Karlsruher Institut für Technologie

Higgs Physics at the LHC

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Course "Higgs Physics"

Lectures 10-11, 12-19/07/2012

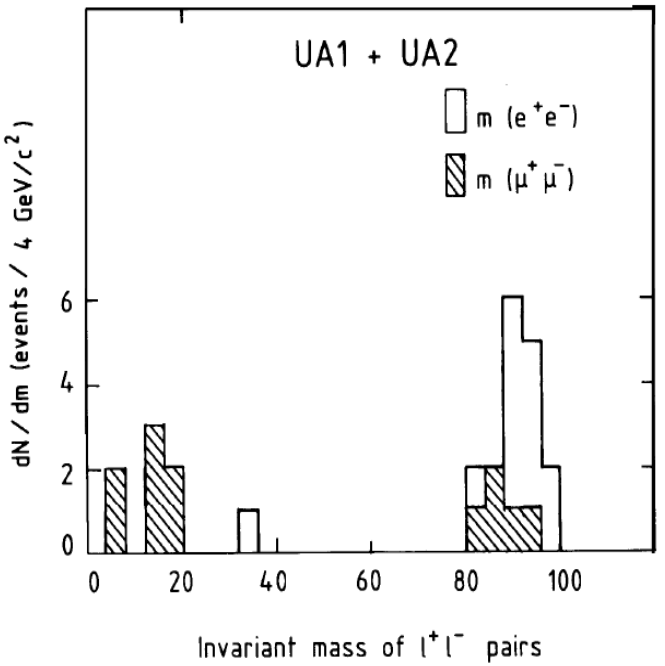
KIT – Universität des Landes Baden-Württemberg und

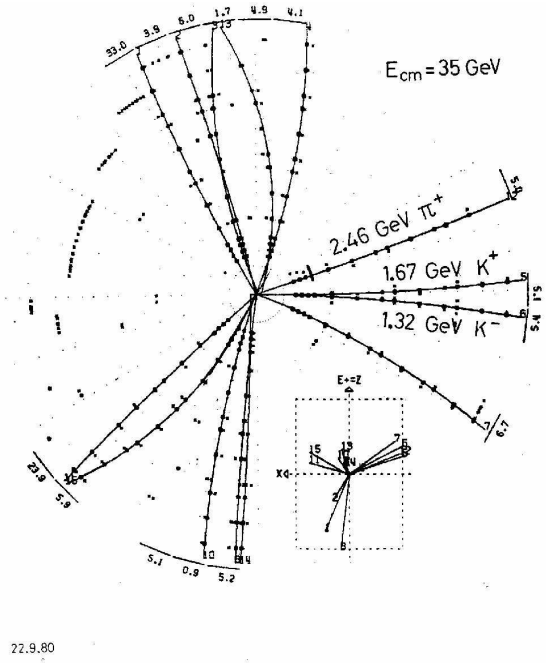
Nationales Forschungszentrum in der Helmholtz-Gemeinschaft

www.kit.edu

Machines of the Past

- **Super-p$\bar{p}$-Synchrotron (CERN)**
  - → p$\bar{p}$ collisions
  - → c-o-m energy up to 450 GeV
  - → legacy : discovery of $W^{\pm}$, Z
    - – Noble prize in physics
      - C. Rubbia
      - S. van der Meer





- **PETRA (DESY)**
  - → e^+e^- collider; c-o-m energy up to 38 GeV
  - → legacy : discovery of gluons
- **HERA (DESY)**
  - → ep collisions (E_e=28 GeV, E_p=900 GeV)
  - → legacy : precise knowledge of proton structure

Machines of the Past

- **Large Electron Positron collider**

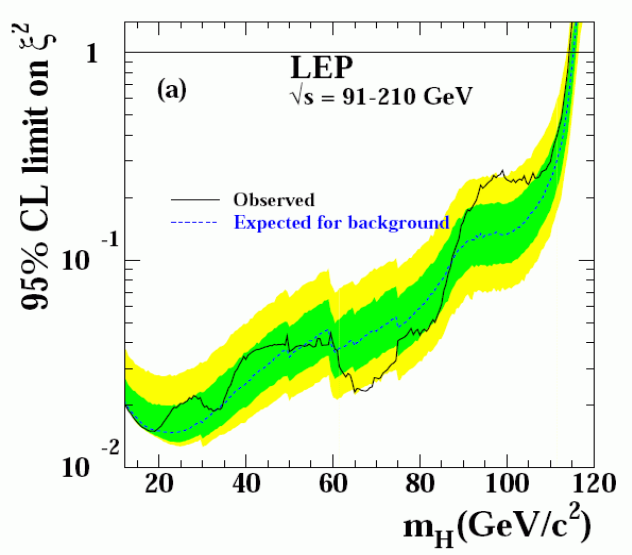
  → e^+e^- collisions @ 91 GeV (Z peak) – 209 GeV

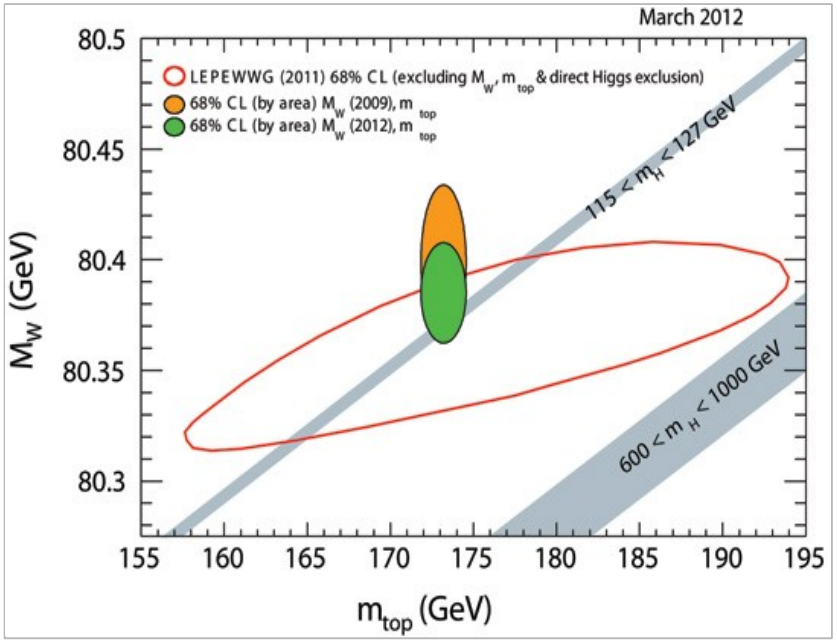
- **LEP legacy**

  → precise electroweak measurements at Z peak

  → tested SM with high accuracy

  → lower bound on m_H > 114 GeV





- **Tevatron**

  → $p\bar{p}$ collisions at ~ 2 TeV

- **Tevatron Legacy**

  → discovery of top-quark

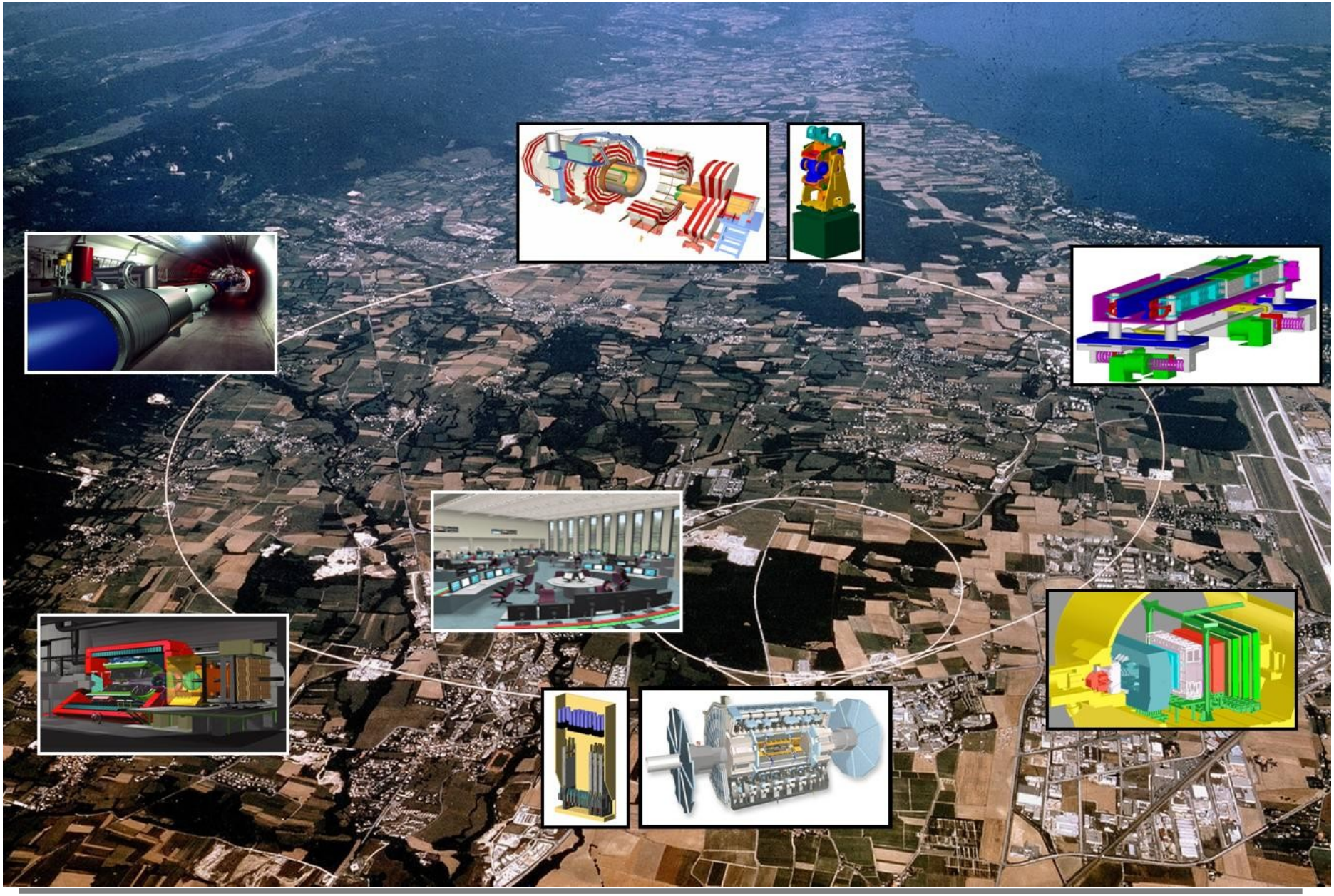
  → precise measurements of m_t and m_W

  → constraints on m_H

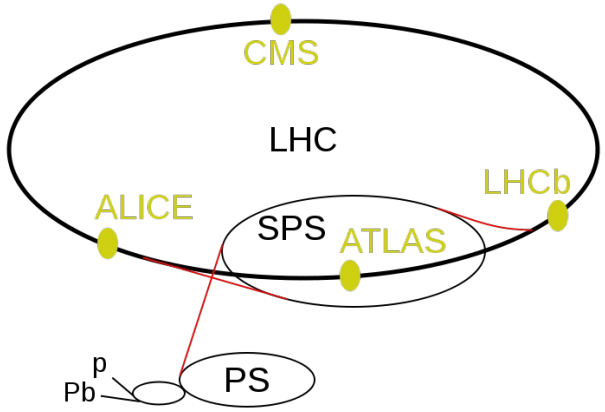
Why LHC ?

- **High energy reach : pp @ 7 → 8 → 14 TeV**
  - → high mass reach for “hunted” particles (Higgs, SUSY)
  - → higher signal cross sections
- **High luminosity (design : L = 10^{34} cm^{-2} s^{-1})**
  - → large statistics
  - → more compelling evidence for signal
- **Inherits LEP tunnel**
  - → reduced construction cost
- **Run by CERN Accelerator division**
  - → expertise in accelerator physics, cryogenics, detector physics, ...
- **Located at CERN**
  - → international project
  - → participation of many institutes from many countries
  - → competent outreach policy

LHC Community



LHC in Numbers



LHC accelerator complex

- Proton (Pb) linac → 50 MeV
- Proton Synchrotron Booster → 1.4 GeV
- Proton Synchrotron → 28 GeV
- Super-proton-synchrotron → 450 GeV
- Large Hadron Collider → 8 TeV

http://www.cern.ch/lhc

- **Circumference : 27 km**
- **Dipole magnets : 1,232**
- **Quadrupole magnets : 932**
- **Proton beams : sequence of bunches: 2,808 bunches / beam**
- **11,000 revolutions / second**
- **Bunch separation : 25 ns**

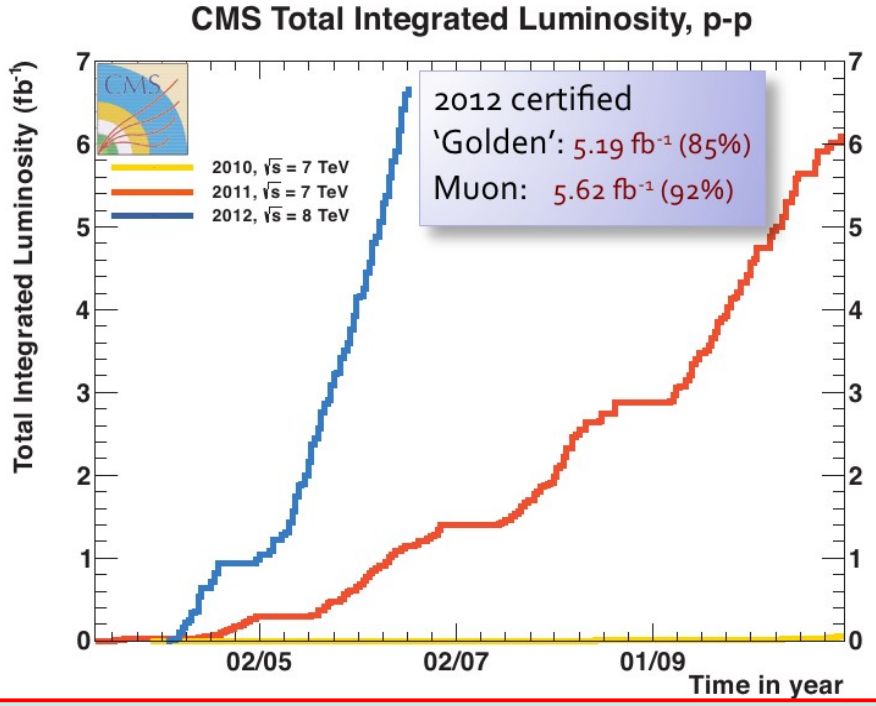
  → bunch collision rate : 40 MHz
- **~ 100 billion protons / bunch**
- **Design luminosity : 10^{34} cm^{-2} s^{-1}**

$$\sqrt{s} = 8 \text{ TeV} \quad m_H = 125 \text{ GeV}$$

$$\sigma(pp \to H) \approx 20 \text{ pb}$$

→ at what rate Higgs bosons are produced?

LHC Machine Performance

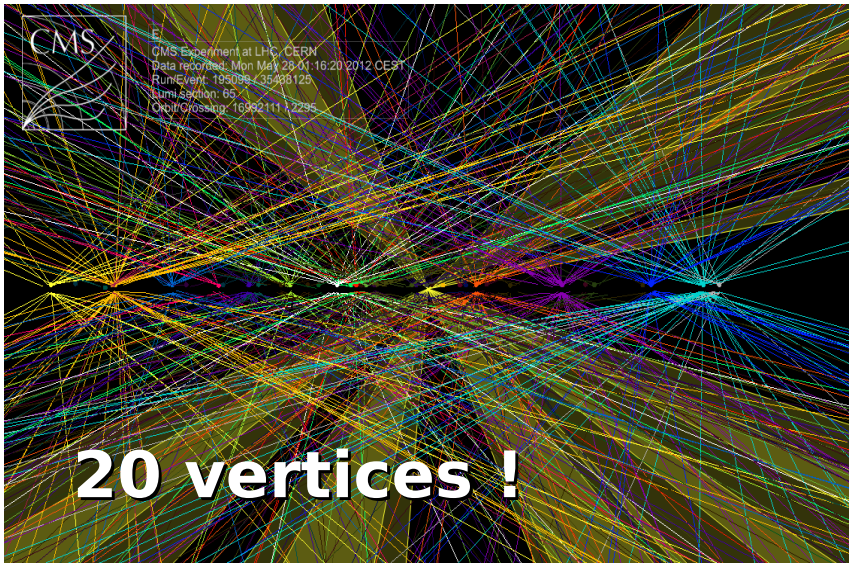


Peak luminosity in 2012

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

steady performance of LHC enables experiments to produce significant physics results

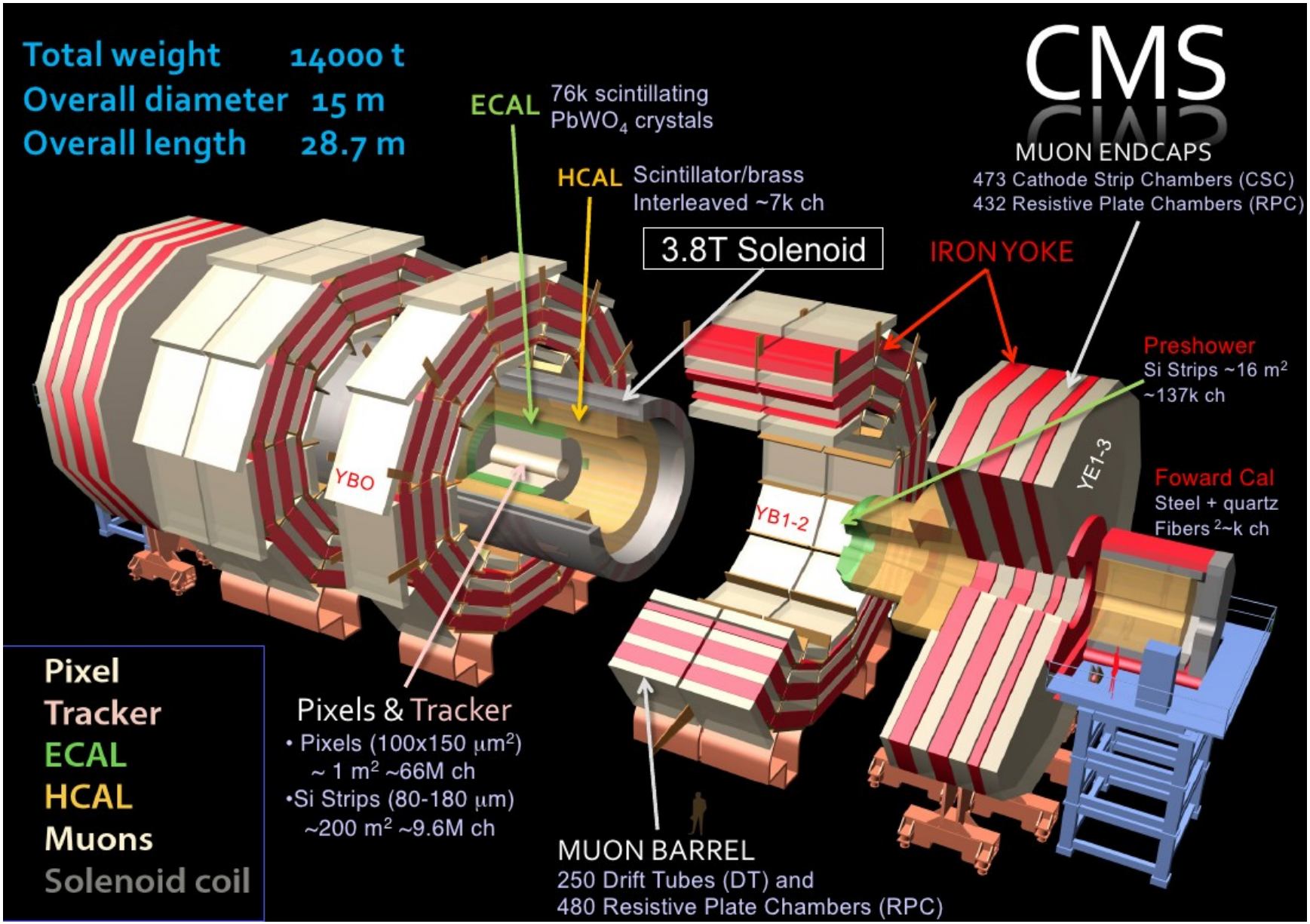
Main challenge : Pile-up



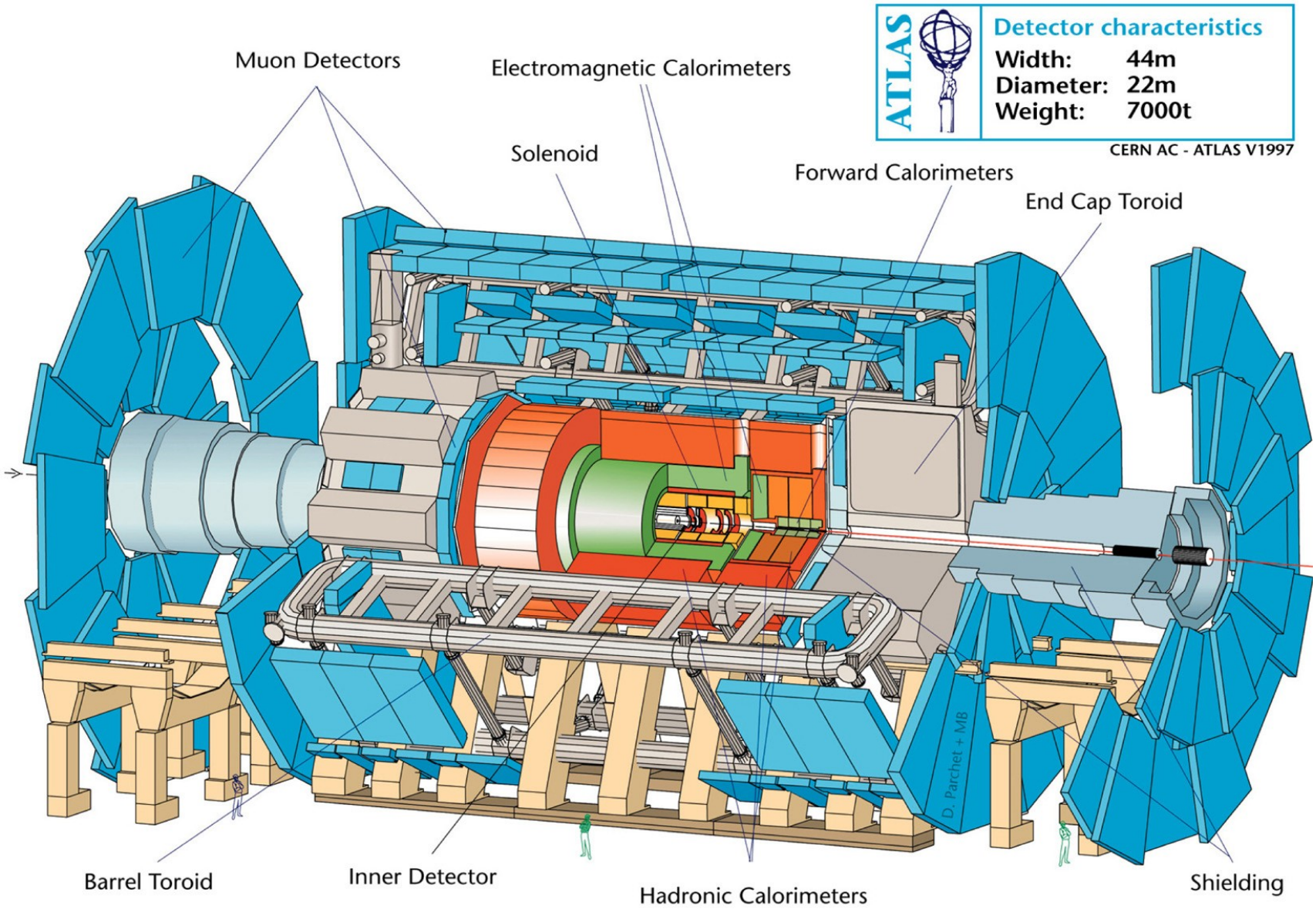
Special task force to prepare for 2012 data taking and mitigate effect of PU on trigger, reconstruction of physics objects, CPU time, event size

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

CMS Detector

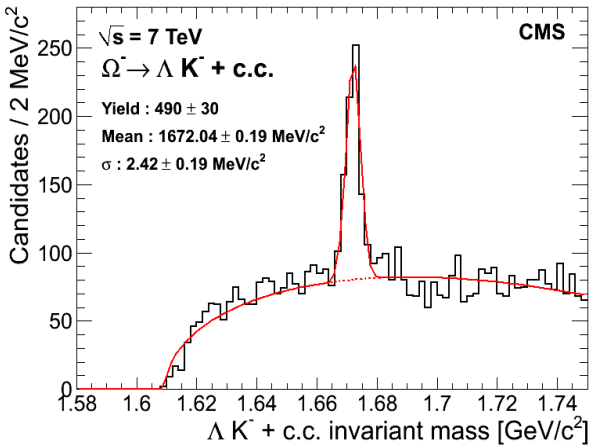


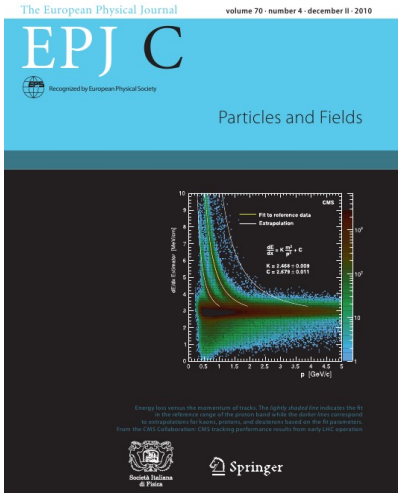
ATLAS Detector



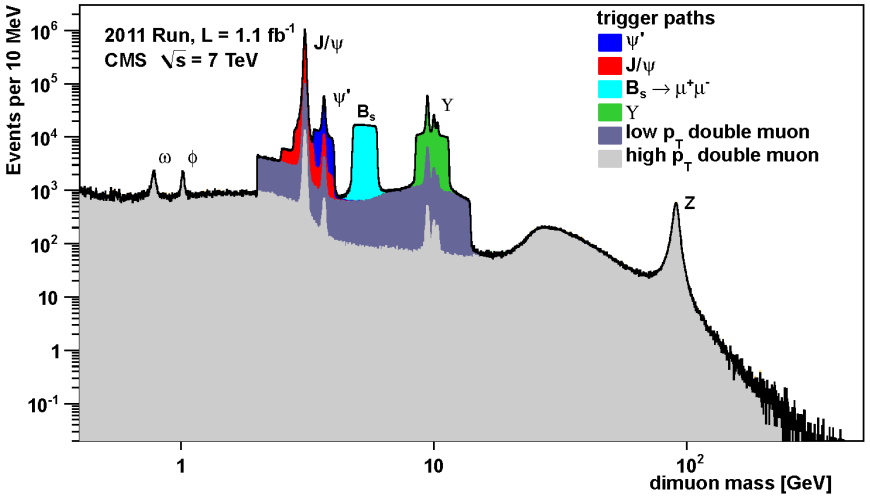
Commissioning of Detector and Reconstruction Tools

Tracking & Vertexing

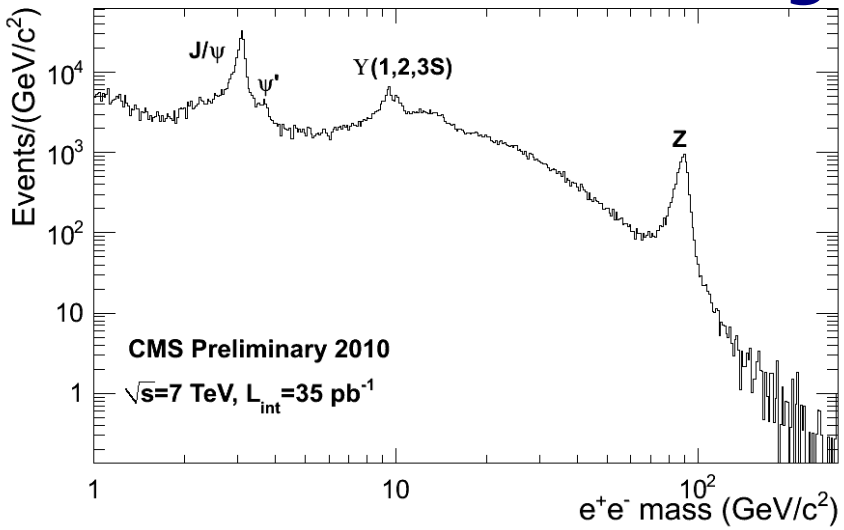




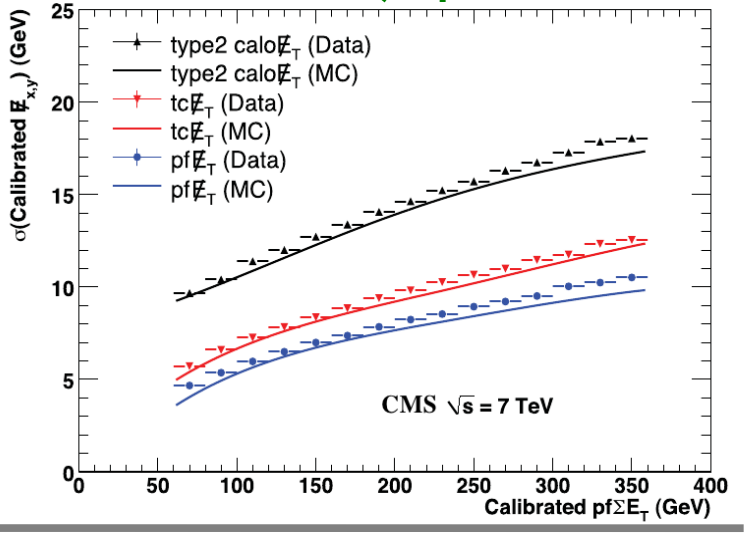
Muon System



ECAL Commissioning

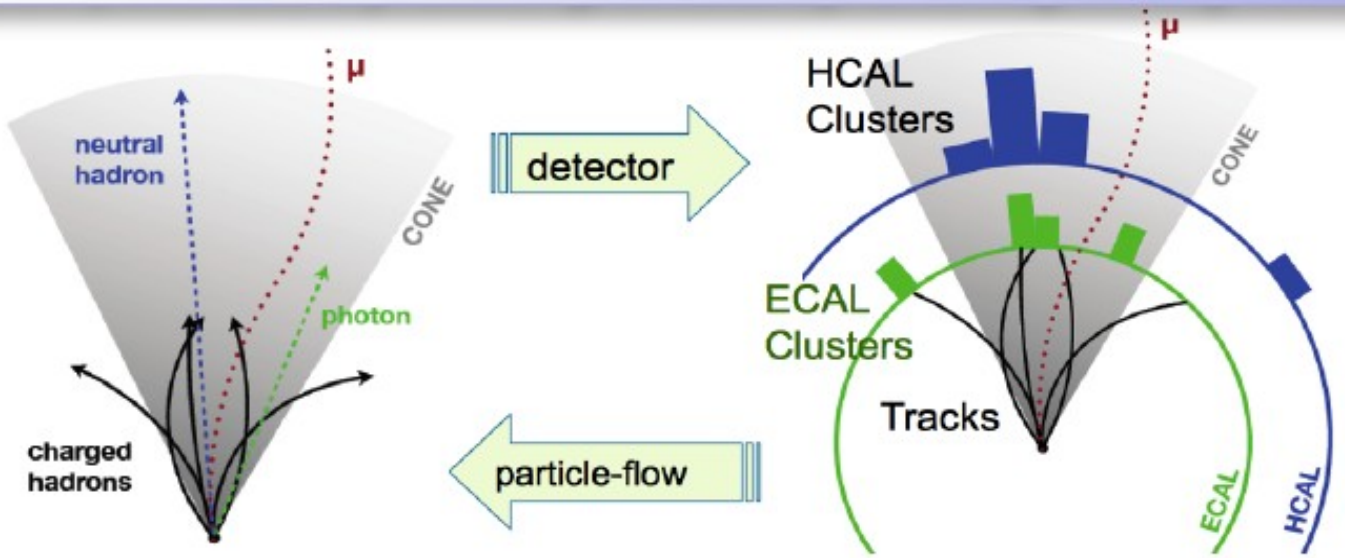


PFlow, $\not{E}_T$, Jets



Particle Flow Concept

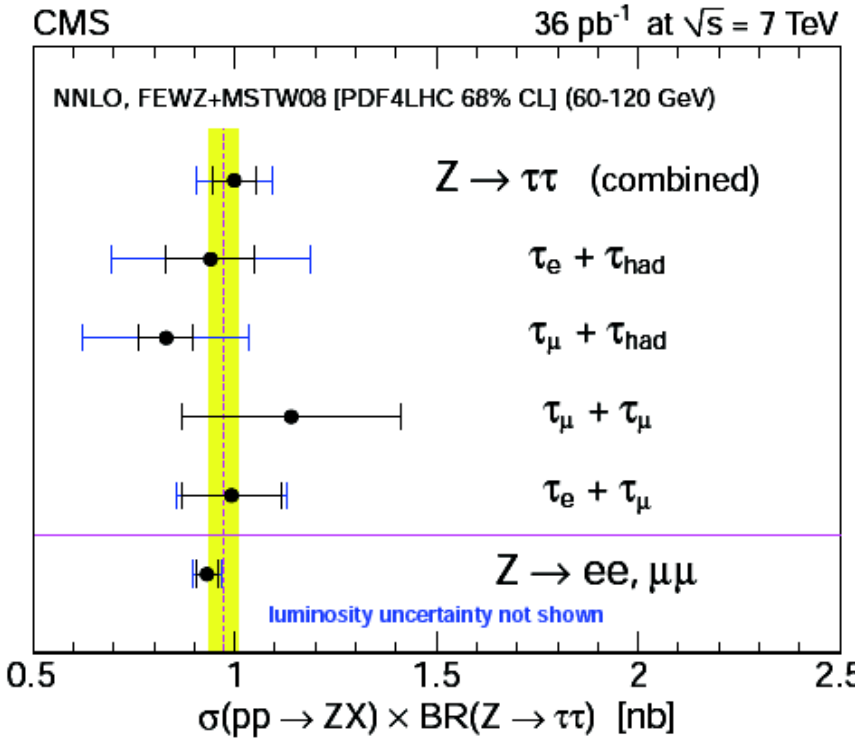
Made possible by CMS granularity and high magnetic field

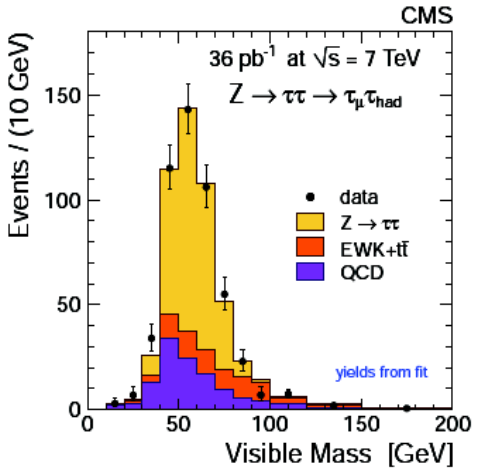


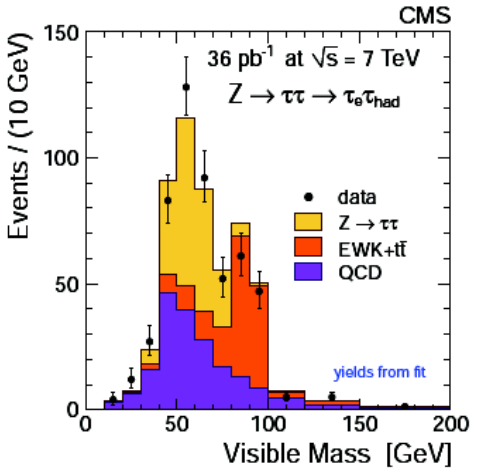
- Optimal combination of information from all subdetectors
- Returns a list of reconstructed particles
  - e,μ,γ, charged and neutral hadrons
    - Used in the analysis as if it came from a list of generated particles
    - Used as building blocks for jets, taus , missing transverse energy , isolation and PU particle identification

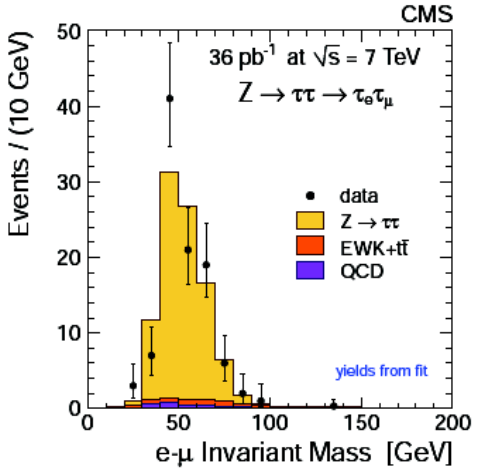
Calibration of Searches with Standard Candles

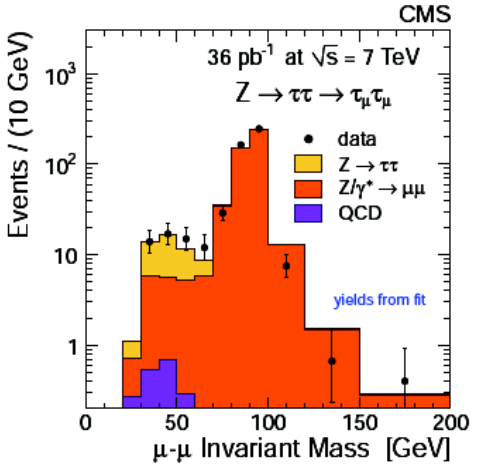
- **Analyses searching for the Higgs Boson were commissioned with "Standard Candles"**
- **Example : the H → ττ search is commissioned with the study of inclusive Z production followed by Z → ττ**











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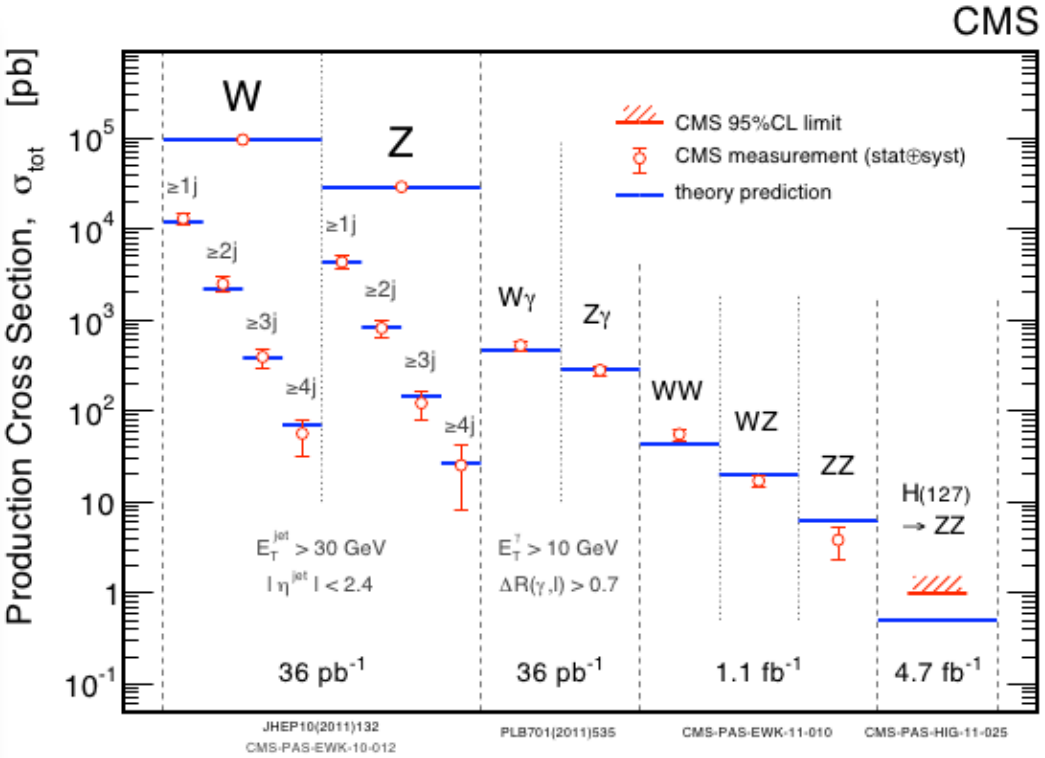
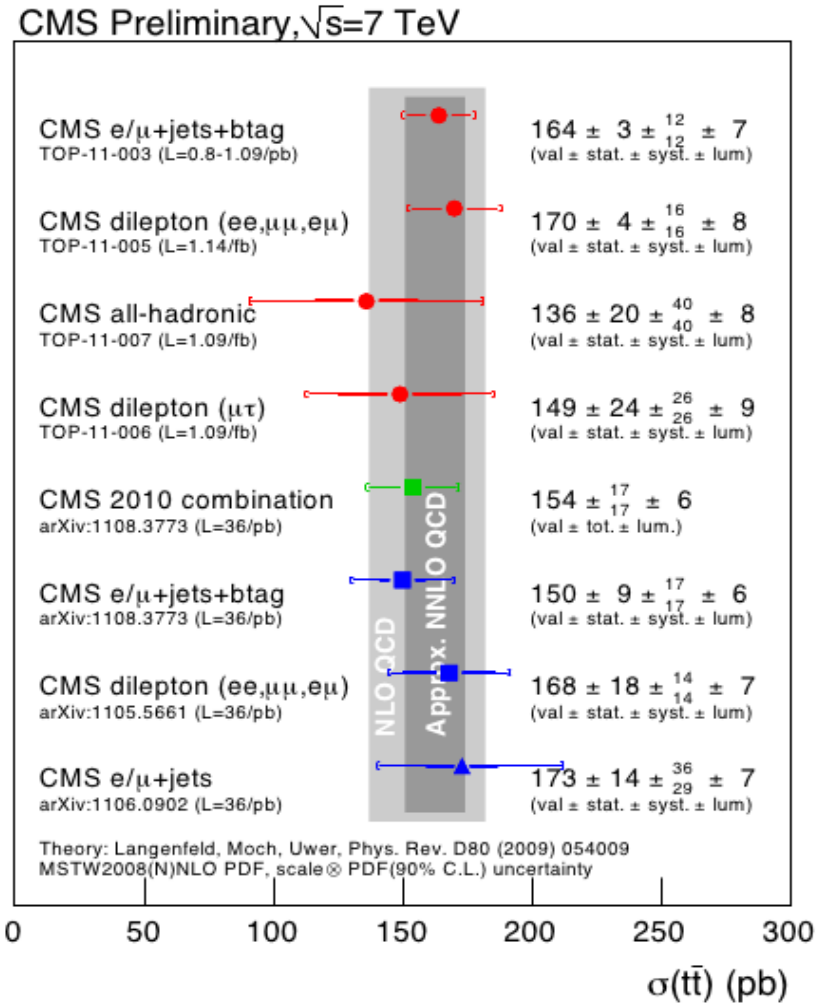
Standard Model at 7 TeV



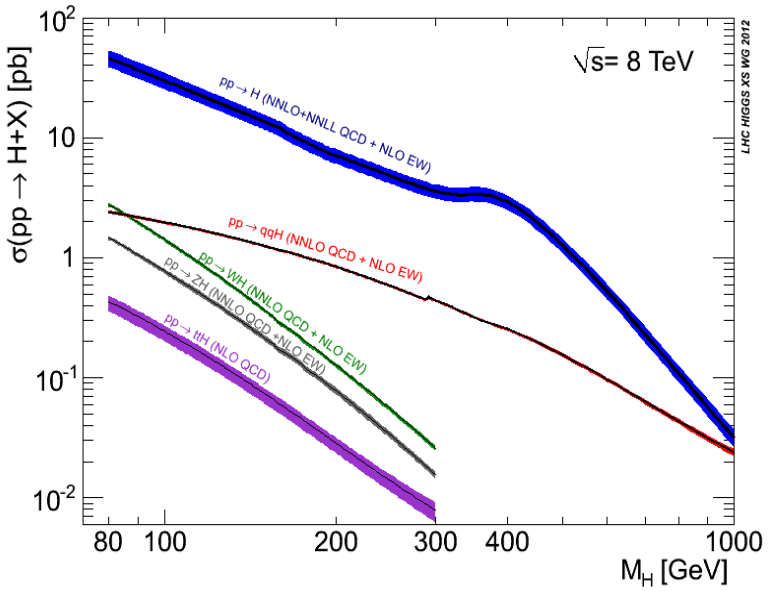
- **remarkable agreement with SM**
- **lots of data**

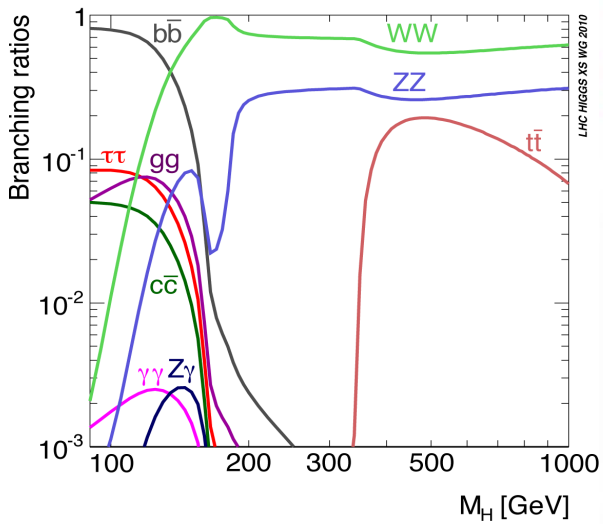
→ **ready for Higgs hunt**

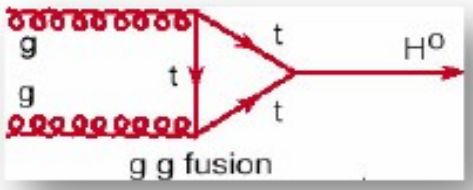
$t\bar{t}$ cross section

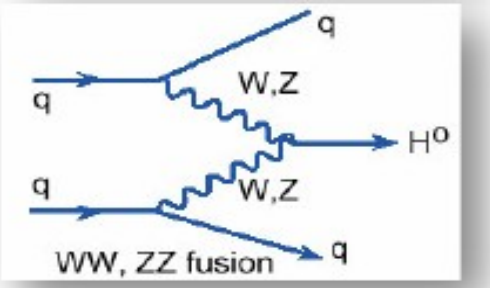


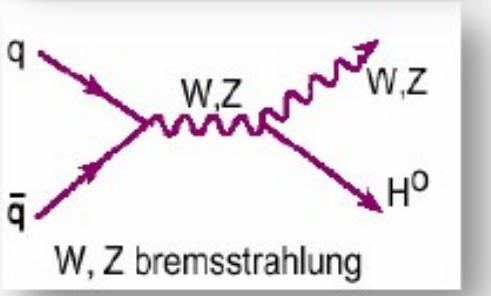
Standard Model Higgs Boson at LHC

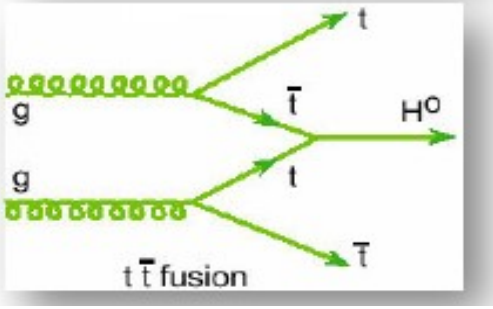






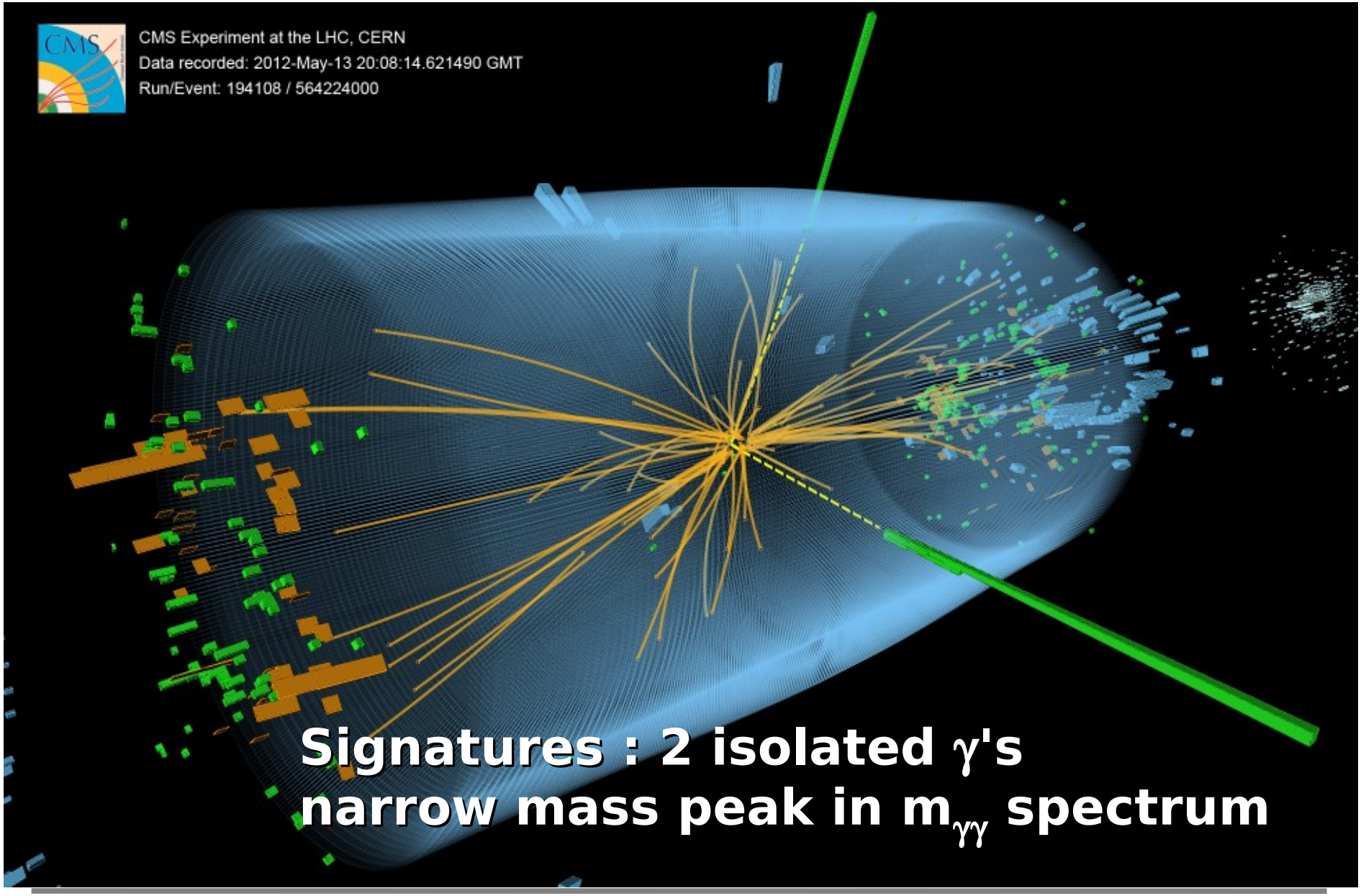






Main search channels ($m_H \leq 150$ GeV)	
qqH / gg→H	***H→γγ***
qqH / gg→H	***H→WW→2ℓ2ν***
gg→H	***H→ZZ→4ℓ***
qq→VH	***Z→ℓℓ,νν / W→ℓν / H→bb***
ttH	***H → bb***
qqH / VH / gg→H	***H→ττ***

$H \rightarrow \gamma\gamma$



Di-jet Tag (VBF Event Category)

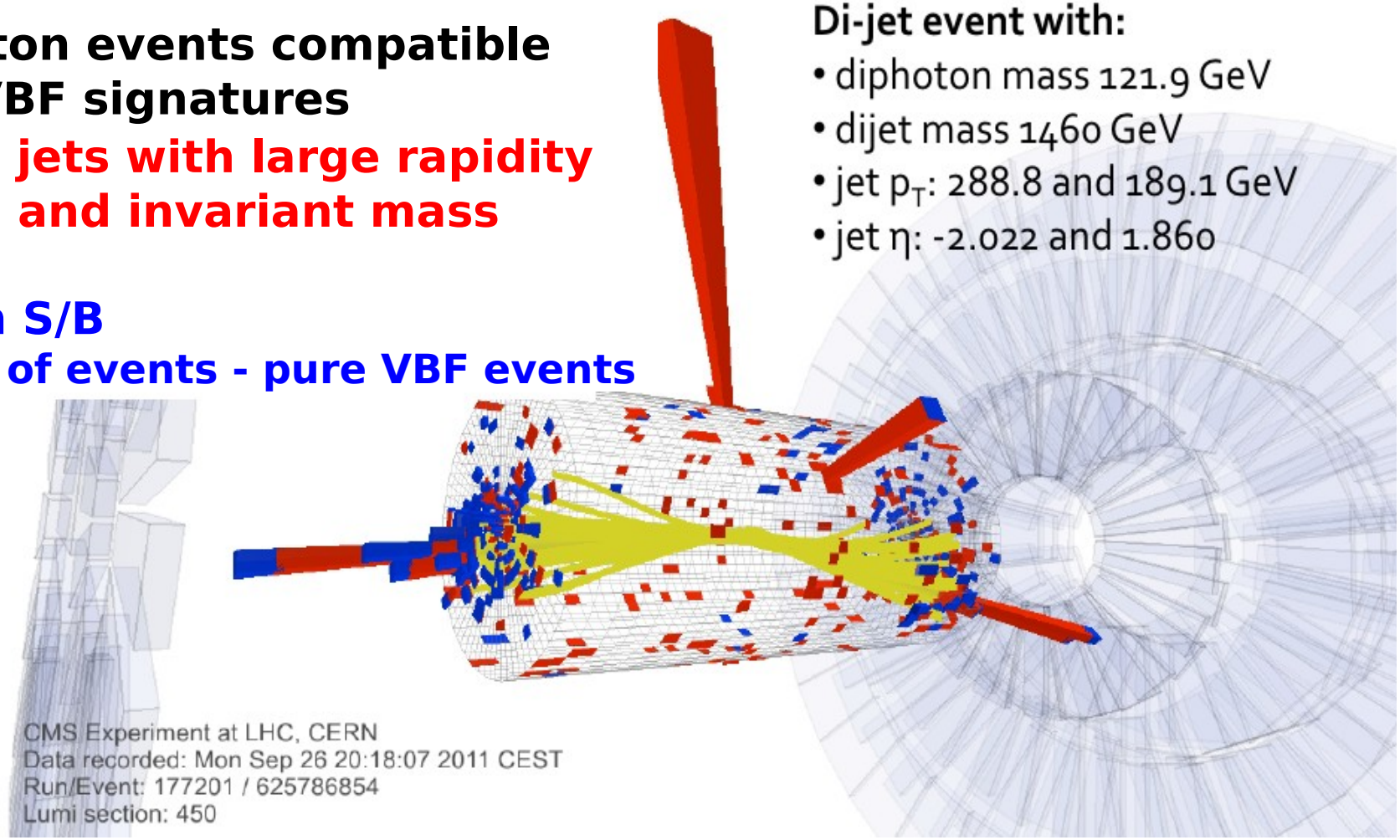
Exclusive di-jet category

diphoton events compatible with VBF signatures

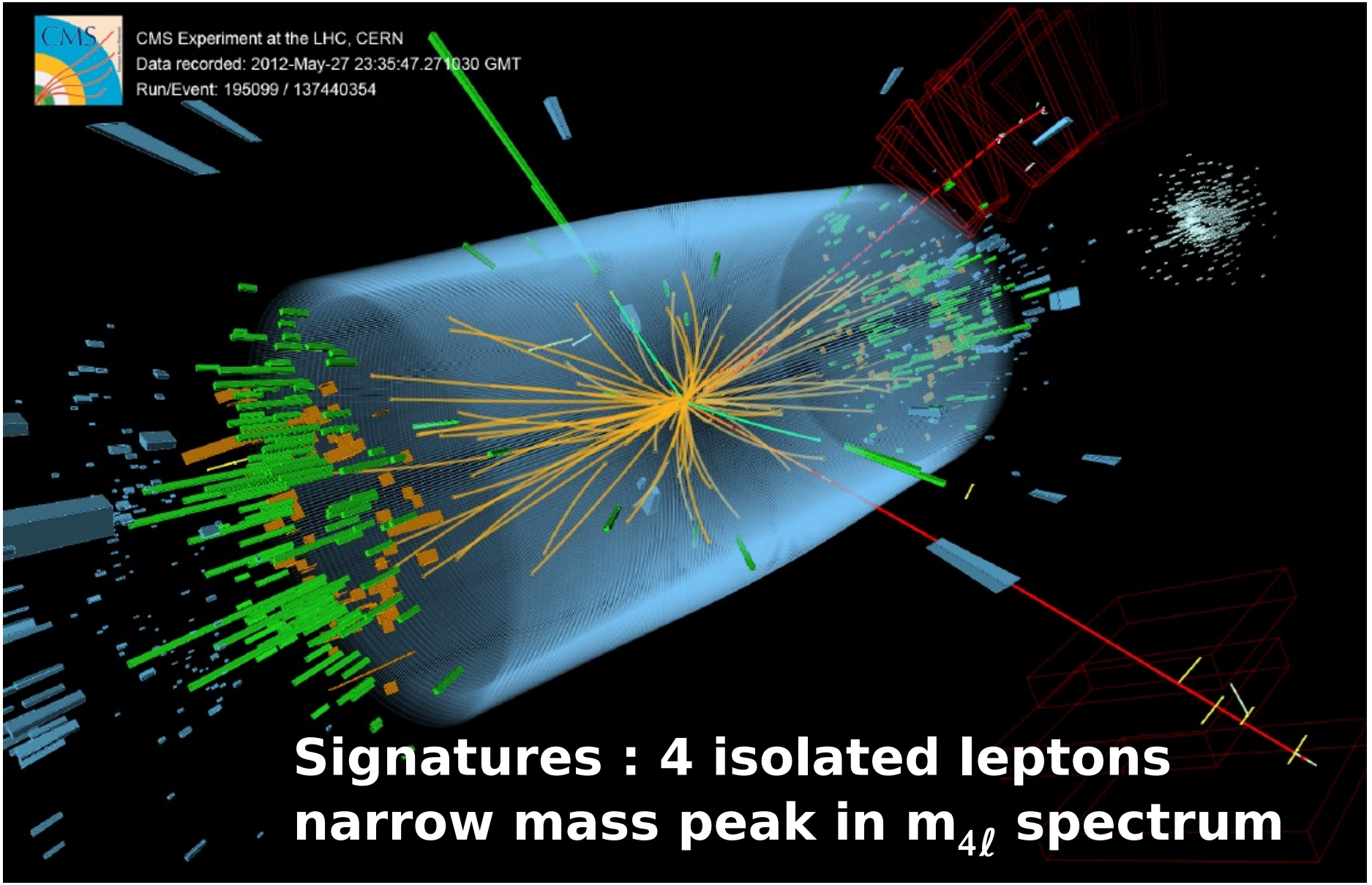
two jets with large rapidity gap and invariant mass

→ high S/B

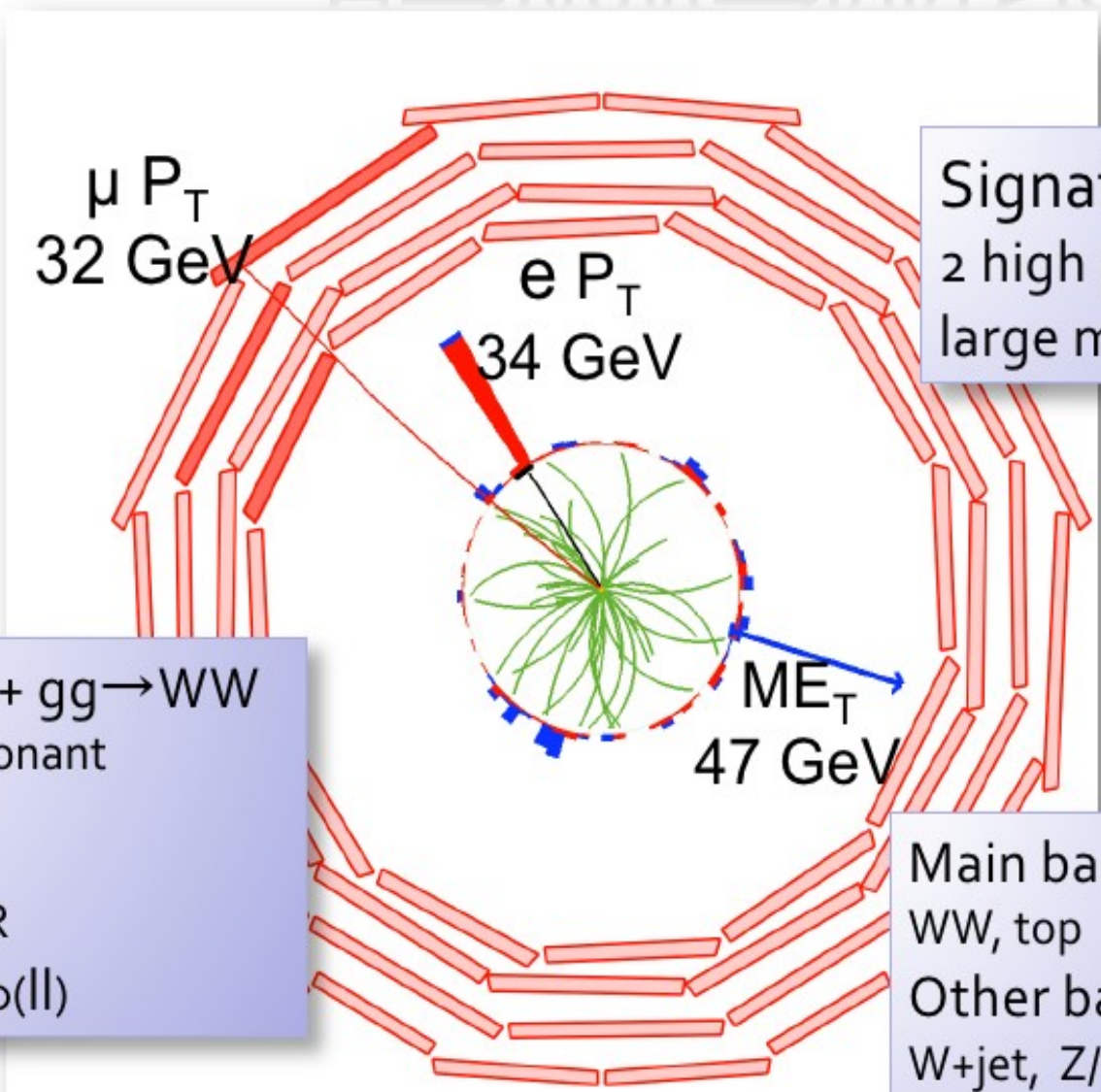
80% of events - pure VBF events



$H \rightarrow ZZ \rightarrow 4\ell$



H→WW→2ℓ2ν



Signature:
2 high p_T leptons
large missing E_T

qq→WW + gg→WW
- Non-resonant

H→WW
- Large BR
- Small Δϕ(ll)

Main backgrounds:
WW, top
Other backgrounds:
W+jet, Z/γ*, WZ, ZZ, Wγ

H → ττ Final States

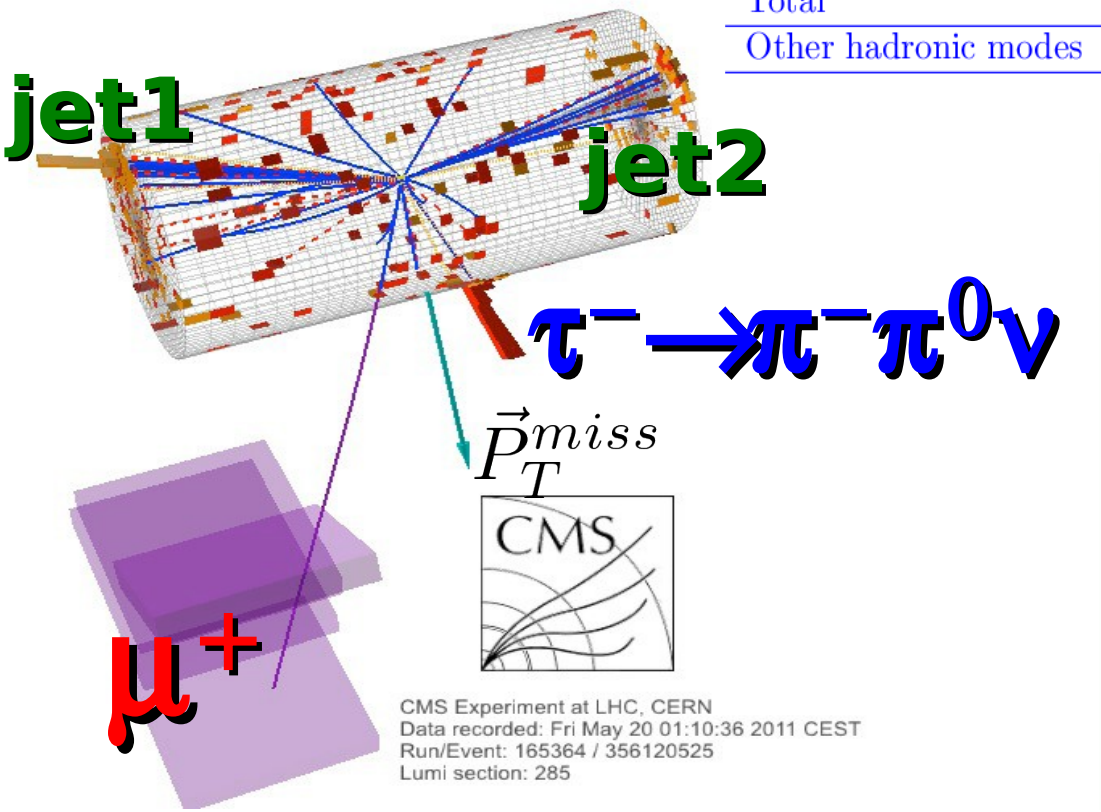
Leptonic tau decays

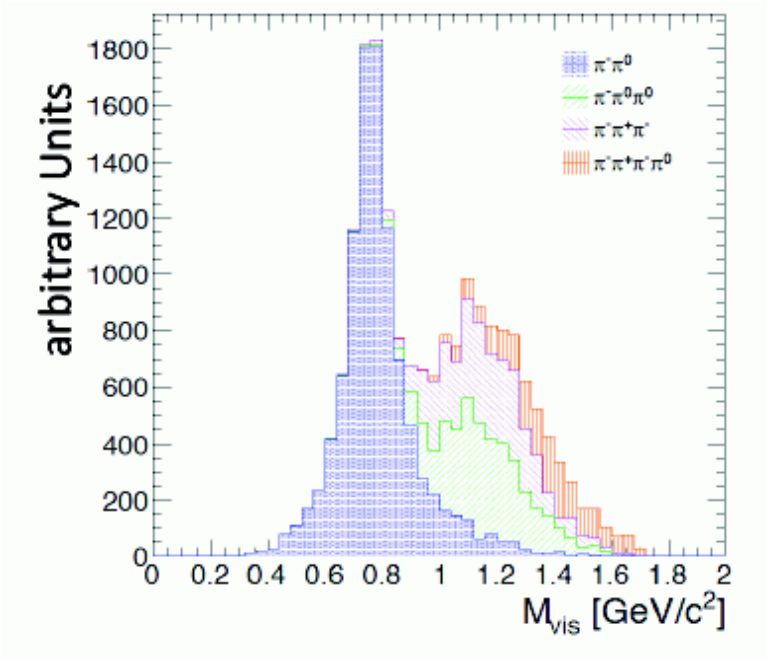
$$\tau \to e\nu_e\bar{\nu}_\tau \;:\; 17\%$$

$$\tau \to \mu\nu_\mu\bar{\nu}_\tau \;:\; 17\%$$

semi-hadronic tau decays

Decay mode	Resonance	Mass [MeV/c^2]	Branching ratio
$\tau^- \to \pi^-\nu_\tau$	-	135	10.9%
$\tau^- \to \pi^-\pi^0\nu_\tau$	ρ	770	25.5%
$\tau^- \to \pi^-\pi^0\pi^0\nu_\tau$	a_1	1200	10.8%
$\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$	a_1	1200	9.8%
$\tau^- \to \pi^-\pi^+\pi^-\pi^0\nu_\tau$	a_1	1200	4.5%
Total			59.2%
Other hadronic modes			5.6%

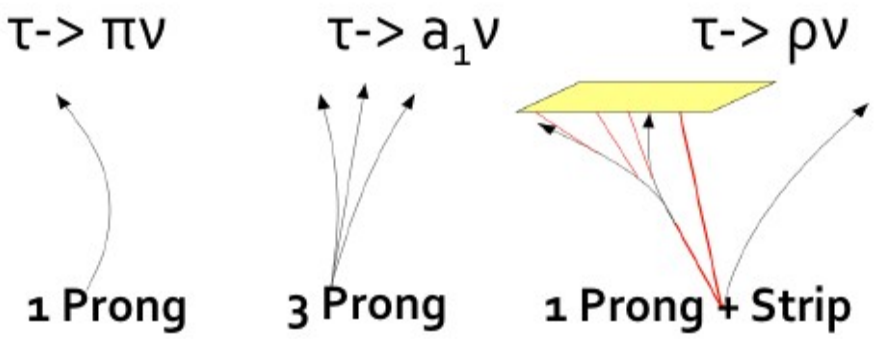




Tau Lepton Identification in CMS

Tau Identification

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

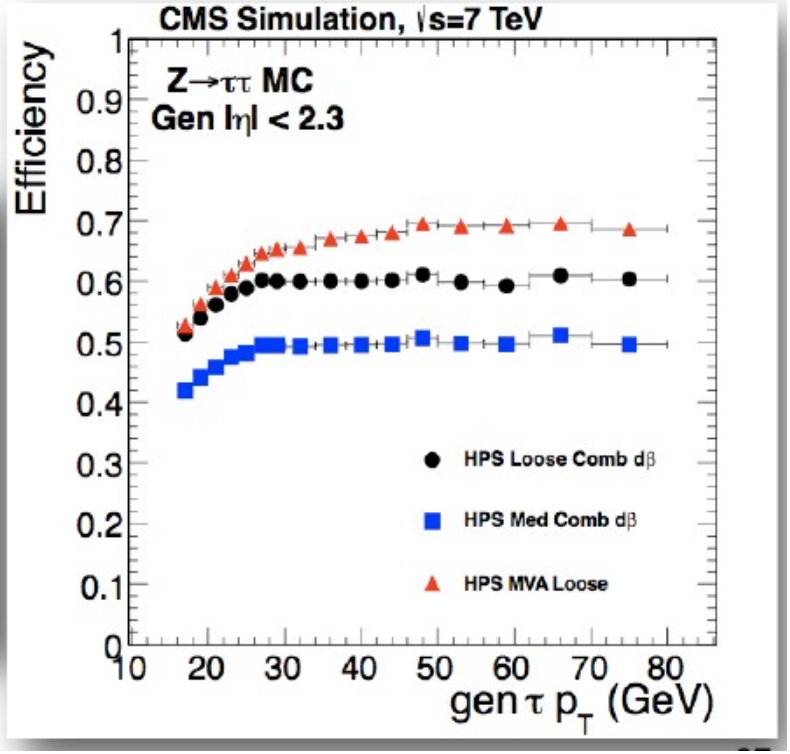


Tau isolation based on MVA approach

→ absolute energy sum in ΔR rings

Efficiency > 60%

for a tau fake rate of 6%



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

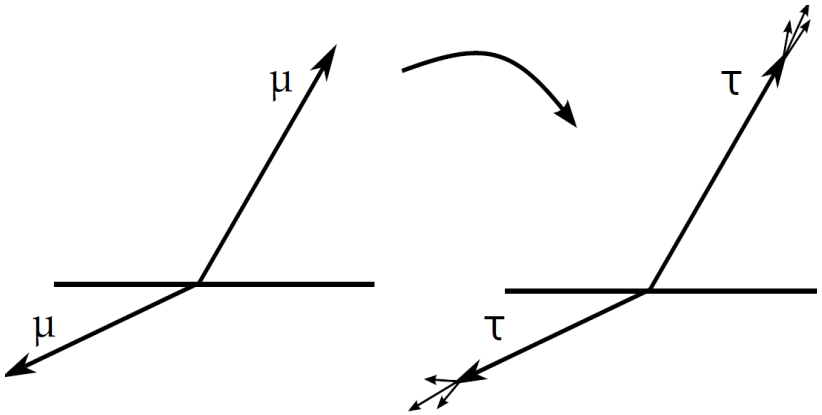
event environment taken from real event

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

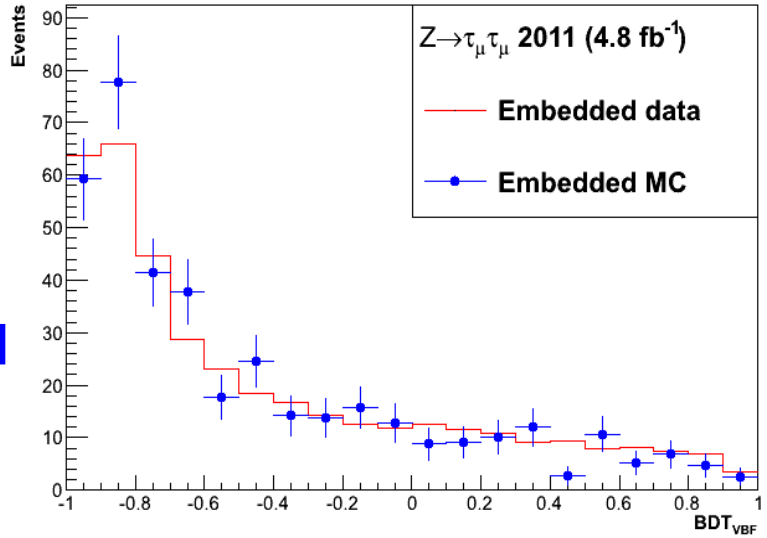
→ reduced systematic effects

technique is know as tau embedding

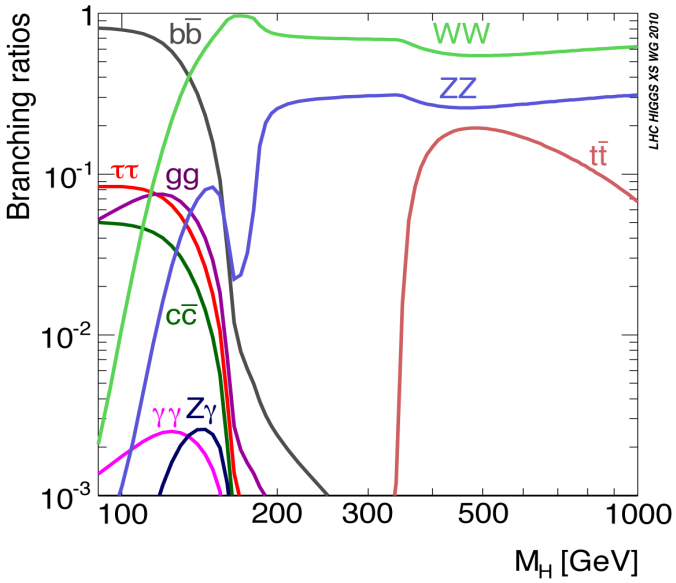
- **tools developed and maintained by** Karlsruher Institut für Technologie **and** DESY

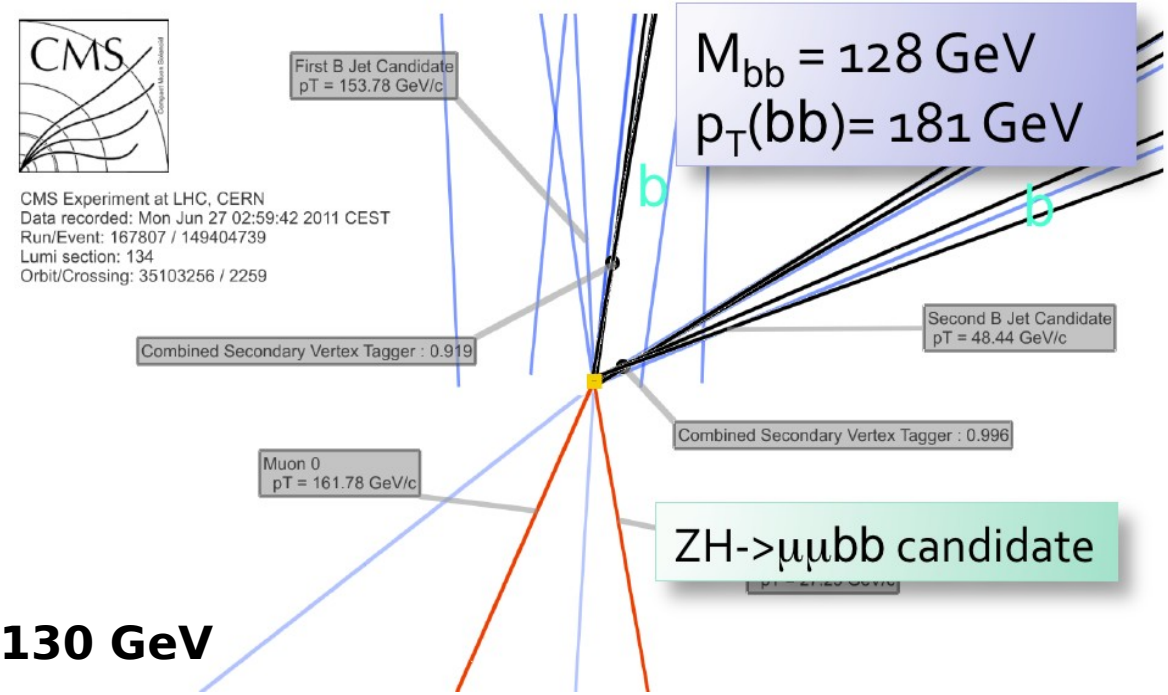


Validation of VBF MVA performance with embedding

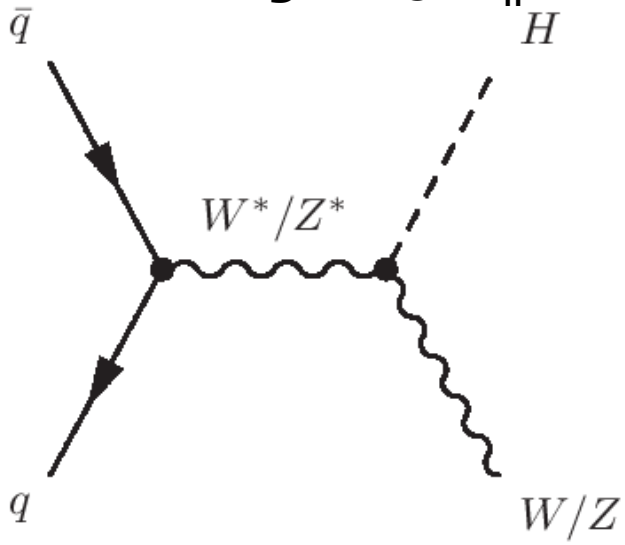


VH, H → bb Search





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



inclusive search impossible due to overwhelming QCD background

→ exploit VH production

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

General Search Strategy

- Selection of events compatible with signal signatures
  - Cut based approach
    - Robust (less prone to systematic effects)
    - less performant than multi-variate approach
  - Multi-variate approach
    - Prone to systematics (correlations between variables)
    - more performant than cut based approach
- Evaluation of backgrounds in the selected sample
  - Monte Carlo simulation (shapes)
  - normalization from side-bands (background enriched samples)
  - Shapes from data
- Construction of signal model
  - From Monte Carlo simulation
- Choice of discriminating object
  - 1D distribution of reconstructed mass
  - 2D distribution (mass vs. signal discriminant)

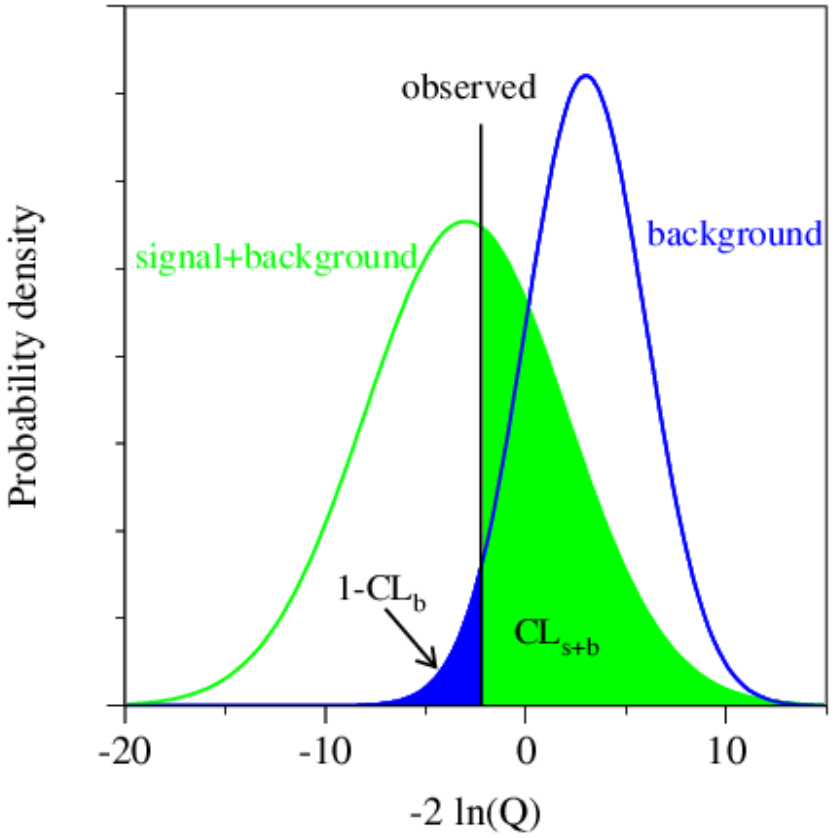
Statistical Analysis

- **Array of analysis bins combines information from all bins from all channels**
- **bin : signal expectation, background expectation, observed data → construction of likelihood**
- **systematic uncertainties are incorporated through nuisance parameters θ (vector of systematic errors)**
- **Statistical analysis using profiled likelihood**

$$-2ln(Q) = \frac{\mathcal{L}(data|\mu, \hat{\theta}_\mu)}{\mathcal{L}(data|\hat{\mu}, \hat{\theta})}$$

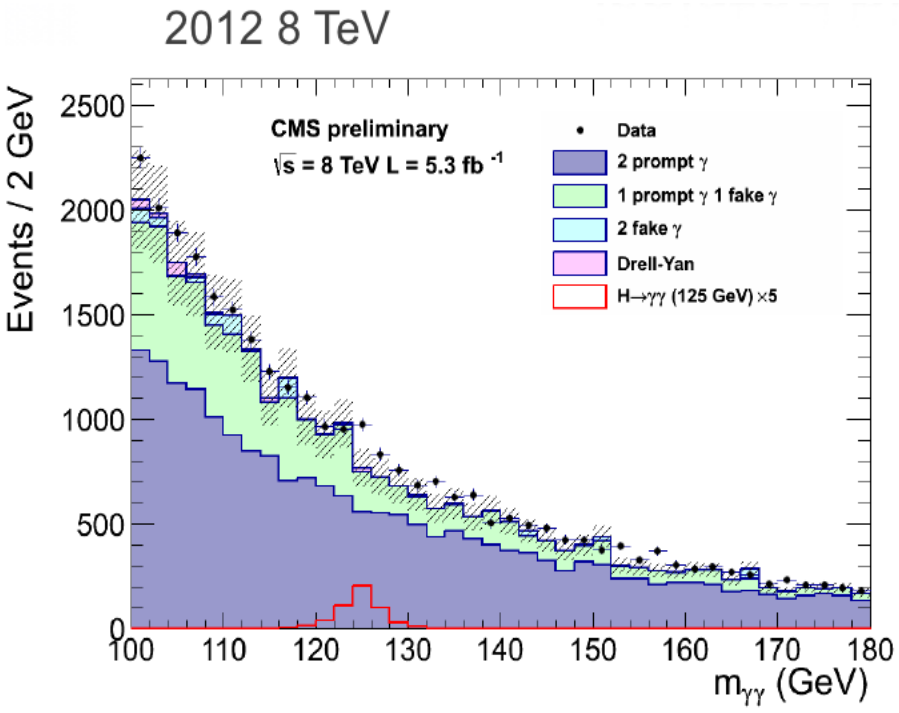
- **Toy experiments → two statistical ensembles**
- **background only**
- **signal+background**
- **Confidence levels**

→ statistical inference



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**



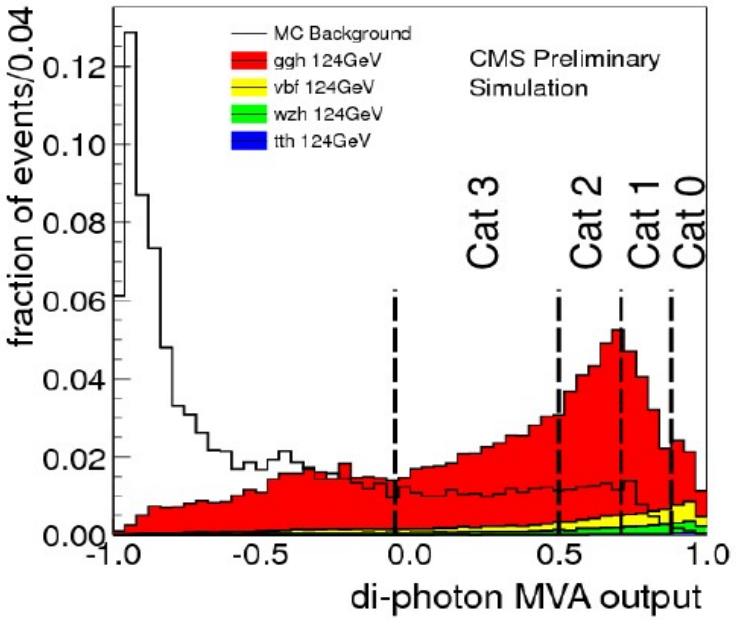
possible bias studied with various smooth functions, modeling background shape

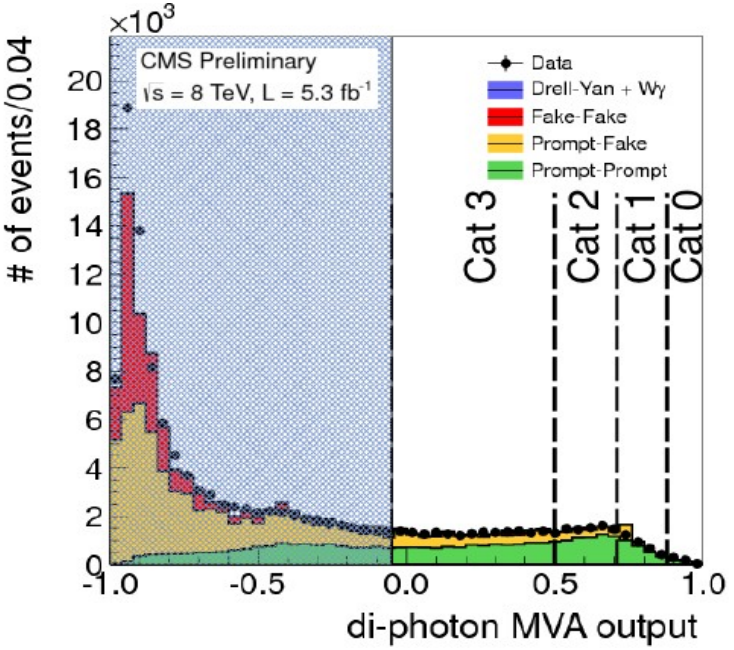
bias due to presence of possible signal < 20% of stat. error of fit

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

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**





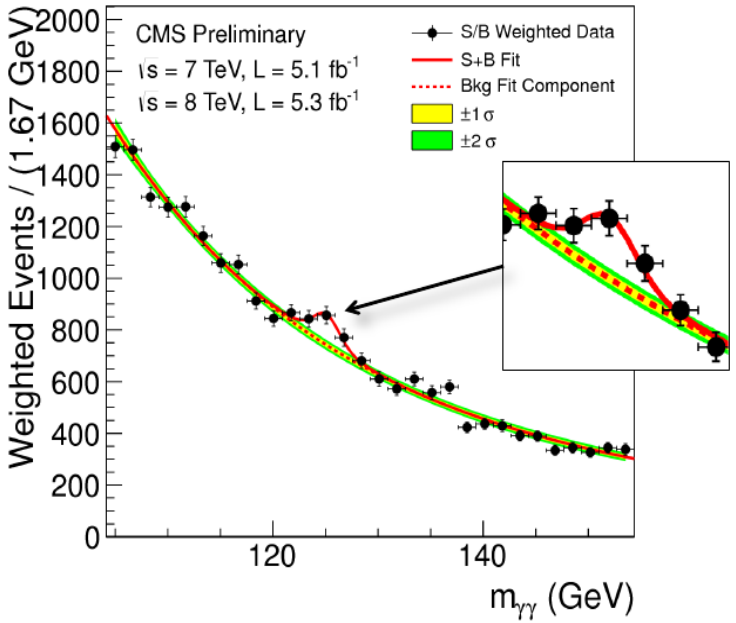
- **Exclusive di-jet categories : events compatible with VBF signatures**
  - **two jets with large rapidity gap and invariant mass**

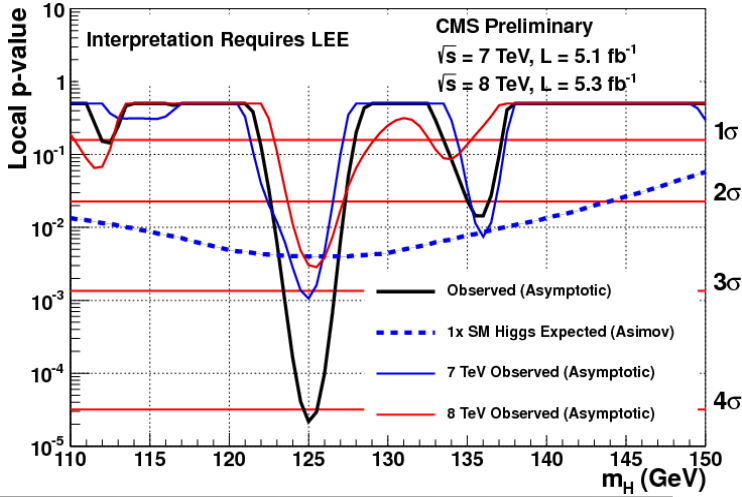
    → S/B enhancement (80% of events are pure VBF events)

H → γγ Search

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

S/B-weighted sum





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→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

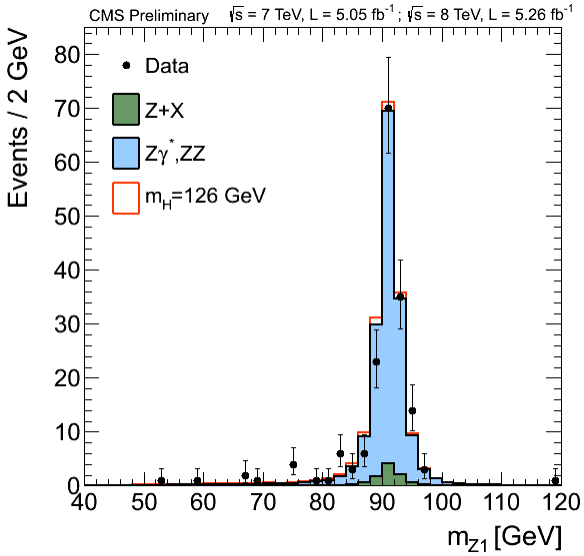
minimal lepton p_T = 5 GeV (μ), 7 GeV (e)

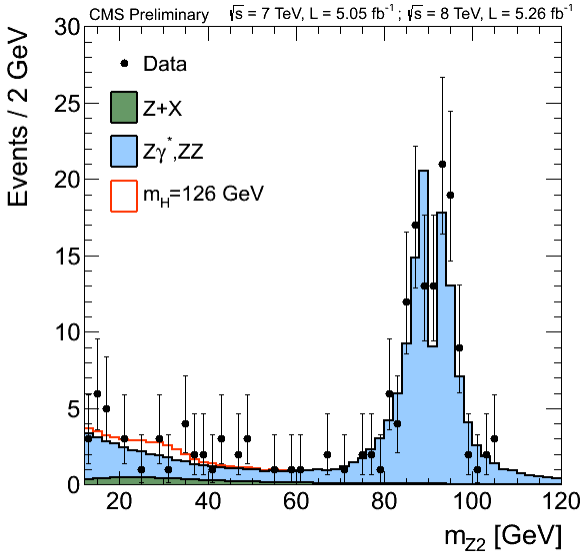
at least one lepton with p_T > 20 GeV

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**

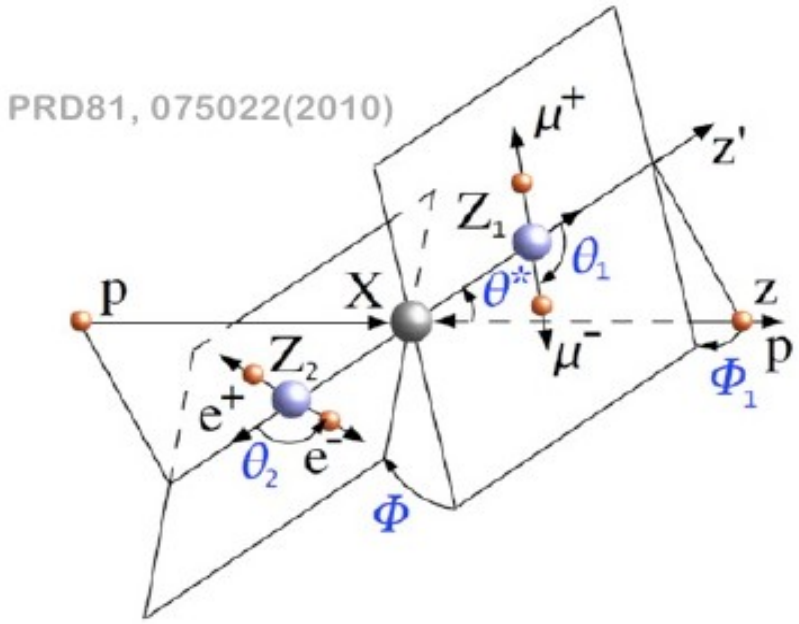
Matrix Element Likelihood Analysis

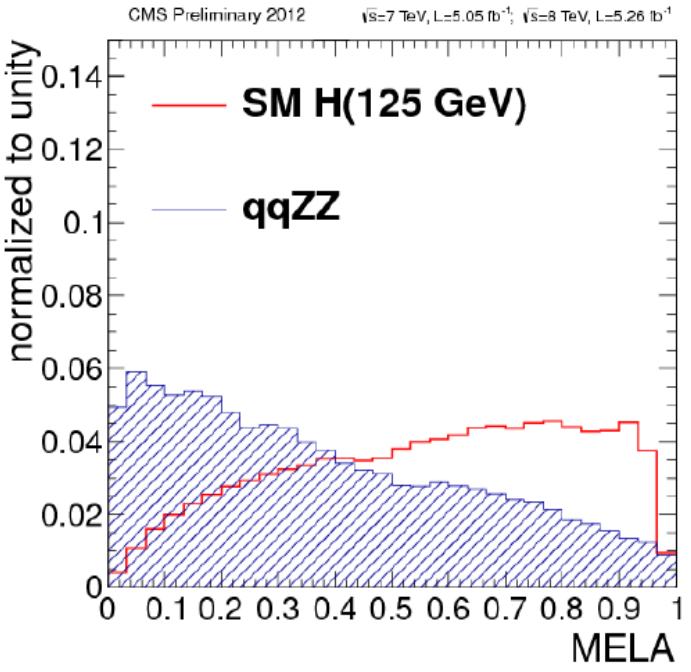
dynamics of decay described fully by 2 masses and 5 angles

Matrix Element Likelihood Analysis

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

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

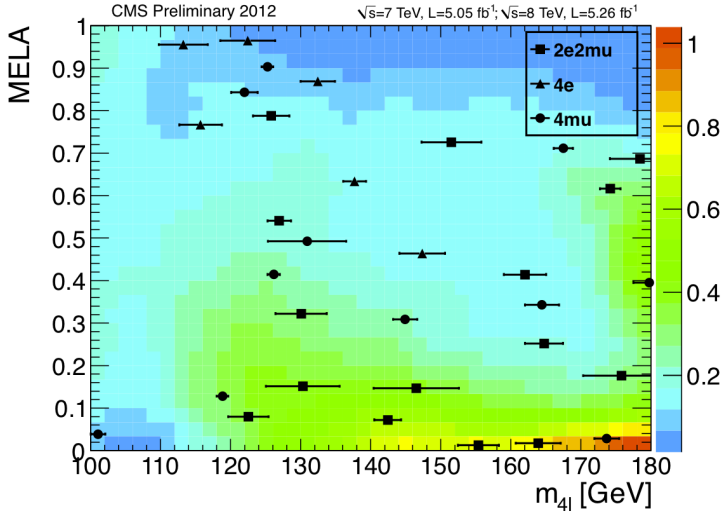


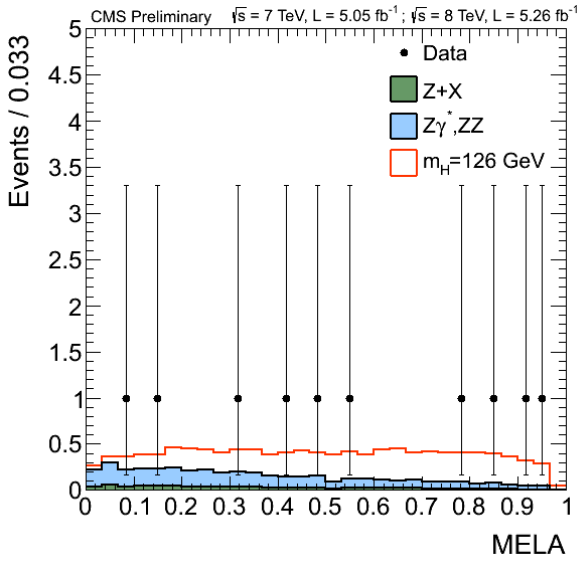


Statistical Analysis in Z → ZZ* → 4 Channel

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

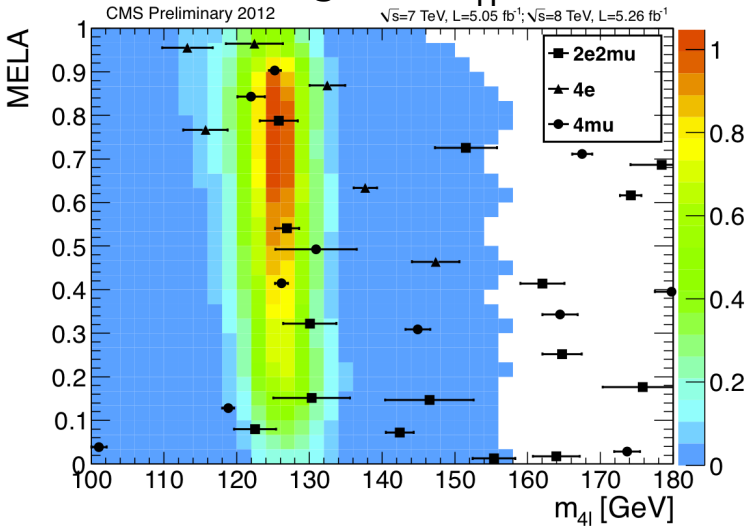
data vs. background

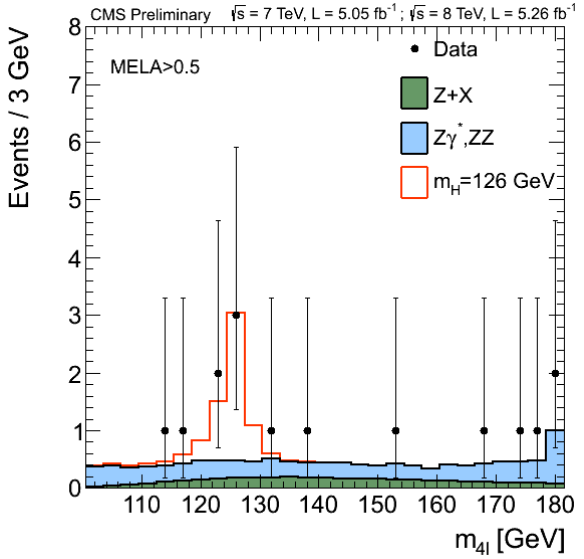




for illustration:
MELA projection in
m_{4l} 121–131 GeV

data vs. signal (m_H=126GeV)



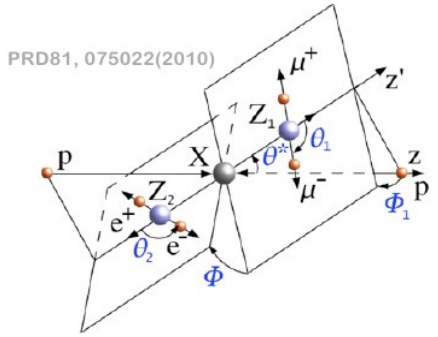


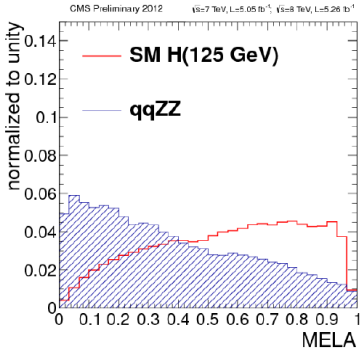
for illustration:
m_{4l} distribution
for MELA > 0.5

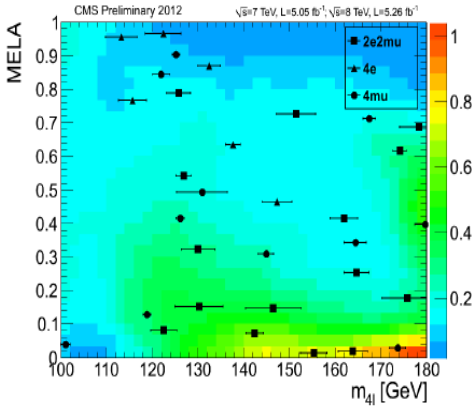
Results of H → ZZ → 4ℓ Search

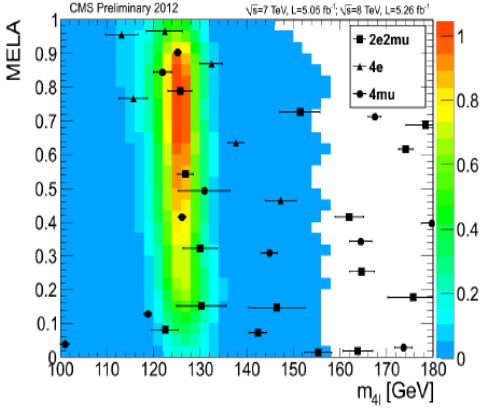
statistical inference performed with 2D distribution [MELA, m_{4l}]

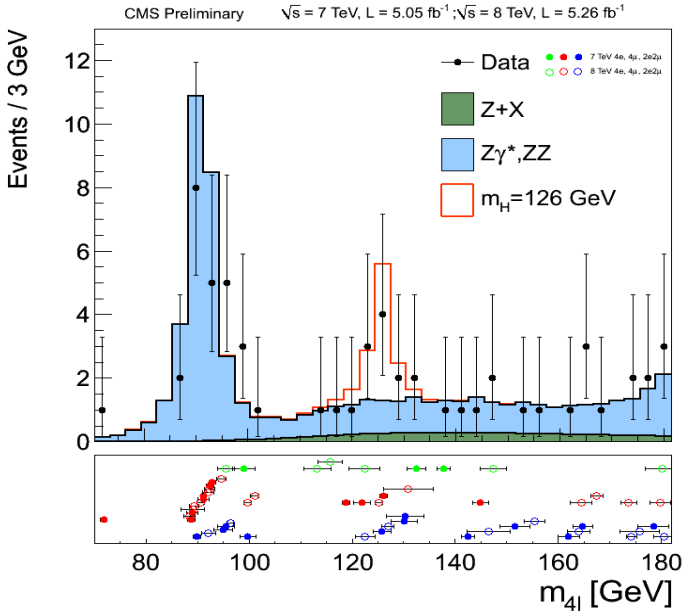
Matrix Element Likelihood Analysis

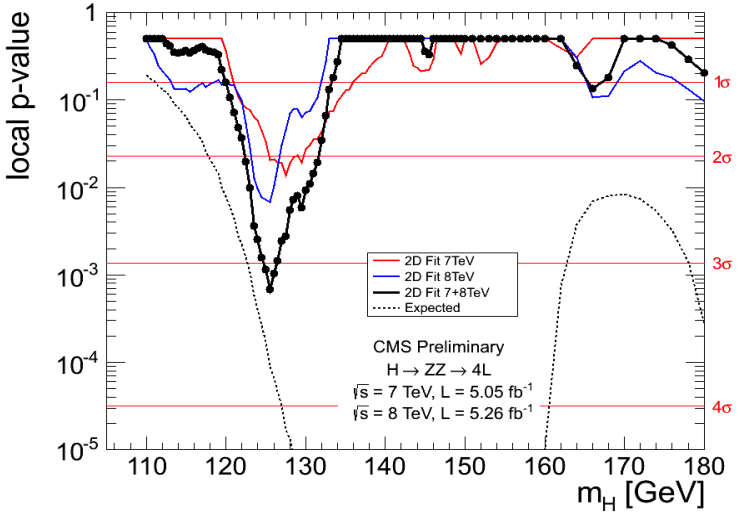












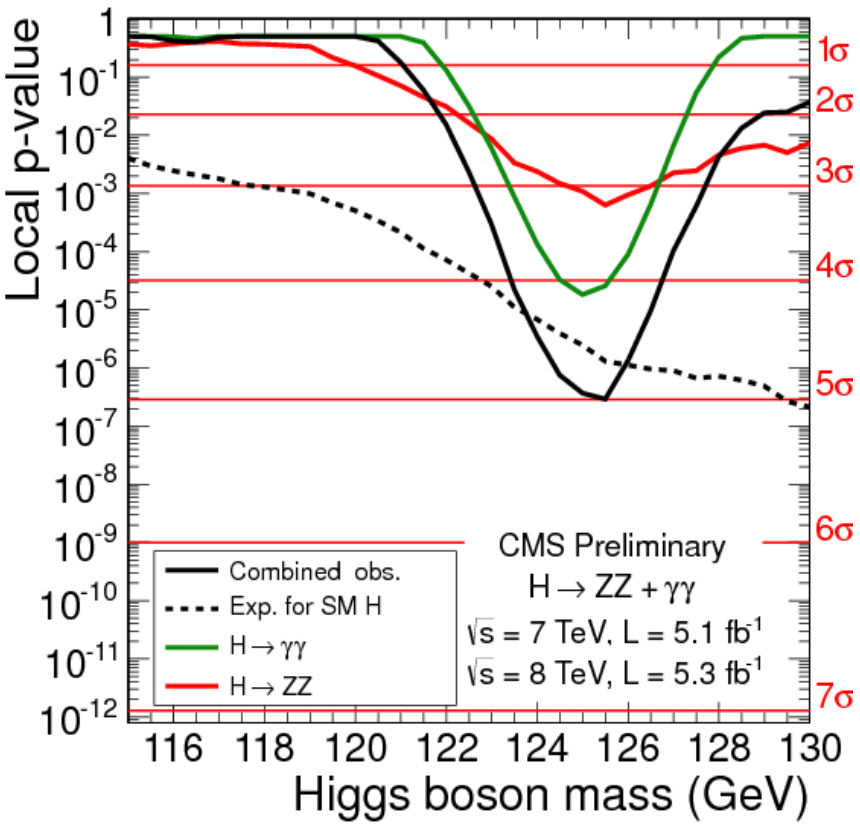
Lowest p-value at $m_H \approx 125.5$ GeV

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
  $m_X \approx 125$ 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 → 2ℓ + 2ν Channel

Signatures

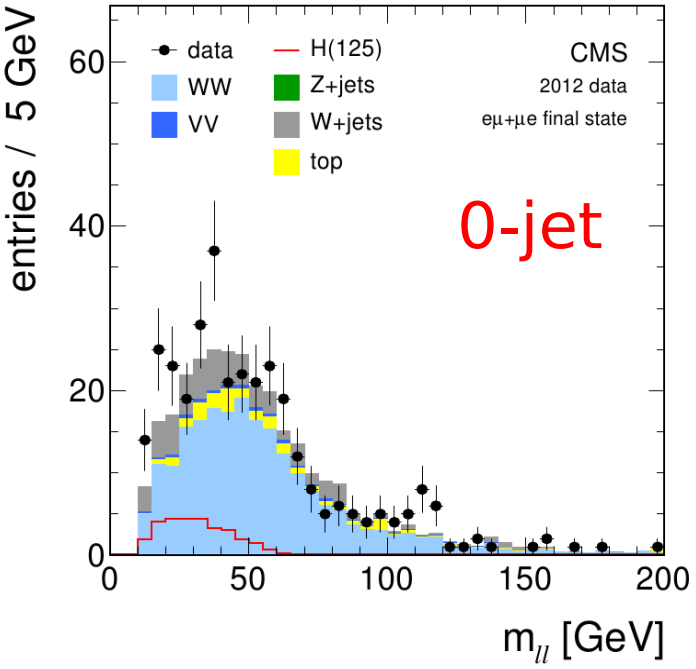
→ 2 hight p_T isolated leptons (μμ, ee, eμ)

→ large missing E_T

→ small $\Delta\varphi(\ell\ell)$

Main backgrounds

WW, top, W+jets, Z+jets, WZ



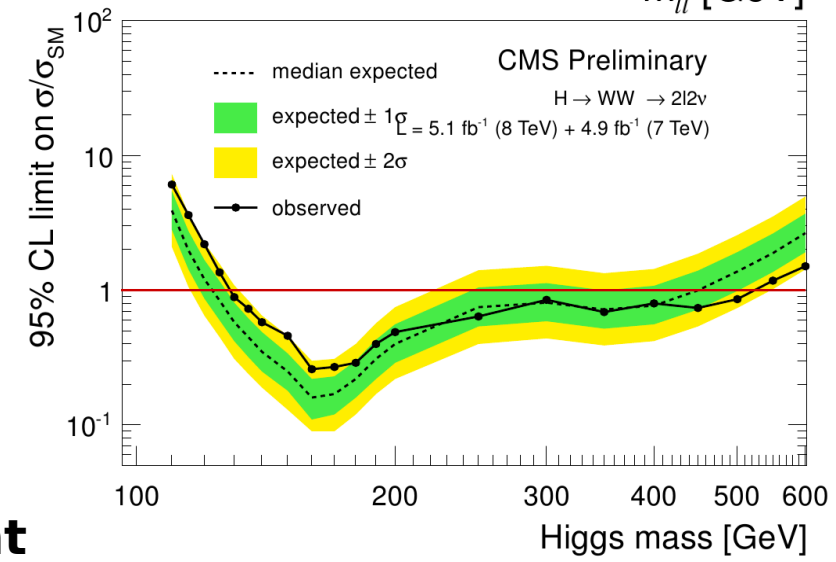
Search strategy

cut based selection exploiting lepton kinematics;

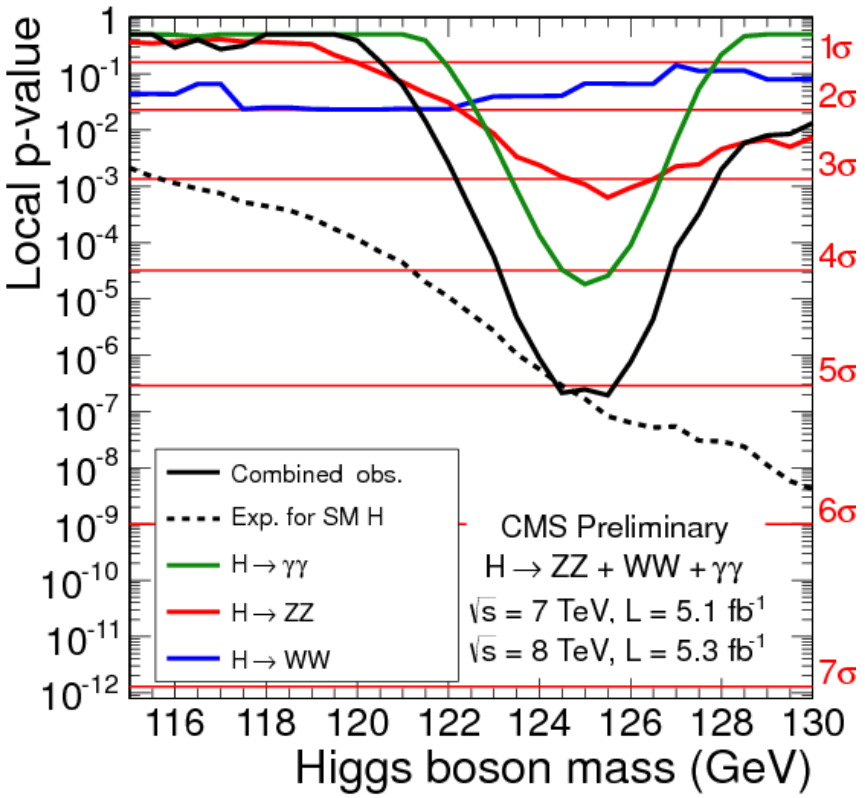
event categorization based on jet multiplicity

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

Dilepton mass as final discriminant



Combining H → γγ, ZZ and WW Channels



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

  γγ + ZZ → 4ℓ

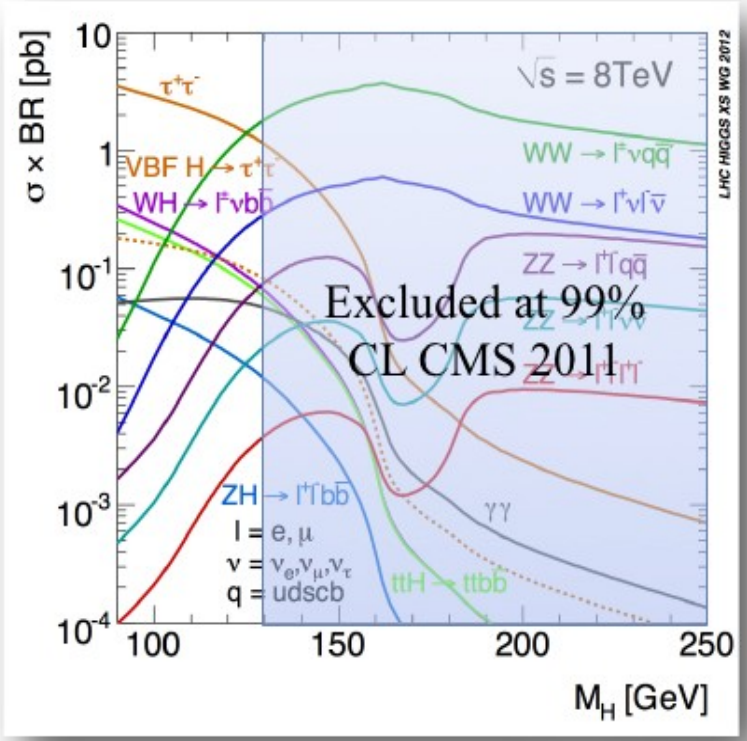
  and high sensitivity, but low mass resolution channel

  WW → 2ℓ2ν

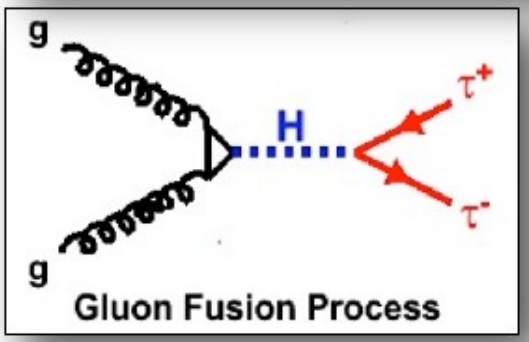
- **Combined significance : 5.1σ**

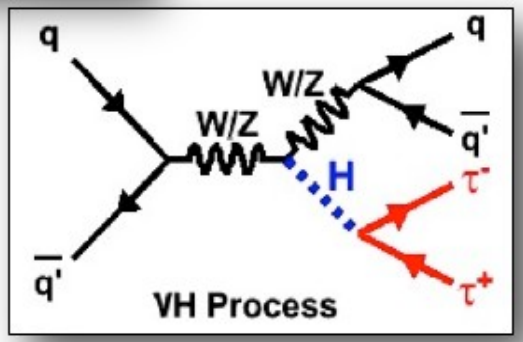
- **Expected significance for SM Higgs boson : 5.2σ**

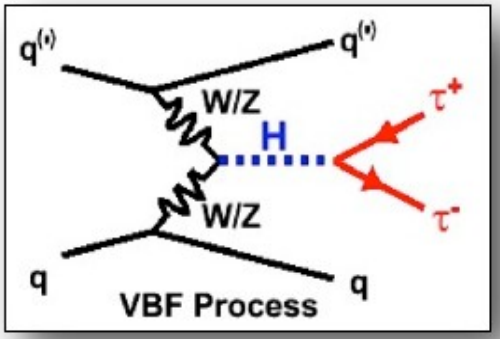
H → ττ Search : Introduction



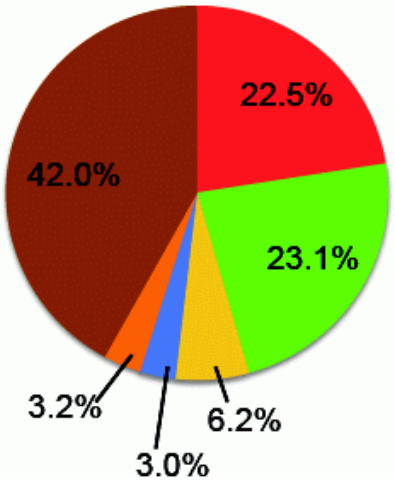
- Large σ × Br at low mass
- The most sensitive among fermionic decay channels
- Sensitive to all production mechanisms
- Direct probe of Higgs boson couplings to leptons







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 KIT Karlsruher Institut für Technologie

Jets p_T > 30 GeV

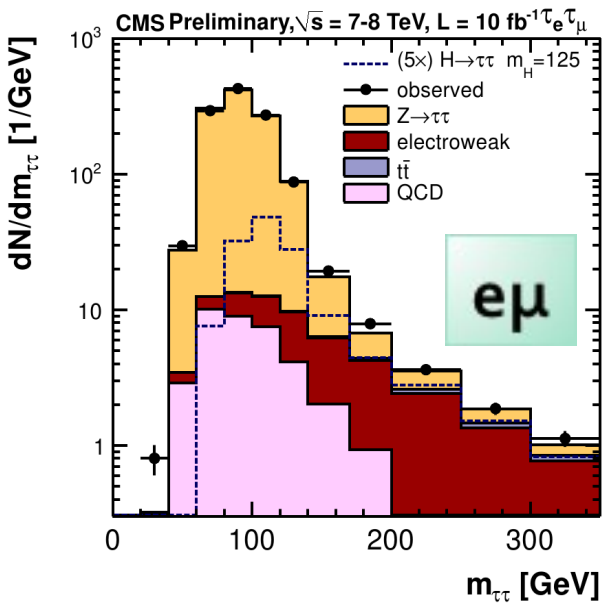
τ_h or μ p_T^1

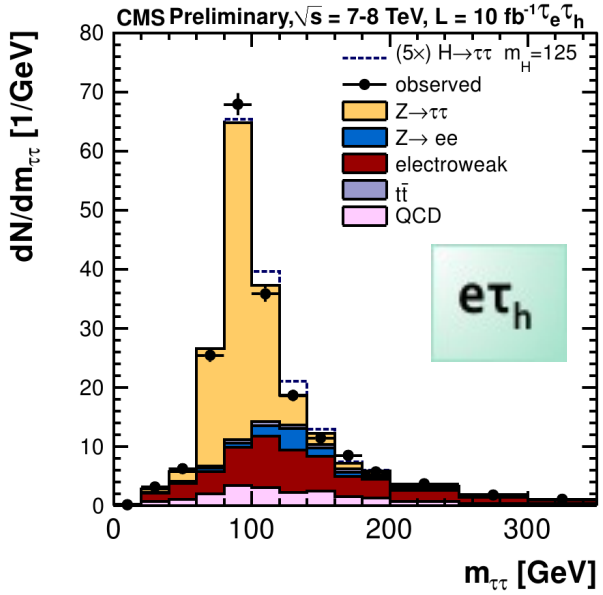
0 Jet, Low p_T High background	**1 Jet, Low p_T** Enhancement from jet requirement
0 Jet, High pT Lepton p_T spectrum harder from H	**1 Jet, High p_T** Enhancement from p_T and jet requirement

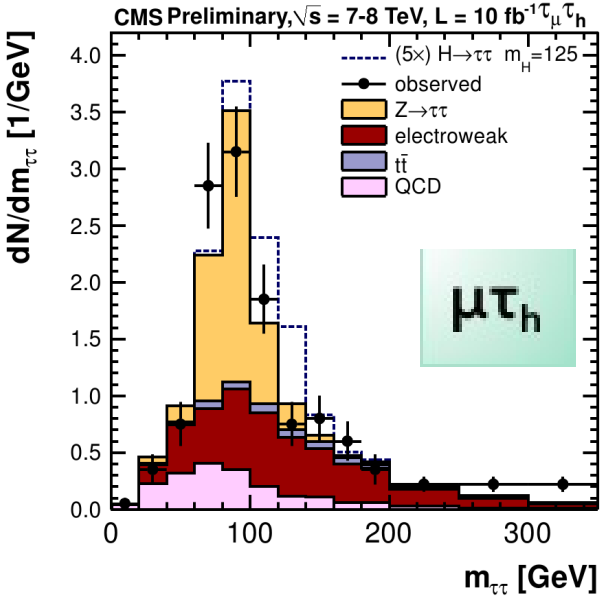
VBF
2 jets, no jets in rapidity gap
MVA based selection

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

Mass Distributions in Event Categories







0-jet category

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

1-jet category

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

VBF category

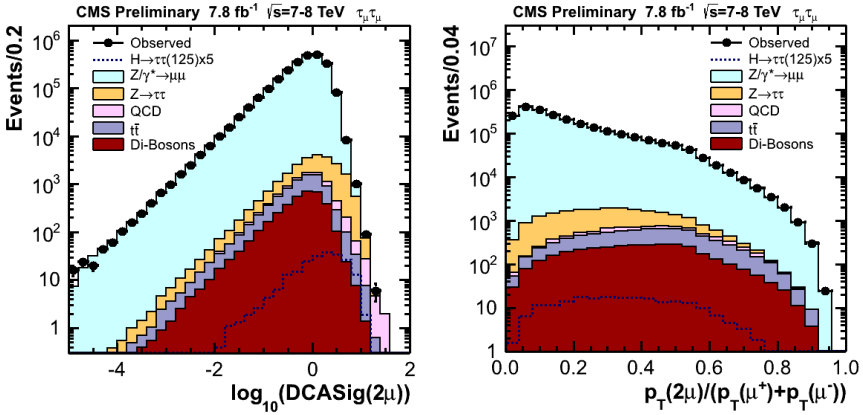
- **Clean mode**
- **Highest S/B**

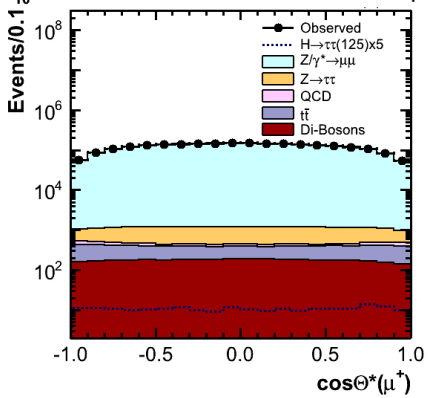
→ highest sensitivity at $m_H \leq 130$ GeV

Multi-variate Analysis

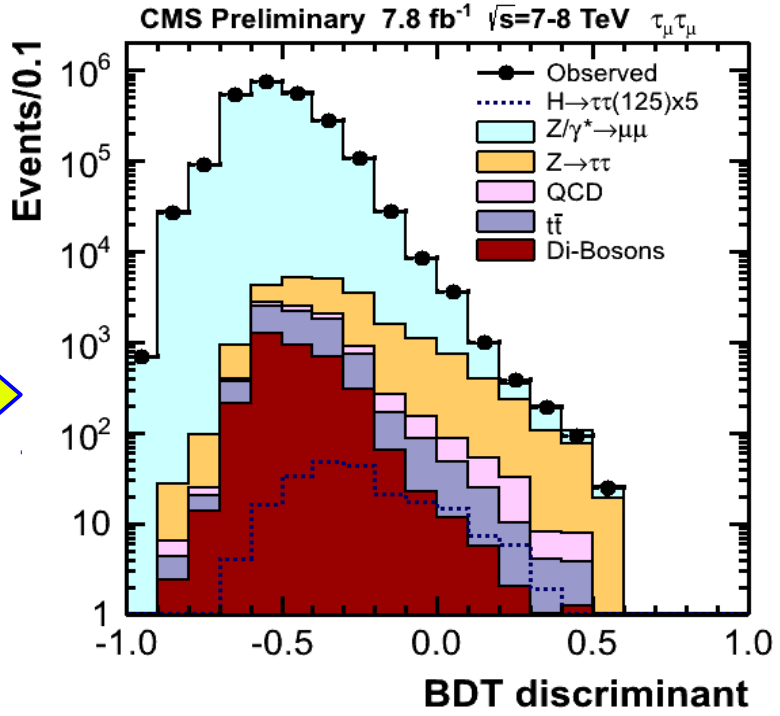
In many cases rectangular cuts are not efficient in signal against background discrimination

Multi-Variate Analysis
Optimal Combination of Discriminating Variables into one Discriminant





H → 2τ → 2μ channel



Mass Distributions in H → ττ → 2μ4ν Channel

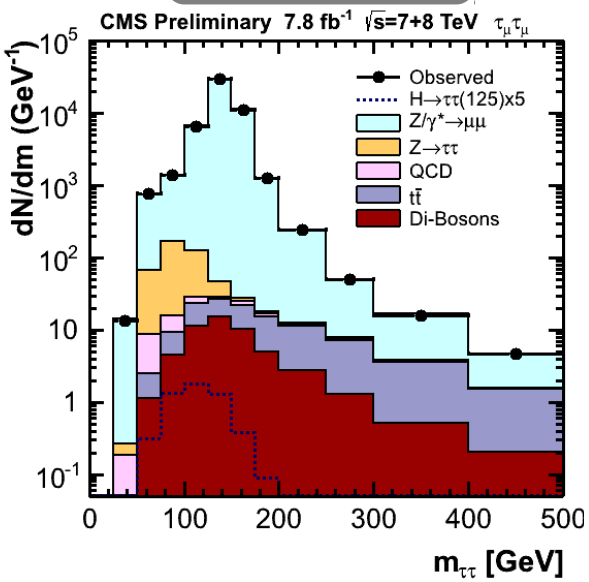
MVA(ττ) + MVA(VBF) discriminants → final selected samples

Karlsruher Institut für Technologie

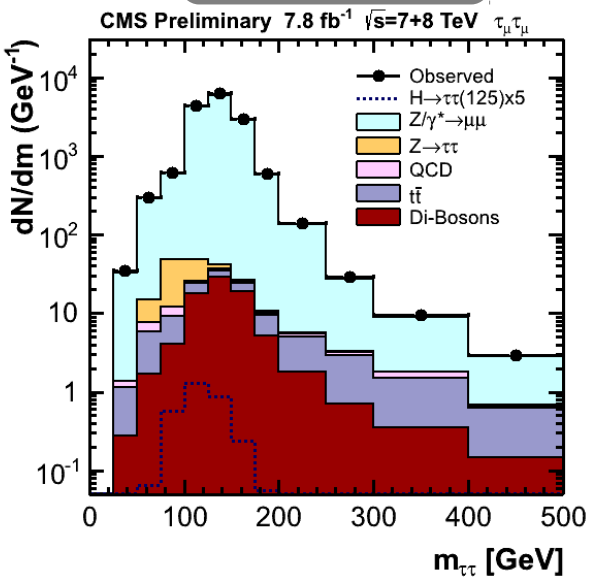
Statistical inference with 2D distributions [M(μμ) , M(ττ)]
→ sensitivity boosted by factor 1.5 – 2.0

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

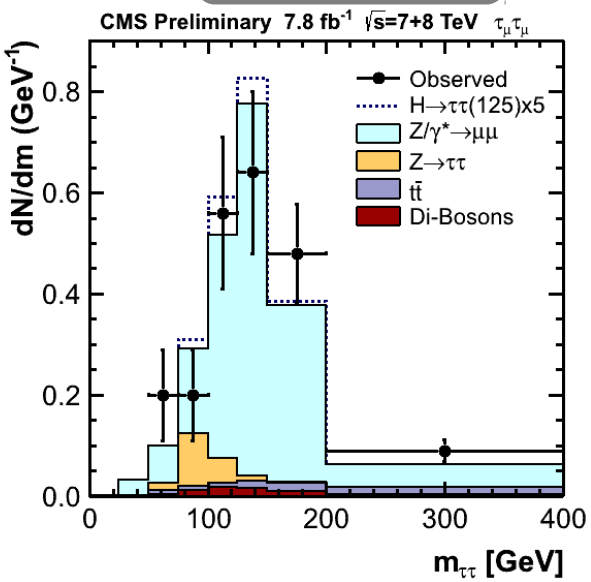
0-jet



1-jet

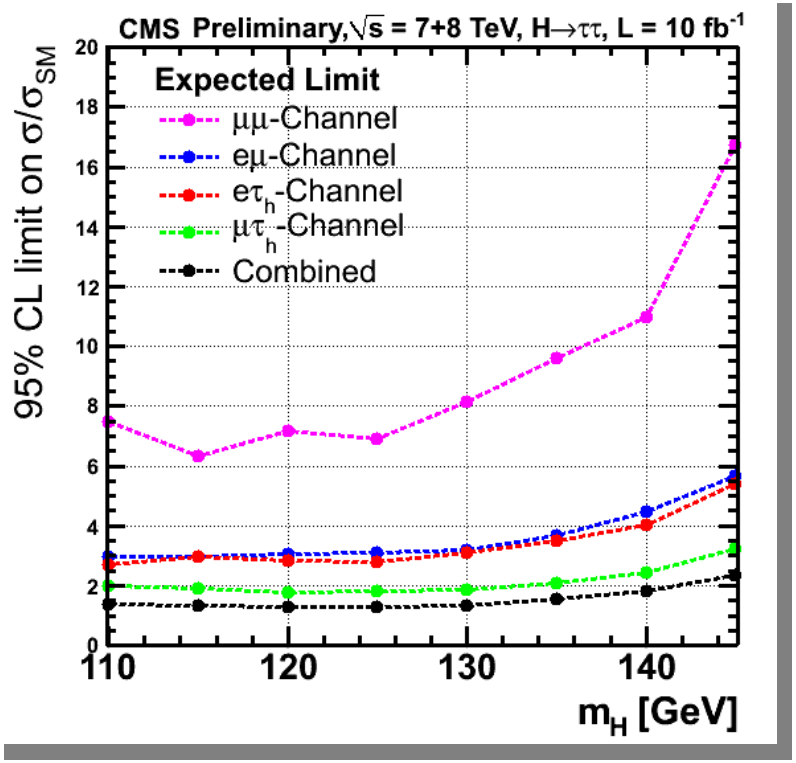


VBF

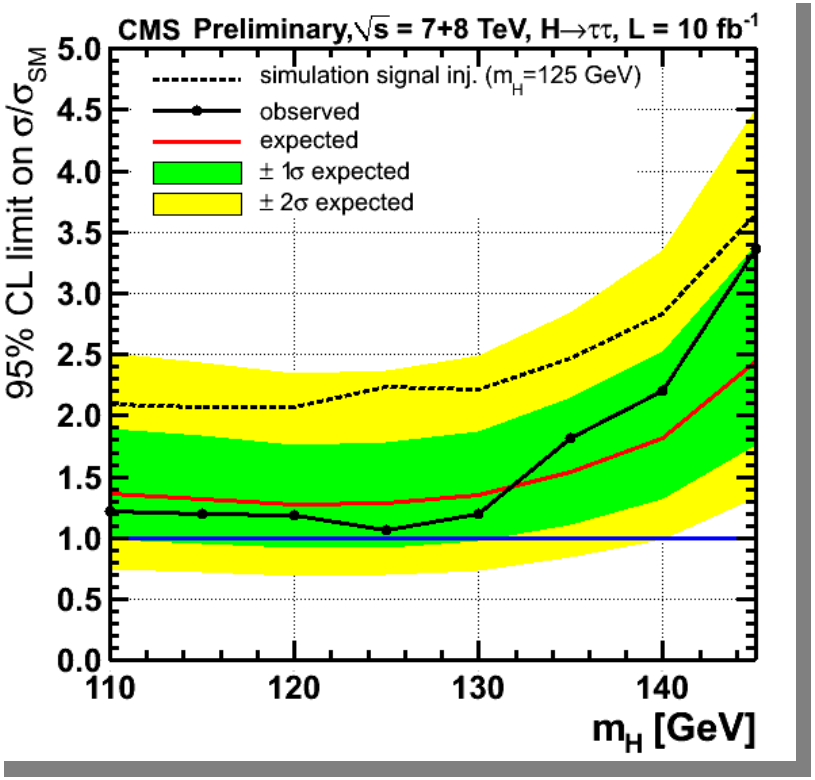


H → ττ Search Results

sensitivity / channel



combined results



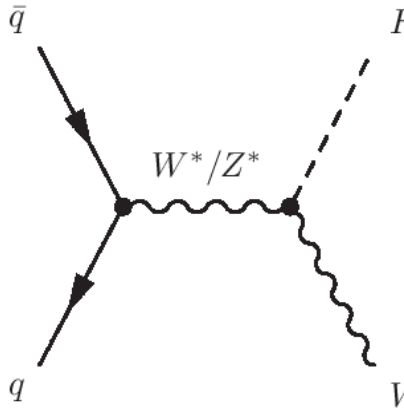
- **analysis approached sensitivity to signal**
- **no significant departure from SM background expectation**
  - ➔ **Observed exclusion : $1.06 \times \sigma_{SM}$ for $m_H = 125$ GeV**
  - ➔ **Expected exclusion at $m_H = 125$ GeV : $1.28 \times \sigma_{SM}$**

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

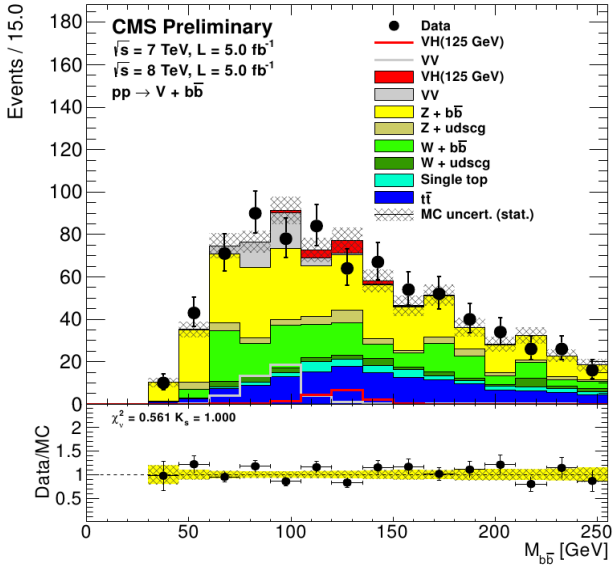


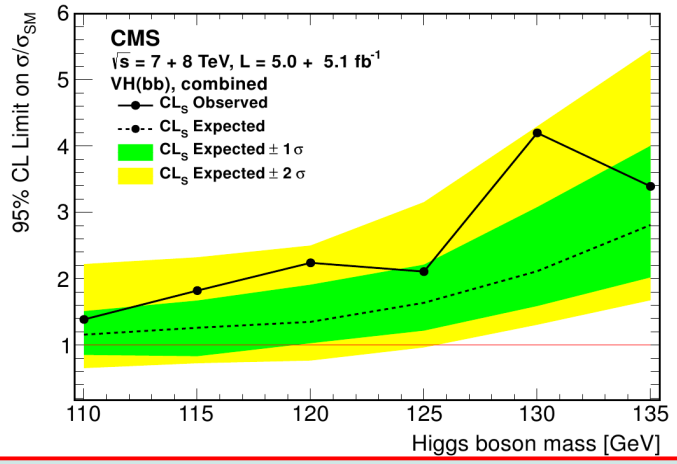
$$Z \to ee, \mu\mu, \nu\nu$$
$$W \to e\nu, \mu\nu$$
$$H \to b\bar{b}$$

MVA shape analysis

MVA combines

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

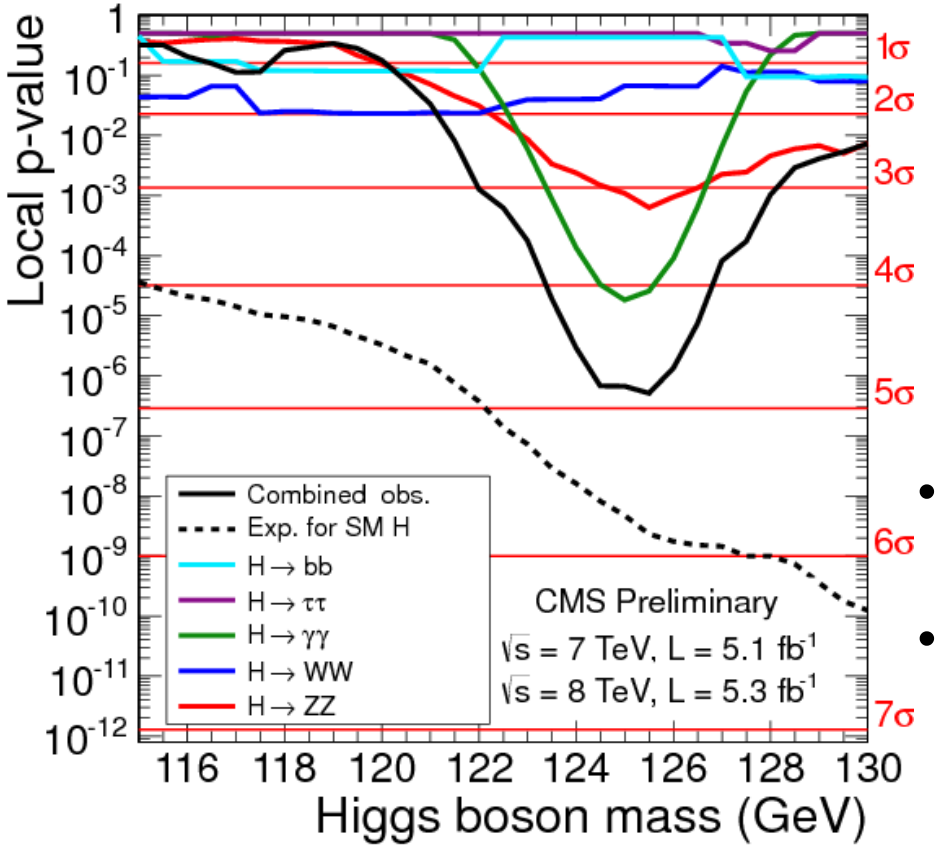




results of analysis compatible with either background or signal from m_H = 125 GeV

→ more data needed

Combining Bosonic and Fermionic Channels



- **Combining bosonic modes**

  γγ + ZZ → 4ℓ + WW → 2ℓ2ν

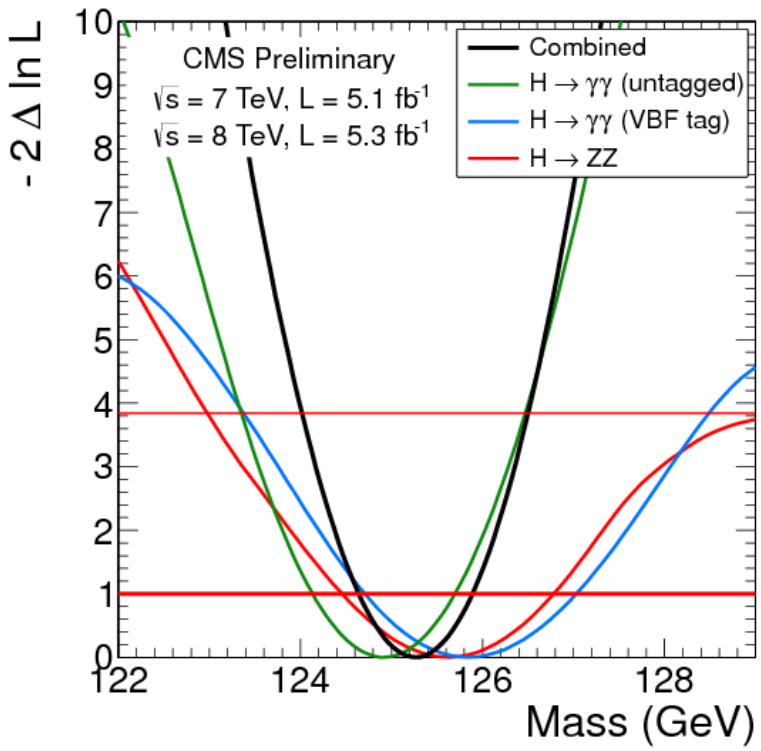
  with fermionic channels

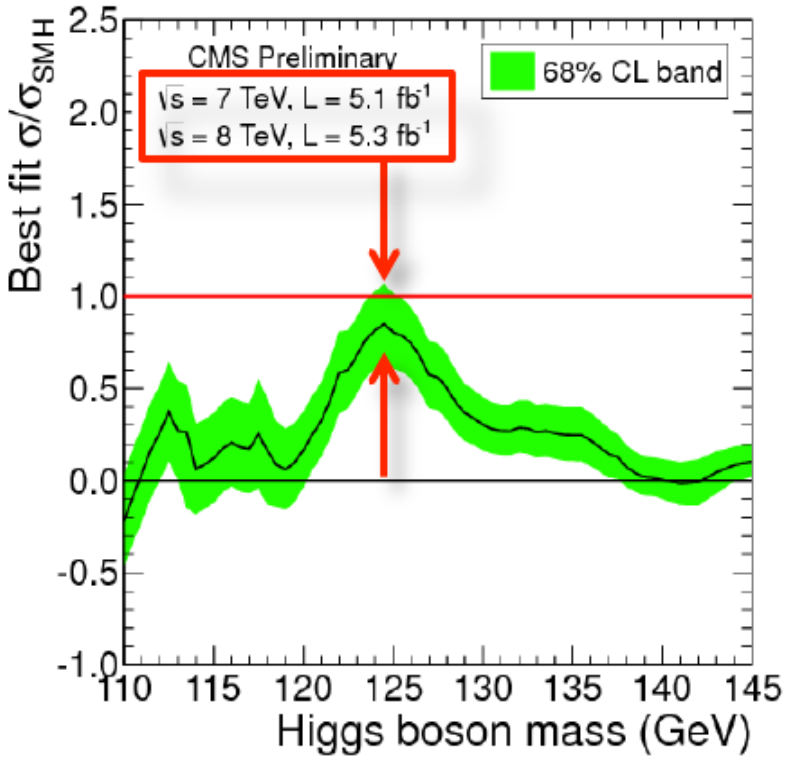
  ττ + VH, H → bb

- **Combined significance : 4.9σ**

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

Characterization of a New State @ CMS





fitted mass

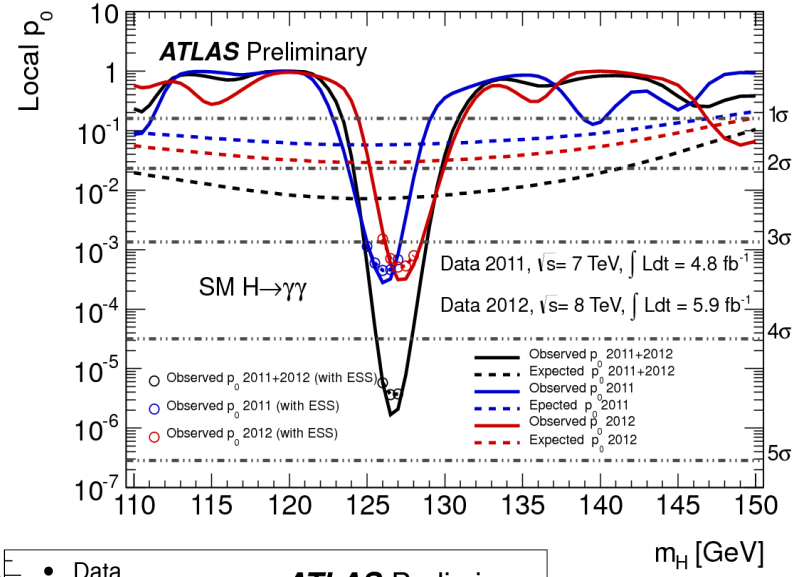
$M_X = 125.3 \pm 0.6$ GeV

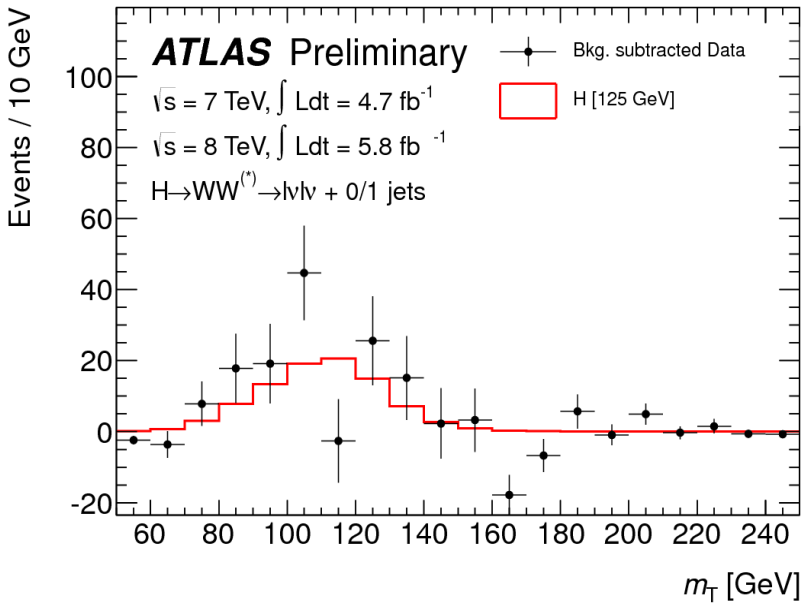
Best fit of signal strength in combination

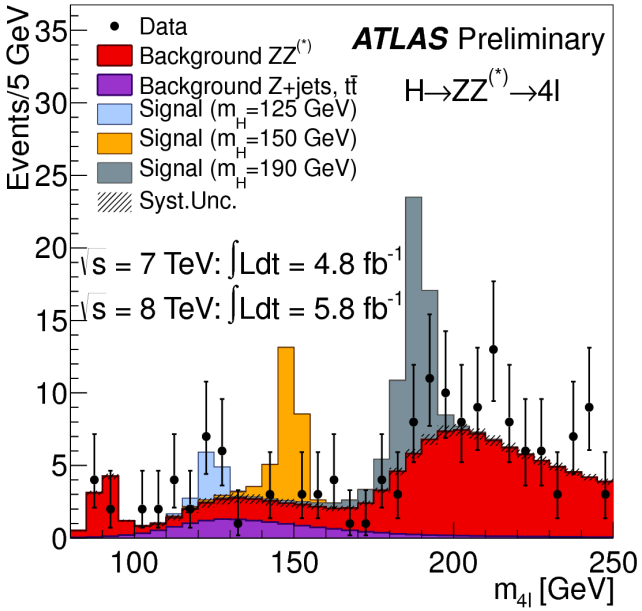
$\sigma/\sigma_{SM} = 0.80 \pm 0.22$

ATLAS Results

- **Channels updated by ATLAS with 5.8/fb @ 8 TeV**
  - **H → γγ**
  - **H → ZZ → 4ℓ**
  - **H → WW (July 17th)**







ATLAS Results

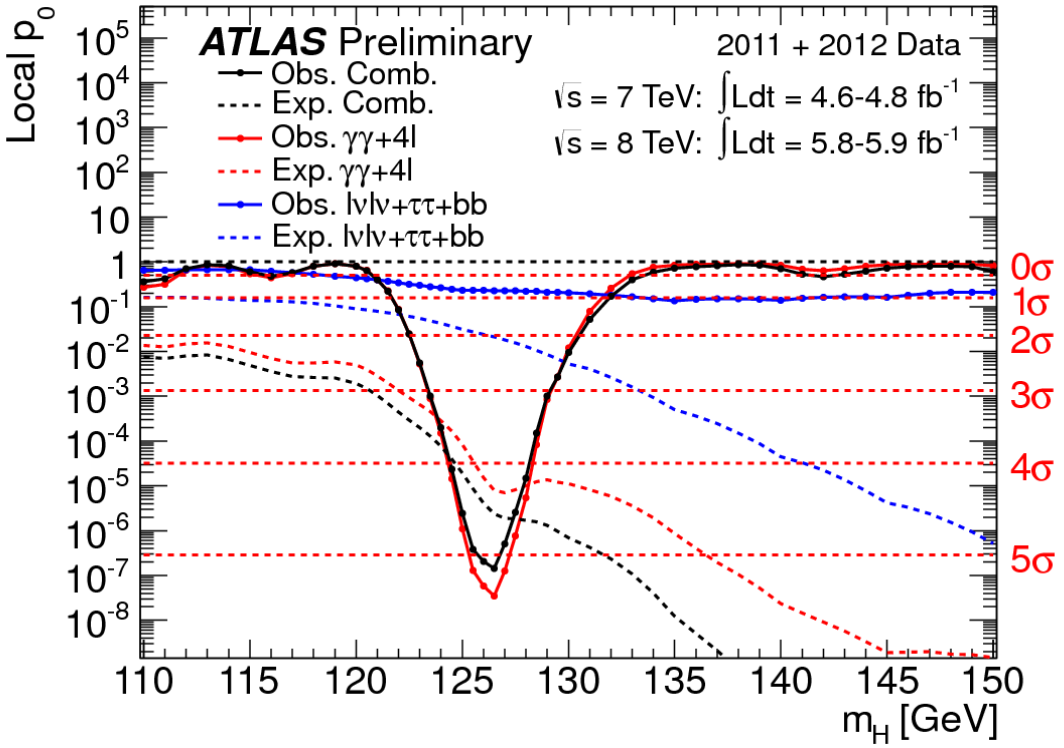
- **ATLAS Combination:**

➔ **5.8/fb @ 8 TeV**

- **H → γγ**
- **H → ZZ → 4ℓ**

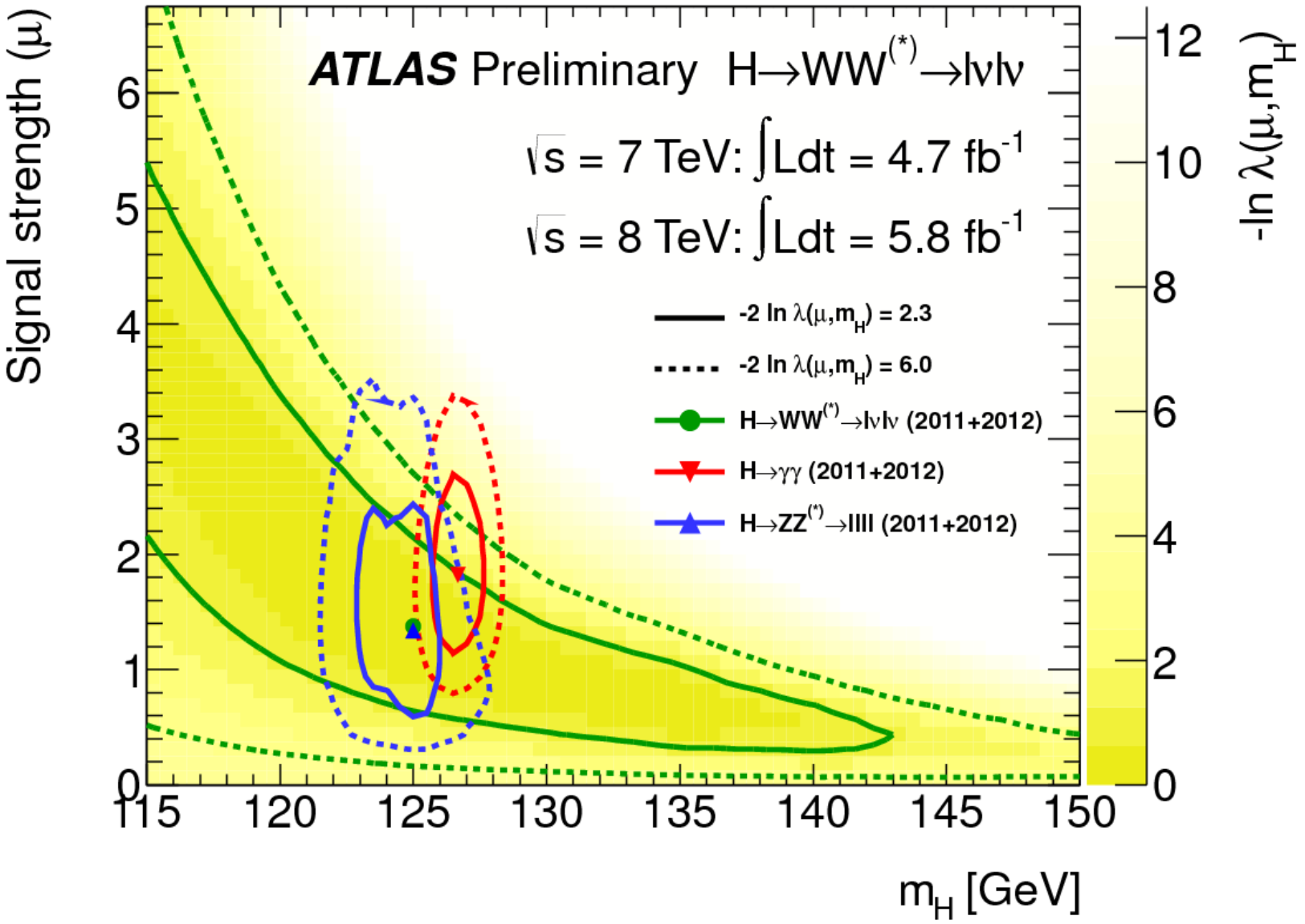
➔ **4.9/fb @ 7 TeV**

- **H → γγ**
- **H → ZZ → 4ℓ**
- **H → WW → 2ℓ2ν**
- **H → ττ**
- **VH, H → bb**



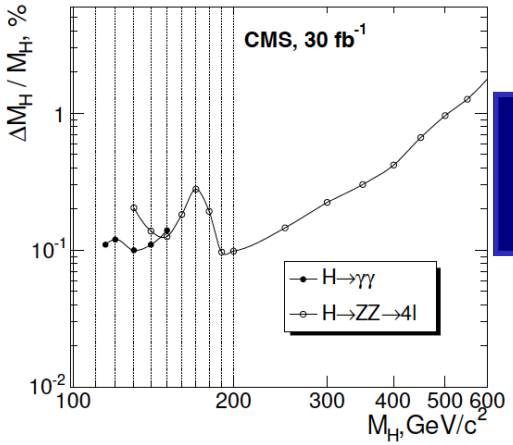
Observation of excess @ 126 GeV
with local significance : 5.0σ
Expected significance : 4.6σ

ATLAS Results : Mass vs. Cross Section



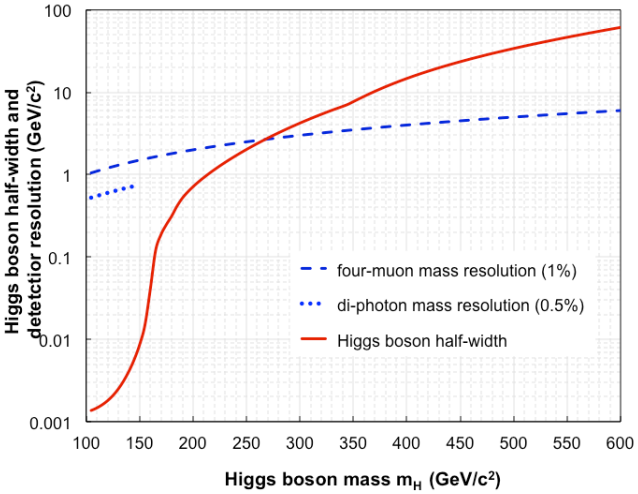
Measuring Higgs Properties with 30 fb^{-1} at 8 TeV

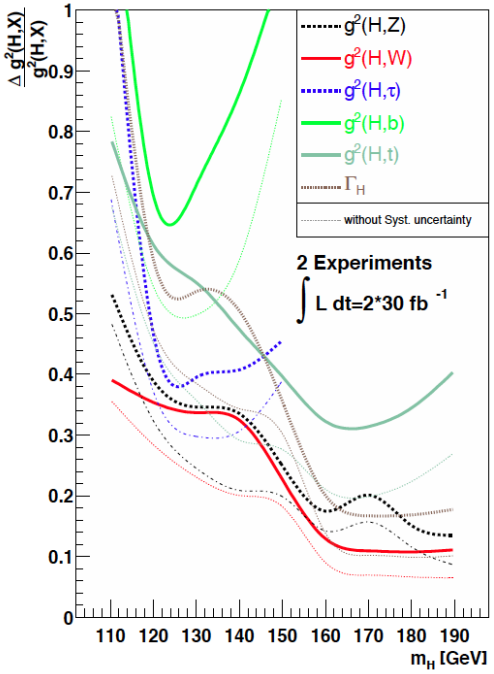
CMS TDR 14TeV



Mass
Δm/m ≈ 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

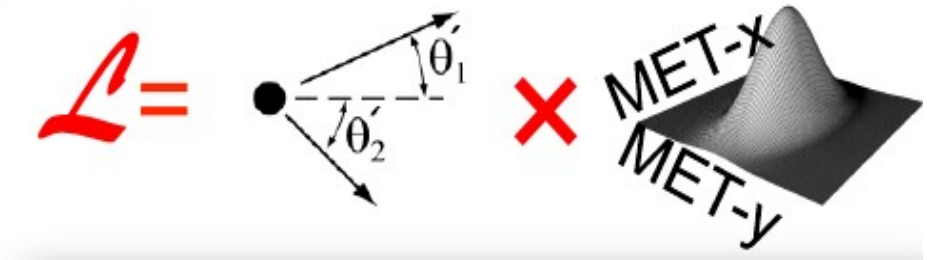
- **fully model-independent measurements impossible**
- **minimal assumptions → $\Delta g^2/g^2$ = 20 - 30%**
- **dedicated machinery for grand fits needed**

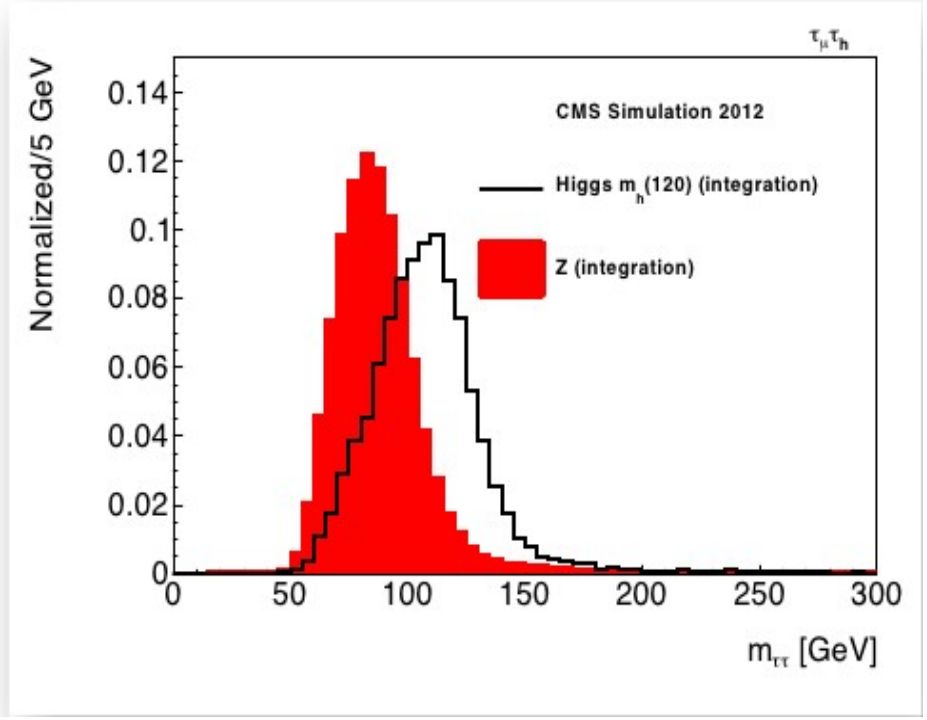
Summary

- **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?**

Backup

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