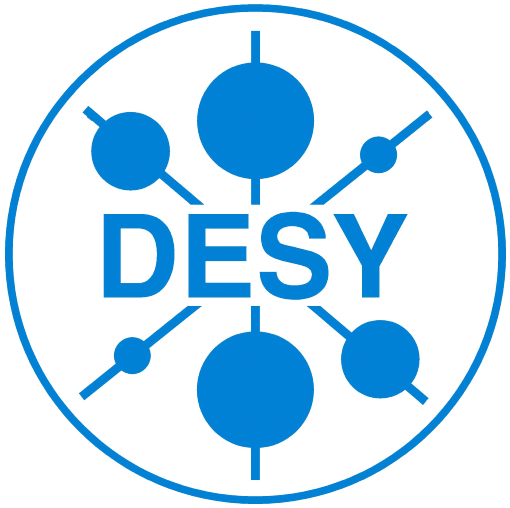


Exploring the Mechanism of Electroweak Symmetry Breaking at the LHC and the ILC

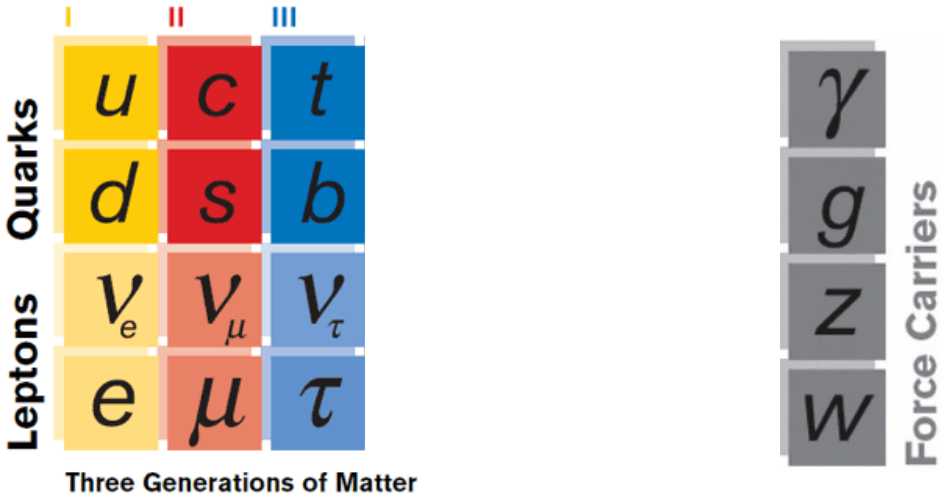
Alexei Raspereza – DESY

Physics Seminar

DESY Hamburg – 2012 July 10th

Standard Model

- **Building blocks of Standard Model**

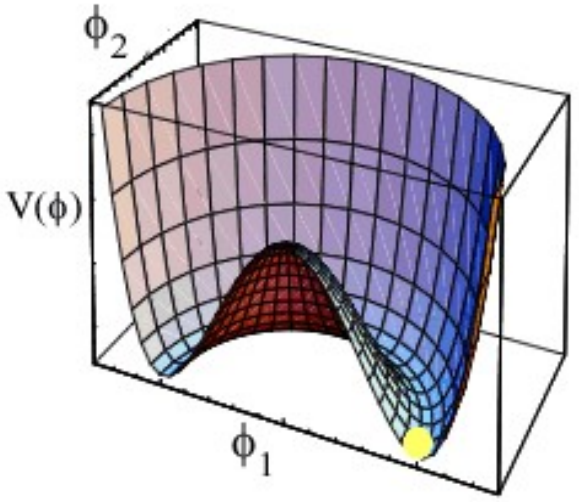


- **Standard Model features**
  - **$U(1)_Y \times SU(2)_L \times SU(3)_C$ symmetry → gauge interactions**
- **Lagrange formalism describes this very well but only for massless particles**
- **terms** $m(\bar{f}_R f_L + \bar{f}_L f_R), \quad M^2 V^\mu V_\mu$ **break $U(1)_Y \times SU(2)_L$ symmetry**
- **model is consistent with experimental data assuming massive fermions and weak bosons**

Higgs Mechanism

- **Need gauge invariant mechanism to generate particle masses**
- **Mechanism in the Standard Model :**
  - **one Higgs doublet with specific potential**

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \qquad V(\Phi^\dagger\Phi) = \lambda\left(\Phi^\dagger\Phi - \frac{v^2}{2}\right)^2$$



- **4 degrees of freedom**
- **vacuum expectation value (v/$\sqrt{2}$) ≠ 0**
- **radial excitation of the ground state → additional physical state (Higgs boson)**
- **motions along valley of minima → three longitudinal polarization states of *W*± and *Z***

$$\mathcal{D}_\mu\langle\Phi\rangle \rightarrow m_Z, m_W$$

$$Y_f\left(\bar{f}_R\langle\Phi\rangle^\dagger f_L + \bar{f}_L\langle\Phi\rangle f_R\right) \rightarrow m_f$$

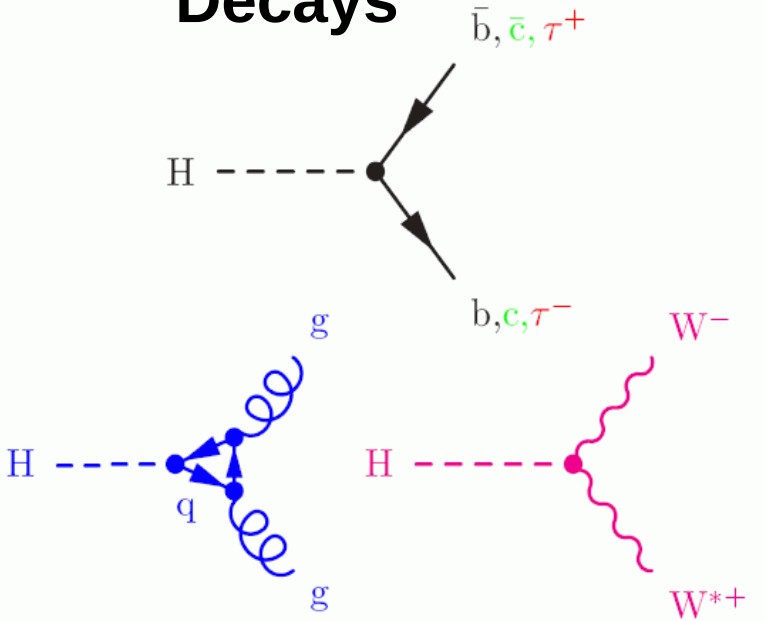
- **Prominent consequence of Higgs mechanism :**

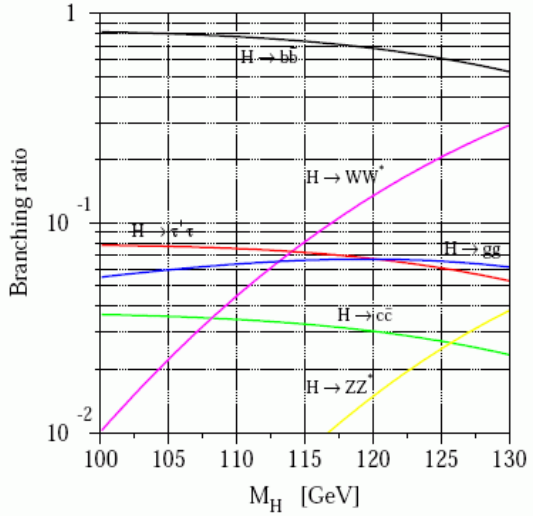
Higgs boson couples stronger to a more massive particles

SM Higgs Searches: Status before July 4^{th} 2012

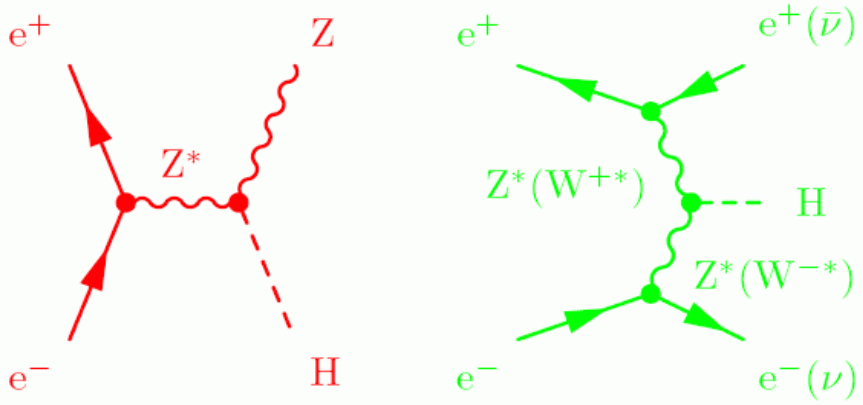
SM Higgs Boson at LEP

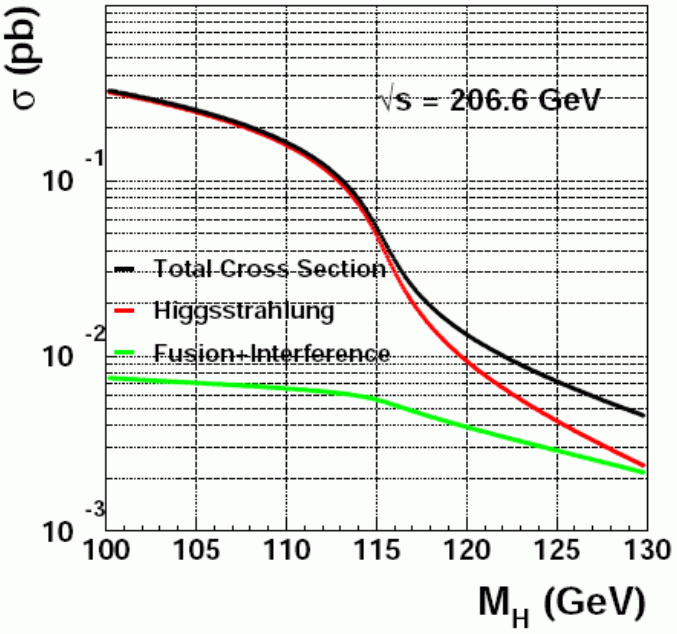
Decays



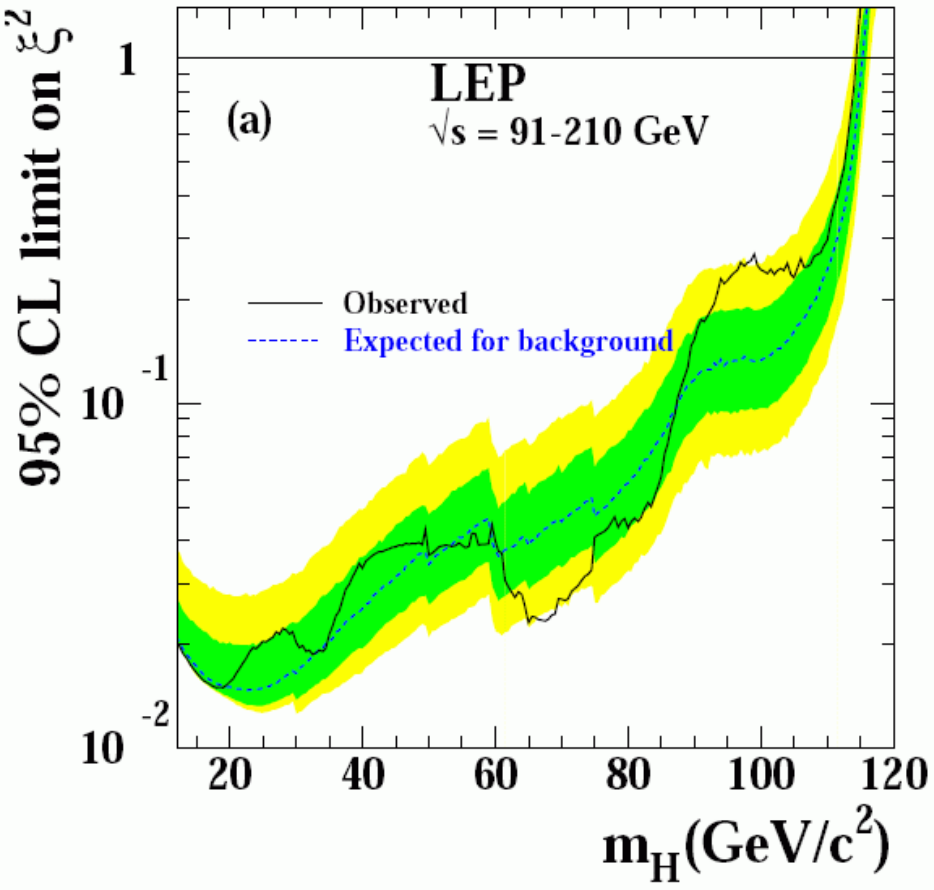


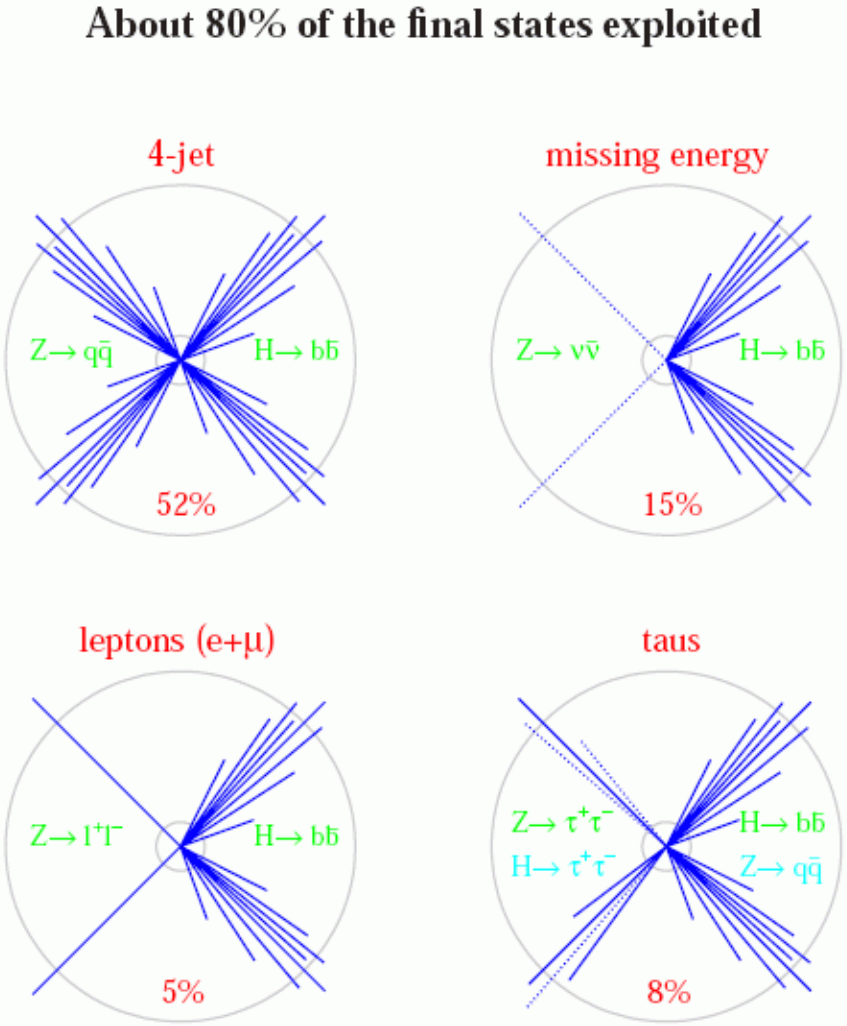
Production





SM Higgs Searches at LEP

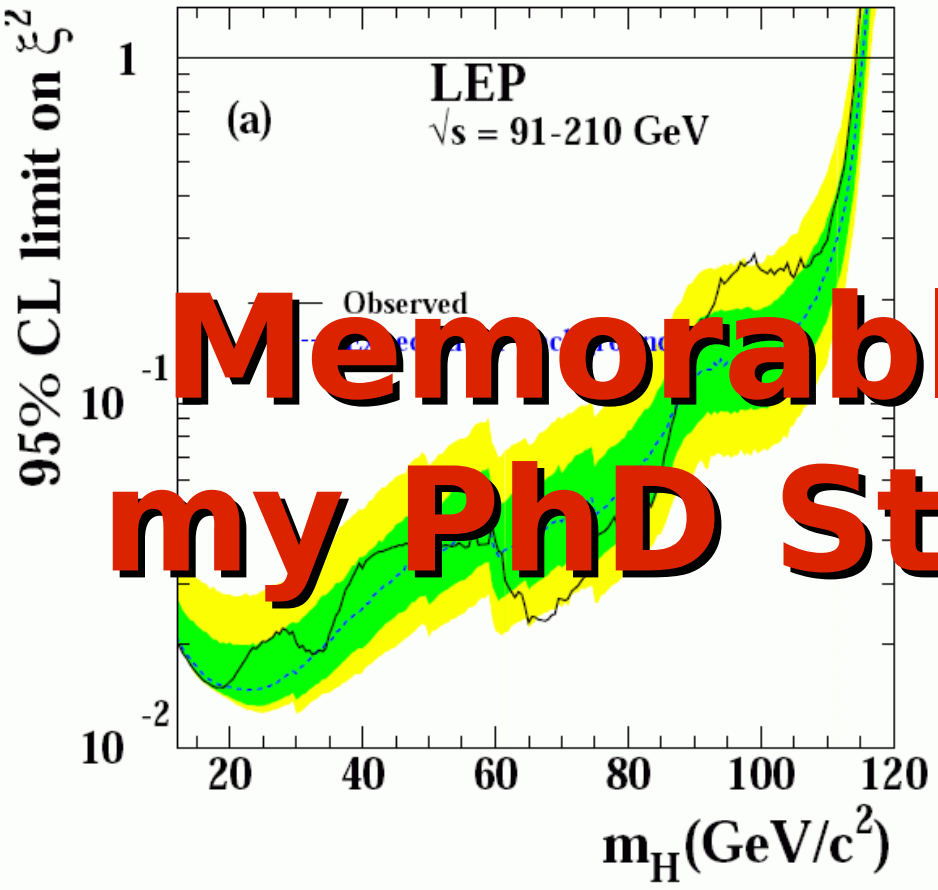


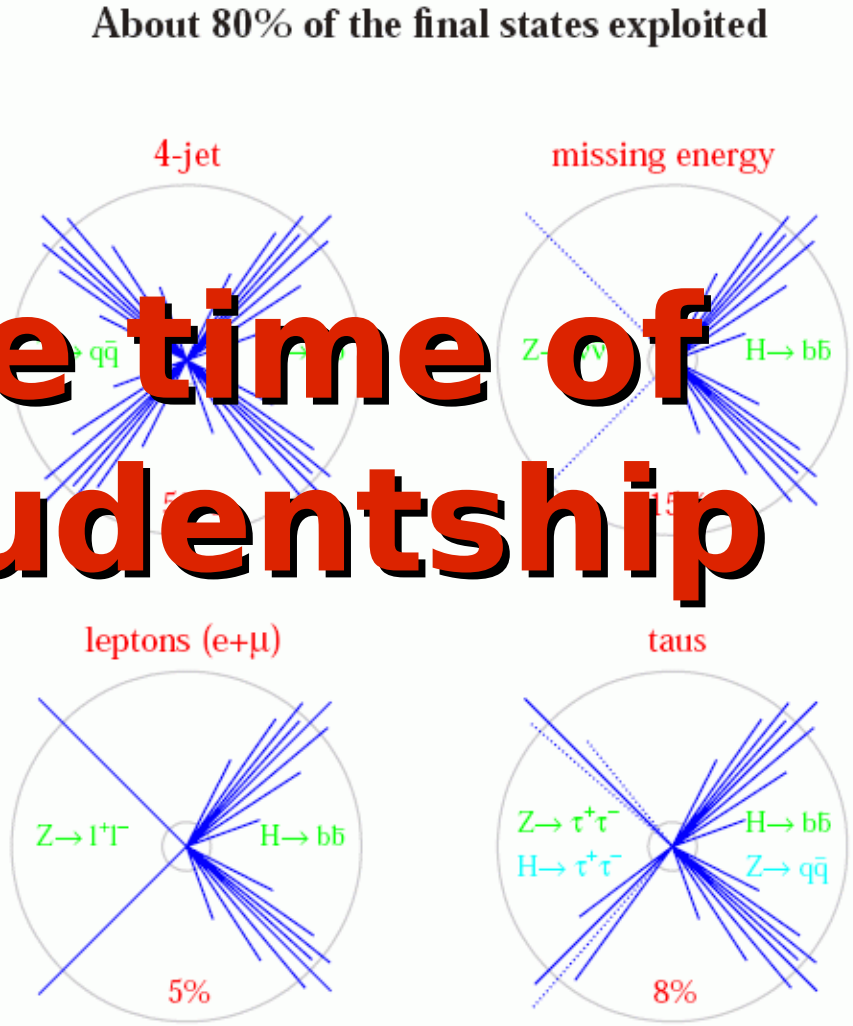


- **No evidence for Higgs**

→ ***m_H > 114 GeV @ 95% C.L.***

SM Higgs Searches at LEP



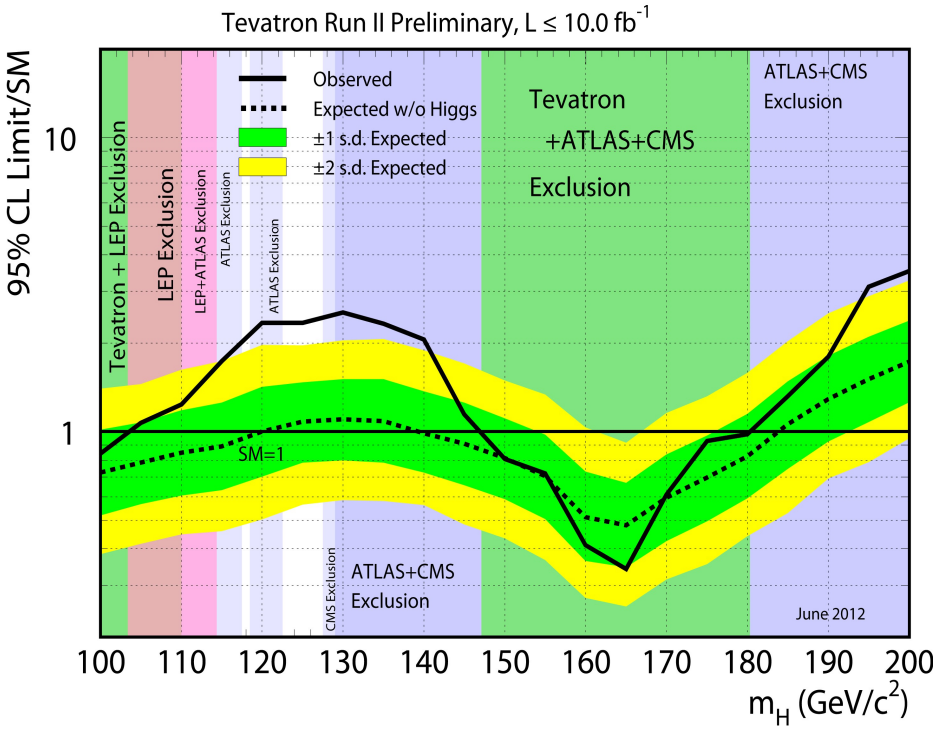


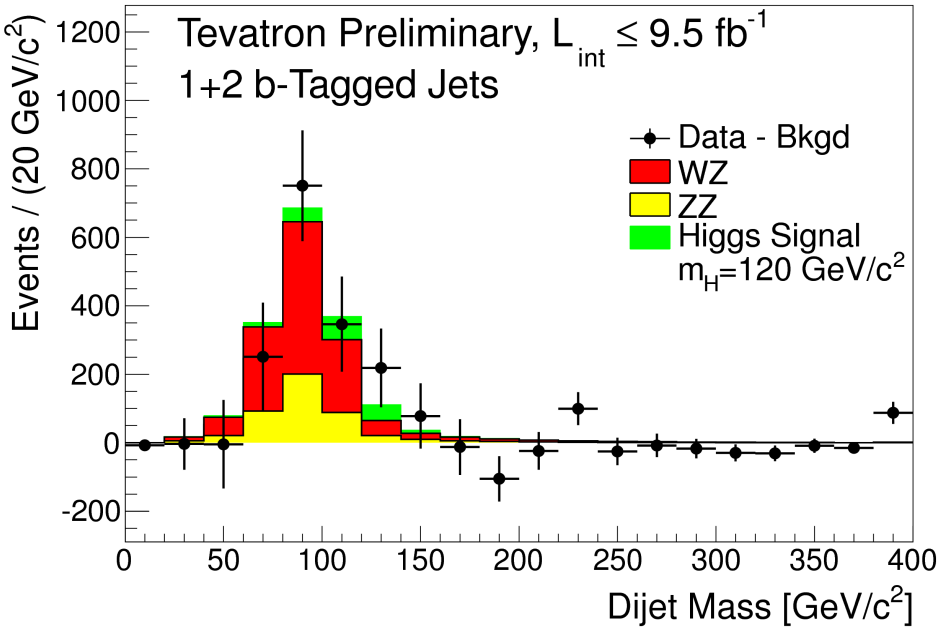
Memorable time of my PhD Studentship

- **No evidence for Higgs**

→ ***m_H > 114 GeV @ 95% C.L.***

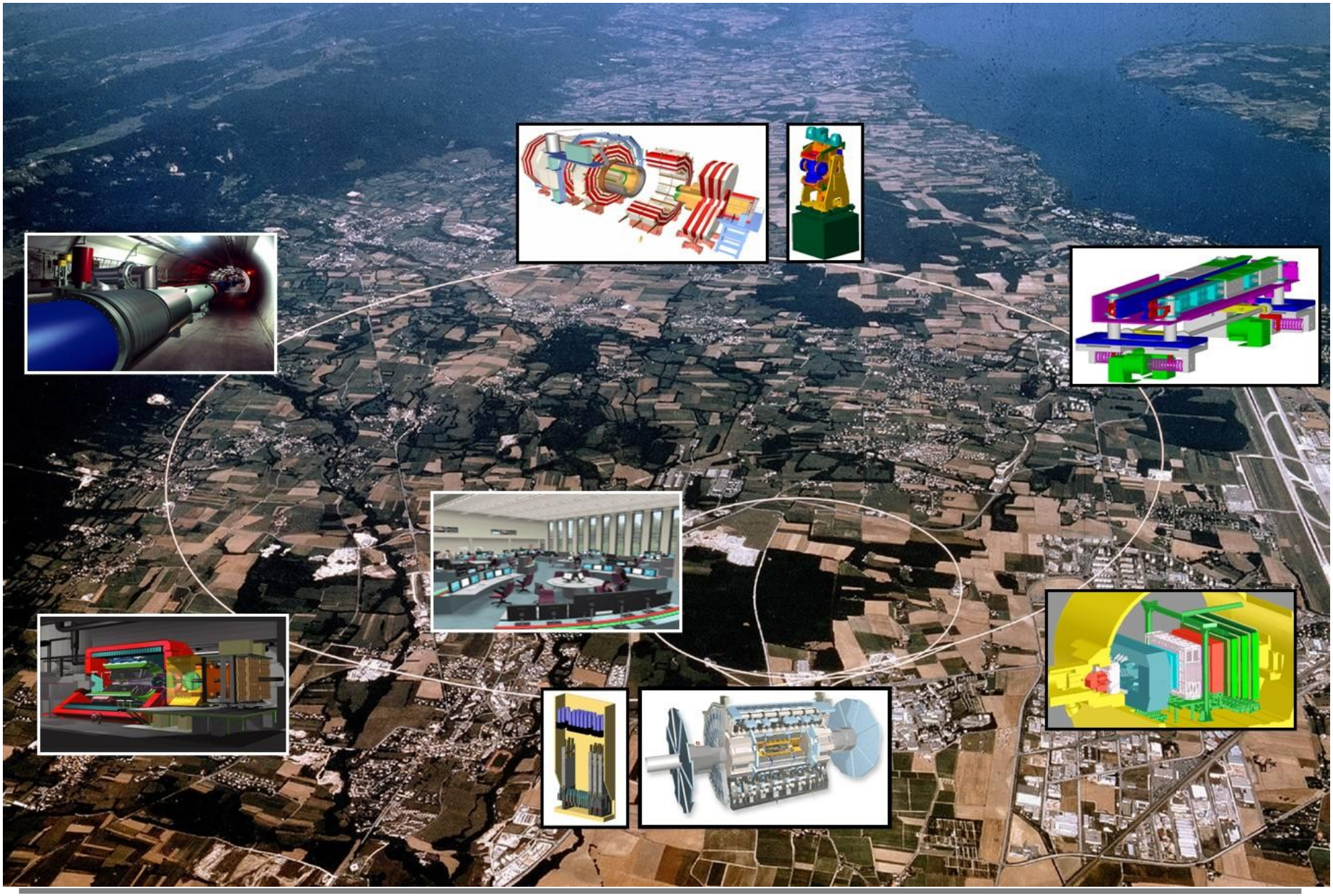
Updated Tevatron Results



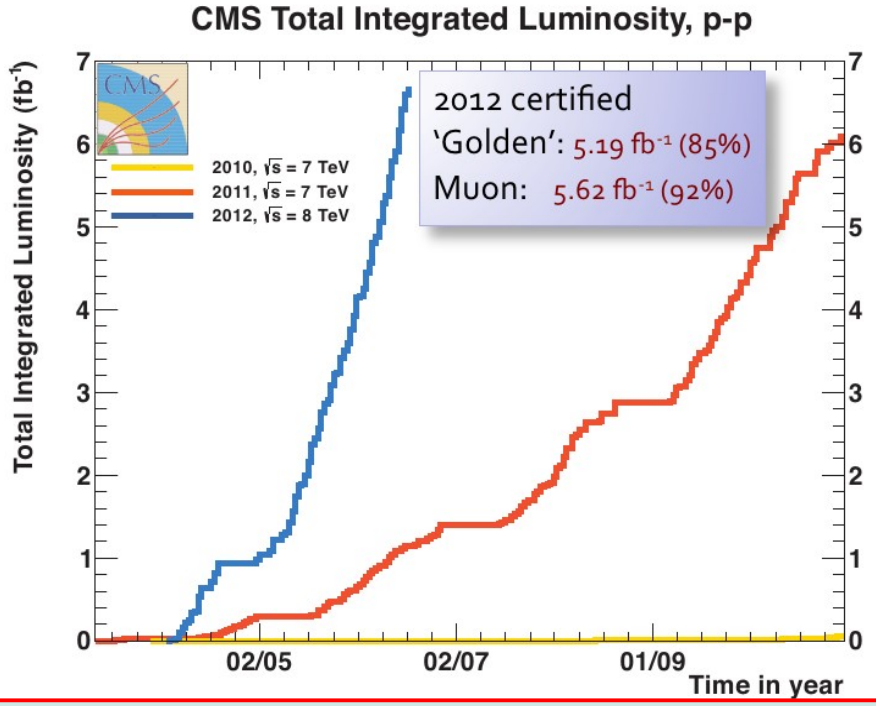


- **improved analysis techniques**
- **all statistics analyzed : 10 fb^{-1} / experiment**
- **analyses show clear sensitivity to "standard candles", e.g. WZ, ZZ production followed by Z → bb**
- **excess > 2σ in the mass range m_H = 115 – 140 GeV**
- **Very nice analyses and very nice results!**

Your Word, LHC Community!



Machine Performance

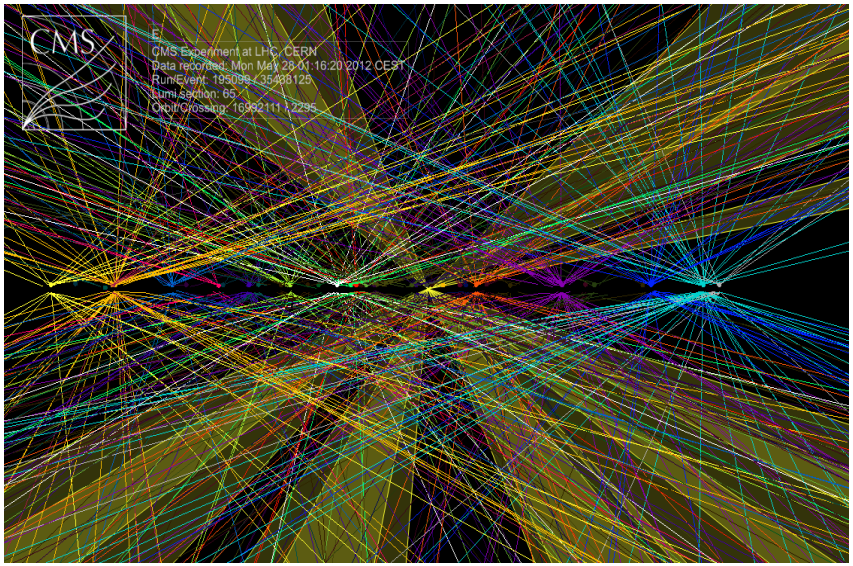


Peak luminosity in 2012

$L \approx 7 \times 10^{33}\ cm^{-2}s^{-1}$

steady performance of LHC enables experiments to produce significant physics results

Main challenge : Pile-up

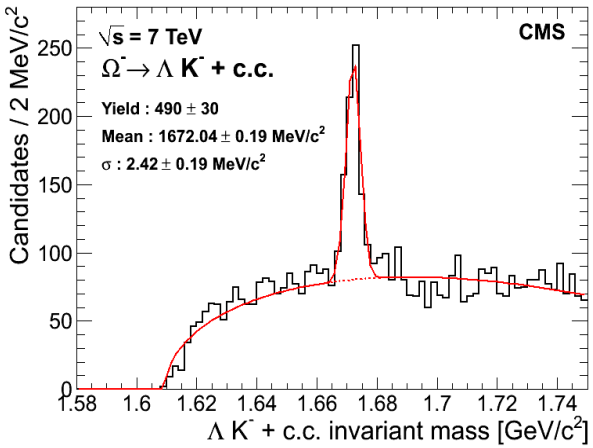


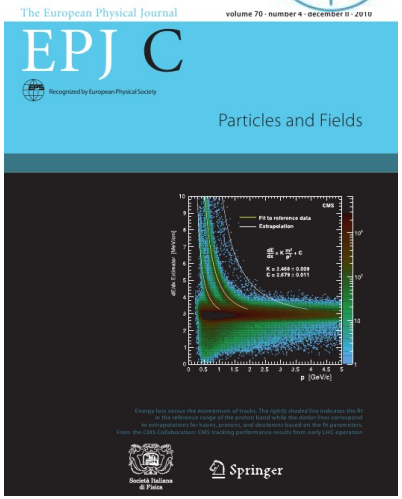
Special task force to prepare for 2012 data taking and mitigate effect of PU on trigger, reconstruction of physics objects, CPU time, event size

→ physics performance unchanged, e.g. for most of triggers thresholds are kept the same as in 2011

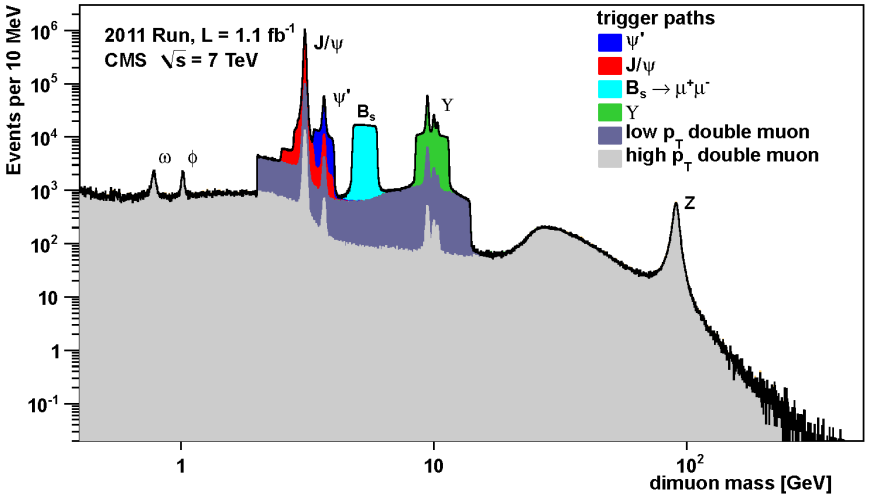
Commissioning of Detector and Reconstruction Tools

Tracking & Vertexing

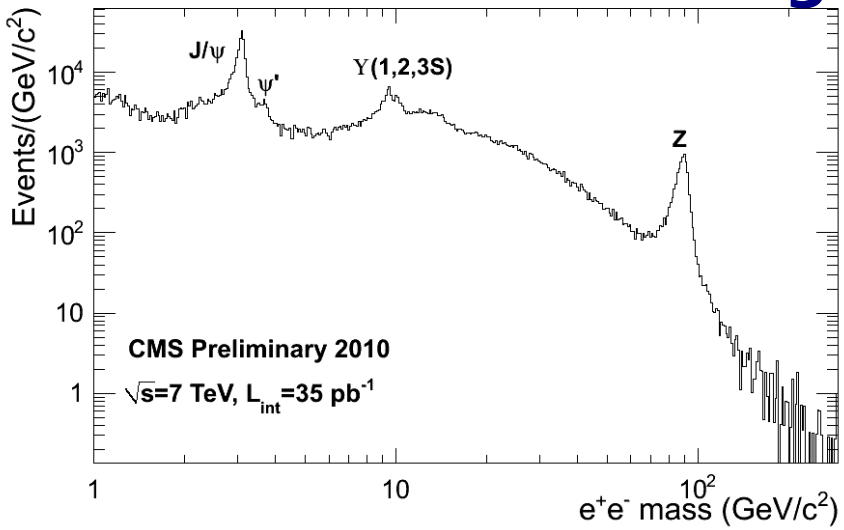




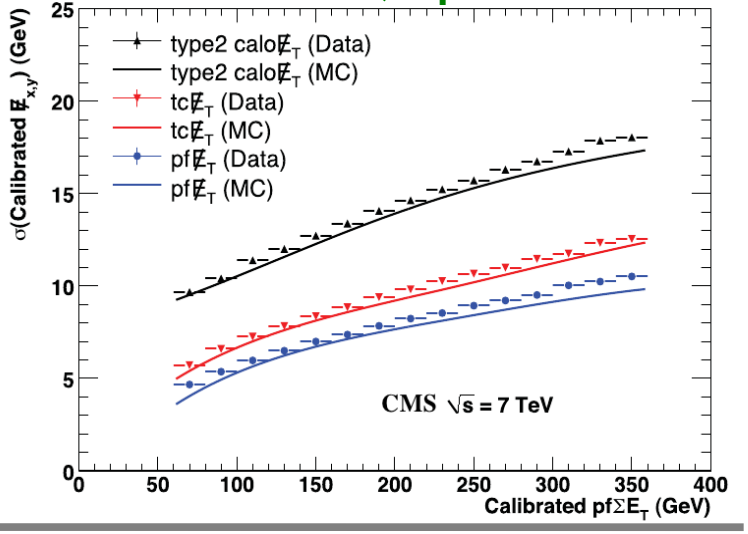
Muon System



ECAL Commissioning

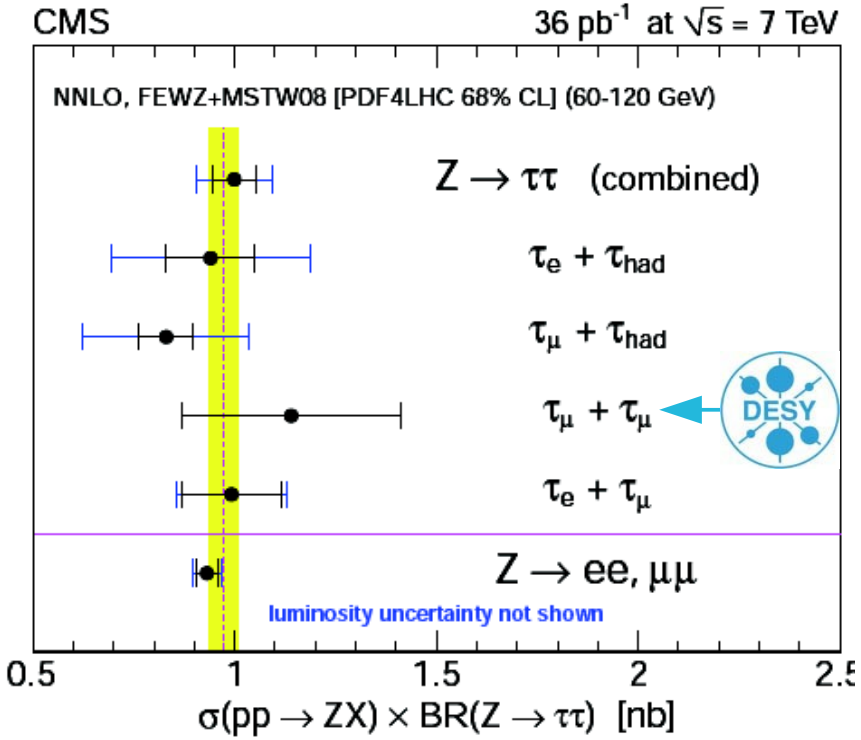


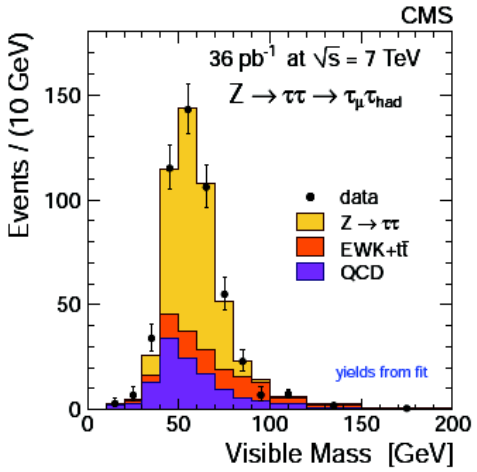
PFlow, $\not{E}_T$, Jets

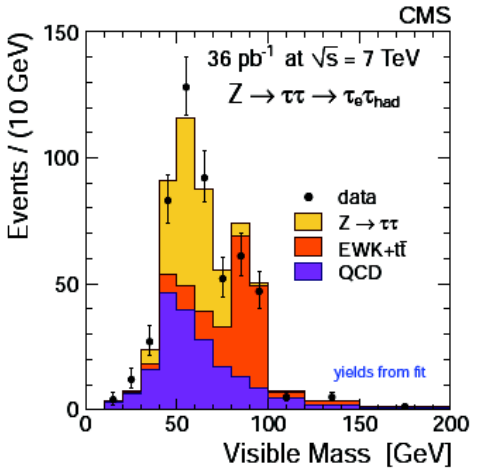


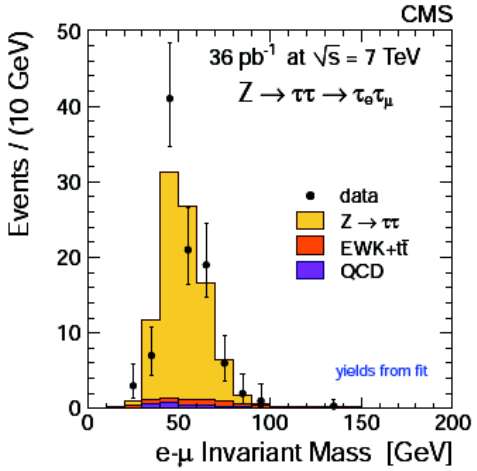
Calibration of Searches with Standard Candles

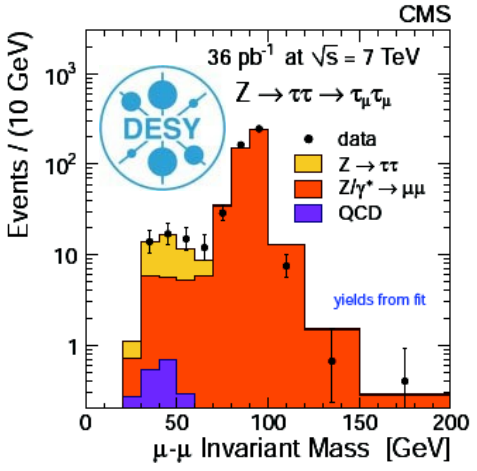
- **Analyses searching for the Higgs Boson were commissioned with "Standard Candles"**
- **Example : the H → ττ search is commissioned with the study of inclusive Z production followed by Z → ττ**











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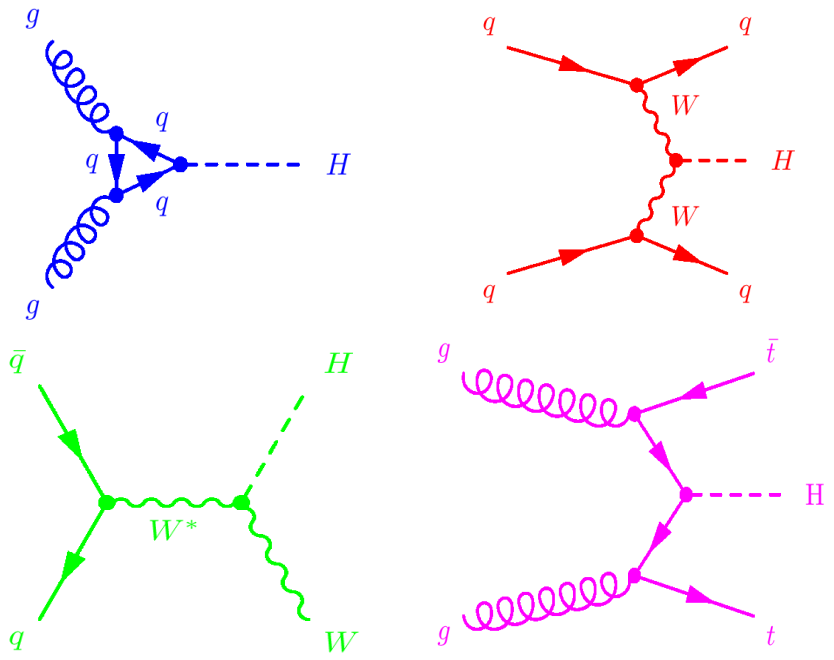
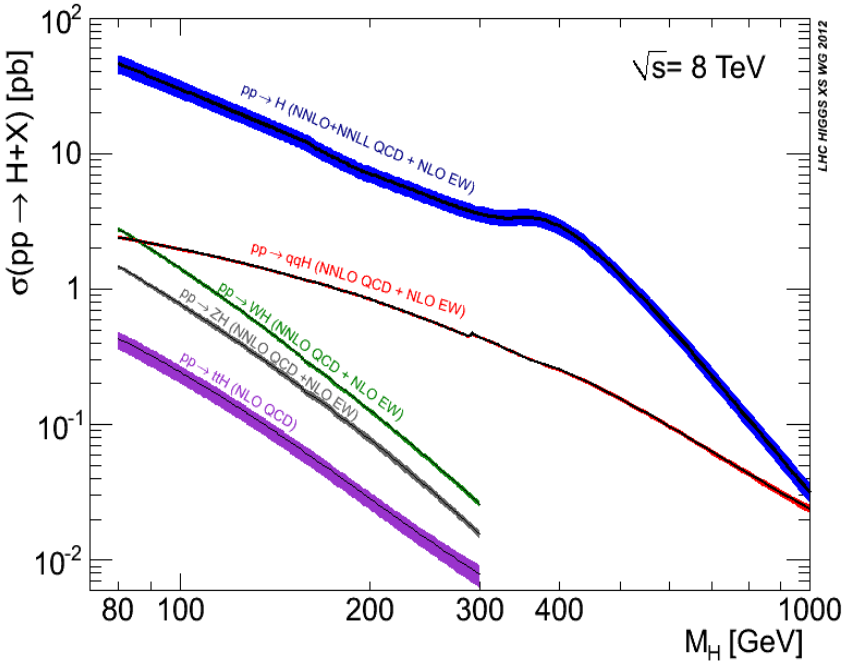
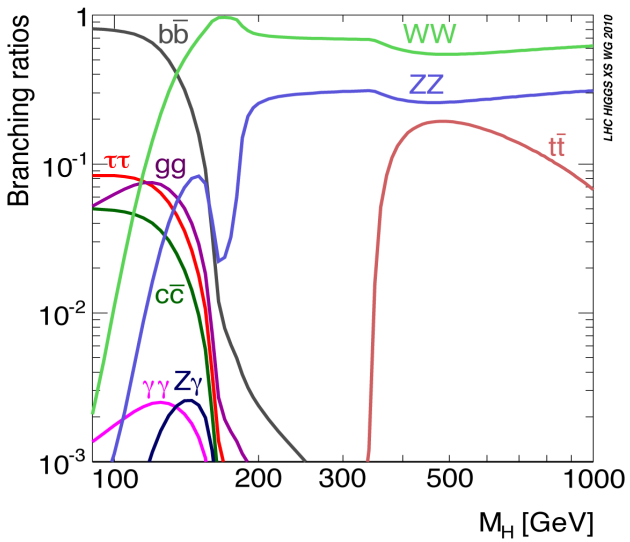
Standard Model Higgs Boson at LHC

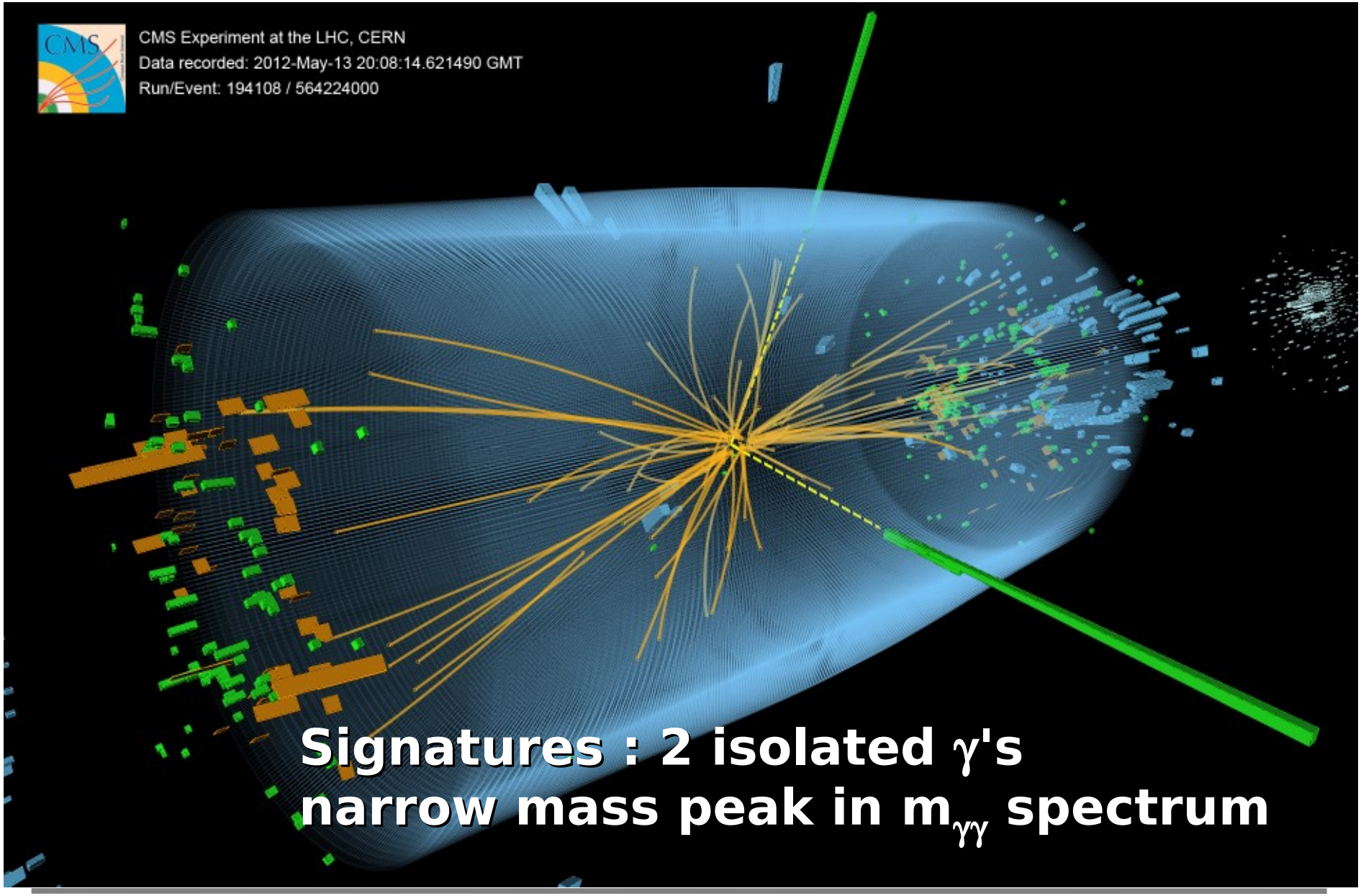




Main search channels ($m_H \leq 150$ GeV)	
qqH / gg→H	***H→γγ***
qqH / gg→H	***H→WW→2ℓ2ν***
gg→H	***H→ZZ→4ℓ***
qq→VH	***Z→ℓℓ,νν / W→ℓν / H→bb***
ttH	***H → bb***
qqH / VH / gg→H	***H→ττ***



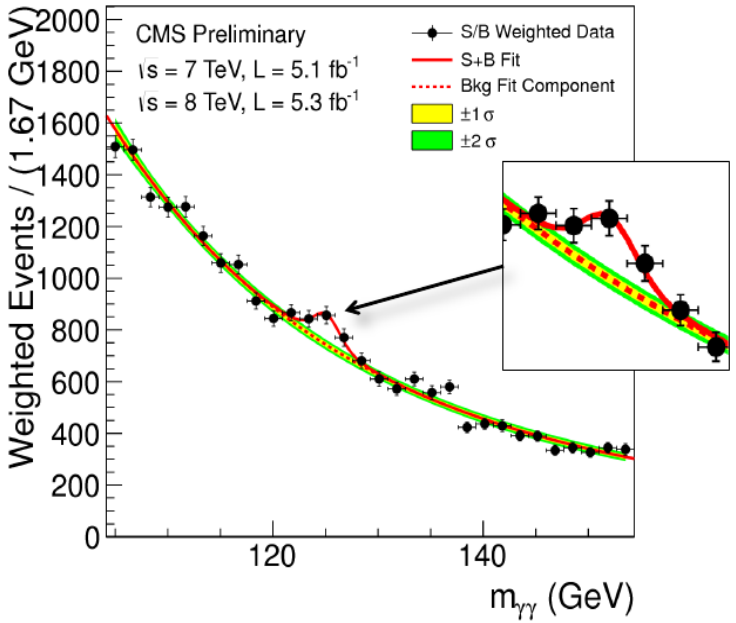
$H \rightarrow \gamma\gamma$

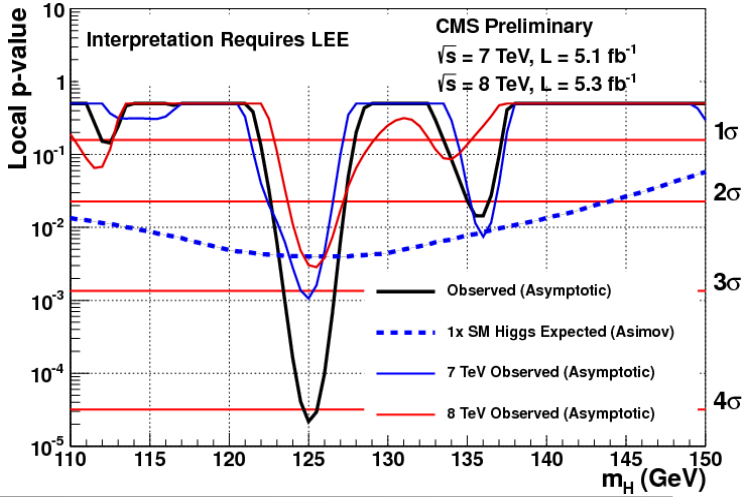


H → γγ Search

- **Multi-Variate Analysis**
- **Event categorization based on**
  - **→ MVA output**
  - **→ compatibility with Vector Boson Fusion signatures:**
  - **o 2 jets with large $\Delta\eta$(jj) & large m(jj)**
- **No prior background model**
- **background shape and normalization**
  - **→ fits of mass distributions with smooth function**

S/B-weighted sum of $m_{\gamma\gamma}$



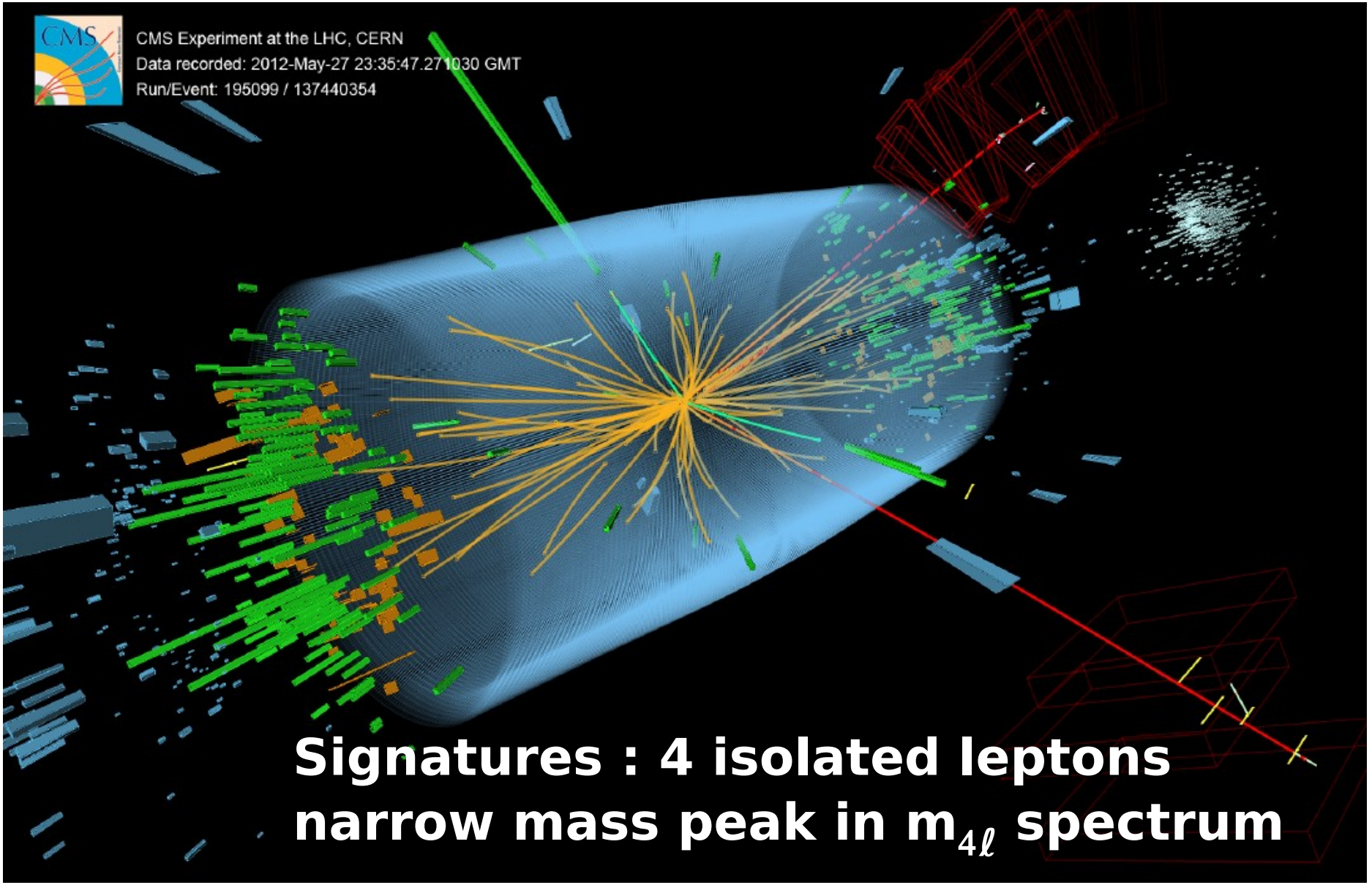


Lowest p-value at $m_H \approx 125$ GeV

Local significance : 4.1σ

Global significance in the mass range 110 – 150 GeV : 3.2σ

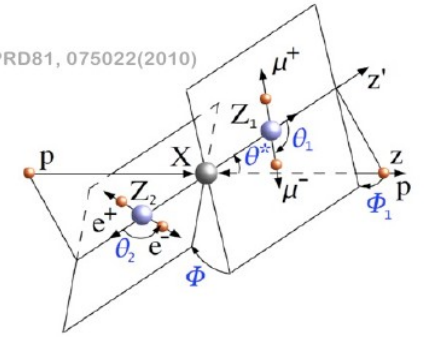
$H \rightarrow ZZ \rightarrow 4\ell$

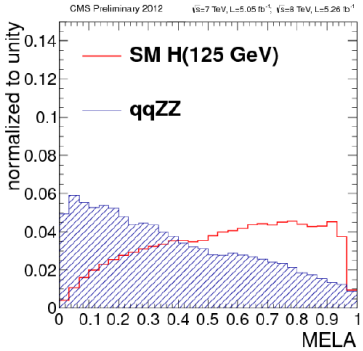


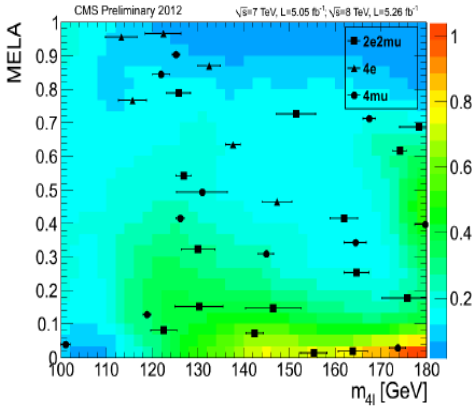
Results of H → ZZ → 4ℓ Search

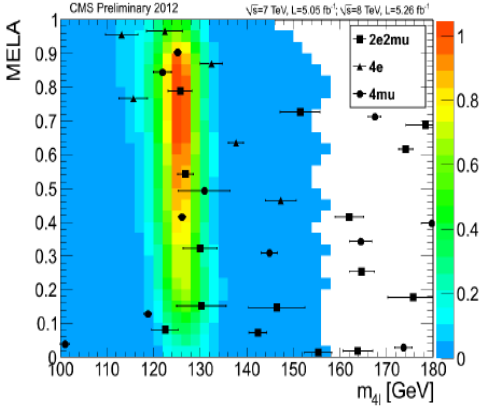
statistical inference performed with 2D distribution [MELA, m_{4l}]

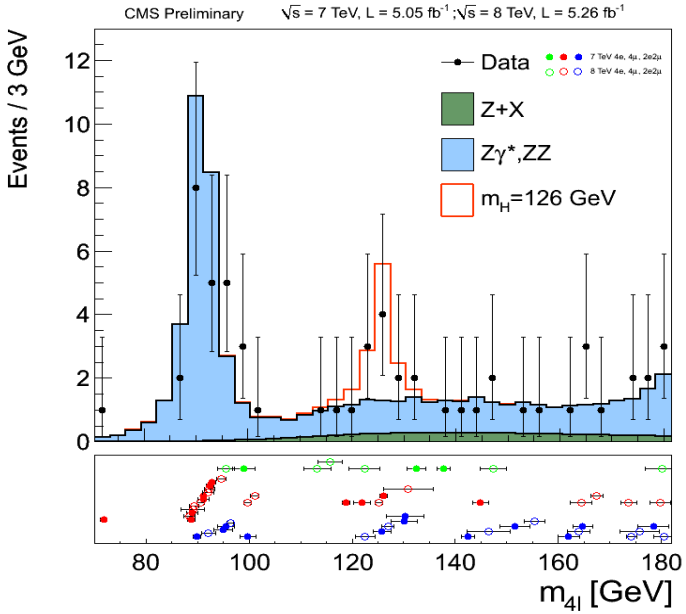
Matrix Element Likelihood Analysis

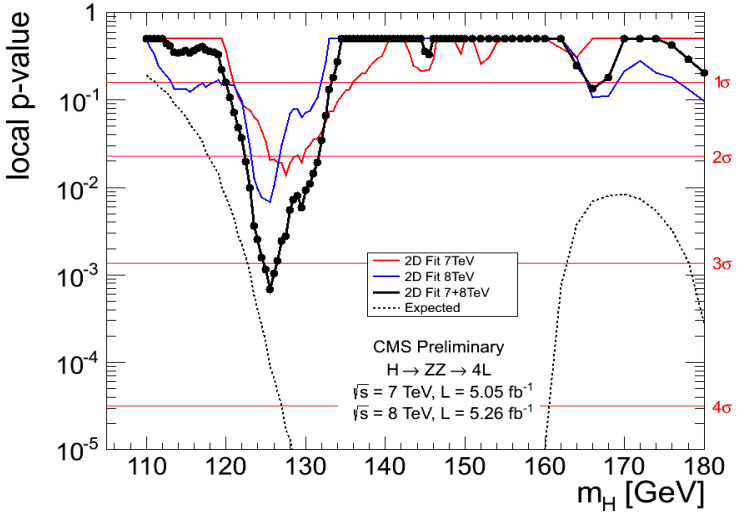












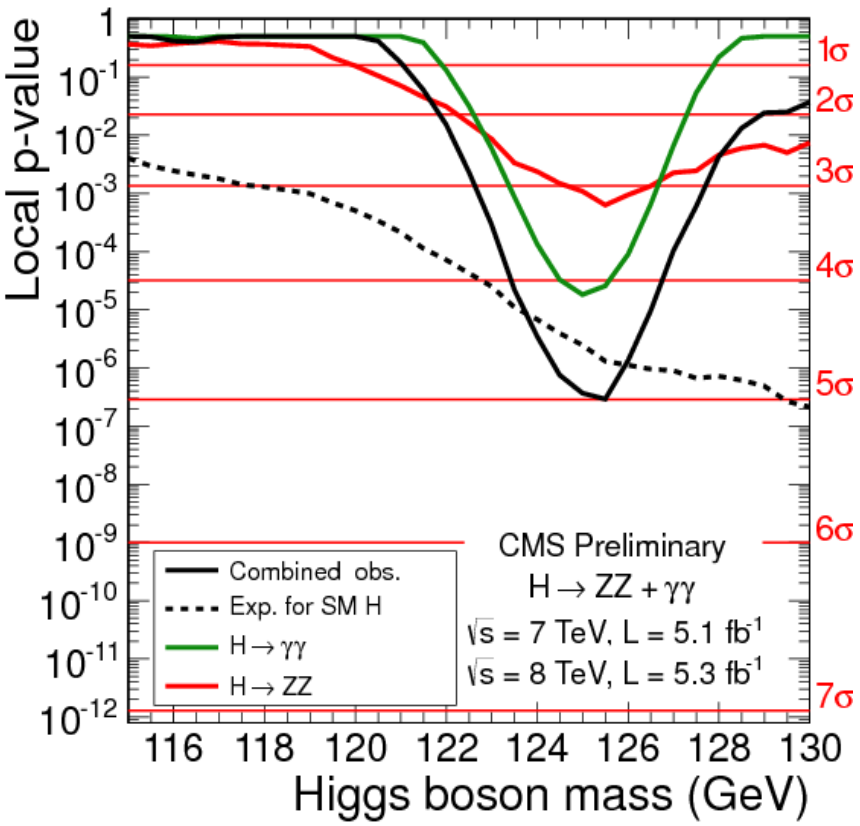
Lowest p-value at $m_H \approx 125.5$ GeV

local significance of excess : 3.2σ

Expected significance at

$m_H = 125.5$ GeV : 3.8σ

Combining H → γγ and H → ZZ → 4ℓ



- **High sensitivity, high mass resolution channels**

  γγ : 4.1σ

  4 leptons : 3.2σ

  near the same mass $m_H \approx 125$ GeV

- **Combined significance 5.0σ**

Observation of new state with $m_X \approx 125$ GeV

- **Expected significance for SM Higgs boson : 4.7σ**

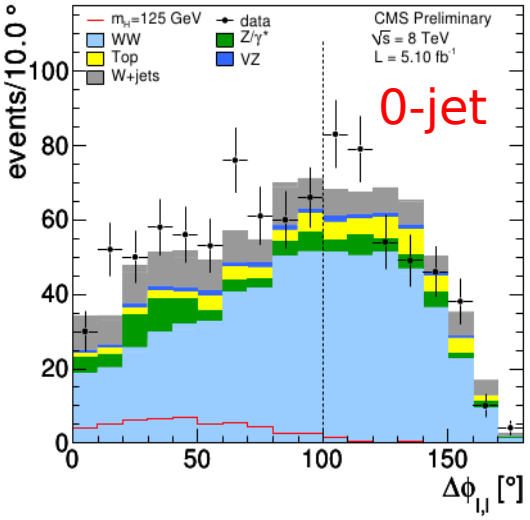
H→WW→2ℓ2ν

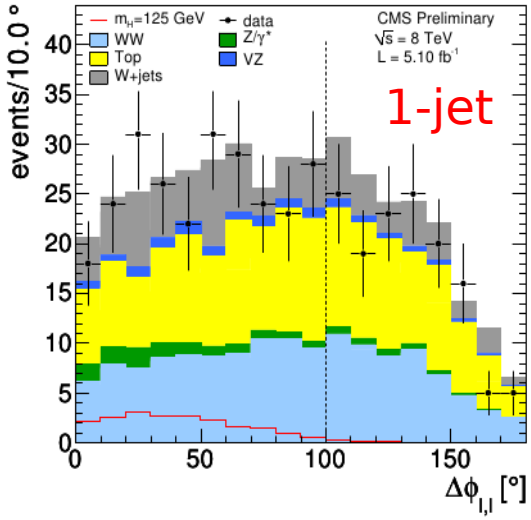
Signatures

- 2 hight p_T isolated leptons (μμ, ee, eμ)
- Large missing E_T
- small $\Delta\varphi(\ell\ell)$

Main backgrounds

WW, top, W+jets, WZ



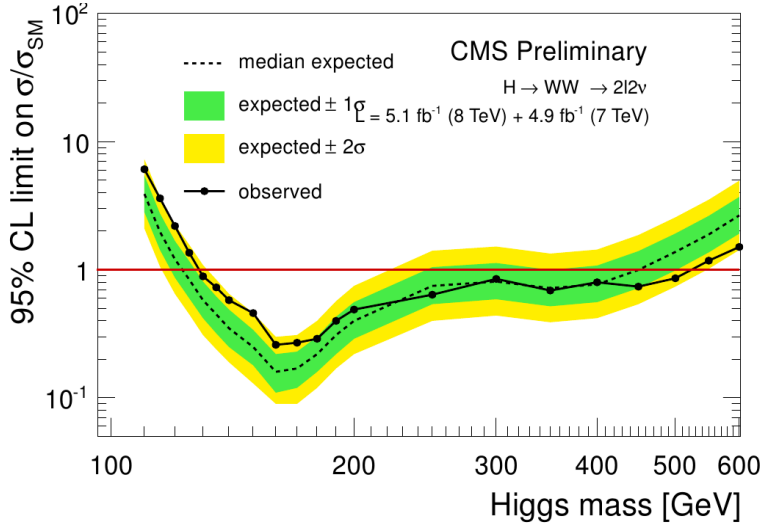


Search strategy

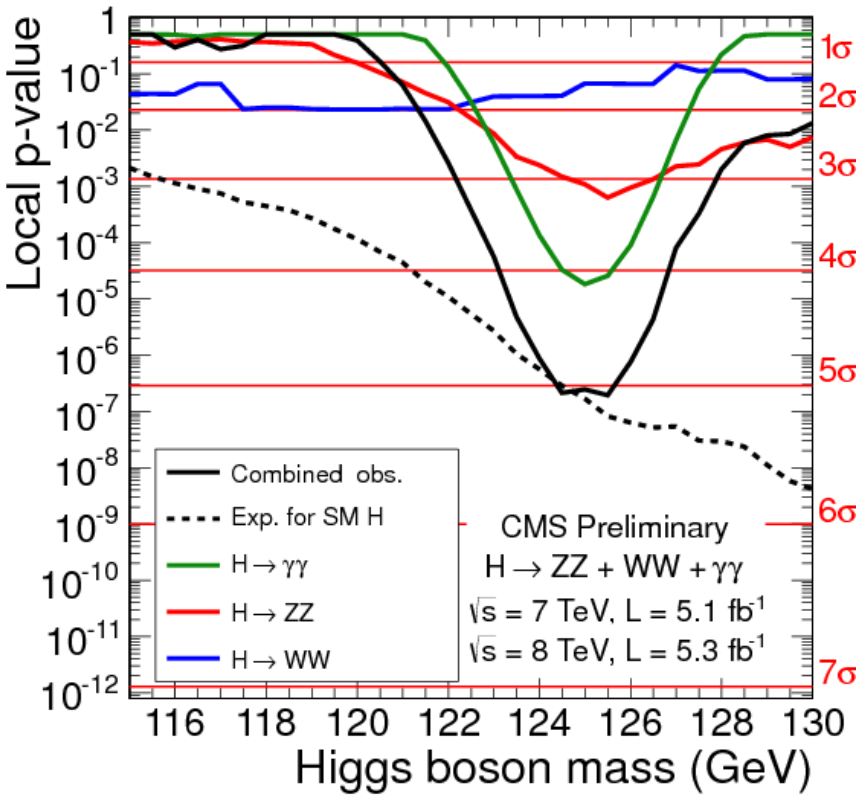
cut based selection exploiting lepton kinematics;

event categorization based on jet multiplicity

- 0-jet
- 1-jet
- VBF (2-jets)



Combining H → γγ, ZZ and WW Channels



- **Combining high sensitivity, high mass resolution channels**

  γγ + ZZ → 4ℓ

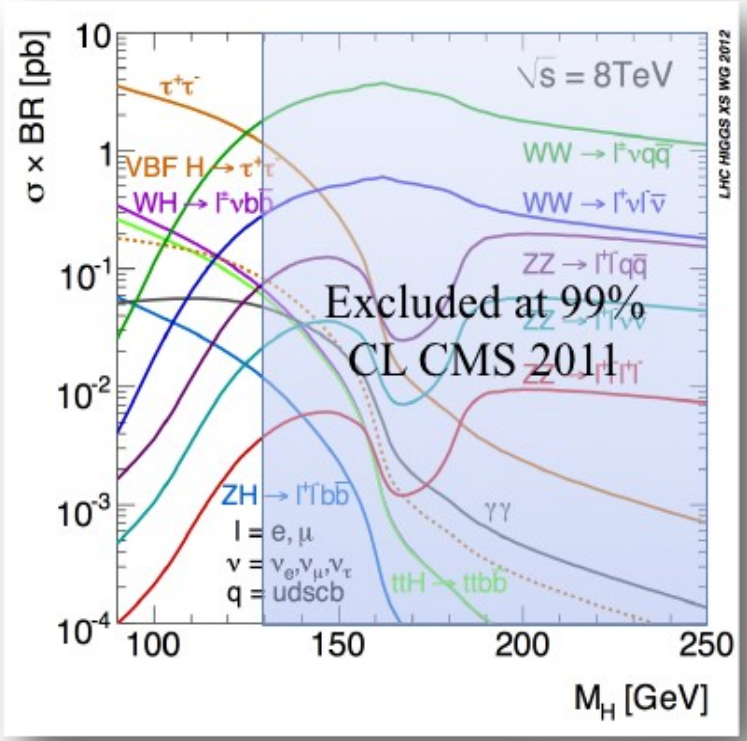
  and high sensitivity, but low mass resolution channel

  WW → 2ℓ2ν

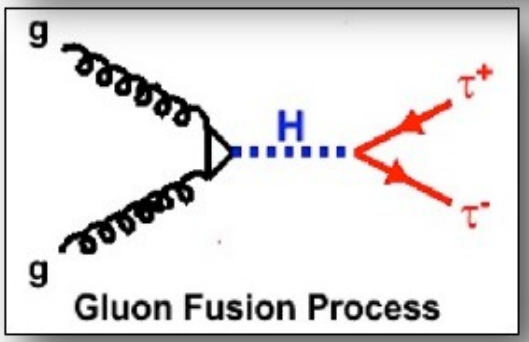
- **Combined significance : 5.1σ**

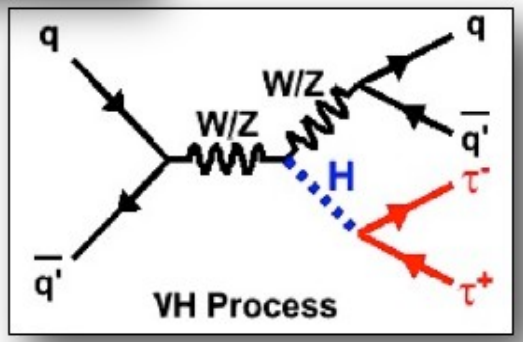
- **Expected significance for SM Higgs boson : 5.2σ**

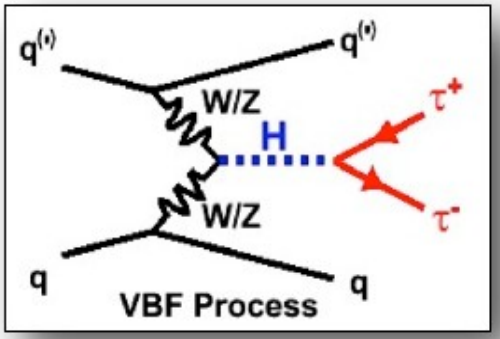
H → ττ Search : Introduction



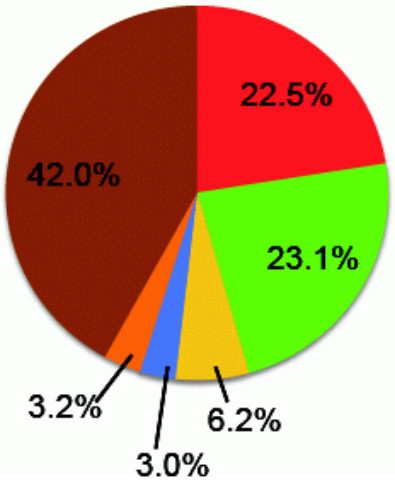
- Large σ × Br at low mass
- The most sensitive among fermionic decay channels
- Sensitive to all production mechanisms
- Direct probe of Higgs boson couplings to leptons







H → ττ Search



Included in CMS Analysis

- mu + had
- e + had
- e + mu
- mu + mu
- e + e
- had + had

DESY

Karlsruher Institut für Technologie

Analyses being developed with participation of DESY

Jets p_T > 30 GeV

τ_h or μ p_T^1

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
MVA based selection

full reconstruction of ditau mass from ττ decay kinematics, $\not{E}_T$, ττ decay matrix element

Evaluation of Z → ττ Background in H → ττ Search

Z → ττ main irreducible background for H → ττ search

Can be evaluated in a data-driven way

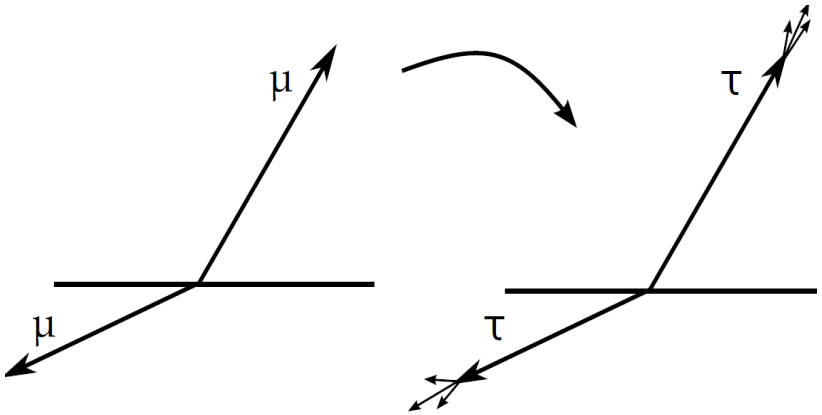
1) Select Z → μμ events
2) Replace muons by simulated tau decays
3) Overlay simulated tau decay products with the reminder of event

   event environment taken from real event

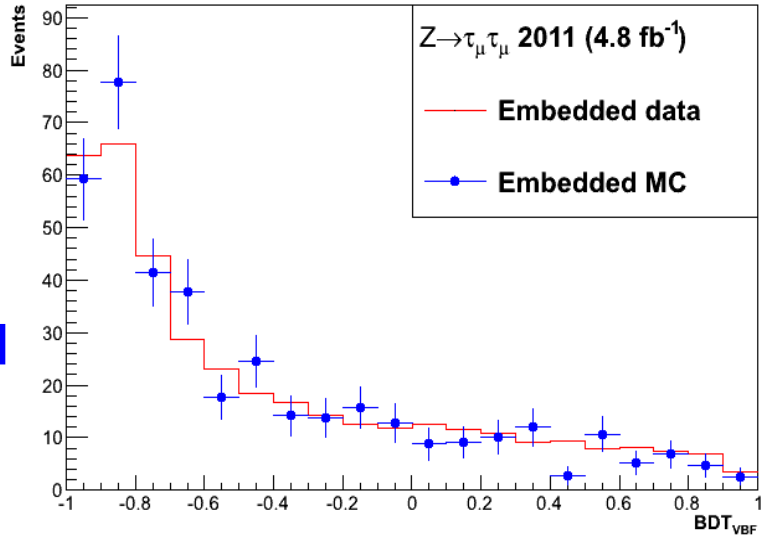
→ proper modeling of PU, UE, jets, missing E_T

→ reduced systematic effects

technique is know as **tau embedding**

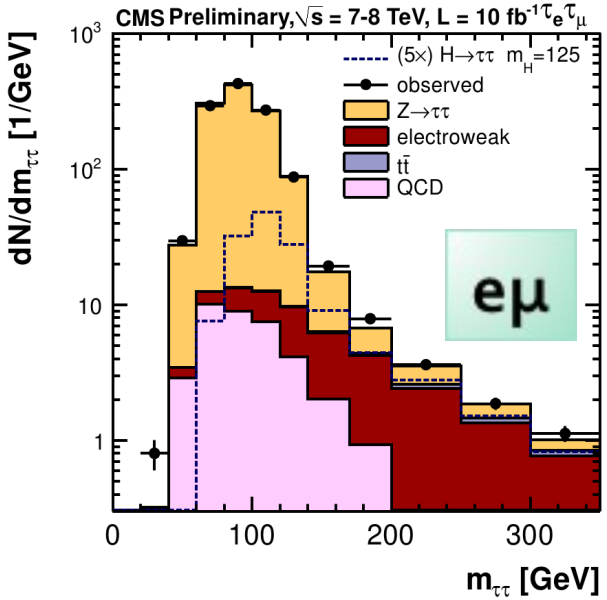


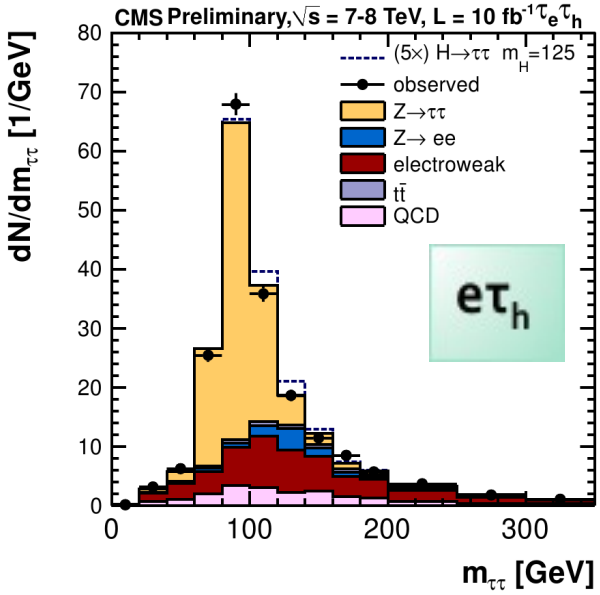
Validation of VBF MVA performance with embedding

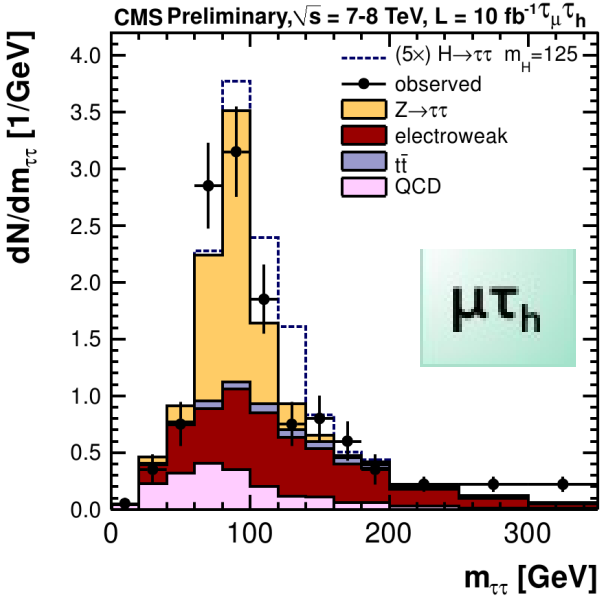


- **tools developed and maintained by** Karlsruher Institut für Technologie **and** DESY

Mass Distributions in Event Categories







0-jet category

- **Constraints energy, scales, efficiencies**
- Large DY background
- Sensitivity boosted by low / high p_T split

1-jet category

- **Enhanced sensitivity to gg → H**
- Improved mass resolution
- Sensitivity boosted by low / high p_T split

VBF category

- **Clean mode**
- **Highest S/B**

→ highest sensitivity at $m_H \leq 130$ GeV

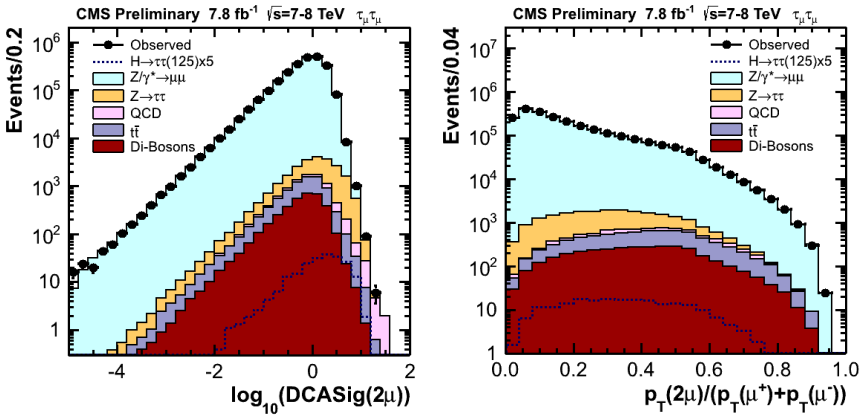
Search for H → ττ → 2μ4ν

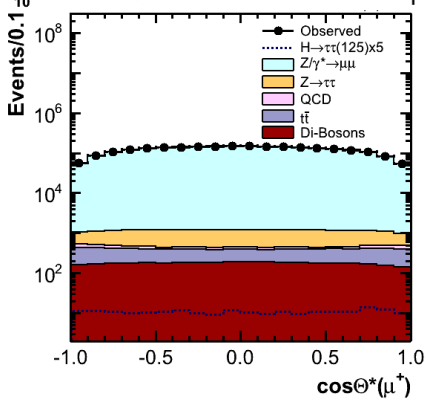
precise information from fermionic channels is desperately needed to characterize new state
→ every single final state counts

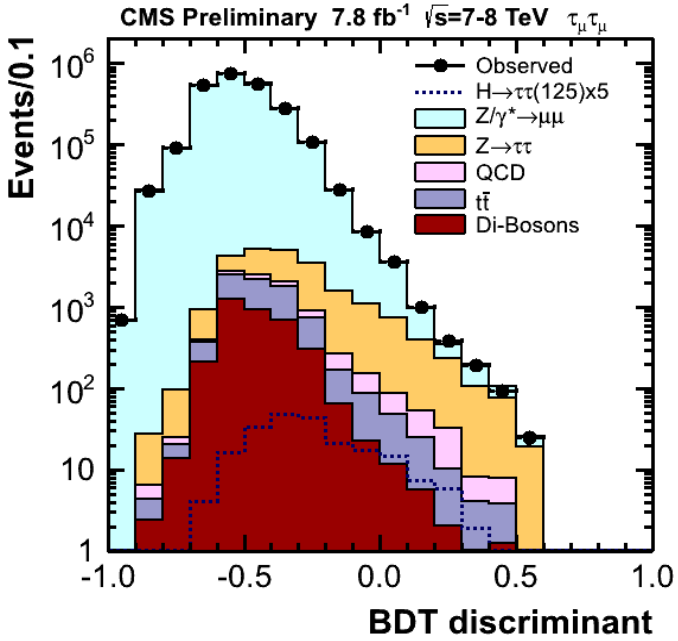
Challenge of H → ττ → 2μ4ν channel

- **huge Z →μμ background**
- **Small Br(ττ→2μ4ν) = 3%**

dedicated MVA selection of ττ final states







Mass Distributions in H → ττ → 2μ4ν Channel

MVA(ττ) + MVA(VBF) discriminants → final selected samples

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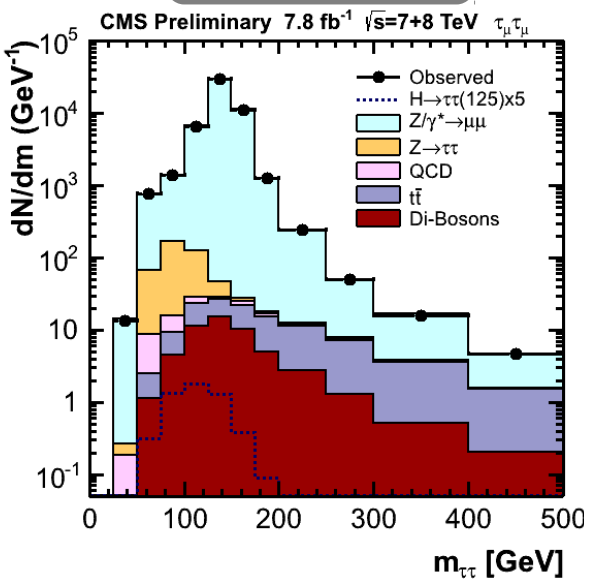
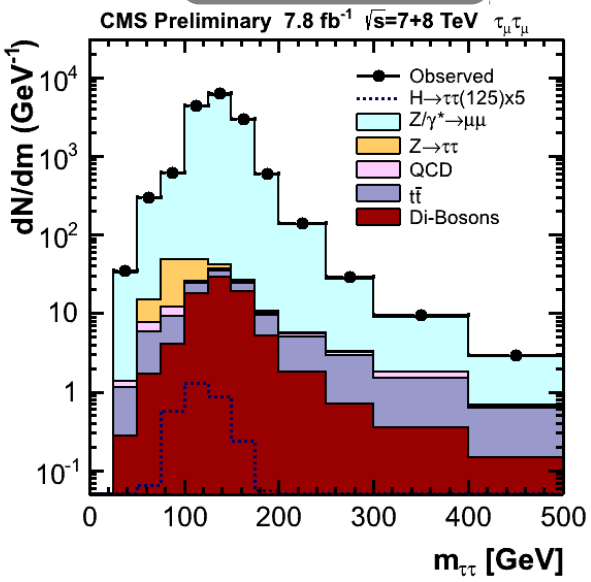
Statistical inference with 2D distributions [M(μμ) , M(ττ)]
→ sensitivity boosted by factor 1.5 – 2.0

Shown are the M[ττ] projections of 2D distributions

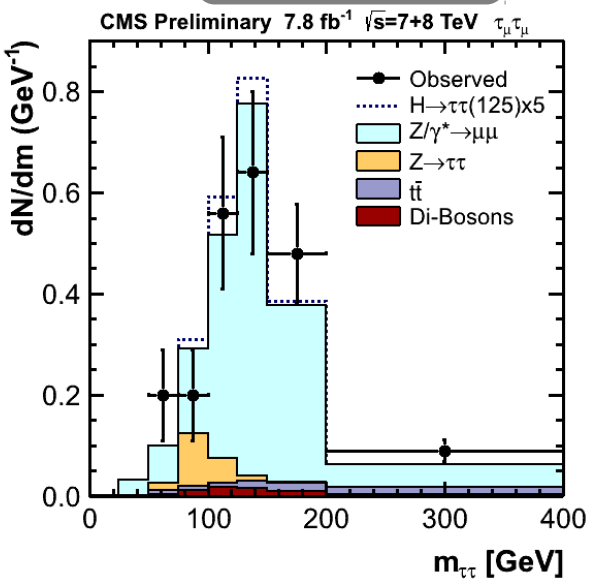
0-jet



1-jet

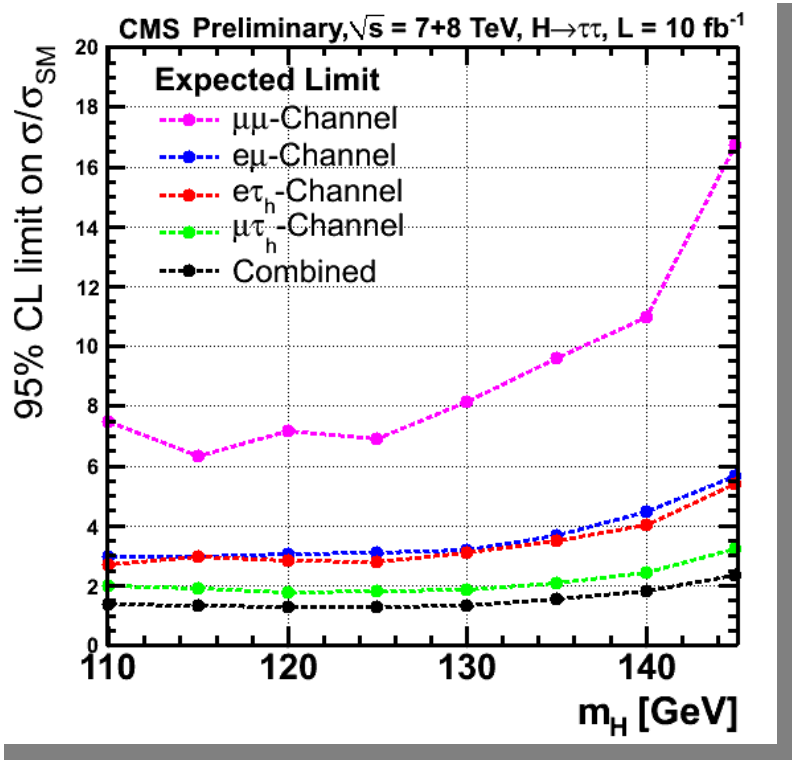


VBF

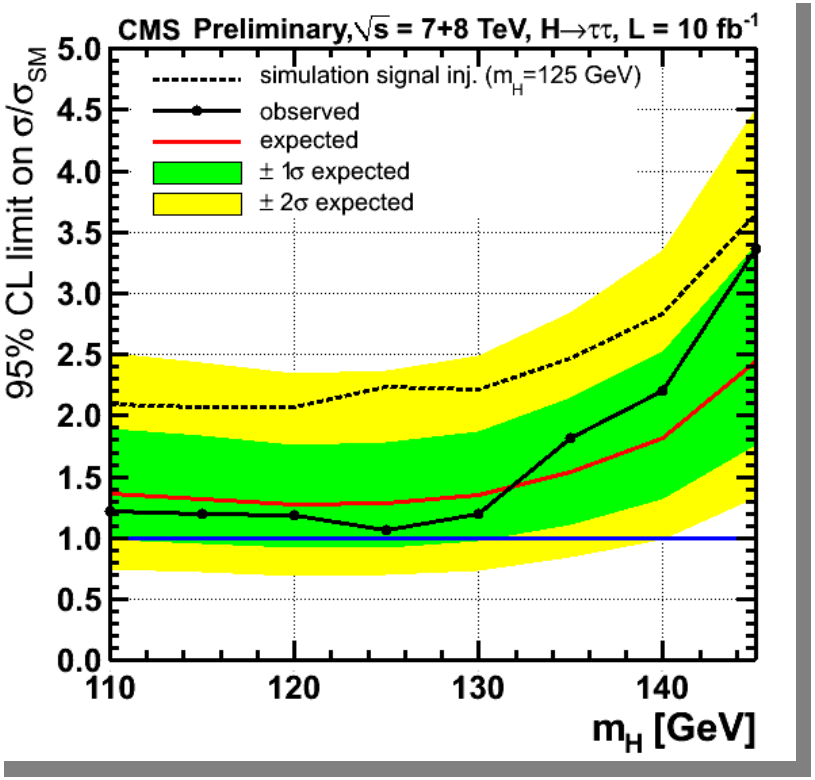


H → ττ Search Results

sensitivity / channel

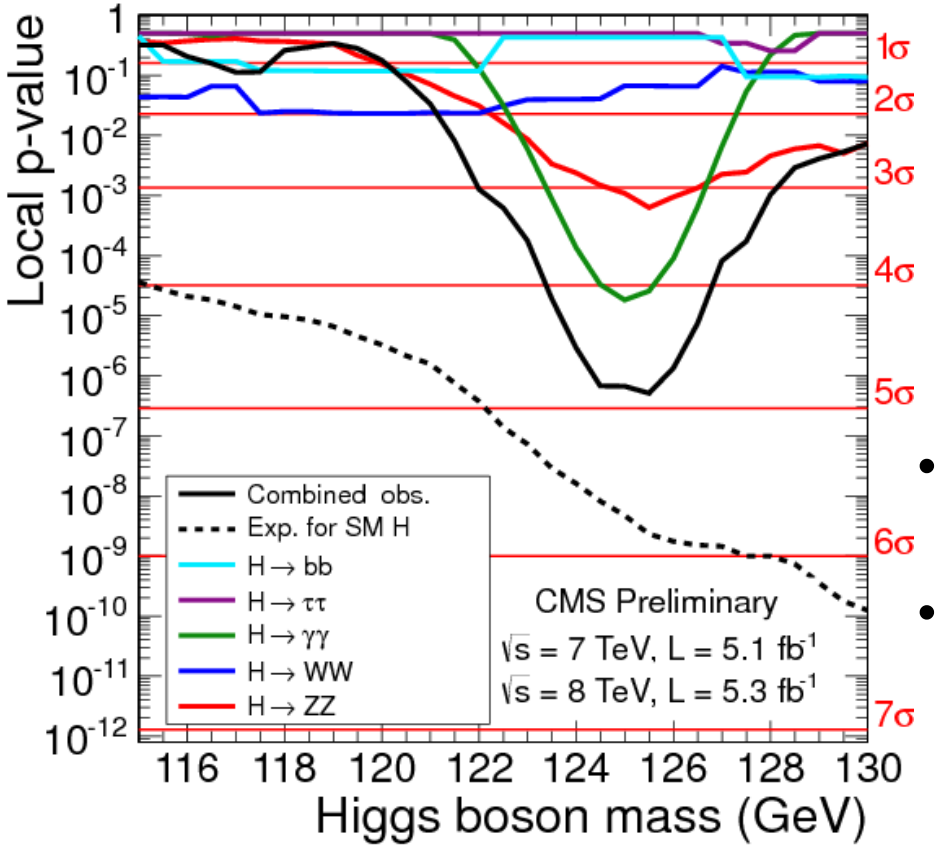


combined results



- **analysis approached sensitivity to signal**
- **no significant departure from SM background expectation**
  - ➔ **Observed exclusion : $1.06 \times \sigma_{SM}$ for $m_H = 125$ GeV**
  - ➔ **Expected exclusion at $m_H = 125$ GeV : $1.28 \times \sigma_{SM}$**

Combining Bosonic and Fermionic Channels



- **Combining bosonic modes**

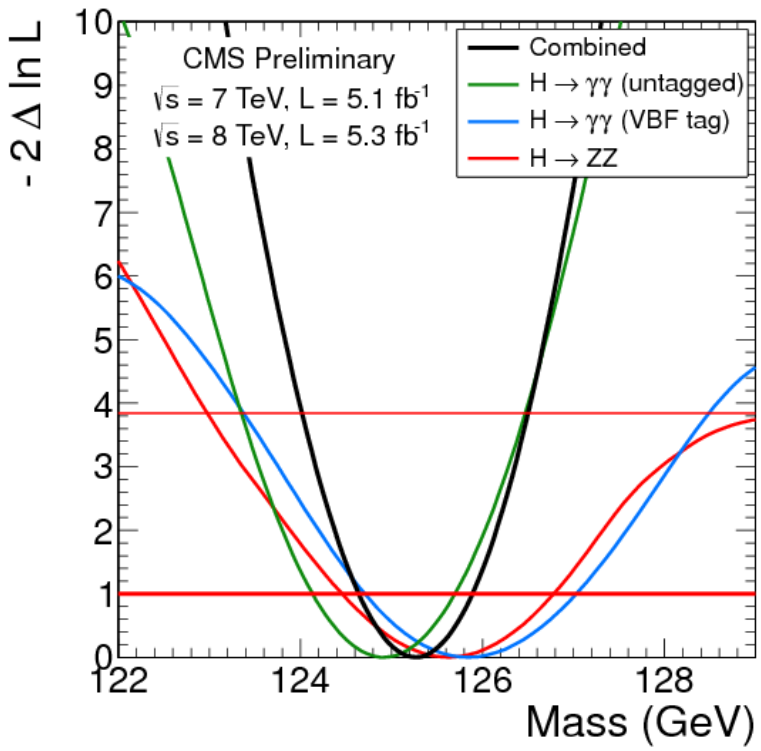
  γγ + ZZ → 4ℓ + WW → 2ℓ2ν

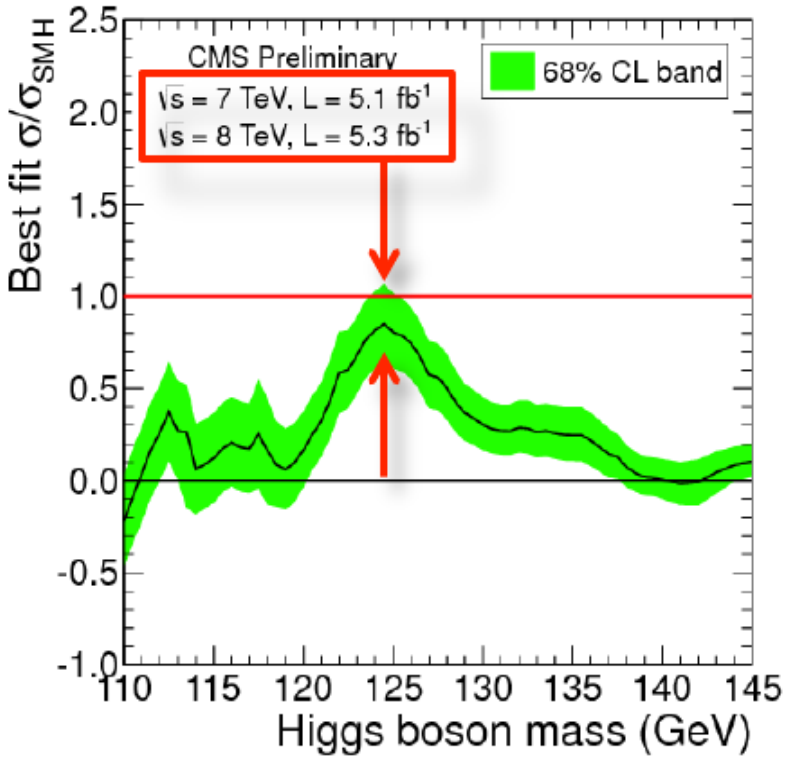
  with fermionic channels

  ττ + VH, H → bb

- **Combined significance : 4.9σ**
- **Expected significance for SM Higgs boson : 5.9σ**

Characterization of a New State





fitted mass

$M_X = 125.3 \pm 0.6$ GeV

Best fit of signal strength in combination

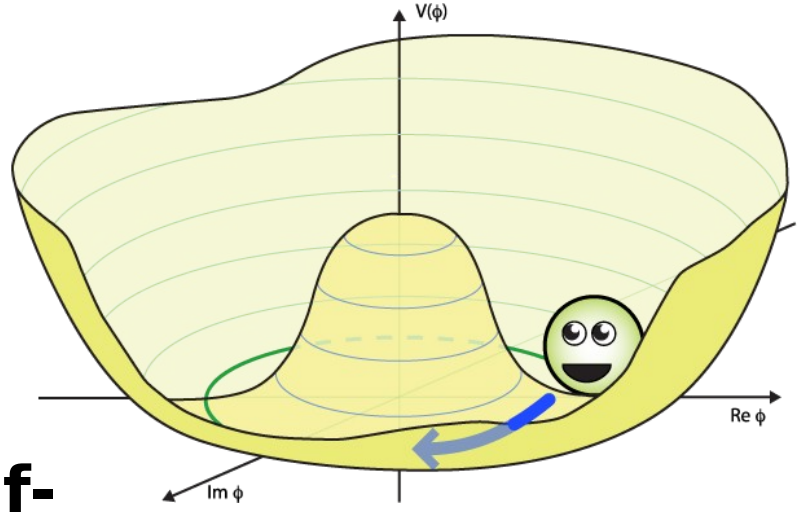
$\sigma/\sigma_{SM} = 0.80 \pm 0.22$

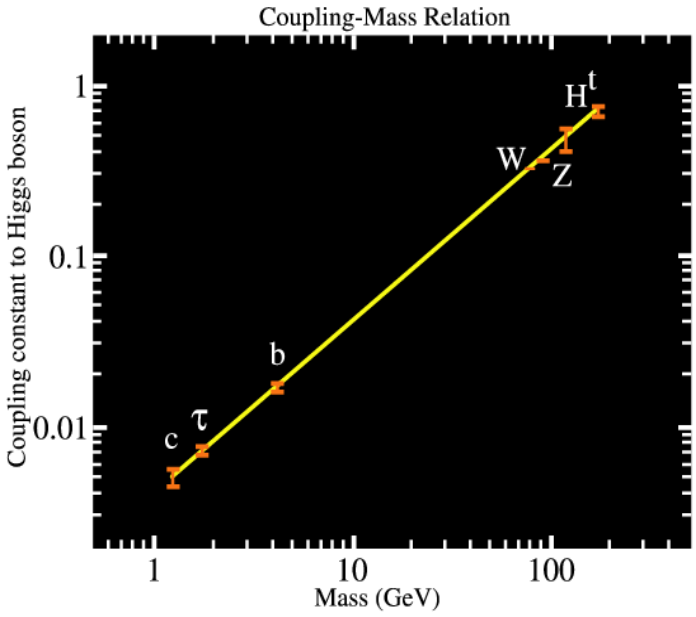
Path towards Establishment of Higgs Mechanism

- **Complete establishment of Higgs mechanism implies:**
- **Investigation of coupling - mass relations**
- **Measurements of Higgs quantum numbers**
- **Measurements of Higgs self-coupling**

  → **reconstruction of Higgs potential**
- **Investigation of the structure of the Higgs sector**

  → **single doublet of “Minimal model” vs. extended Higgs sector of BSM theory**





Is what we observe the Higgs Boson of the "minimal" SM or it is one of the states expected in theories extending SM?

Analyses are ongoing to address this question

Higgs Sector in MSSM

Higgs Sector in MSSM → Two Higgs Doublet Model

$$\Phi_1 = \begin{pmatrix} \Phi_1^+ \\ \Phi_1^0 \end{pmatrix} \qquad \Phi_2 = \begin{pmatrix} \Phi_2^+ \\ \Phi_2^0 \end{pmatrix}$$

$$\langle \Phi_1 \rangle = \begin{pmatrix} 0 \\ \nu_1 \end{pmatrix} \qquad \langle \Phi_2 \rangle = \begin{pmatrix} 0 \\ \nu_2 \end{pmatrix}$$

5 physical states: h, H, A, $H^{\pm}$

$$\tan\beta = \nu_1/\nu_2$$

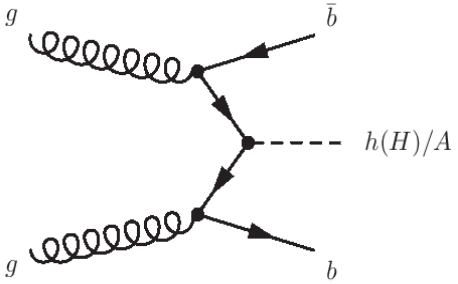
$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \phi_1^0 \\ \phi_2^0 \end{pmatrix}$$

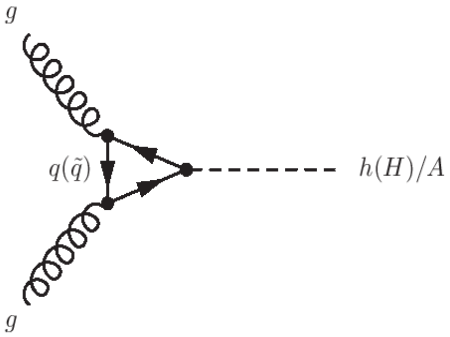
- 2HDM in MSSM
  - Φ_1 couples to down-type quarks and charged leptons
  - Φ_2 couples to up-type quarks
- **Modified couplings to gauge and fermion fields**

	h	H	A
W^+W^-	$\sin(\beta-\alpha)$	$\cos(\beta-\alpha)$	0
ZZ	$\sin(\beta-\alpha)$	$\cos(\beta-\alpha)$	0
$u\bar{u}$ (up-type quarks)	$\cos\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\cot\beta$
$d\bar{d}$ (down-type quarks)	$\sin\alpha/\cos\beta$	$\cos\alpha/\cos\beta$	$\tan\beta$
$\ell\bar{\ell}$ (charged leptons)	$\sin\alpha/\cos\beta$	$\cos\alpha/\cos\beta$	$\tan\beta$

Search for MSSM Higgs Bosons in $\Phi \rightarrow \tau\tau$

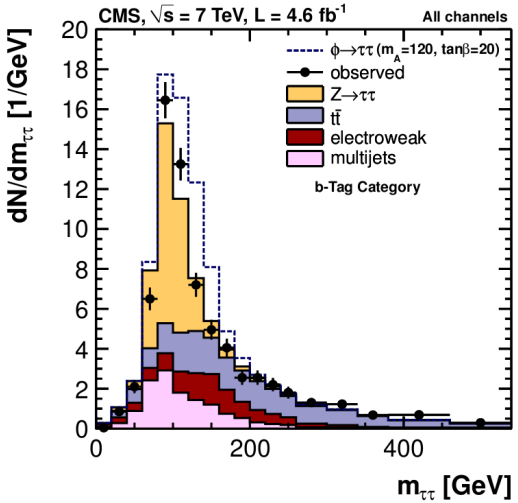
- **three channels initially studied : $e+\tau_h$, $\mu+\tau_h$, $e+\mu$**
- **search exploits two production mechanisms**



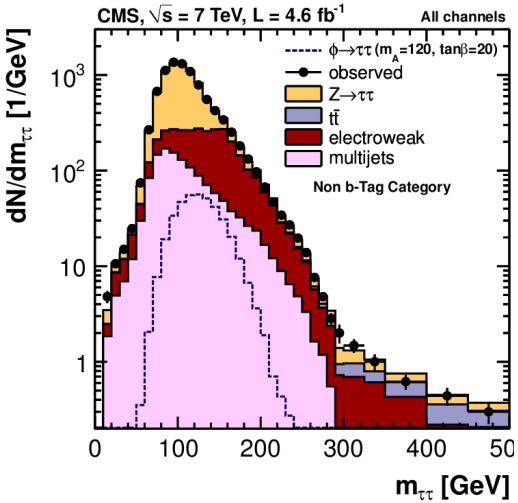


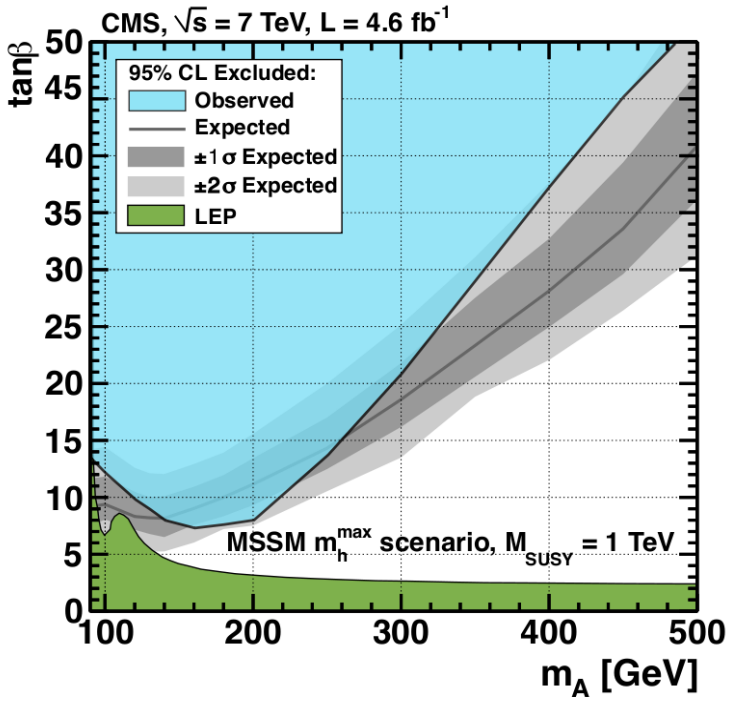
→ events categories

≥ 1 b-jet



no b-jets





Neutral MSSM Higgs Bosons in $\Phi \rightarrow \tau\tau \rightarrow 2\mu 4\nu$

Adding one more channel

– $\Phi \rightarrow \tau\tau \rightarrow 2\mu 4\nu$

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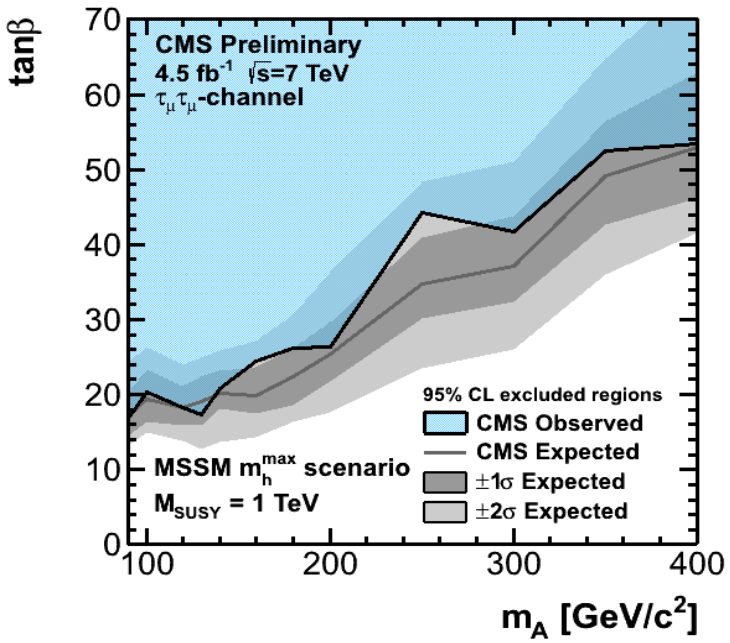
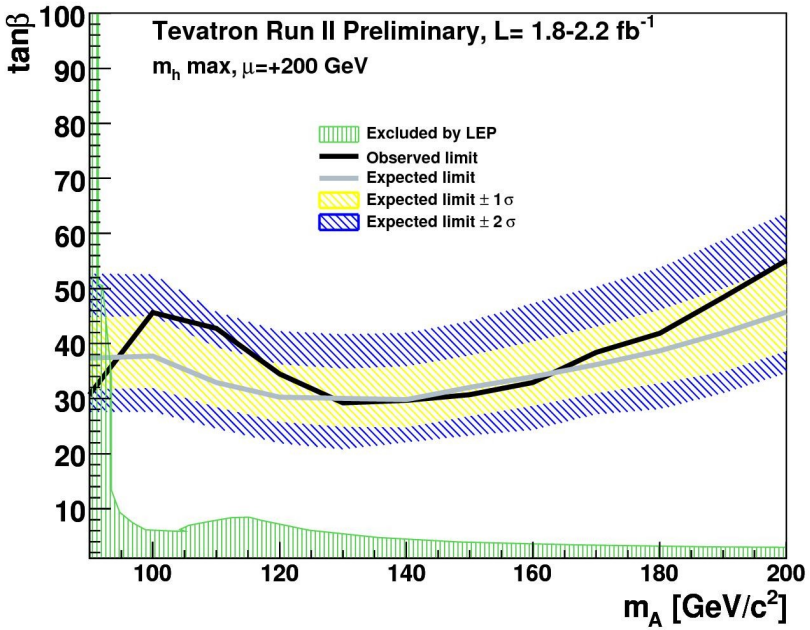
Search strategy similar to the analyses in $e+\tau_h$, $\mu+\tau_h$, $e+\mu$

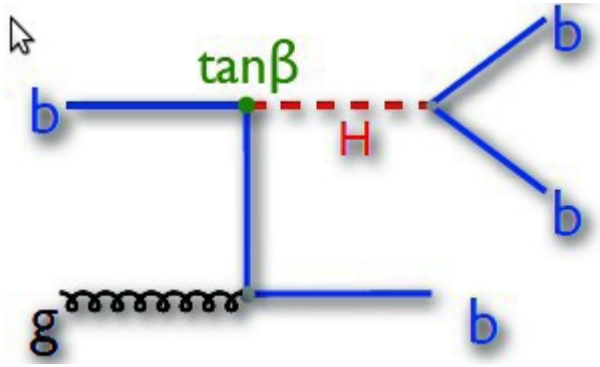




This channel alone supersedes sensitivity of recent combined Tevatron searches

MSSM bΦ → 3b Search

- **Search for MSSM Higgs bosons in the process**



- **Dedicated fully hadronic trigger developed**
  - **3 high p_T jets && 2 jets are b-tagged**
- **Largest background – QCD multi-jets**
  - **cannot rely on MC simulation**

→ Data-driven background model

- **double tag data sample used to construct background templates for various flavor compositions of three jets**
- **b-tagging of third jet is modeled by event weighting accounting for tagging efficiency (mis-tag rate)**

→ data-driven background templates

MSSM bΦ → 3b Search

Statistical inference with 2D distribution

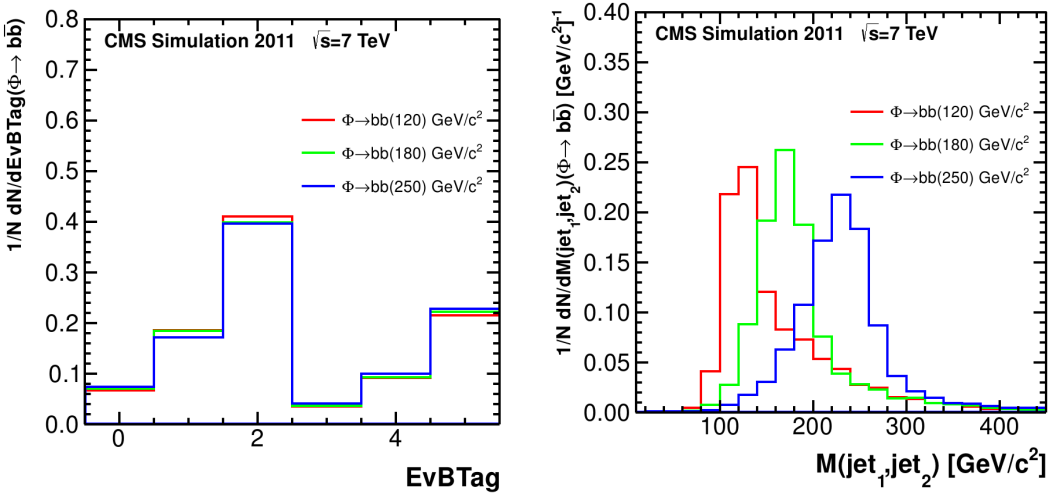
[M(jj), Event BTag]

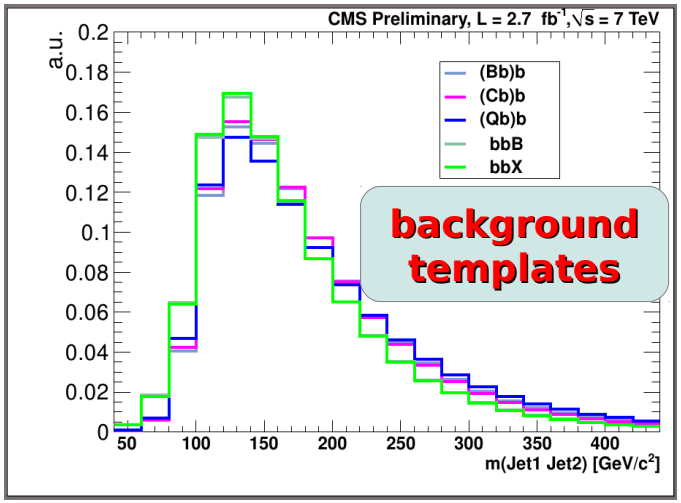
Event BTag : discrete variable based on secondary vertex mass information

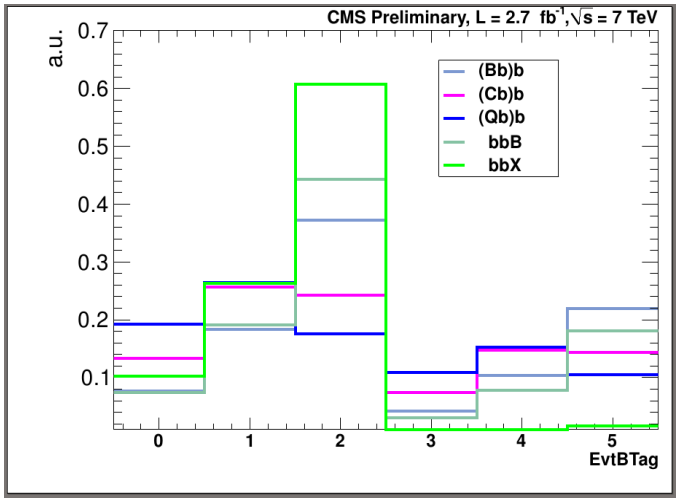
Signal yields from fits of data with linear combination of background and signal templates

Signal yield + luminosity + signal acceptance (from MC) → access to signal cross section

signal templates

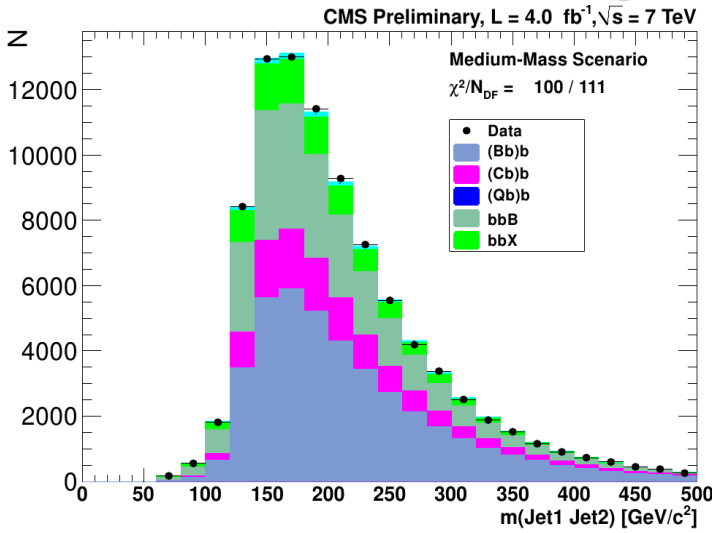


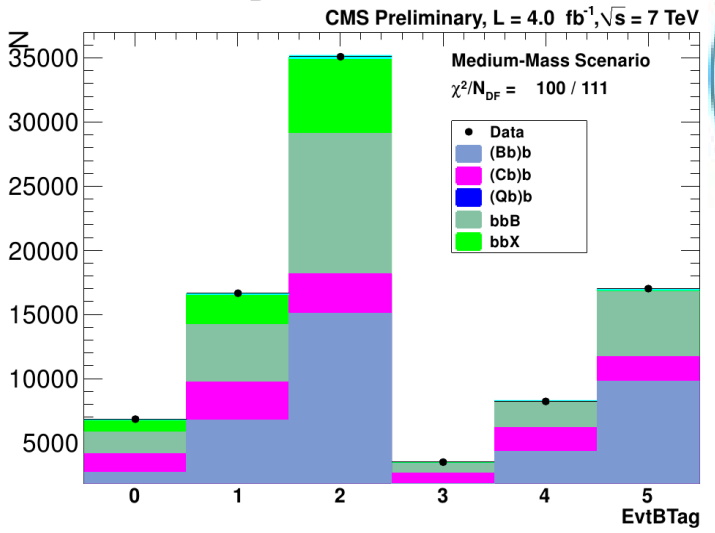




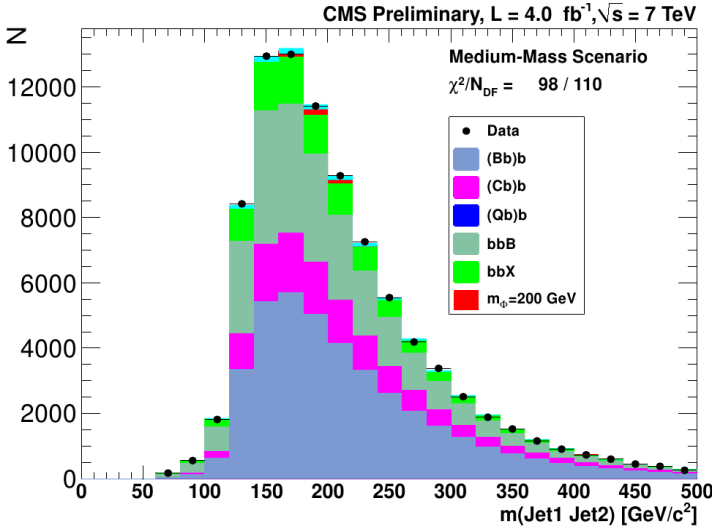
Fits with Background and Signal Templates

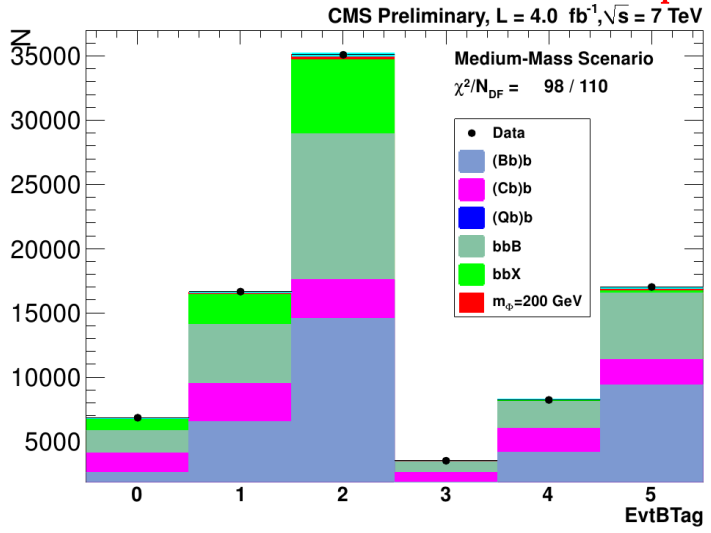
Background-only fit





Representative example of signal+background fit for m_Φ = 200 GeV

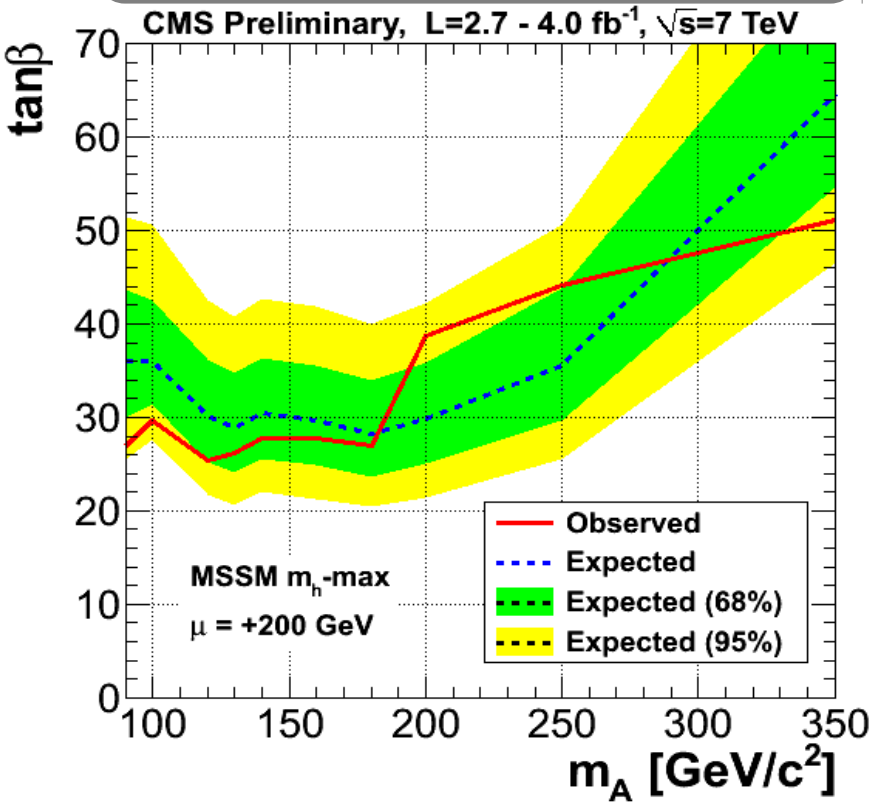




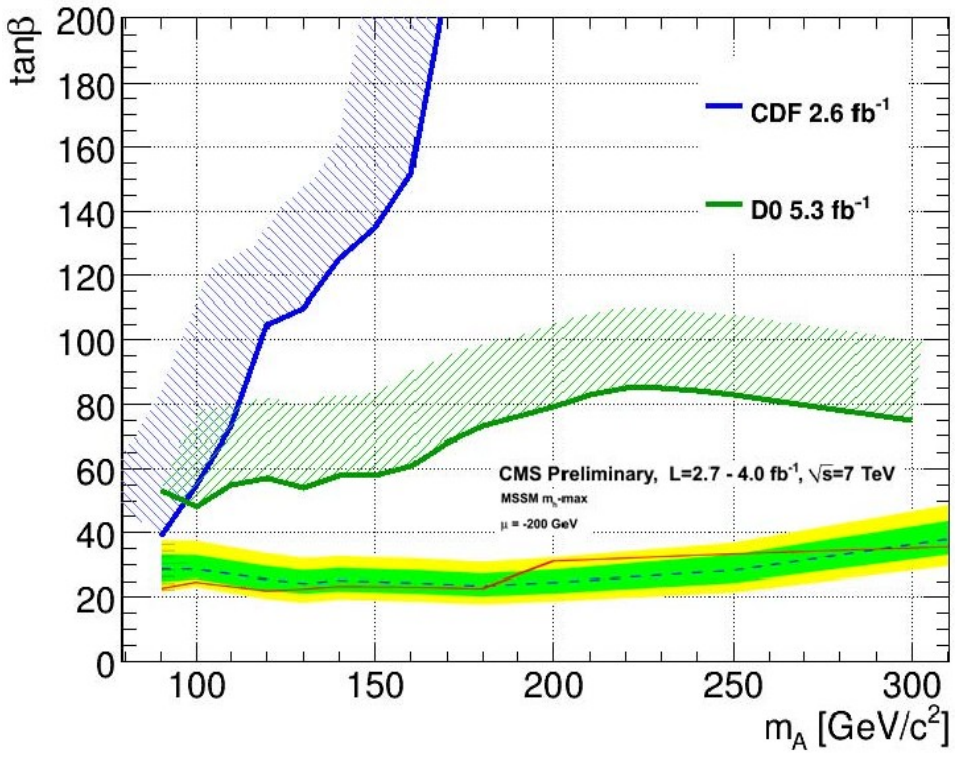
Results of bΦ → 3b Search

No evidence of signal in the probed mass range
90 – 350 GeV → constraints on MSSM parameters

MSSM m_h-max
μ = + 200 GeV

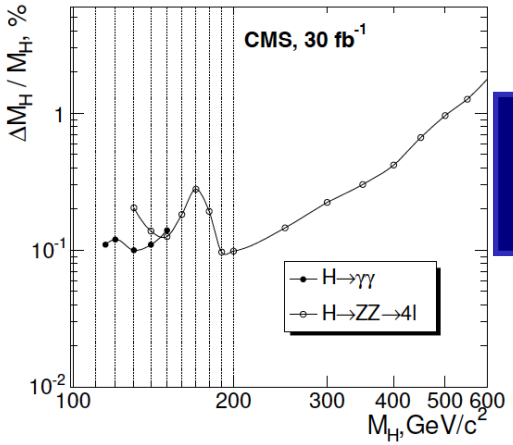


MSSM m_h-max
μ = – 200 GeV



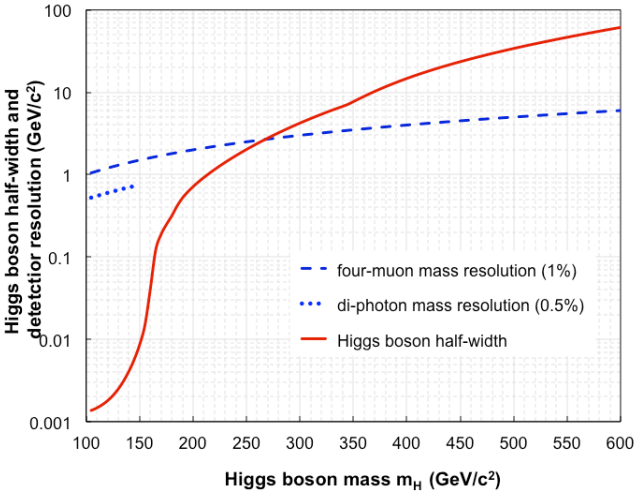
Measuring Higgs Properties with 30 fb^{-1} at 8 TeV

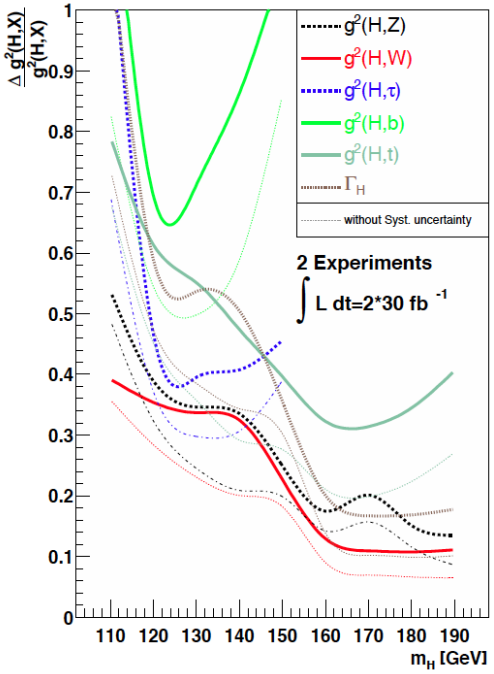
CMS TDR 14TeV



Mass
$\Delta m/m \approx 0.2\%$

Measuring Γ_H impossible
@ $m_H < 140$ GeV





Spin/Parity : 0^+

observation *H→γγ* rules out *J=1*

observation of *H→WW and WW→2ℓ2ν* with trend to small *Δφ(ℓ,ℓ)* rules out *J=2*

angular and m_{Z^*} spectra in *H→ZZ distinguish $0^+/0^-$ state → separation at 3σ level expected before shutdown**

Couplings

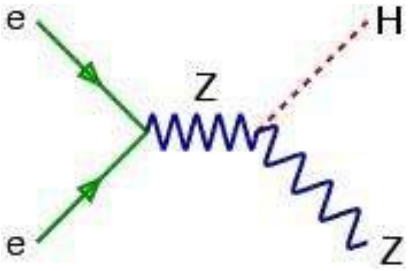
- **fully model-independent measurements impossible**
- **minimal assumptions → $\Delta g^2/g^2$ = 20 - 30%**
- **dedicated machinery for grand fits needed**

International Linear Collider

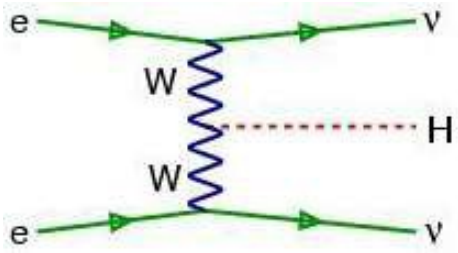
- **LHC alone won't be able to provide a complete and comprehensive picture of Higgs mechanism**
  - **precision of measurements insufficient to discriminate between different models e.g. H_{SM} and h_{MSSM}**
  - **model independent coupling measurements not possible**
  - **Higgs-self coupling is hard to access at LHC**
  - **some corners of MSSM parameter space are difficult to access, e.g. moderate tanβ and high m_A**
- **A new high precision machine needed**
- **A (sub)TeV linear collider is an ideal candidate**
  - **more than 10 years of detector and machine R&D and physics studies demonstrated high potential of the machine and its complementarity to LHC**

What can we do with Linear Collider

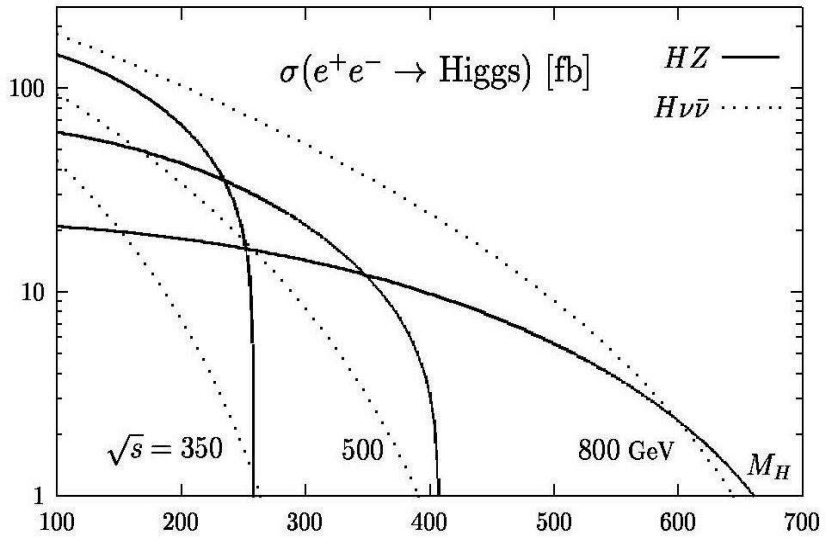
- **International linear collider = Higgs factory**
- **Model independent measurements in Higgs sector with high precision**
- **Channels to explore in SM and MSSM**



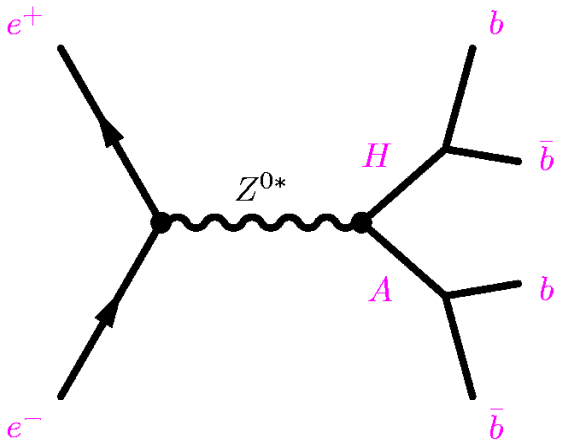
σ~1/s



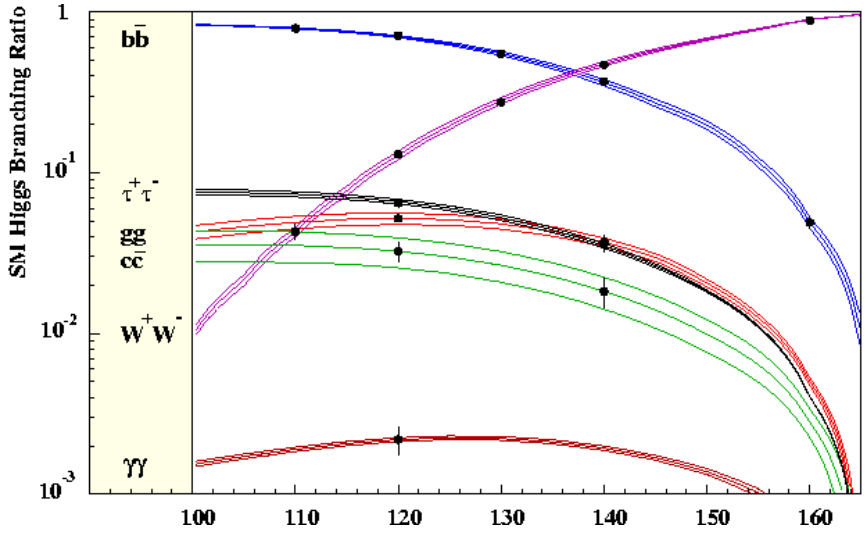
σ~ln(s)



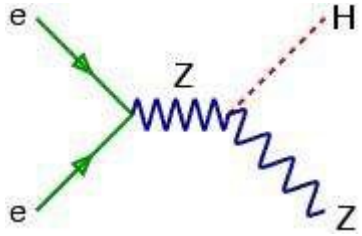
Access to heavy SUSY states

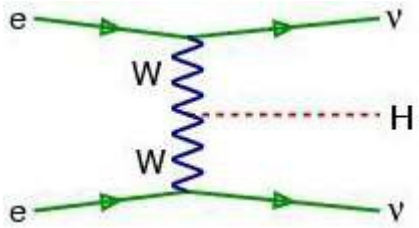


Higgs Couplings to SM Particles



- **Couplings to Z and W via production rates**





$\sigma(ZH) \sim g^2_{HZZ} \rightarrow \Gamma_{ZZ}$

$\sigma(ZH) \sim g^2_{HWW} \rightarrow \Gamma_{WW}$

Mode	ΔBr/Br
bb*	2.7 %
cc*	12 %
gg*	29 %
ττ#	5 %
WW#	4 %
γγ#	25 %

$\Gamma = \Gamma_{WW}/Br(H\rightarrow WW)$ + $Br(H\rightarrow X)$ → Γ_X

*** ILD Letter of Intent**

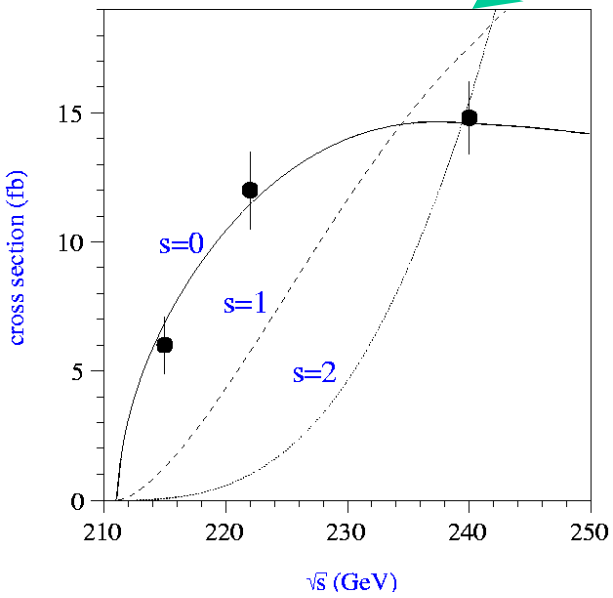
$\sqrt{s} = 250$ GeV ; $L = 250$ fb^{-1} ; $m_H = 120$ GeV

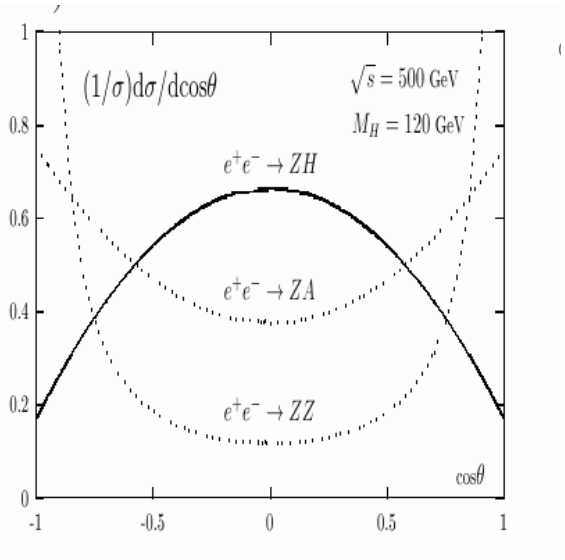
 # TESLA TDR

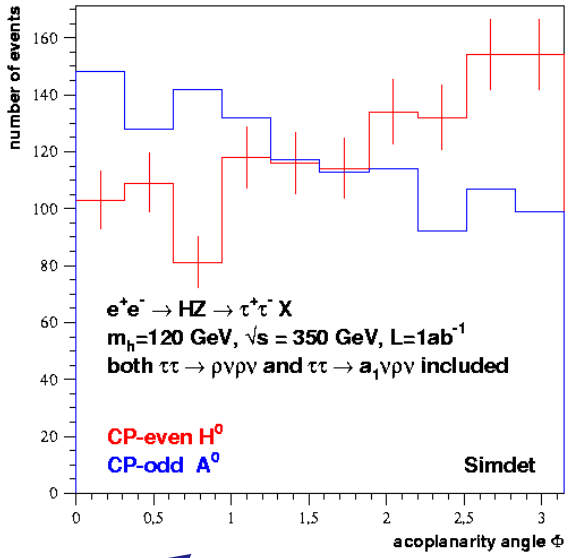
$\sqrt{s} = 350$ GeV ; $L = 500$ fb^{-1} ; $m_H = 120$ GeV

Higgs Quantum Numbers and Self-Coupling

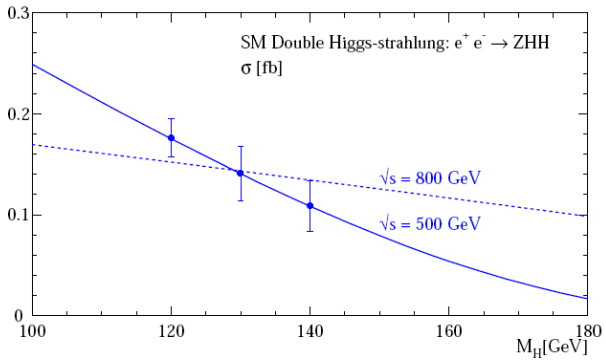
Higgs spin via *ZH* threshold scan







Parity from *σ(ZH/A)* & angular spectra + transverse spin correlations in *H→ττ*



Self-coupling via *ZHH* and *ννHH* production

Summary

- **Despite its phenomenological success, the SM is incomplete**
  - **mechanism of symmetry breaking not established yet**
  - **most favored scenario – Higgs mechanism**
  - **predicts one more physical state – Higgs boson**
- **Searches for Higgs bosons at LEP and Tevatron found no compelling signal → constraints on model parameters**
- **LHC experiments observe a new state with $m_X \approx 125$ GeV**
  - **consistent with expectations from SM Higgs boson**
  - **more data needed to reveal the nature of observed state**
- **Searches for BSM Higgs bosons are ongoing in parallel with SM Higgs searches, reinforcing constraints on new models**
- **Higgs hunters are impatiently waiting for new LHC data in order to answer the questions**
  - **Is what we see now really Higgs boson?**
  - **Is it THE Higgs or A Higgs?**

Contributions of CMS Higgs group to ICHEP'12 Results

Document	Analysis
PAS HIG-12-015	H → γγ Search
PAS HIG-12-016	H → ZZ → 4ℓ Search
PAS HIG-12-017	H → WW → 2ℓ2ν Search
PAS HIG-12-018	H → ττ Search
PAS HIG-12-019	VH, H → bb Search
PAS HIG-12-020	CMS Combined Search for Higgs
PAS HIG-12-021	H → WW → ℓνjj
PAS HIG-12-022	Search for Fermiophobic Higgs
PAS HIG-12-023	H → ZZ → 2ℓ2ν
PAS HIG-12-025	ttH, H → bb Search
PAS HIG-12-026	MSSM bΦ → 3b (fully hadronic)
PAS HIG-12-027	MSSM bΦ → 3b (semileptonic)

Members of DESY CMS Higgs Group


Andreas Meyer


Rainer Mankel


Wolfgang Lohmann


Caroline Riedl

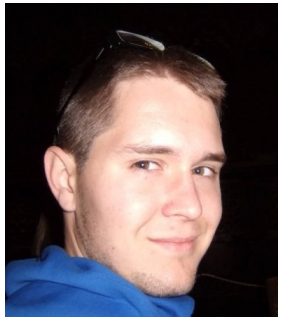

Roberval Walsh


Alexei Raspereza

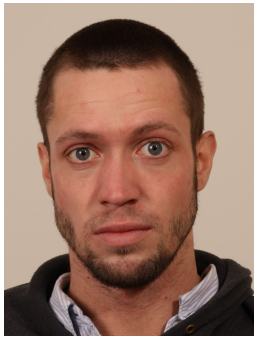

Agni Bethani


Sasha Spiridonov


Igor Marfin


Luigi Calligaris


Armin Burgmeier


Jakob Salfeld-Nebgen


Gregor Hellwig

Backup

Di-jet Tag (VBF Event Category)

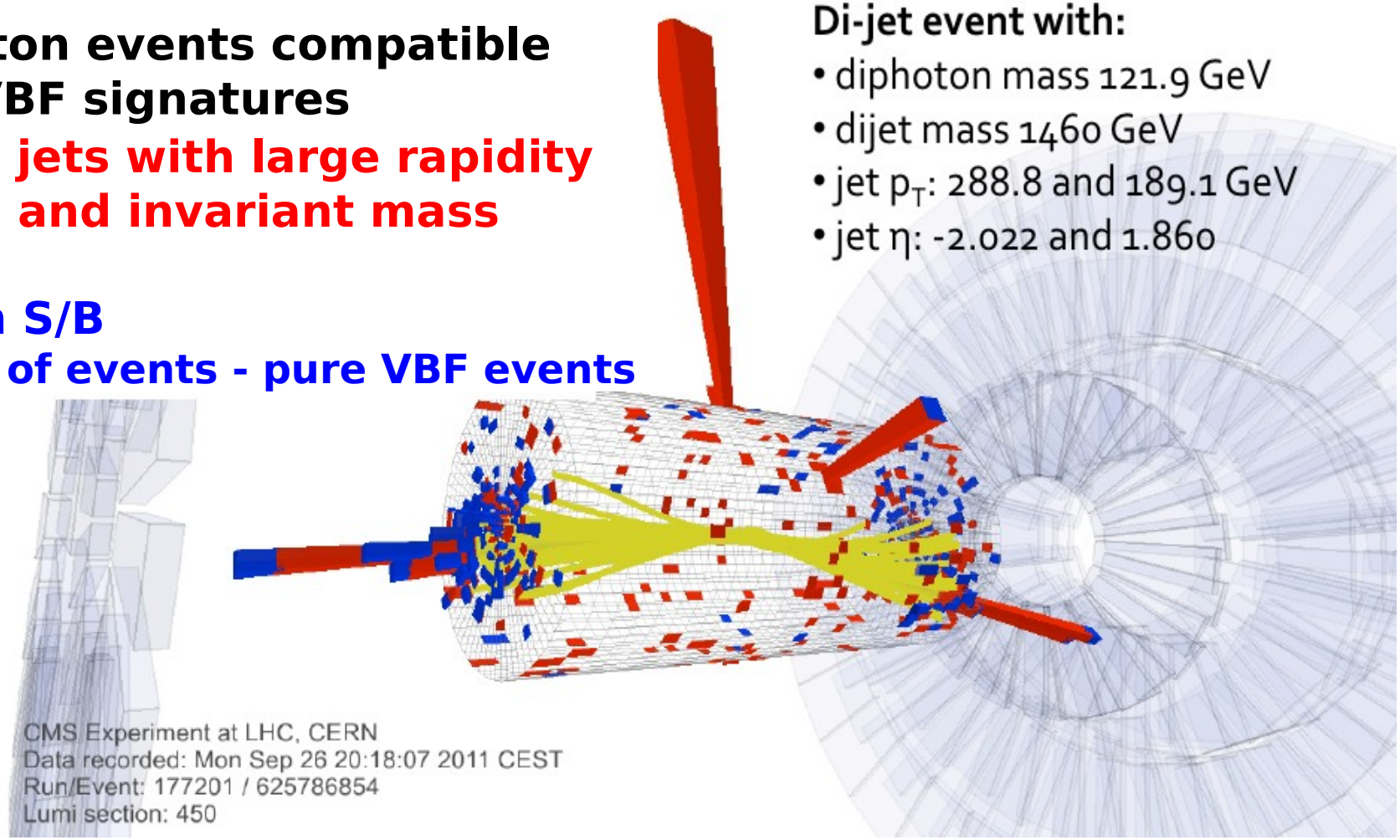
Exclusive di-jet category

diphoton events compatible with VBF signatures

two jets with large rapidity gap and invariant mass

→ high S/B

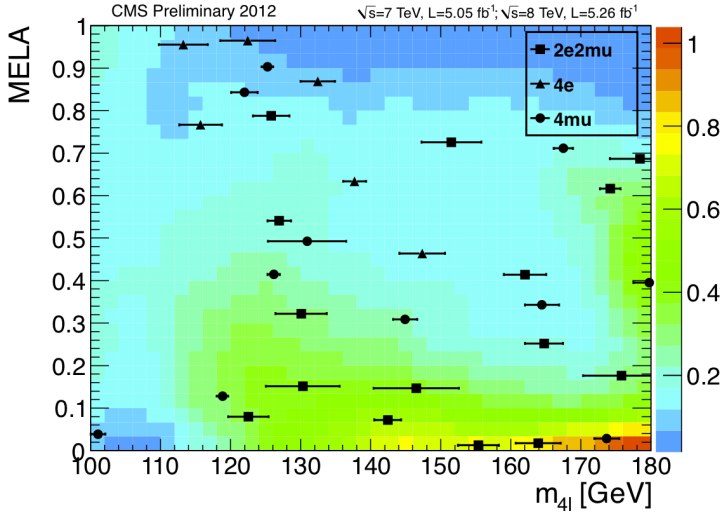
80% of events - pure VBF events

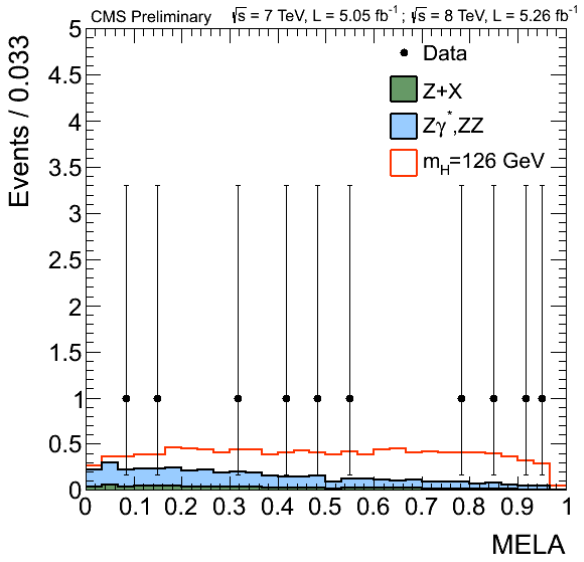


Statistical Analysis in Z → ZZ* → 4 Channel

statistical inference performed with 2D distribution [MELA, m_{4l}]

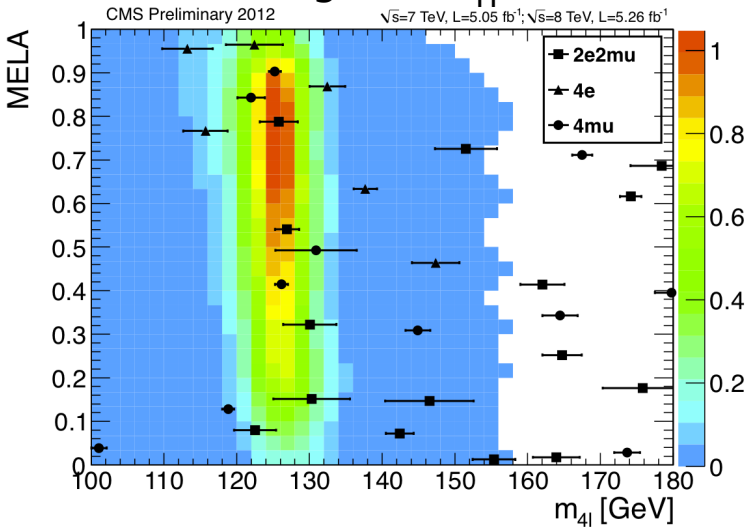
data vs. background

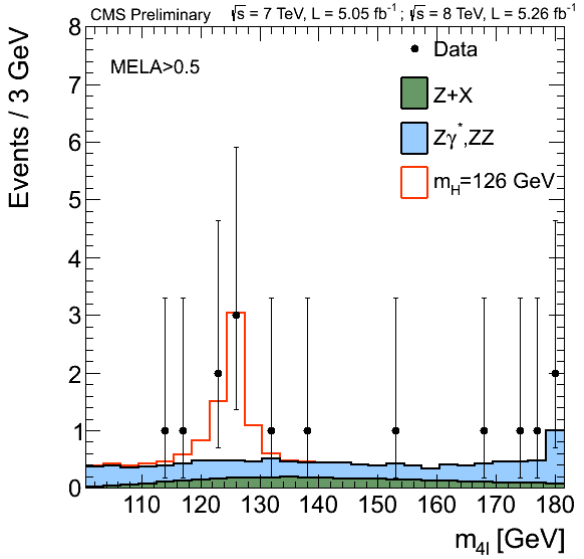




for illustration:
MELA projection in
m_{4l} 121–131 GeV

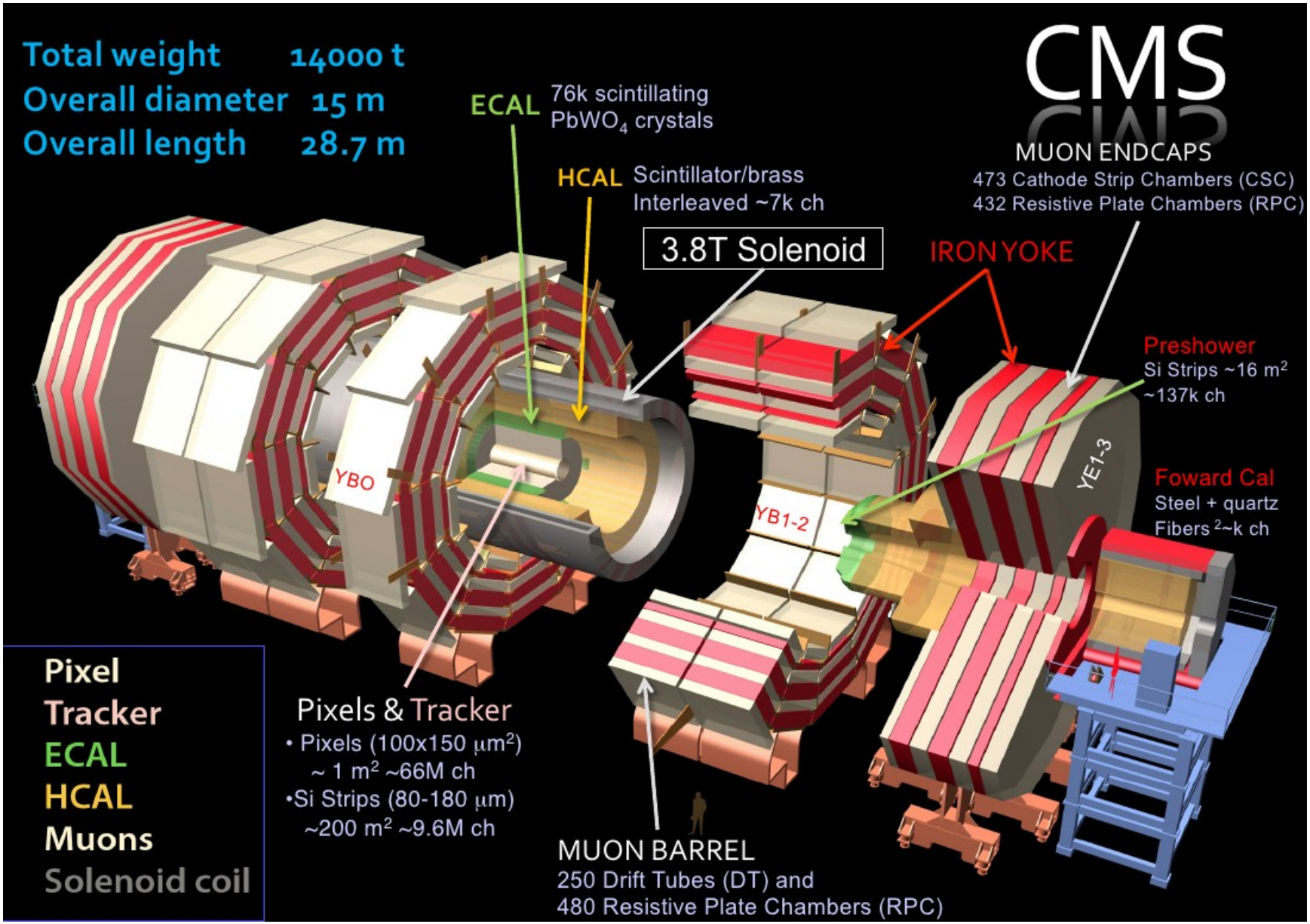
data vs. signal (m_H=126GeV)





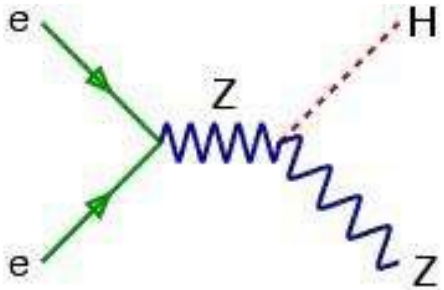
for illustration:
m_{4l} distribution
for MELA > 0.5

CMS Detector

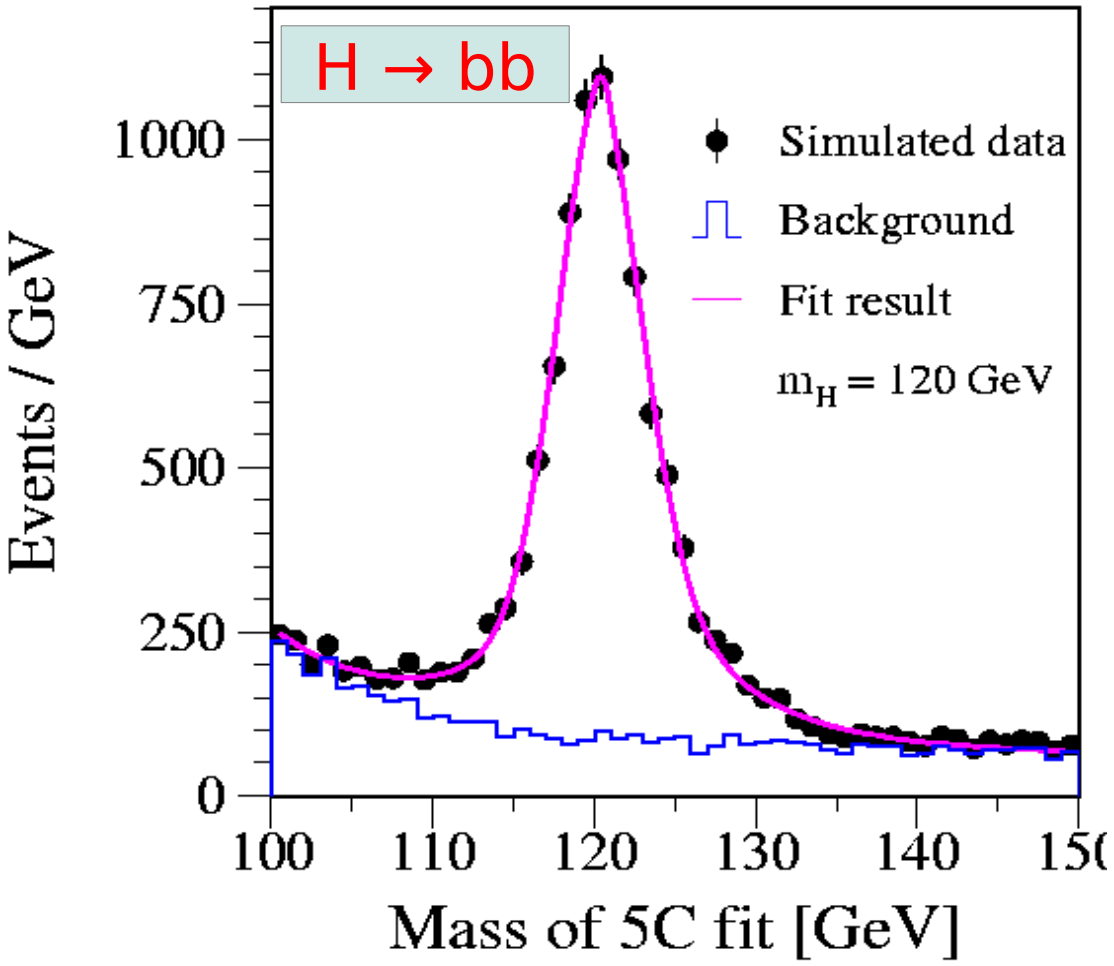


Higgs Mass Measurement at ILC

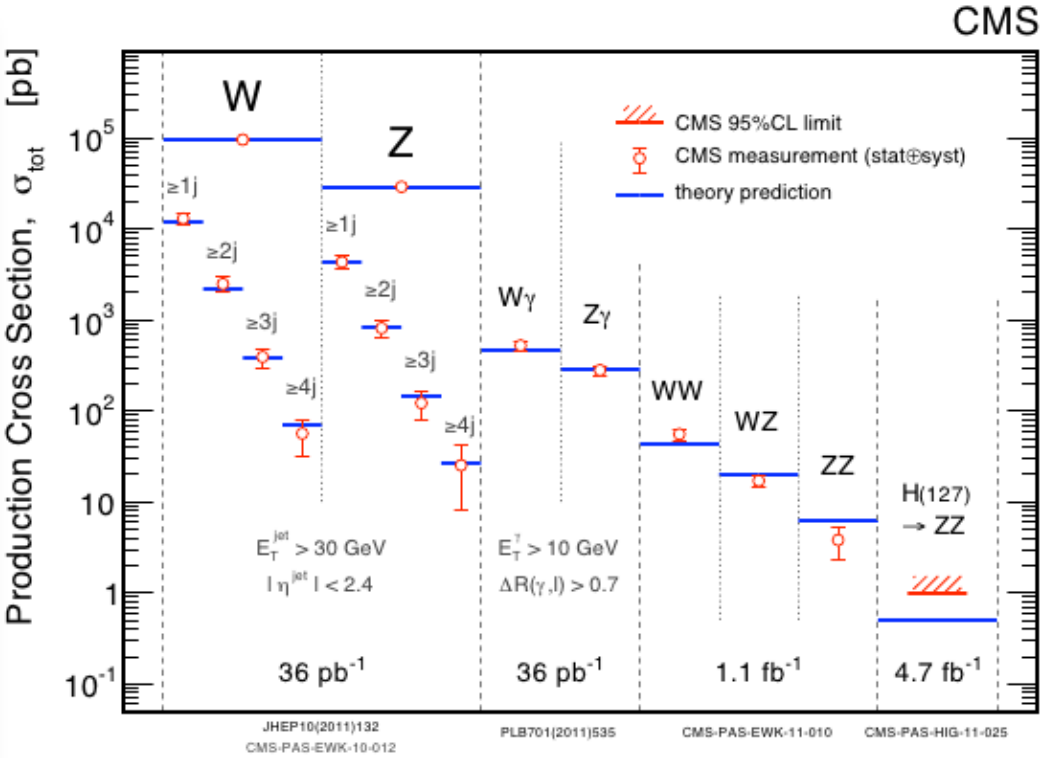
- ***Exploited channel***



- ***Z → ee, μμ, qq***
  - ***Use of kinematic fits***
  - ***→ 4C fit : 4P (Z→ee, μμ)***
  - ***→ 5C fit : 4P+m_z(Z→qq)***
- ***√s = 350 GeV, L=0.5/fb***
  - ***m = 120 GeV, H→bb***
  - ***→ Δm = 40 MeV***



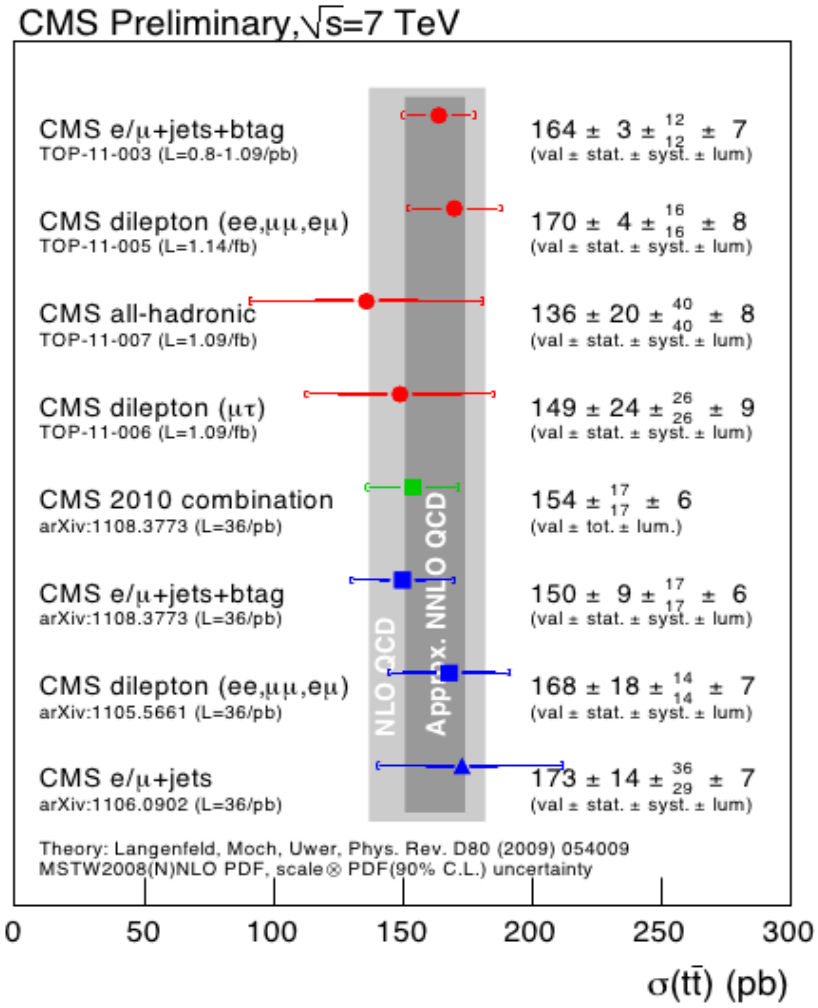
Standard Model at 7 TeV



- **remarkable agreement with SM**
- **lots of data**

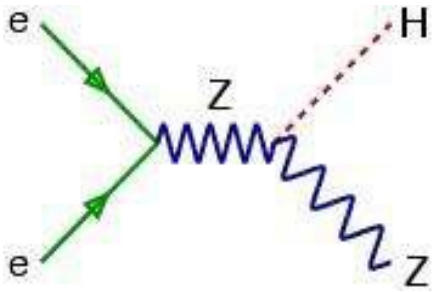
→ **ready for Higgs hunt**

$t\bar{t}$ cross section



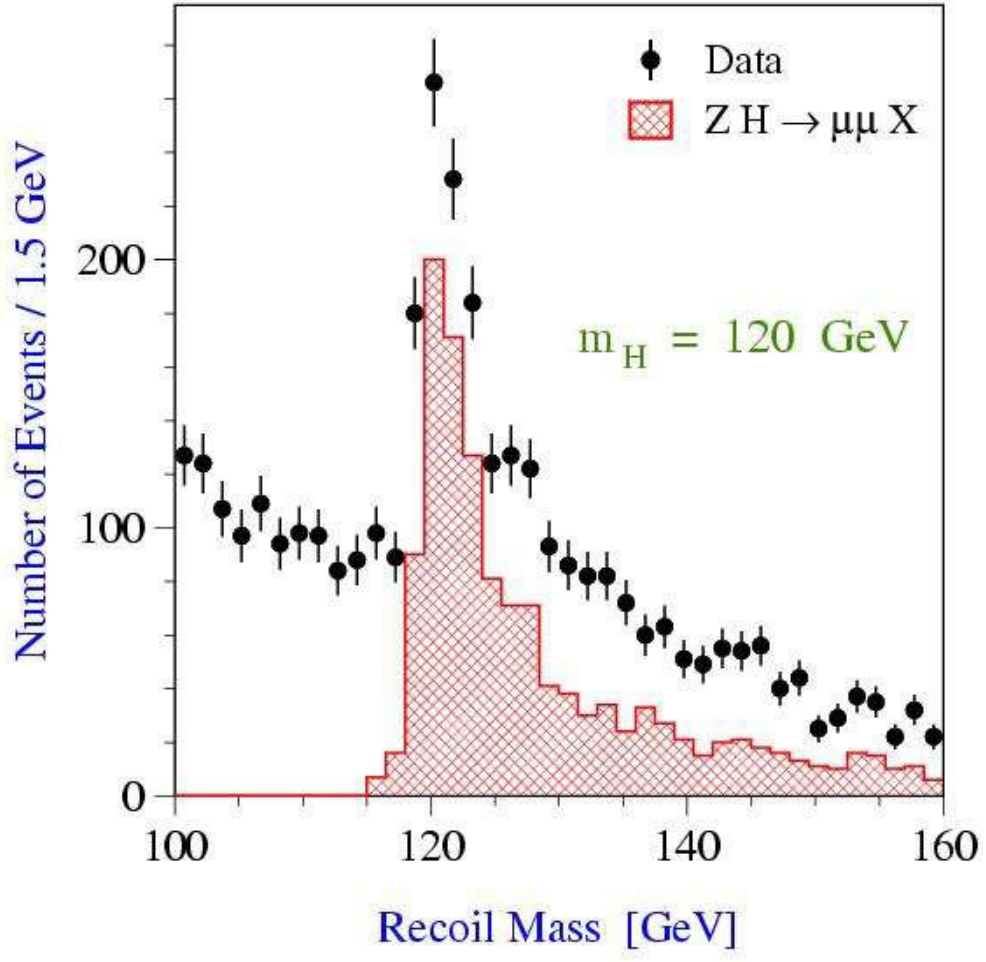
Decay Independent Higgs Detection

- **At ILC Higgs boson can be detected independent of its decay mode**



$$Z \to \ell^+\ell^-, \quad \ell = e, \mu$$

- **signal : peak in the recoil mass spectrum**



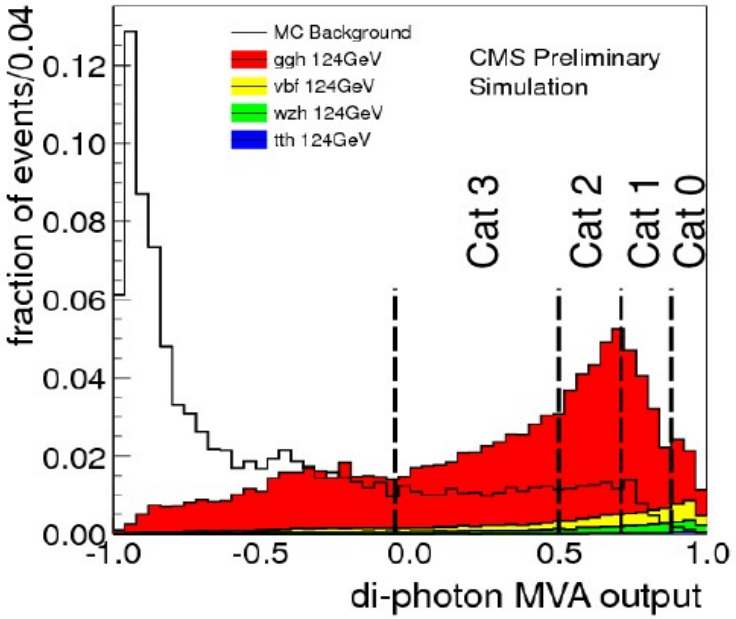
- **Model independent extraction of HZZ coupling**

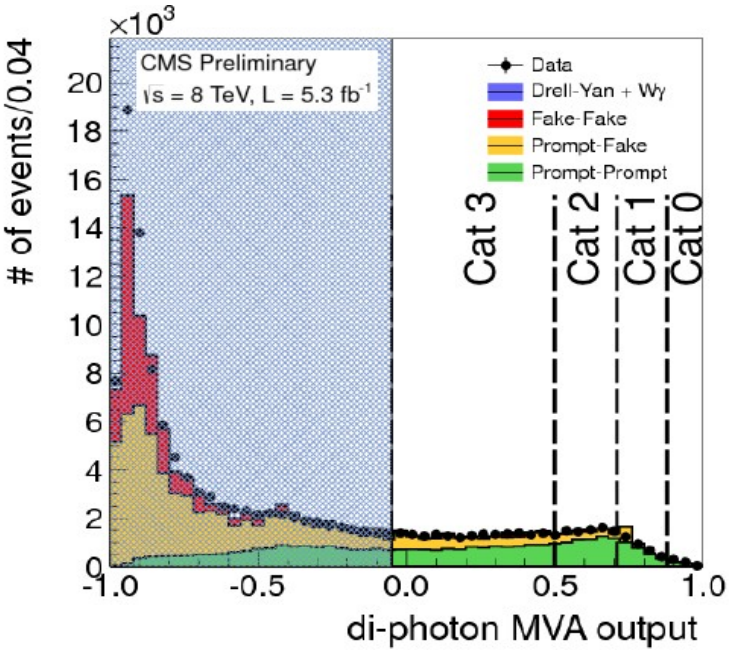
$$\sigma \sim g^2_{HZZ}$$

$$\Delta\sigma/\sigma \approx 3\% \text{ for } m_H = 120 \text{ GeV}, \sqrt{s} = 350 \text{ GeV}, L = 0.5 \text{ fb}^{-1}$$

Diphoton MVA

- **Diphoton MVA combines variables independent**
  - **photon kinematics**
  - **MVA based photon IDs**
  - **Per-event diphoton mass resolution and vertex probability**
- **4 categories depending on MVA output**



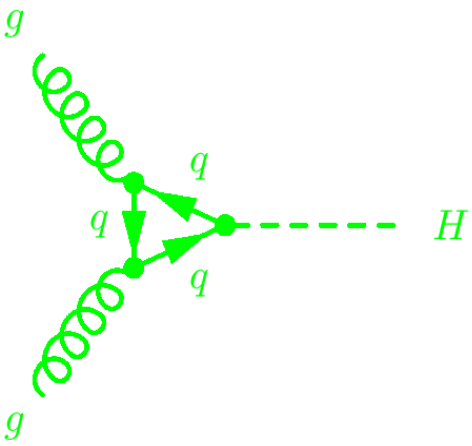


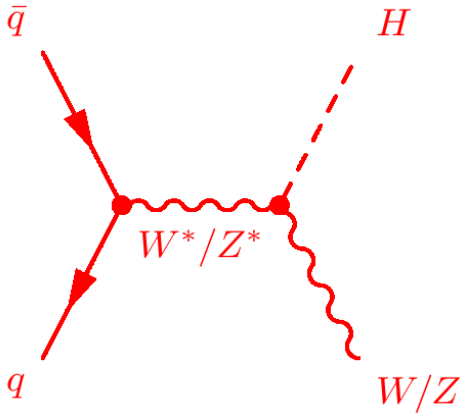
- **Exclusive di-jet categories : events compatible with VBF signatures**
  - **two jets with large rapidity gap and invariant mass**

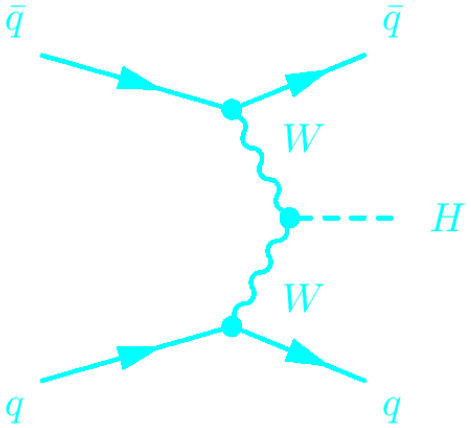
    → S/B enhancement (80% of events are pure VBF events)

SM Higgs Boson at Tevatron

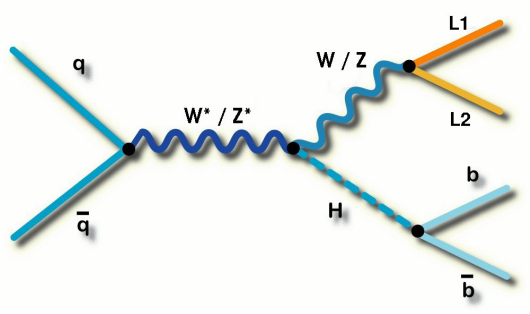
Main production mechanisms:



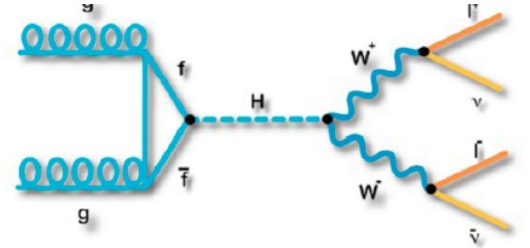




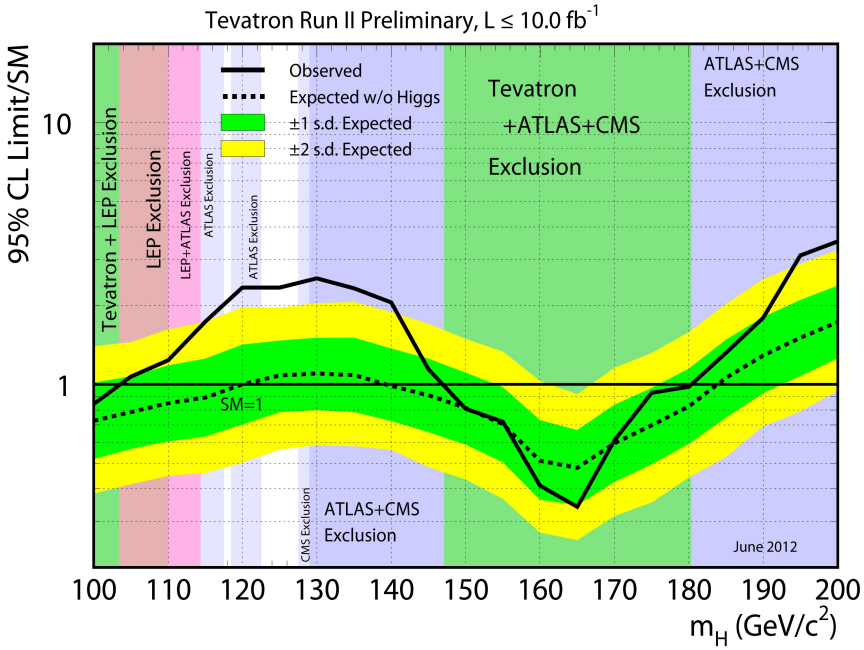
Channels yielding highest sensitivity:



$m_H \leq 130$ GeV

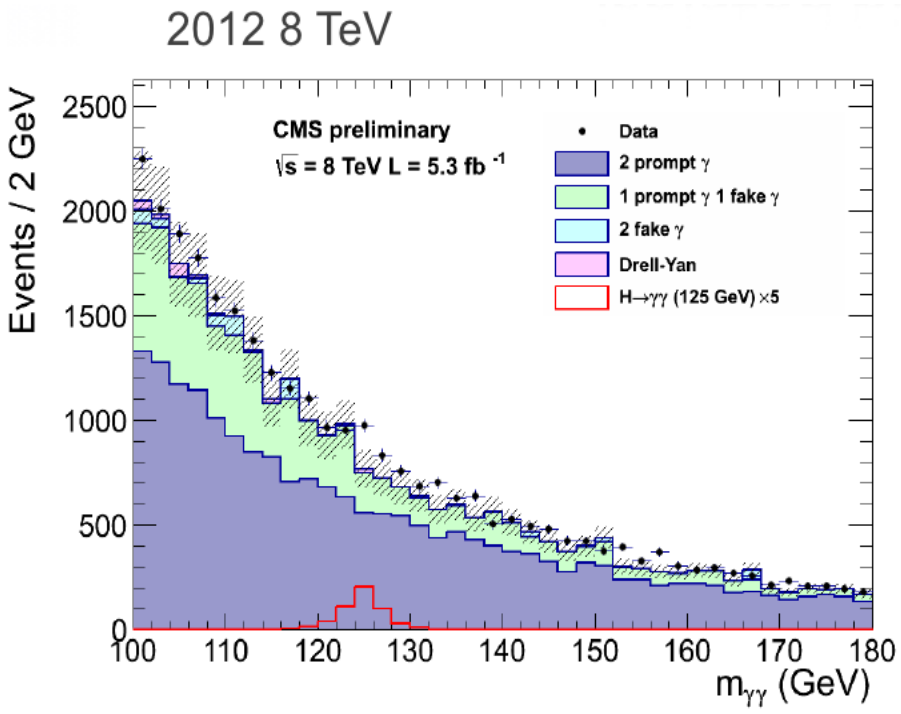


$m_H \geq 130$ GeV



Overview of H → γγ Search in CMS

- **H→ γγ signatures : two isolated photon, narrow mass peak**
- **Search exploits MVA approach**
  - **event categorization based on MVA output and information about accompanying jets (VBF tag)**
- **MC used only for the analysis optimization**
- **No prior model for background : background determined from fits of mass spectra in each event category separately assuming no-signal**



possible bias studied with various smooth functions, modeling background shape

bias due to presence of possible signal < 20% of stat. error of fit

Z → e^+e^- sample is used to measure γ energy scale and resolution

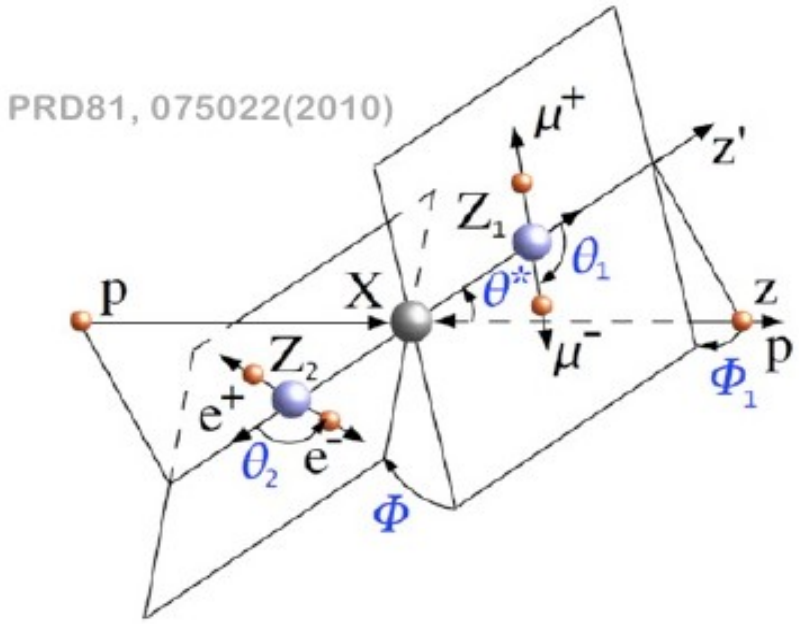
Matrix Element Likelihood Analysis

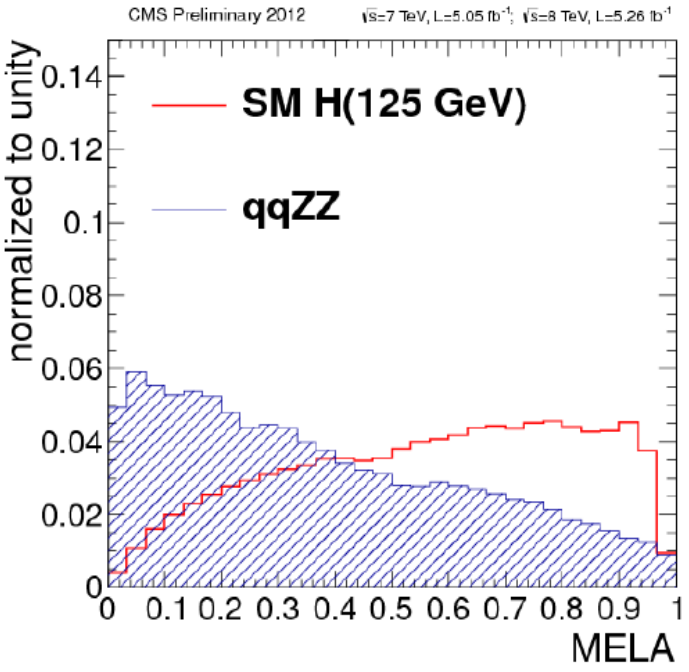
dynamics of decay described fully by 2 masses and 5 angles

Matrix Element Likelihood Analysis

discriminates $J^P = 0^+$ state from background

$$\mathrm{MELA} = \left[1 + \frac{\mathcal{P}_{\mathrm{bkg}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}{\mathcal{P}_{\mathrm{sig}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}\right]^{-1}$$





H→ZZ*→4ℓ Search Channel : Overview

- **Golden channel**
  - clean signature : 4 isolated leptons
  - excellent momentum resolution of leptons
  - Narrow mass peak m_{4l}
- **Backgrounds :**
  - irreducible : ZZ*
  - reducible : Z+jets/ttbar/WZ

Channels studied : 4μ, 2μ2e, 4e

Lepton selection

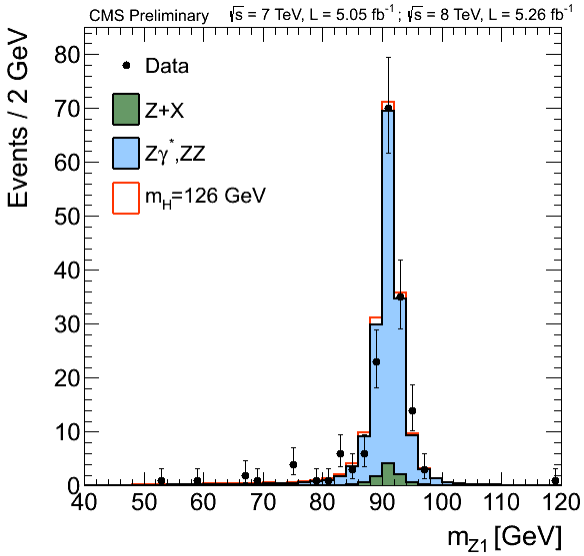
minimal lepton p_T = 5 GeV (μ), 7 GeV (e)

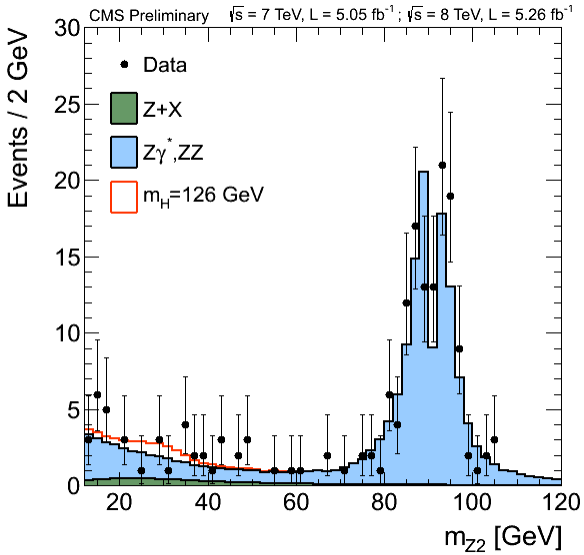
at least one lepton with p_T > 20 GeV

at least two leptons with p_T > 10 GeV

Z1 candidate : pair with mass closest to m(Z)

Z2 candidate : built from remaining leptons with highest p_T



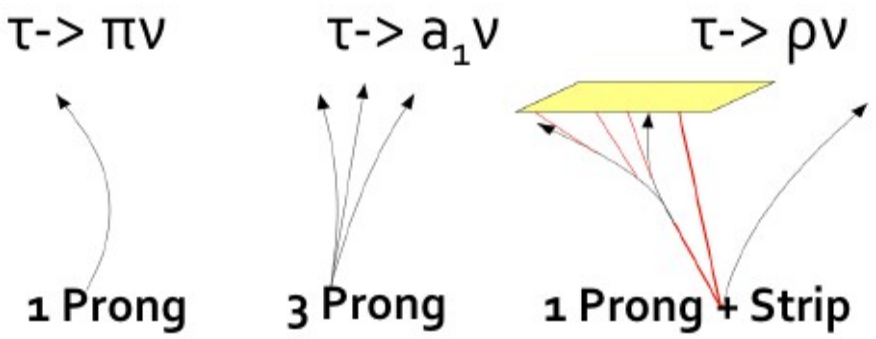


40 GeV < m(Z1) < 120 GeV **4 GeV < m(Z2) < 120 GeV**

Tau Lepton Identification

Tau Identification

- Reconstruction of individual decay modes
- charged hadrons + EM objects
- EM strips to account for material effects

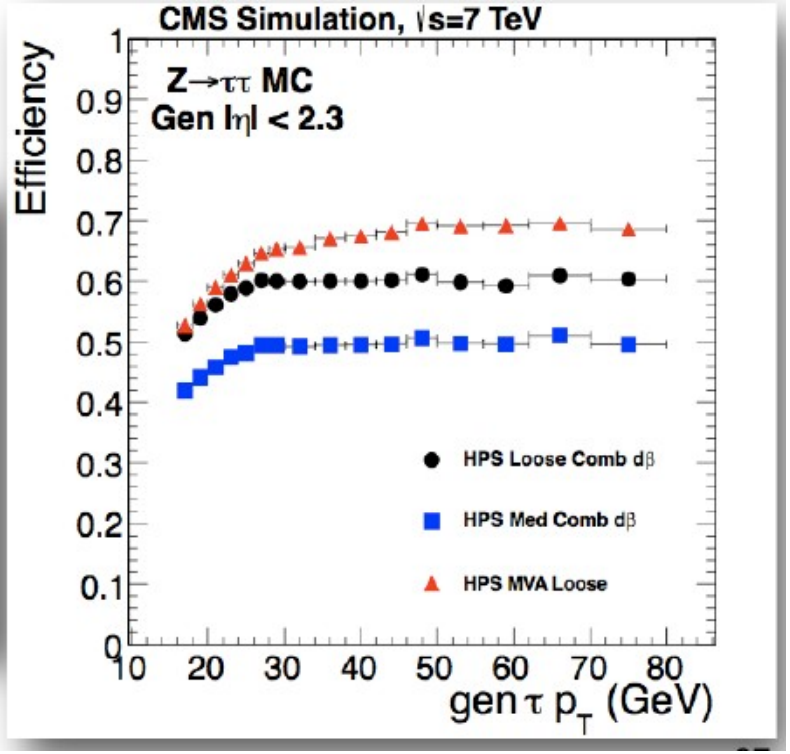


Tau isolation based on MVA approach

→ absolute energy sum in ΔR rings

Efficiency > 60%

for a tau fake rate of 6%

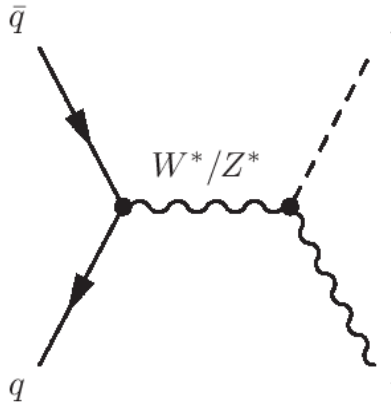


Search for Z(ℓℓ)H, Z(νν)H, W(ℓν)H with H→bb

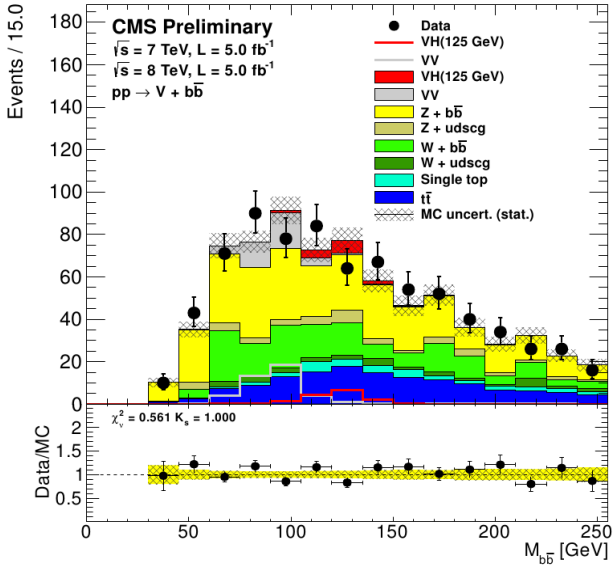
Br(H → bb) is largest at $m_H \leq 130$ GeV

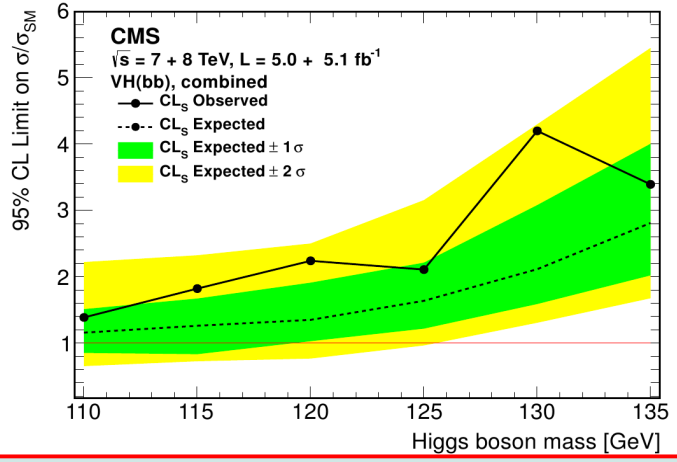
inclusive search impossible due to overwhelming QCD background

→ exploit VH production



$$Z \to ee, \mu\mu, \nu\nu$$
$$W \to e\nu, \mu\nu$$
$$H \to b\bar{b}$$





MVA shape analysis

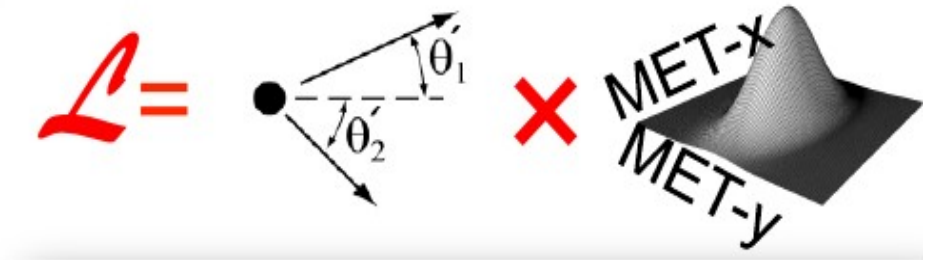
MVA combines

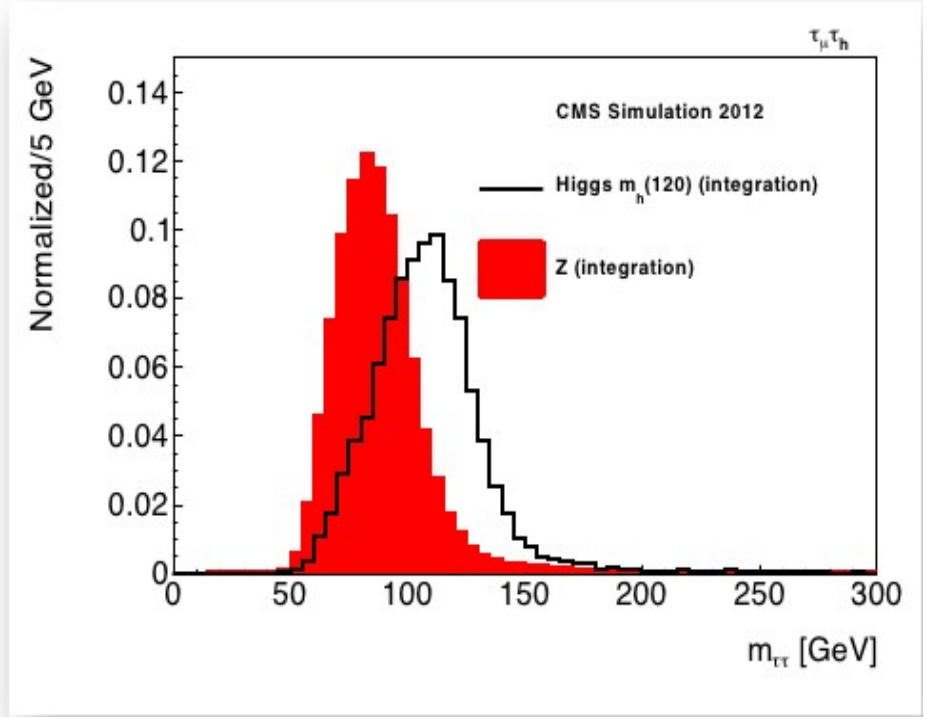
- **lepton kinematics**
- **b-tag information**
- **jet kinematics**
- **mass information**
- **missing E_T**

results of analysis compatible with either background or signal from m_H = 125 GeV

→ more data needed

Reconstruction of Ditau Mass in H → ττ Search





- SVFit
  - Event-by-event estimator of true m(ττ) likelihood
    - Matrix Element used for τ→lνν
    - Phase-Space is used for τ→π
    - Nuisance parameters are integrated out
- Mass peaks at true value
  - 20 % improved resolution
    - With respect to 2011
  - Better separation of H from Z