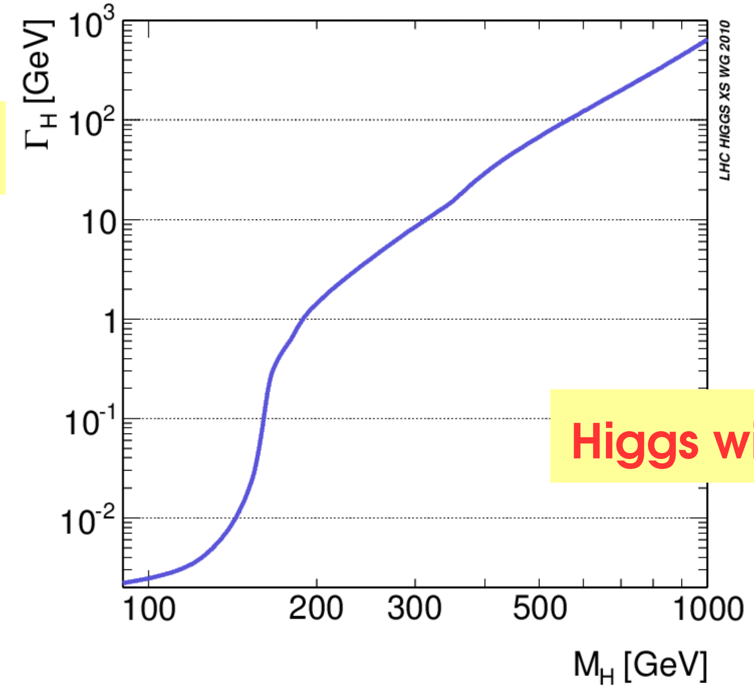
The CMS detector



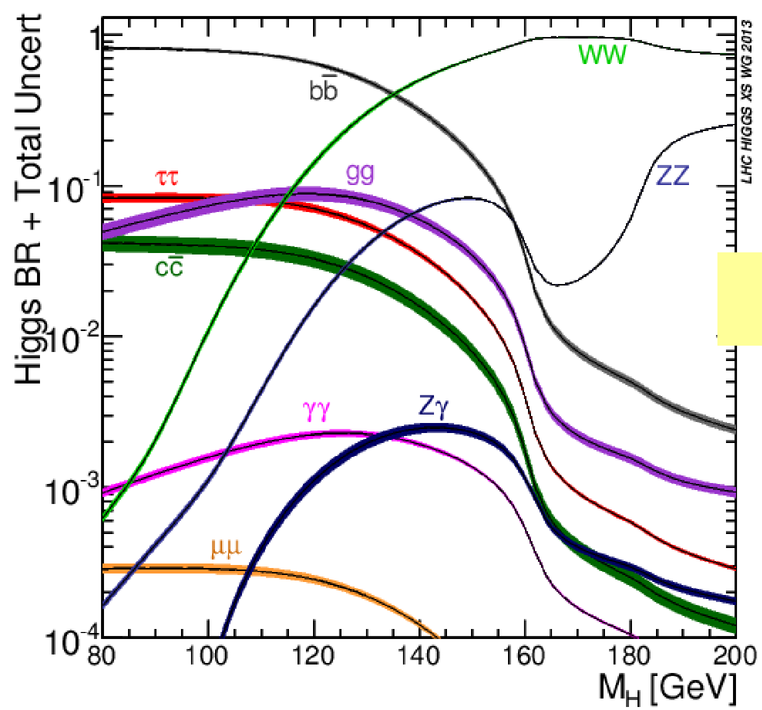
SM Higgs



Cross-section

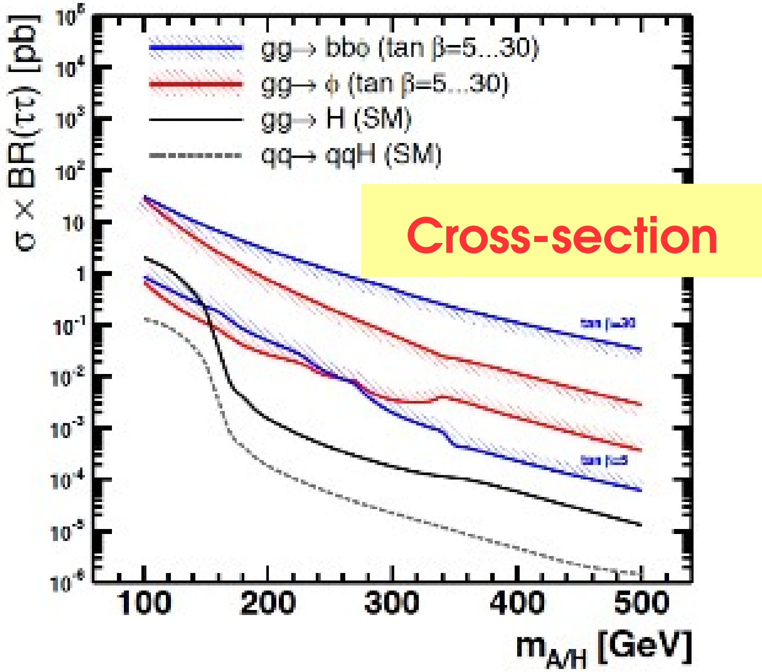


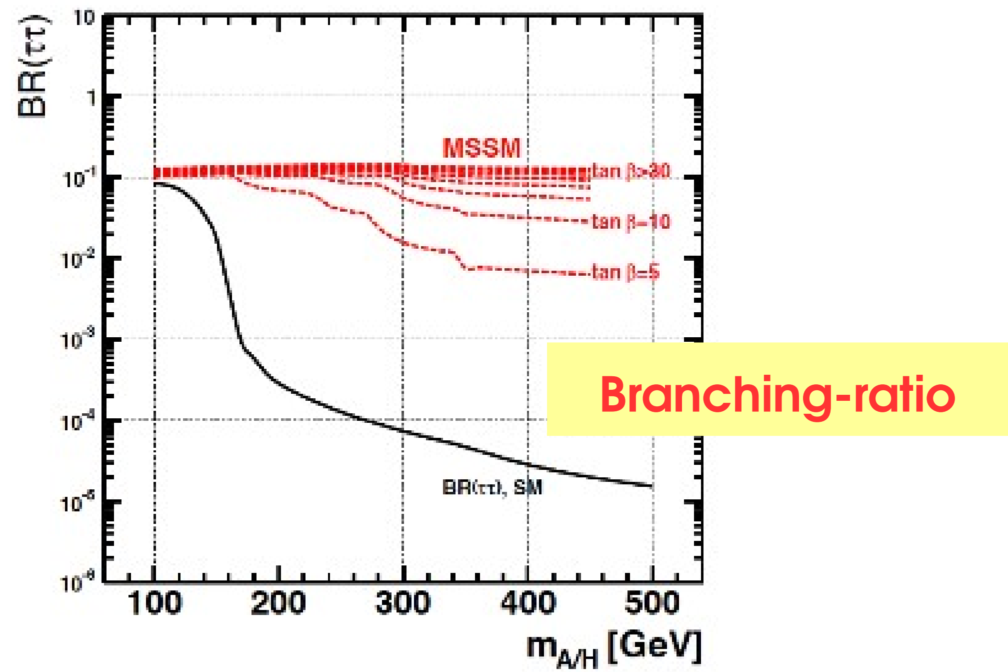
Higgs width



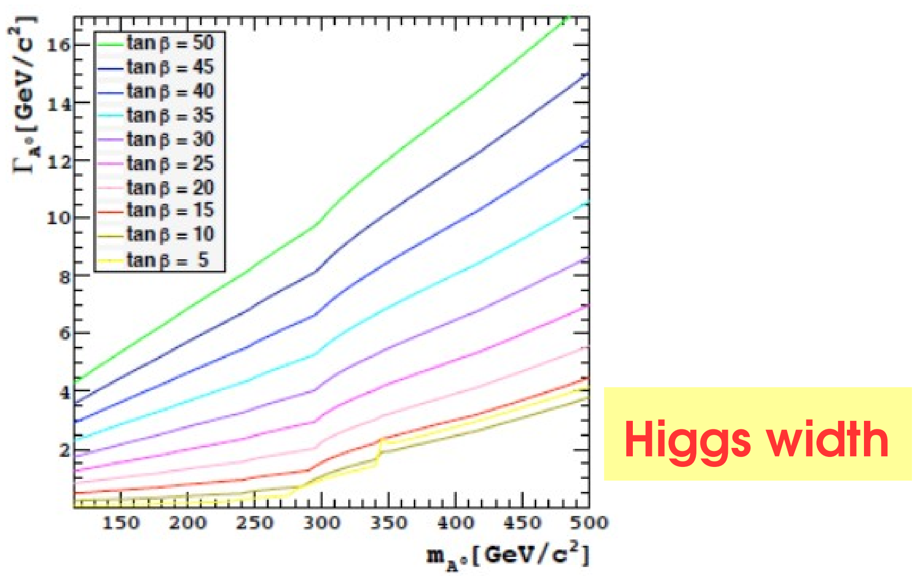
Branching-ratio

MSSM neutral Higgs

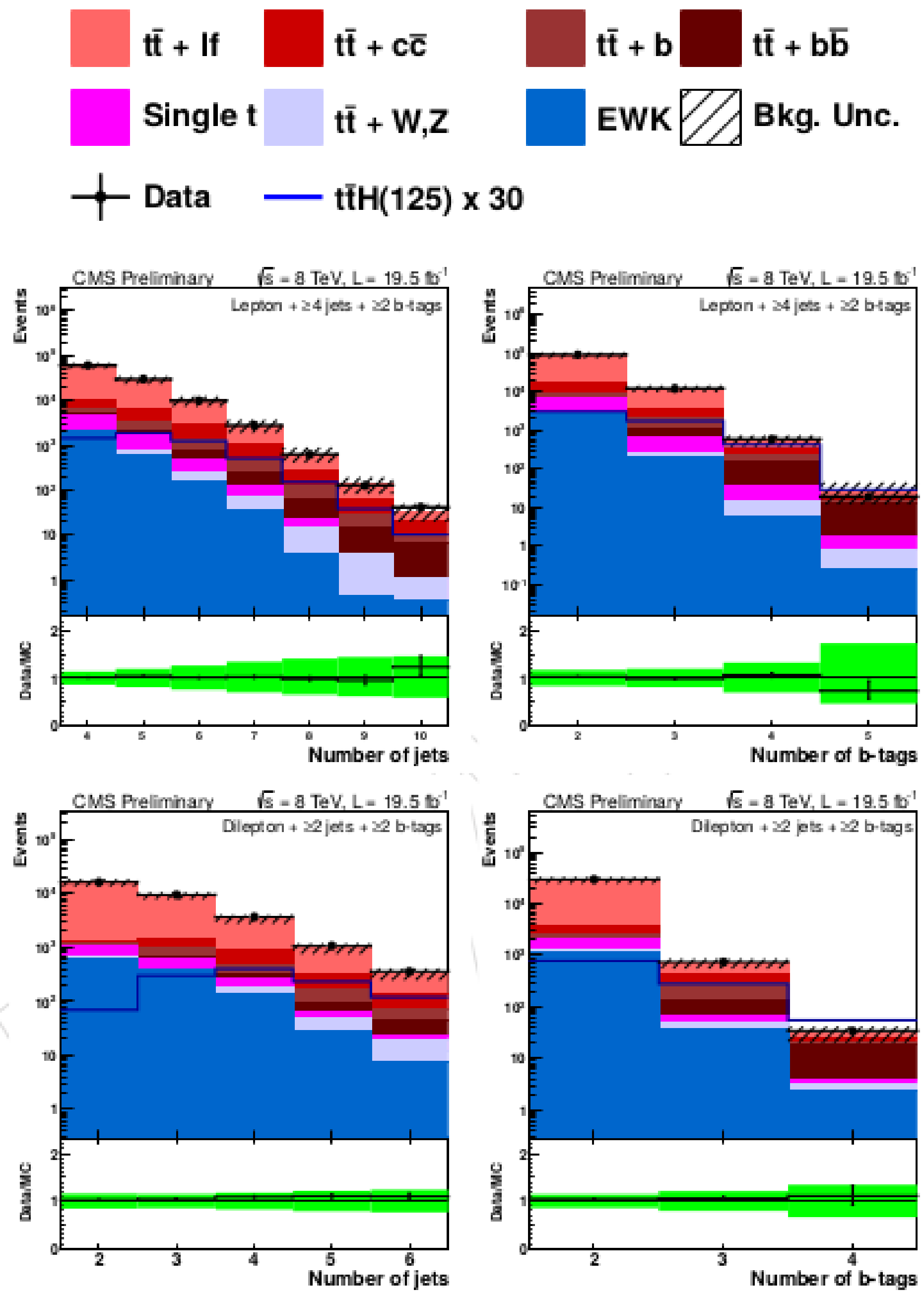




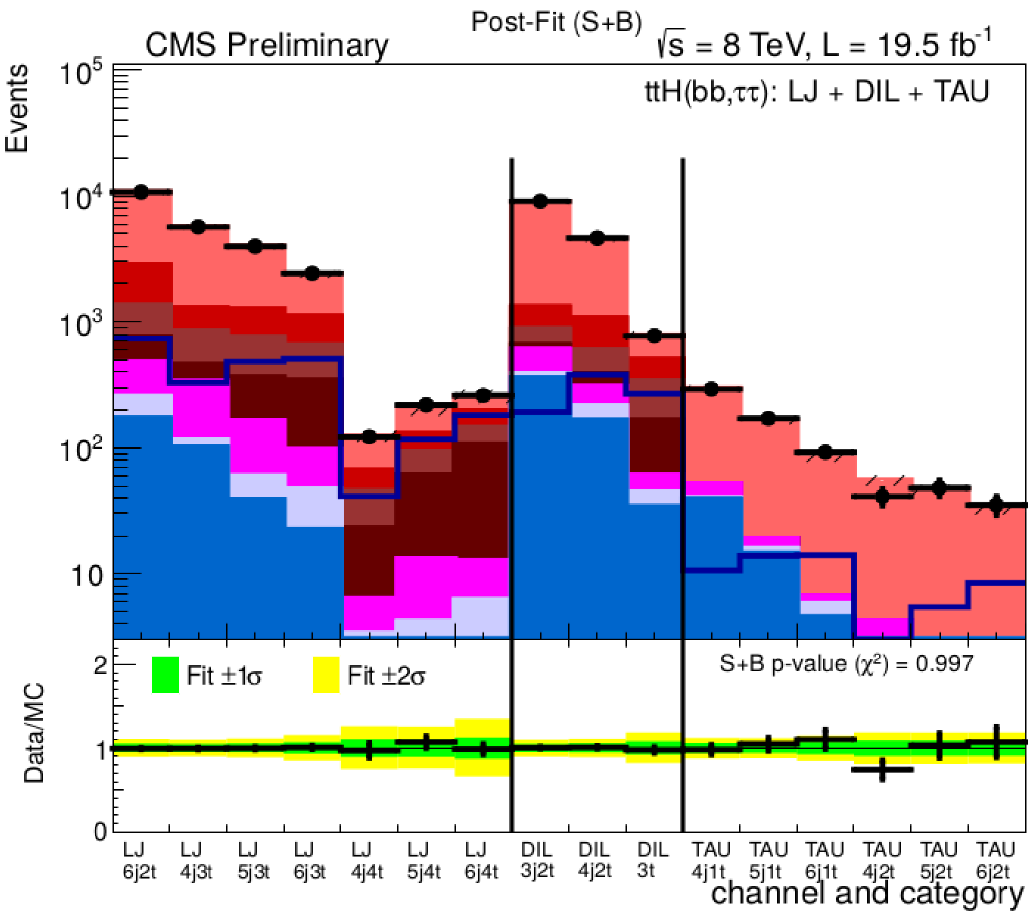
- Signal cross-section decreases with the Higgs mass
- For high tanβ values the Higgs-tau fermion coupling is highly enhanced



H → hadrons analysis: #jets, #b-jets



H → hadrons analysis: backgrounds

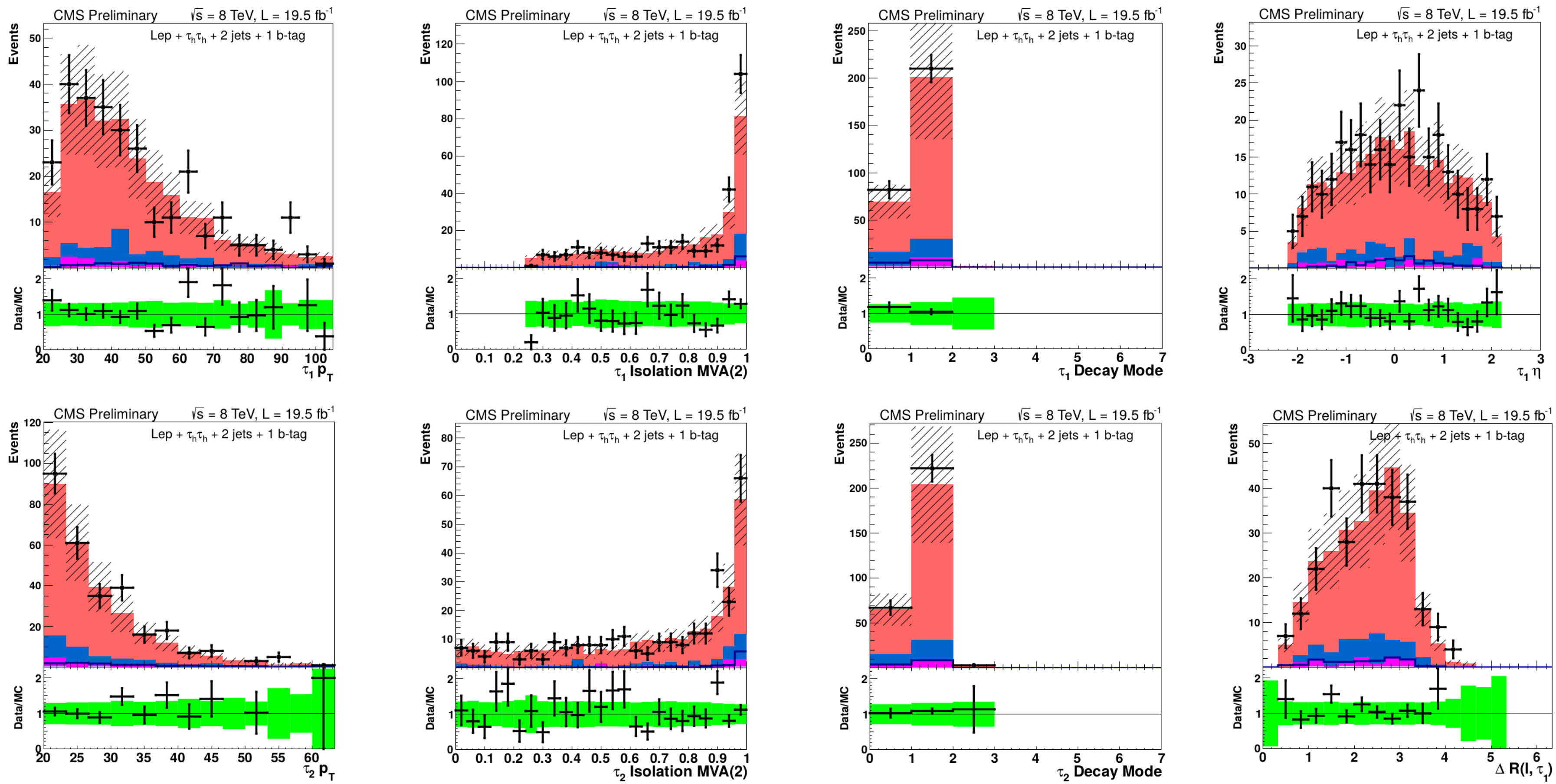


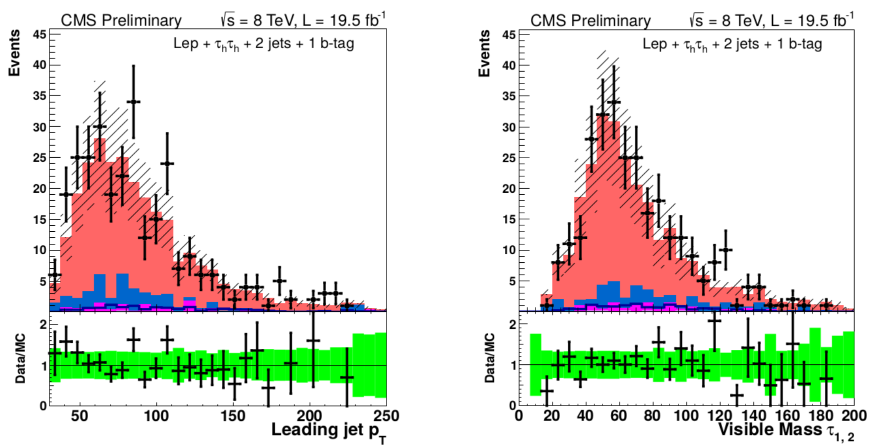
(POST-FIT) Comparison of yields for all the different categories and channels using the best fit nuisance parameter values

- → All bkg modeled with MC simulation
- → **Main bkg tt+jets** (MadGraph tt+3 extra parton) separated in sub-samples to account for different uncertainties:
  - ○ tt+cc
  - ○ tt+bb
  - ○ tt+b

  } tt+HF(high flavor)
  - ○ tt+LF (light flavor)
- → 50% a priori uncertainty assigned to tt+HF because of the difficulty to constrain the normalization of these backgrounds

H → hadrons analysis: TAU BDT inputs



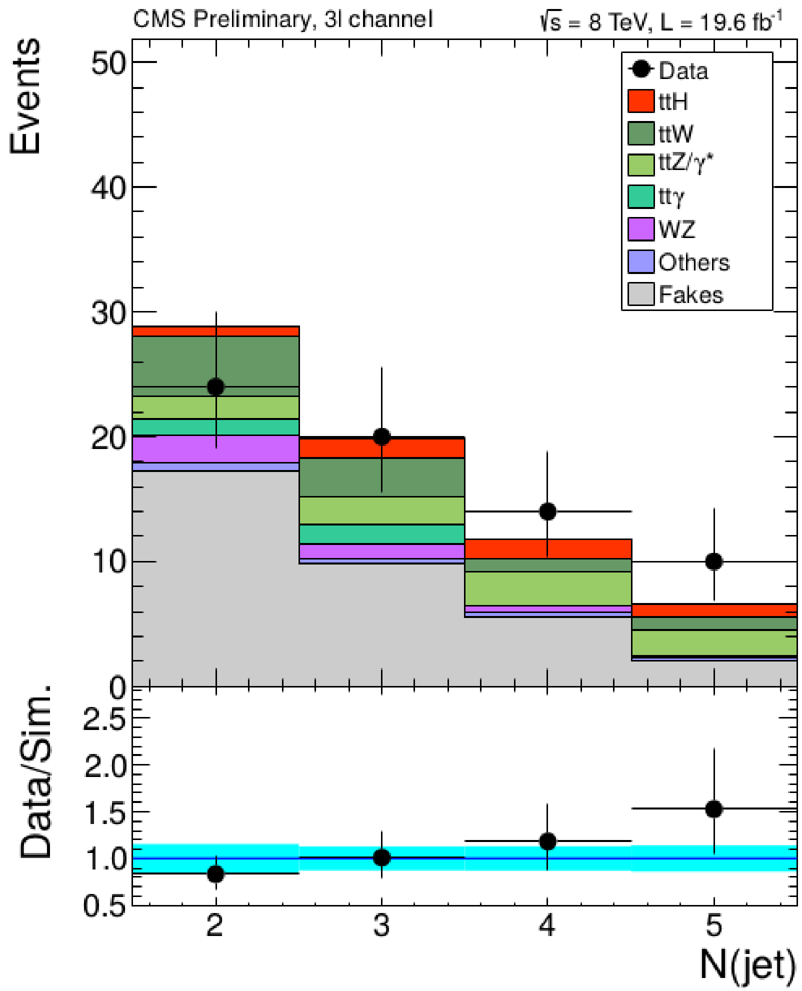


Variable	Description
Tau1Pt	The p_T of the more energetic τ
Tau2Pt	The p_T of the less energetic τ
Tau1Eta	The $\|\eta\|$ of the more energetic τ
Tau1IsolationMVA2Raw	The HPS MVA2 score of the more energetic τ
Tau2IsolationMVA2Raw	The HPS MVA2 score of the less energetic τ
DitauVisibleMass	The reconstructed visible mass from the τ-pair
DeltaRTau1Lepton	The distance between the more energetic τ and the lepton
Tau1DecayMode	The decay mode of the more energetic τ
Tau2DecayMode	The decay mode of the less energetic τ
LeadingJetPt	The leading jet p_T, excluding jets from the selected τ

H → hadrons analysis: systematics

Source	Shape	Remarks
Luminosity	No	Signal and all backgrounds
Lepton ID/Trigger efficiency	No	Signal and all backgrounds
Pileup	No	Signal and all backgrounds
Top p_T reweighting	Yes	Only $t\bar{t}$ background
Jet Energy Resolution	No	Signal and all backgrounds
Jet Energy Scale	Yes	Signal and all backgrounds
b-Tag bottom-flavor contamination	Yes	Signal and all backgrounds
b-Tag bottom-flavor statistics (linear)	Yes	Signal and all backgrounds
b-Tag bottom-flavor statistics (quadratic)	Yes	Signal and all backgrounds
b-Tag light-flavor contamination	Yes	Signal and all backgrounds
b-Tag light-flavor statistics (linear)	Yes	Signal and all backgrounds
b-Tag light-flavor statistics (quadratic)	Yes	Signal and all backgrounds
b-Tag Charm uncertainty (linear)	Yes	Signal and all backgrounds
b-Tag Charm uncertainty (quadratic)	Yes	Signal and all backgrounds
QCD Scale ($t\bar{t}$H)	No	Scale uncertainty for NLO $t\bar{t}$H prediction
QCD Scale ($t\bar{t}$)	No	Scale uncertainty for NLO $t\bar{t}$ and single top predictions
QCD Scale (V)	No	Scale uncertainty for NNLO W and Z prediction
QCD Scale (VV)	No	Scale uncertainty for NLO diboson prediction
PDF (gg)	No	Parton distribution function (PDF) uncertainty for gg initiated processes ($t\bar{t}$, $t\bar{t}$Z, $t\bar{t}$H)
PDF ($q\bar{q}$)	No	PDF uncertainty for $q\bar{q}$ initiated processes ($t\bar{t}$W, W, Z).
PDF (qg)	No	PDF uncertainty for qg initiated processes (single top)
Madgraph Q^2 Scale ($t\bar{t}$+0p,1p,2p)	Yes	Madgraph Q^2 scale uncertainty for $t\bar{t}$+jets split by parton number. There is one nuisance parameter per parton multiplicity and they are uncorrelated.
Madgraph Q^2 Scale ($t\bar{t}$+b/$b\bar{b}$/$c\bar{c}$)	Yes	Madgraph Q^2 scale uncertainty for $t\bar{t}$+b/$b\bar{b}$/$c\bar{c}$.
Madgraph Q^2 Scale (V)	No	Varies by jet bin.
Extra $t\bar{t}$+hf rate uncertainty	No	A 50% uncertainty in the rate of $t\bar{t}$+b, $t\bar{t} + b\bar{b}$, $t\bar{t} + c\bar{c}$.
τ Energy Scale	Yes	Tau signal and background
τ ID efficiency	Yes	Tau signal and background
τ Jet Fake Rate	Yes	Tau signal and background
τ Electron Fake Rate	Yes	Tau signal and background

H → leptons analysis: backgrounds



- → **ttV (ttZ, ttW, ttWW):** estimated from MC simulation
- → **Dibosons (WZ, ZZ):** estimated from MC simulation with data-driven corrections applied to the yields coming from dedicated control regions (vetoing events with a loose b-tag. Diboson events mainly produced in association with light jets).
- → **Fakes:** data-driven estimate. Control region defined by selecting events with the same kinematics as the signal region, but for which at least one of the leptons fails the multivariate lepton discriminant. The extrapolation to the signal region is performed by weighting the events in the control region as function of the probabilities for background-like leptons to pass the final requirements.

H → leptons analysis: systematics

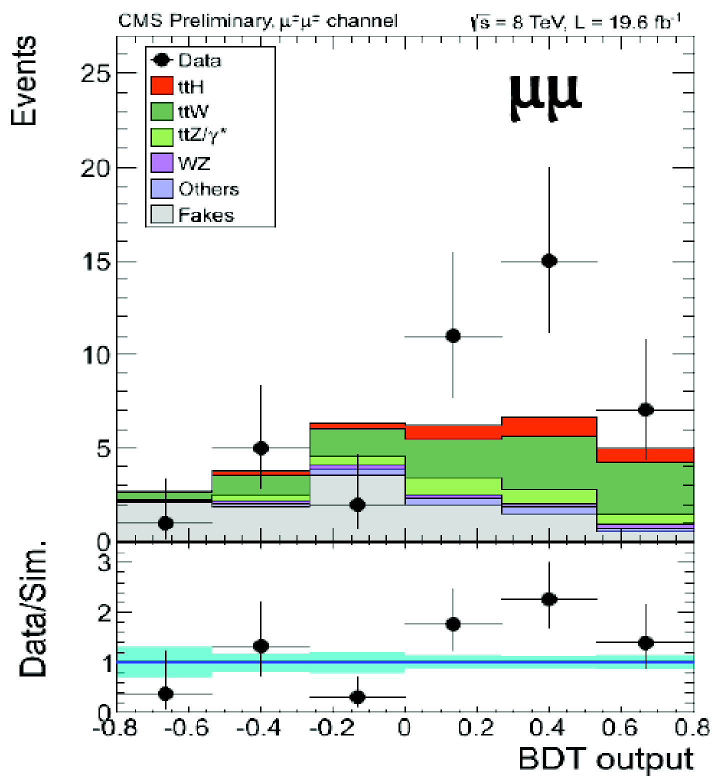
Syst Name	Rate or Shape	Description
$t\bar{t}H$ higher orders	rate	Theoretical uncertainty on $t\bar{t}H$ cross section.
$t\bar{t}W$ higher orders	rate	Theoretical uncertainty on $t\bar{t}W$ cross section.
$t\bar{t}Z$ higher orders	rate	Theoretical uncertainty on $t\bar{t}Z$ cross section.
PDF	rate	Theoretical uncertainty on cross sections for $t\bar{t}H$, $t\bar{t}W$, $t\bar{t}Z$. Correlated in all channels for all processes sharing a dominant production mechanism.
$t\bar{t}H$ PDF Shape	shape only	Theoretical uncertainty from PDF on shape.
$t\bar{t}W$ PDF Shape	shape only	Theoretical uncertainty from PDF on shape.
$t\bar{t}Z$ PDF Shape	shape only	Theoretical uncertainty from PDF on shape.
$t\bar{t}H$ PYTHIA tune	shape only	Theoretical uncertainty on MC modeling.
$t\bar{t}W$ MADGRAPH tune	shape only	Theoretical uncertainty on MC modeling.
$t\bar{t}Z$ MADGRAPH tune	shape only	Theoretical uncertainty on MC modeling.
Non-prompt Fake Rate	envelope	Applied to reducible non-prompt backgrounds.
Charge-flip	envelope	Applied to charge flip background for 2ℓ channel.
WZ	rate	Uncertainty from fit in control region.
ZZ	rate	Uncertainty from fit in control region.
Jet Energy Scale	template	Applied to WZ,ZZ,$t\bar{t}W$,$t\bar{t}Z$,$t\bar{t}H$.
b-tagging efficiency	rate	Applied to WZ,ZZ,$t\bar{t}W$,$t\bar{t}Z$,$t\bar{t}H$.
b-tagging fake rate	rate	Applied to WZ,ZZ,$t\bar{t}W$,$t\bar{t}Z$,$t\bar{t}H$.
Lepton Trigger Scale factor	rate	Applied to WZ,ZZ,$t\bar{t}W$,$t\bar{t}Z$,$t\bar{t}H$.
Lepton preselection Scale factor	rate	Applied to WZ,ZZ,$t\bar{t}W$,$t\bar{t}Z$,$t\bar{t}H$.
Lepton MVA discriminator scale factor	rate	Applied to W,ZZ,$t\bar{t}W$,$t\bar{t}Z$,$t\bar{t}H$.
Luminosity	rate	Applied to WZ,ZZ,$t\bar{t}W$,$t\bar{t}Z$,$t\bar{t}H$.

$t\bar{t}$H with H→ lepton
SS di-muon excess

From C. Botta talk (Moriond 2014)

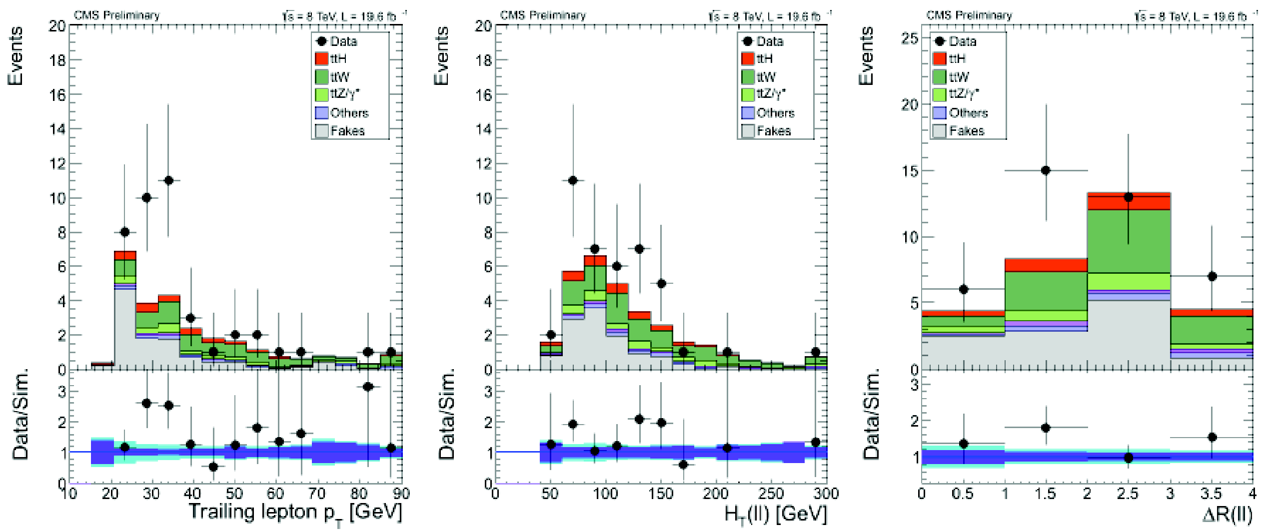
Nominal result

- The results in the different channels are fairly close to the SM Higgs predictions except in the $\mu^\pm\mu^\pm$ final state
  - **Excess of events** compared to the expectations, in the **signal-like region** of the final BDT discriminator

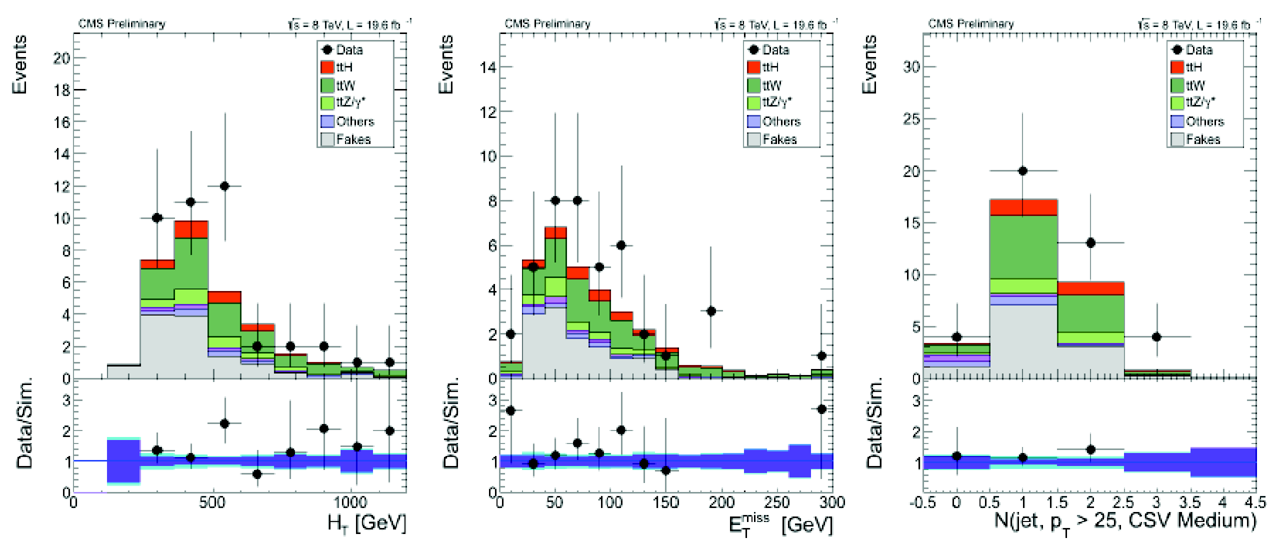


Process	Expected ± syst.
ttH	2.7 ± 0.4
ttW	8.2 ± 1.4
ttZ/γ*	2.5 ± 0.5
WZ	0.8 ± 0.9
Others	1.4 ± 0.1
Reducible	10.8 ± 4.8
Data	41

Event kinematics

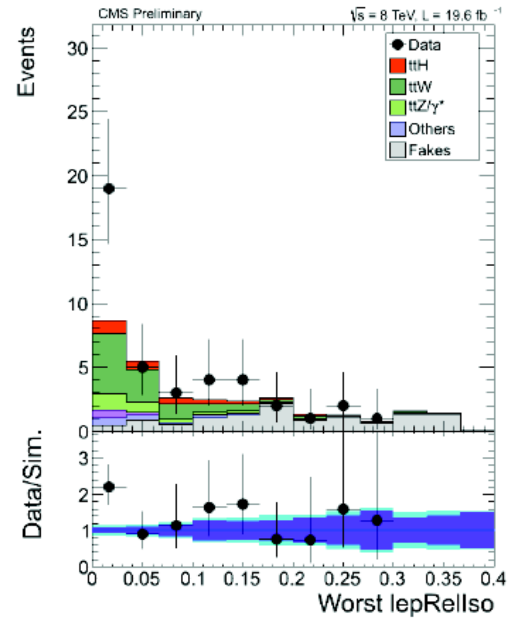


- The **kinematic of the leptons** in the events does not show anomalies and is compatible with that of signal or ttV events

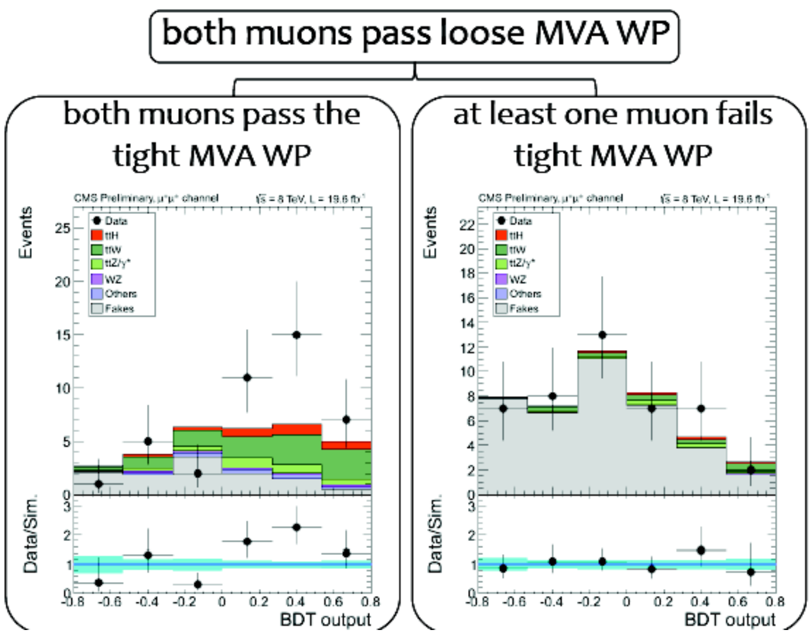


- **Jets and E_T^{miss}** are more compatible with signal or ttV.
- The multeplicity of **b-tags** is also signal-like (while the reducible background has more often only 1 b-tag since the other b-jet is misidentified as a lepton)

Leptons



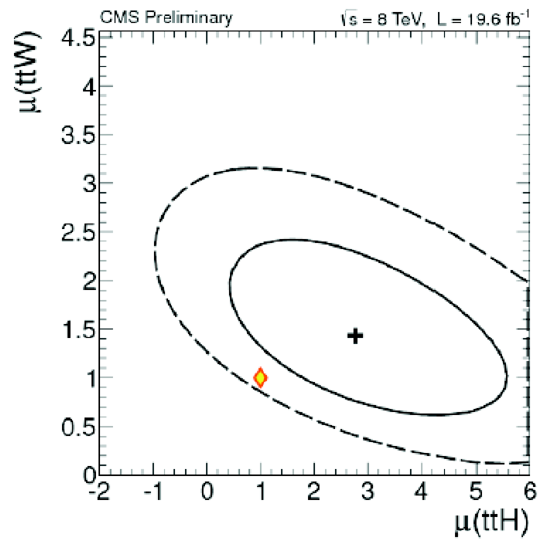
- The events in excess are characterized by having both leptons **very well isolated.**
- Scrutiny of the events also confirms that both leptons are **well reconstructed** in the tracker and muon system, and that their charge is correctly assigned
- The analysis was also repeated using a **looser working point of the lepton MVA**
  - the excess is visible only when both leptons pass the tight MVA wp
  - the rest of the sample is well described by the background model
- The analysis was also repeated with a **cut-based muon selection.** The result is compatible with the nominal one but the sensitivity is worse



Irreducible bkg check

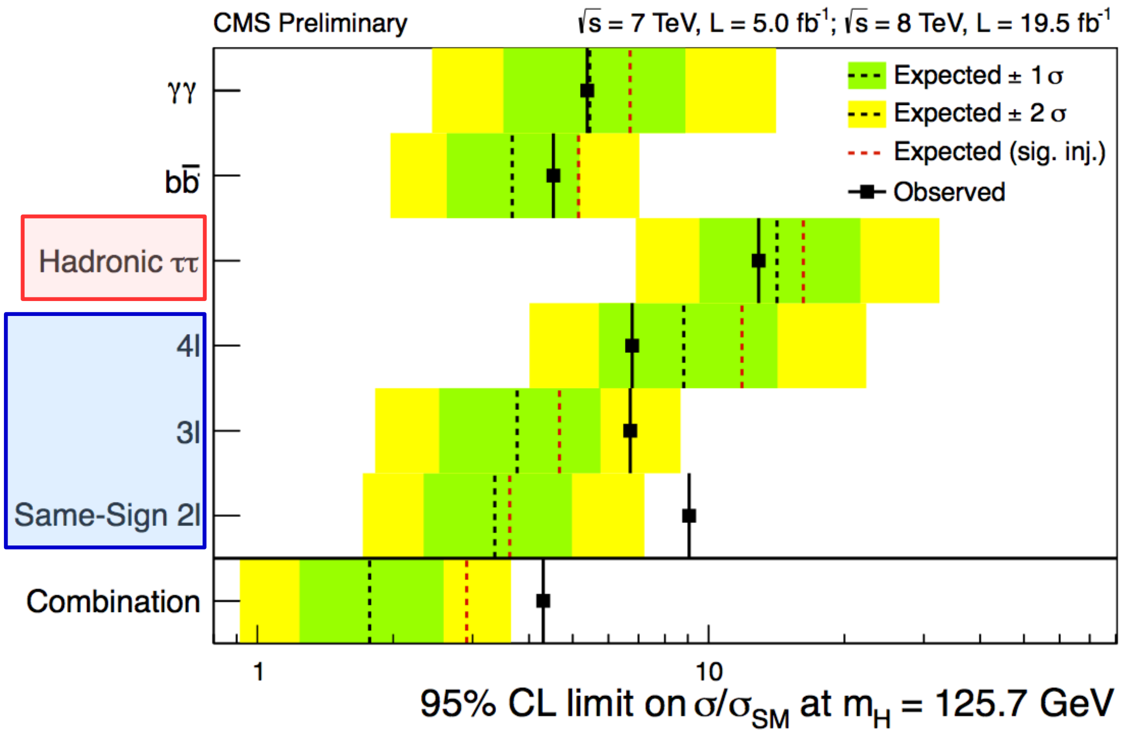
- A **more general fit** is performed:
  - leaving unconstrained the yields of ttW, ttZ, and reducible background (for fake e, μ separately)
  - including additional control regions in the fit: trilepton events with one Z candidate (mostly ttZ), and dilepton events with 3 jets (ttW & red. bkg.)
- Results **compatible with the nominal ones** (but ~20% worse sensitivity)
- All backgrounds yields remain **within 1σ from their input value:** no indication of issues with ttW & ttZ
  - results for ttH and ttW are correlated, all the others are well resolved

parameter	expected	observed
$\mu(\mathrm{ttH})$	$1.0^{-1.3}_{+1.5}$	$2.8^{-1.6}_{+1.8}$
$\mu(\mathrm{ttW})$	$1.0^{-0.5}_{+0.5}$	$1.4^{-0.5}_{+0.6}$
$\mu(\mathrm{ttZ})$	$1.0^{-0.3}_{+0.4}$	$1.1^{-0.3}_{+0.4}$
$\mu(\mathrm{fake}\ \mu)$	$1.0^{-0.3}_{+0.3}$	$0.7^{-0.3}_{+0.4}$
$\mu(\mathrm{fake\ e})$	$1.0^{-0.3}_{+0.3}$	$0.9^{-0.3}_{+0.3}$



SM ttH final limits on μ

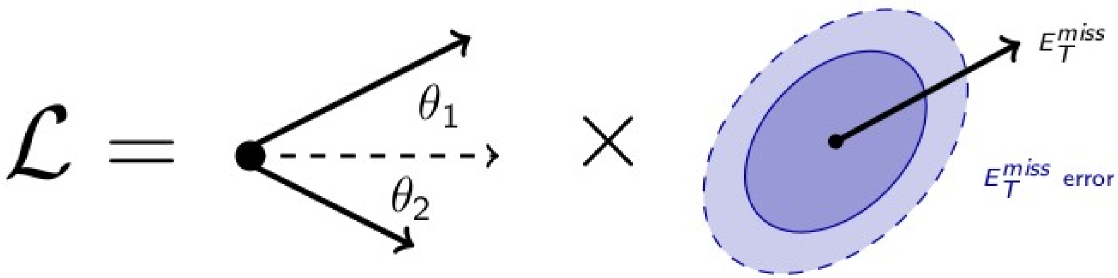
Observed and expected 95% CL upper limits on the signal strength parameter $\mu = \sigma/\sigma_{SM}$ for each ttH channel at mH = 125.7 GeV and assuming SM branching ratios



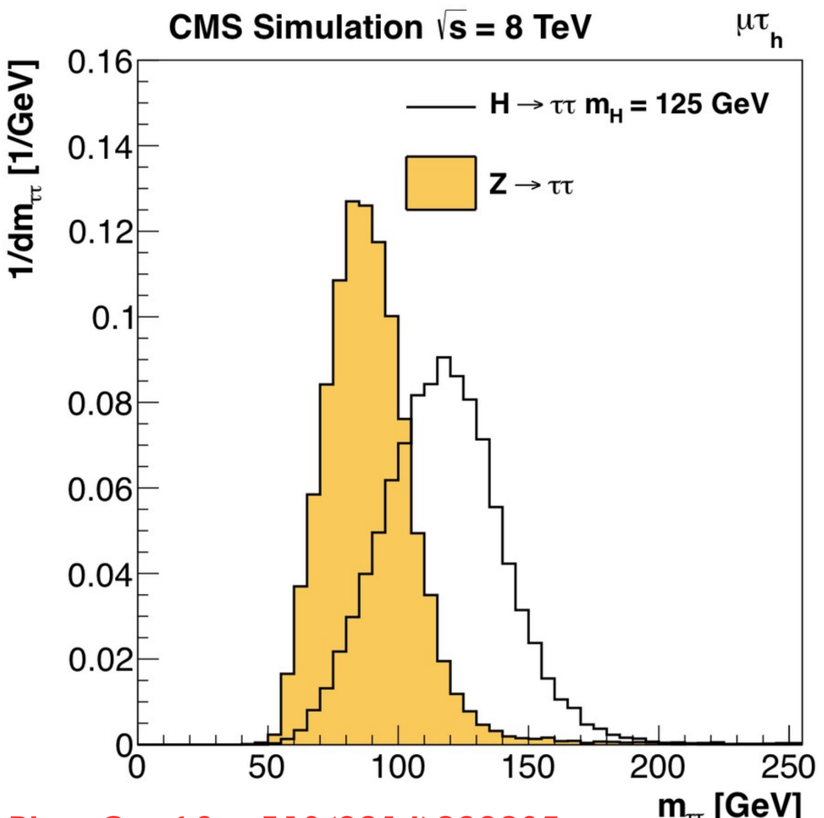
ttH Channel	95% CL upper limits on $\mu = \sigma/\sigma_{SM}$ ($m_H = 125.7$ GeV)				
		Expected			
	Observed	Median Signal Injected	Median	68% CL Range	95% CL Range
$\gamma\gamma$	5.4	6.7	5.5	[3.5,8.9]	[2.4,14.1]
$b\bar{b}$	4.5	5.2	3.7	[2.6,5.2]	[2.0,7.0]
$\tau\tau$	12.9	16.2	14.2	[9.5,21.7]	[6.9,32.5]
4l	6.8	11.9	8.8	[5.7,14.2]	[4.0,22.4]
3l	6.7	4.7	3.8	[2.5,5.8]	[1.8,8.7]
Same-sign 2l	9.1	3.6	3.4	[2.3,5.0]	[1.7,7.2]
Combined	4.3	2.9	1.8	[1.2,2.6]	[0.9,3.6]

di-τ mass reconstruction - SVFit

Likelihood method used to reconstruct the mass of the di-τ system



- → Inputs: four-vector information of visible leptons, x- and y- component of E_T on event basis
- → Find minimum of the Likelihood for given $m_{\tau\tau}$ and scan over all possible values of $m_{\tau\tau}$ to find global minimum.
- → 10-20% resolution of the reconstructed $m_{\tau\tau}$ mass depending on decay mode



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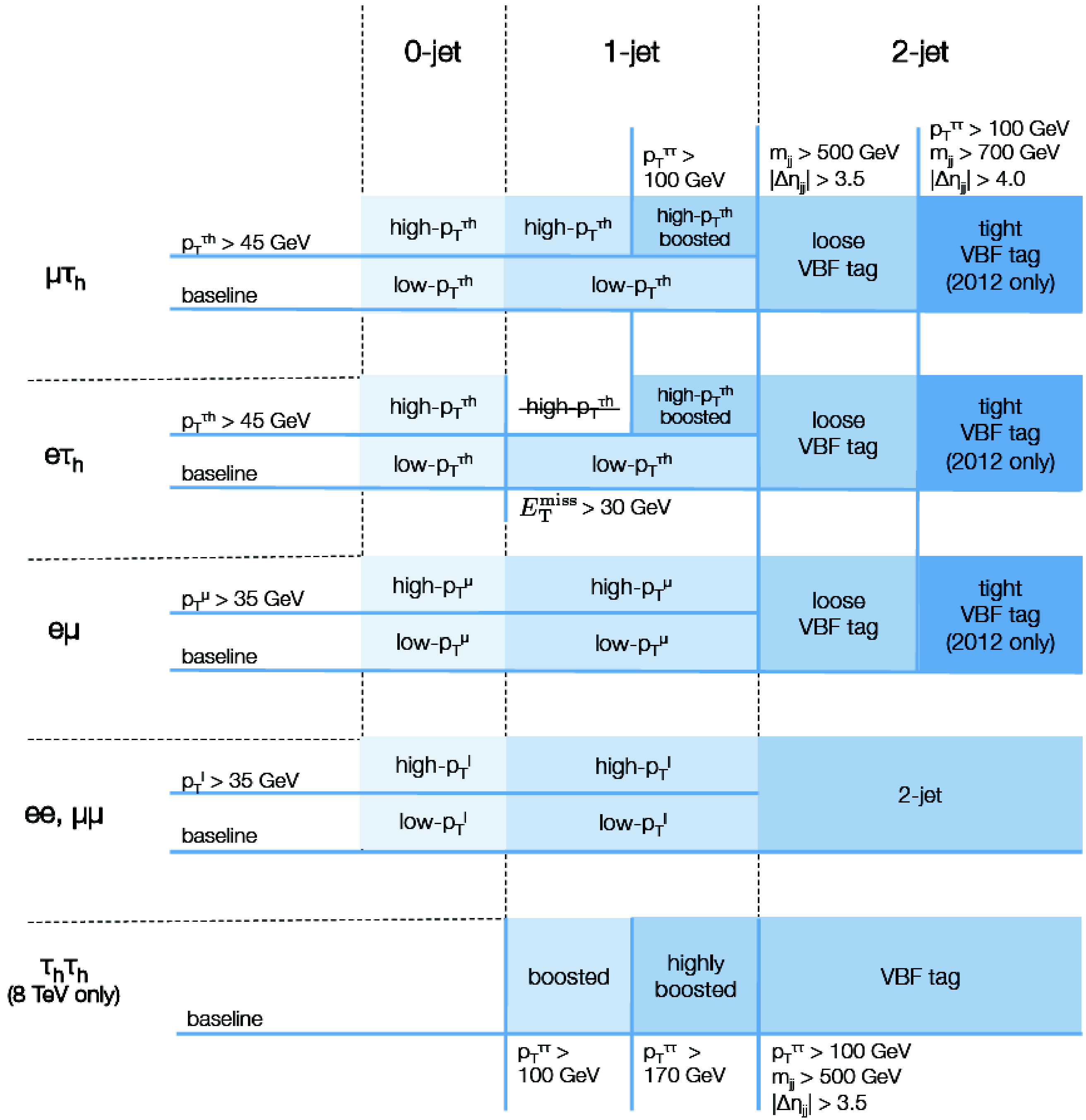
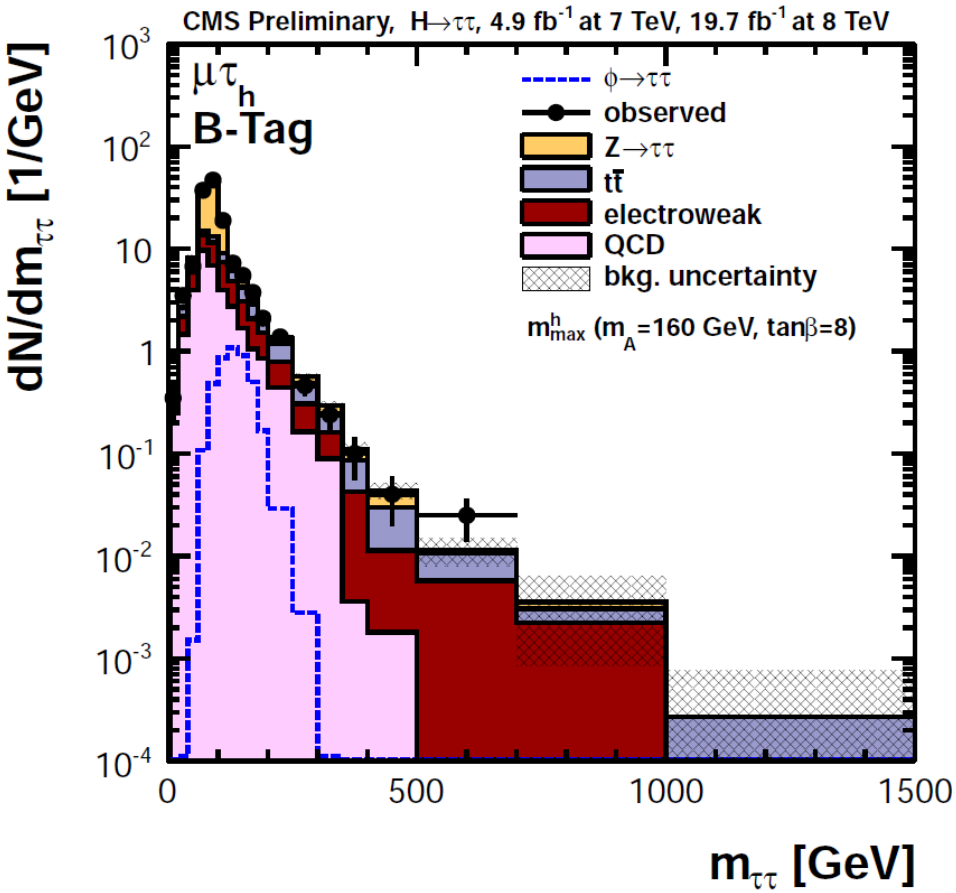
SM H $\rightarrow \tau\tau$ analysis: categorization



MSSH H → ττ analysis: backgrounds



Z/γ* → ττ

Obtained using the embedding technique: Z → μμ events selected in data, reconstructed muons replaced by simulated taus

QCD

Data-driven estimate. Normalization (shape) obtained from SS events with isolated (not-isolated) muons

Electroweak (W+jets, diboson, Z→ee/ μμ)

Shape from MC simulation. Normalization of W+jets obtained by extrapolation from high mT control region in data, others from simulation

tt, single top

Shape from MC simulation, normalization from data

MSSH H → ττ analysis: di-τ mass shapes