Higgs → ττ in CMS

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March 20th 2015

The Large Hadron Collider

Circumference: 27km

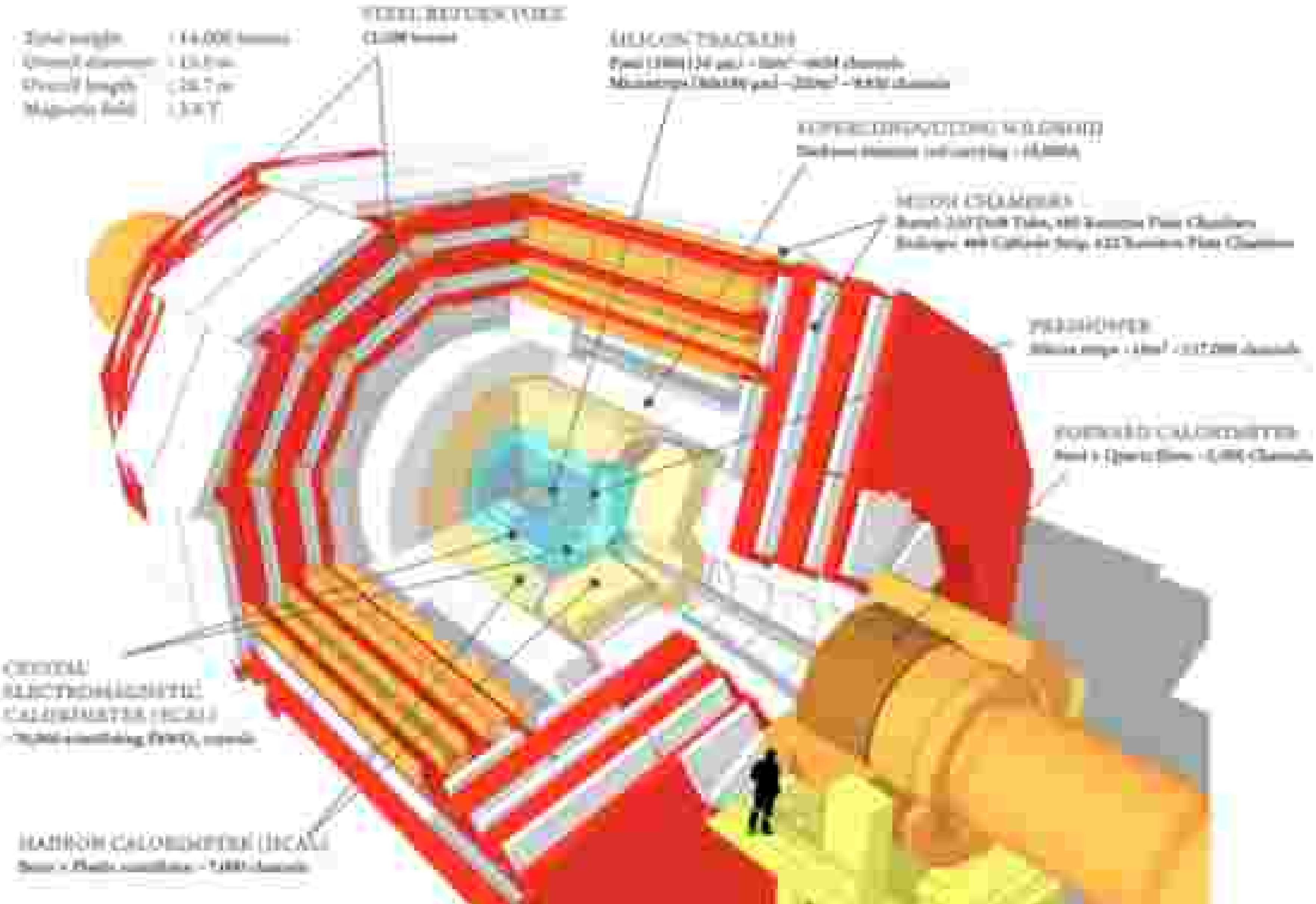
Beam energy: 3.5 TeV (2011), 4 TeV (2012)

Collision frequency: 20 MHz

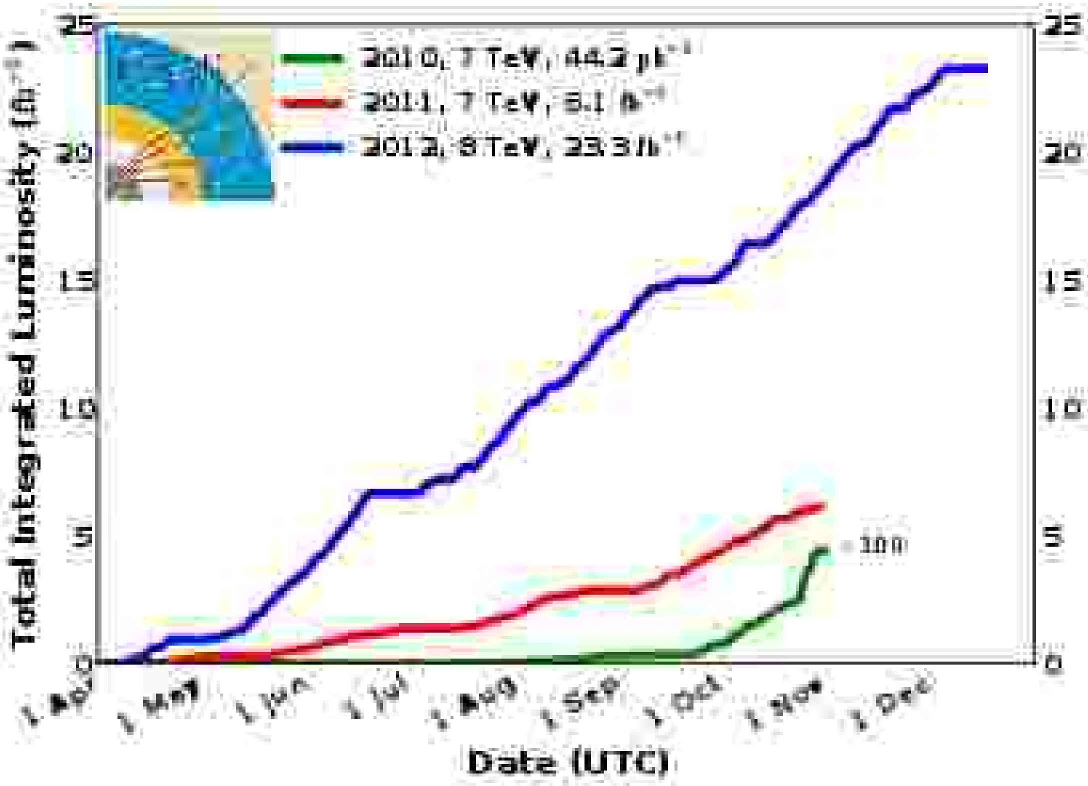
Peak luminosity: $7.7 \cdot 10^{33}\ cm^{-2}s^{-1}$

(≈200 Z bosons produced per second)

The Compact Muon Solenoid Detector



Integrated Luminosity of LHC Run 1 Data

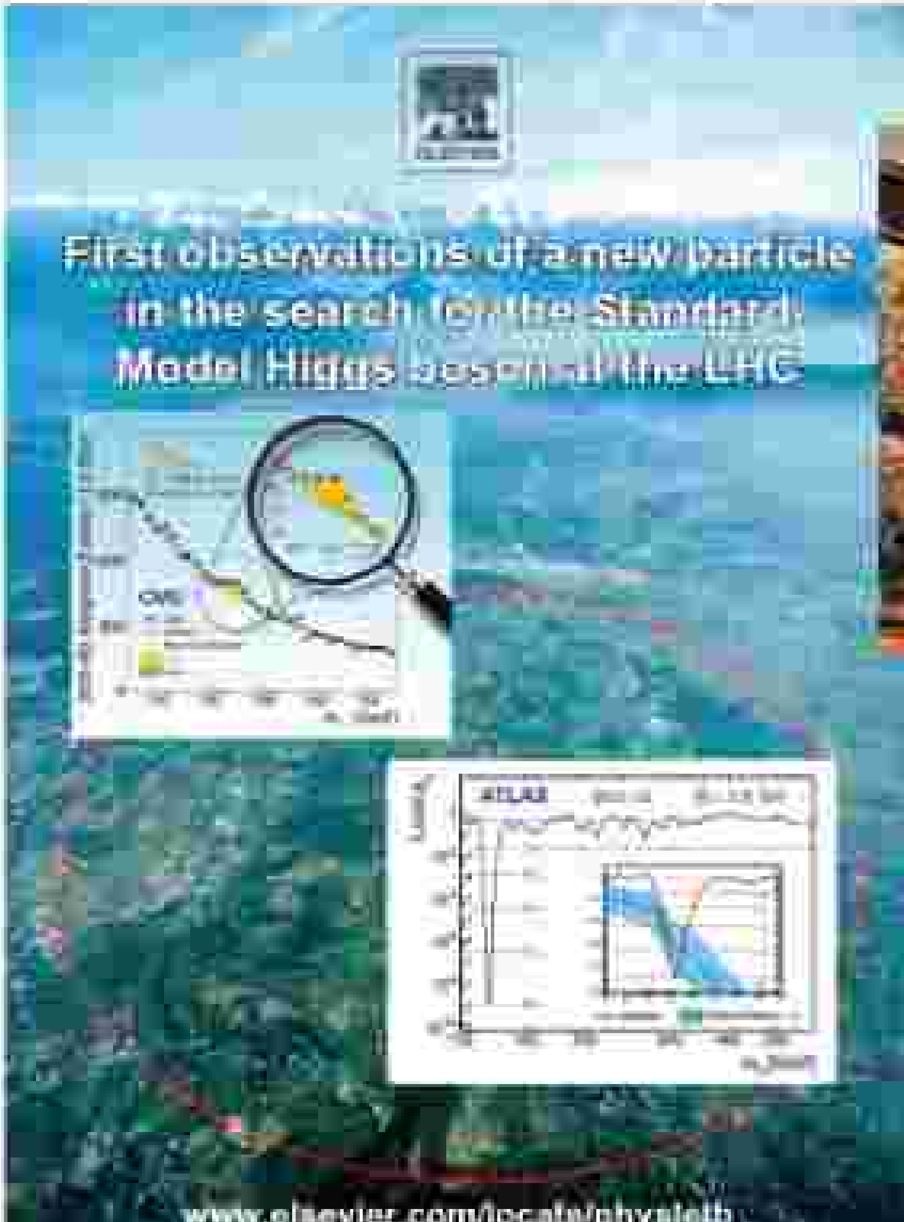


After data quality selection:

4.9 fb^{-1} at 7 TeV pp center-of-mass energy

19.7 fb^{-1} at 8 TeV

Discovery of the Higgs boson



July 2012

Observed Significance

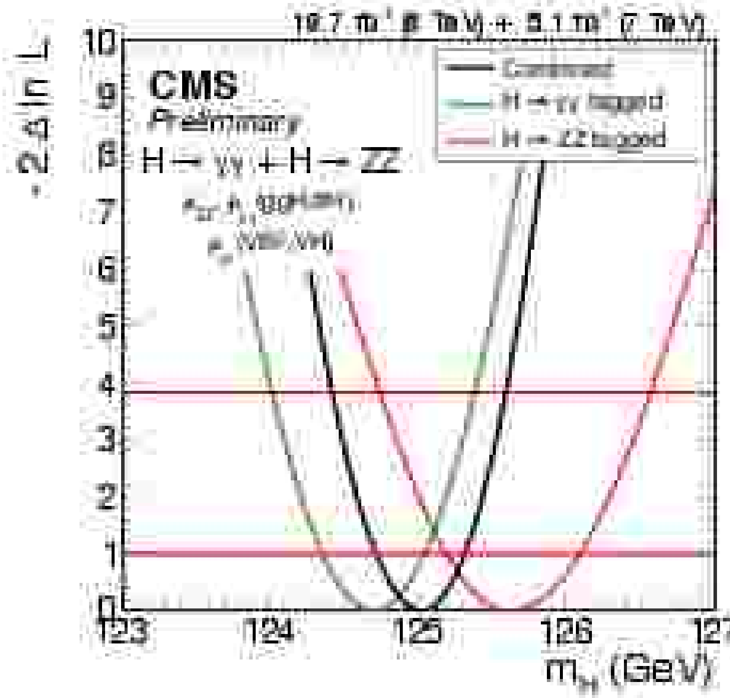
CMS: 5.0σ (5.8σ expected)

ATLAS: 5.9σ (4.9σ expected)

driven by Higgs → γγ, ZZ, WW channels

Higgs Results for full CMS Run 1 Data

Presence of Higgs signal discovered unambiguously in different channels with significance > 5σ



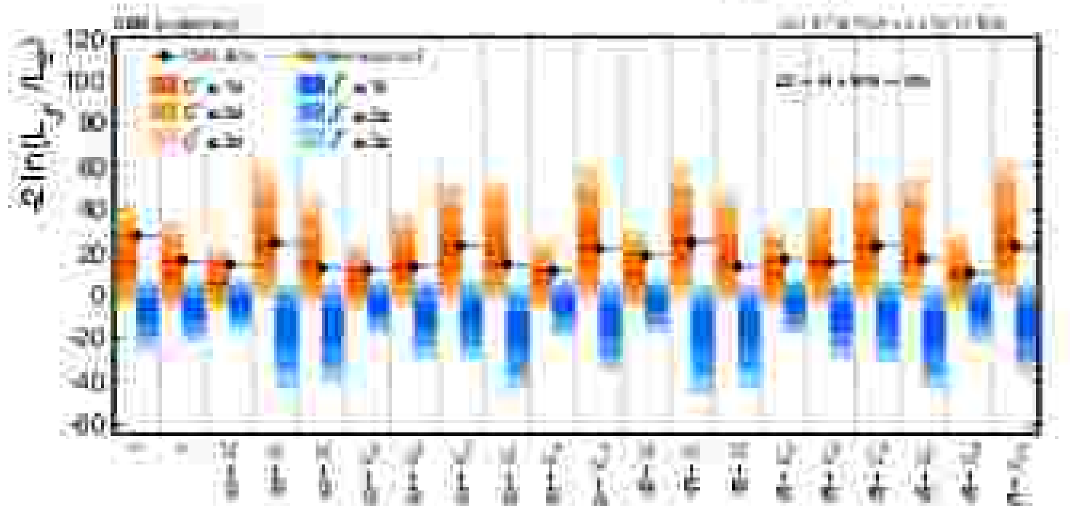
Measured Mass

$m_H = 125.0 \pm 0.3$ GeV

compatible among channels

Resonance has spin 0

Spin 1 and spin 2 hypotheses ruled-out with ≥ 99% CL



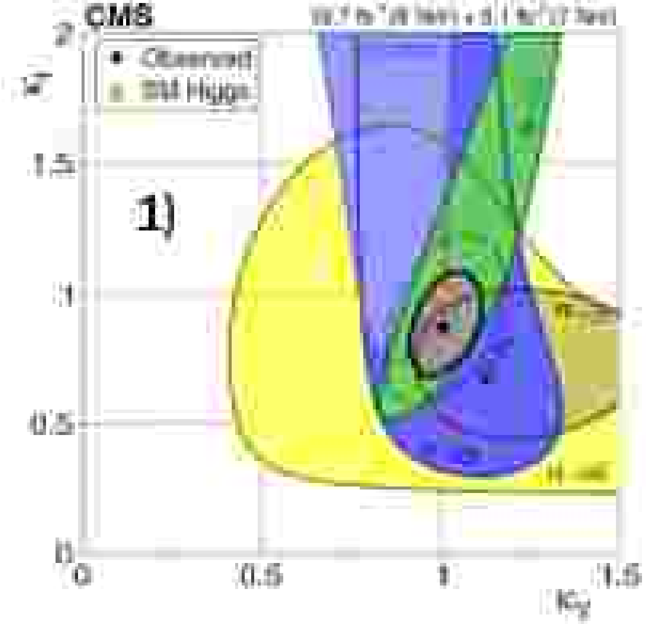
Why Higgs → ττ ?

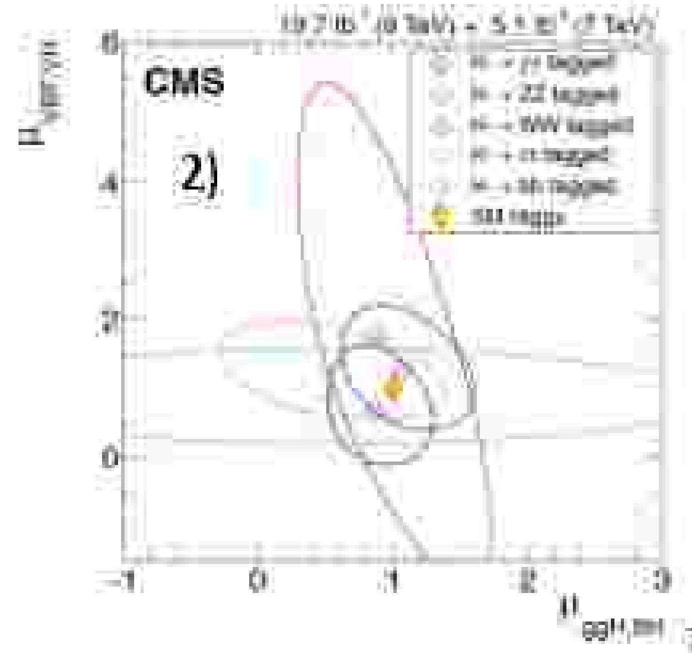
Higgs → ττ most sensitive channel to probe:

1) direct coupling of Higgs to fermions

2) VBF Higgs production mode

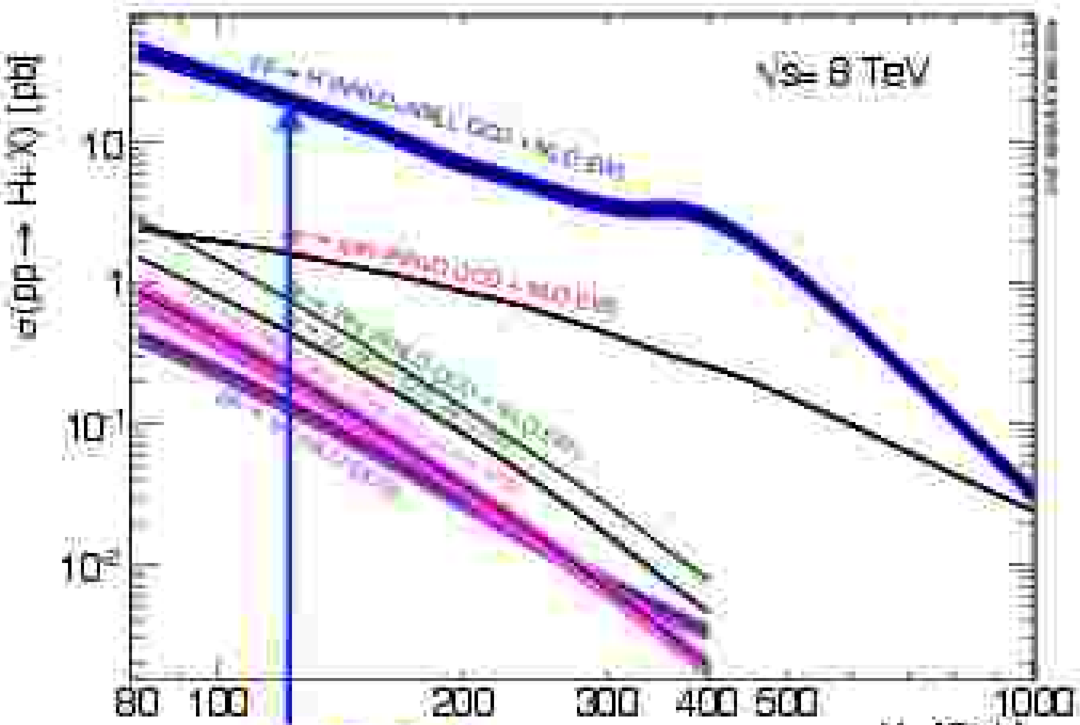
3) BSM Higgs sector (e.g. MSSM)





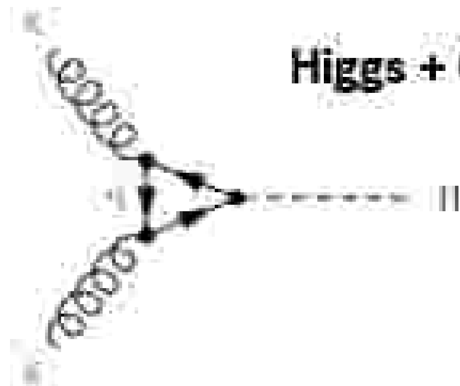
SM Higgs → ττ

Higgs Production at the LHC

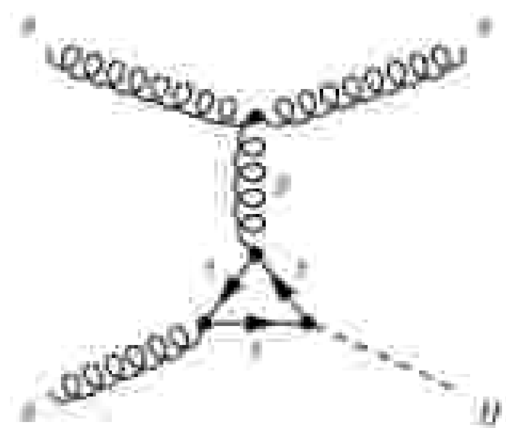


Gluon-fusion

Higgs + 0 jet



Higgs + 1 jet

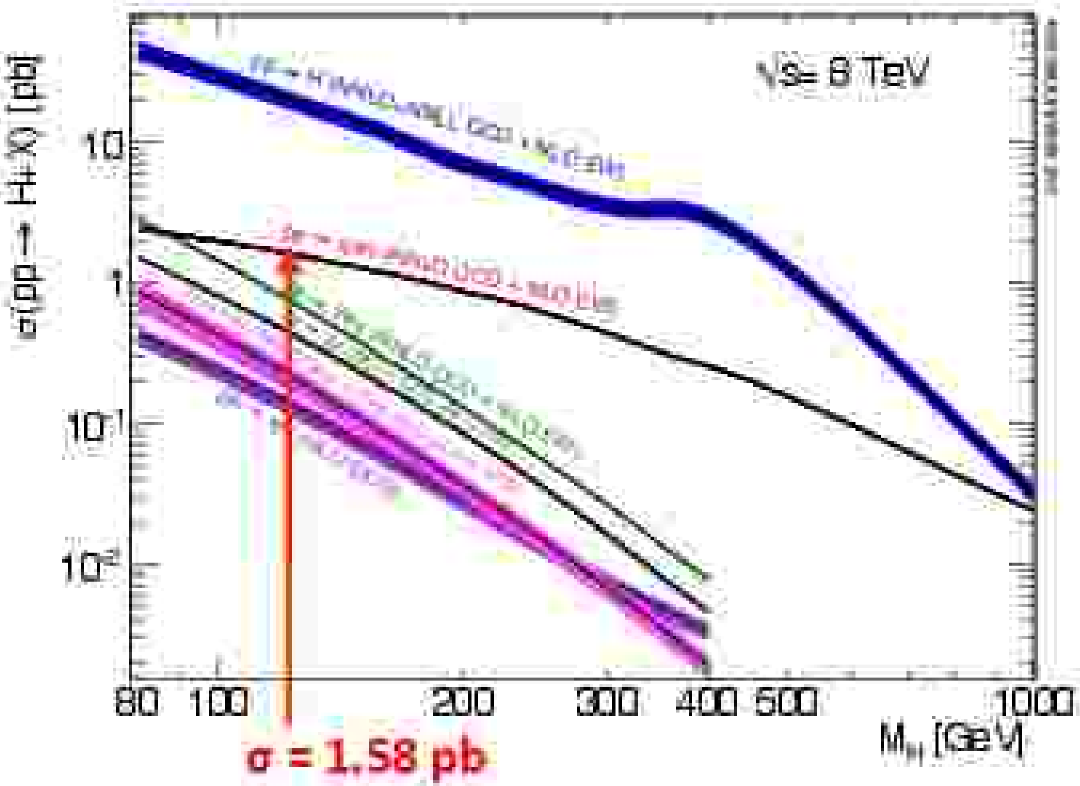


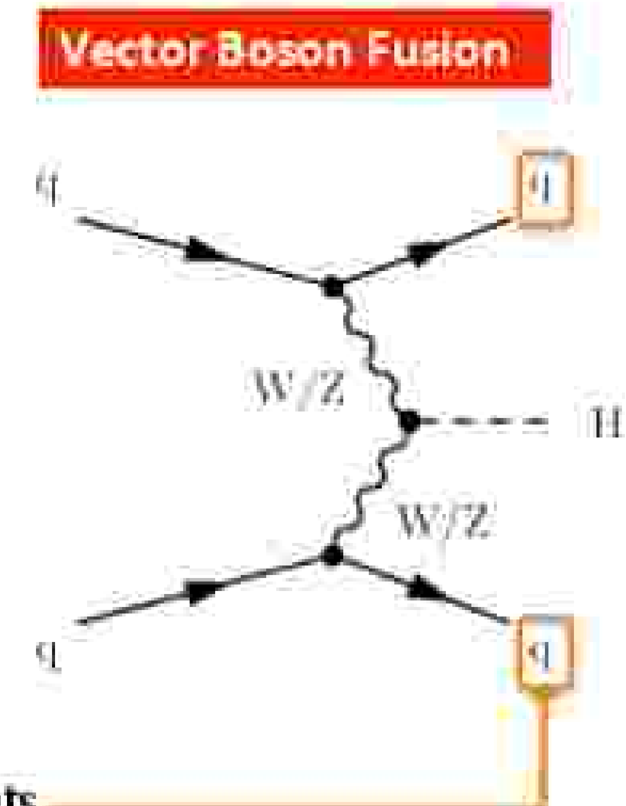
Gluon Fusion (ggH)

Largest cross-section,
but highest contamination by backgrounds also

Signal/background ratio improves in case Higgs recoils a high p_T jet ("boosted Higgs")

Higgs Production at the LHC



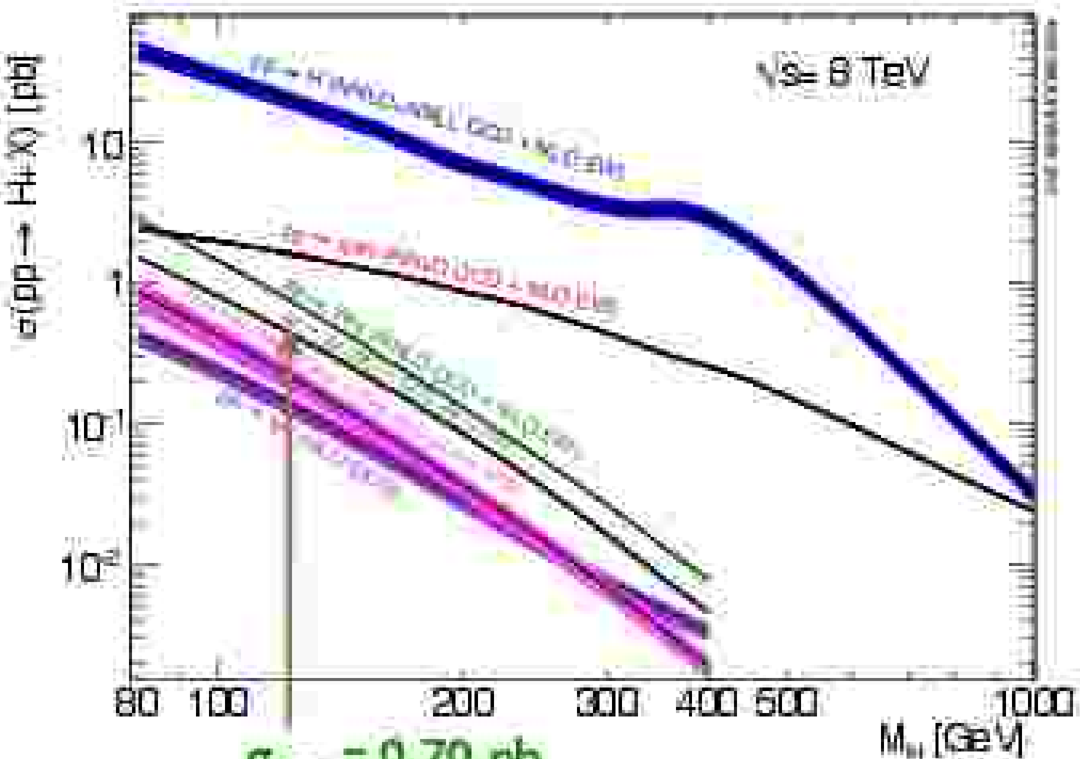


Vector Boson Fusion (VBF)

Smaller cross-section compared to gluon fusion

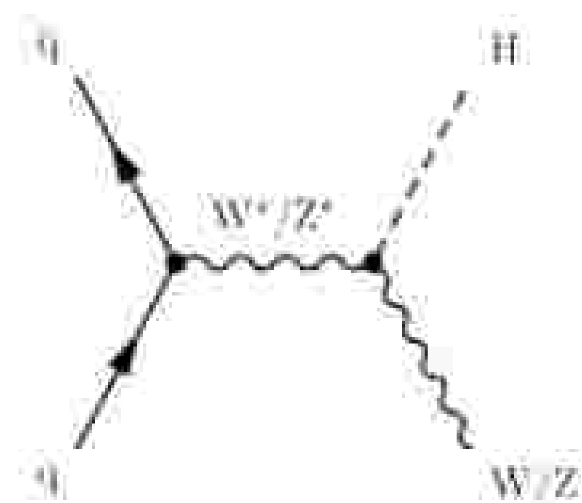
Distinct event characteristic of forward/backward jets provides powerful handle to reduce backgrounds

Higgs Production at the LHC



σ_{WH} = 0.70 pb
σ_{ZH} = 0.42 pb

Associated Production

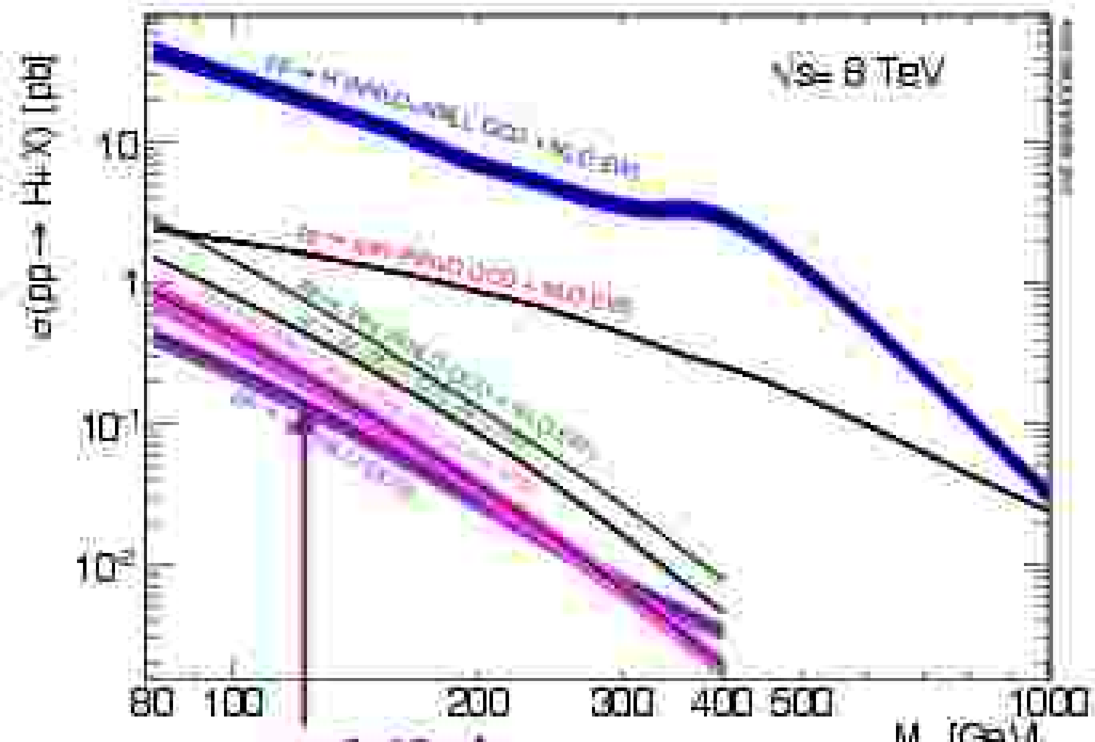


Associated Production (WH, ZH)

Small cross-section

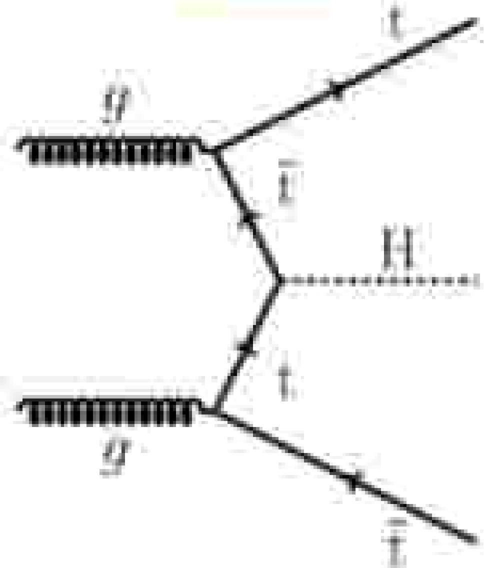
Clean signature in case W or Z boson decays to leptons

Higgs Production at the LHC



σ = 0.13 pb

ttH

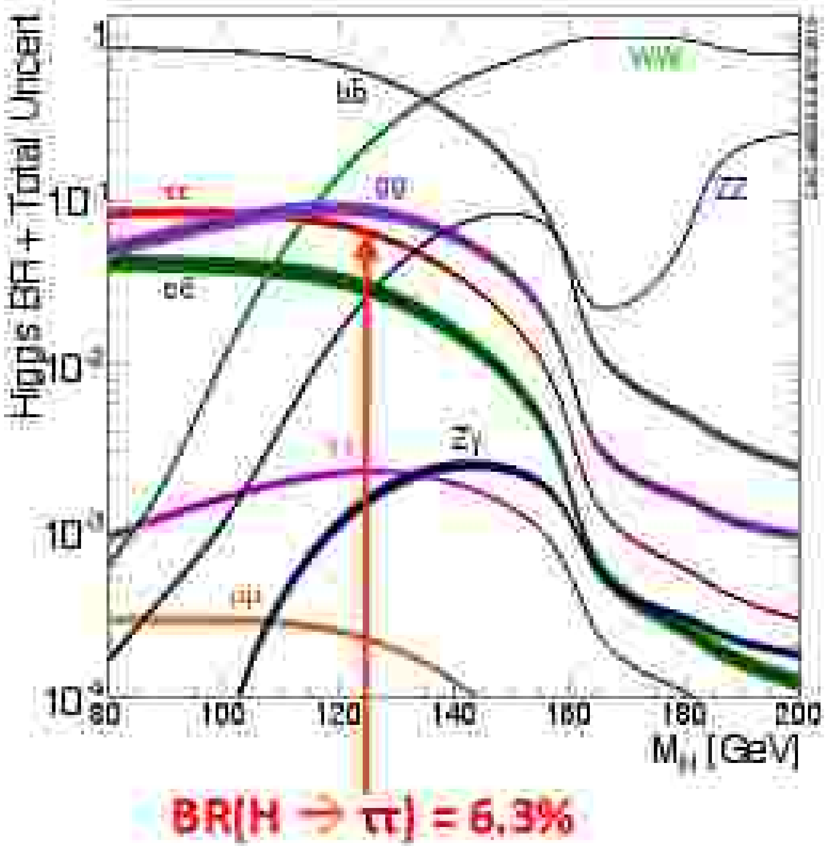


ttH

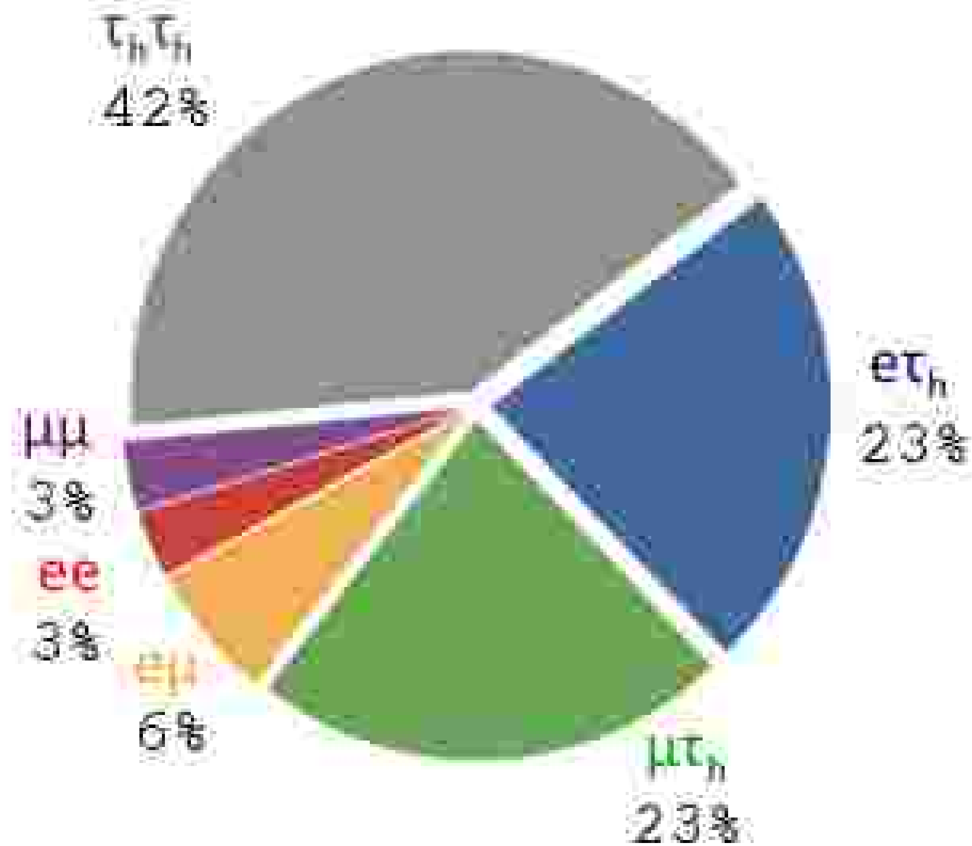
Allows measurement of top Yukawa coupling

LHC run 1 data not yet sensitive to SM ttH production, due to small cross-section

Higgs Decay Channels



ττ Decay channels



All ττ decay channels included in analysis

Event Selection

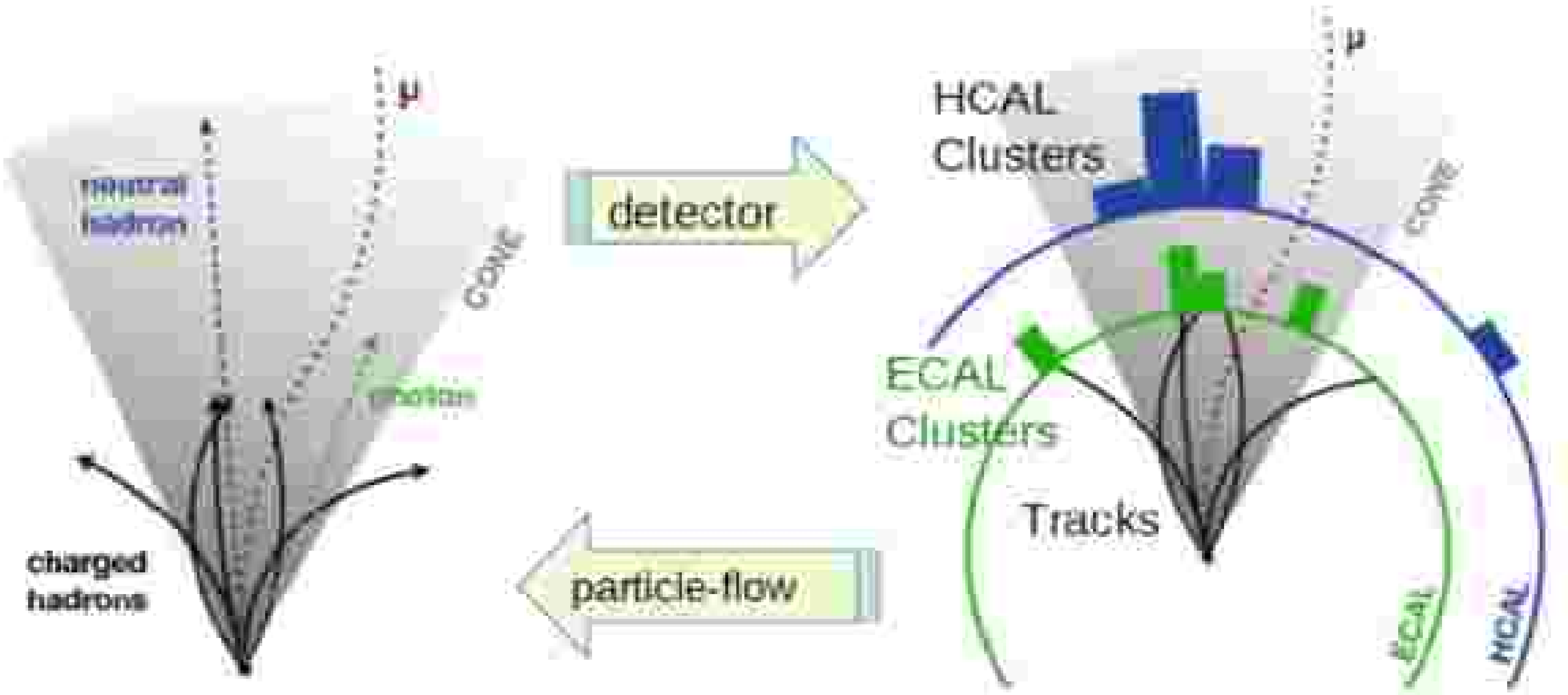
Channel	7 TeV [fb^{-1}]	8 TeV [fb^{-1}]	Offline p_T Requirements
$e\tau_h$	4.9	19.7	$p_T(e) > 24$ GeV, $p_T(\tau_h) > 30$ GeV ($p_T(e) > 20$ GeV at 7TeV)
$\mu\tau_h$	4.9	19.7	$p_T(\mu) > 20$ GeV, $p_T(\tau_h) > 30$ GeV ($p_T(\mu) > 17$ GeV at 7TeV)
$e\mu$	5.0	19.7	$p_T(l_1) > 20$ GeV, $p_T(l_2) > 10$ GeV
$\tau_h\tau_h$	-	19.7	$p_T(\tau_h) > 45$ GeV, $p_T(\tau_h) > 45$ GeV
ee	4.8	19.7	$p_T(e_1) > 20$ GeV, $p_T(e_2) > 10$ GeV
$\mu\mu$	4.8	19.7	$p_T(\mu_1) > 20$ GeV, $p_T(\mu_2) >10$ GeV

P_T thresholds driven by trigger requirements

$\tau_h\tau_h$ channel analyzed in 8 TeV data only,
because $\tau_h\tau_h$ trigger was not yet online during 7 TeV data-taking

Event Reconstruction by Particle-Flow

Consistent interpretation of all detector signal in terms of individual particles:
e, μ, photons, charged hadrons, neutral hadrons



Higher level objects are reconstructed using individual particles as input:
τ_h, jets (incl. b-tagging), E_T^{miss}

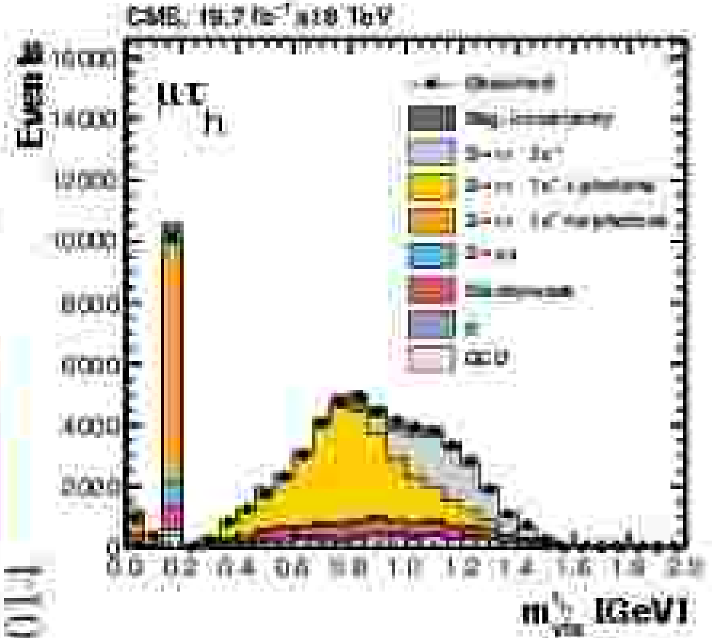
Identification of hadronic tau decays

Mass $m_\tau = 1.78$ GeV

Lifetime $c \cdot \bar{\tau} = 87$ μm

Decay Mode	Resonance	BR [%]
$\tau^- \to e^- \bar{\nu}_e \nu_\tau$		17.8
$\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$		17.4
$\tau^- \to h^- \nu_\tau$		11.5
$\tau^- \to h^- \pi^0 \nu_\tau$	$\rho(770)$	26.0
$\tau^- \to h^- \pi^0 \pi^0 \nu_\tau$	$a_1(1260)$	10.8
$\tau^- \to h^- h^+ h^- \nu_\tau$	$a_1(1260)$	9.8
$\tau^- \to h^- h^+ h^- \pi^0 \nu_\tau$		4.8
Other hadronic modes		1.8
All hadronic modes		64.8

PDG 2014



τ_h Identification ≡ reconstruction of $\pi^\pm$, $\rho^\pm$, $a_1^\pm$ signatures

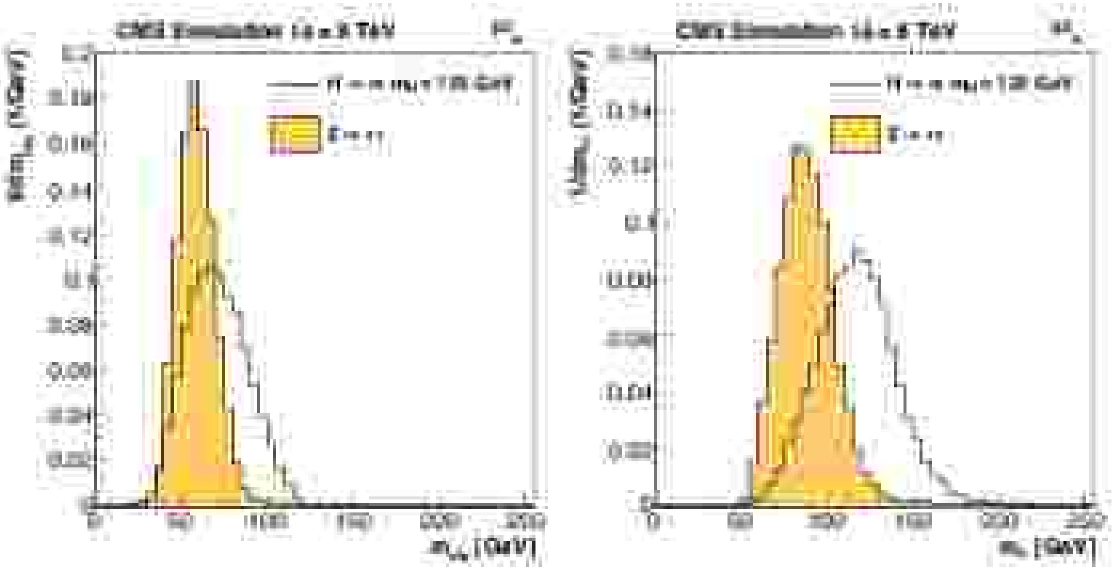
Main handle to reduce large jet background: Isolation

Electrons and muons from $\tau \to e$ and $\tau \to \mu$ decays reconstructed by standard CMS electron and muon reconstruction algorithms

Higgs Mass Reconstruction

Reconstruction of ditau mass, $m_{\tau\tau}$, based on Likelihood method, using as input:

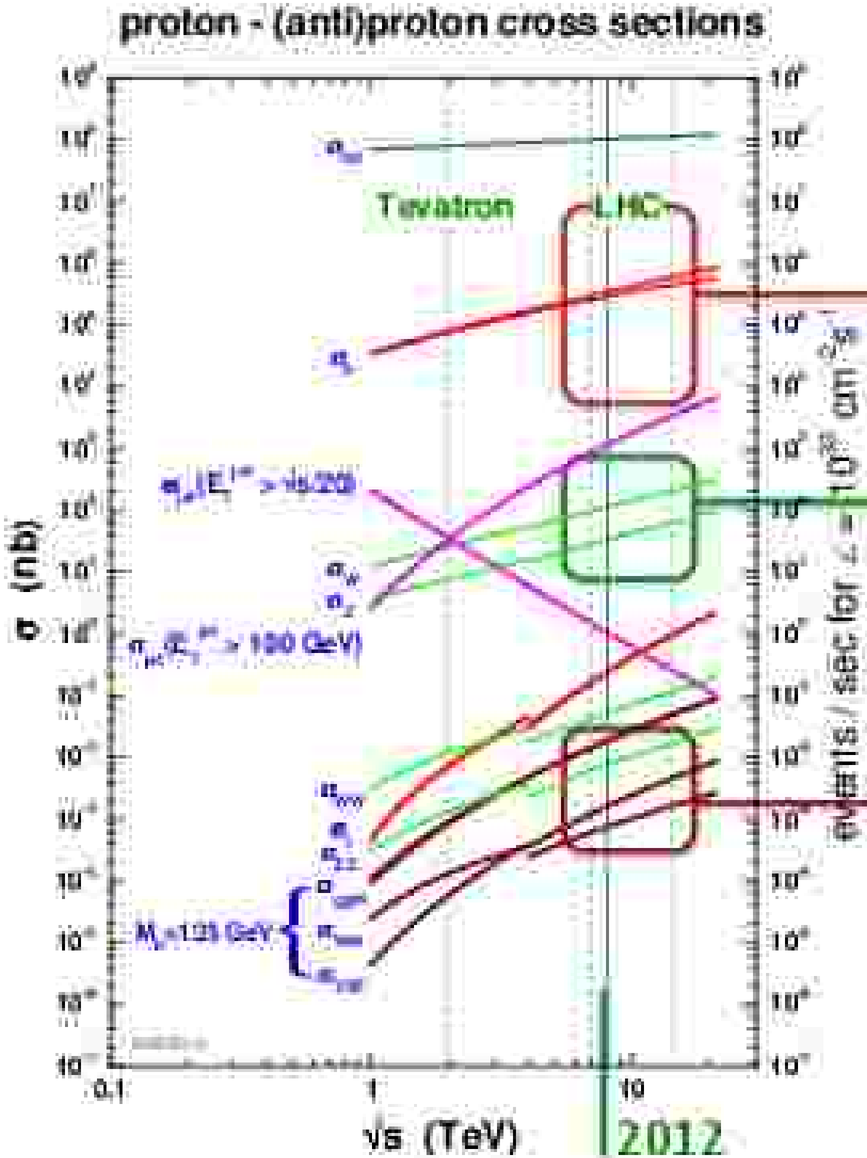
- Measured e, μ, τ_h-jet momenta
- Reconstructed MET and event-by-event estimate of MET resolution



Resolution on $m_{\tau\tau}$ is O(20%), improves separation of signal from backgrounds

Algorithm ("SVfit") finds physical solution for (almost) every event

The Challenge of the Analysis

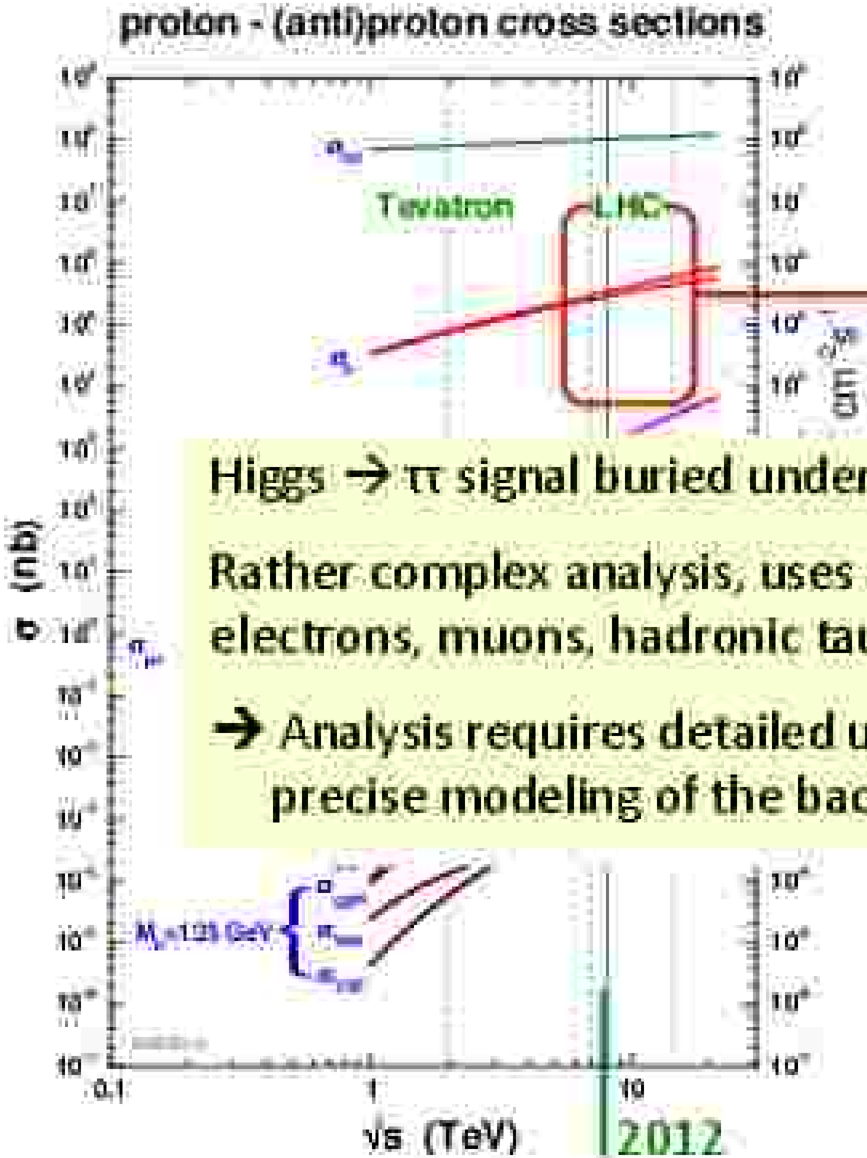


Large background from QCD multi-jet production

W → τν and Z/γ* → ττ are the dominant sources for taus in the Standard Model: "Standard Candle" for tau ID commissioning

Higgs → ττ

The Challenge of the Analysis



Large background from QCD multi-jet production

Higgs → ττ signal buried underneath very large background

Rather complex analysis, uses all objects reconstructed by CMS: electrons, muons, hadronic taus, jets (incl. b-tagging), E_T^{miss}

→ Analysis requires detailed understanding of the detector and precise modeling of the backgrounds

Analysis Strategy

Conceptual Idea

Search for "bump" in $m_{\tau\tau}$ distribution
that exceeds background expectation
and shows-up at the same mass in all decay channels

Complication

Signal/background ratio is small, typically S/B < 0.01,
i.e. Higgs signal is within the systematic uncertainty on the backgrounds

Analysis Strategy (cont'd)

Solution

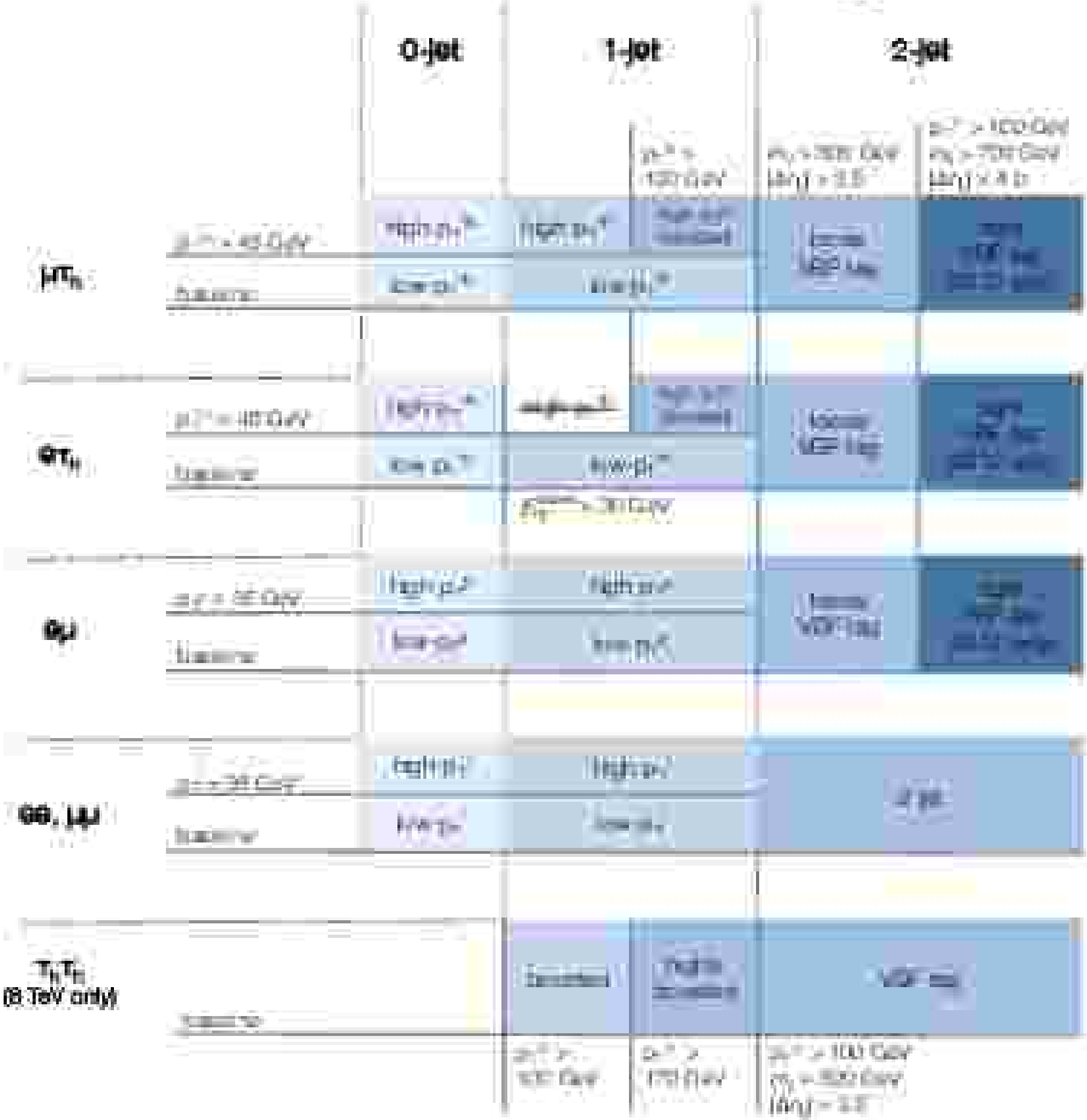
Analyze events with high S/B separately from events with lowhigh S/B

Determine signal and background yields in simultaneous maximum likelihood fit:

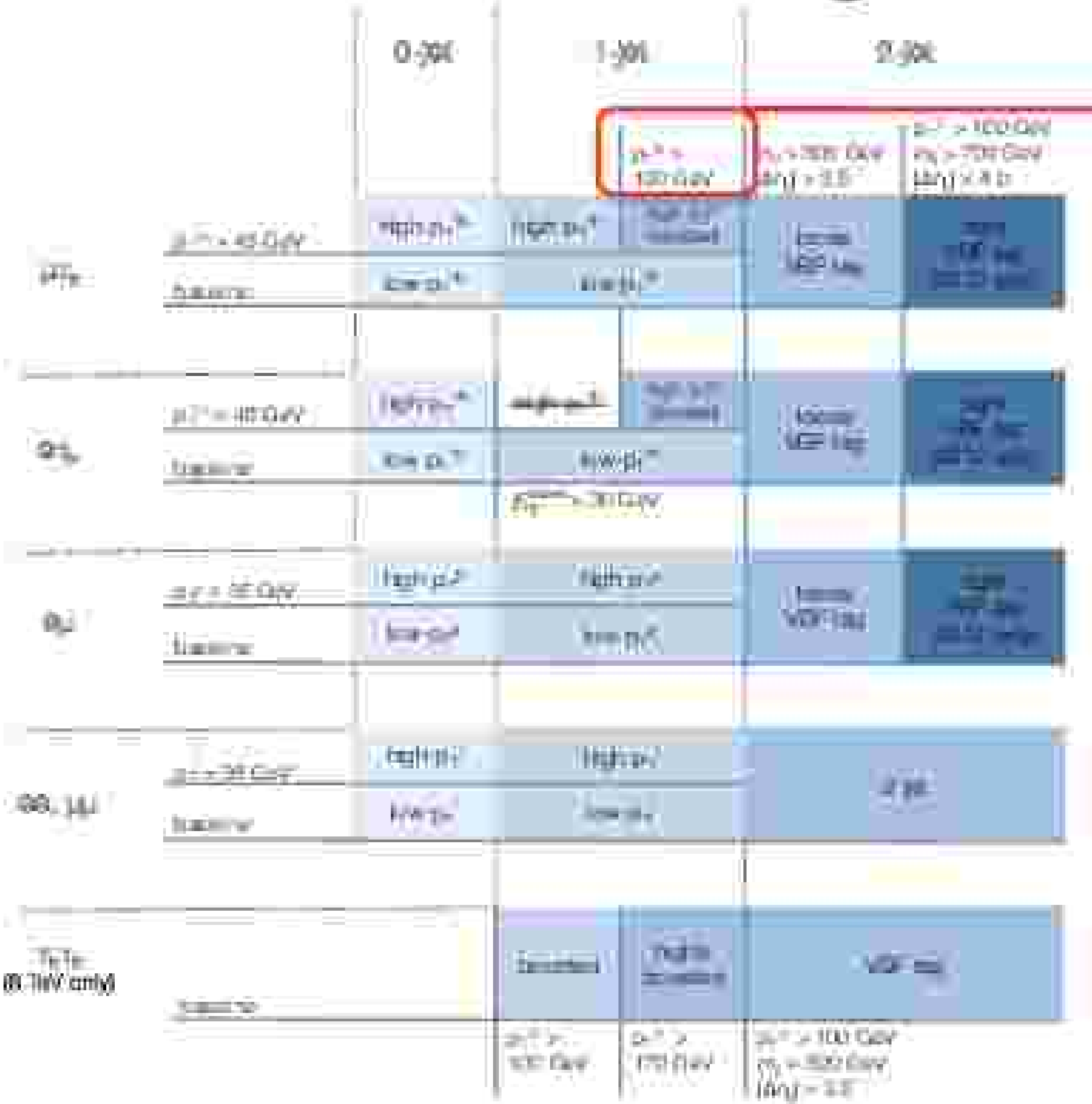
- Inputs to the fit: $m_{\tau\tau}$ spectra observed in data plus shape templates for background processes and for the Higgs signal
- Systematic uncertainties are represented by nuisance parameters in the fit
- All channels and event categories are fitted simultaneously
- Higgs signal yield is included as freely floating parameter in the fit

→ Event categories with low S/B, but high event statistics, constrain nuisance parameters, thereby reducing the systematic uncertainty on backgrounds in the event categories with high S/B

Event Categorization



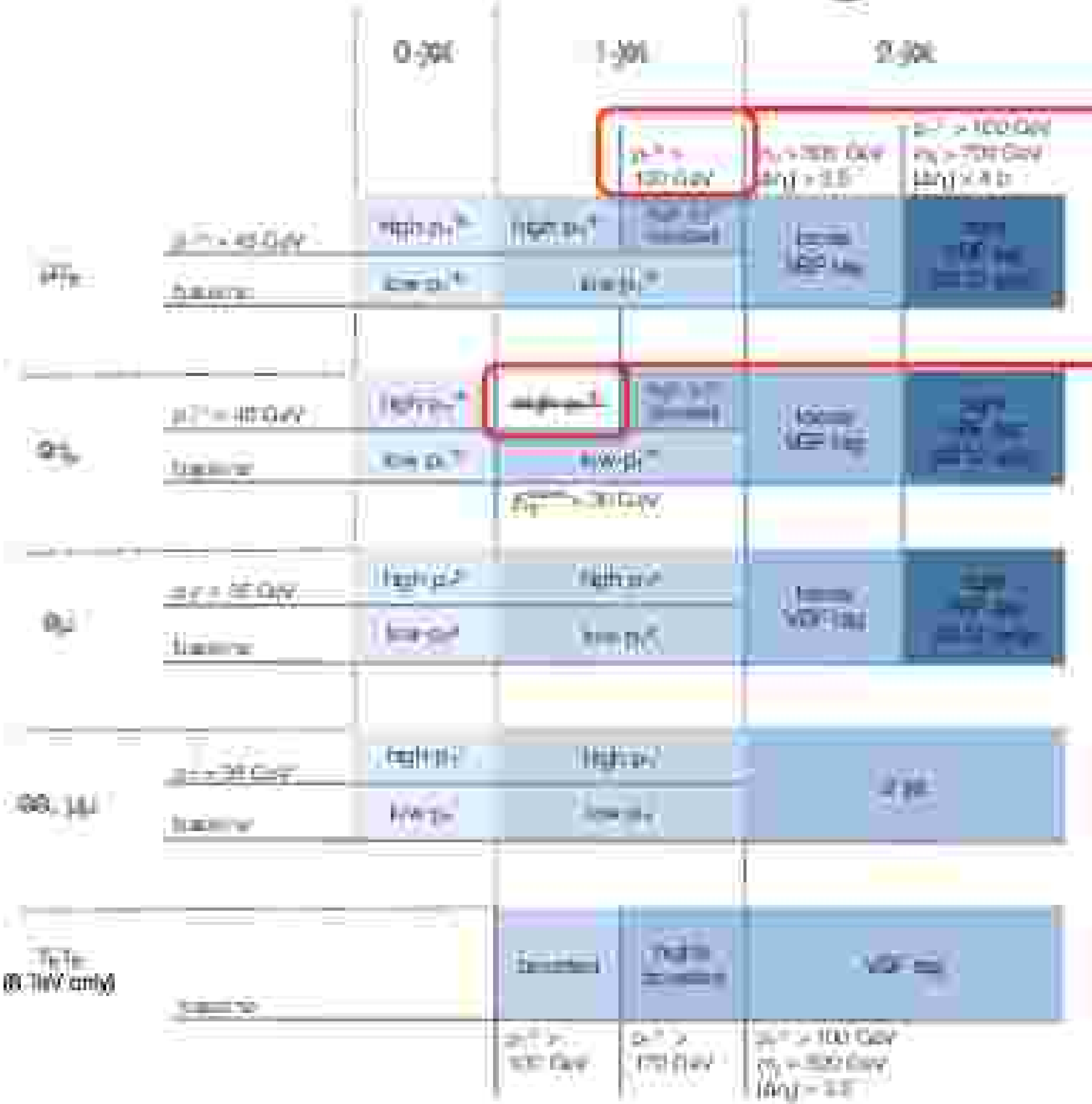
Event Categorization



$$p_T^{\tau\tau} = |\vec{p}_T(L) + \vec{p}_T(L') + E_T^{miss}|$$

L, L′ : e, μ, τ_h
produced in tau decays

Event Categorization



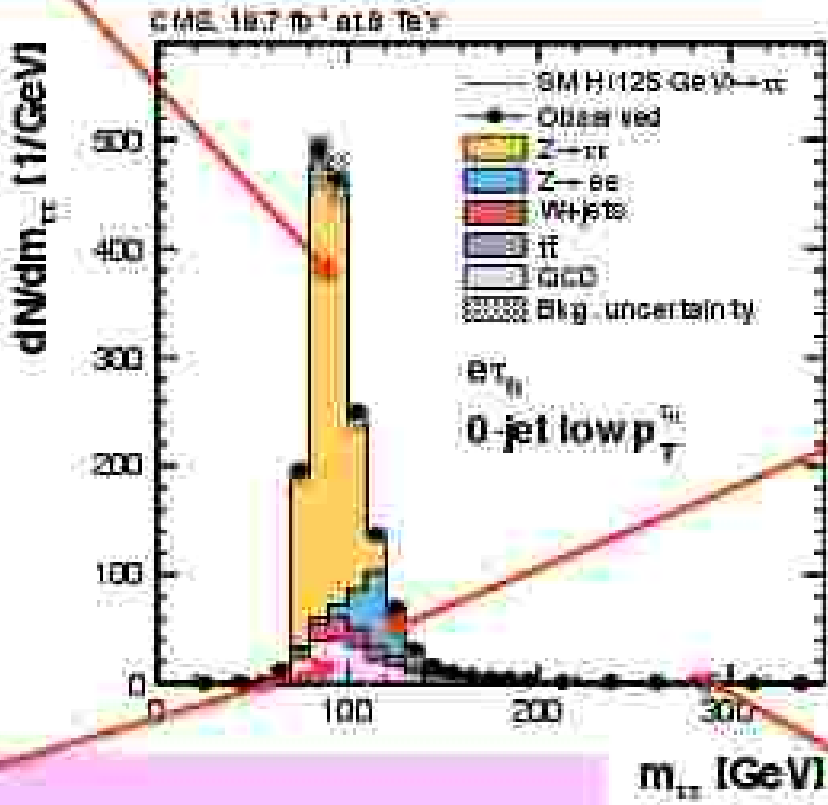
$p_T^{\tau\tau} = |\vec{p}_T(L) + \vec{p}_T(L') + E_T^{miss}|$

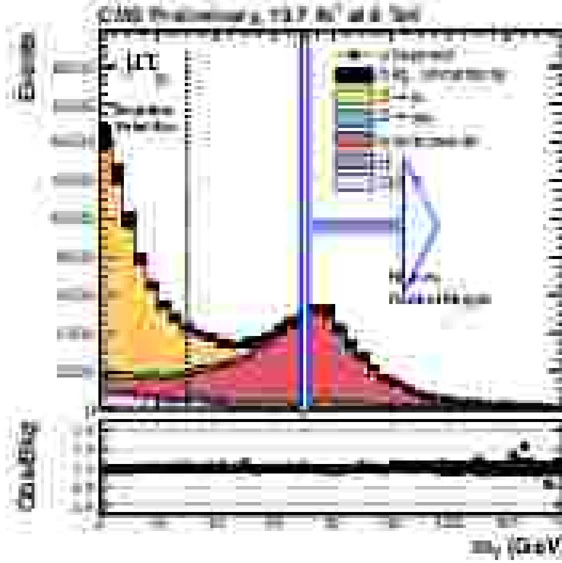
L, L' : e, μ, τ_h
produced in tau decays

not used in analysis

Relevant Backgrounds

$Z/\gamma^* \to \tau\tau$
Obtained using Embedding technique:
$Z \to \mu\mu$ events selected in data,
reconstructed muons replaced by simulated taus





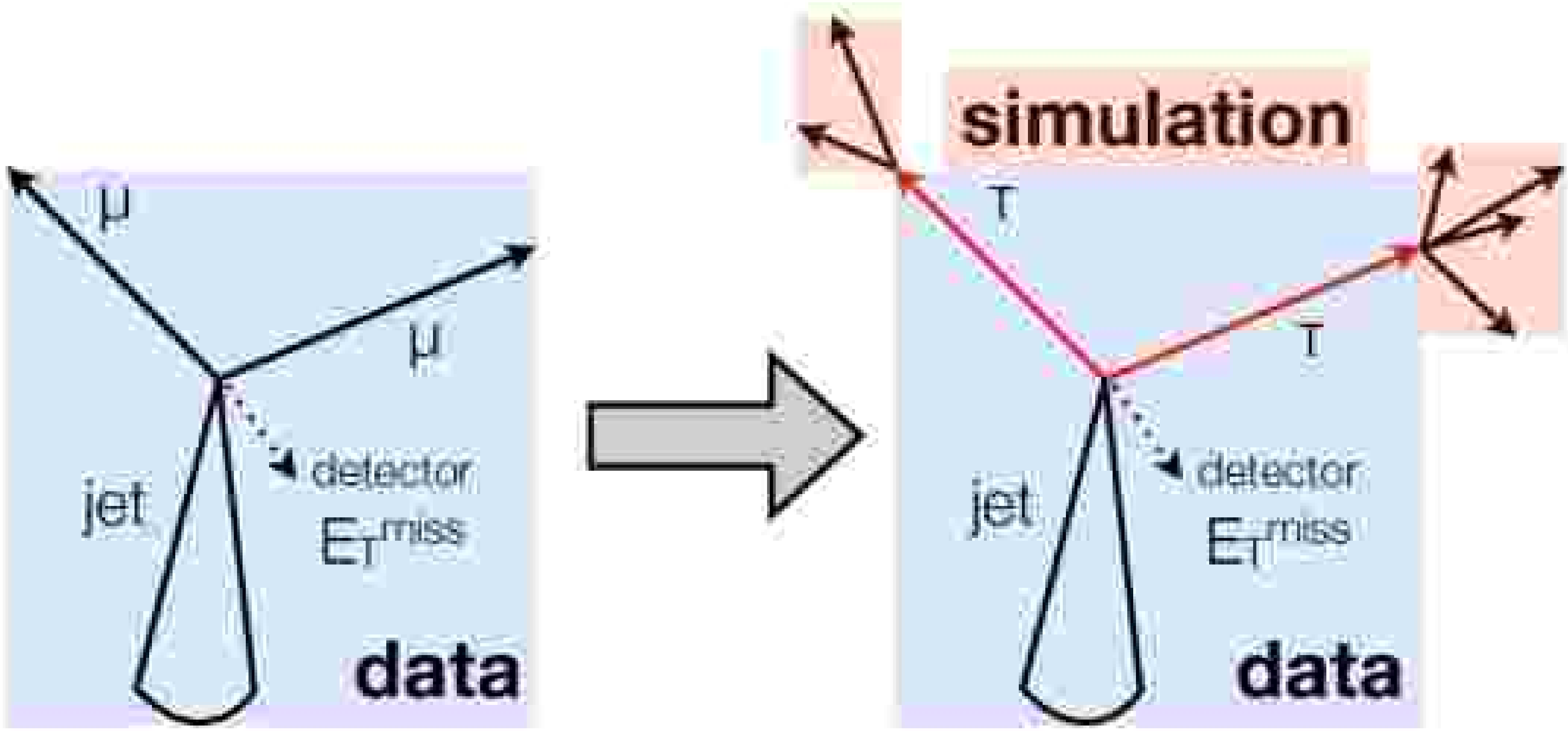
Electroweak (W+jets, diboson, $Z \to ee/\mu\mu$)
Shapes from MC simulation
Normalization of W+jets obtained by extrapolation from high m_T control region in data, others from MC simulation

QCD
Fully data driven: Normalization (shape) obtained from same-sign events with isolated (non-isolated) muons

$t\bar{t}$, single top
Shape from MC simulation,
normalization from data

Embedding

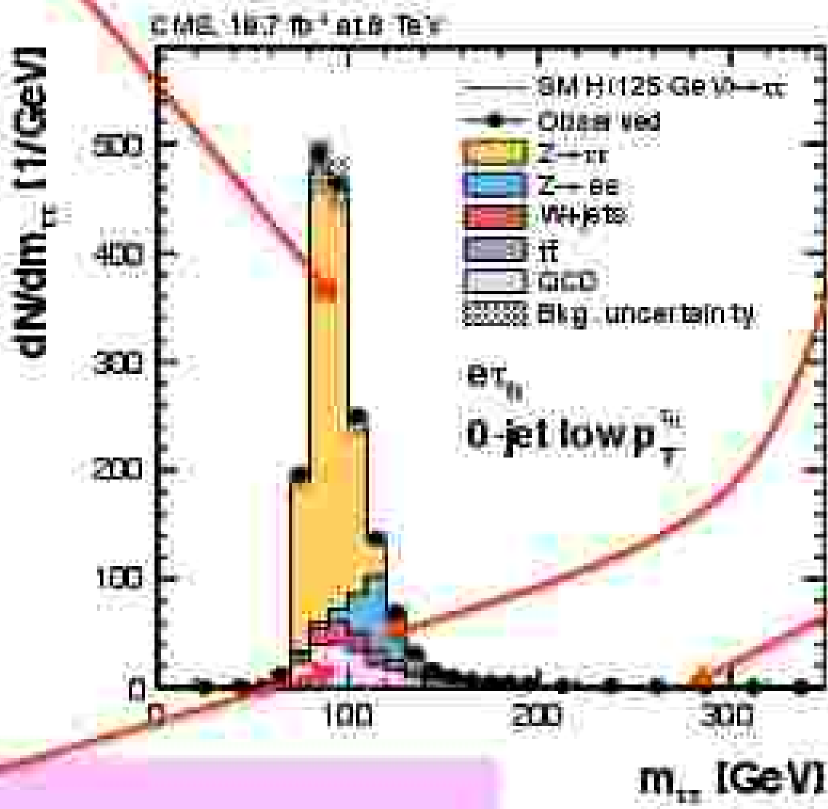
Dominant irreducible $Z/\gamma^* \rightarrow \tau\tau$ background modeled by selecting $Z/\gamma^* \rightarrow \mu\mu$ events in data and replacing the reconstructed muons by simulated tau decays



Modeling of jet activity (incl. VBF production), E_T^{miss} resolution, underlying event and pileup determined from data

Systematic Uncertainties

$Z/\gamma^* \rightarrow \tau\tau$
Normalization: 8-13% τ_h identification and trigger efficiency
Shape: 3% τ_h energy scale



W+jets
Normalization: 10-100% on extrapolation and statistical uncertainty in control region

$Z \rightarrow ee/(\mu\mu)$
Normalization: 20-74% on rate for e, μ to be misidentified as τ_h
Shape: 2% energy scale

Diboson
Normalization: 6-45%

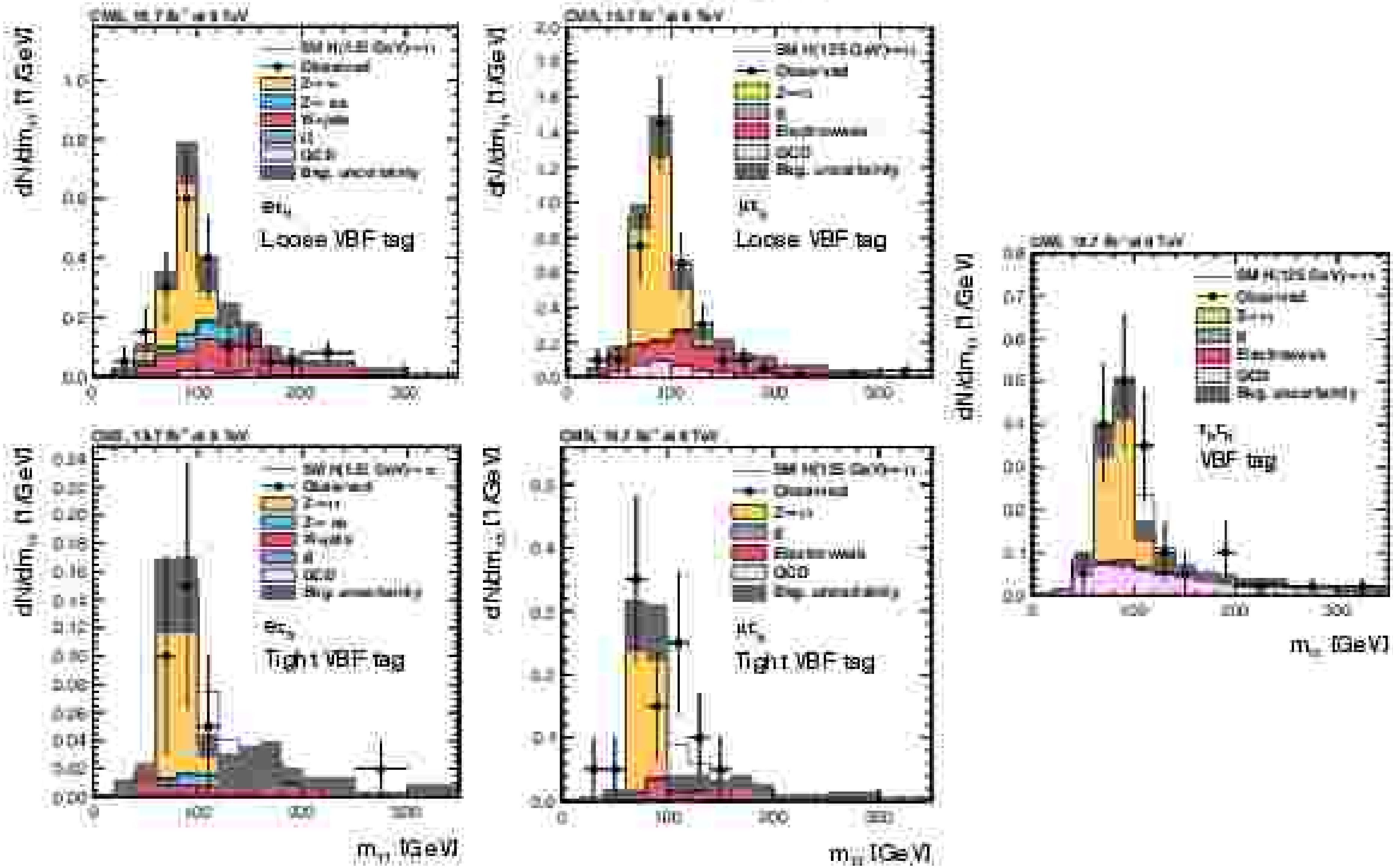
$t\bar{t}$, single top
Normalization: 8-35%

QCD
Normalization: 6-70% statistical uncertainty in sideband

Theory Uncertainties on signal

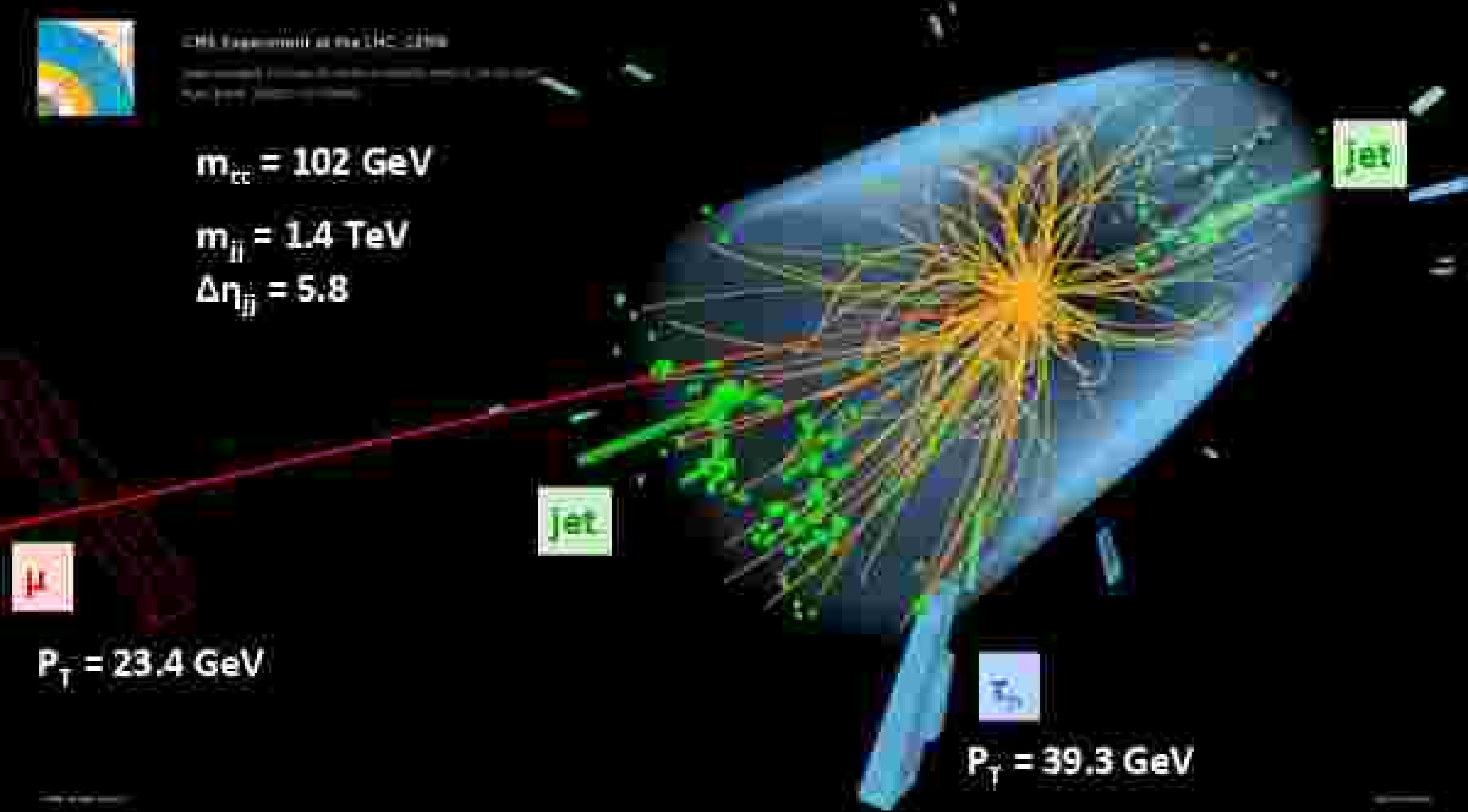
	ggH	qqH
PDF	10%	4%
Scale	10-41%	1-3%
UEPS	2-10%	

Results



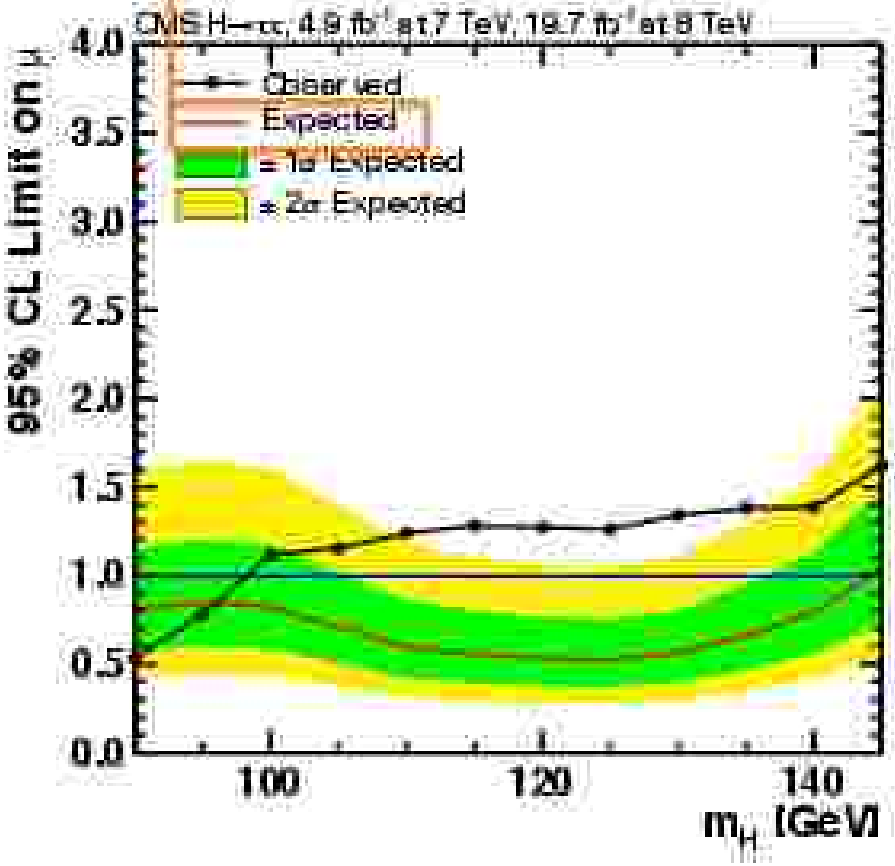
➔ Evidence for signal can be seen "by eye"

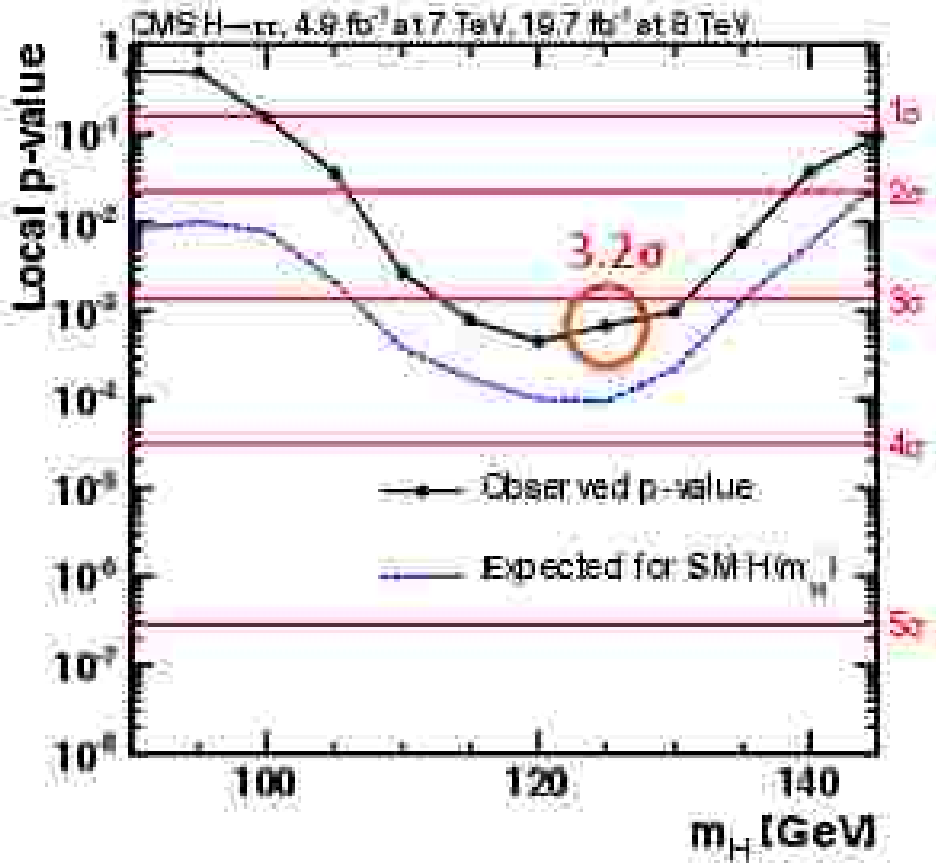
VBF Higgs → ττ → $\mu\tau_h$ Candidate Event



Statistical Significance of Signal

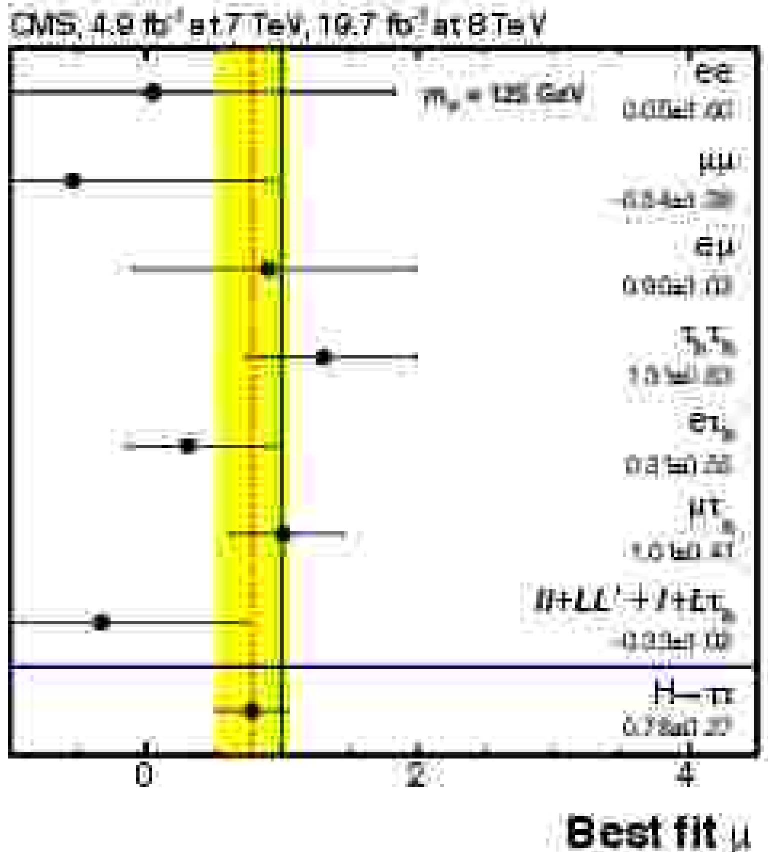
Limit on Higgs → ττ signal yield expected relative to the SM expectation, computed for background-only hypothesis

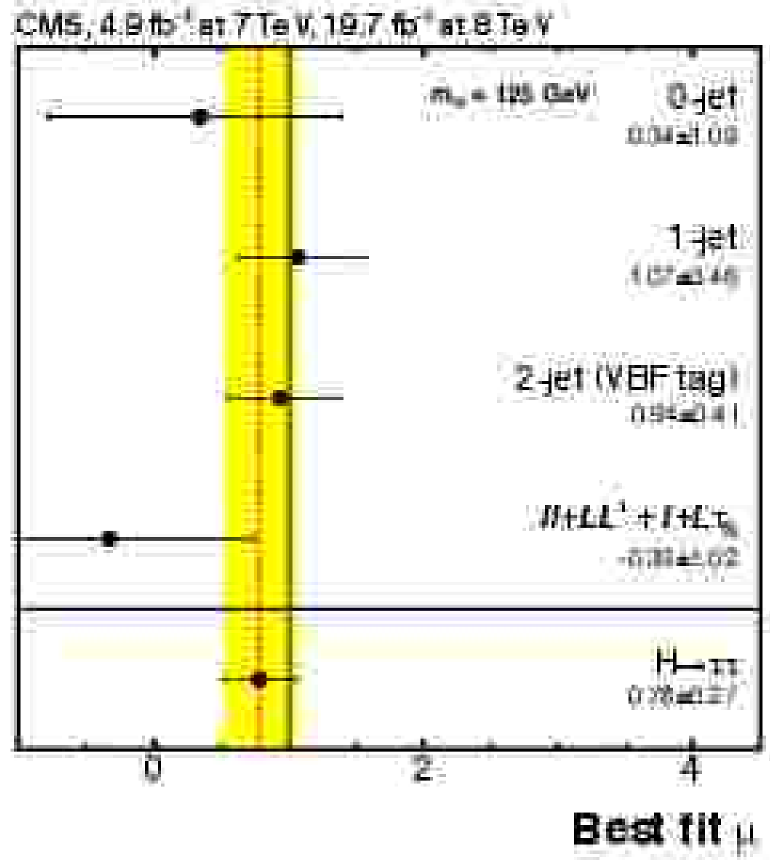




→ Significance of signal observed in combination of all ττ decay channels and event categories 3.2σ (3.7σ expected)

Compatibility of different Channels



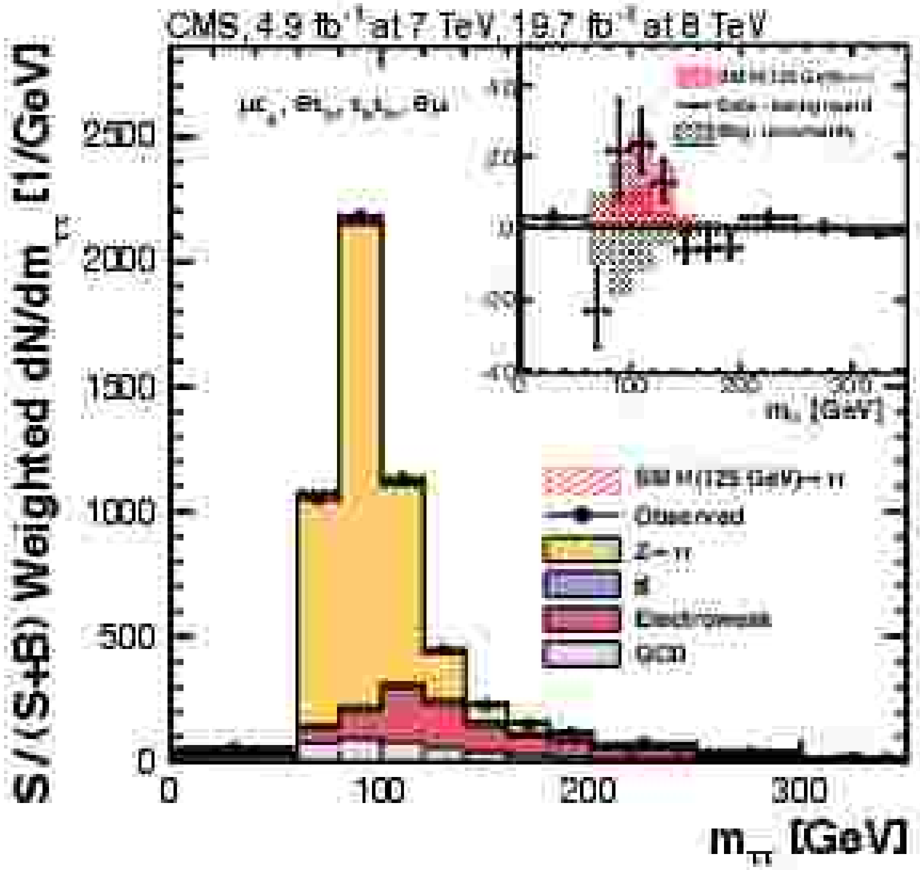


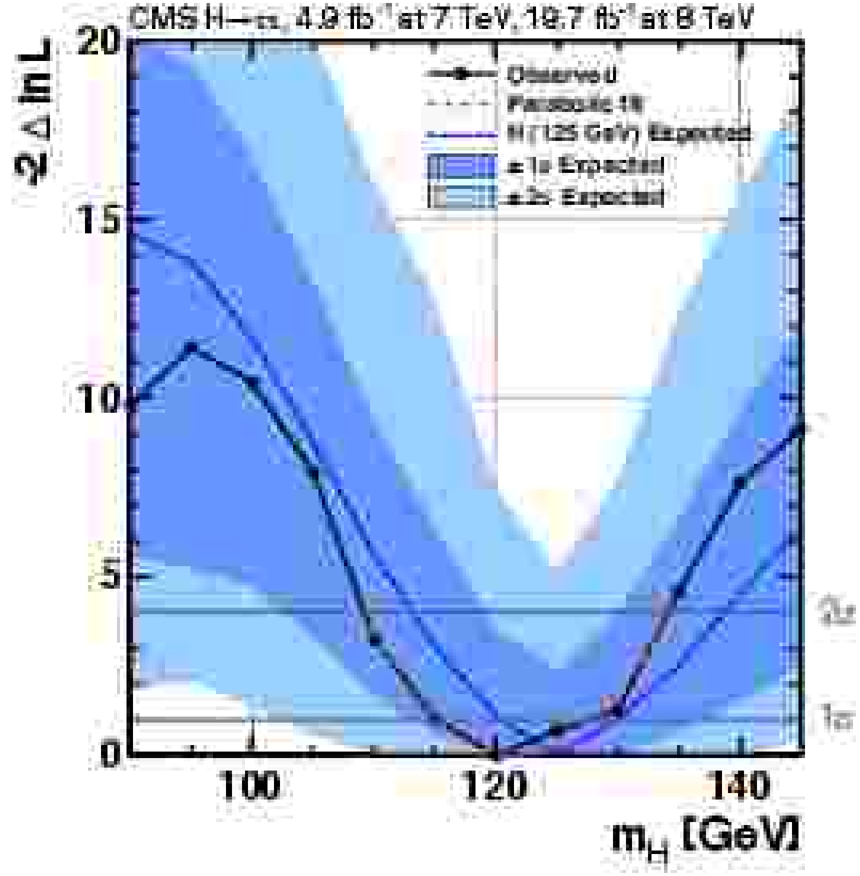
μ = observed signal rate relative to expectation for SM Higgs of mass m_H = 125 GeV

→ Signal rates observed in different ττ decay modes and event categories in good agreement

→ Best-fit value for signal rate compatible with expectation for SM Higgs

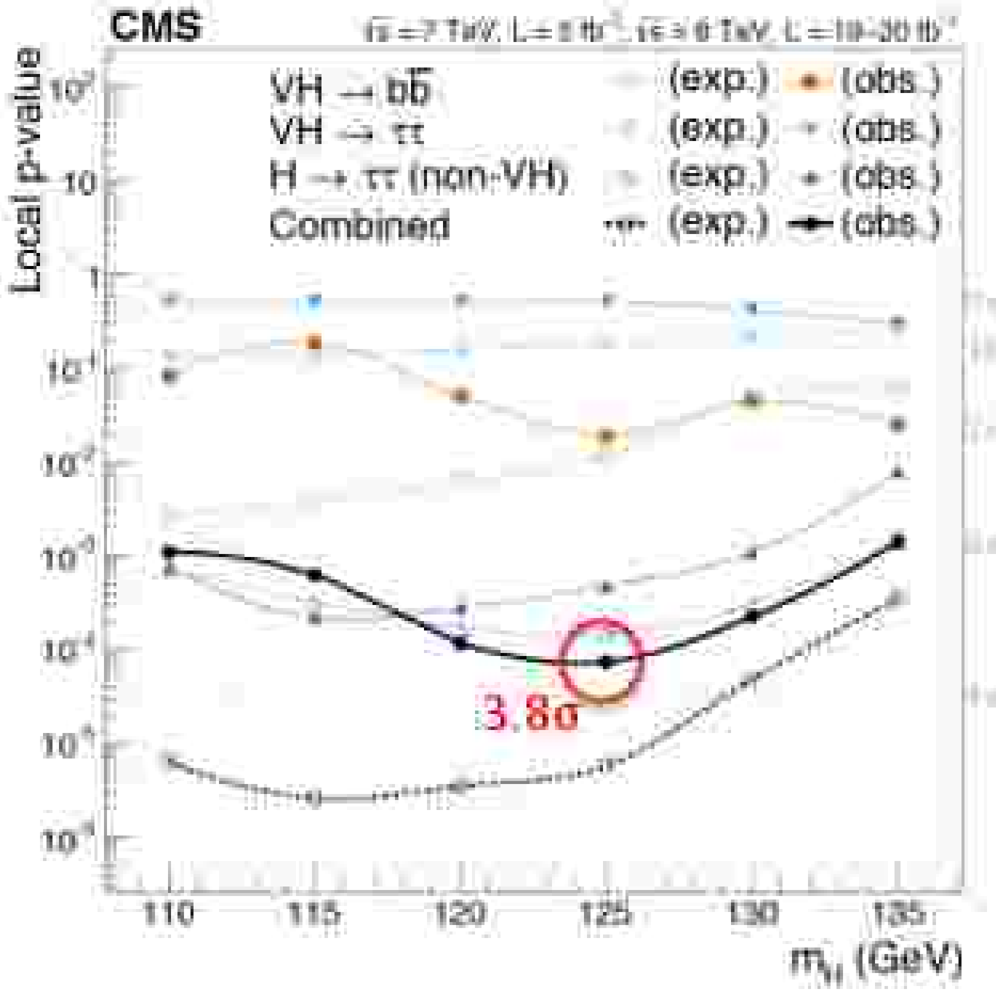
Compatibility with m_h = 125 GeV





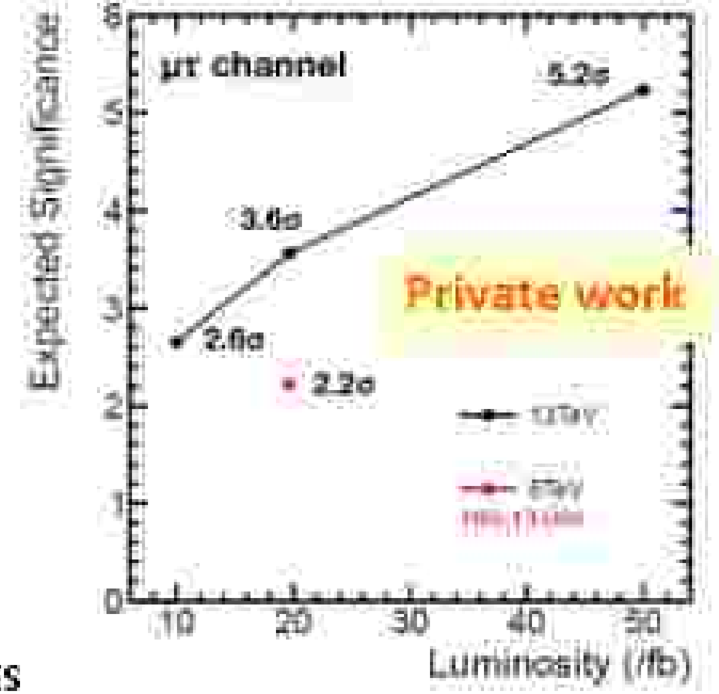
→ Position of signal peak in $m_{\tau\tau}$ distribution in agreement with m_h = 125 GeV, measured in Higgs → γγ and ZZ channels

Combination with Higgs → bb



→ Higgs decays to fermions observed with significance of 3.8σ (4.4σ expected) in combination of Higgs → ττ and bb channels

What's next ?



- Observe Higgs → ττ signal with > 5σ significance in LHC run 2

- Improve precision of Higgs coupling measurements

- Study tth production in Higgs → ττ channel
  Tallinn CMS group plans to be one of the main contributors to this analysis!

- Measure Higgs CP quantum numbers in Higgs → ττ

Higgs → ττ beyond the SM

MSSM Higgs → ττ

2 Higgs doublets $H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}, \quad H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}$

give rise to 5 physical Higgs bosons:

2 scalars:	h, H
1 pseudo-scalar:	A
2 charged Higgs bosons:	H^+, H^-

Cross-section increases proportional to $\tan\beta^2$
($\tan\beta$ = ratio of vacuum expectation value of the two Higgs doublets)

→ Compared to the SM, the Higgs → ττ cross-section may be enhanced by up to two orders of magnitude in the MSSM

MSSM Higgs → ττ

2 Higgs doublets

$$H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}, \quad H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}$$

give rise to 5 physical Higgs bosons:

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($\tan\beta$ = ratio of vacuum expectation value of the two Higgs doublets)

→ Compared to the SM, the Higgs → ττ cross-section may be enhanced by up to two orders of magnitude in the MSSM

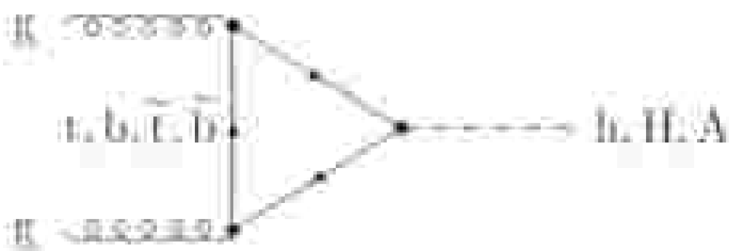
Observed SM-like Higgs boson interpreted as either light h or heavy scalar H

NB.: m_h = 125 GeV is right where SUSY predicted the Higgs boson to be!

Event Categories for MSSM Higgs → ττ

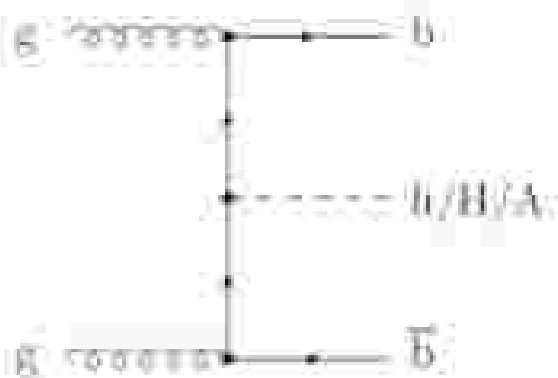
Events are analyzed in 2 Categories,
targeting different MSSM neutral Higgs production mechanisms:

1. No-B-tag: Events without b-tagged jets



pp → ϕ **gluon-gluon Fusion**
dominates cross-section
in case tanβ is small

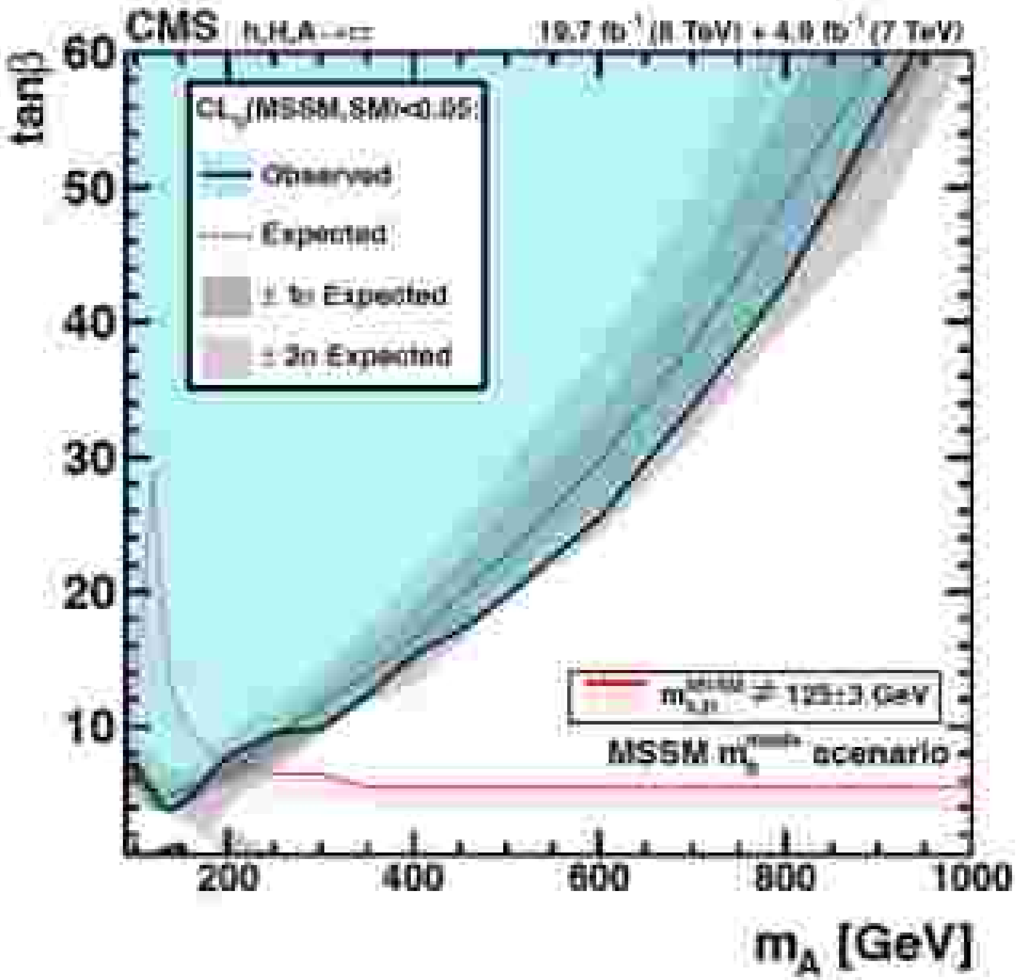
2. B-tag: Events containing ≥ 1 b-tagged jet of $P_T > 20$ GeV & $|\eta| < 2.4$



pp → ϕb **b-associated Production**
dominates cross-section
in case tanβ is large

NB.: Simplified event categories chosen for analysis to remain model independent

MSSM Higgs → ττ Status after LHC Run 1



CMS MSSM Higgs → ττ analysis has been the most sensitive probe for the MSSM Higgs sector during LHC run 1

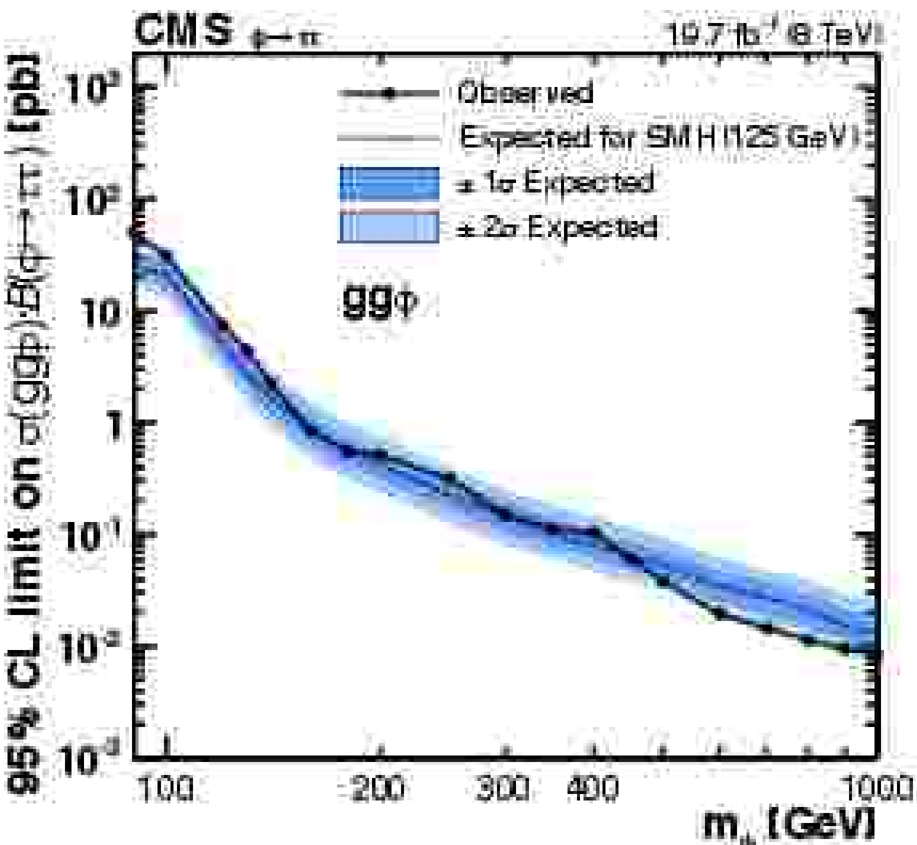
No evidence for a Higgs → ττ signal beyond 125 GeV found yet

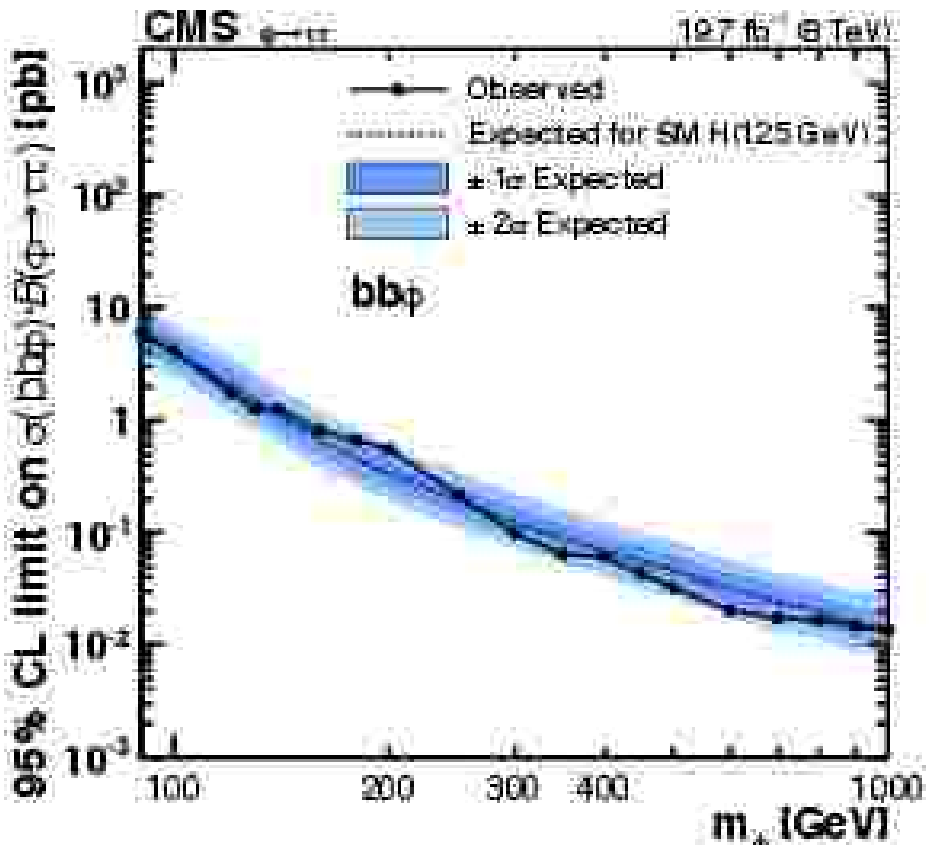
Improved analysis underway that will increase sensitivity by an amount corresponding to an increase in luminosity by a factor 3-4

Model independent Limits on Higgs → ττ

$m_{\tau\tau}$ spectra observed in **B-tag** and **No-B-tag** category are fitted simultaneously, with shape templates for $\phi \rightarrow \tau\tau$ signal and for background processes.

pp → φb (pp → φ) cross-section treated as **nuisance parameter** when computing limit on pp → φ (pp → φb)





Outlook on LHC Run 2

Expected Luminosity Increase

LHC machine parameters:

	Run 1	Run 2
Beam Energy	4 TeV	6.5 TeV
Collision frequency	20 MHz	40 MHz
Peak luminosity	$7.7 \cdot 10^{33}$ $cm^{-2}s^{-1}$	$1.7 \cdot 10^{34}$ $cm^{-2}s^{-1}$

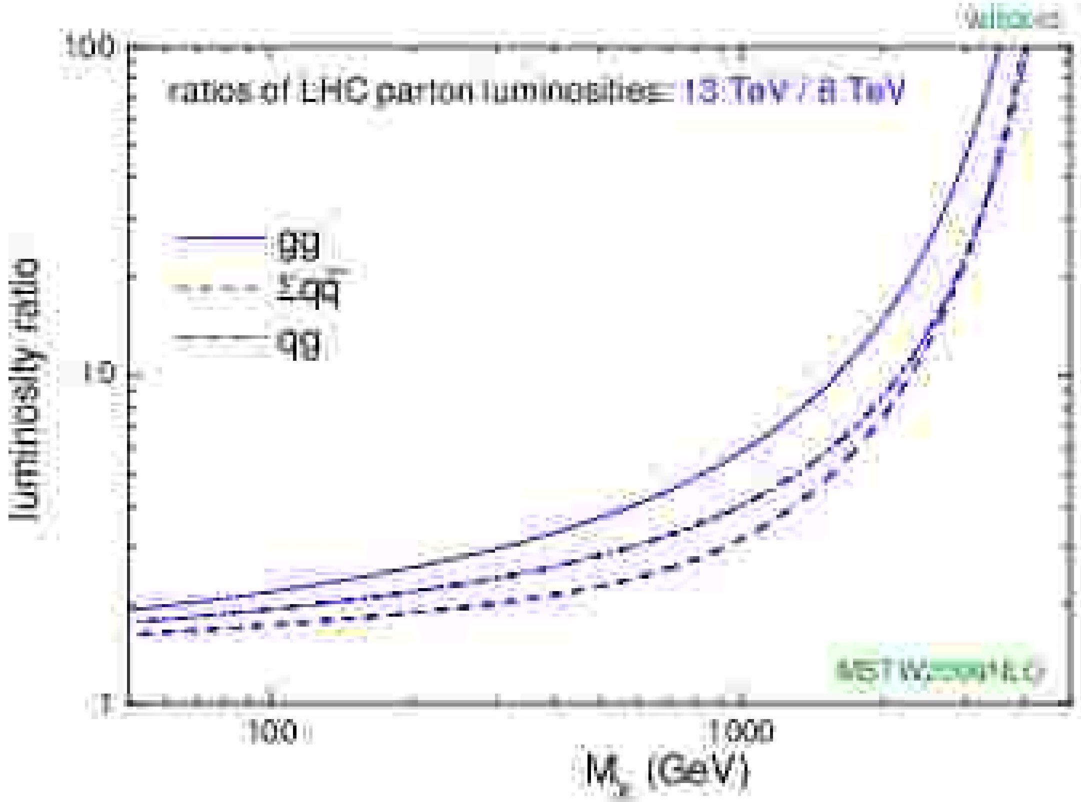
Expected luminosity:

Year	Total integrated Luminosity
2015	10 fb^{-1}
2016	40-45 fb^{-1}
2017	40-45 fb^{-1}

→ 100 fb^{-1} of 13 TeV data expected for LHC run 2 in total (2015-2017)

Expected Increase in Cross-section

Cross-section for different Higgs production processes will increase significantly in LHC run 2, due to increase in parton luminosity at higher center-of-mass energy



Increase in SM Higgs production cross-section:

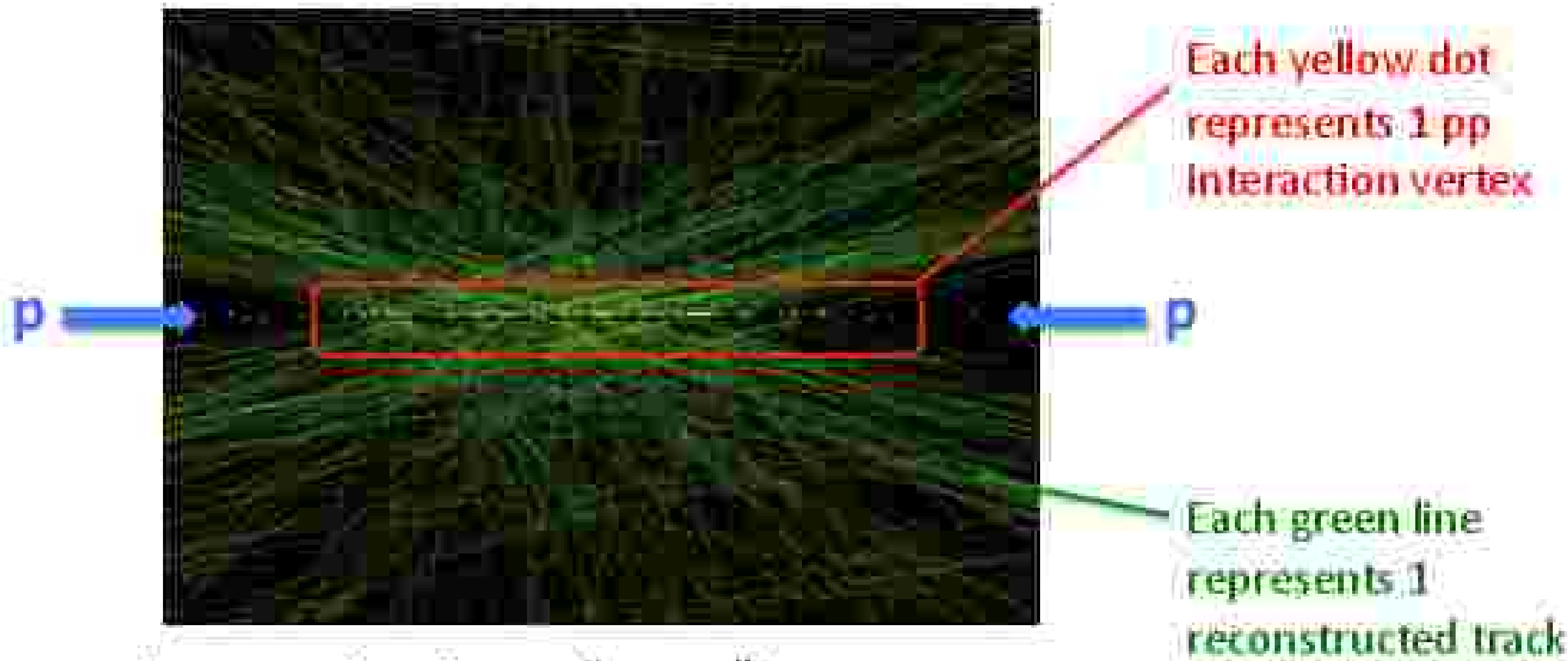
Gluon fusion	2.4
VBF	2.2
tth	4.0

➔ SM Higgs signal yield will increase by factor 10 or more compared to run 1

➔ BSM Higgs sector will be probed up to Higgs masses of 2-3 TeV

Pileup expected for Run 2

O(40) simultaneous pp interactions expected per bunch-crossing



CMS detector is hardly ever "empty"!

Furthermore:

40 MHz bunch-crossing frequency of same order as calorimeter time resolution

→ Need to carefully separate energy deposits in calorimeter by bunch-crossing

Status of Pileup Mitigation

- Calorimeter energy reconstruction has been retuned for 40 MHz bunch-crossing frequency

- New pileup mitigation methods for particle isolation, jet and E_T^{miss} reconstruction have been developed for run 2

→ Effect of pileup on physics analyses reduced to the level of run 1

Trigger Thresholds for Run 2

Path	Run 1	Run 2
Single e	27 GeV	32 GeV
Single μ	24 GeV	24 GeV
e+μ	17+8 GeV	20+10 GeV
$e+\tau_h$	22+20 GeV [*]	22+20 GeV [**]
$\mu+\tau_h$	17+20 GeV [*]	17+20 GeV [**]
$\tau_h+\tau_h$	35 GeV	40 GeV [***]

[*] Tau trigger requirement applied on HLT level

[**] Tau trigger requirement applied on L1 and HLT level (less sharp turn-on)

[***] Tau isolation requirements tightened (less sharp turn-on)

→ Sensitivity of $e\tau_h$ and $\mu\tau_h$ channels expected to be similar to run 1

$\tau_h\tau_h$ channel will loose O(20%) in sensitivity

Some loss in sensitivity expected for eμ channel,

as electrons and muons produced in tau decays are typically low P_T

Summary

Summary

- **SM Higgs → ττ signal observed with 3.2σ significance (3.7σ expected)**
- Higgs → ττ channel provides good sensitivity to probe BSM Higgs sector:
  No evidence for a Higgs signal beyond the SM observed yet
- **LHC run 2 will start this summer:**
  Integrated luminosity expected to increase by factor 4 compared to run 1
  Cross-section increases by factor ≥ 2
  Experimental challenges concerning pileup and trigger have been met
- **The run 2 data will allow us to:**
  Observe a SM Higgs → ττ signal with > 5σ significance
  Measure the τ Yukawa coupling with 10-20% precision
  Observe tth production in the H → ττ channel (I hope!)
  Probe the BSM Higgs sector up to Higgs masses of 2-3 TeV

Backup

Event Yields $\mu\tau_h$

within $m_{\tau\tau}$ mass window
that contains 68% of the signal for m_h = 125 GeV

Event category	SM Higgs (m_H = 125 GeV) ggH	VBF	VH	Σ signal	Background	Data	$\frac{S}{S+B}$	RMS (GeV)
$\mu\tau_h$								
0-jet low-$p_T^{\tau_h}$ 7 TeV	23.1	0.2	0.1	23.5 ± 3.4	11950 ± 590	11959	0.002	17.4
0-jet low-$p_T^{\tau_h}$ 8 TeV	83.0	0.8	0.4	85.0 ± 11.0	40800 ± 1900	40353	0.003	16.3
0-jet high-$p_T^{\tau_h}$ 7 TeV	17.5	0.2	0.2	17.9 ± 2.6	1595 ± 83	1594	0.022	15.1
0-jet high-$p_T^{\tau_h}$ 8 TeV	66.2	0.7	0.6	67.5 ± 9.3	5990 ± 250	5789	0.020	15.2
1-jet low-$p_T^{\tau_h}$ 7 TeV	9.1	1.6	0.8	11.5 ± 1.7	2020 ± 120	2047	0.012	18.8
1-jet low-$p_T^{\tau_h}$ 8 TeV	36.0	6.0	3.0	45.0 ± 6.0	9030 ± 360	9010	0.010	18.6
1-jet high-$p_T^{\tau_h}$ 7 TeV	7.7	1.1	0.6	9.4 ± 1.3	796 ± 39	817	0.033	19.1
1-jet high-$p_T^{\tau_h}$ 8 TeV	29.6	4.3	2.4	36.3 ± 4.6	3180 ± 130	3160	0.029	19.7
1-jet high-$p_T^{\tau_h}$ boosted 7 TeV	2.6	0.8	0.5	3.9 ± 0.6	282 ± 16	269	0.054	17.7
1-jet high-$p_T^{\tau_h}$ boosted 8 TeV	11.5	2.9	2.0	16.5 ± 2.6	1265 ± 62	1253	0.072	17.2
VBF tag 7 TeV	0.2	1.3	—	1.6 ± 0.1	22 ± 2	23	0.14	19.6
Loose VBF tag 8 TeV	1.1	3.4	—	4.5 ± 0.4	81 ± 7	76	0.17	17.0
Tight VBF tag 8 TeV	0.3	2.0	—	2.4 ± 0.2	15 ± 2	20	0.49	18.1

width of $m_{\tau\tau}$ distribution for m_h = 125 GeV signal

Event Yields $e\tau_h$

within $m_{\tau\tau}$ mass window
that contains 68% of the signal for m_h = 125 GeV

Event category	SM Higgs (m_H = 125 GeV) ggH	VBF	VH	Σ signal	Background	Data	$\frac{S}{S+B}$	RMS (GeV)
$e\tau_h$								
0-jet low-$p_T^{\tau_h}$ 7 TeV	11.8	0.1	0.1	12.0 ± 1.8	6140 ± 320	6238	0.002	16.4
0-jet low-$p_T^{\tau_h}$ 8 TeV	33.4	0.3	0.2	34.0 ± 4.6	16750 ± 750	17109	0.002	15.8
0-jet high-$p_T^{\tau_h}$ 7 TeV	11.1	0.1	0.1	11.3 ± 1.7	1159 ± 62	1191	0.015	14.3
0-jet high-$p_T^{\tau_h}$ 8 TeV	31.4	0.3	0.3	32.1 ± 4.4	4380 ± 170	4536	0.010	15.4
1-jet low-$p_T^{\tau_h}$ 7 TeV	3.1	0.6	0.3	4.0 ± 0.6	366 ± 25	385	0.029	19.6
1-jet low-$p_T^{\tau_h}$ 8 TeV	9.1	1.8	1.0	11.9 ± 1.6	1200 ± 56	1214	0.025	16.5
1-jet high-$p_T^{\tau_h}$ boosted 7 TeV	1.2	0.3	0.2	1.8 ± 0.3	150 ± 9	167	0.089	15.5
1-jet high-$p_T^{\tau_h}$ boosted 8 TeV	5.1	1.4	0.9	7.3 ± 1.1	497 ± 27	476	0.11	15.5
VBF tag 7 TeV	0.2	0.7	–	0.9 ± 0.1	14 ± 2	13	0.24	15.9
Loose VBF tag 8 TeV	0.6	1.8	–	2.4 ± 0.2	45 ± 4	40	0.14	16.7
Tight VBF tag 8 TeV	0.3	1.3	–	1.6 ± 0.1	9 ± 2	7	0.51	16.2

width of $m_{\tau\tau}$ distribution for m_h = 125 GeV signal

Event Yields $\tau_h\tau_h$

within $m_{\tau\tau}$ mass window
that contains 68% of the signal for m_h = 125 GeV

Event category	SM Higgs (m_H = 125 GeV) ggH	VBF	VH	Σ signal	Background	Data	$\frac{S}{S+B}$	RMS (GeV)
$\tau_h\tau_h$								
1-jet boosted 8 TeV	7.2	2.1	1.0	10.3 ± 1.7	1133 ± 49	1120	0.054	15.2
1-jet highly-boosted 8 TeV	3.6	1.6	1.2	8.4 ± 1.2	380 ± 23	366	0.14	13.1
VBF tag 8 TeV	0.5	2.4	–	3.0 ± 0.3	29 ± 4	34	0.32	14.3

width of $m_{\tau\tau}$ distribution for m_h = 125 GeV signal

Event Yields eμ

within $m_{\tau\tau}$ mass window
that contains 68% of the signal for m_h = 125 GeV

Event category	SM Higgs (m_H = 125 GeV) ggH	VBF	VH	Σ signal	Background	Data	$\frac{S}{S+B}$	RMS (GeV)
$e\mu$								
0-jet low-p_T^{μ} 7 TeV	20.8	0.2	0.2	21.1 ± 3.0	11320 ± 260	11283	0.002	24.4
0-jet low-p_T^{μ} 8 TeV	70.3	0.7	0.7	71.7 ± 9.6	40410 ± 830	40381	0.002	23.6
0-jet high-p_T^{μ} 7 TeV	7.5	0.1	0.1	7.8 ± 1.1	1636 ± 55	1676	0.007	22.7
0-jet high-p_T^{μ} 8 TeV	24.0	0.2	0.5	24.7 ± 3.3	6000 ± 150	6095	0.006	20.7
1-jet low-p_T^{μ} 7 TeV	9.0	1.6	1.0	11.7 ± 1.5	2475 ± 74	2482	0.009	23.7
1-jet low-p_T^{μ} 8 TeV	40.6	6.5	3.7	50.8 ± 6.1	10910 ± 250	10926	0.007	23.8
1-jet high-p_T^{μ} 7 TeV	4.7	1.0	0.6	6.2 ± 0.8	928 ± 37	901	0.015	23.3
1-jet high-p_T^{μ} 8 TeV	18.0	3.4	2.6	23.9 ± 2.9	4040 ± 110	4050	0.014	23.1
Loose VBF tag 7 TeV	0.2	1.0	–	1.2 ± 0.1	19 ± 1	12	0.13	23.0
Loose VBF tag 8 TeV	0.6	2.6	–	3.3 ± 0.3	99 ± 6	112	0.054	23.5
Tight VBF tag 8 TeV	0.2	1.3	–	1.6 ± 0.1	14 ± 1	17	0.31	17.8

width of $m_{\tau\tau}$ distribution for m_h = 125 GeV signal

Kinematics of ττ Decays

$\tau \rightarrow \tau_h \nu$ ($\tau \rightarrow \ell\nu\nu$) Decays parametrized by 2 (3) variables:

- θ^*
- ϕ^*
- $m_{\nu\nu}$ (leptonic τ decays only)

Decay angles in τ restframe

➔ 4 unknown variables in $\tau\tau \rightarrow \tau_h\tau_h$, 5 in $\tau\tau \rightarrow \ell\tau_h$, 6 in $\tau\tau \rightarrow \ell\ell$ decays

NB.: Decay angle θ^* is related to visible energy fraction $x = E_{vis}/E_\tau$ in laboratory system

Mass of visible τ decay products

$$\cos\theta^* = \frac{2x - 1 - m_{vis}^2/m_\tau^2}{1 - m_{vis}^2/m_\tau^2}$$

(with assumption β = 1)

Unknown variables constrained by 2 observables:

- $\Sigma p_x^\nu = E_x^{miss}$
- $\Sigma p_y^\nu = E_y^{miss}$

within experimental resolution of O(10) GeV

➔ Problem of reconstructing $M_{\tau\tau}$ is underconstrained

SVfit Algorithm

$M_{\tau\tau}$ Solutions obtained by finding maximum of probability density:

$$\frac{dL(M_{\tau\tau})}{dM_{\tau\tau}} = \int_{\Omega} \frac{df(\mathbf{x}_u|\mathbf{x}_m)}{d\mathbf{x}_u} \delta(M_{\tau\tau} - M_{\tau\tau}(\mathbf{x}_u, \mathbf{x}_m)) d\mathbf{x}_u$$

Histogram

x_u: unknown variables θ^*, ϕ^*, $m_{\nu\nu}$

x_m: measured observables E_x^{miss}, E_y^{miss}; momenta of visible τ decay products

Likelihood function f incorporates our knowledge about:

- τ decay kinematics
- Experimental resolution on E_x^{miss}, E_y^{miss}

Integral over likelihood function is computed numerically.

2 methods implemented in SVfit:

- Adaptive integration (VEGAS, part of GNU scientific library)
- Markov Chain (custom Implementation in SVfit)

Likelihood for $\tau \to \ell\nu\nu$ Decays

Matrix element for $\tau \to \ell\nu\nu$:

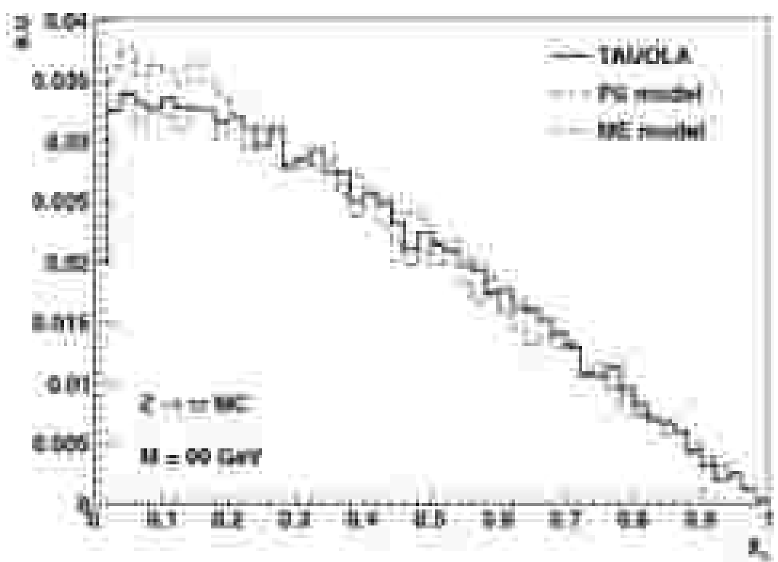
$$\frac{d\Gamma}{dx\ dm_{\nu\nu}} \sim \frac{m_{\nu\nu}}{4m_\tau^2}[(m_\tau^2+2m_{\nu\nu}^2)(m_\tau^2-m_{\nu\nu}^2)]$$

(with assumption that τ is unpolarized)

Physical region: $0 \leq x \leq 1$, $0 \leq m_{\nu\nu} \leq \sqrt{1-x}$

Implementation of likelihood for $\tau \to \ell\nu\nu$ decays validated by implementing ME in toy MC and comparing to TAUOLA:

- Toy MC agrees well with TAUOLA
- Significant difference wrt. 3-body phase-space decay model (= constant matrix element)



NB.: visible decay products in leptonic τ decays tend to be low P_T

Likelihood for $\tau \rightarrow \tau_h \nu$ Decays

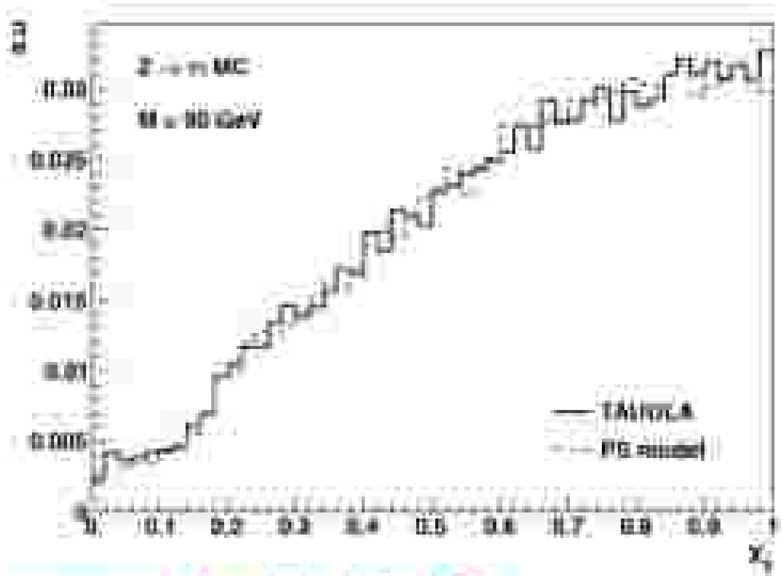
Phase-space for 2-body decay:

$$\frac{d\Gamma}{dx} = \frac{1}{1 - \frac{m_{vis}^2}{m_\tau^2}}$$

Physical region: $\frac{m_{vis}}{m_\tau} \leq x \leq 1$

Implemented 2-body PS model for $\tau \rightarrow \tau_h \nu$ decays in toy MC and compared to TAUOLA

→ Simple 2-body PS model represents good approximation to sum of all hadronic τ Decay modes



NB.: visible decay products in hadronic τ decays tend to be high P_T

E_T^{miss} Likelihood

$$L(\vec{E}_T^{miss} | \sum_i \vec{p}_T^{\nu\,i}) = \frac{1}{\sqrt{2\pi|\mathbf{V}|}} e^{\frac{1}{2}(\vec{E}_T^{miss} - \sum_i \vec{p}_T^{\nu\,i})^T \mathbf{V}^{-1} (\vec{E}_T^{miss} - \sum_i \vec{p}_T^{\nu\,i})}$$

τ-neutrino momentum $p_T^\nu = p_T^\nu(\theta, \phi, m_{\nu\nu})$

E_T^{miss} significance matrix V computed by summing resolutions expected for individual particles i reconstructed by PF algorithm:

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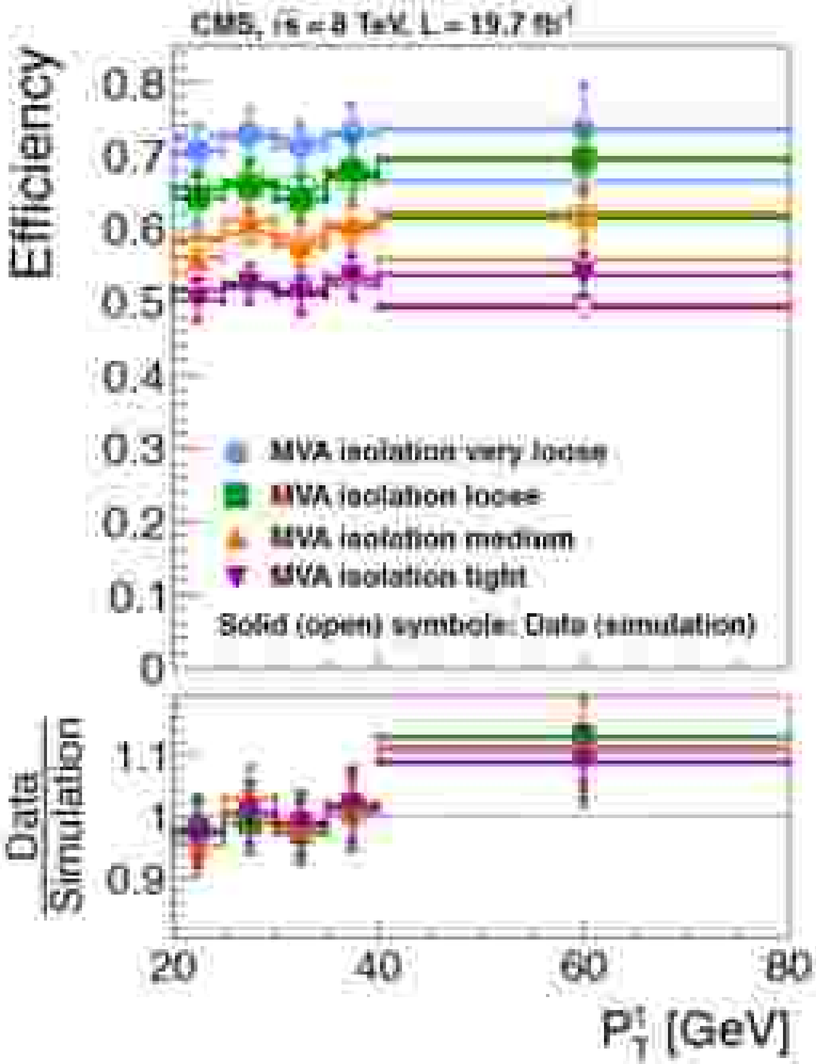
$$V = \Sigma_i\ R^{-1}(\phi_i)\, U_i\, R(\phi_i)$$

transformation from eigensystem of particle i to laboratory system

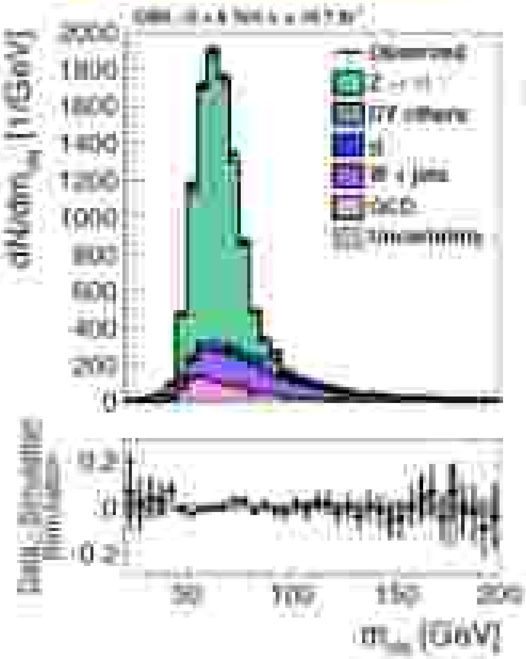
$$U_i = \begin{pmatrix} \sigma^2_{E_T} & 0 \\ 0 & E_T^2 \sigma^2_{\phi} \end{pmatrix}$$

obtained from MC simulation,
separately for e/γ, μ, τ_h, jets, "unclustered" charged and neutral hadrons

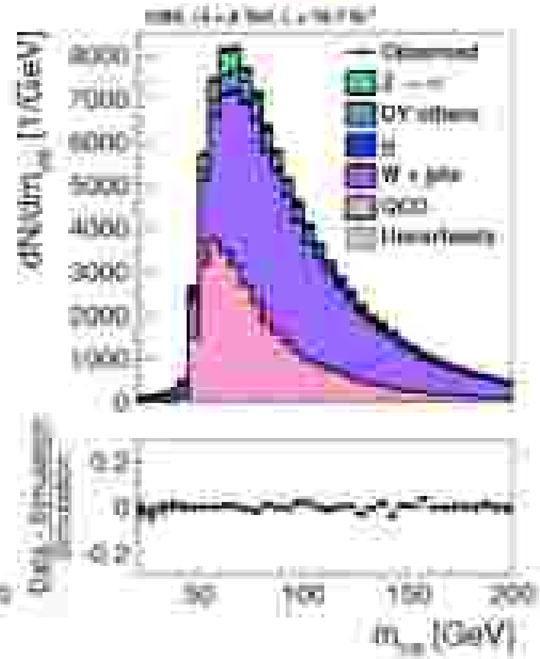
Tau identification efficiency



Tag & Probe: Pass



Fail



Jet → τ_h Misidentification rate