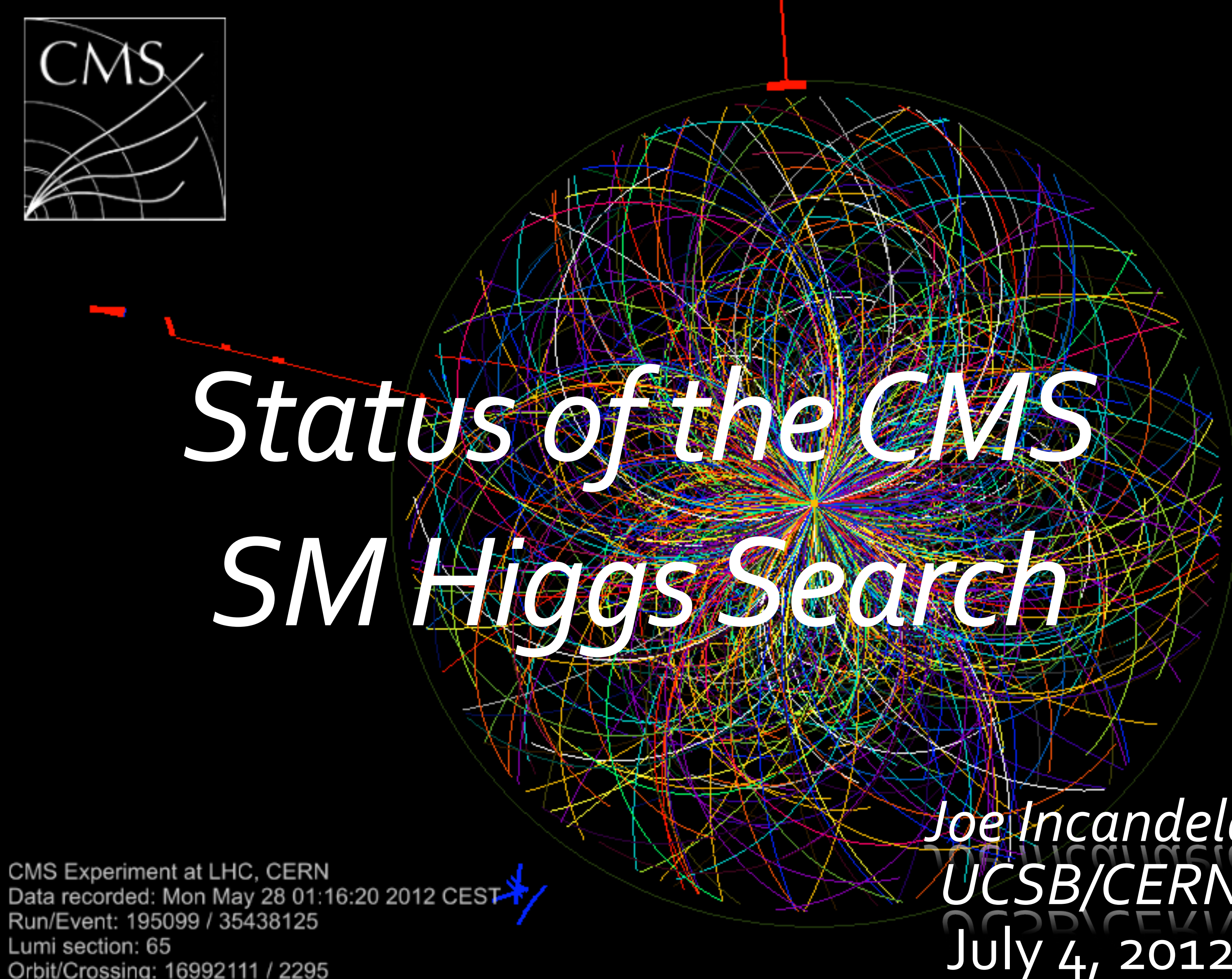
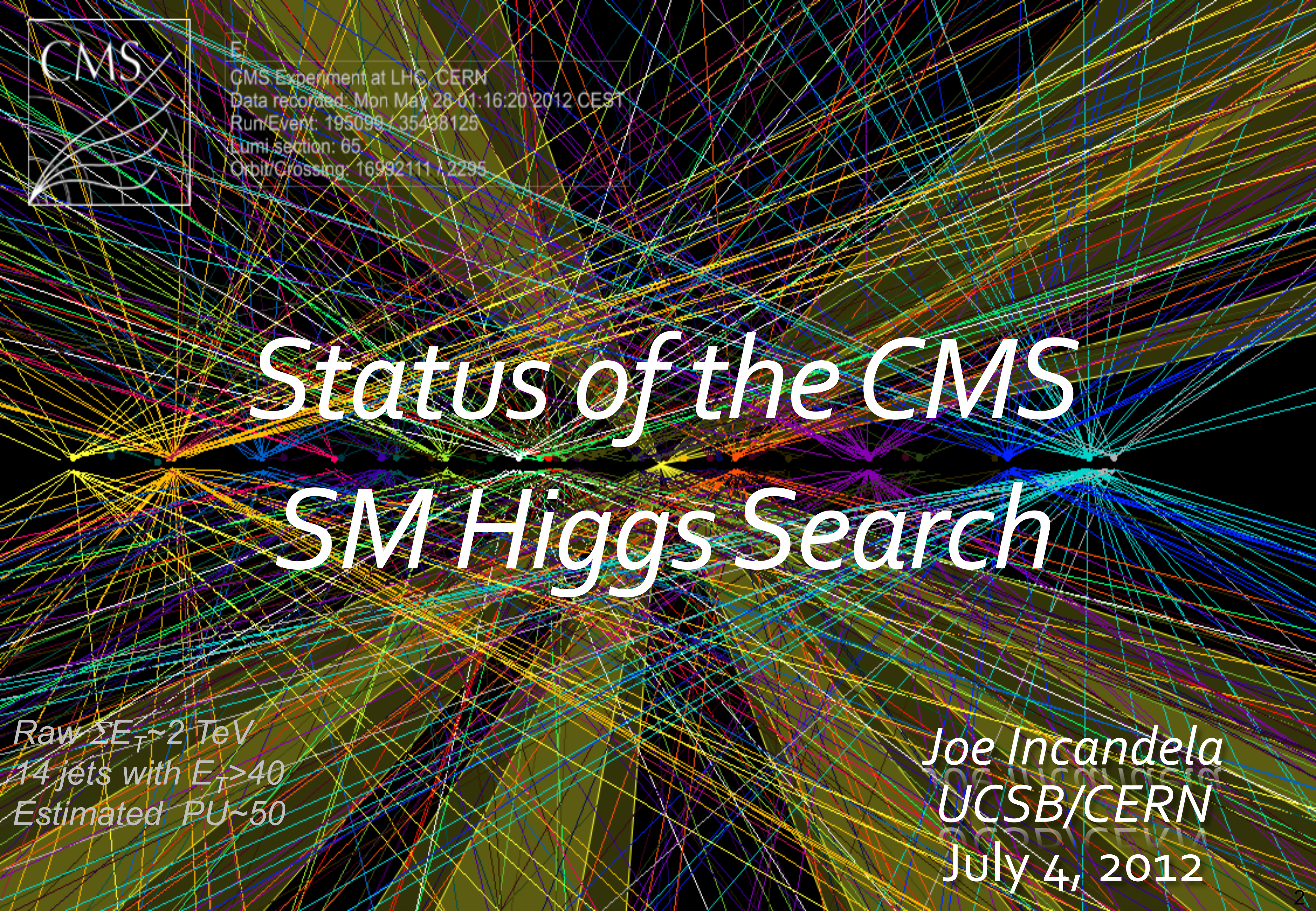
Status of the CMS SM Higgs Search



Joe Incandela
UCSB/CERN
July 4, 2012



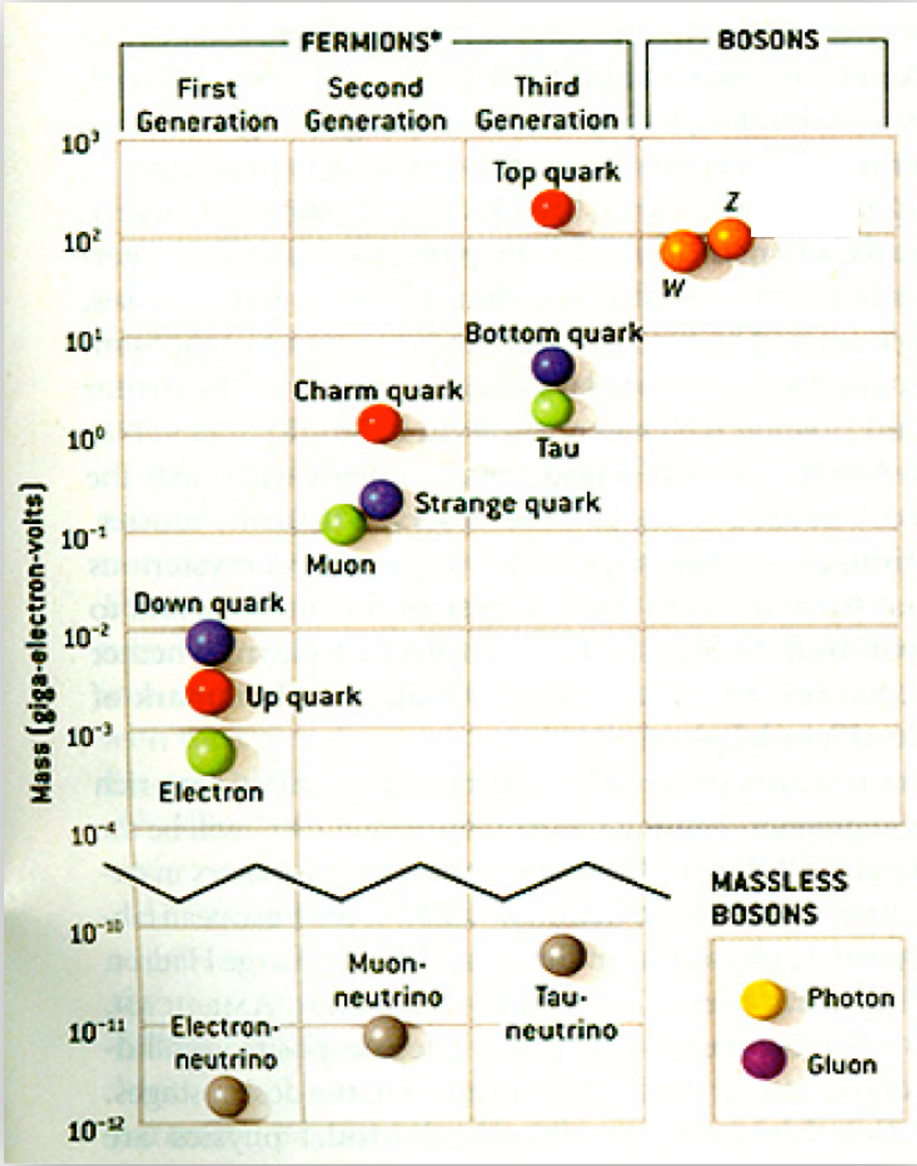
Status of the CMS SM Higgs Search

Joe Incandela
UCSB/CERN

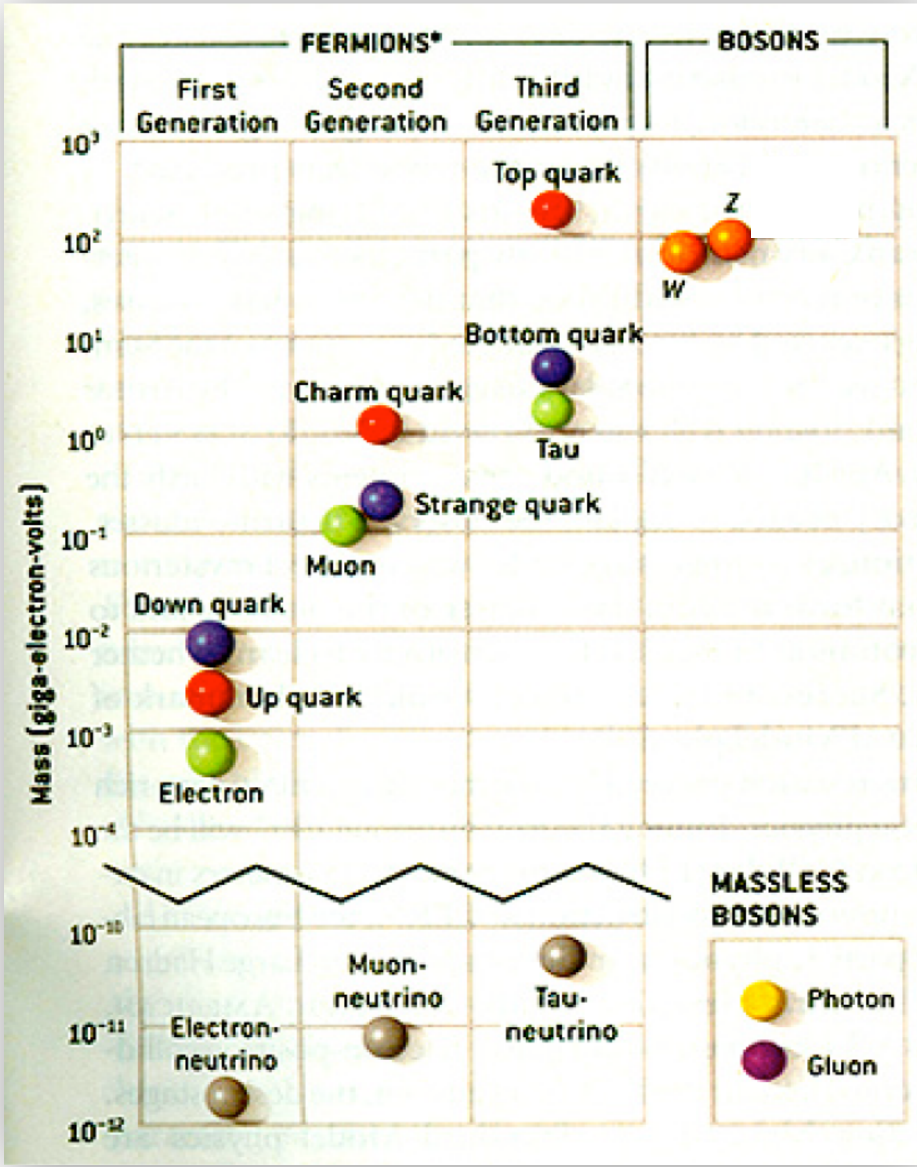
July 4, 2012

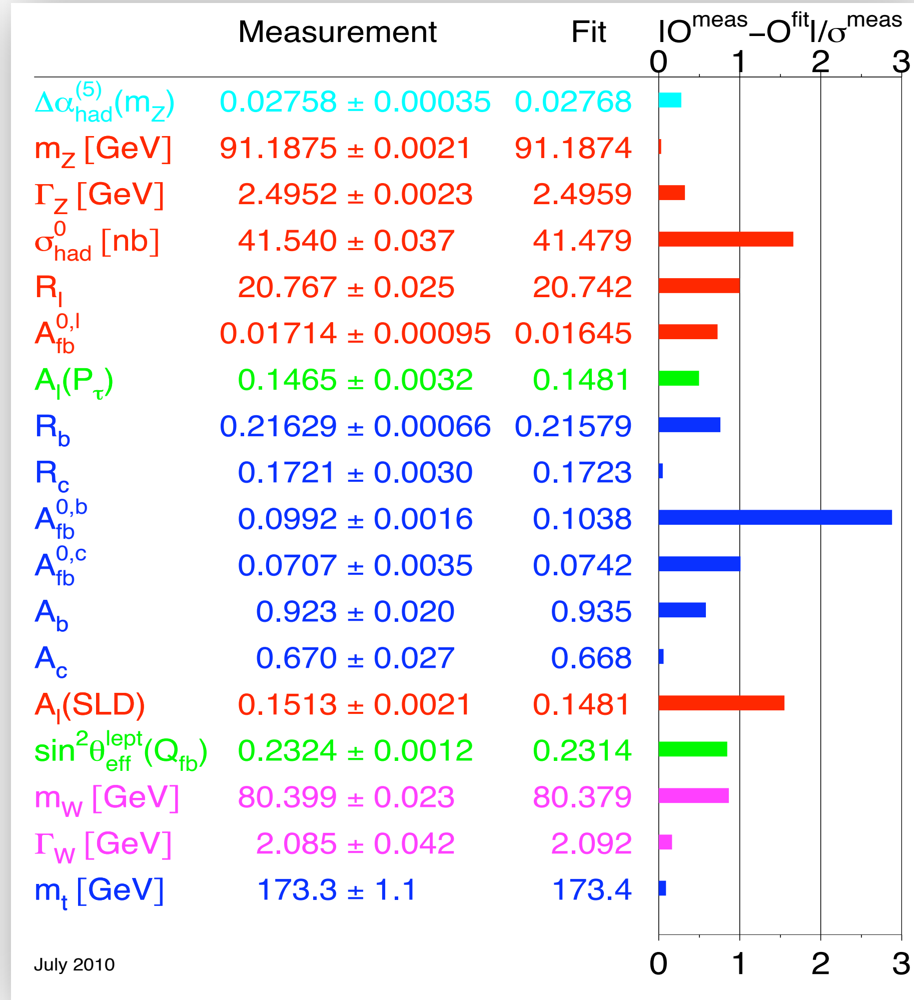
On behalf of the CMS Collaboration

The Standard Model

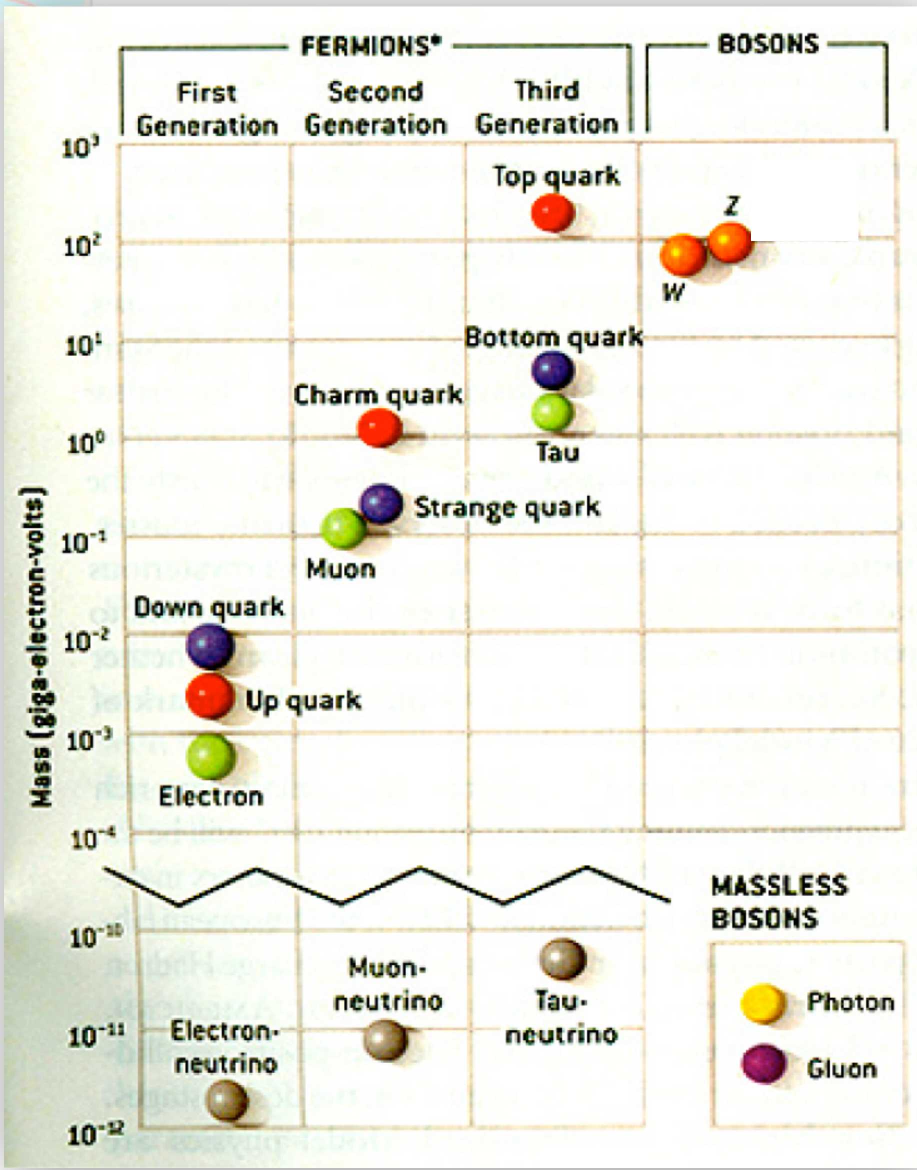


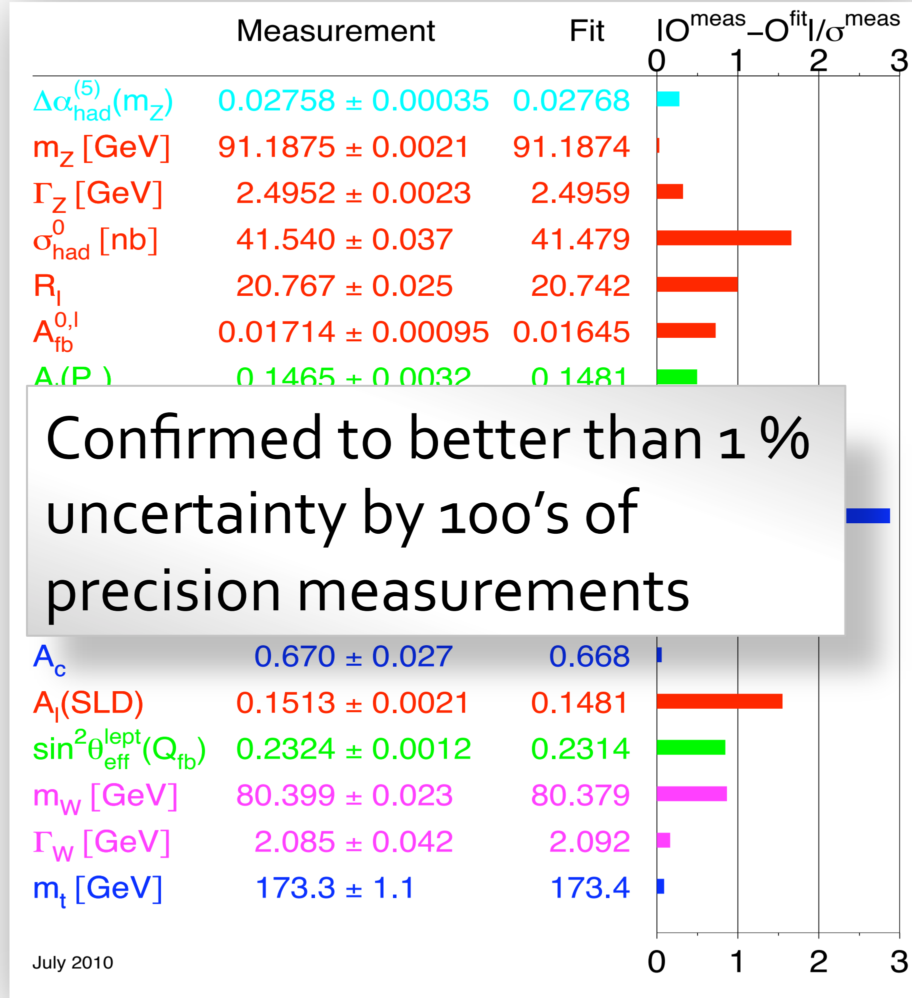
The Standard Model





The Standard Model

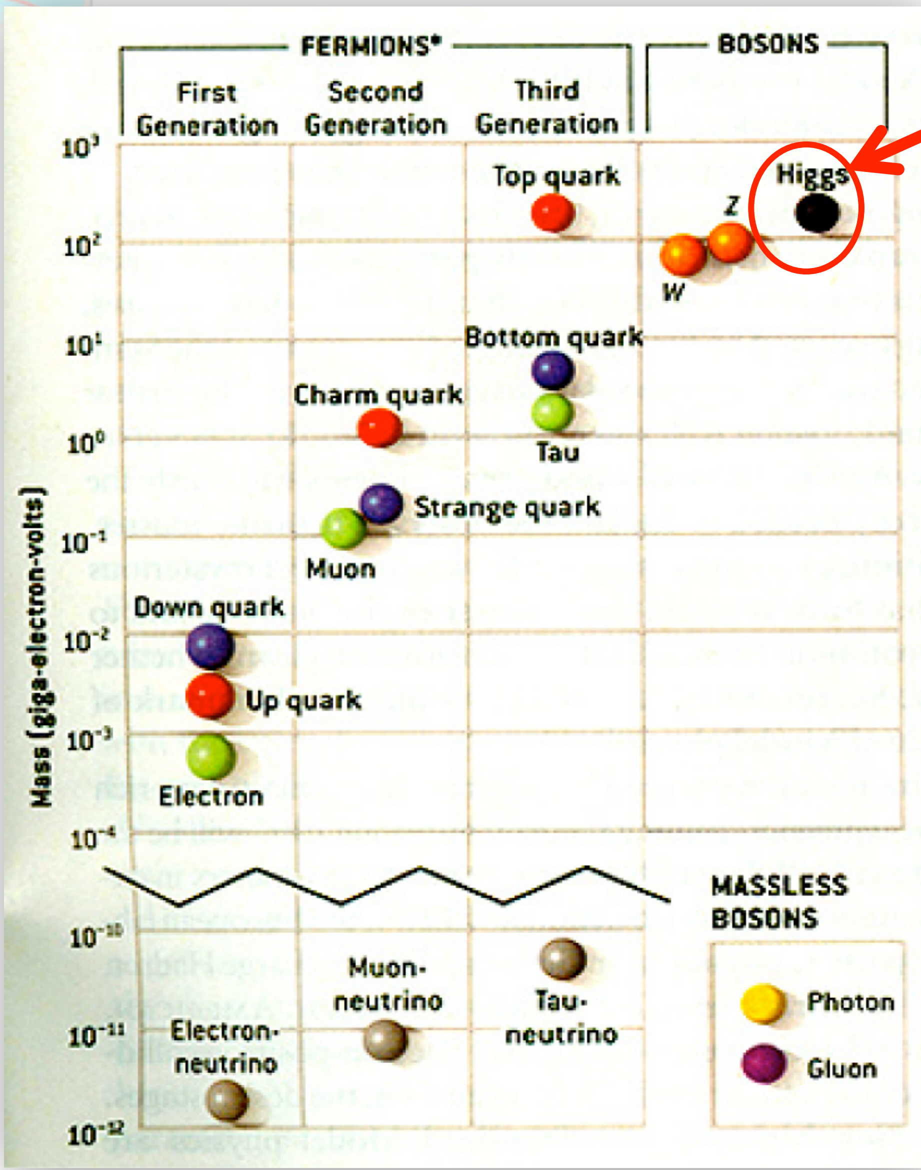


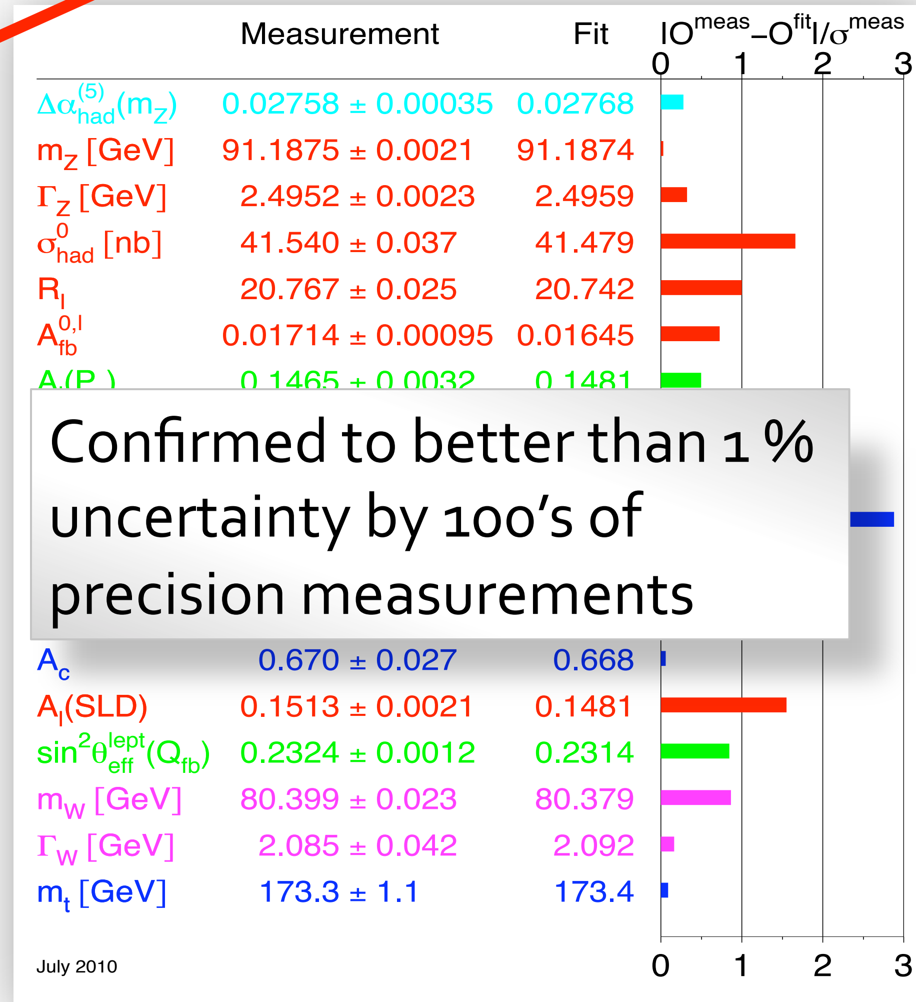


Confirmed to better than 1 % uncertainty by 100's of precision measurements

The Standard Model

1 Missing piece: Higgs





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The Standard Model

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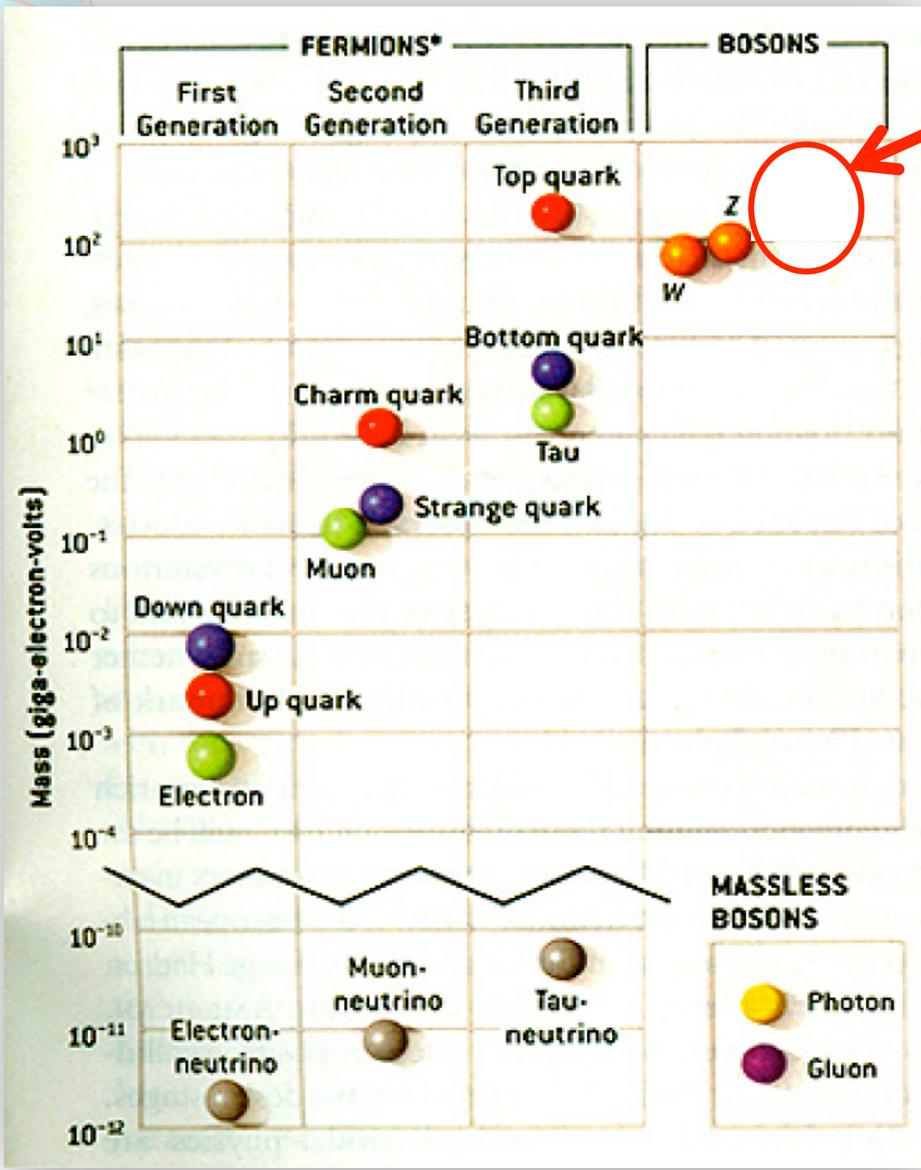
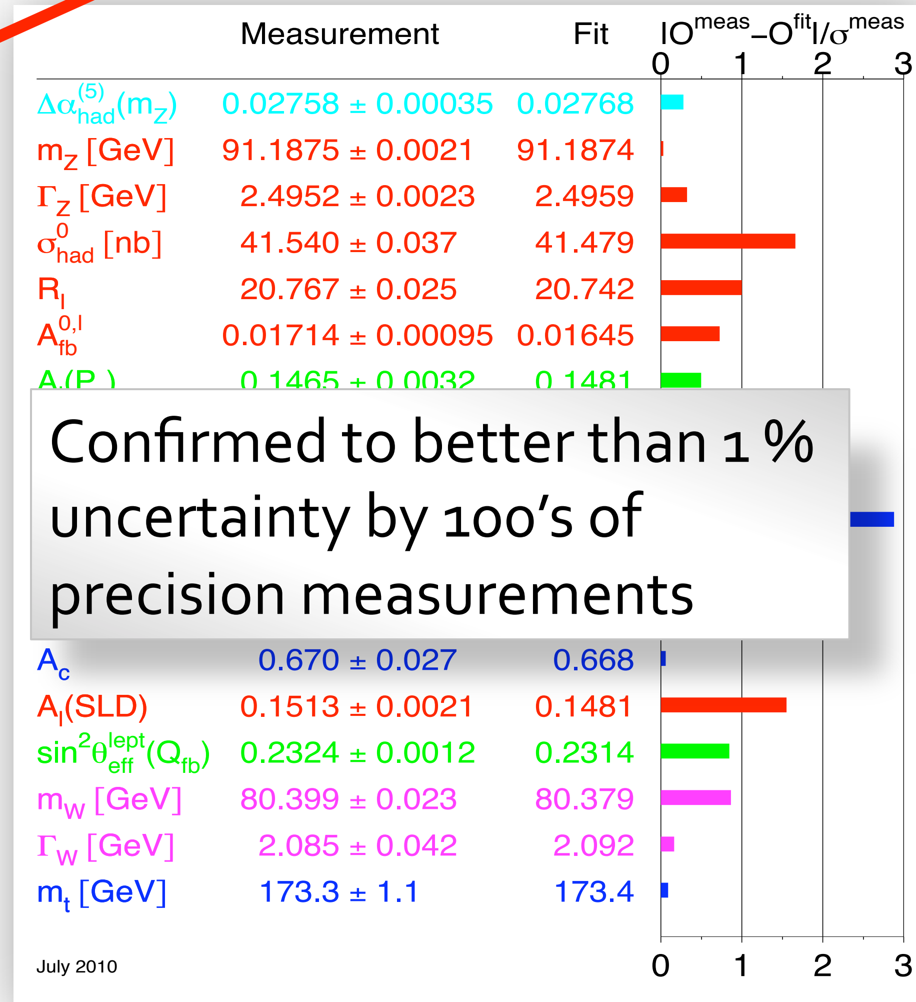
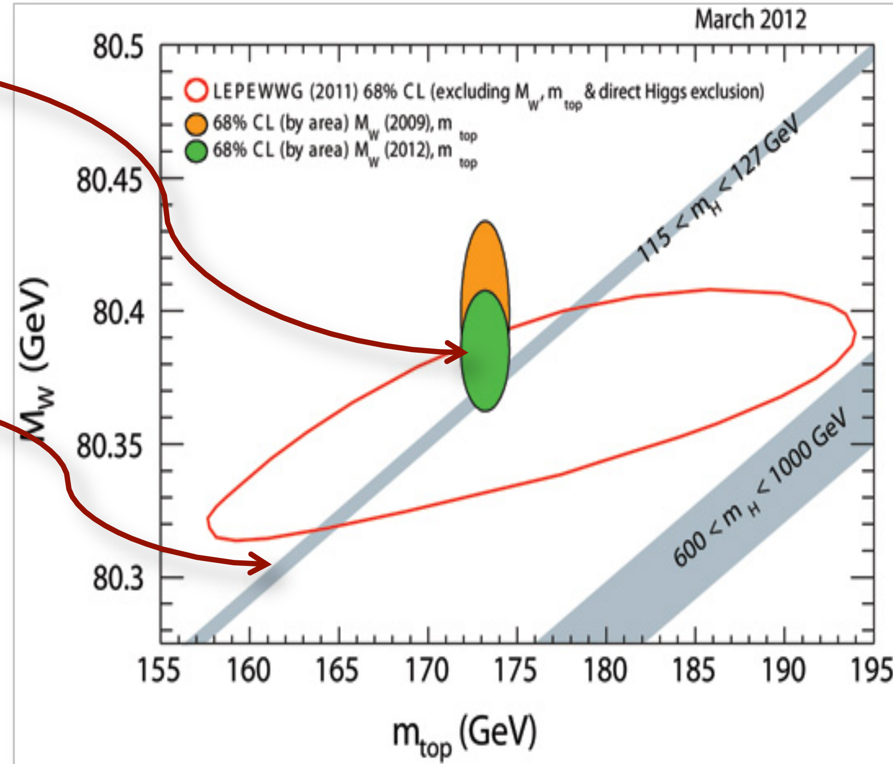


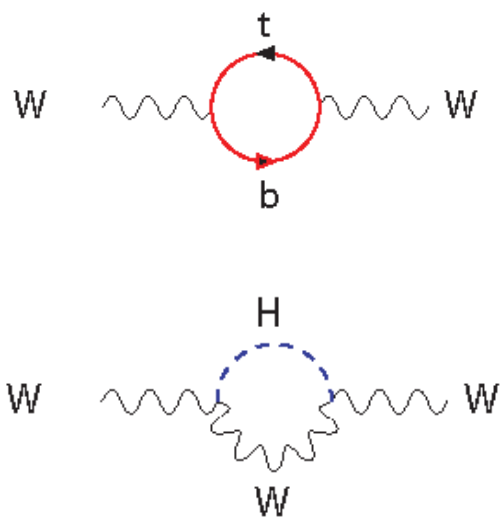


Confirmed to better than 1 % uncertainty by 100's of precision measurements

Where we stood last week

1. M_{top} vs. M_W
   - Tevatron M_W *Tour de Force!!*
     - m_W = 80385 ± 15 MeV (World Ave – Mar 2012)
   - Shifts for SM Higgs expectation
2. Colliders leave little space





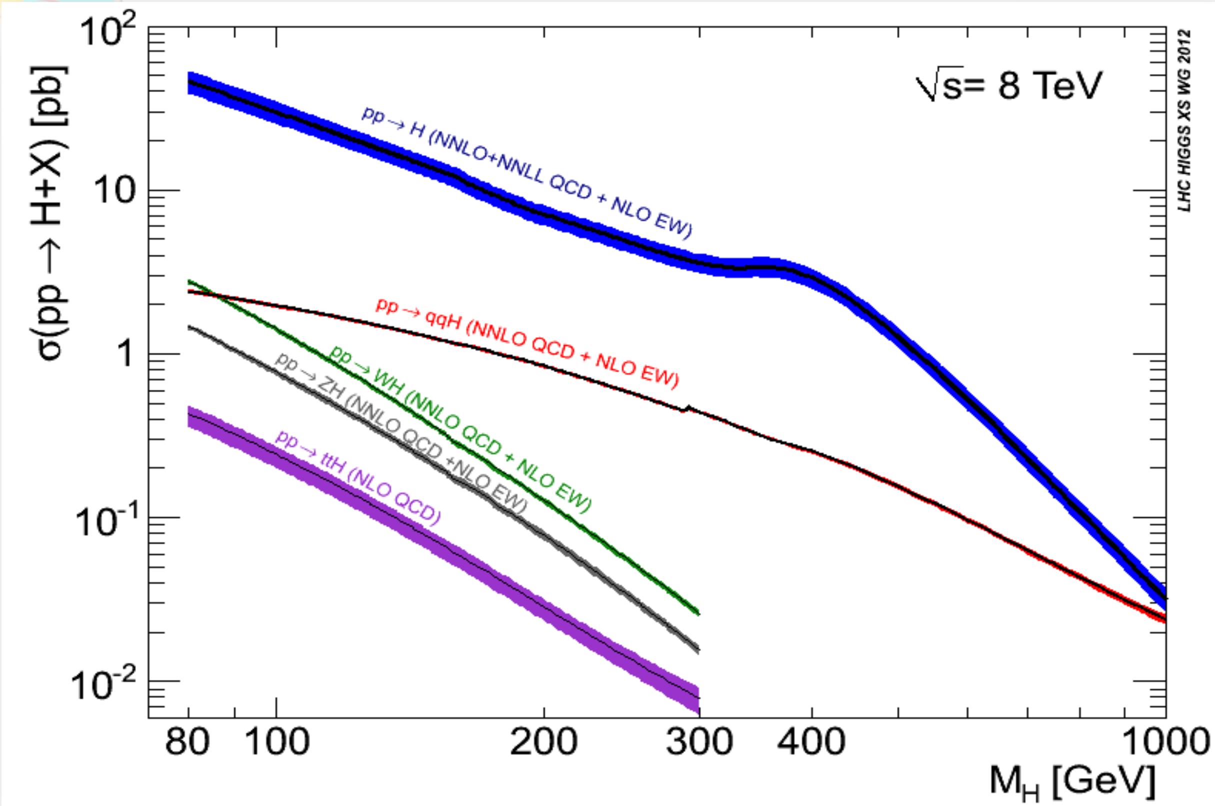
$\sim M_t^2$

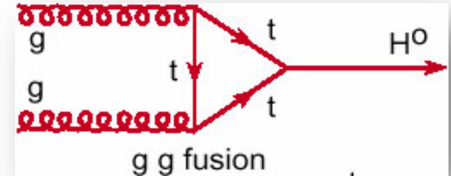
$\sim \ln(m_H)$

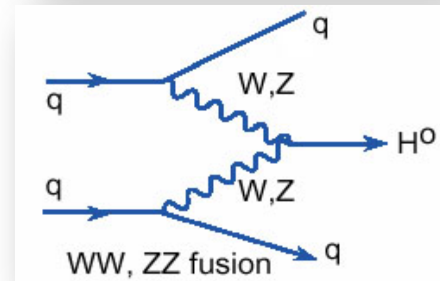
This is the main story of the past year

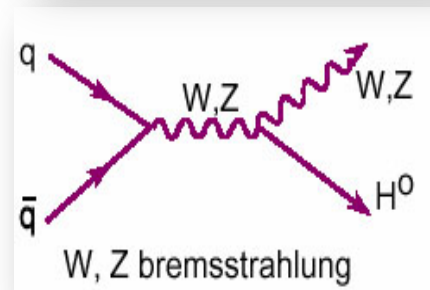
Eliminated ~475 GeV of the mass range.

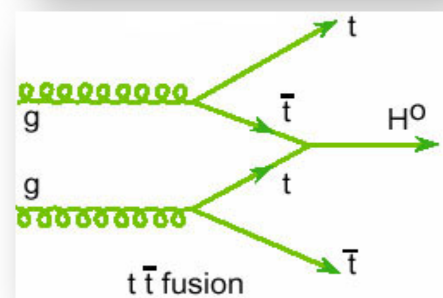
Higgs boson production





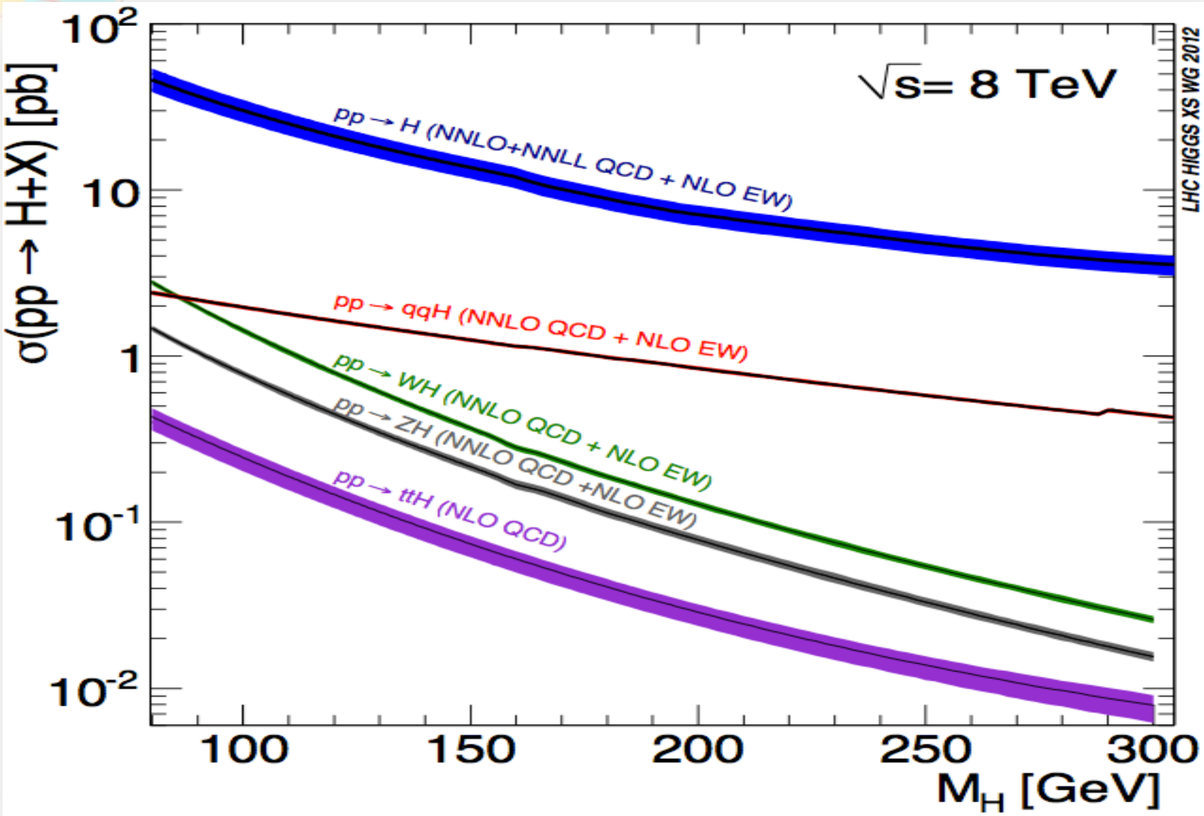


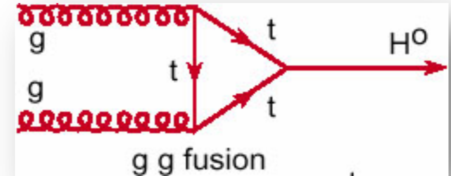


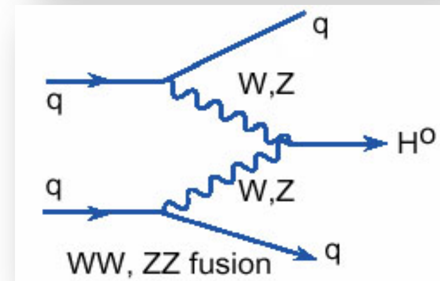


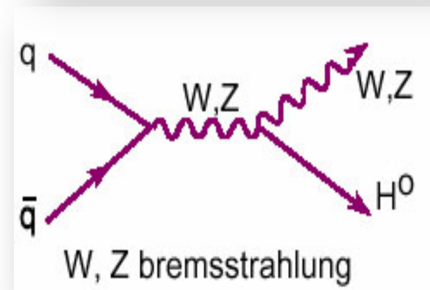
- $\sqrt{s}$=8 TeV: 25-30% higher σ than $\sqrt{s}$=7 TeV at low m_H
- All production modes to be exploited
  - gg VBF VH ttH
  - Latter 3 have smaller cross sections but better S/B in many cases

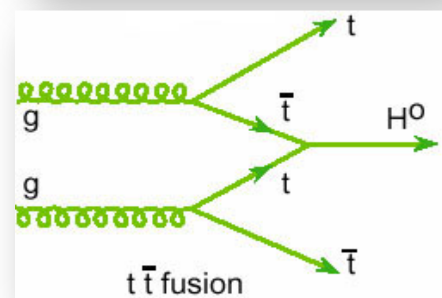
Higgs boson production











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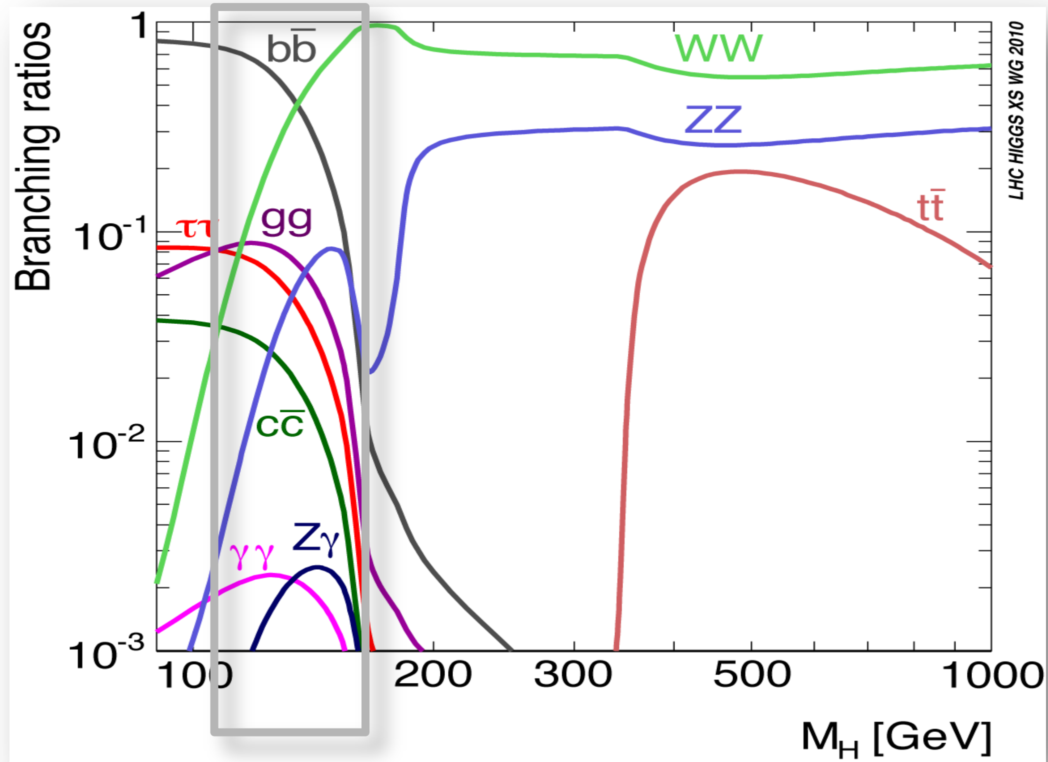
Higgs boson decays

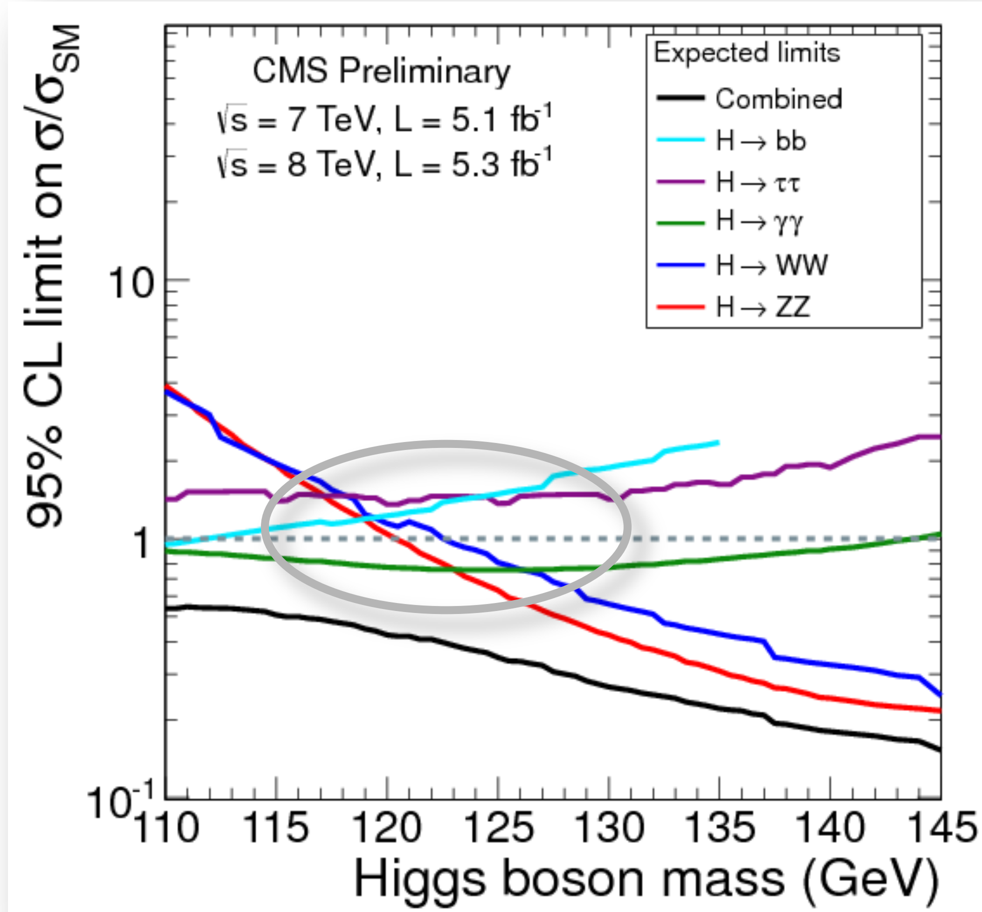
5 decay modes exploited

- High mass: WW, ZZ
- Low mass: $b\bar{b}$, ττ, WW, ZZ, γγ
- Low mass region is very rich but also very challenging:
  main decay modes ($b\bar{b}$, ττ) are hard to identify in the huge background
- Very good mass resolution (1%): H→γγ and H→ZZ→4l



CMS Exclusion Potential

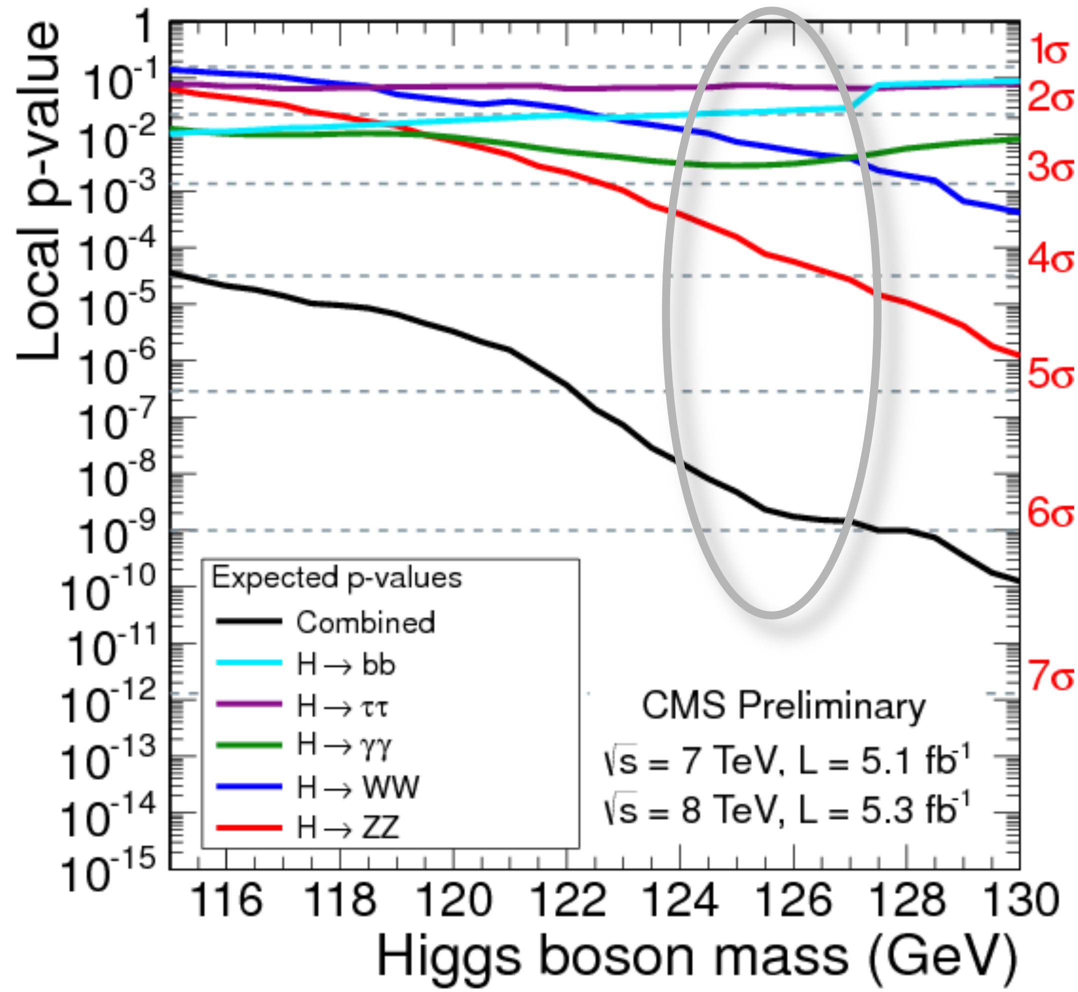
- Not-yet-excluded region: ~[115-130] GeV
- The five decay modes discussed today have comparable sensitivities for exclusion.
- Most analyses used in this combination have been re-optimized. In order to avoid the possibility of an unintended bias, all selection criteria in the analyses of the 2011 and 2012 data were fixed before looking at the result in the signal region.



CMS Discovery potential

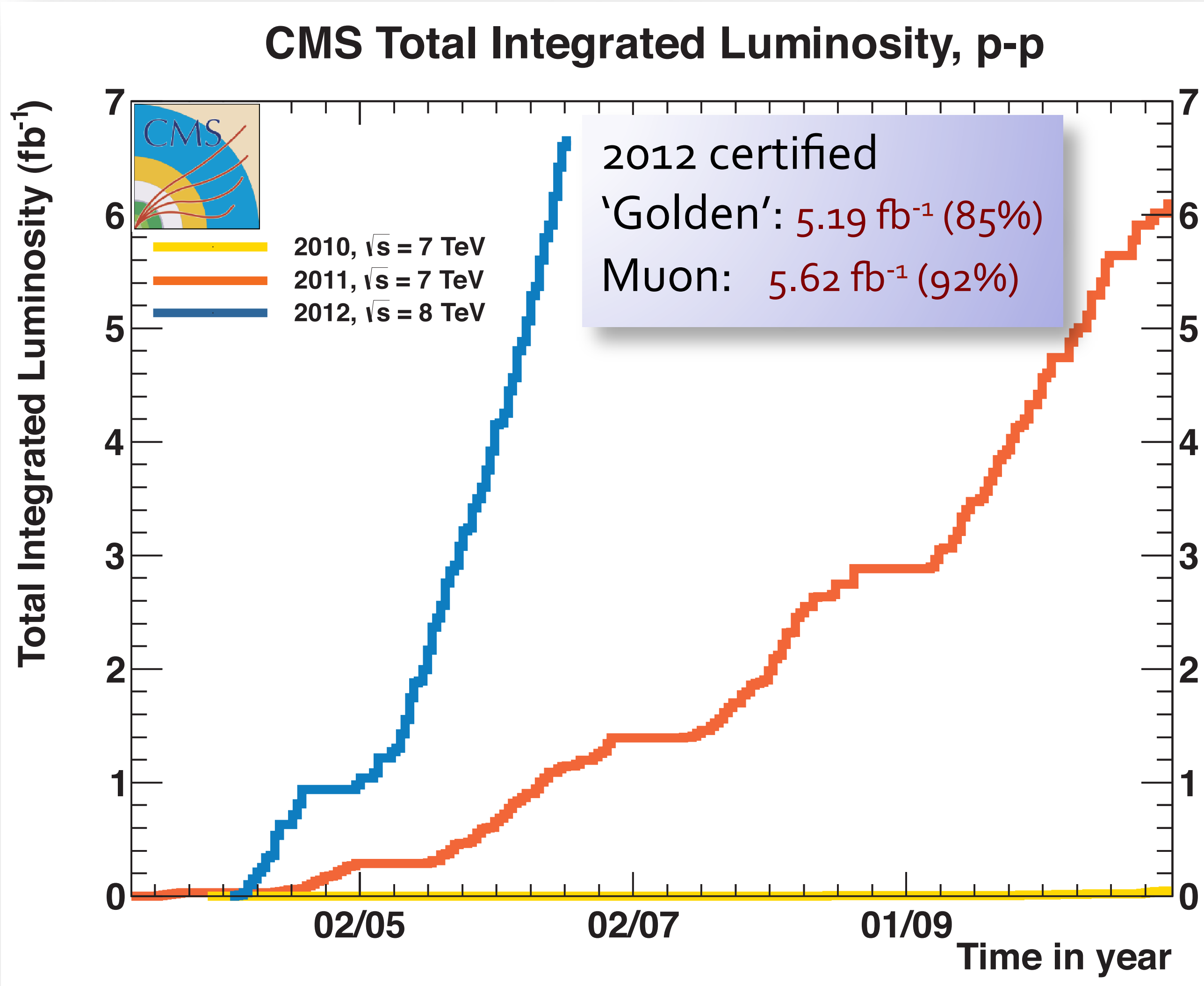
p-values

- Probability that background fluctuates to give an excess as large as the (average) signal size expected for a SM Higgs.
    - Takes into account all analysis steps, estimated backgrounds, etc. for the 5 search channels indicated.
- Excellent prospects for exploring properties



How is it possible to go so far so fast?

LHC performance: 2010-2011-**2012**

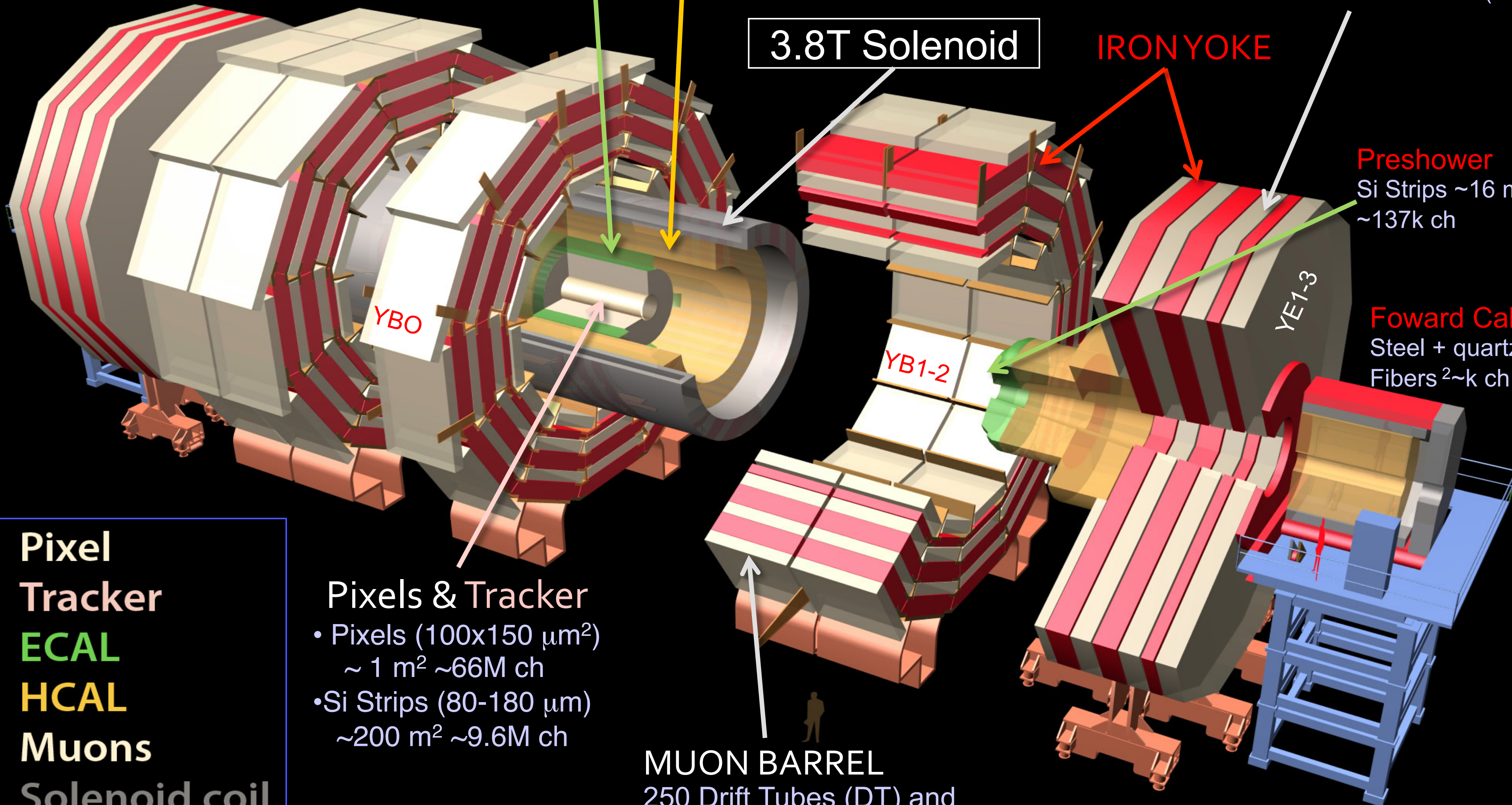


Stellar performance of the LHC enables all experiments to produce significant physics results

Many thanks to the LHC teams and the many others who made this possible!

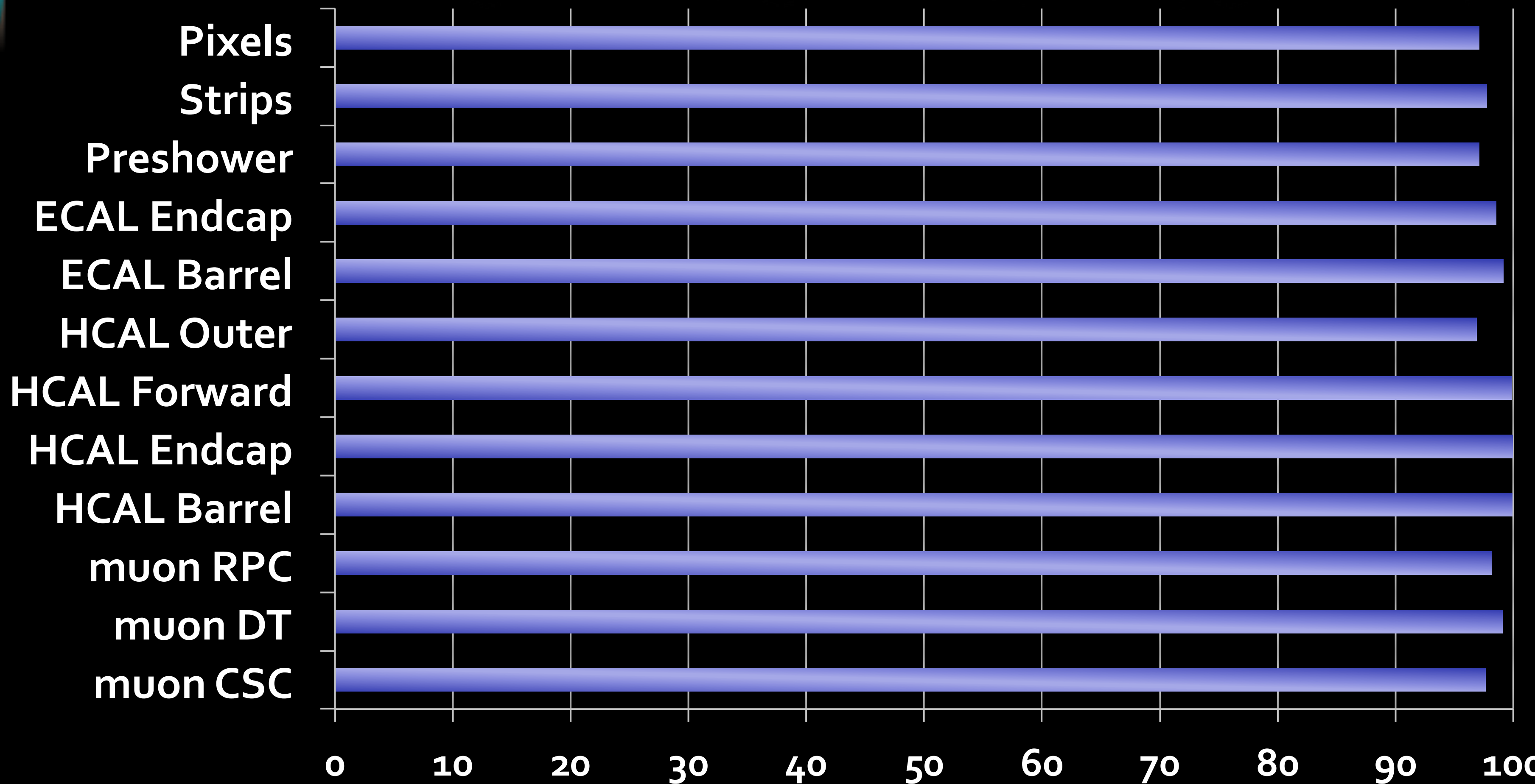
CMS

Total weight 14000 t
Overall diameter 15 m
Overall length 28.7 m



Pixel
Tracker
ECAL
HCAL
Muons
Solenoid coil

Current Operational Status*

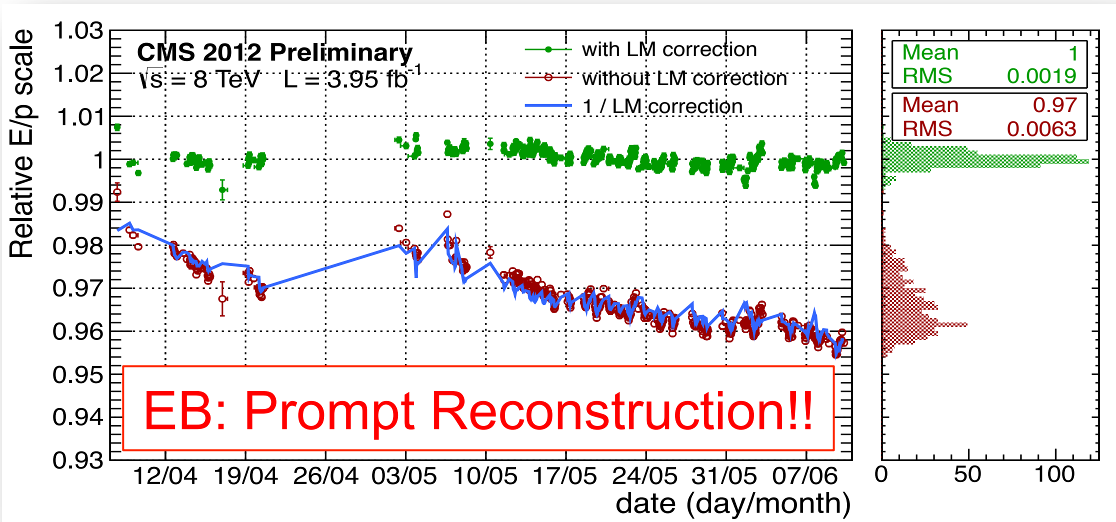


Pixel Tracker	Strip Tracker	Preshower	ECAL Barrel	ECAL Endcaps	HCAL Barrel	HCAL Endcaps	HCAL Forward	HCAL Outer	Muon DT	Muon CSC	Muon RPC
97.1%	97.75%	97.1%	99.16%	98.54%	99.92%	99.96%	99.88%	96.88%	99.1%	97.67%	98.2%

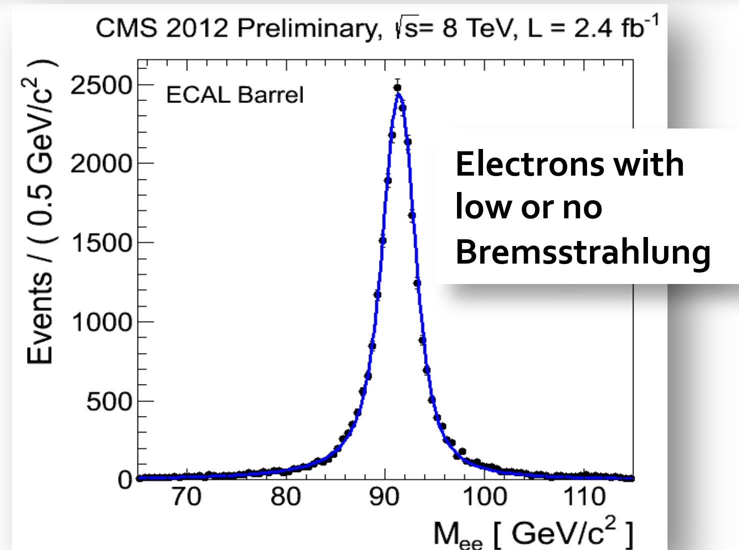
*As of June 15 2012

ECAL calibration, 2012 data

Single electron energy scale (E/p) stability in barrel measured with W →eν events



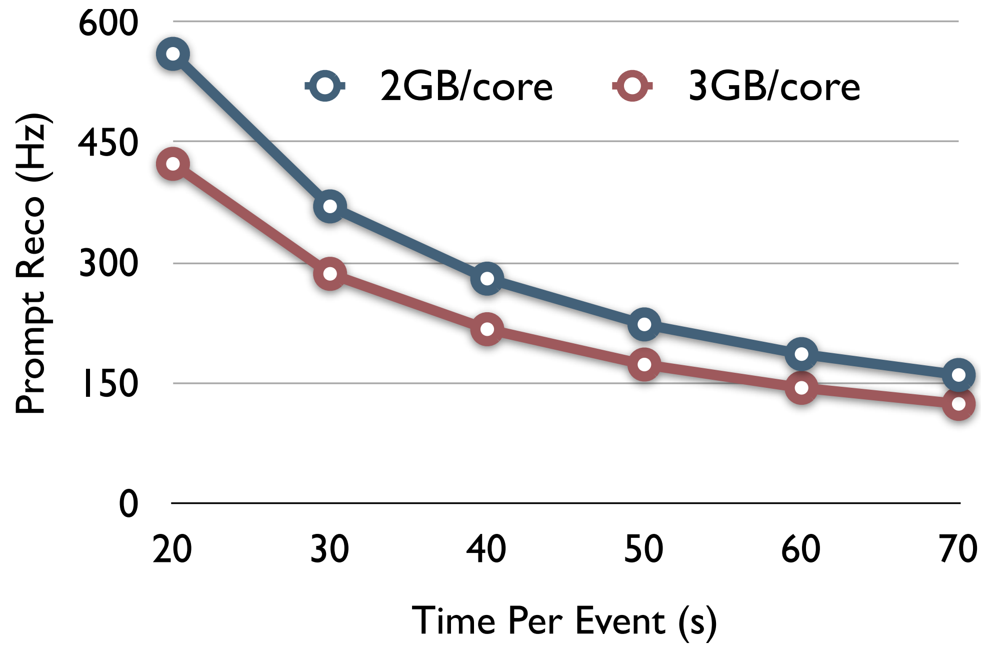
Z→ee invariant mass distribution for electrons measured in the barrel



- **W→eν** E/p: Stable E scale during 2012 run after light monitoring (LM) corrections:
  - ECAL Barrel (EB): RMS stability after corrections 0.19%
- Z→ee: Good resolution with preliminary energy calibration for 2012:
  - Instrumental resolution: 1.0 GeV in ECAL Barrel

CMS Preparations for 8 TeV and high PU in 2012

- Last Autumn
  - cpu time for high PU >40 sec/event
  - Memory usage well above 2 GB.
    - Means we cannot use all the cores!
  - Even 200 Hz looked hard!
- Task force started December
  - Major success!
- Improvements
  - A factor 2.5 in speed
    - Under ~15″ per event on average
  - Much reduced memory use
    - Well under 2 GB
- Physics performance unchanged
  - Kept our AAA rating:
    - E.g. no explicit p_T threshold on tracks

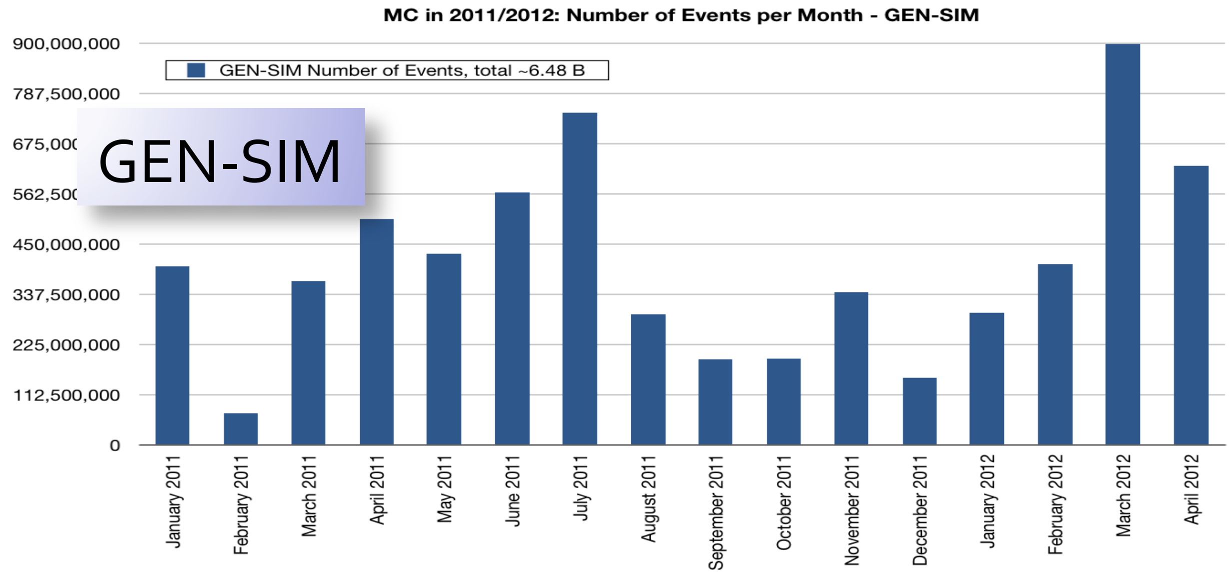


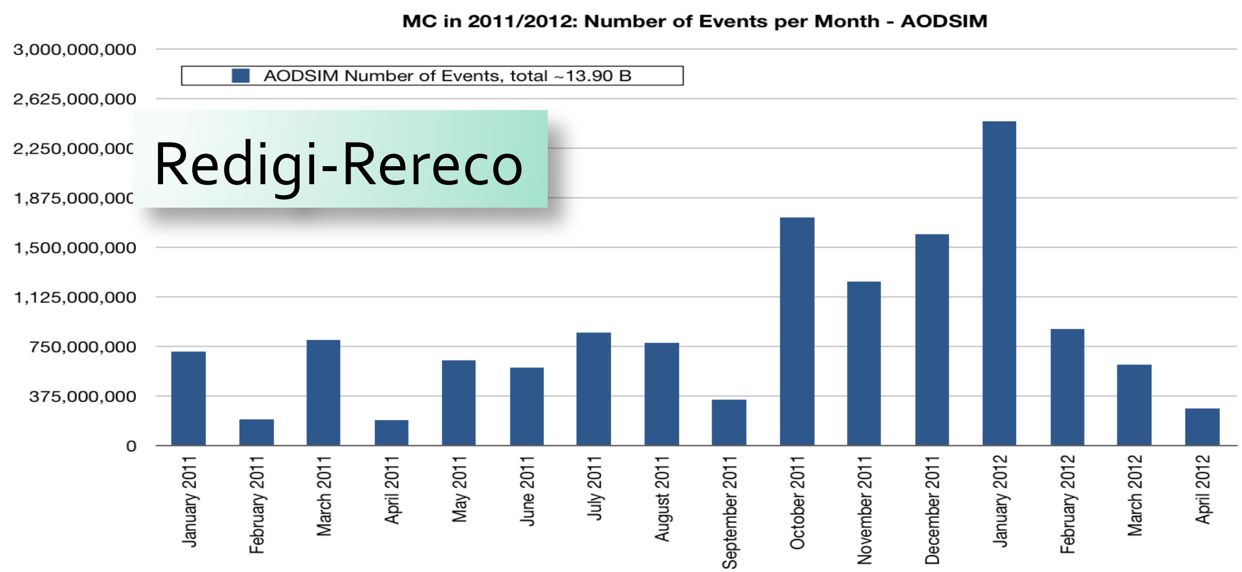
Prompt Reconstruction at Tier-0:
Limit on our data-taking rate versus event processing time for low and high memory use cases

MC Production Capabilities

- Sustain 400M/Month
  - *900M, 600M past 2 months but had help from Tier-1's*

- Sustain 1B/month
  - *Peaks high as 2.3B*

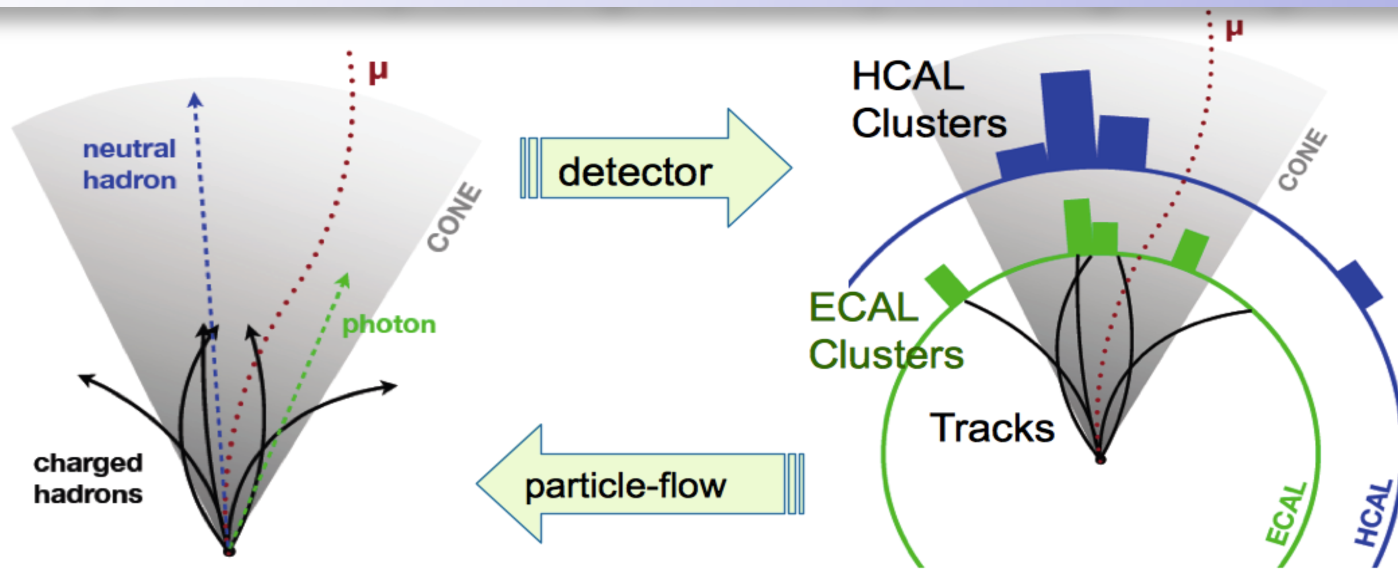




Reconstruction

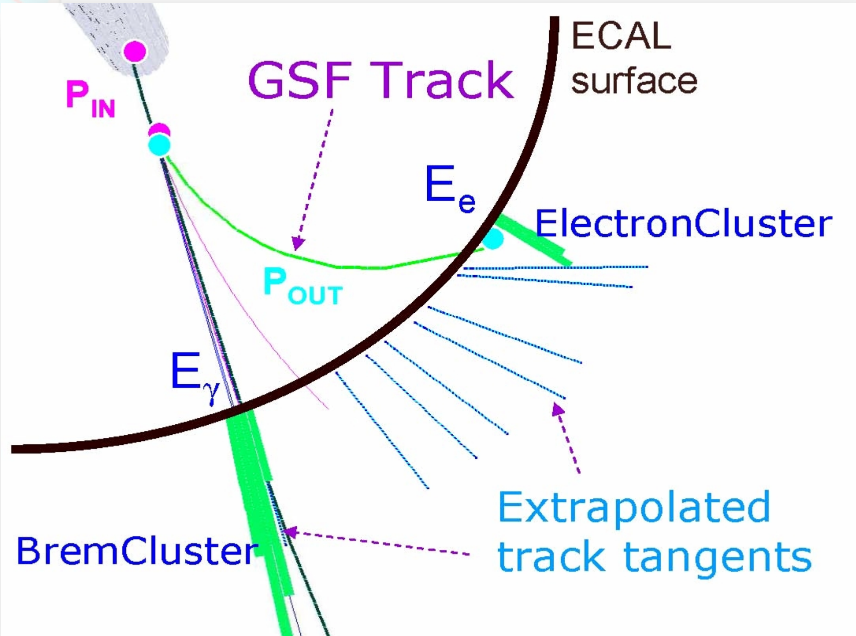
Global Event Description (Pflow)

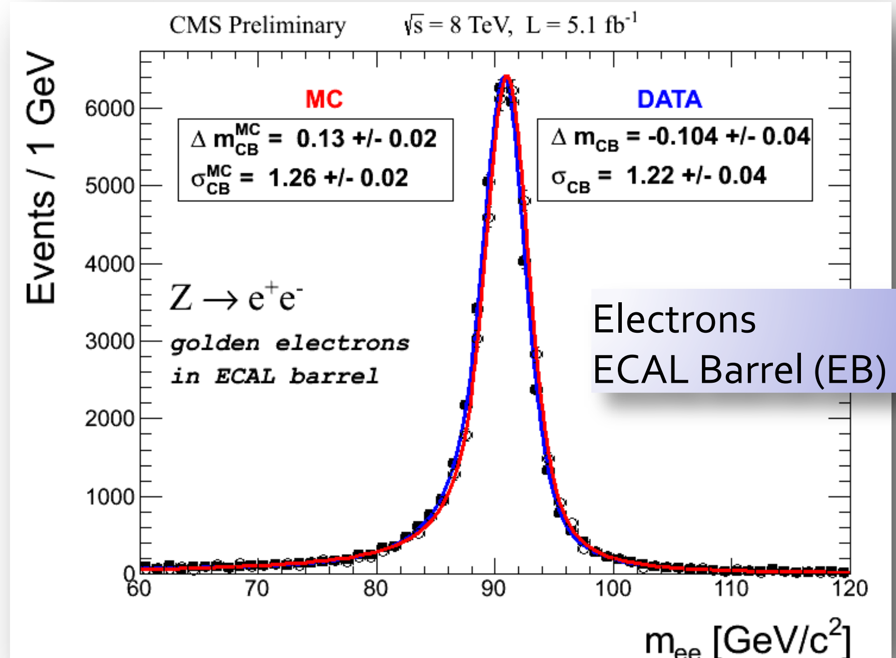
Made possible by CMS granularity and high magnetic field



- 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

Electron/Photon reconstruction

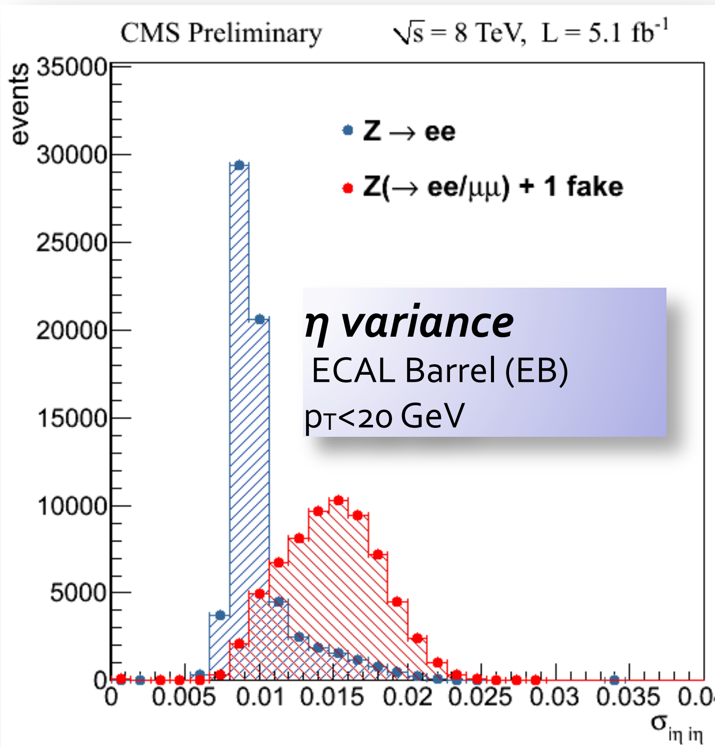


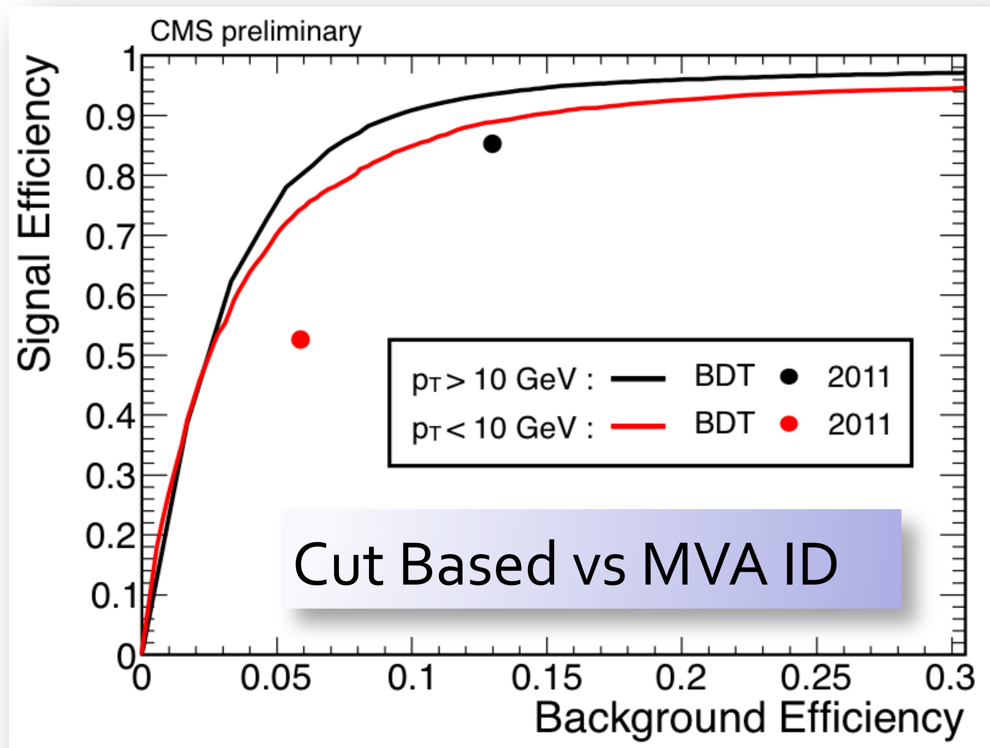


- Cluster reconstruction in ECAL
  - Common for both electrons and photons (Electrons also reconstructed as photons)
  - Designed to collect bremsstrahlung and conversions in extended phi region
- Dedicated track reconstruction for electrons
  - Gaussian Sum Filter allows for tracks w/large bremsstrahlung
- Photon identification specific to H➔γγ
- Energy scale and resolution
  - Extensive control with Z and J/ψ➔ee for both electrons and photons

Electron identification

- Multivariate e identification in 2012
  - ECAL, tracker, ECAL-tracker-HCAL matching, impact parameter
  - 30% efficiency improvement in $H \rightarrow ZZ \rightarrow 4e$ wrt cut based ID
- Multivariate training against background in data

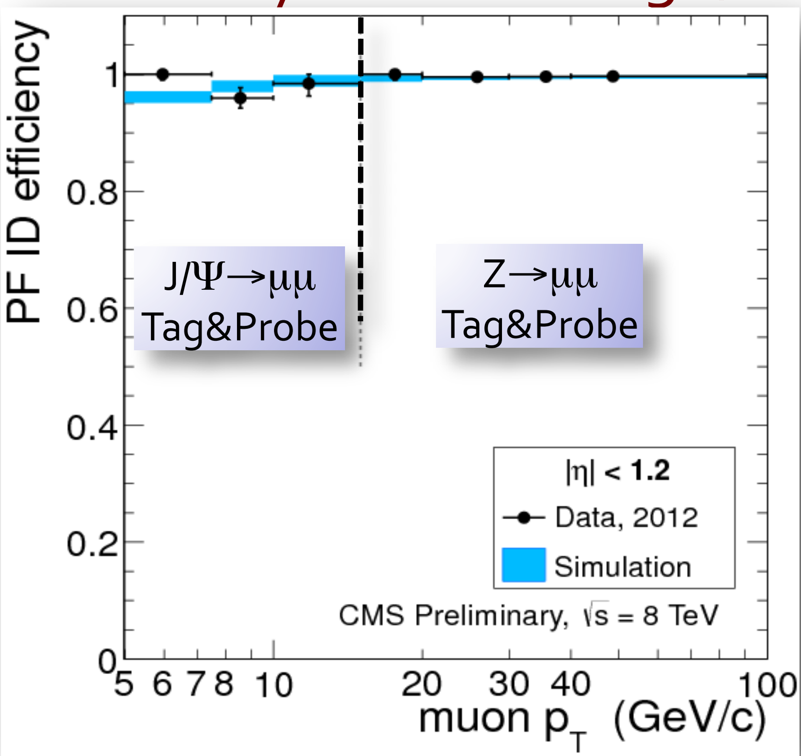


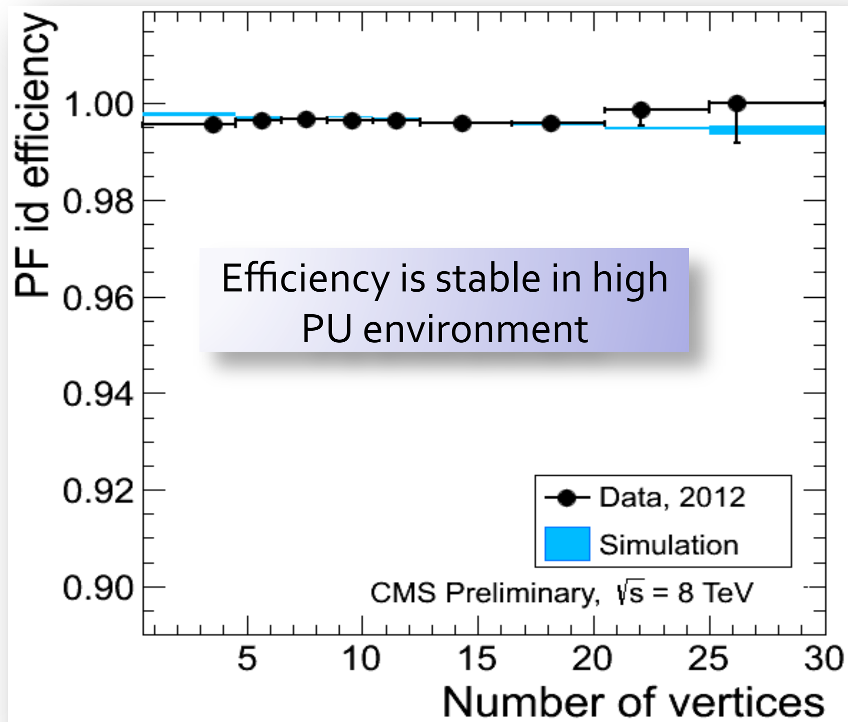


Muon reconstruction and identification

- Start with particle flow muons
- Efficiency above 96% down to $p_T = 5$ GeV
  - Above 99% efficiency for $p_T > 10$ GeV
  - Efficiency in data using J/Ψ and Z peak

Tighter quality criteria applied in some analyses

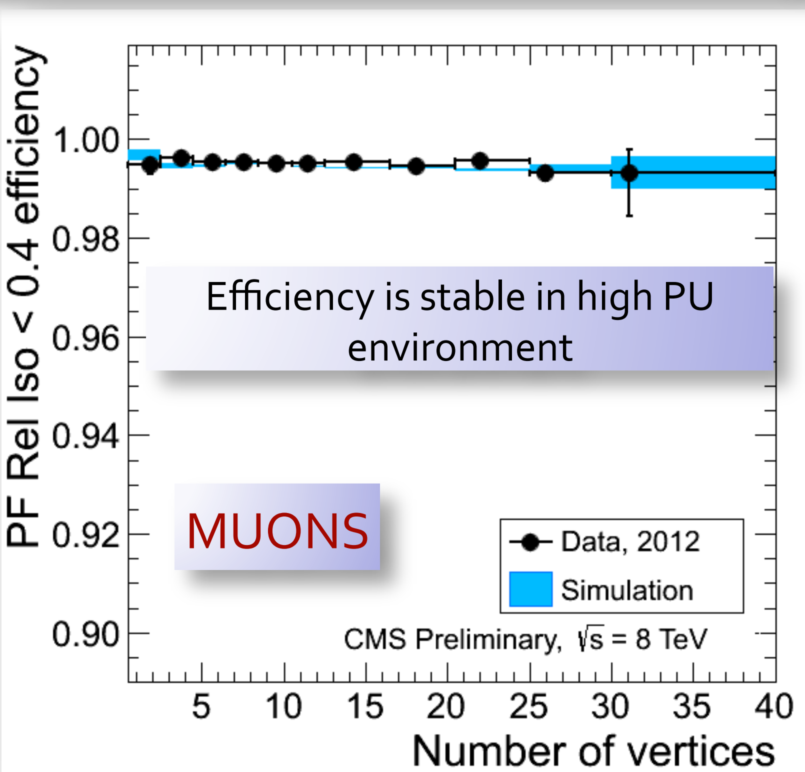




Particle-based isolation

Sum energy of particles in ΔR cone around the lepton

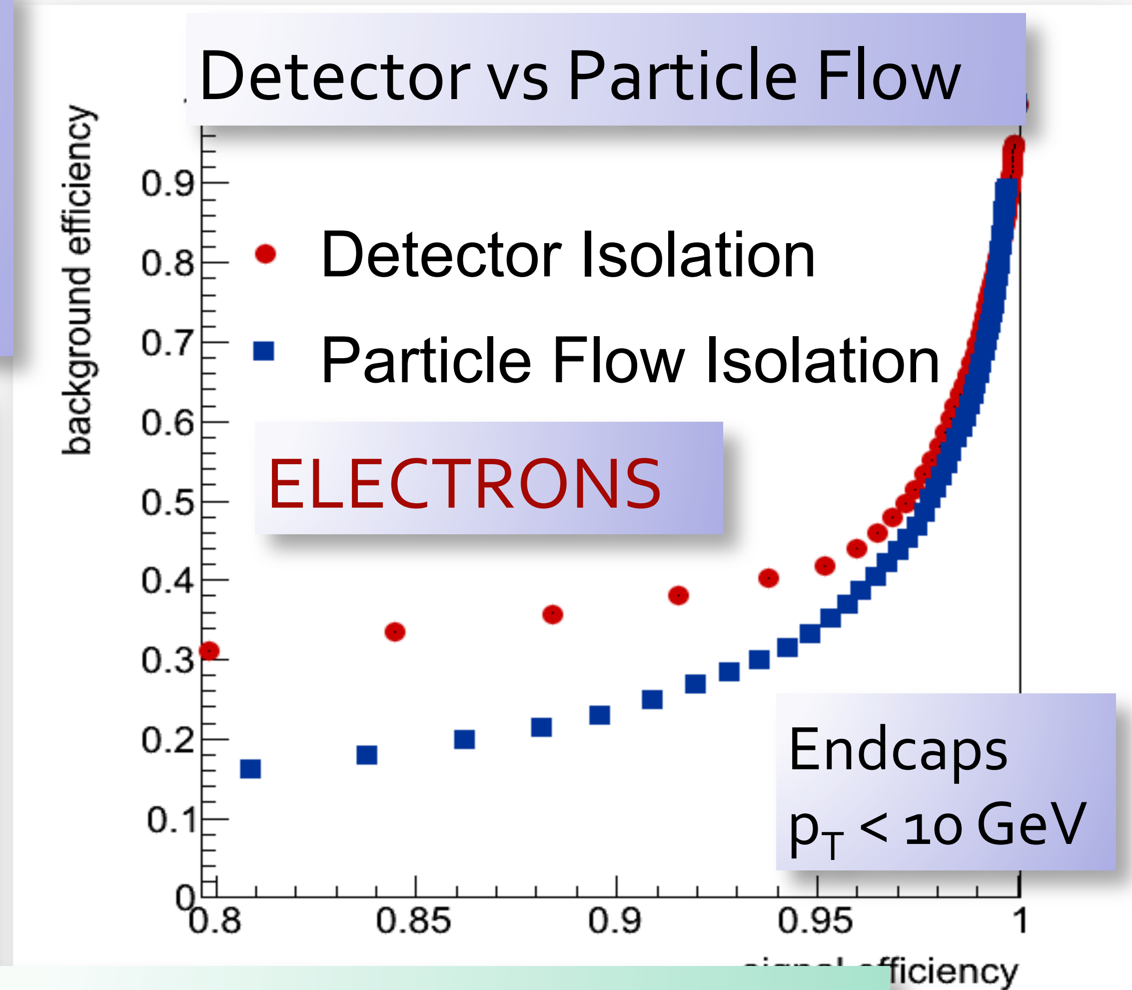
- Global event description eliminates double counting



Efficiency is stable in high PU environment

MUONS

Detector vs Particle Flow



ELECTRONS

Endcaps

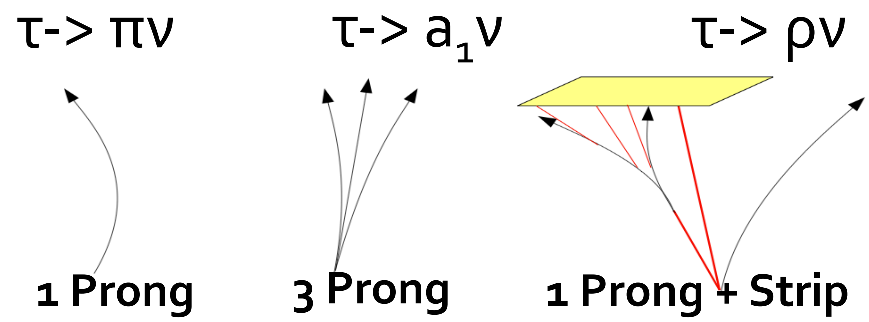
p_T < 10 GeV

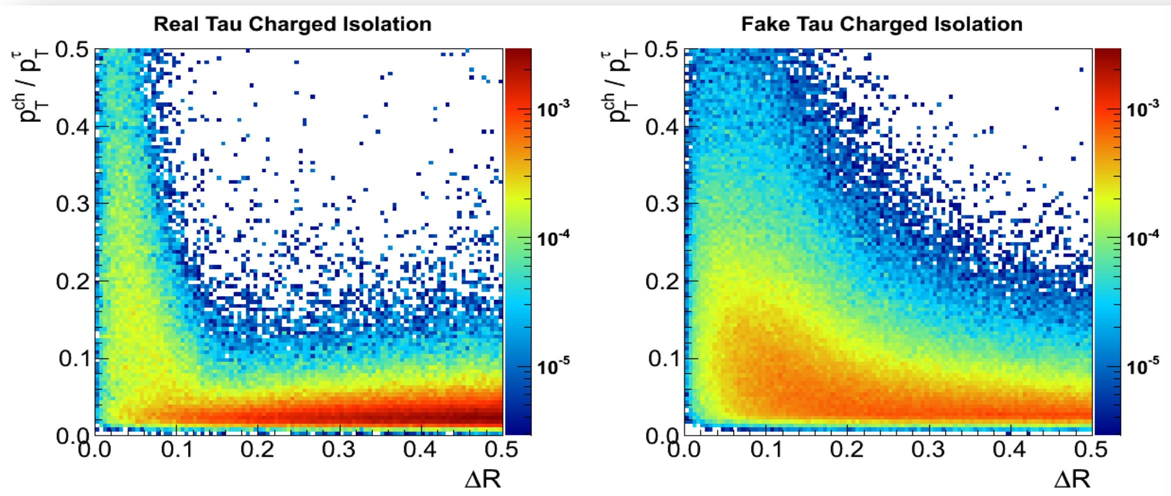
Pile-up contribution:

- Negligible for charged hadrons (vertexing)
- Neutrals corrected w/global energy density (ρ)

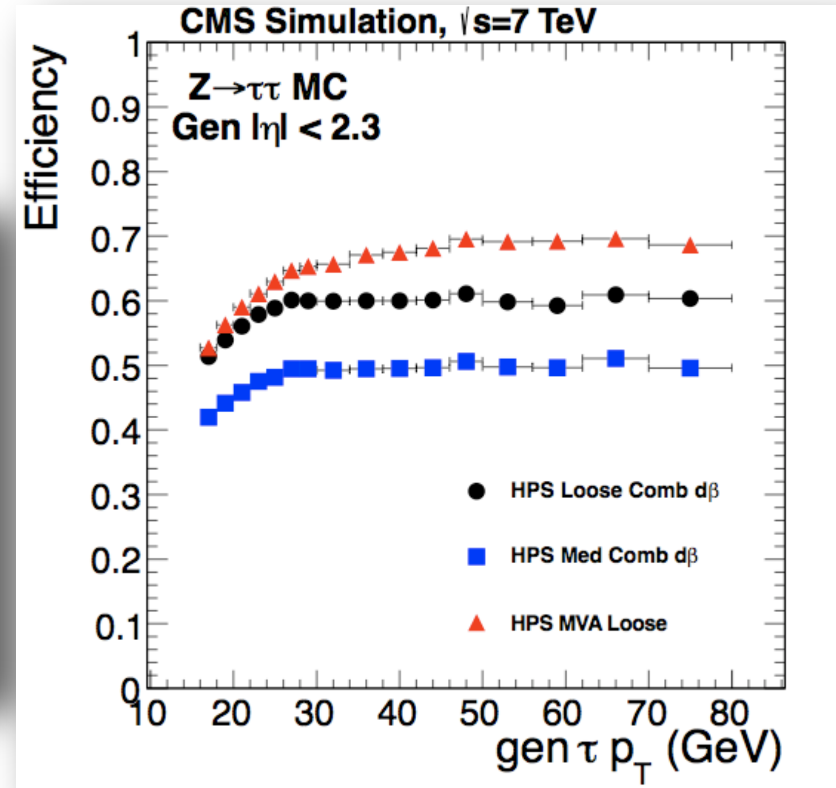
Tau Identification

- Tau identification:
  - Reconstruct individual decay modes
  - Charged hadrons + electromagnetic obj
    - EM strips account for material effects
- Tau isolation:
  - Multivariate discriminator using sum of energy deposits in dR rings around the tau



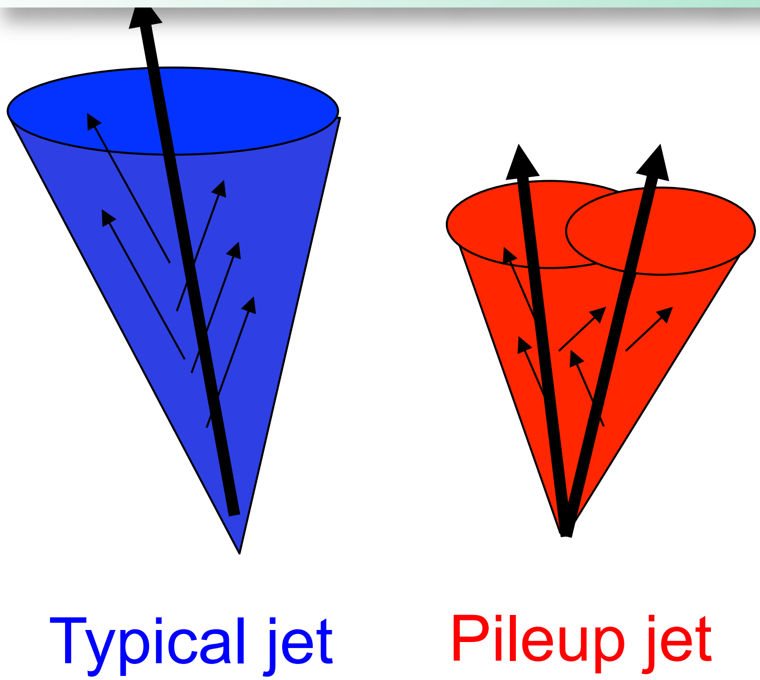


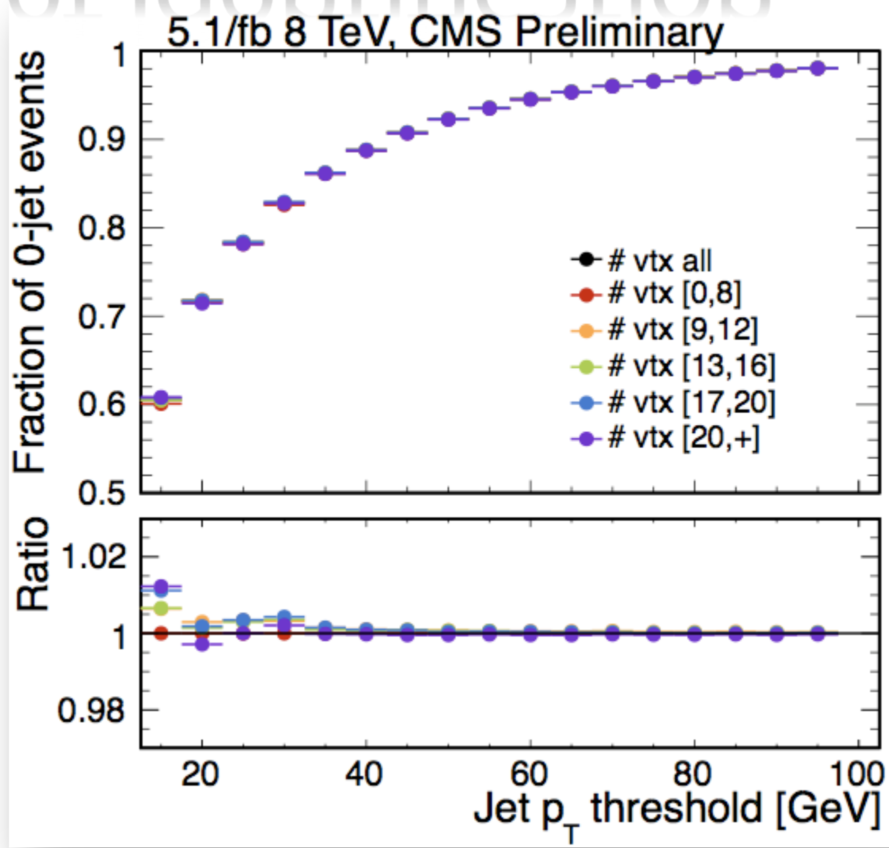
Real taus Fake taus



Jet Identification

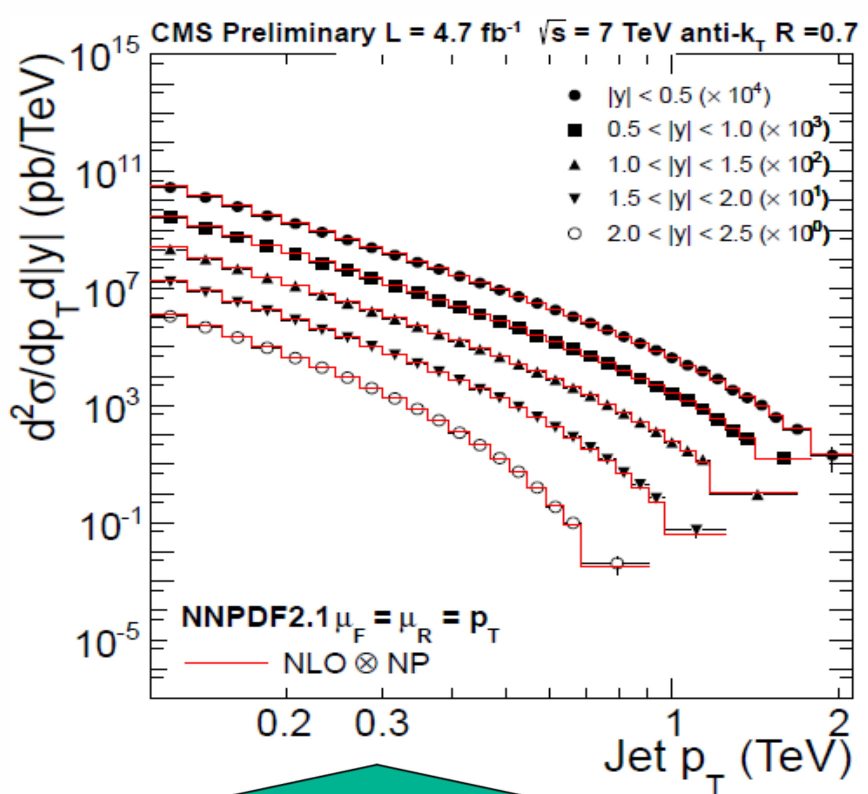
- Jet reconstruction
  - Reconstruction with particle flow objects



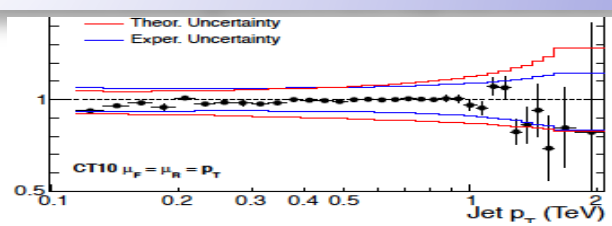


- Pileup jets structure differs wrt regular jets:
  - Pileup jets originate from several overlapping jets which merge together
  - Likelihood grows rapidly with high pileup
- Discriminant exploits shape and tracking variables
  - discrimination both inside and outside tracker acceptance

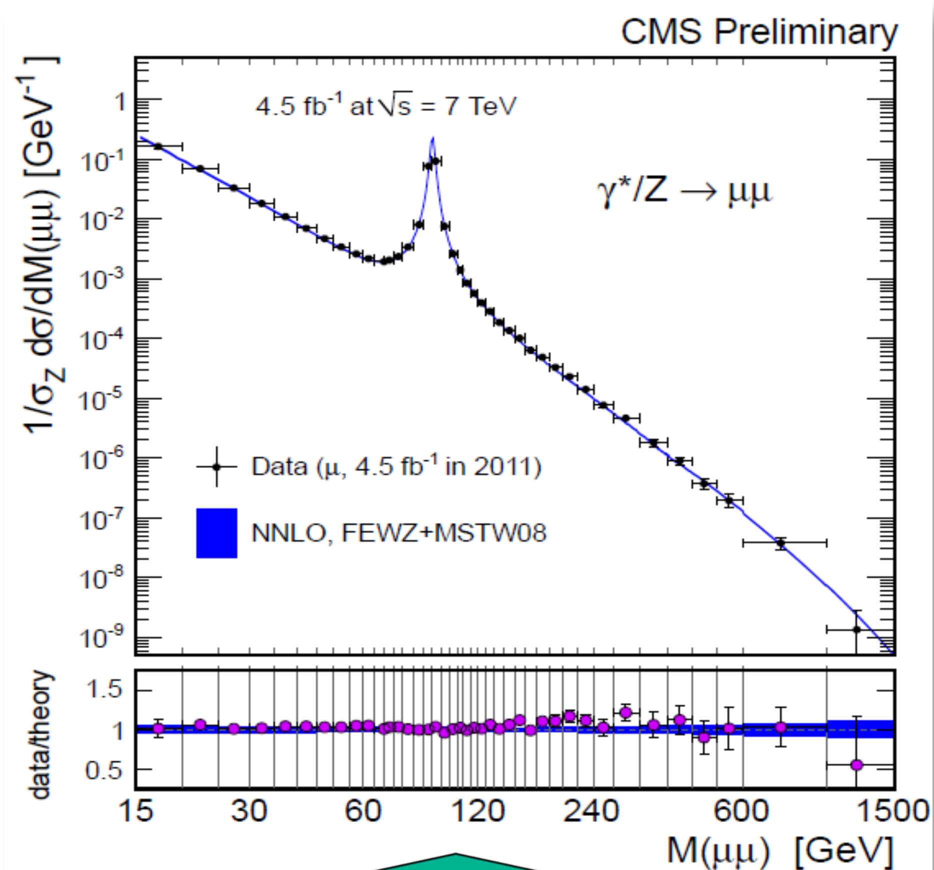
Standard Model: Precision Jets, W, and γ^*/Z



Inclusive jet and dijets. 2-4% JES.
Constrains gluon PDF up to x=0.6



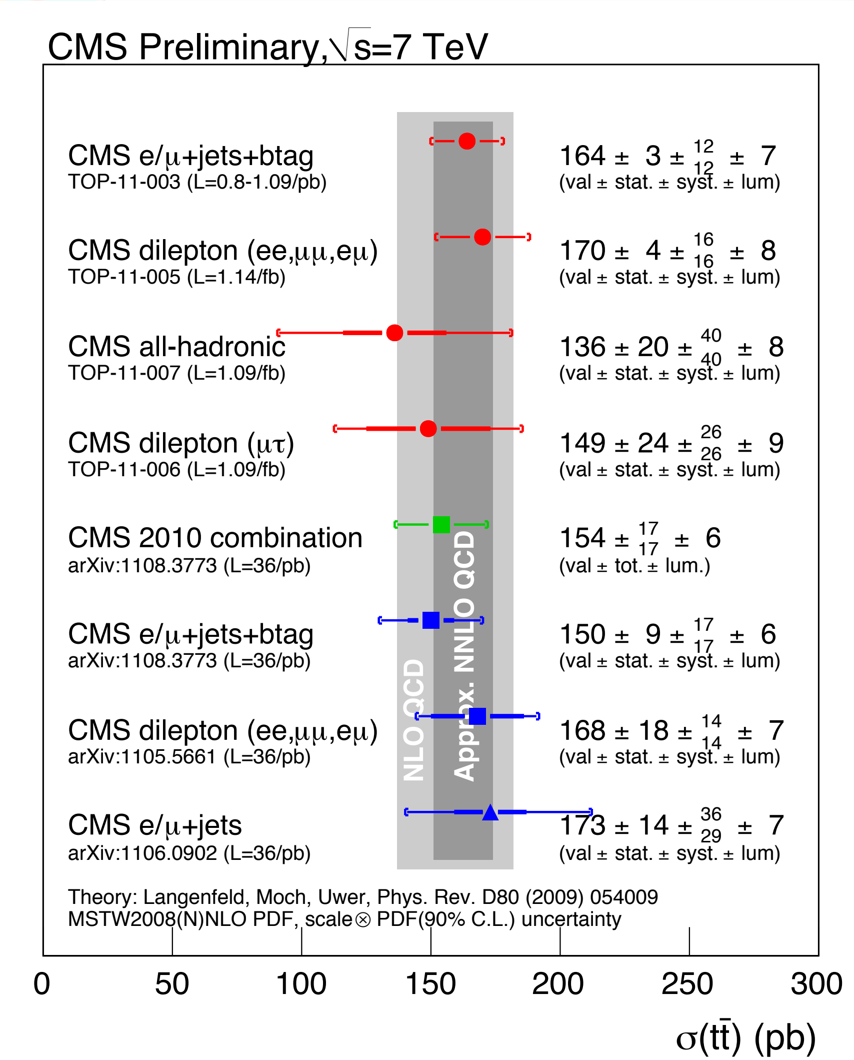
CMS-PAS-QCD-11-004

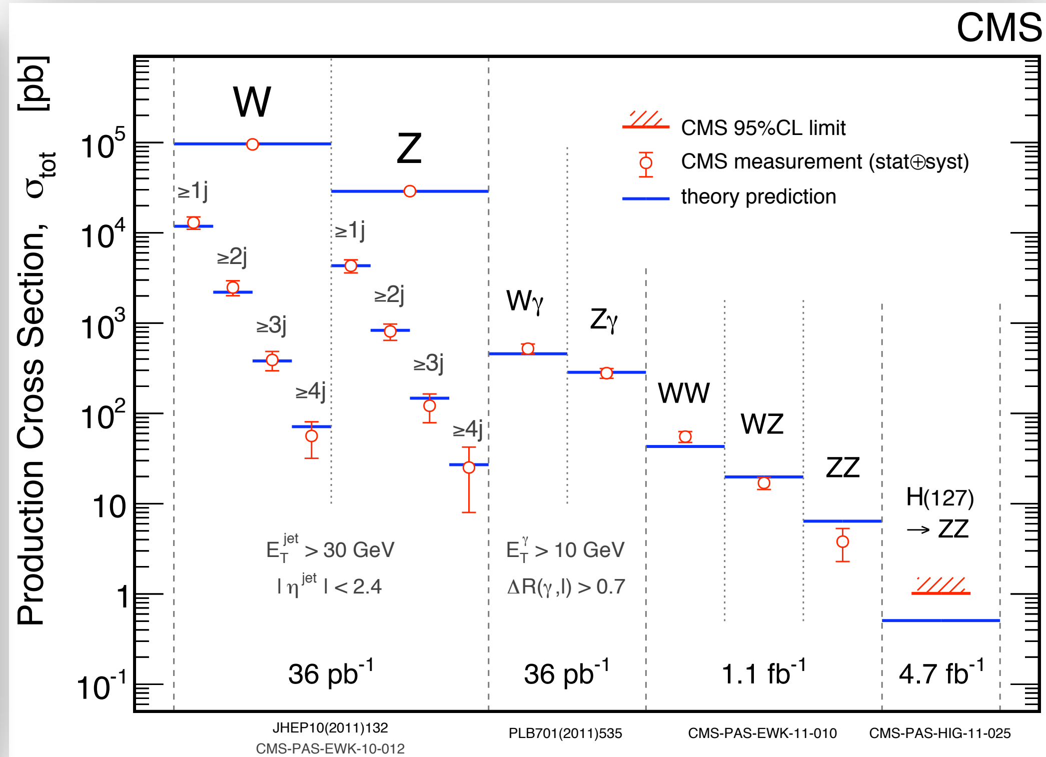


Differential Drell-Yan cross section: 2.5M $\mu\mu$ pairs tests NNLO cross sections and PDFs

CMS-PAS-EWK-11-007

Standard Model at 7 TeV 2010-2011

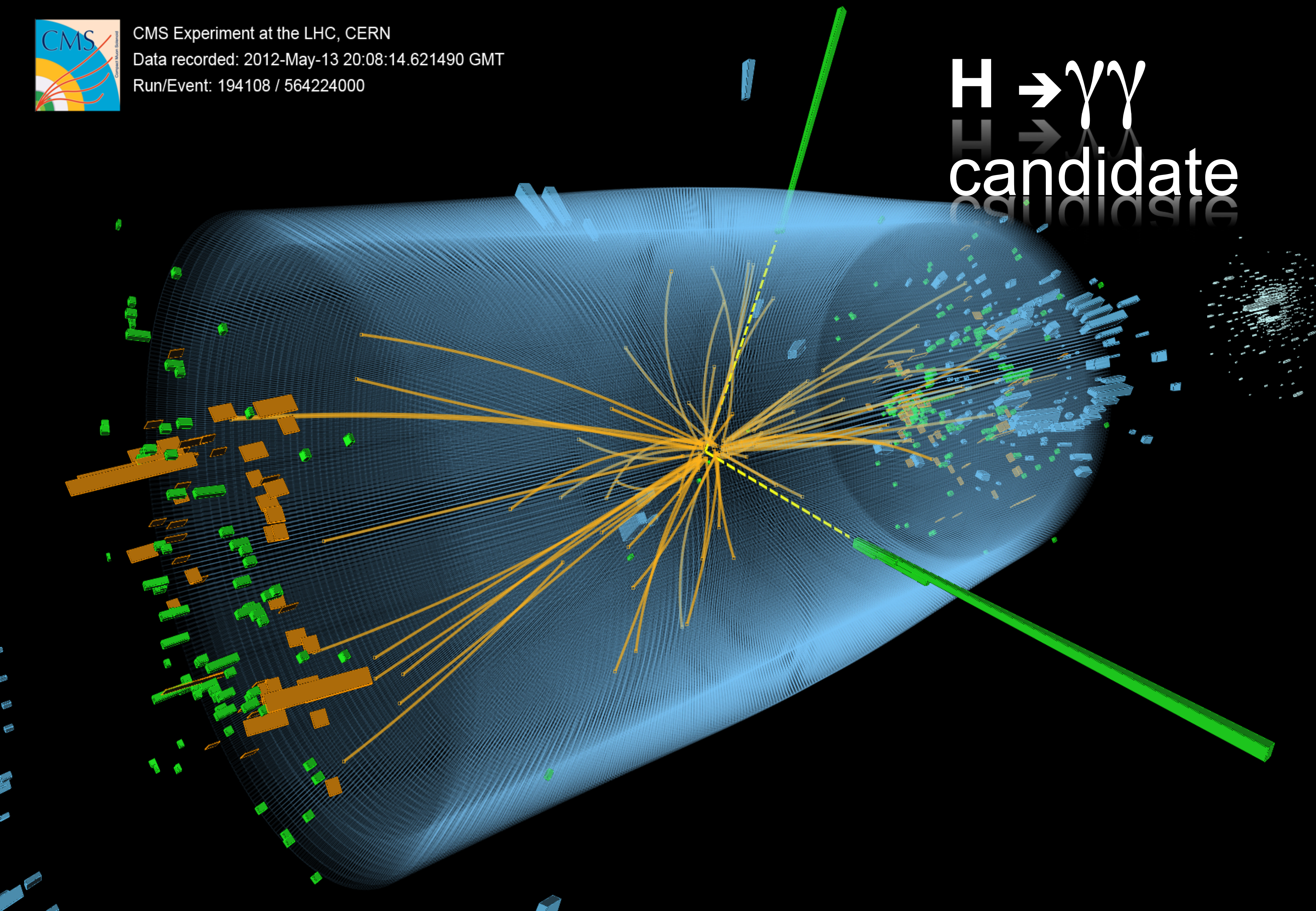




- Fabulous agreement
- Lots of data

… on to the Higgs…

$H \rightarrow \gamma\gamma$

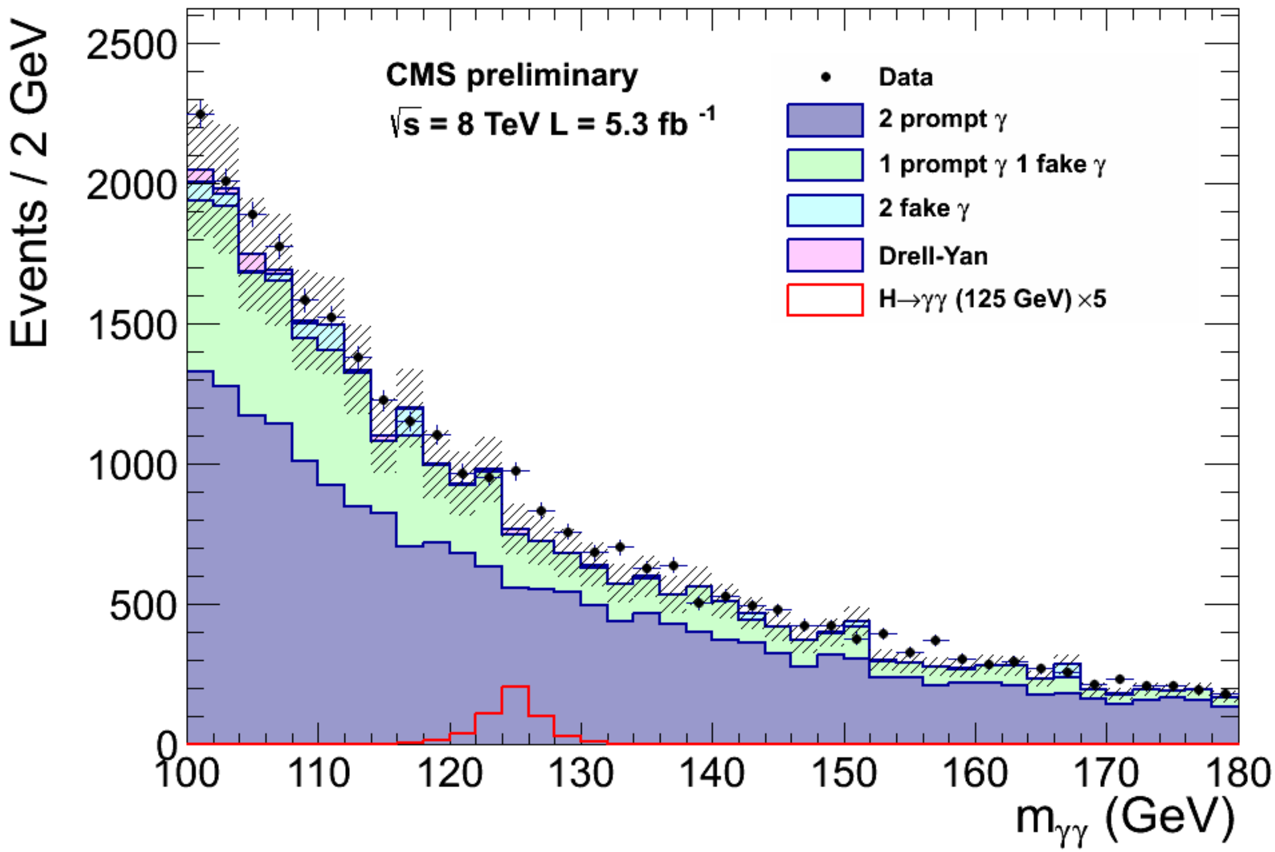

CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000
H →γγ
candidate

$H \to \gamma\gamma$ Overview

- Main analysis is a Multi-Variate-Analysis (MVA)
  - MVAs for photon ID and event classification
    - Fit mass distribution in 4 event classes based on a diphoton MVA output + 2 di-jet categories
  - Improvement in expected limit ~15% over cut-based analysis
  - **Cross-checked with an alternative background model extraction:**
    - Fit output of a 2nd MVA combining diphoton MVA and $m_{\gamma\gamma}$ using data in mass sidebands to construct the background model
- Also cross-checked with a cut based analysis
  - Simple and robust
    - Cut based photon ID and event classification
      - Fit data mass distribution in 2 rapidity x 2 shower shape =4 categories with different Signal over Background (S/B) + 2 di-jet categories
  - Published for 2011 data
    - Phys.Lett. B710 (2012) 403-425 arXiv:1202.1487

Search for a narrow mass peak with two isolated high Et photons

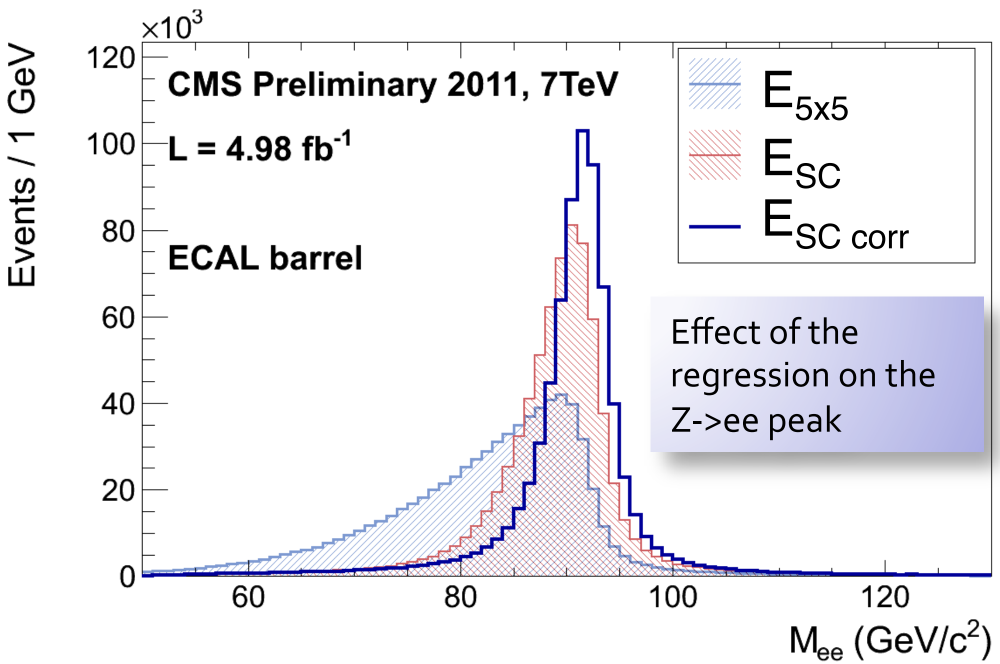
2012 8 TeV



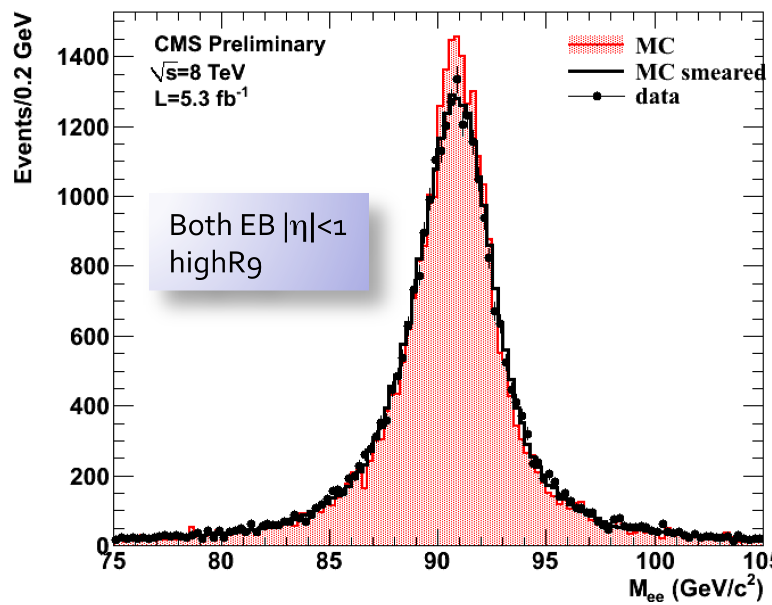
- Blind analysis in 2012
- Re-reco 2011 data into unchanged 2011 analysis
- Background MC only used for analysis optimization, Z->ee also to measure photon efficiencies and resolution with data

Photon Energy Scale and Resolution

- ECAL cluster energies corrected using a MC trained multivariate regression
  - Improves resolution and restores flat response of energy scale versus pileup
    - Inputs: Raw cluster energies and positions, lateral and longitudinal shower shape variables, local shower positions w.r.t. crystal geometry, pileup estimators
- Regression also used to provide a per photon energy resolution estimate
- To measure the Energy Scale and resolution: use $Z \rightarrow e^+e^-$



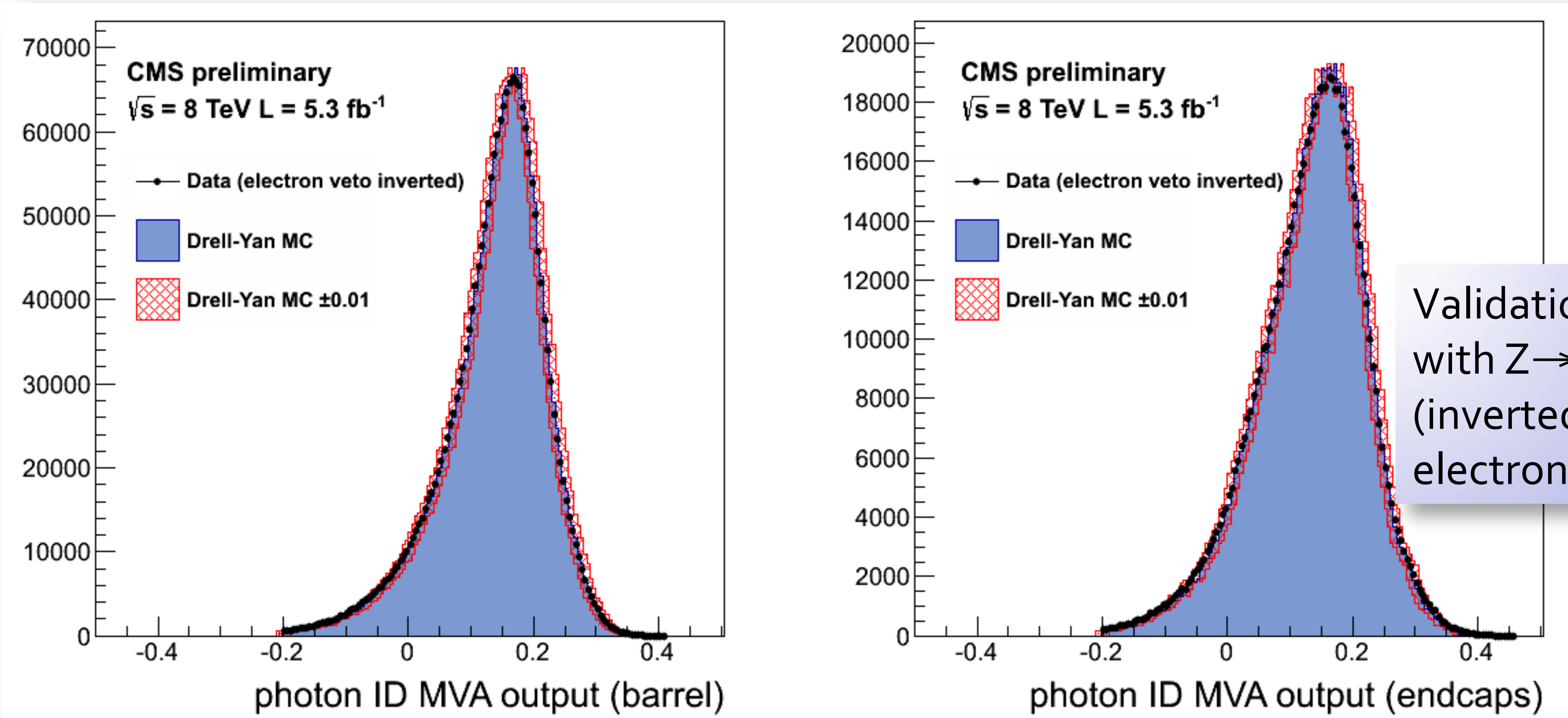
Effect of the regression on the Z->ee peak



Both EB |η|<1 highR9

Photon ID

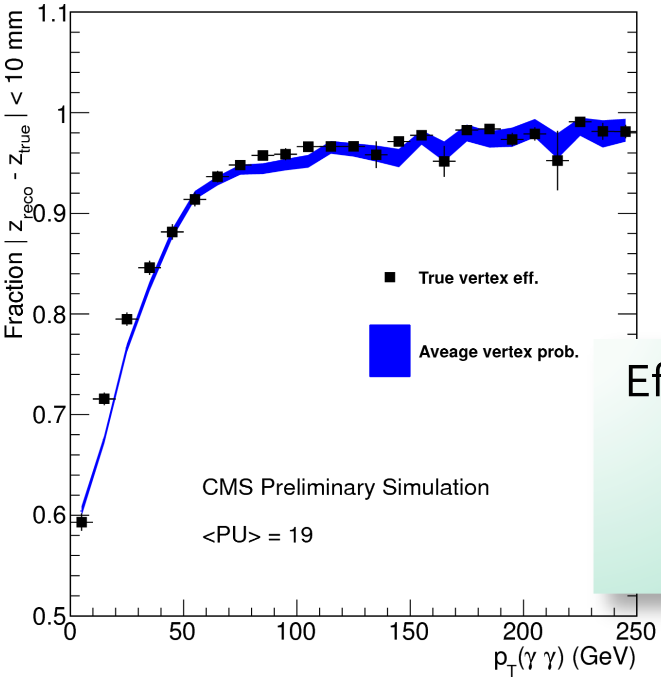
- **Photon pre-selection:**
  - $E_{T\gamma 1}/m_{\gamma\gamma}>3$, $E_{T\gamma 2}/m_{\gamma\gamma}>4$
  - Photon Id a bit tighter than trigger selection and MC EM enrichment filters
    - Efficiency measured using tag and probe with $Z\rightarrow ee$
  - Electron veto: Efficiency measured using tag and probe with $Z\rightarrow\mu\mu\gamma$
- **MVA based photon ID discriminates photons from fakes:**
  - Inputs: isolation, shower shape, per event energy density, pseudorapidity



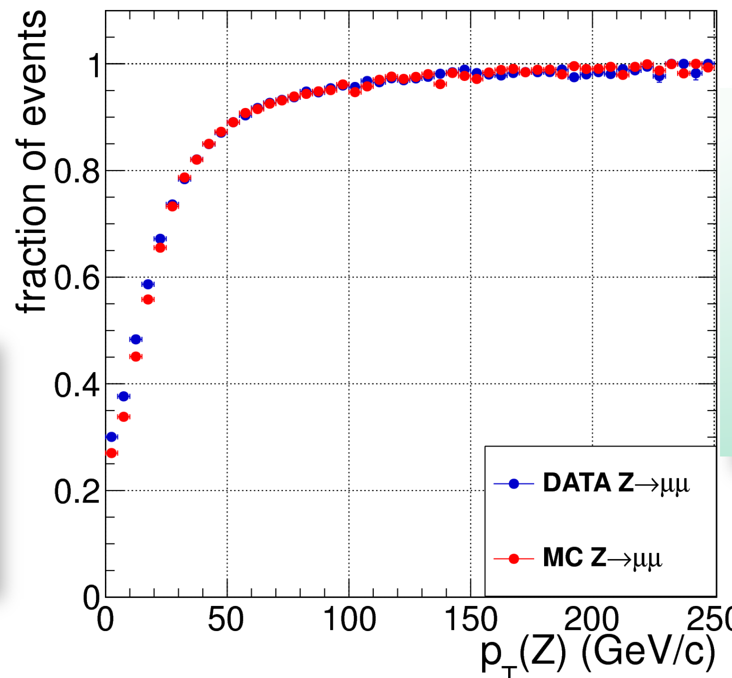
Validation with $Z\rightarrow ee$ (inverted electron veto)

The γγ Vertex Choice

- Mass reconstruction
  - Depends on the correct position of the primary vertex
- Interaction vertex is identified using tracks from recoiling jets and underlying event plus conversions
  - correct in ~83% of cases for pileup in 2011 sample.
  - correct in ~80% of cases for pileup in 2012 sample.
- Vertex identification with a BDT
  - Input variables: Σp_t^2, Σp_t projected onto the γγ transverse direction, p_t asymmetry and conversions
- Correct vertex finding probability also estimated using a BDT



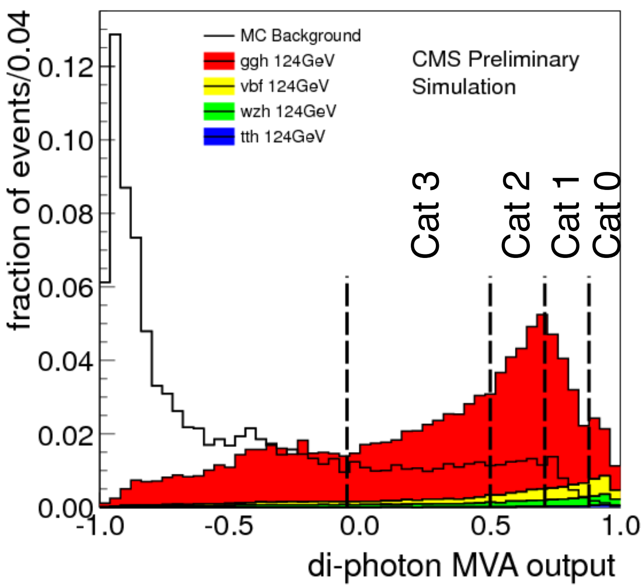
Efficiency to identify correct vertex

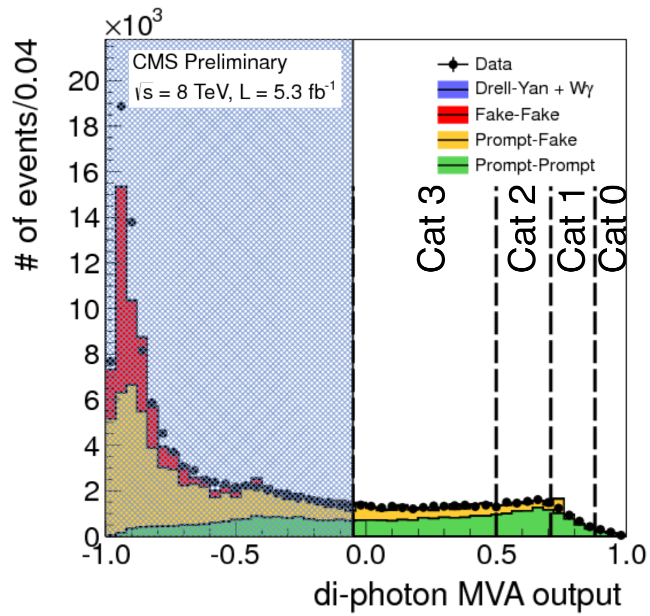


Data-MC efficiency for Z->μμ After removing the μ tracks

Diphoton MVA

- Diphoton MVA trained on signal and background MC with input variables largely independent of $m_{\gamma\gamma}$
  - Kinematics: p_T and η of each photon, and cos$\Delta\phi$ between the 2 photons
  - Photon ID MVA output for each photon
  - per-event mass resolution and vertex probability
- Encode all relevant information on signal vs background discrimination (aside from $m_{\gamma\gamma}$ itself) into a single di-photon MVA output to first order independent of $m_{\gamma\gamma}$



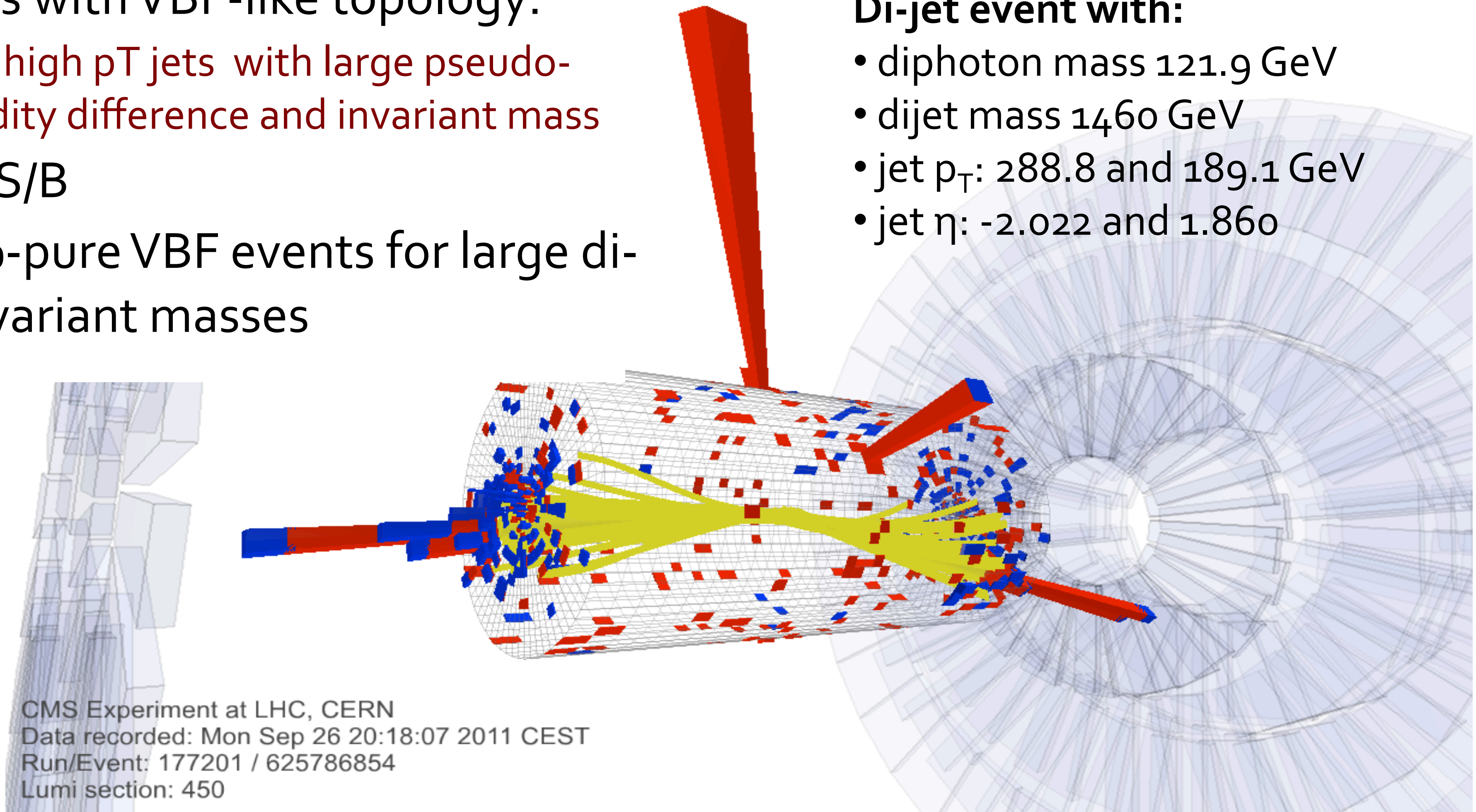


- Residual data-MC disagreement
  - For BG only make analysis sub-optimal
  - For signal would cause some category migration included in the systematic errors

Di-jet Tagging

- Exclusive selection of di-photon events with VBF-like topology:
  - Two high pT jets with large pseudo-rapidity difference and invariant mass
- High S/B
- ~80%-pure VBF events for large di-jet invariant masses

Di-jet event with:
- diphoton mass 121.9 GeV
- dijet mass 1460 GeV
- jet p_T: 288.8 and 189.1 GeV
- jet η: -2.022 and 1.860



Di-jet Tagging: Selection

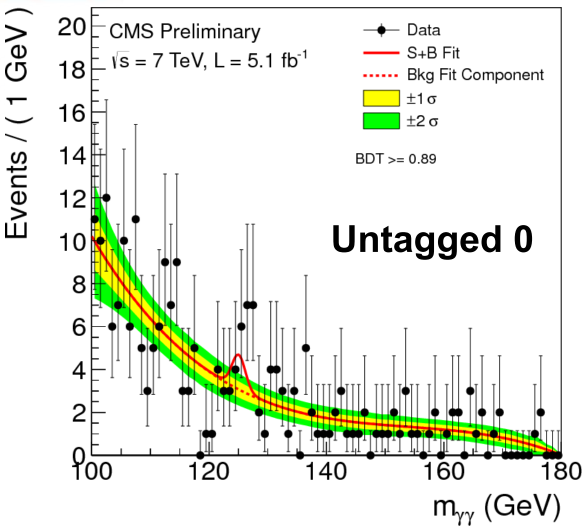
Analysis improvements in 2012:

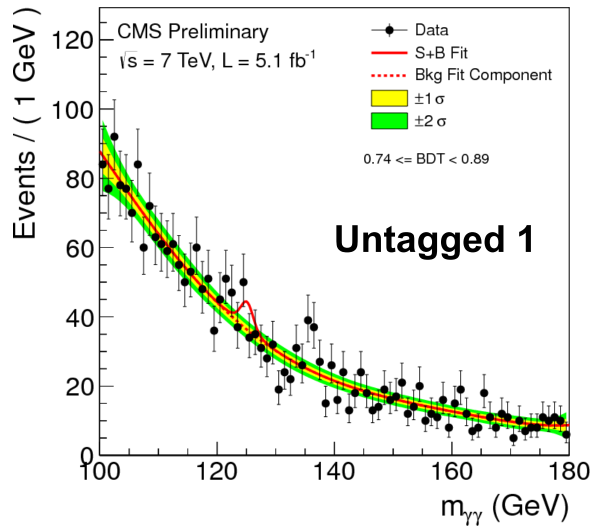
- Split di-jet tagged events in two categories based on M_{jj} and jet p_T
  - ~15% improvement in sensitivity for dijet category
  - better sensitivity to separate different Higgs production modes
- Removal of jets from pileup events
  - Based on the jet shape variables, tracks in jet and vertexing
  - Cross-checked using Z+jet and γ+jet events

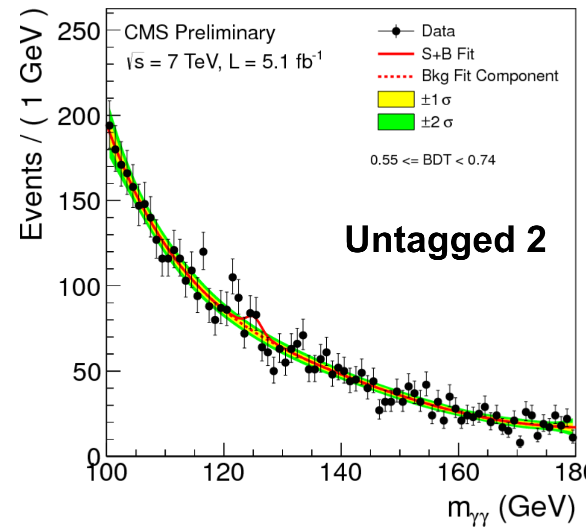
Dijet selection cuts

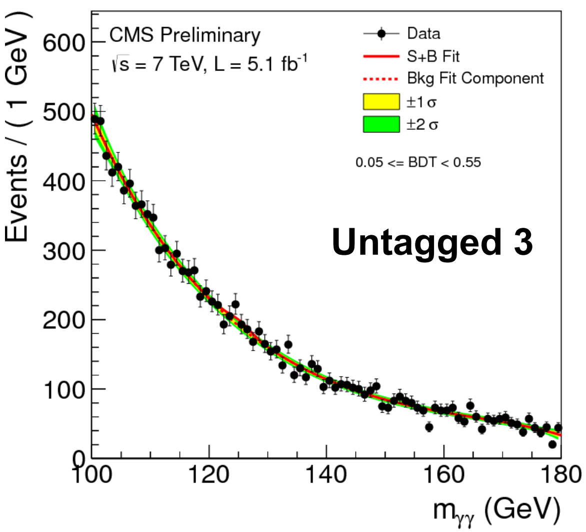
Variable	2011	2012	
		Loose	Tight
$p_T(j_1)$	> 30 GeV		
$p_T(j_2)$	> 20 GeV		> 30 GeV
$\Delta\eta(j_1, j_2)$	> 3.5	> 3.0	
$\lvert\eta_{\gamma\gamma} - \frac{1}{2}(\eta_{j1} + \eta_{j2})\rvert$	< 2.5		
$\Delta\phi(jj, \gamma\gamma)$	> 2.6		
m_{jj}	> 350 GeV	> 250 GeV	> 500 GeV

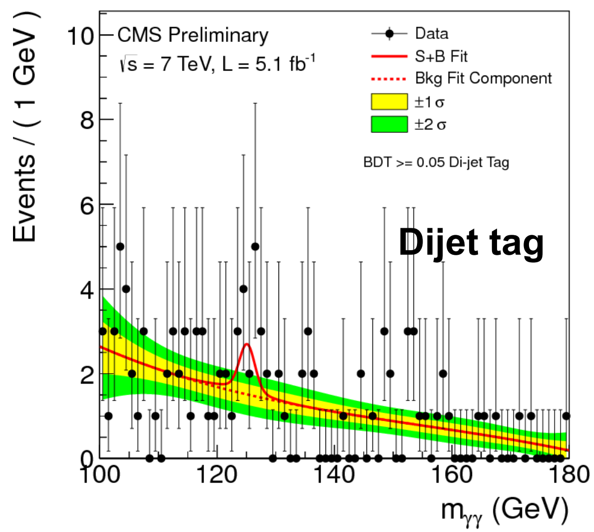
7 TeV Mass Distribution in Categories





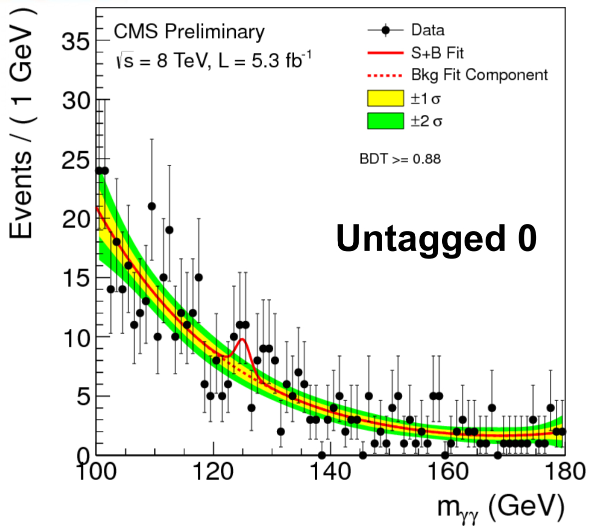


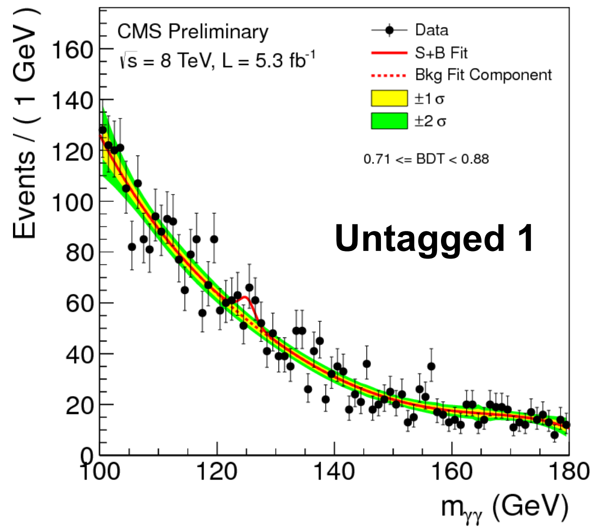


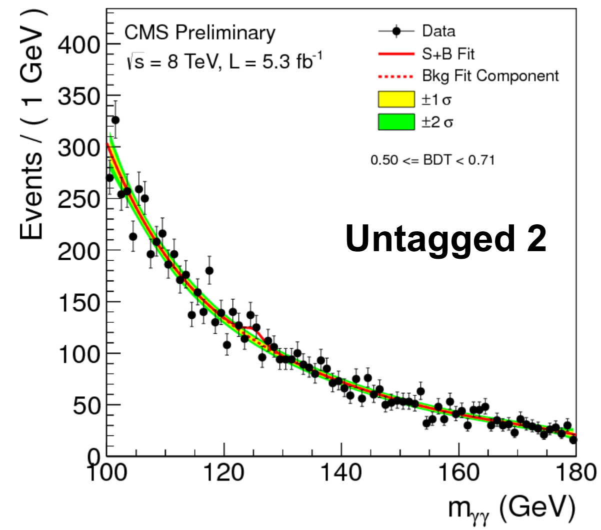


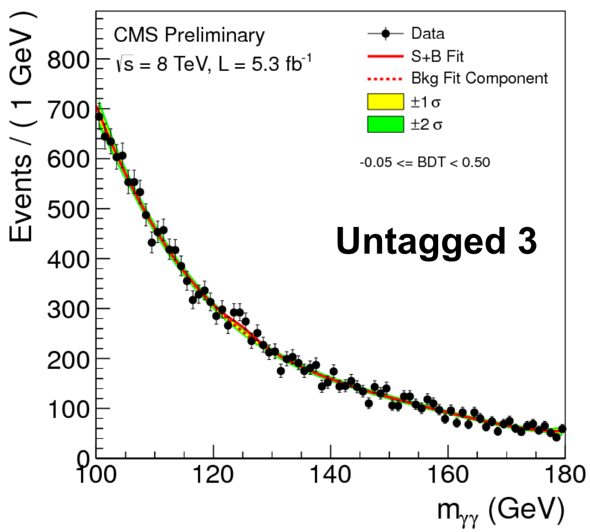
- Background model is entirely from data.
- Fit to mass distribution in each category with polynomial functions (3rd to 5th degree)
  - keep bias below 20% of fit error.
  - causes some loss of performance due to number of parameters in fit function.

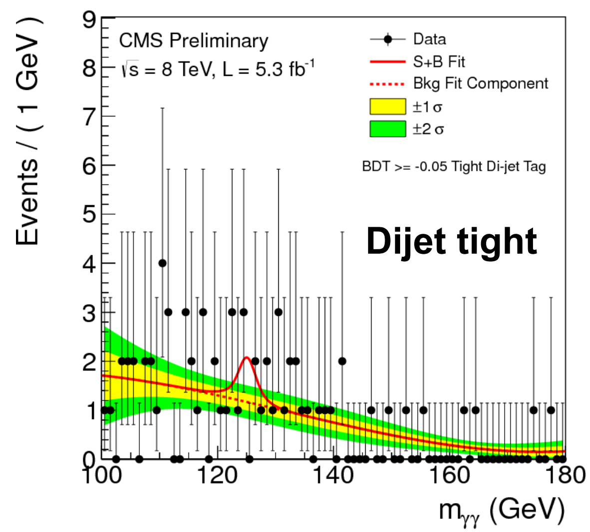
8 TeV Mass Distribution in Categories

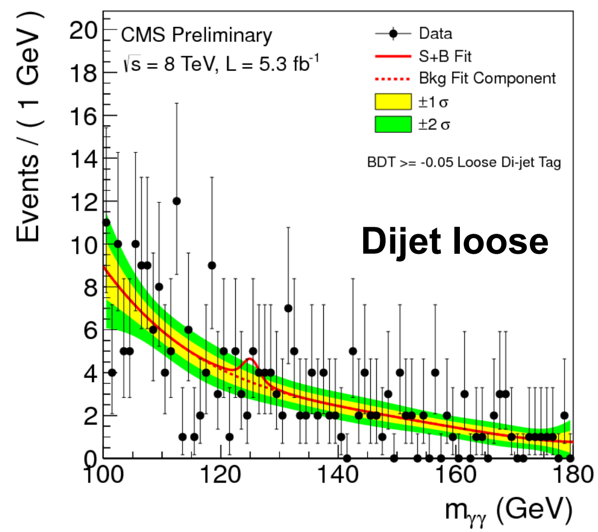






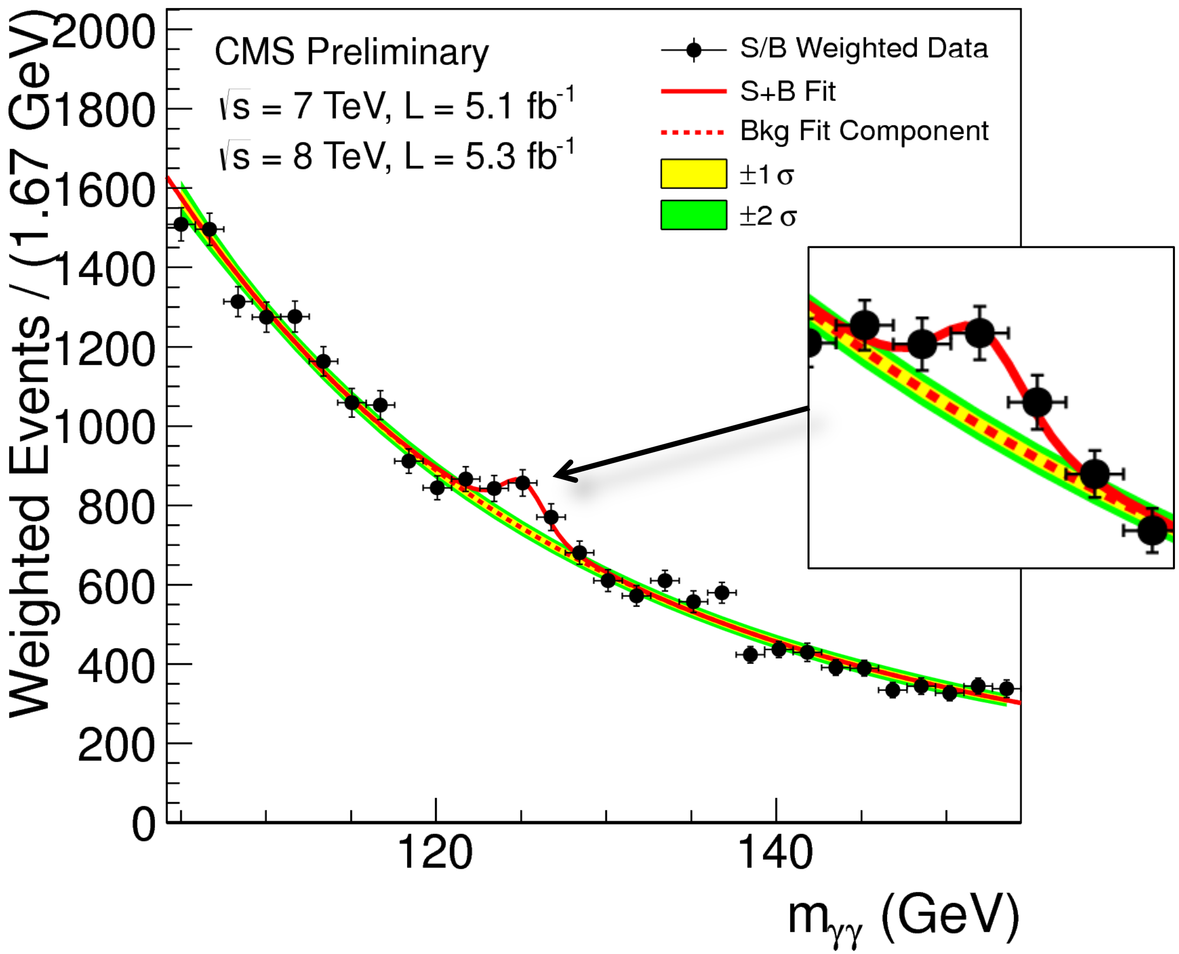




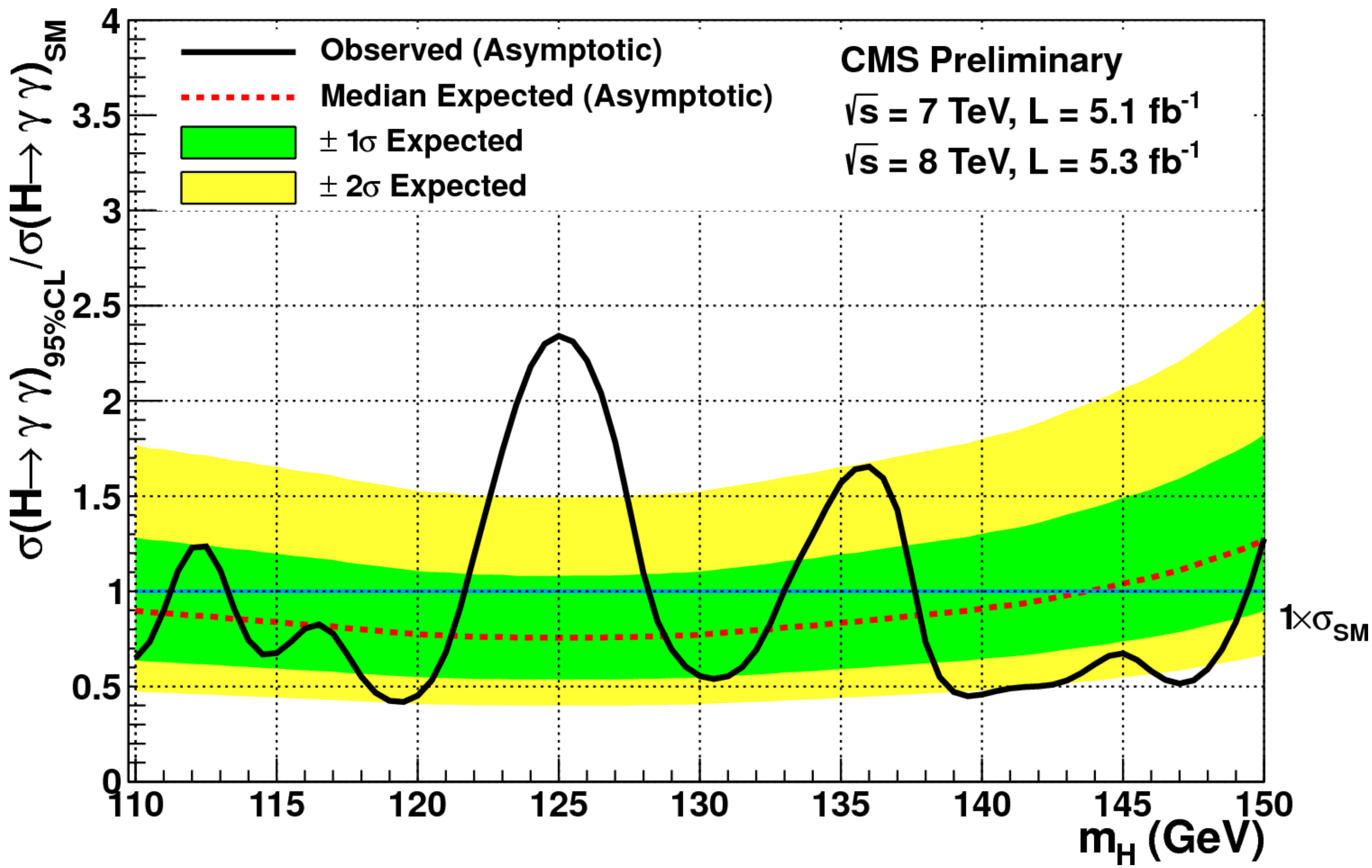


S/B Weighted Mass Distribution

- Sum of mass distributions for each event class, weighted by S/B
  - B is integral of background model over a constant signal fraction interval

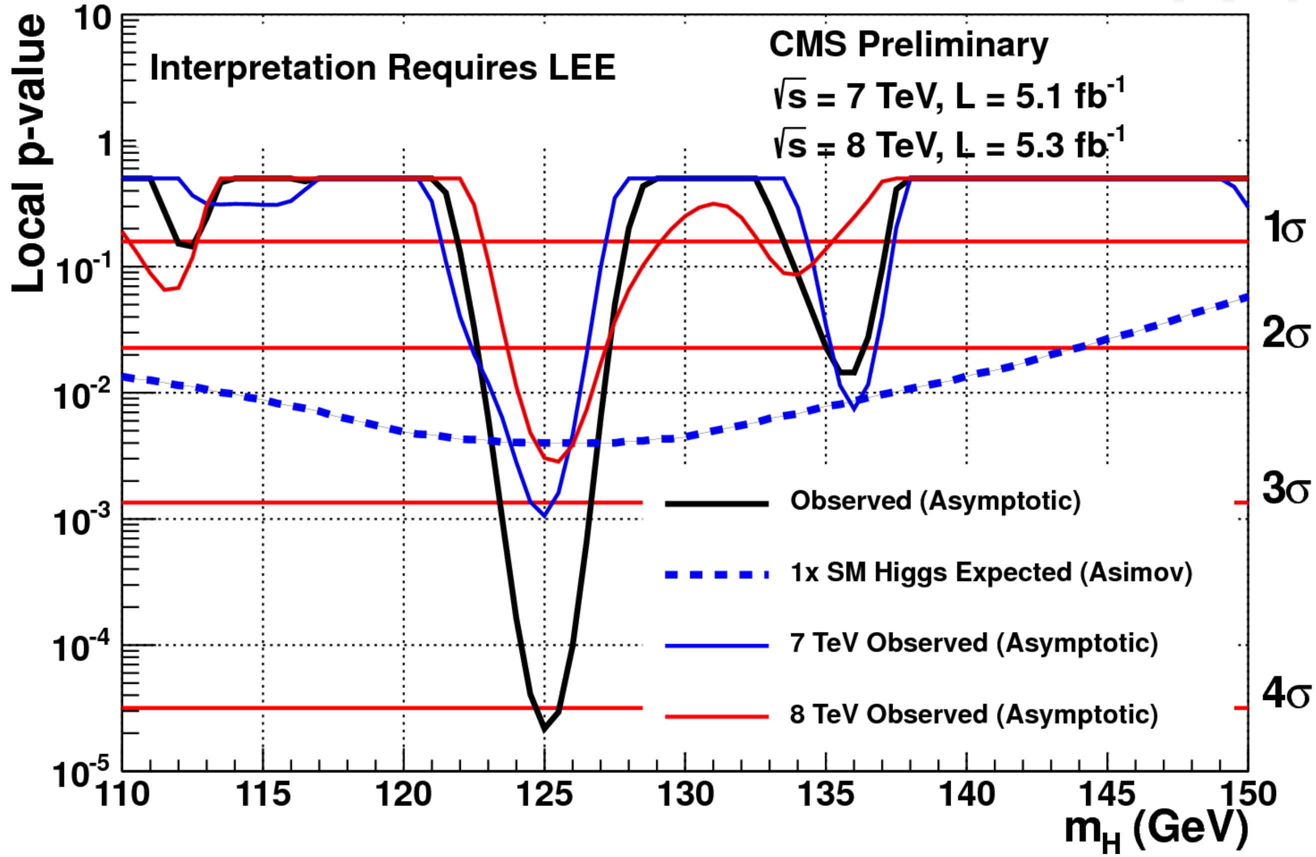


95% CL Exclusion for SM Higgs



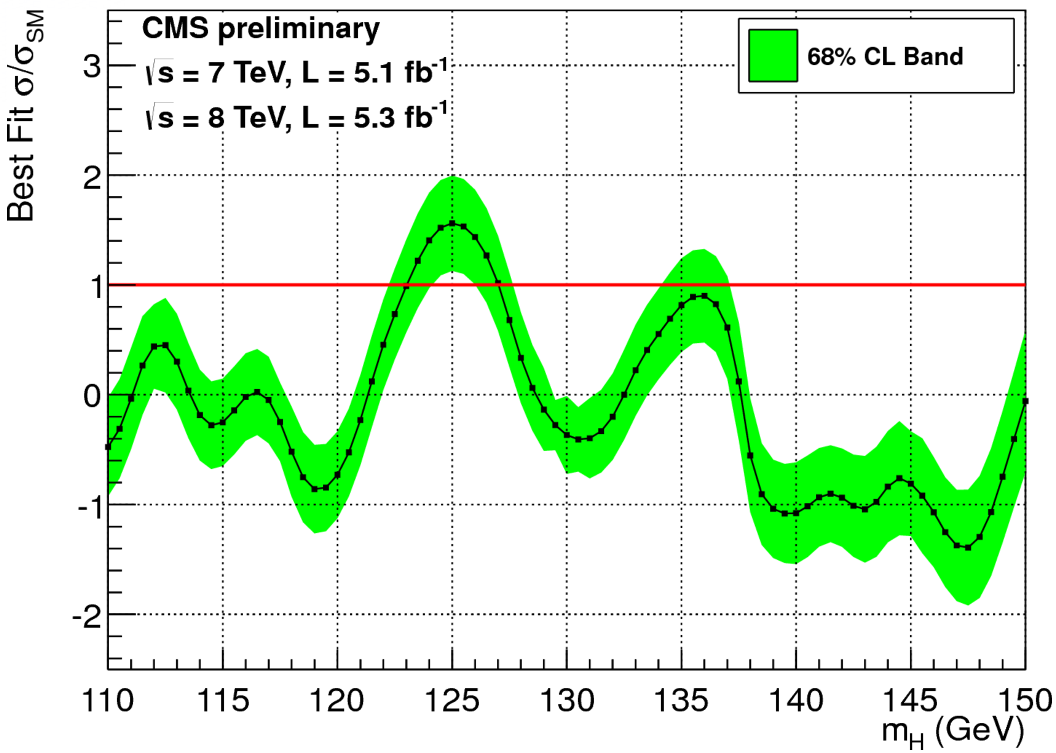
- Expected 95% CL exclusion 0.76 times SM at 125 GeV
- Large range with expected excusion below σ_{SM}
- Largest excess at 125 GeV

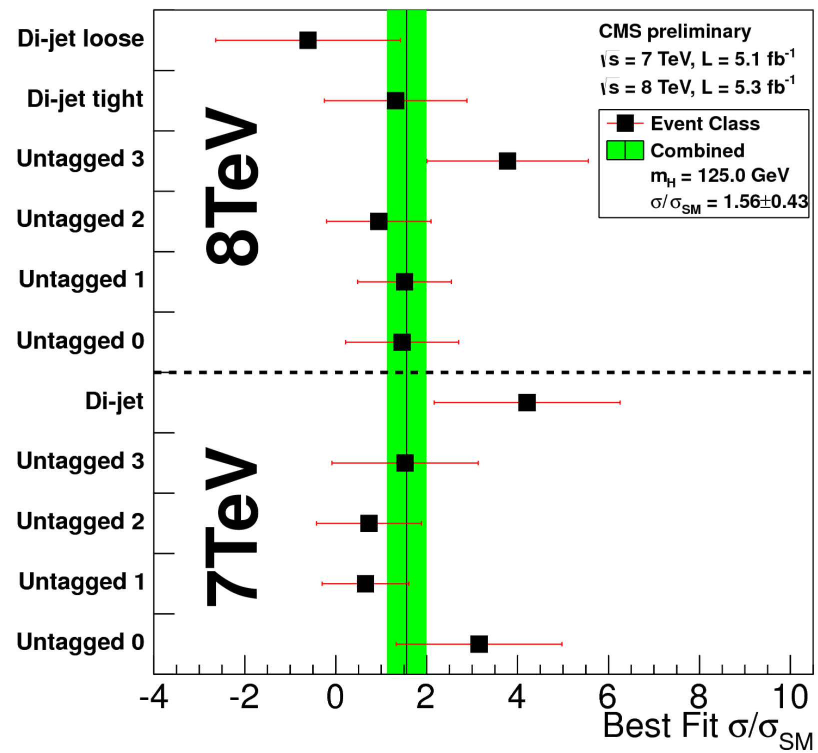
P-Values



- Minimum local p-value at 125 GeV with a local significance of 4.1 σ
- Similar excess in 2011 and 2012
- Independent cross check analyses give similar results
- Global significance in the full search range (110-150 GeV) 3.2 σ

Fitted Signal Strength





Combined best fit signal strength
σ/σ_{SM} = 1.56±0.43 x SM, consistent with SM.

Best fit signal strength consistent between different classes

$H \rightarrow ZZ^*$

$H \to ZZ^{(*)} \to 4l$ ($l = e,\mu$): the golden channel

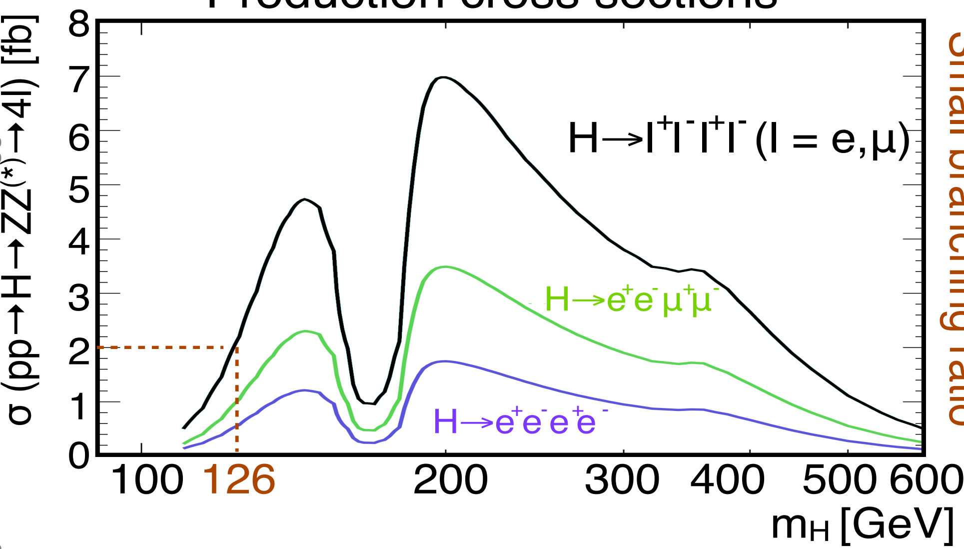
Clean signature: narrow peak, low background

Background: irreducible $ZZ^{(*)}$; reducible Z+jets, ttbar, WZ

One of the best performing channels in the whole mass range ...

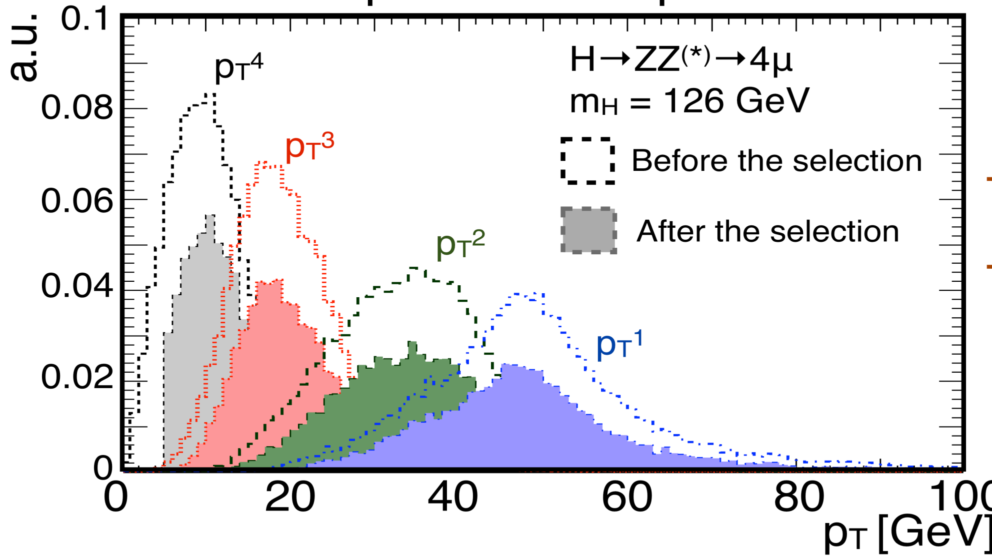
... but extremely demanding channel for selection, requiring the highest possible efficiencies (lepton Reco/ID/Isolation).

Production cross sections



Small branching ratio

pT of the 4 leptons



Low pT leptons

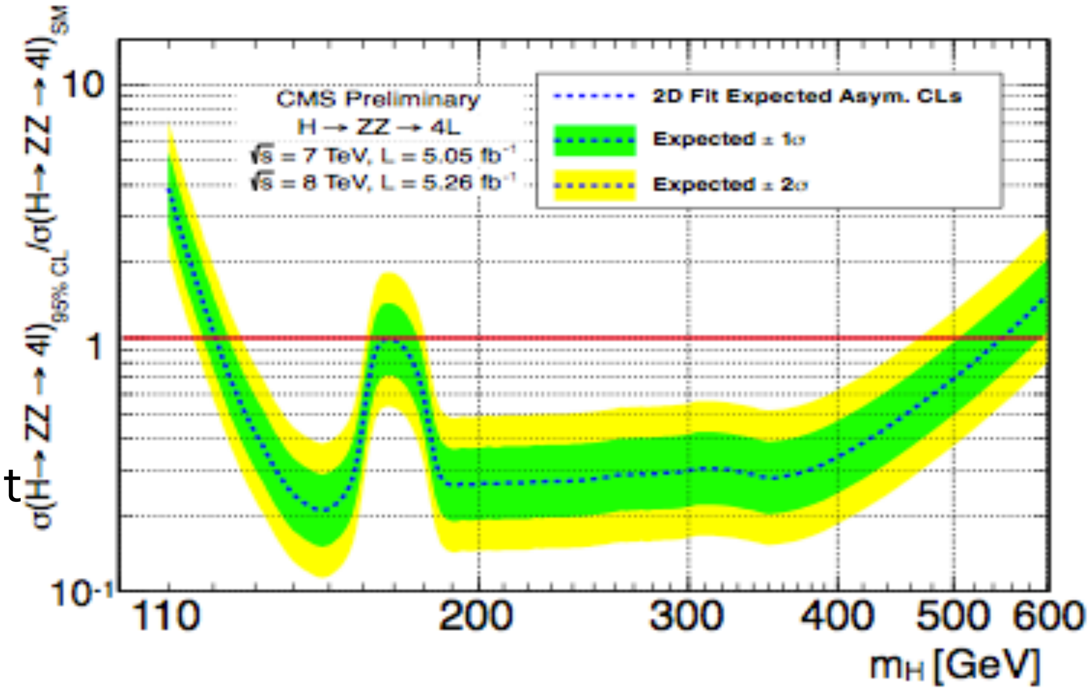
2012 analysis + improvements

Blinding policy: analysis optimized blindly for 2012, applied to 2011 reoptimization

Do NOT look at 110 < m_{4l} <140 GeV, and m_{4l} > 300 GeV

Main changes:

New lepton ID (MVA + PFlow)
New lepton PFlow isolation
Final State Radiation (FSR) recovery
2D analysis: m_{4l} + Kinematic Discriminant

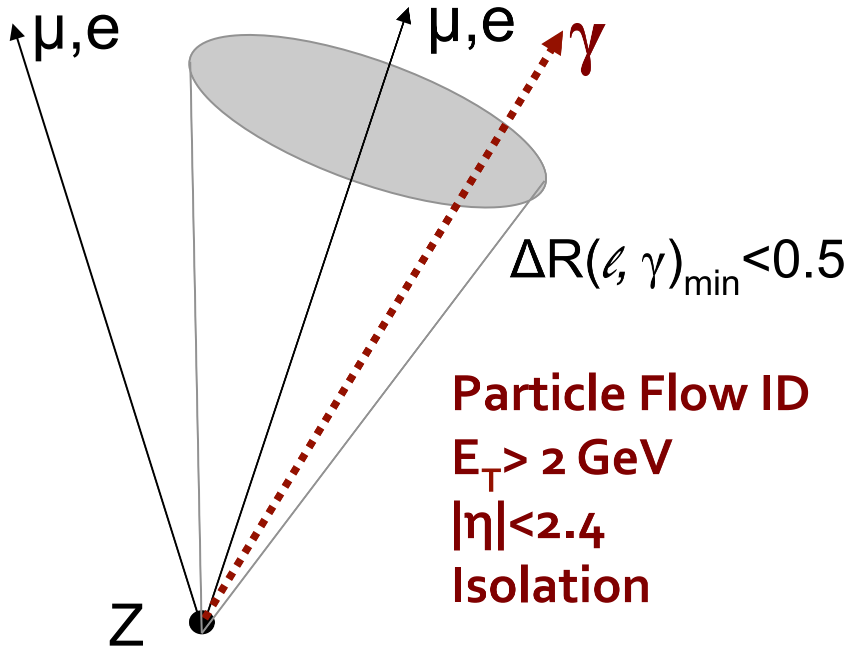


>20% improvement @ m_H = 126 GeV wrt 2011 analysis

Expected exclusion range 121–540 GeV

Final State Radiation recovery algorithm

- **Applied on each Z for photons near the leptons**

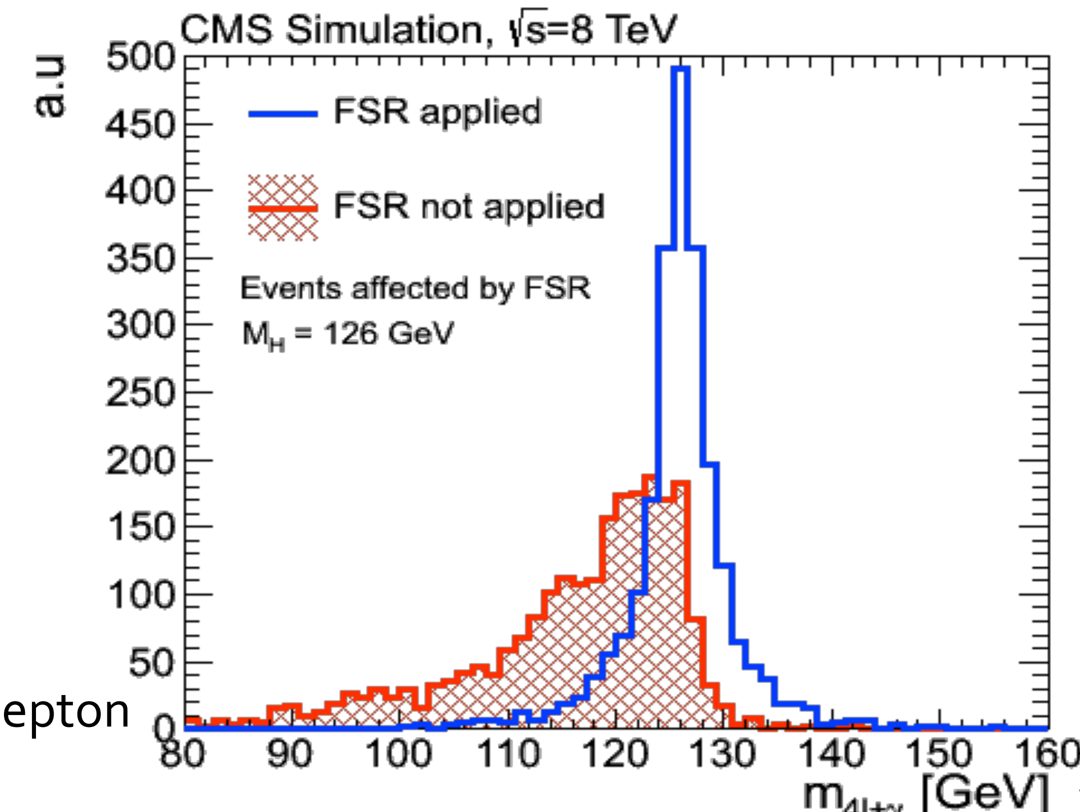


Particle Flow ID
E_T> 2 GeV
|η|<2.4
Isolation

- Associates photon with Z if:
  - $M(ll+\gamma) < 100$ GeV
  - $|M(ll+\gamma)-M_Z| < |M(ll)-M_Z|$
- Removes associated photons from lepton isolation calculation

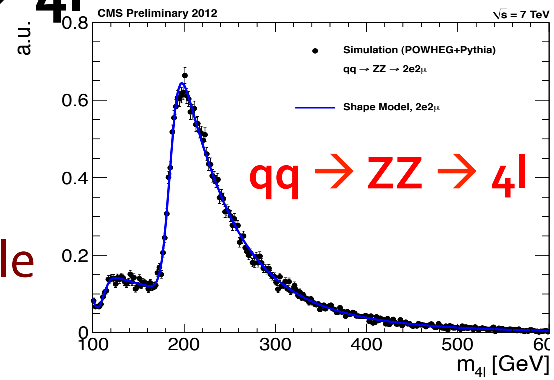
Expected Performance for M_H=126 GeV

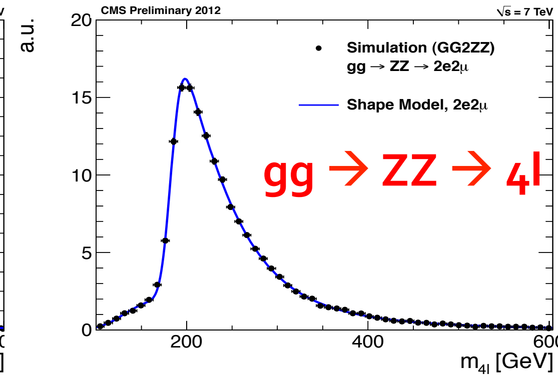
- 6% of events affected
- Average purity of 80%
- 2% added in analysis



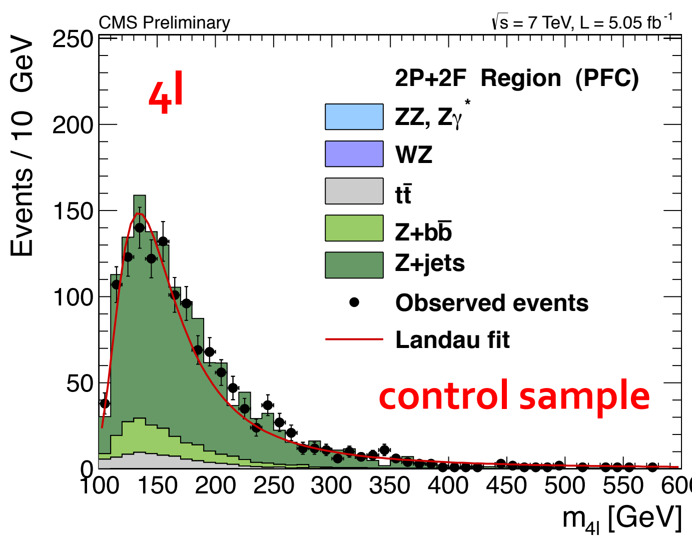
Background models

- **Irreducible background ZZ → 4l**
  - Estimated **using simulation**
  - Phenomenological shape models
  - Corrected for data/simulation scale

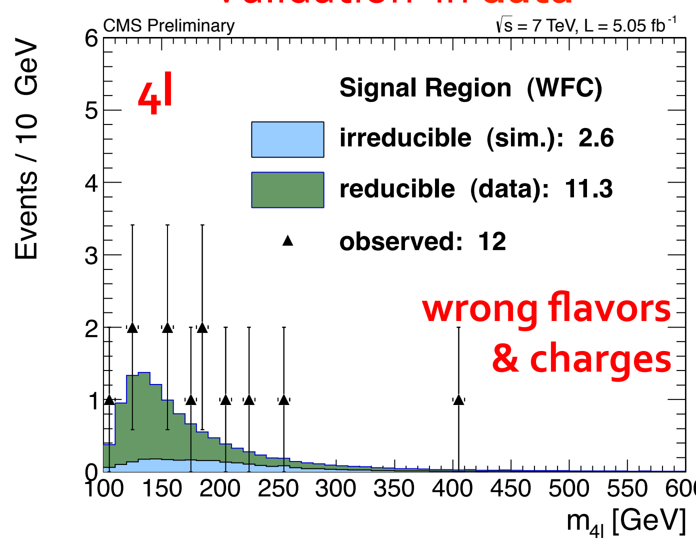




- **Reducible backgrounds estimated from data**
  - Extrapolation from control samples enriched with misidentified leptons
  - Total uncertainty ~50%

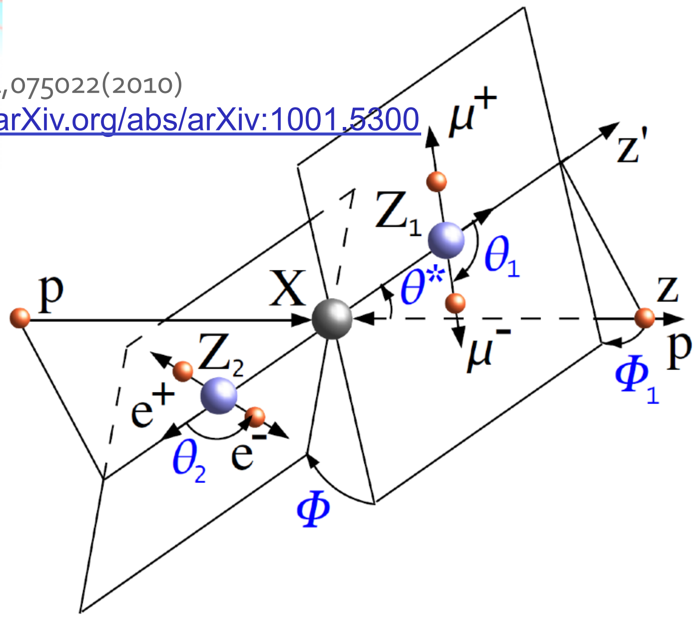


Validation in **data**



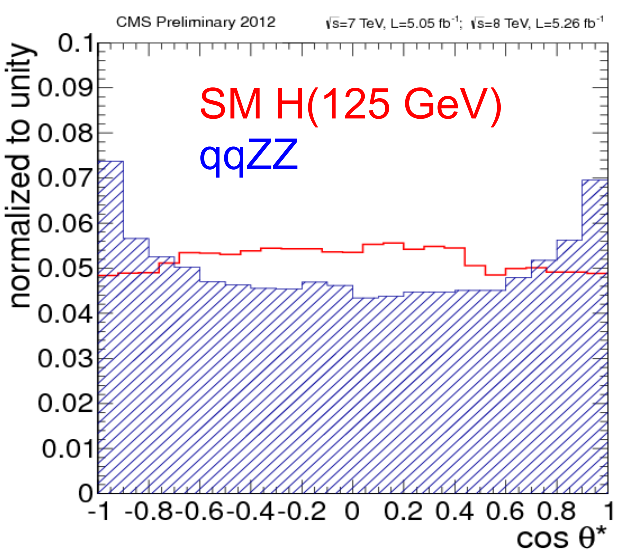
MELA

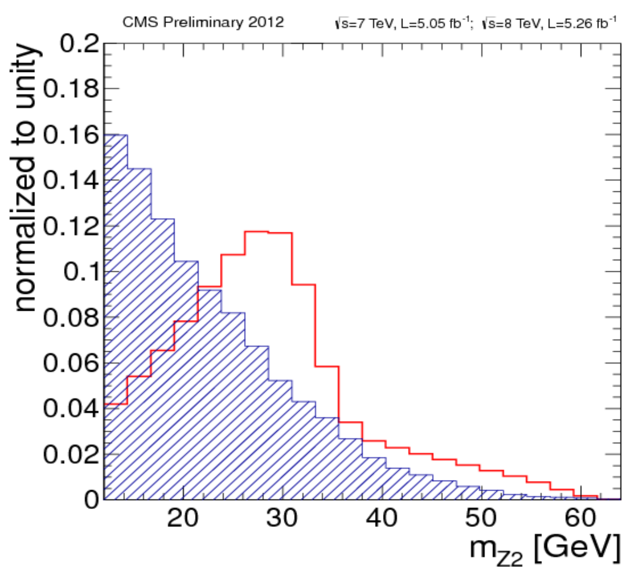
PRD81,075022(2010)
http://arXiv.org/abs/arXiv:1001.5300

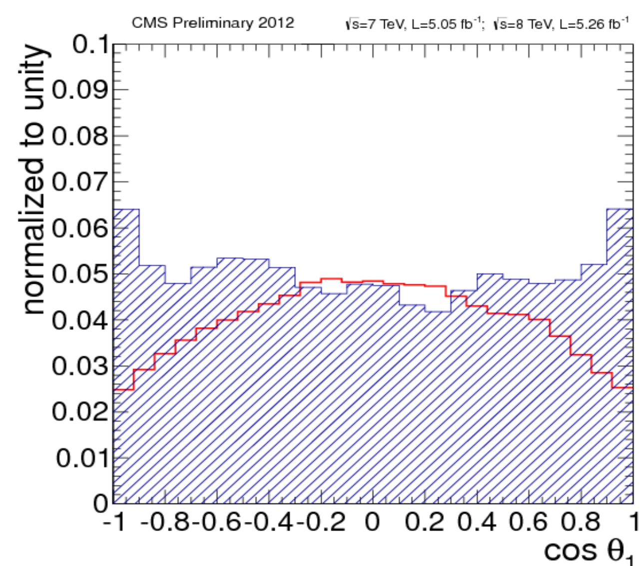


Matrix Element Likelihood Analysis:
uses kinematic inputs for
signal to background discrimination
$\{m_1, m_2, \theta_1, \theta_2, \theta^*, \Phi, \Phi_1\}$

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



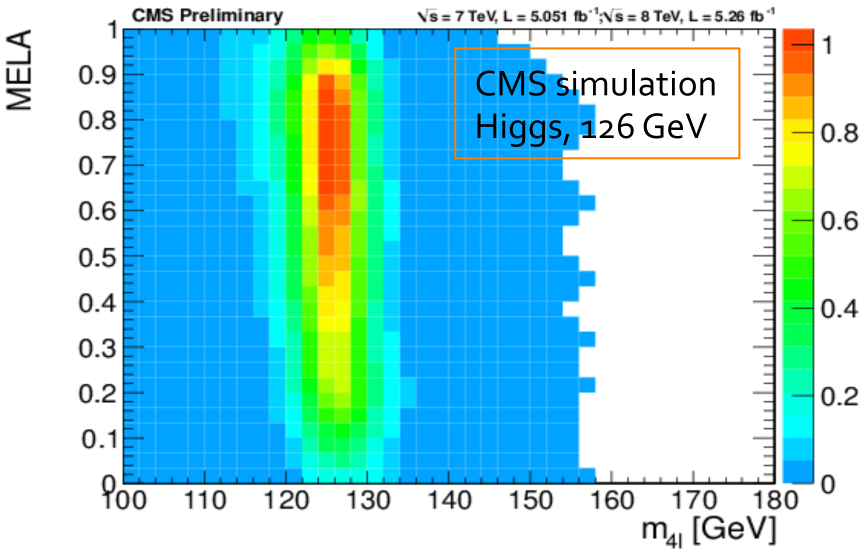




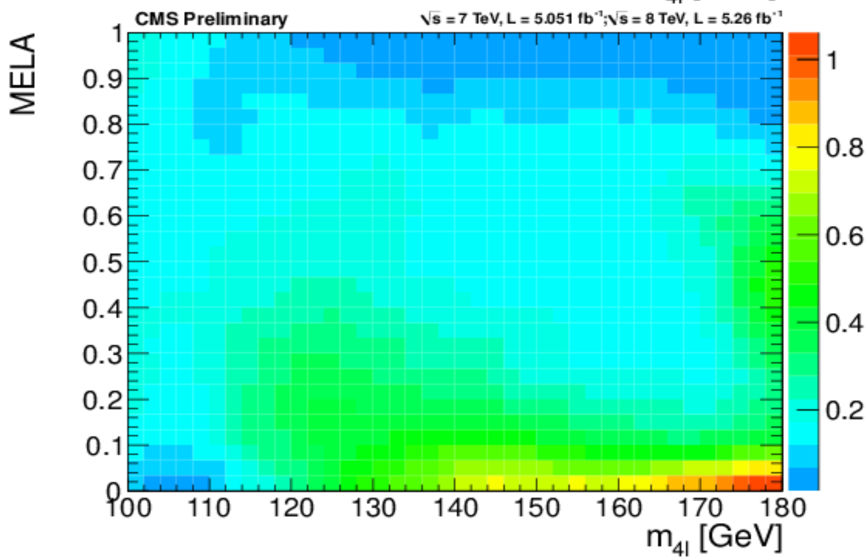
MELA

2D analysis using {m_{4l},MELA}

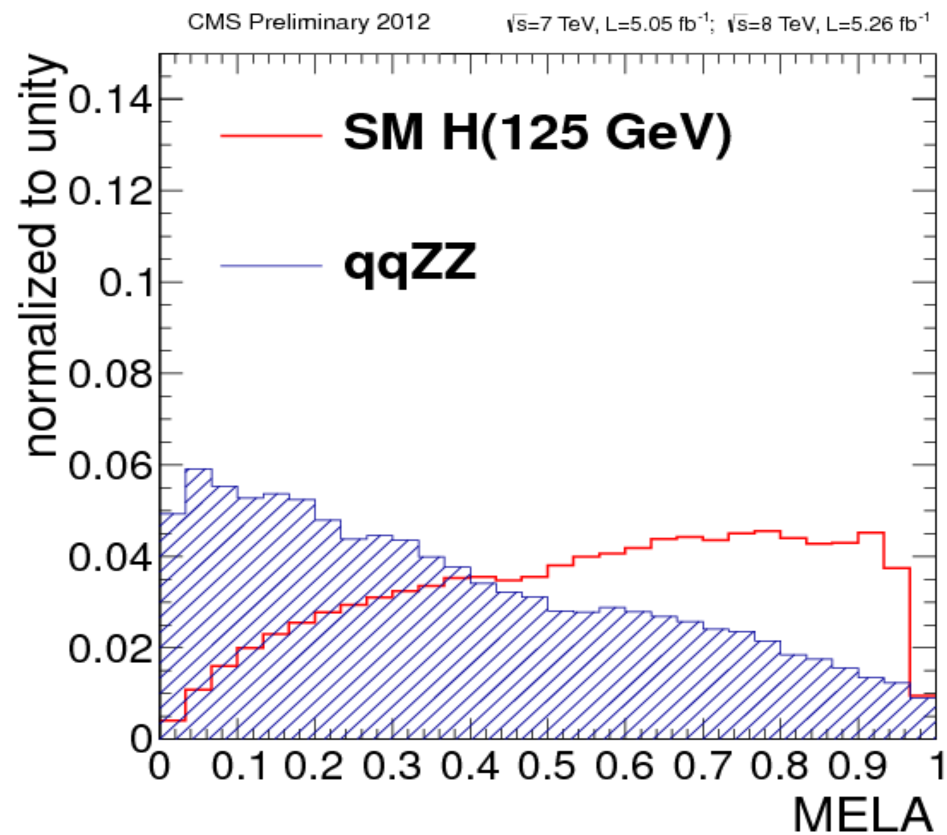
signal



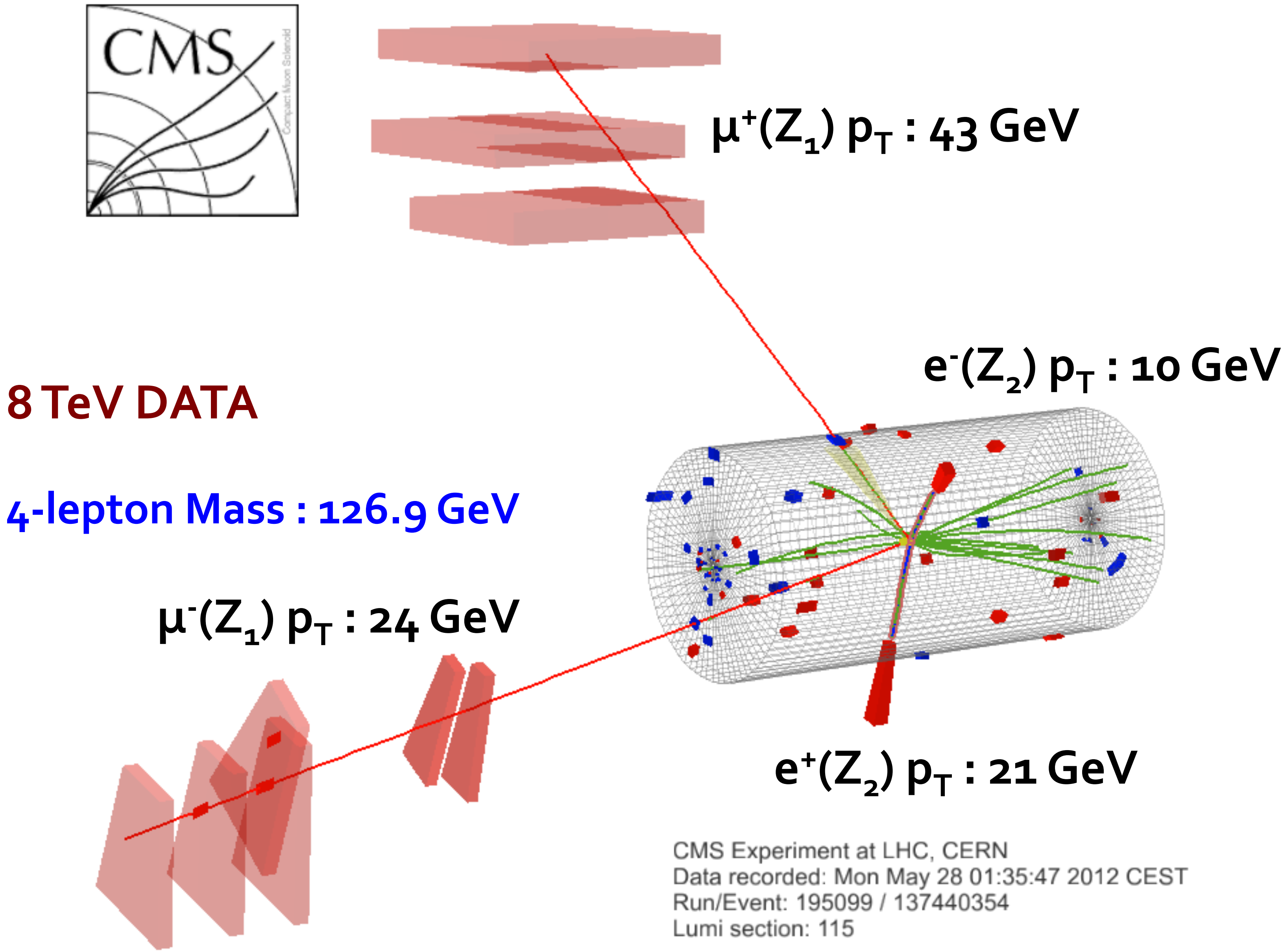
background

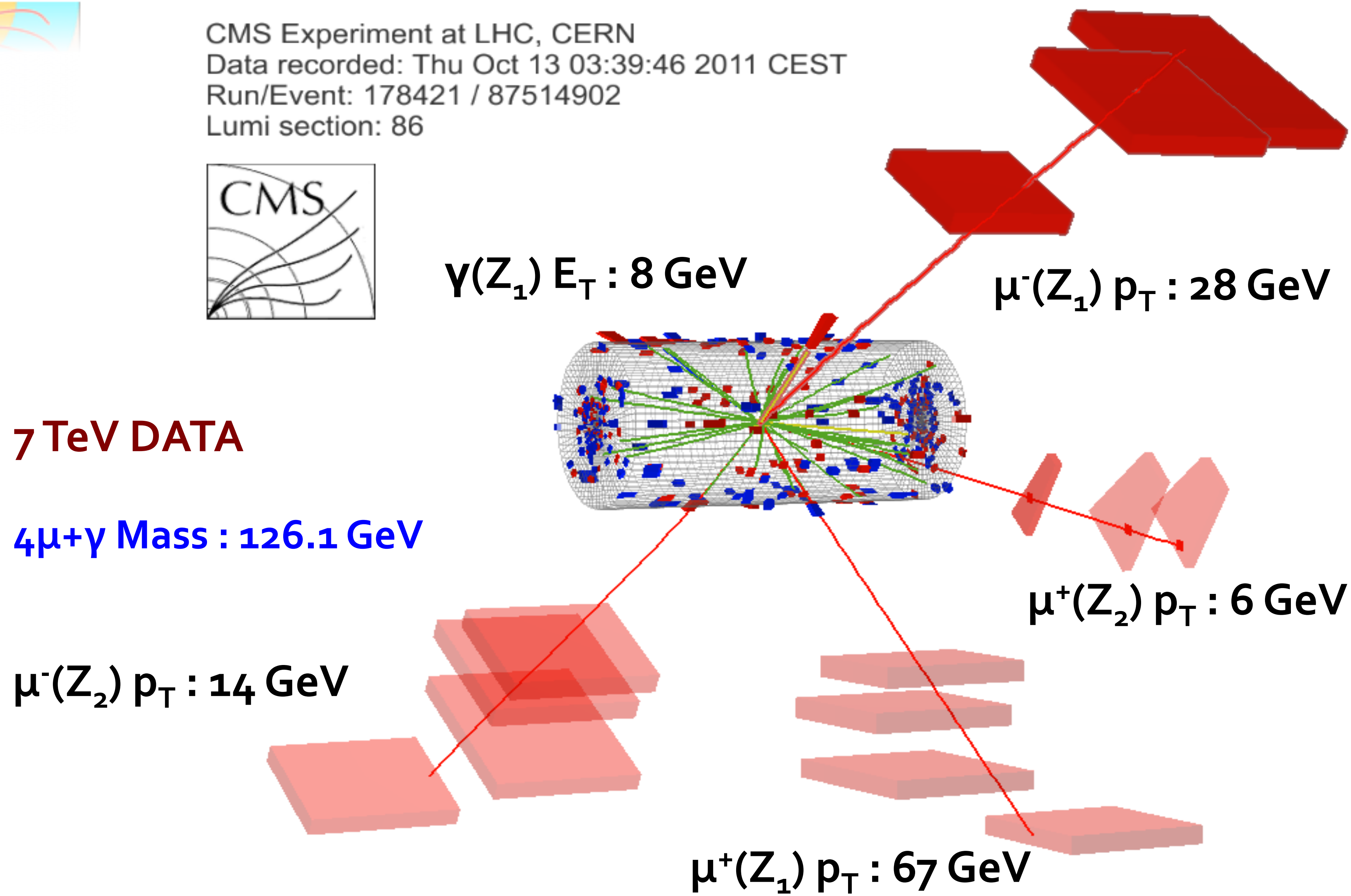


MELA offers powerful discrimination of background



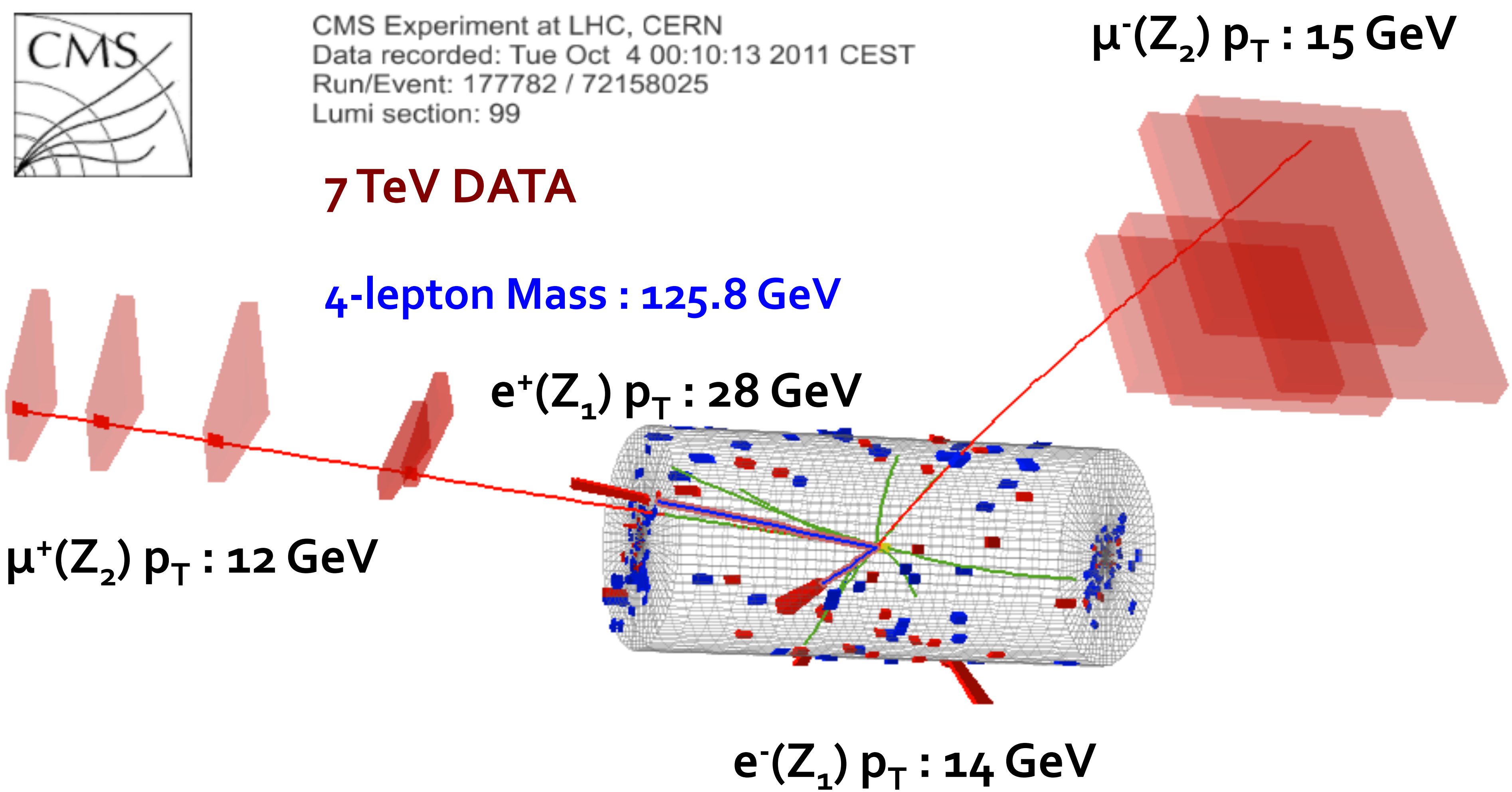
technique applicable for signal hypothesis testing


μ+(Z1) pT : 43 GeV
e-(Z2) pT : 10 GeV
8 TeV DATA
4-lepton Mass : 126.9 GeV
μ-(Z1) pT : 24 GeV
e+(Z2) pT : 21 GeV
CMS Experiment at LHC, CERN
Data recorded: Mon May 28 01:35:47 2012 CEST
Run/Event: 195099 / 137440354
Lumi section: 115

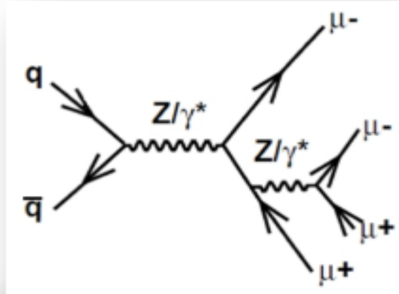


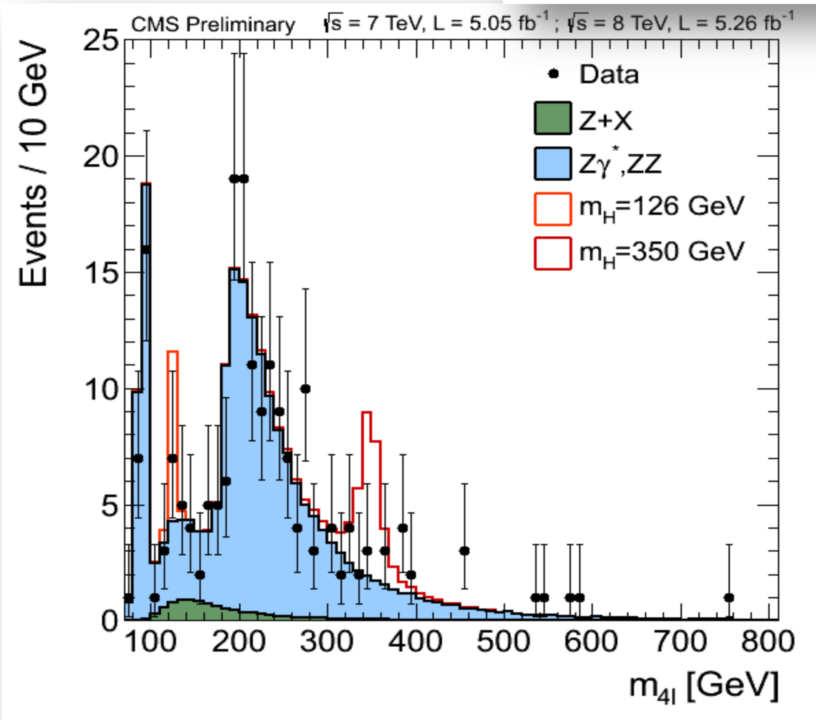
7 TeV DATA

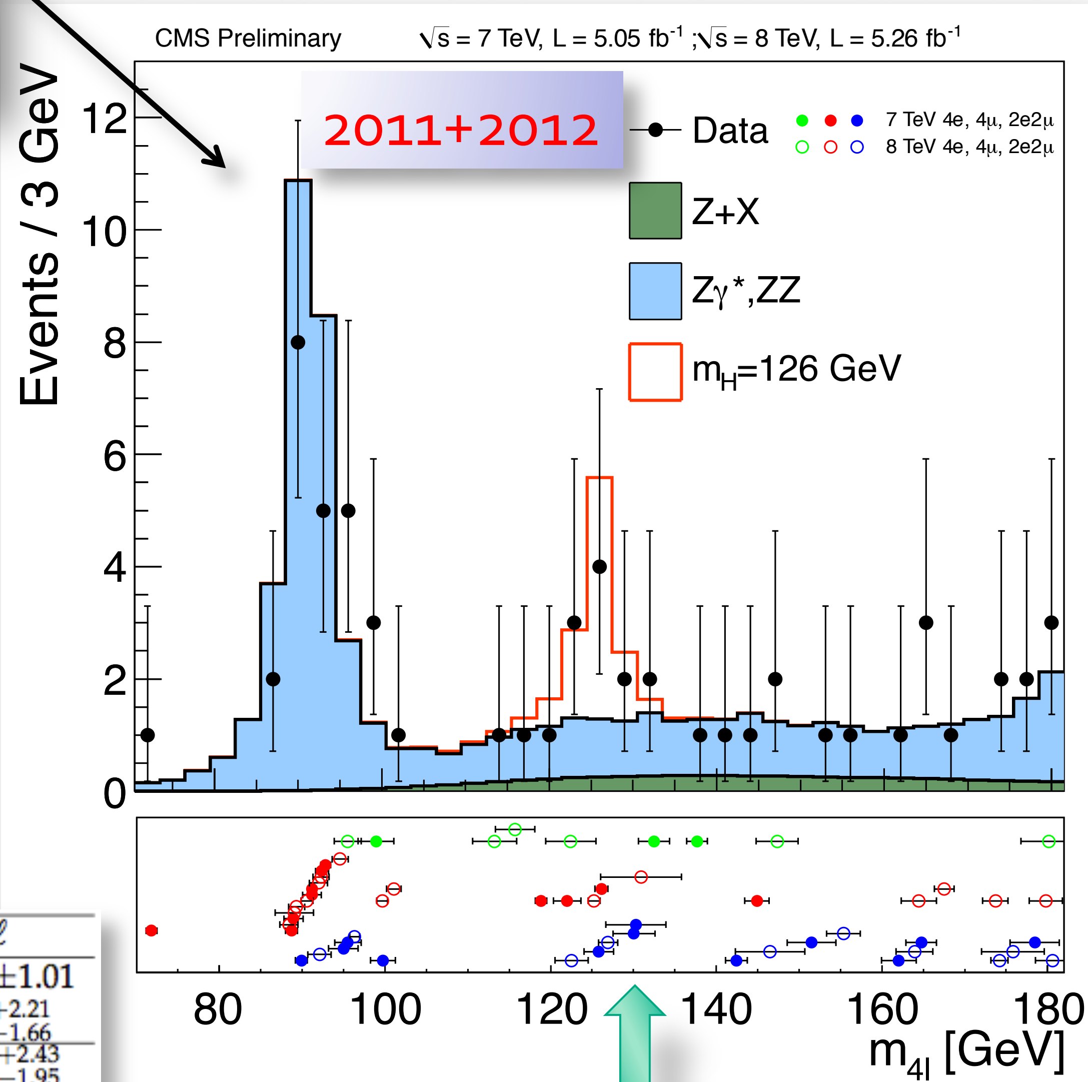
4μ+γ Mass : 126.1 GeV


CMS Experiment at LHC, CERN
Data recorded: Tue Oct 4 00:10:13 2011 CEST
Run/Event: 177782 / 72158025
Lumi section: 99
7 TeV DATA
4-lepton Mass : 125.8 GeV
μ⁻(Z₂) p_T : 15 GeV
e⁺(Z₁) p_T : 28 GeV
μ⁺(Z₂) p_T : 12 GeV
e⁻(Z₁) p_T : 14 GeV

Results: m(4l) spectrum







Event-by-event errors

Yields for m(4l)=110..160 GeV

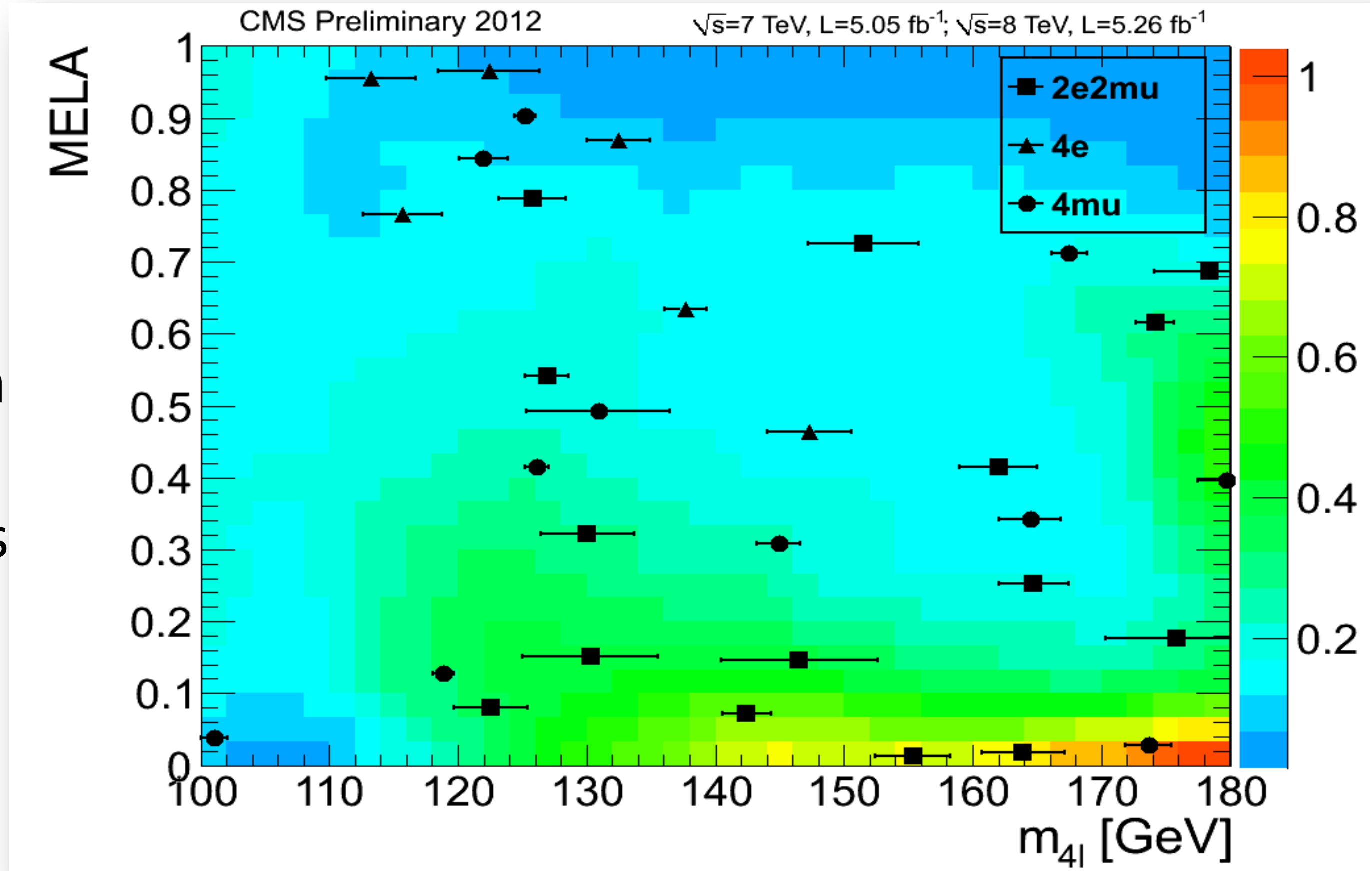
Channel	4e	4μ	2e2μ	4ℓ
ZZ background	2.65 ±0.31	5.65 ±0.59	7.17 ±0.76	15.48 ±1.01
Z+X	$1.20^{+1.08}_{-0.78}$	$0.92^{+0.65}_{-0.55}$	$2.29^{+1.81}_{-1.36}$	$4.41^{+2.21}_{-1.66}$
All backgrounds	$3.85^{+1.12}_{-0.84}$	$6.58^{+0.88}_{-0.81}$	$9.46^{+1.96}_{-1.56}$	$19.88^{+2.43}_{-1.95}$
$m_H = 126$ GeV	1.51 ±0.48	2.99 ±0.60	3.81 ±0.89	8.31 ±1.18

164 events expected in [100, 800 GeV]
172 events observed in [100, 800 GeV]

Results: MELA 2D plots

Perform 2D fit

- MELA discriminant versus m_{4l}
  - Data points shown with per-event mass uncertainties

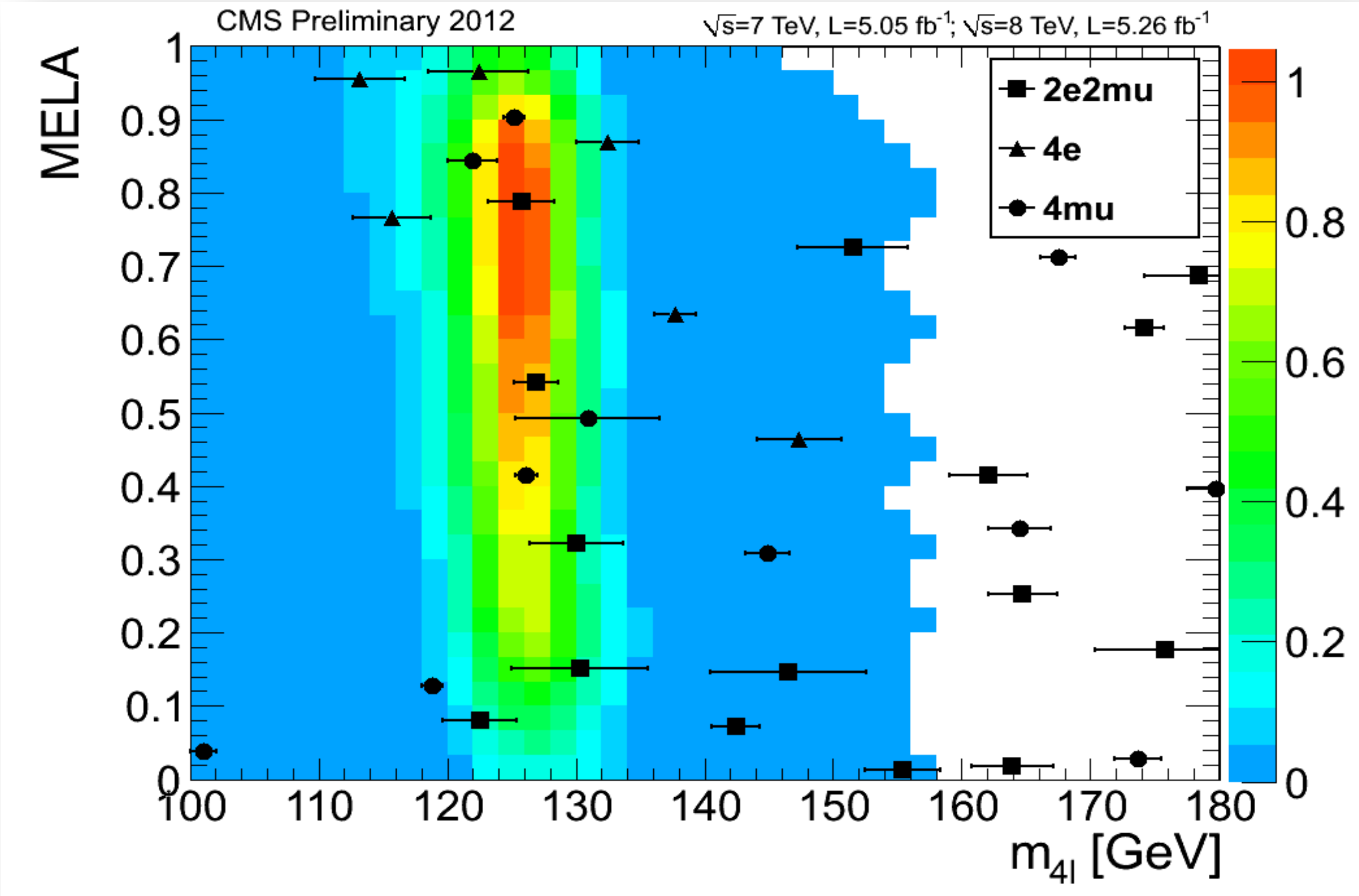


Data w.r.t. background expectation

Results: MELA 2D plots

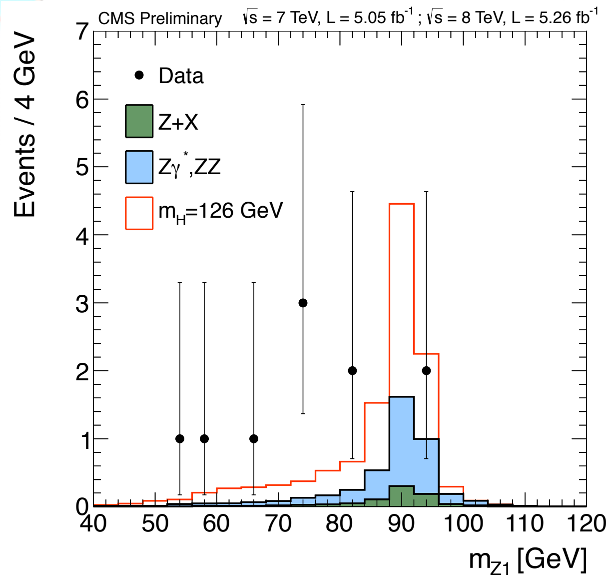
Perform 2D fit

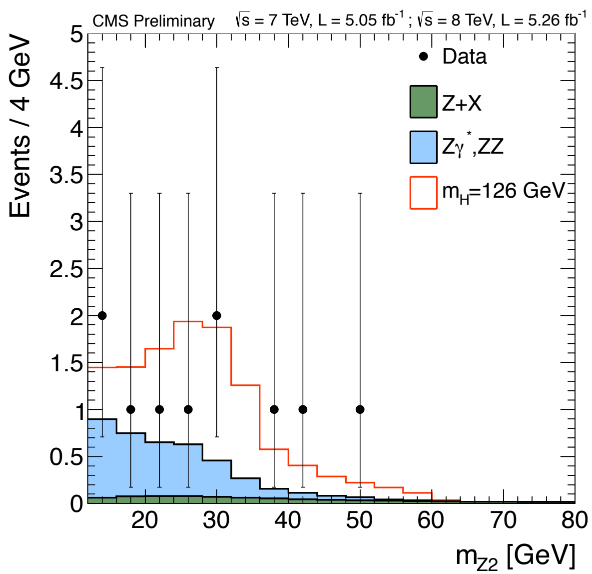
- MELA discriminant versus m_{4l}
  - Data points shown with per-event mass uncertainties

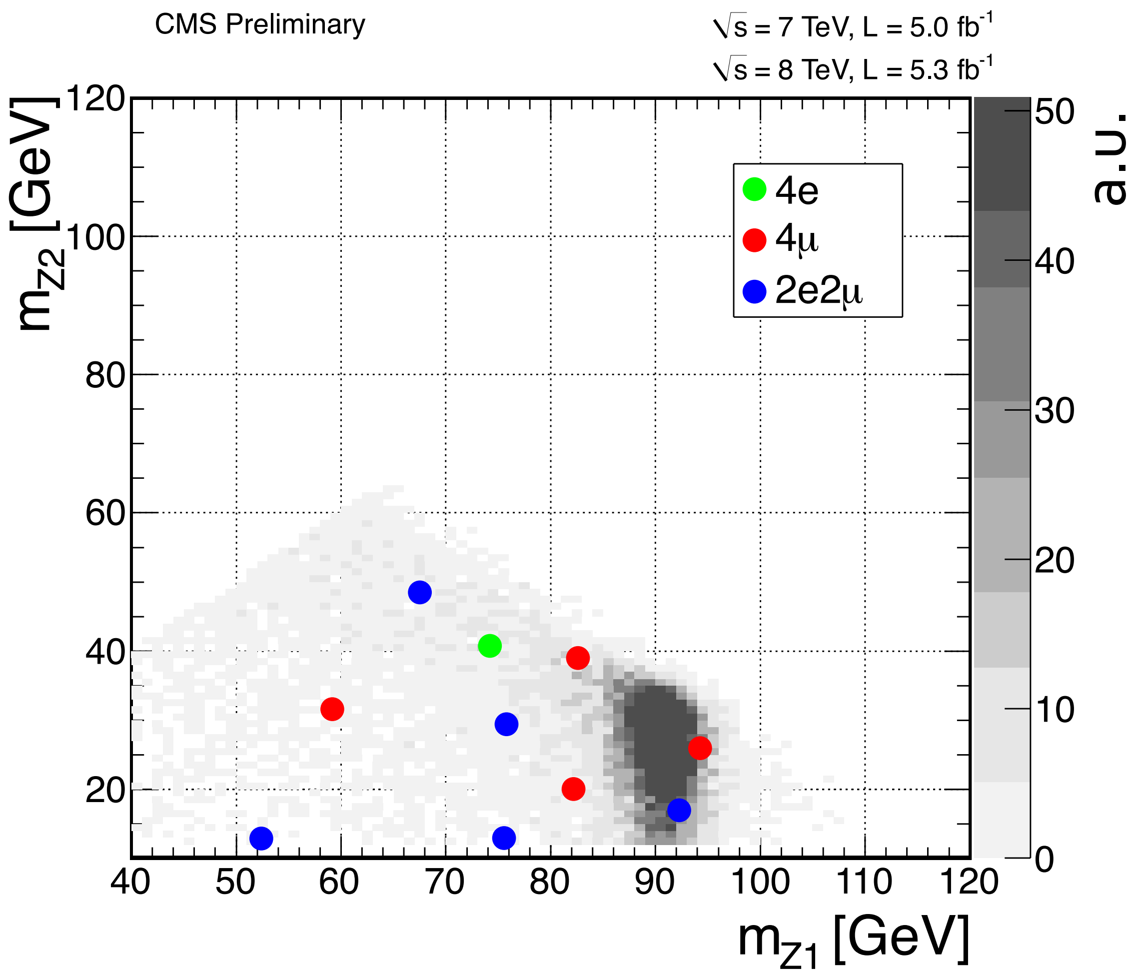


Data w.r.t 126 GeV Higgs Expectation

Two-lepton invariant mass plots



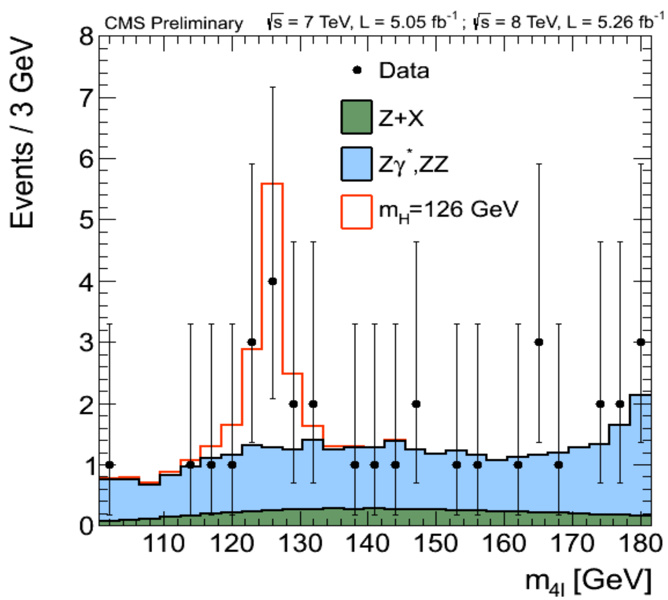


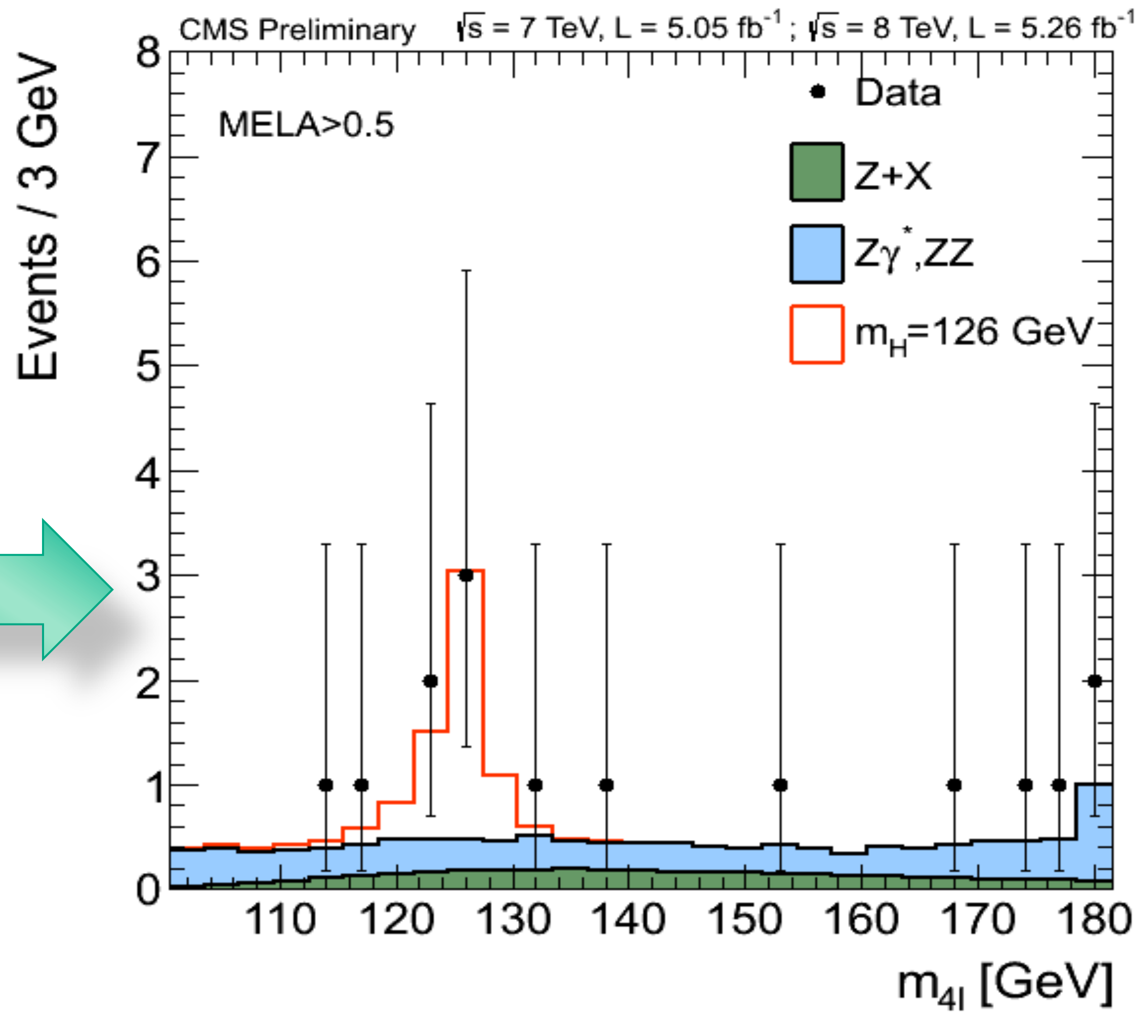


Grey – is simulation (expectation) for Higgs (126 GeV)

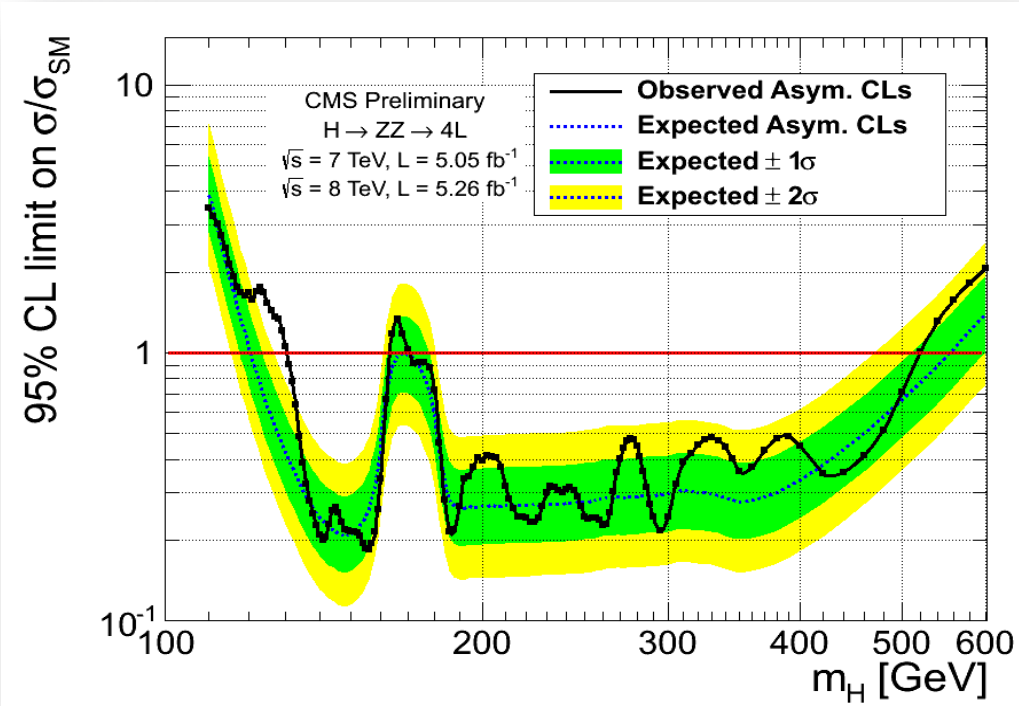
For illustration: Low mass region with MELA cut

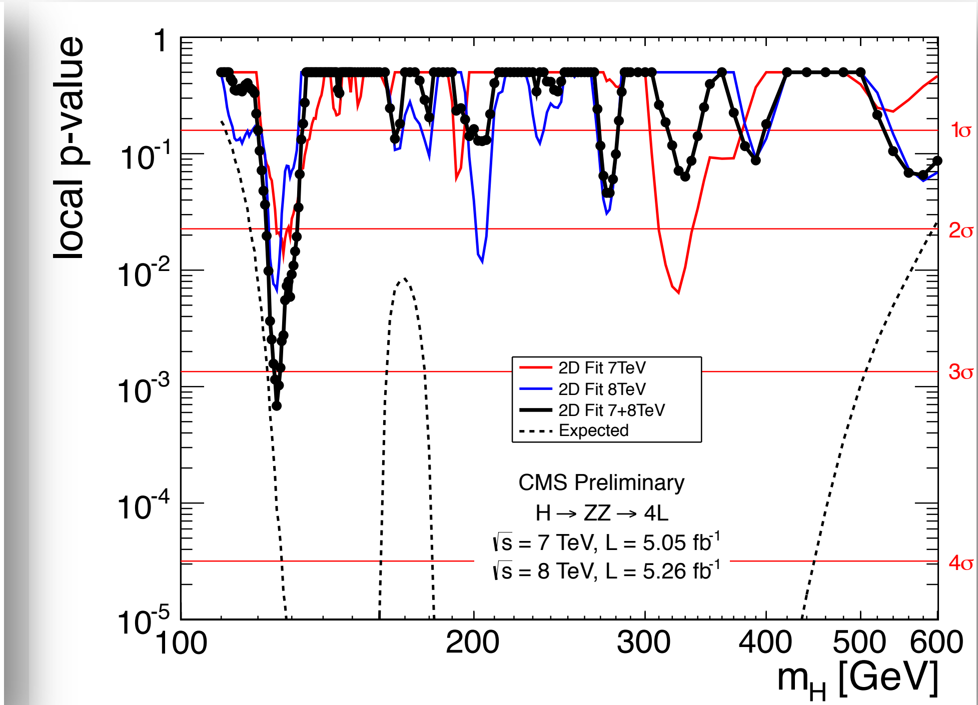
- Enrich the signal content
  - Cut: MELA > 0.5
    - Cut value chosen such that signal probability > background probability





Limits and p-values

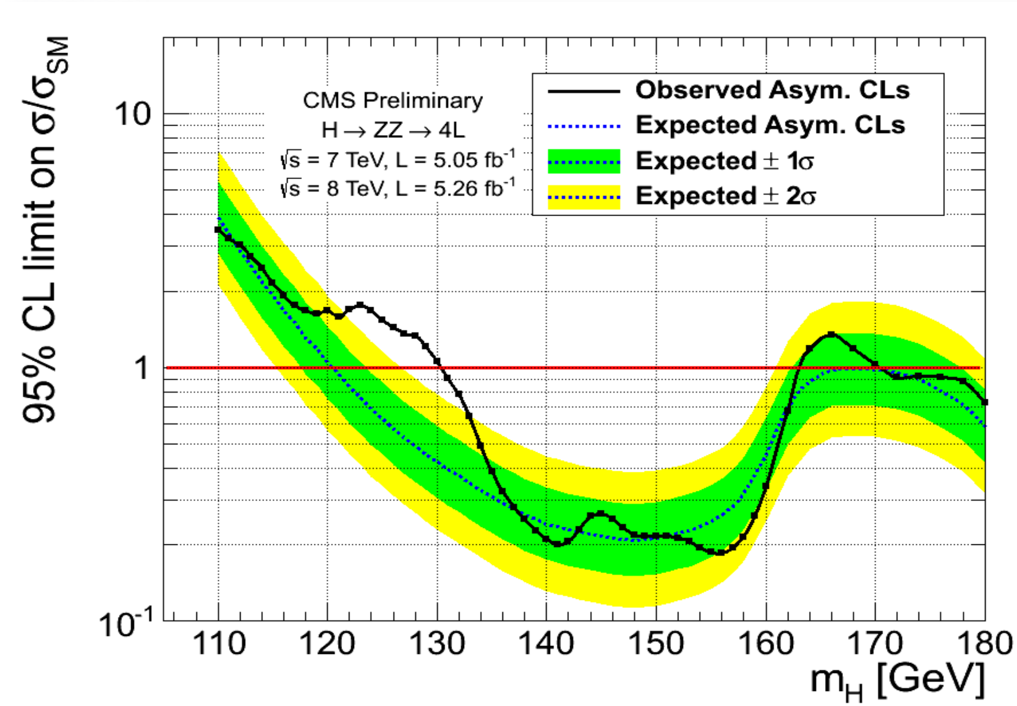


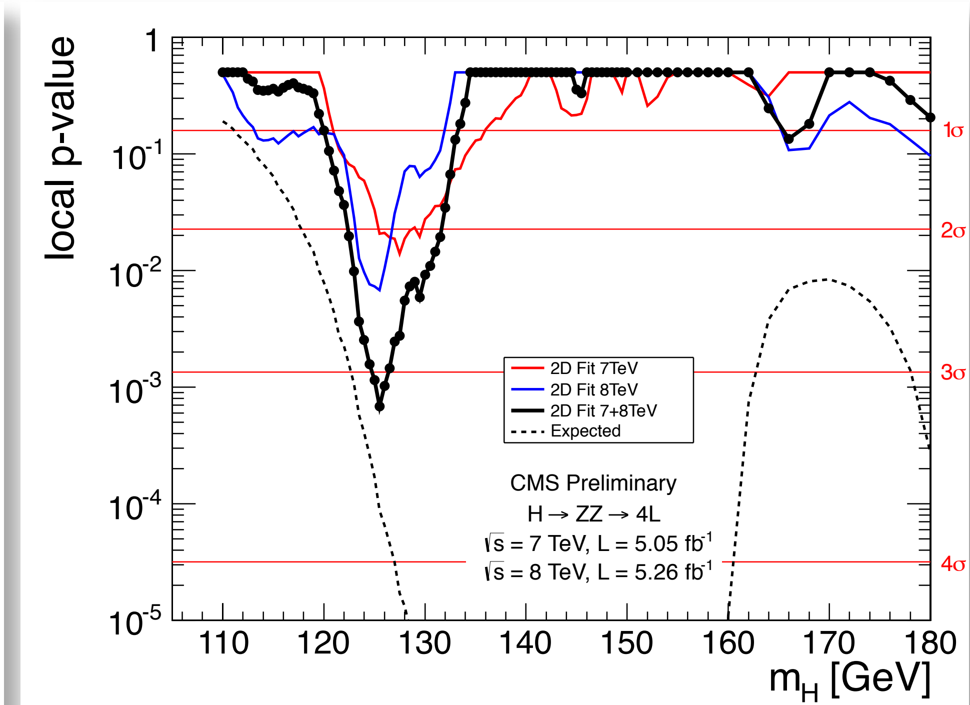


Expected exclusion at 95% CL :
121-550 GeV
Observed exclusion at 95% CL :
131-162 GeV and 172-530 GeV

Expected significance at 125.5 GeV :
3.8 σ
Observed significance at 125.5 GeV:
3.2 σ

Limits and p-values





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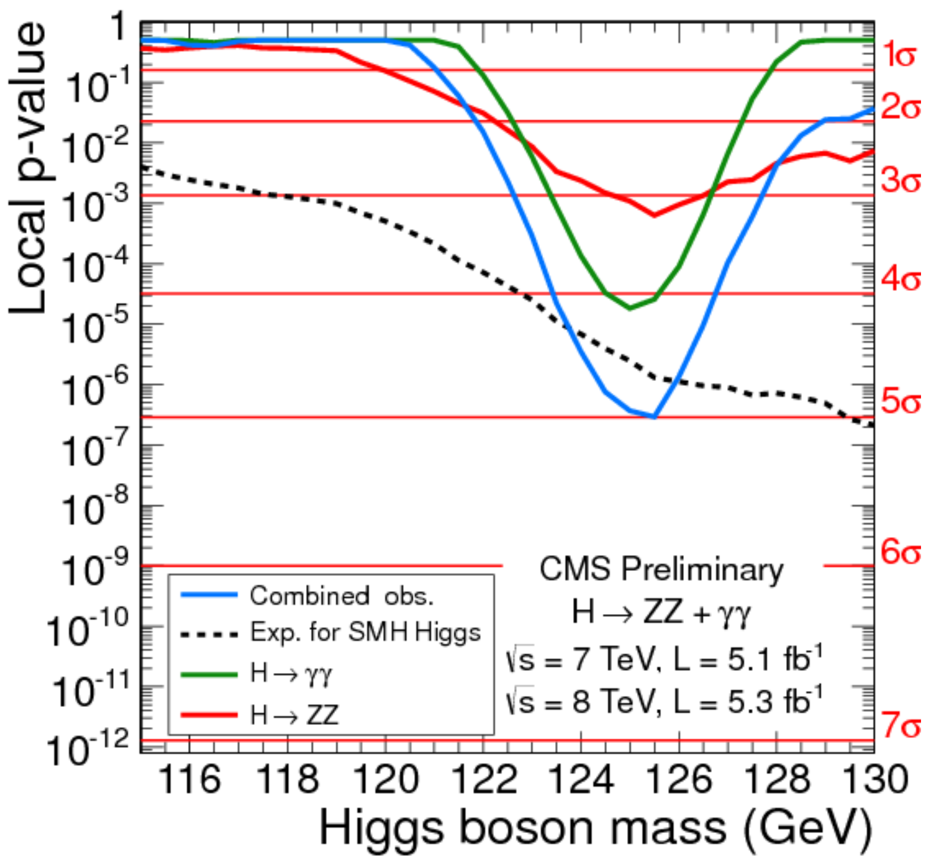
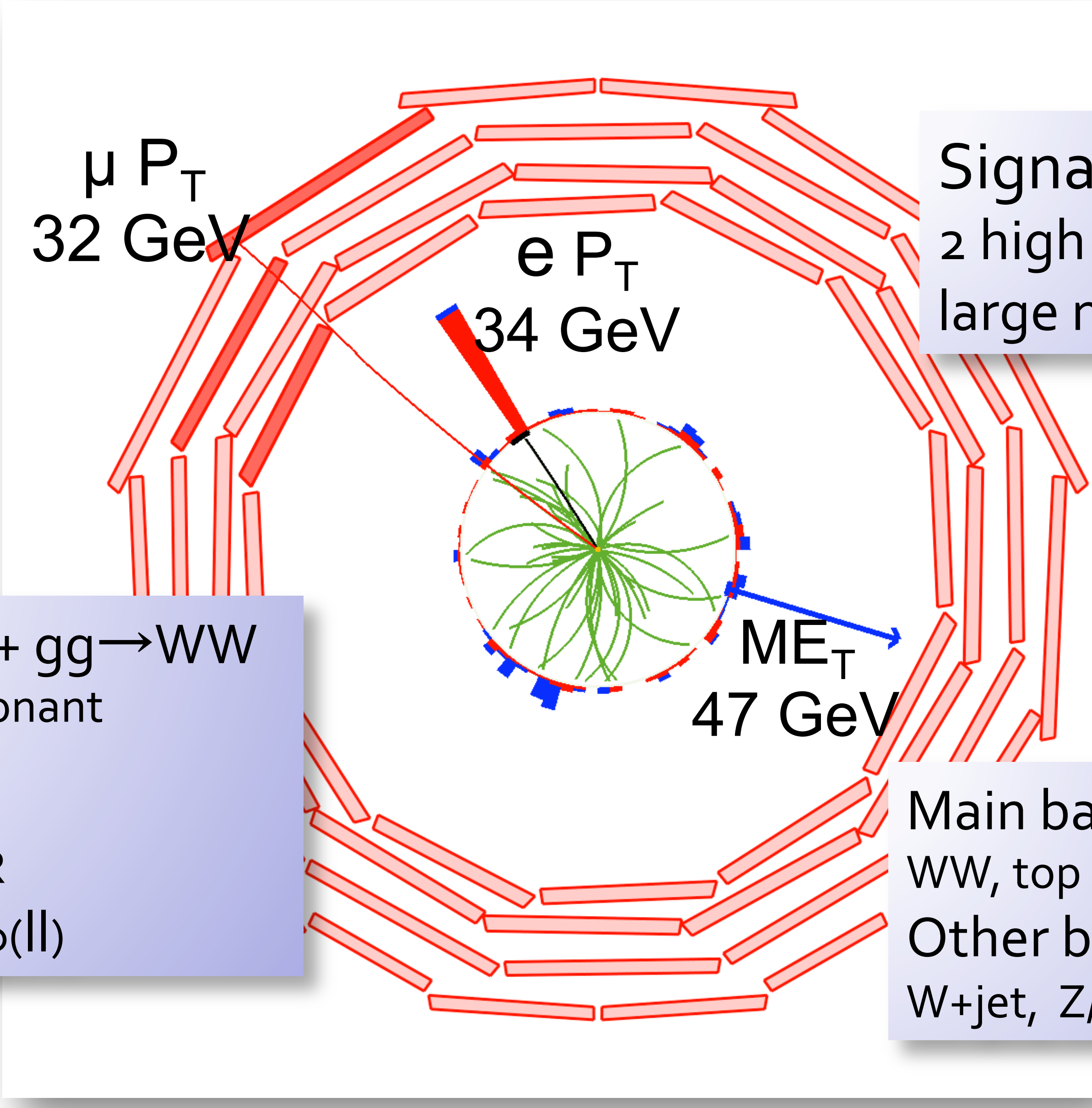
Characterization of excess near 125 GeV



- **high sensitivity, high mass resolution channels: γγ+4l**
  - **γγ: 4.1 σ excess**
  - **4 leptons: 3.2 σ excess**
  - **near the <u>same mass</u> 125 GeV**
- **comb. significance: 5.0 σ**
- **expected significance for SM Higgs: 4.7 σ**

$H \rightarrow WW \rightarrow l\nu l\nu$

H→WW→lνlν Signature



Signature:
2 high p_T leptons
large missing E_T

qq→WW + gg→WW
- Non-resonant

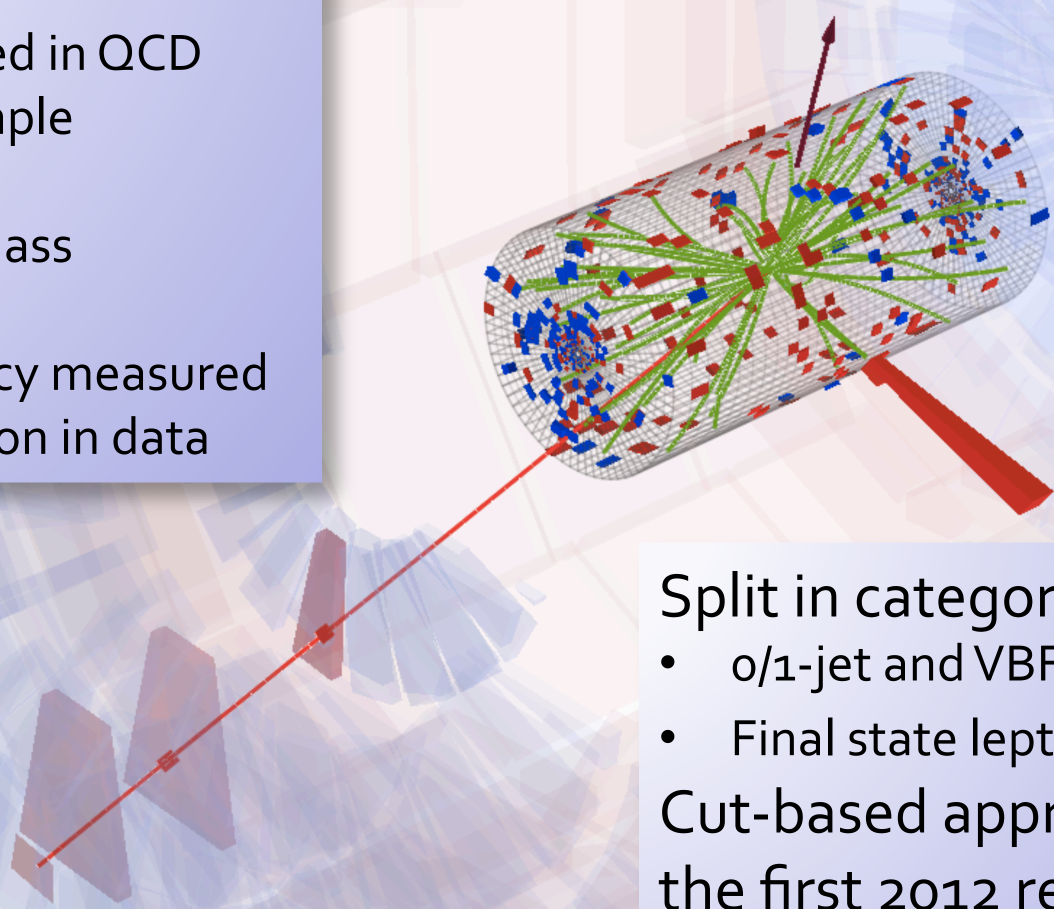
H→WW
- Large BR
- Small Δϕ(ll)

Main backgrounds:
WW, top

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

CMS Experiment at LHC, CERN
Data recorded: Sat Apr 14 18:18:05 2012 CEST
Run/Event: 191247 / 398701455
Lumi section: 272

Analysis Strategies



Data-driven background estimation

- W+jets
  Fake rate measured in QCD enriched data sample
- Z/γ*
  Normalised in Z mass
- Top
  b-tagging efficiency measured in top control region in data

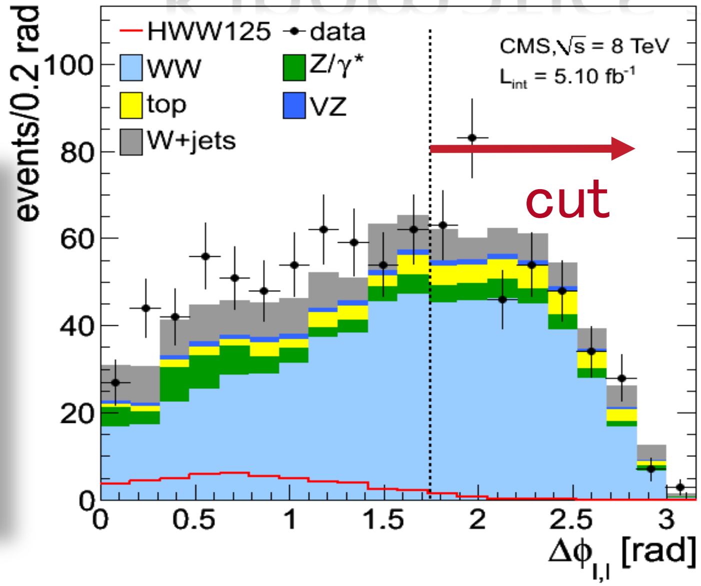
Split in categories

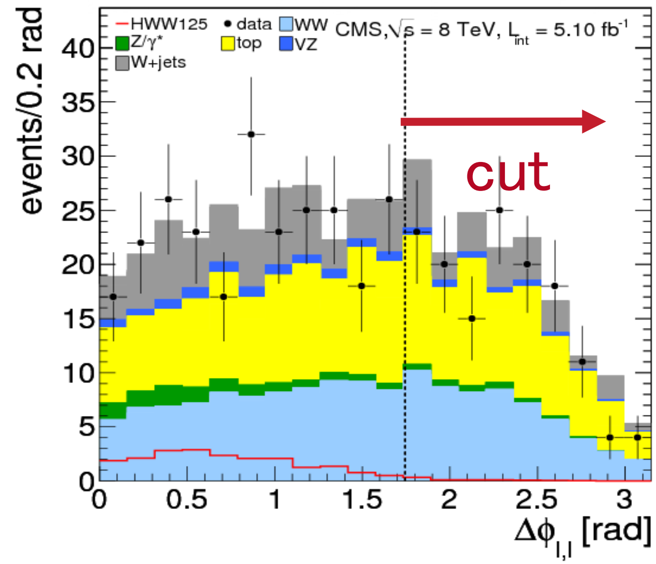
- 0/1-jet and VBF
- Final state lepton flavors

Cut-based approach for the first 2012 result

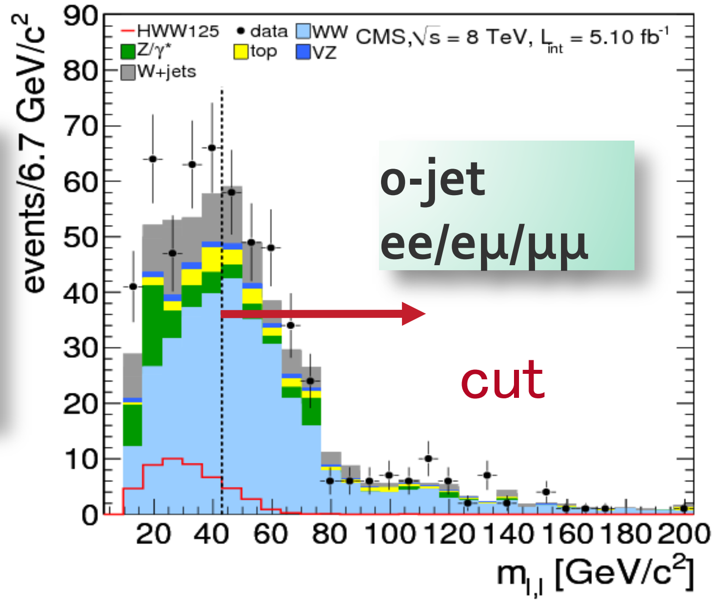
Kinematics at Final Selection

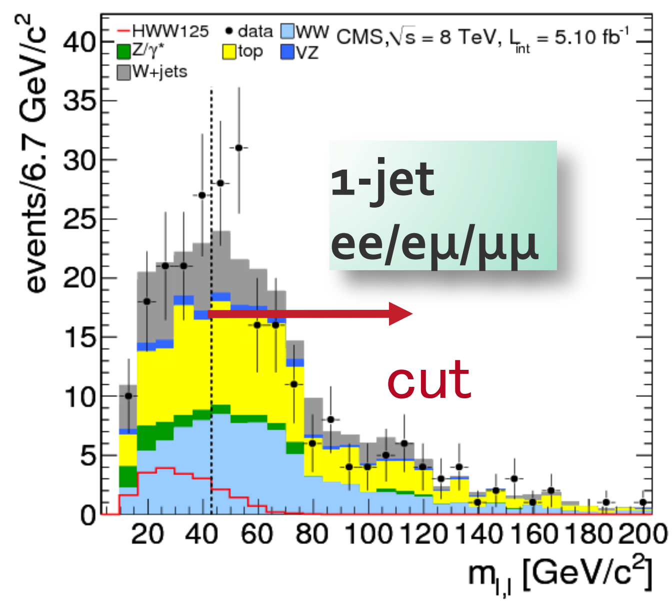
One step before the final selection
(no cuts on Δϕ(ll) and m(ll))



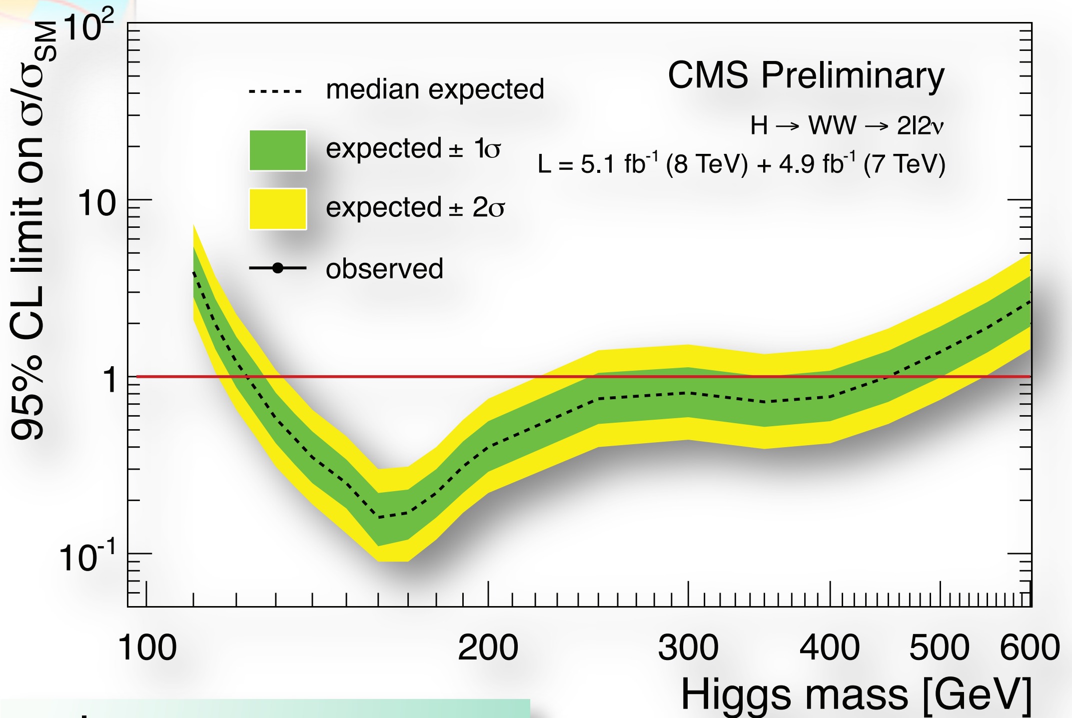


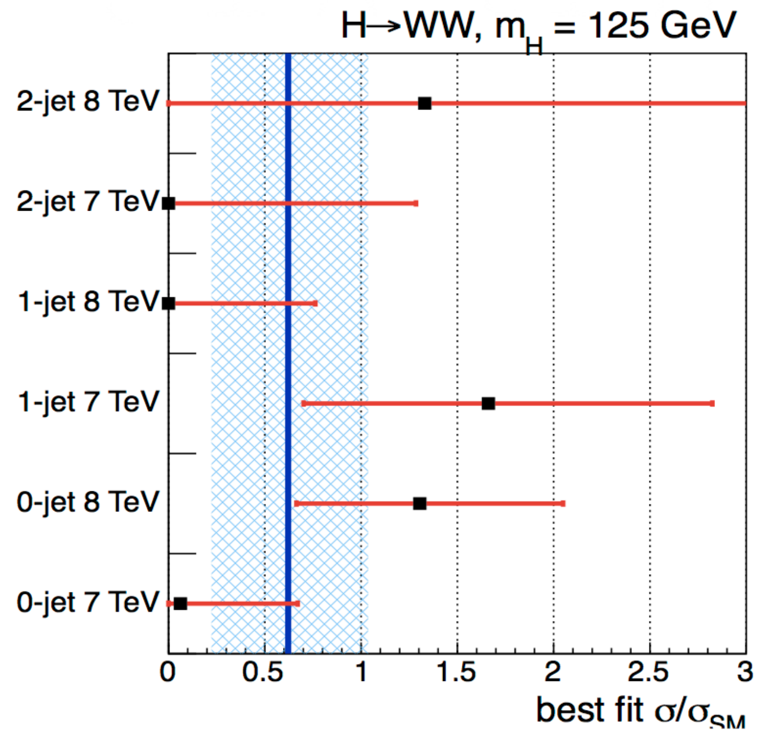
Final selection on m(ll)
(all other selection applied)





Combination of 7 TeV + 8 TeV

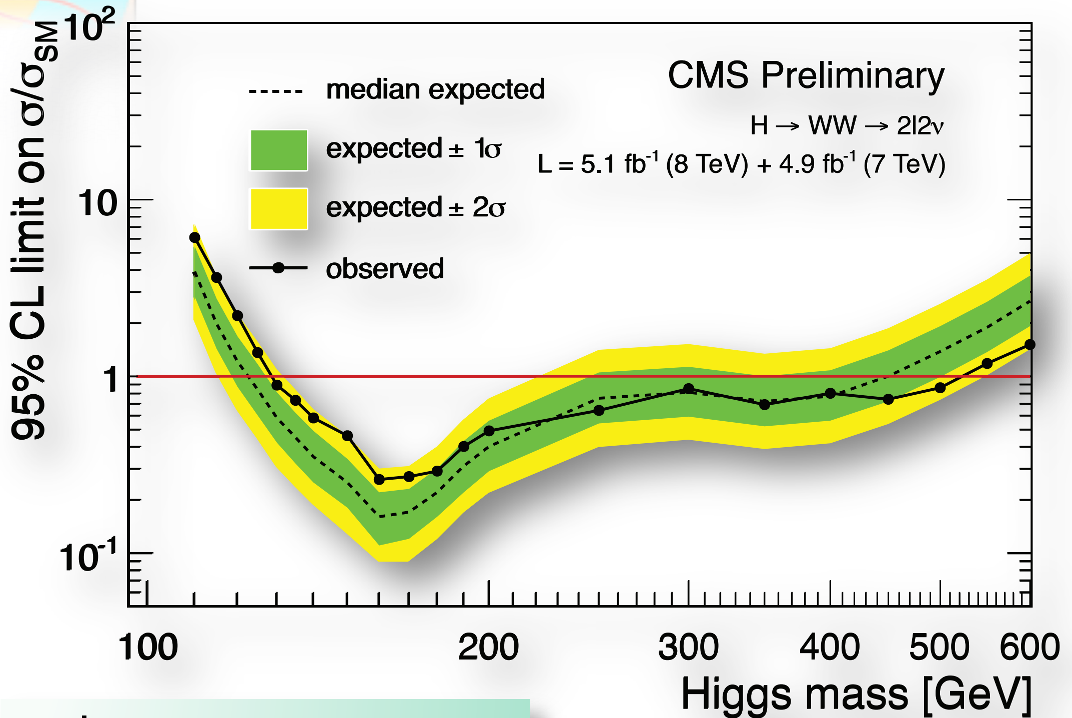


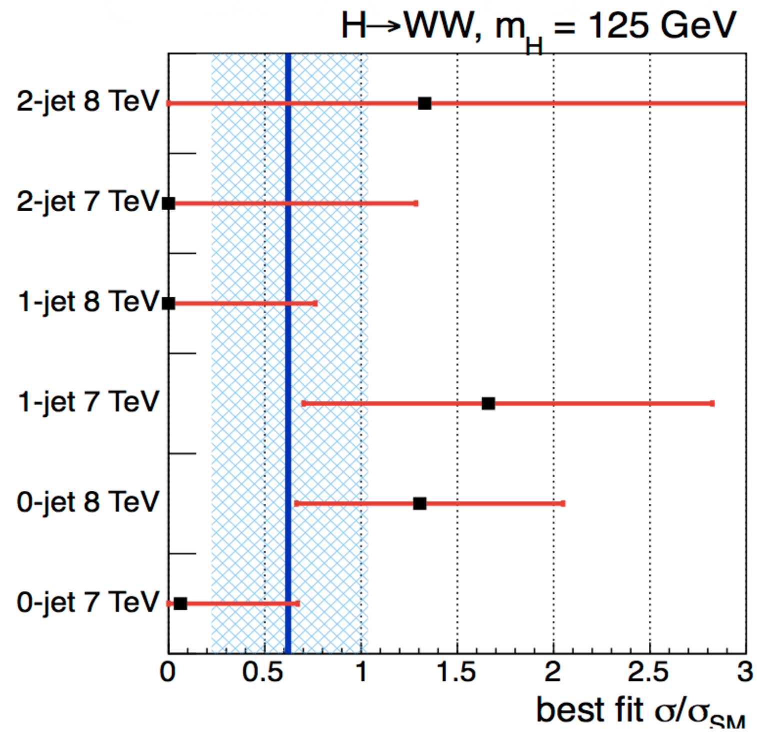


Exclusion range
expected: 123-450 GeV
observed:129-520 GeV

- Combined limits from 2011 and 2012
  - 7 TeV result using a multivariate discriminant and updated with the final luminosity measurement
  - 2012→ 5% improvement in sensitivity coming from new object definitions and selection optimized for 2012 condition

Combination of 7 TeV + 8 TeV





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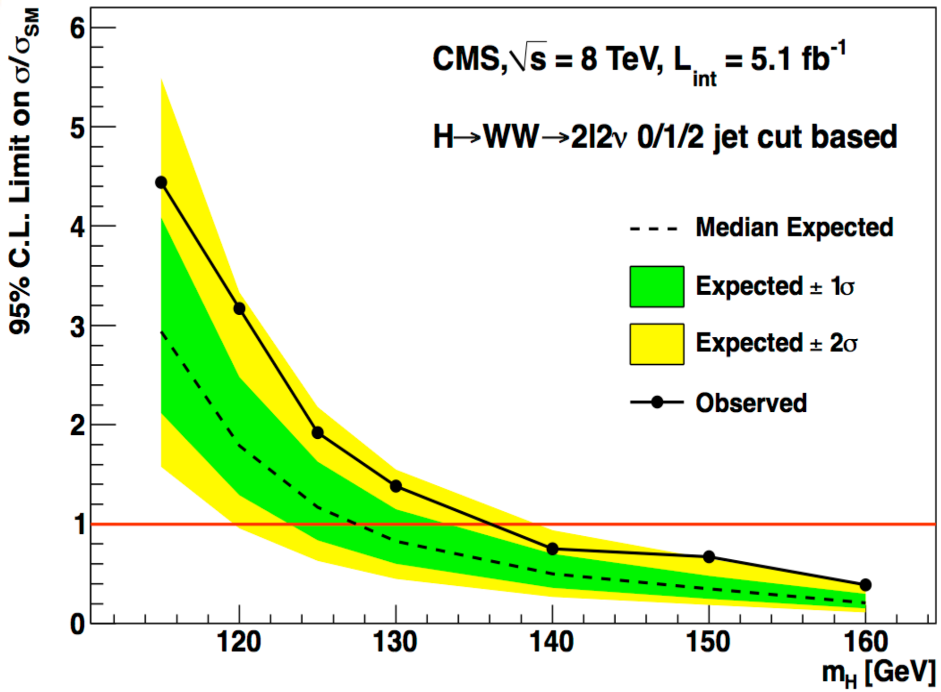
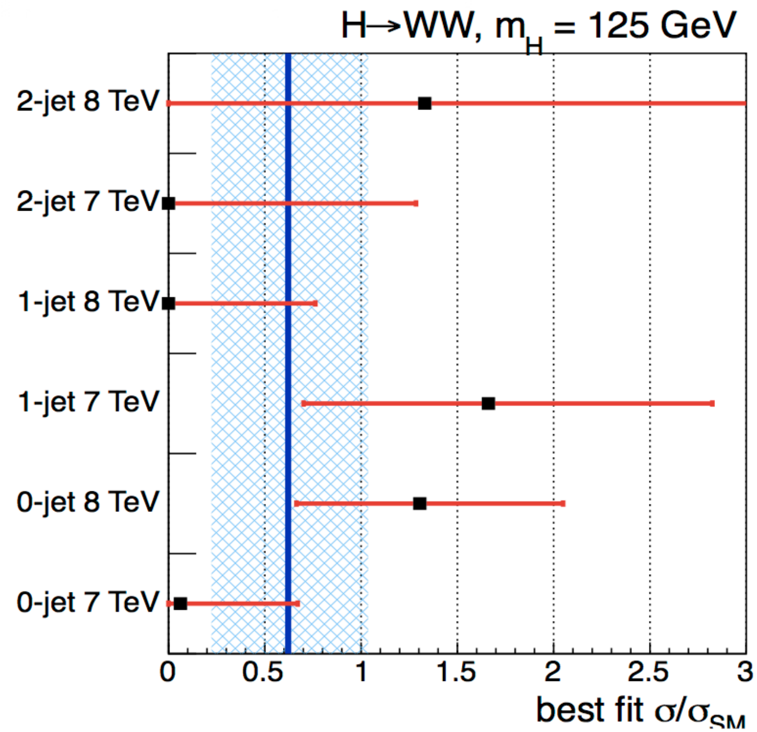
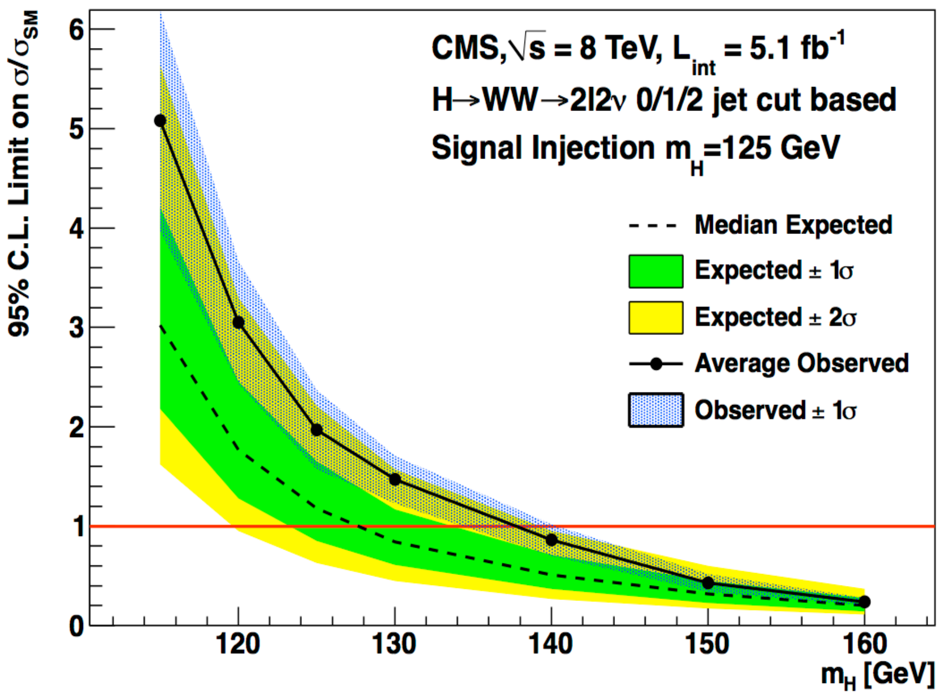
8 TeV – injected SM Higgs signal

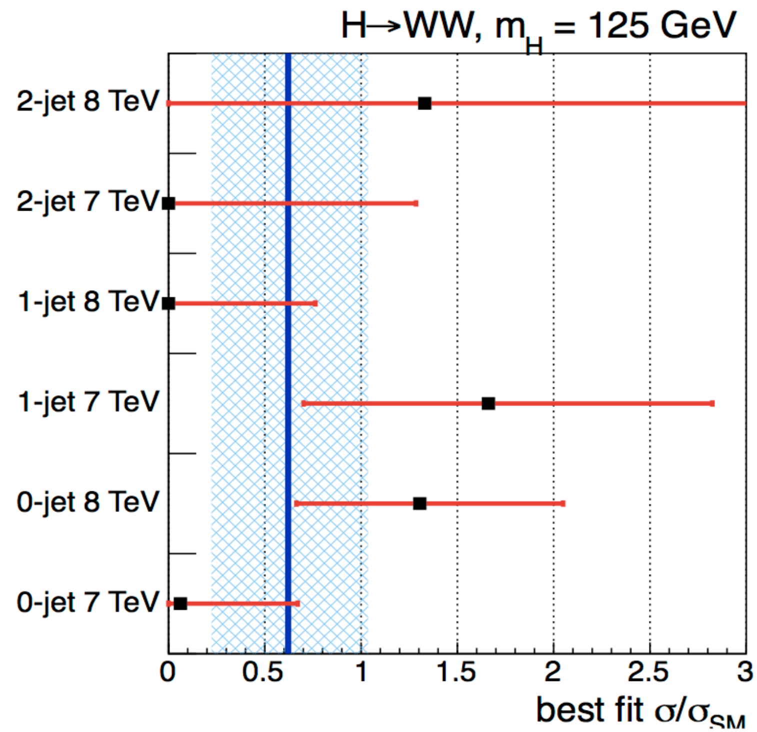




- Signal injection using prediction at 5.1/fb 8 TeV
  - Average background prediction
  - Signal injection for m_H = 125 GeV with toys

8 TeV – injected SM Higgs signal





- Signal injection using prediction at 5.1/fb 8 TeV
  - Average background prediction
  - Signal injection for m_H = 125 GeV with toys

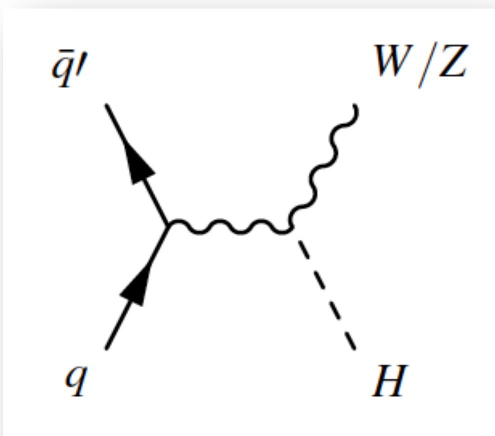
$$VH \rightarrow Vb\bar{b}$$

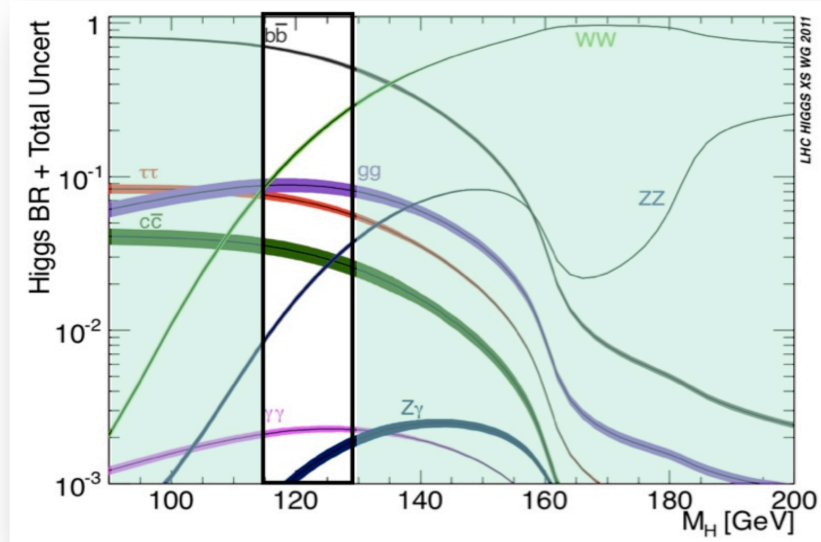
$$V \rightarrow l\nu, ll, \nu\nu$$

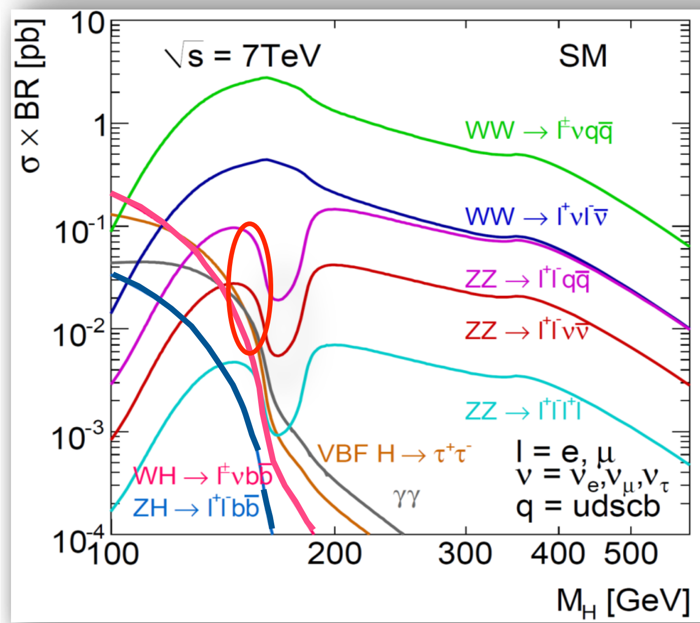
$VH \rightarrow Vb\bar{b}$, $V \rightarrow l\nu$, ll, $\nu\nu$

- Characteristics and importance
  - By far, largest BR for m_H<130 GeV
  - Key piece of the observation puzzle
    - Tests specific production & decay couplings
- But $\sigma_{b\bar{b}}$(QCD) ~ 10^7 σxBR(H-> $b\bar{b}$)!

⇒ Search in associated production with W or Z

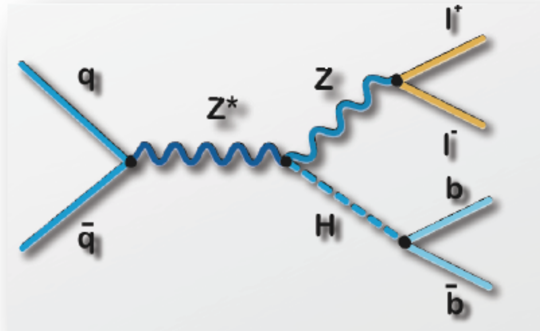






Analysis Strategy

Associated Production
=> final states with
leptons, MET and b-jets



5 channels

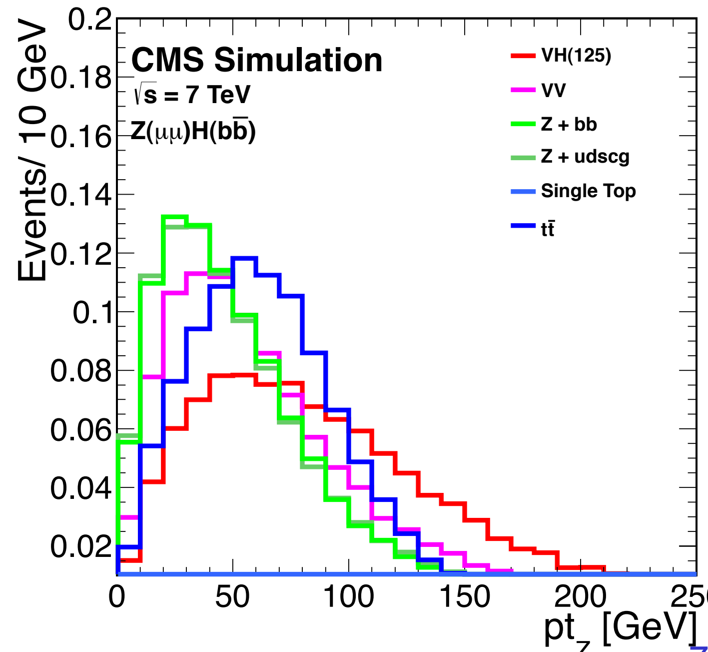
- Z(ll)H(bb)
- Z(νν)H(bb)
- W(lν)H(bb)

Reducible Backgrounds:
QCD, top, W/Z+ light jets

Less reducible:
V+bb, ZZ(bb), WZ(bb)

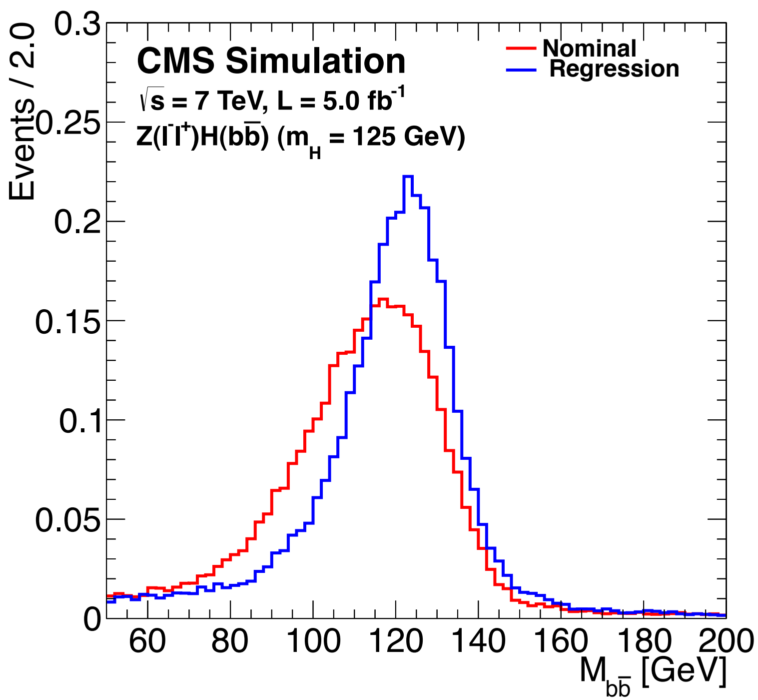
Boosted vector bosons:
$p_T(V)$,
2 b-tagged jets ($H \to b\bar{b}$)
Back-to-back V and H,
reconstruct $m_{b\bar{b}}$

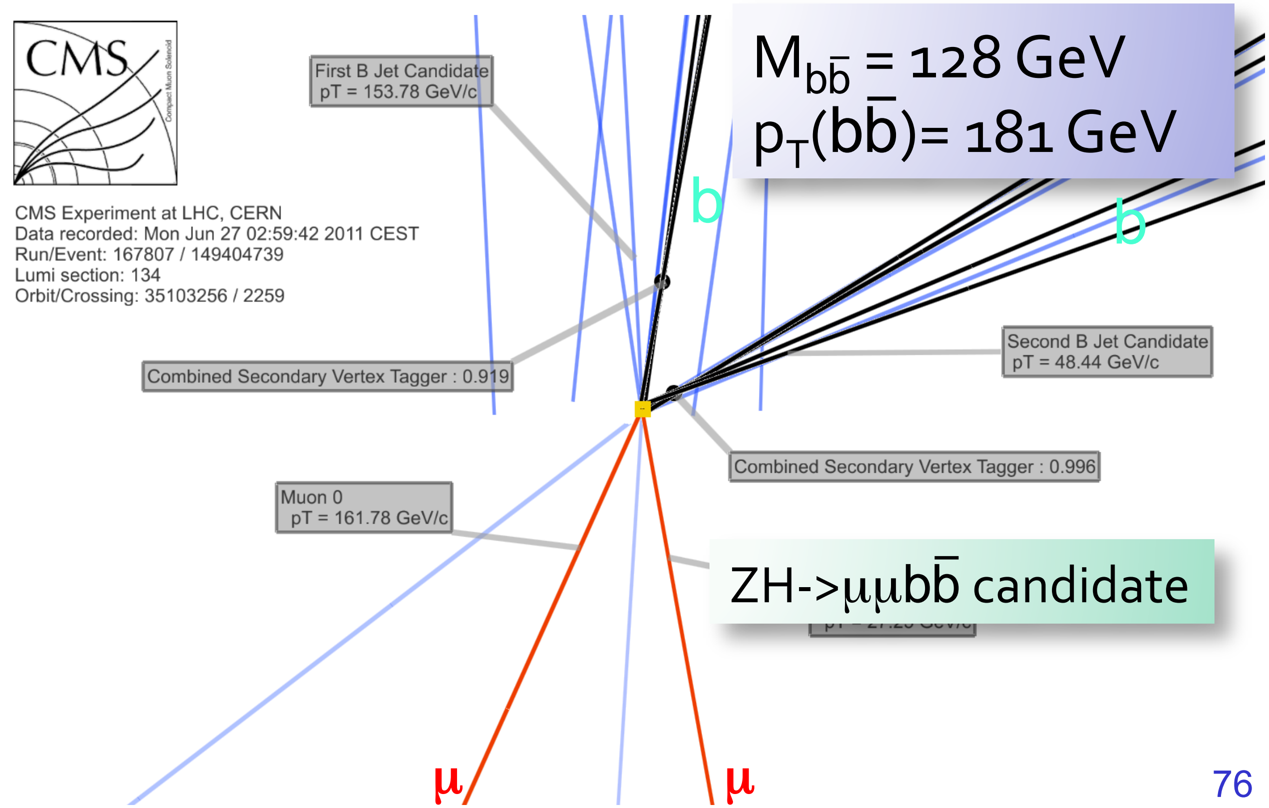
Main backgrounds
estimated from data in
control regions



Event selection

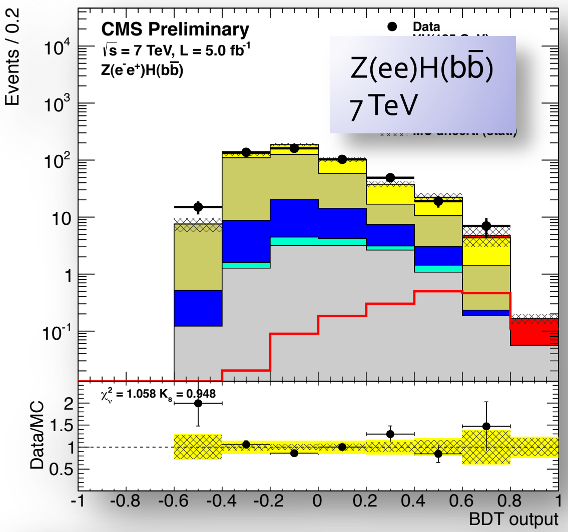
- First CMS VHbb 2011 analysis: Phys. Lett. B 710(2012) 284-306
- Here 5 fb-1 @ 7 TeV (2011) + 5 fb-1 @ 8 TeV (2012)
  - Improvements OF ~ 50% in sensitivity:
  - Two Pt(V) bins: "low" and "high" – see backup
  - Fit the shape of the MVA output distribution (vs cut and count)
  - Improved b-jet energy resolution [MVA regression]

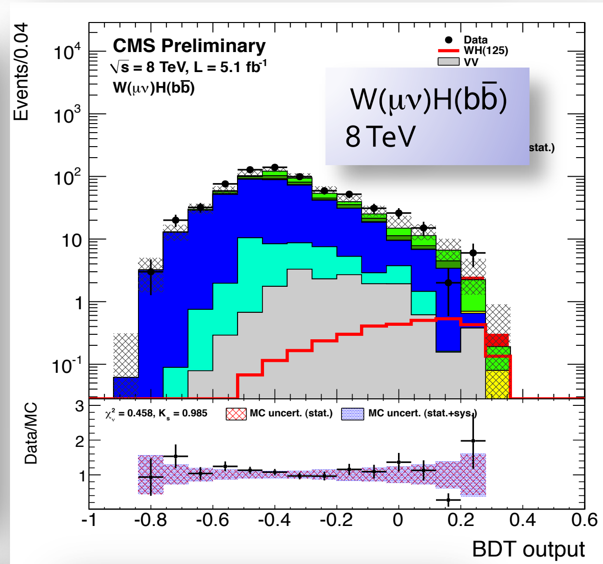




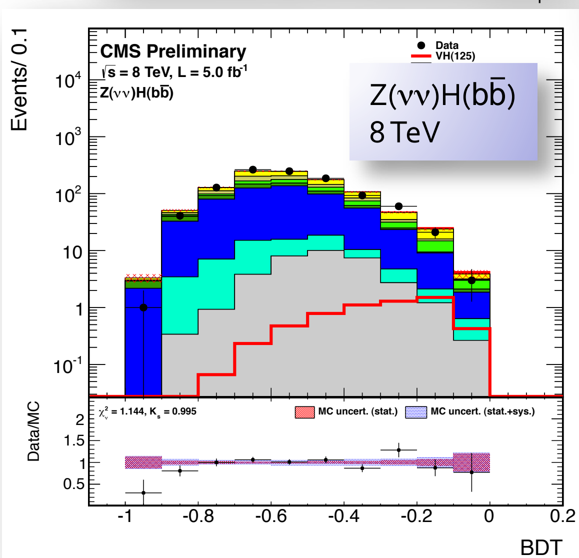
Examples of final MVA distributions

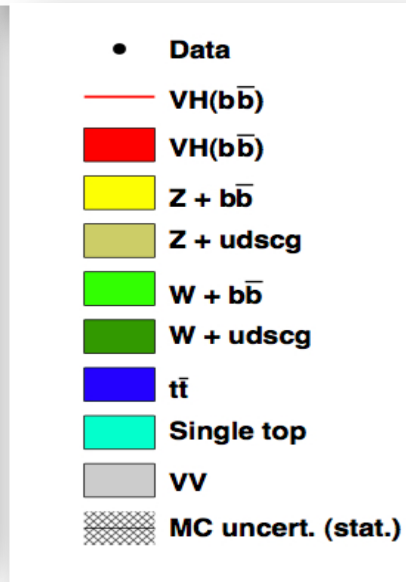
Results

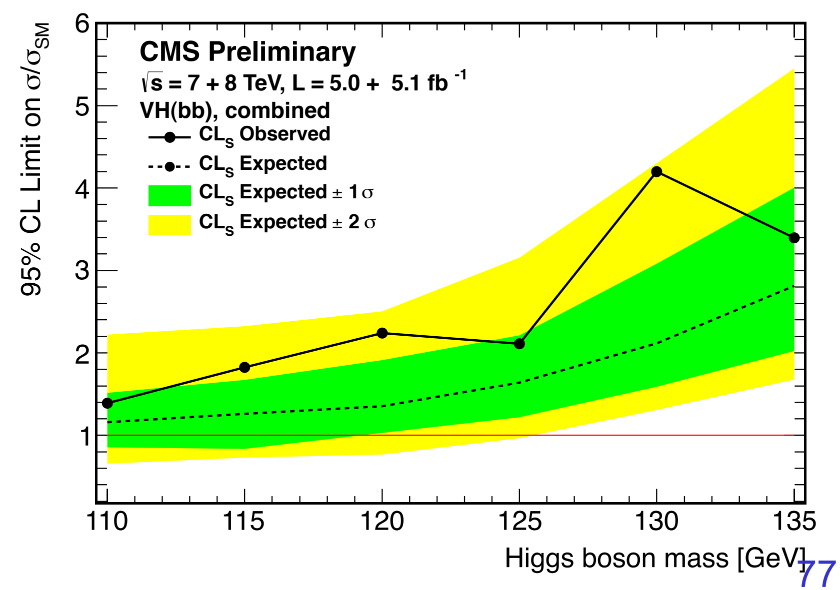




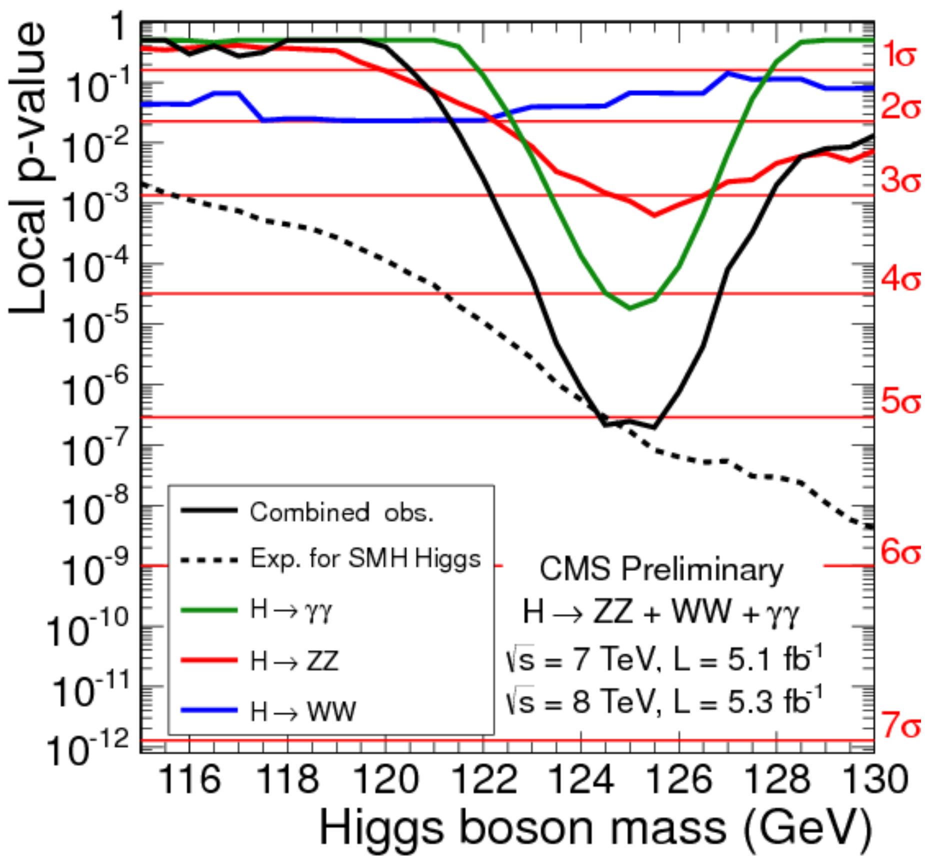
- Observed limits:
  - Compatible with either background or signal from a 125 GeV Higgs







Characterization of excess near 125 GeV



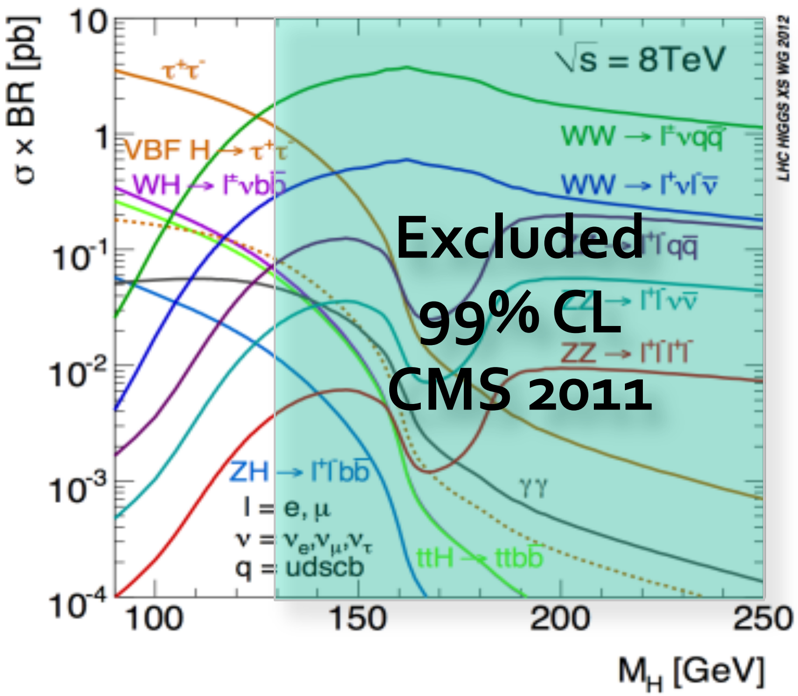
adding high sensitivity, but low mass resolution WW

comb. significance: 5.1 σ

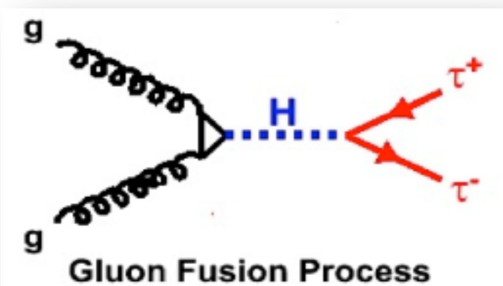
expected significance for SM Higgs: 5.2 σ

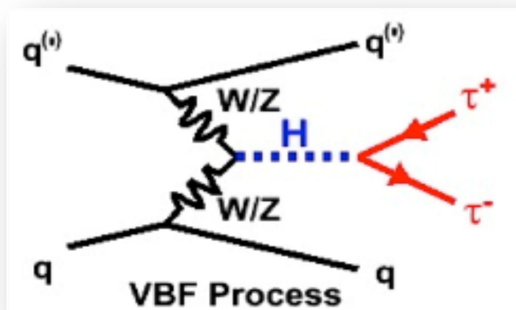
$H \rightarrow \tau\tau$
$\rightarrow \mu\tau_h, e\tau_h, e\mu, \mu\mu$

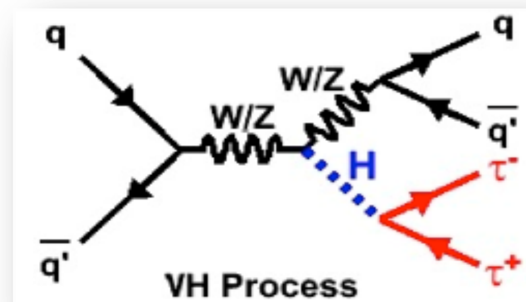
$H \rightarrow \tau\tau$



- Characteristics
  - High σ•BR at low mass
  - Sensitive to all production modes
  - Probes coupling to leptons
  - Enhanced σ x BR in MSSM
  - Challenging large backgrounds:
    - DY→ττ, W+Jets, QCD







Analysis Strategy

- Search performed in 4 tau-pair final states: **$\mu\tau_h$, $e\tau_h$, $e\mu$, $\mu\mu$**
- Analysis divided into 5 categories: mass resolution, S/B
- All categories are fit simultaneously

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

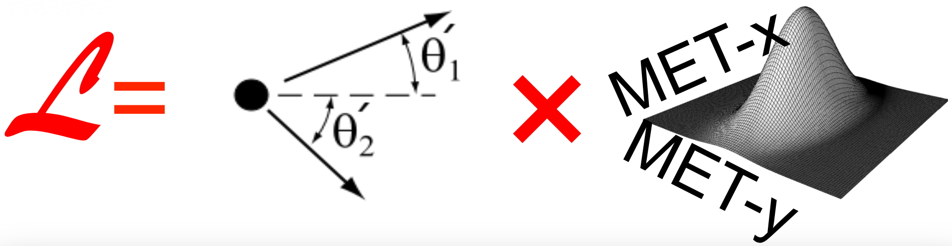
0 Jet, High pT
Lepton p_T spectrum harder from H

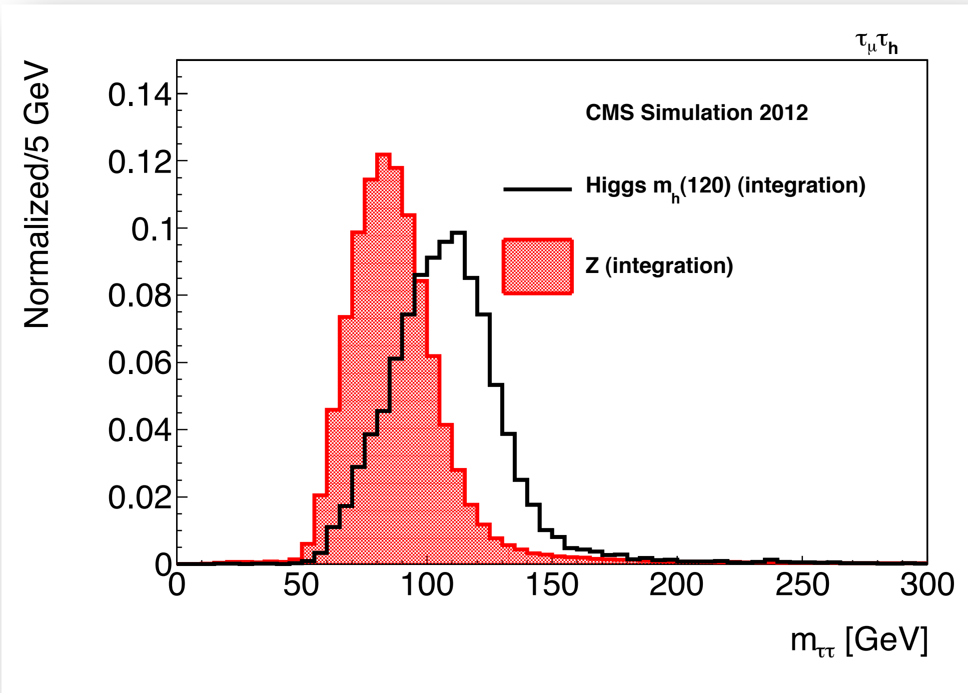
1 Jet, High p_T
Enhancement from p_T and jet requirement

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

[1]categorization based on τ_h p_T for $\mu\tau_h$, $e\tau_h$; μ p_T for $e\mu$; leading μ p_T for $\mu\mu$

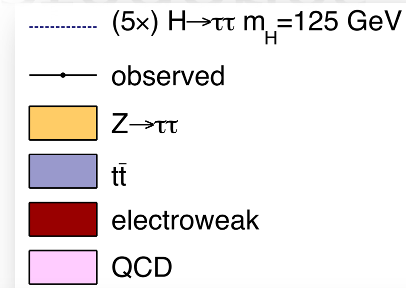
Full m(ττ) Reconstruction

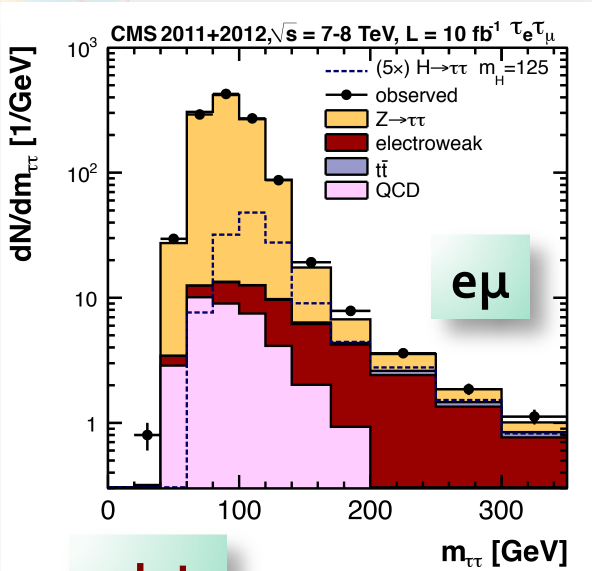




- SVFit
  - Event-by-event estimator of true m(ττ) likelihood
    - Matrix Element used for τ→lνν
    - Phase-Space is used for τ→π
    - Nuisance parameters are integrated out
- Mass peaks at true value
  - 20 % improved resolution
    - With respect to 2011
  - Better separation of H from Z

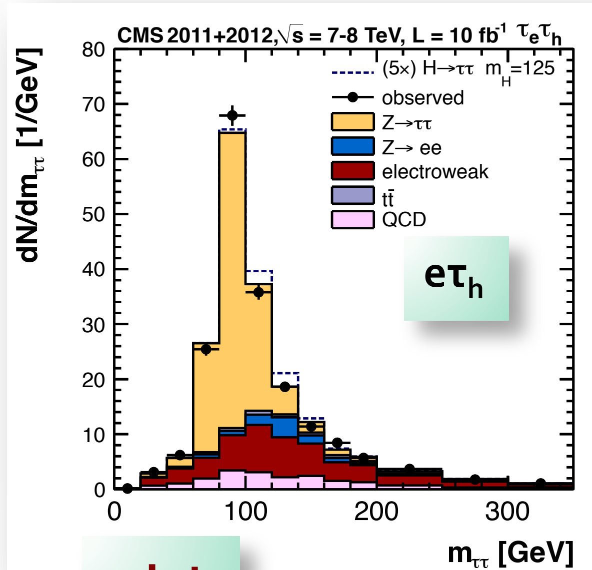
Mass Distributions in Event Categories





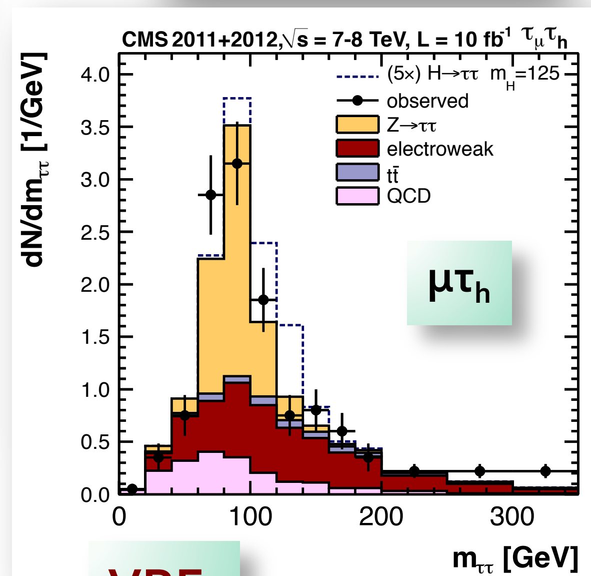
0 Jet

- Constrains energy scales and efficiencies
  - Large Drell-Yan background
  - Sensitivity boosted by low/high p_T split



1 Jet

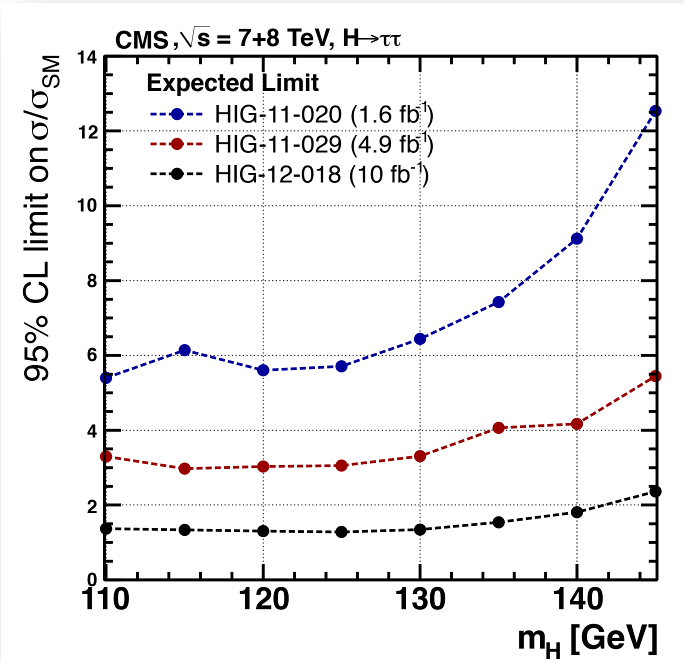
- Enhanced sensitivity to gluon fusion
  - Improved mass resolution
  - Increased sensitivity by splitting into low and high p_T categories

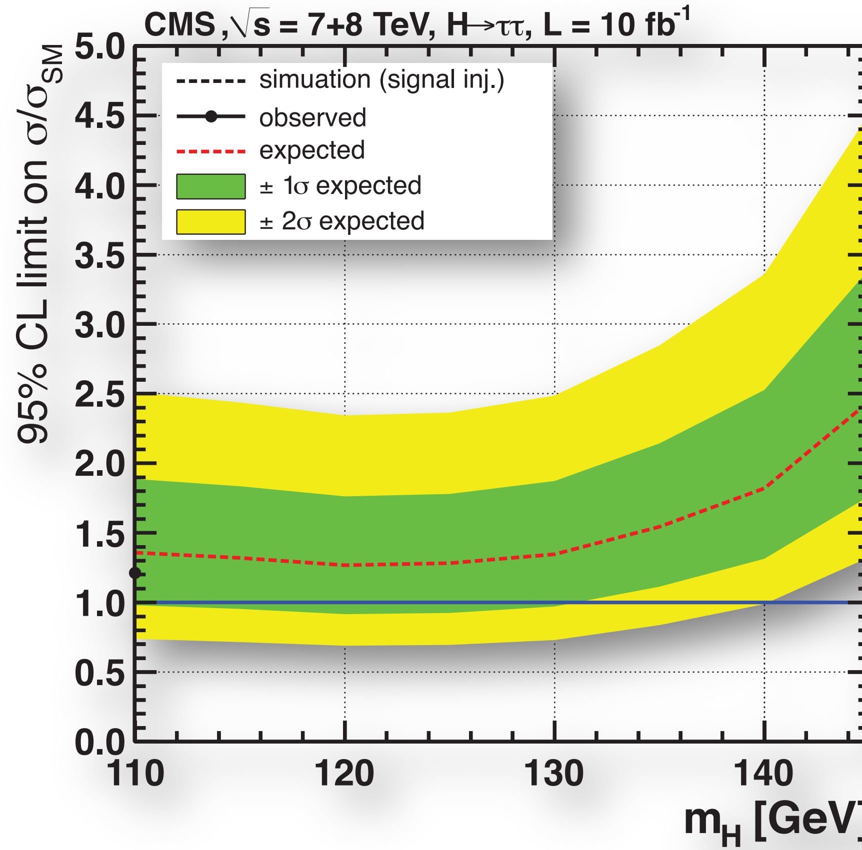


VBF

- Enhanced sensitivity to VBF production
  - Highest sensitivity for $m_H < 130$ GeV

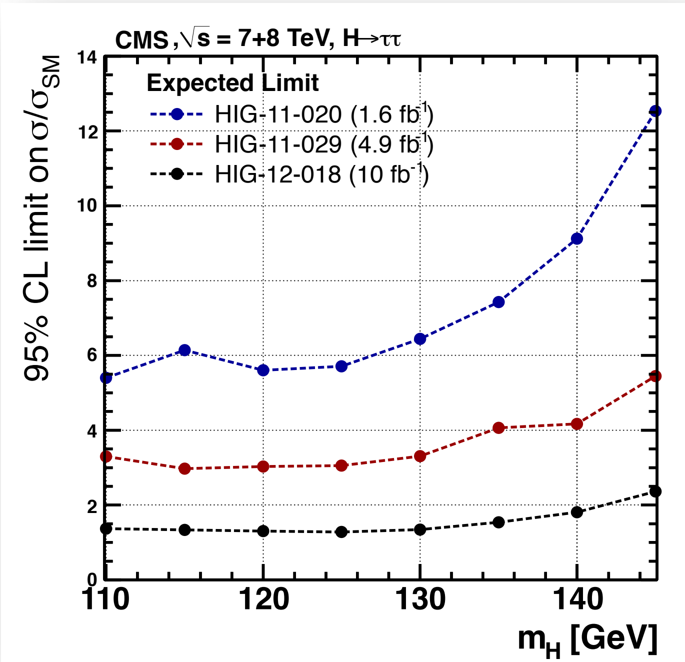
Results for H→ττ

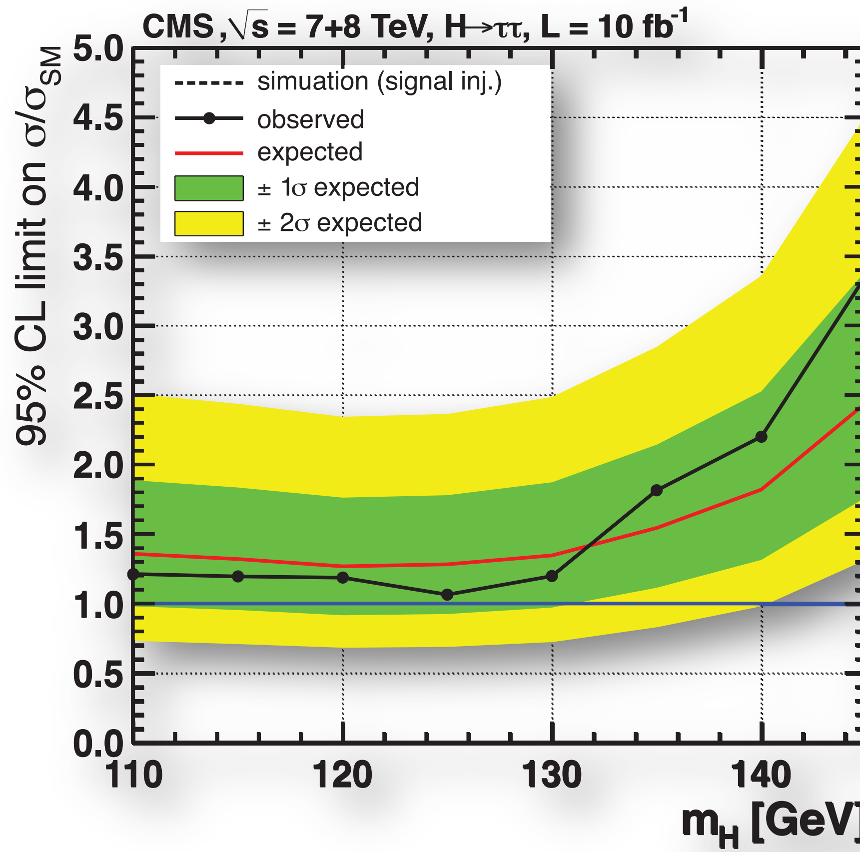




- ~2x improvement in sensitivity in 2011 data alone
  - => 70% improvement in sensitivity on the same data
  - 40% improvement with the additional luminosity
- No significant departure from SM background-only expectation
  - Observed limit of 1.06 x SM at m_H = 125 GeV

Results for H⟶ττ





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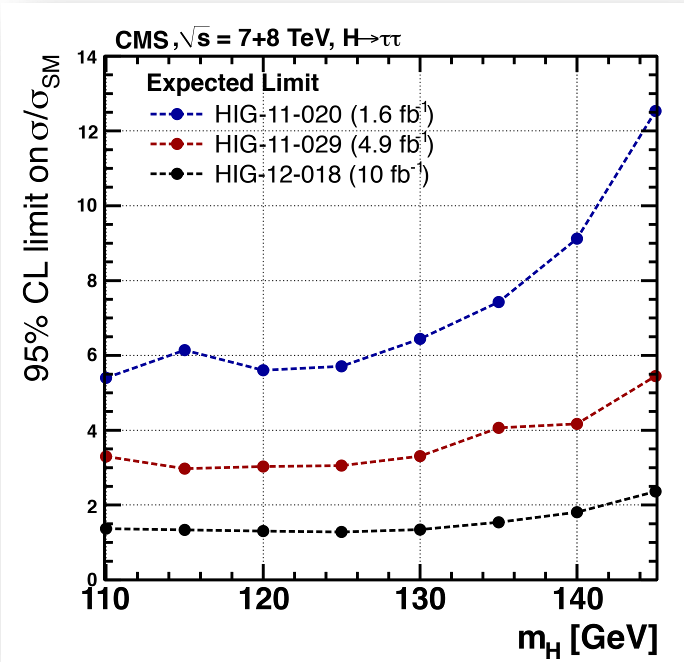
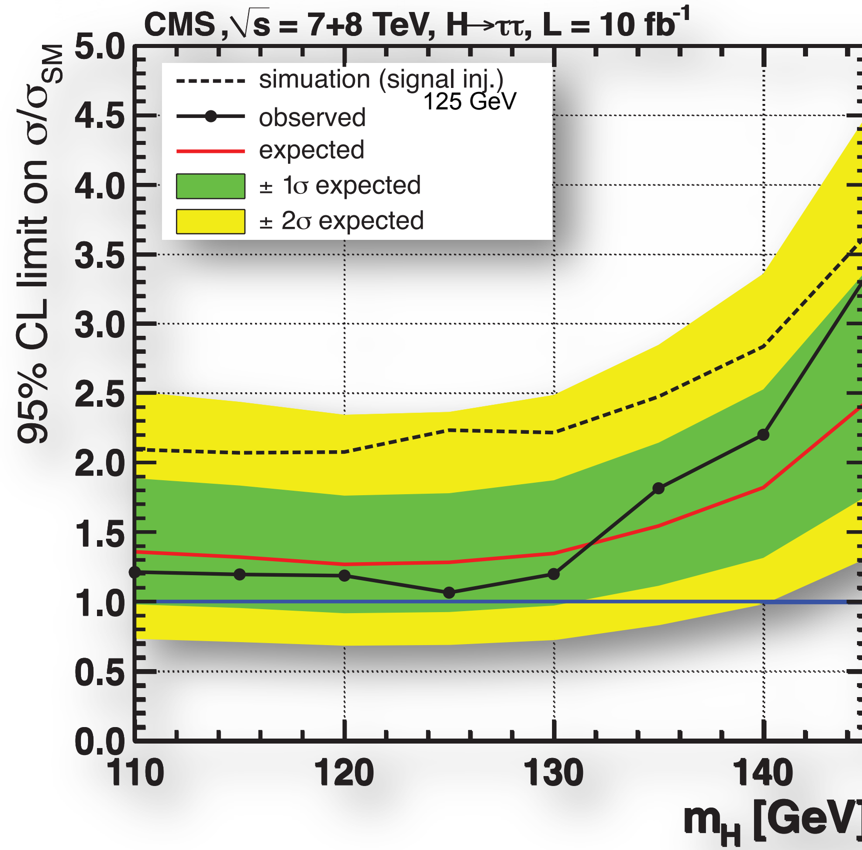
Results for H→ττ





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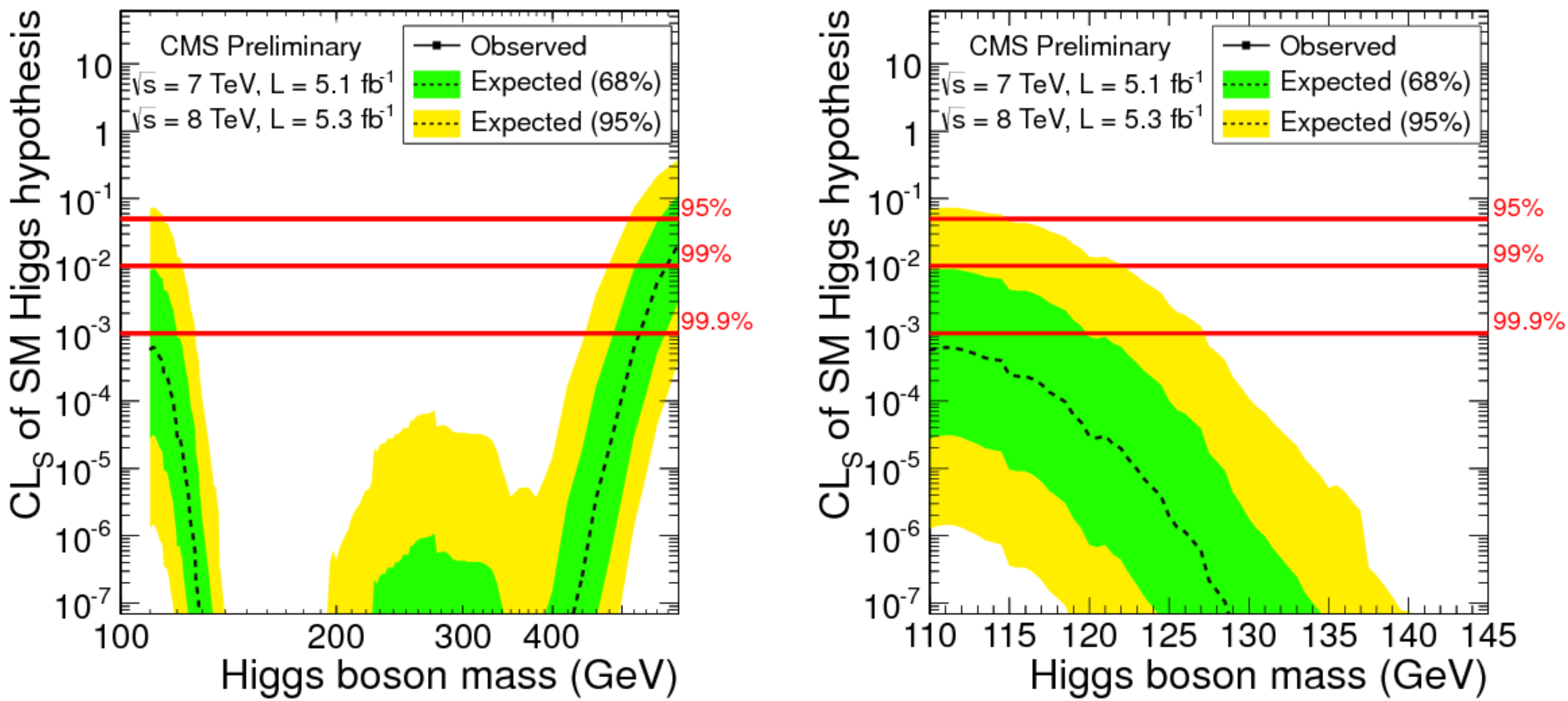
Full result

SM Higgs exclusion: confidence level



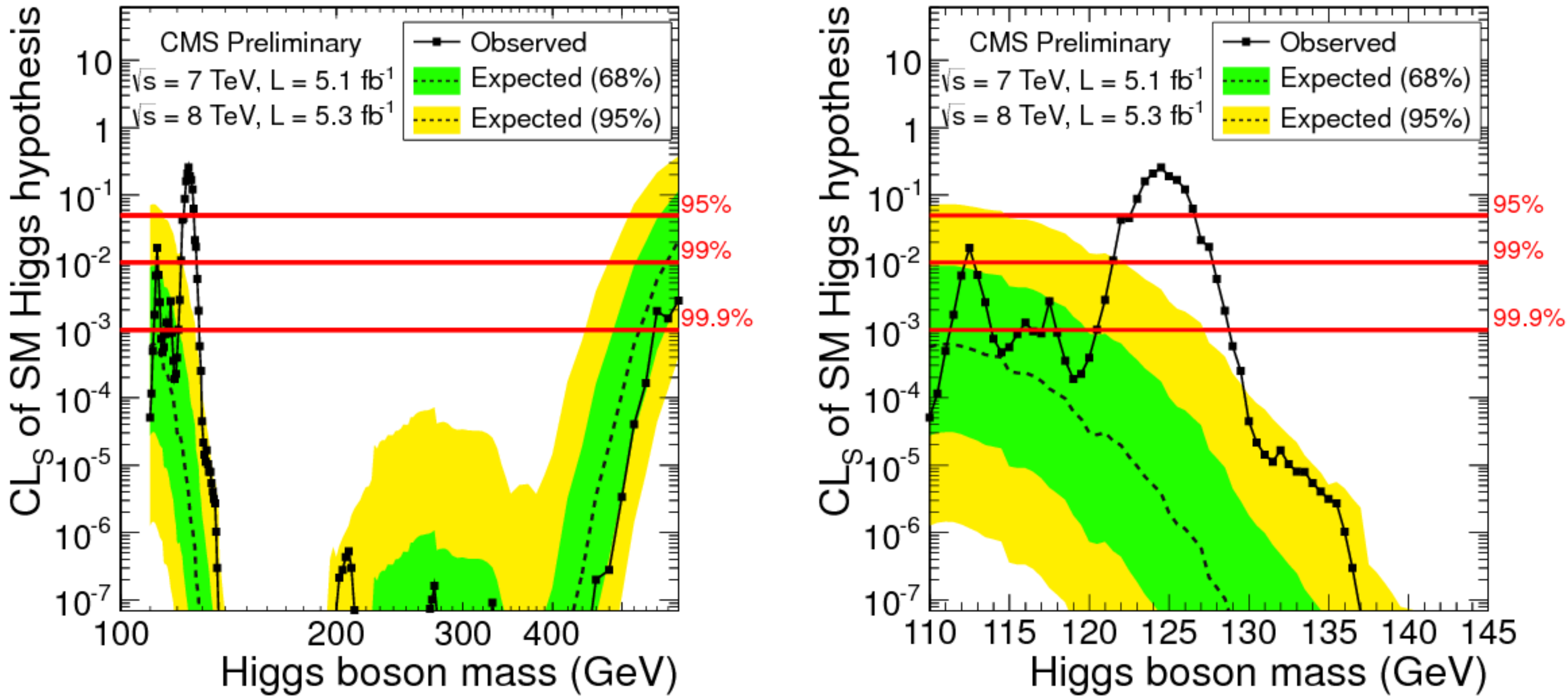
Expected in absence of SM Higgs boson:

110 – 600 GeV at 95% CL

110 – 580 GeV at 99% CL

110 – 520 GeV at 99.9% CL

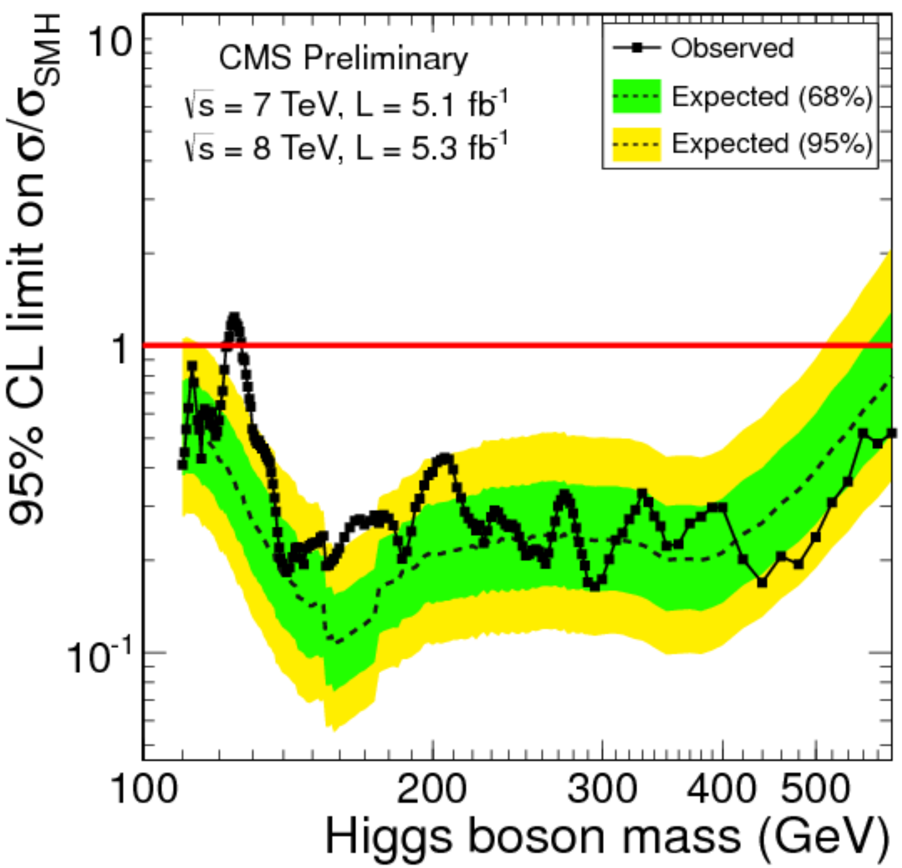
SM Higgs exclusion: confidence level

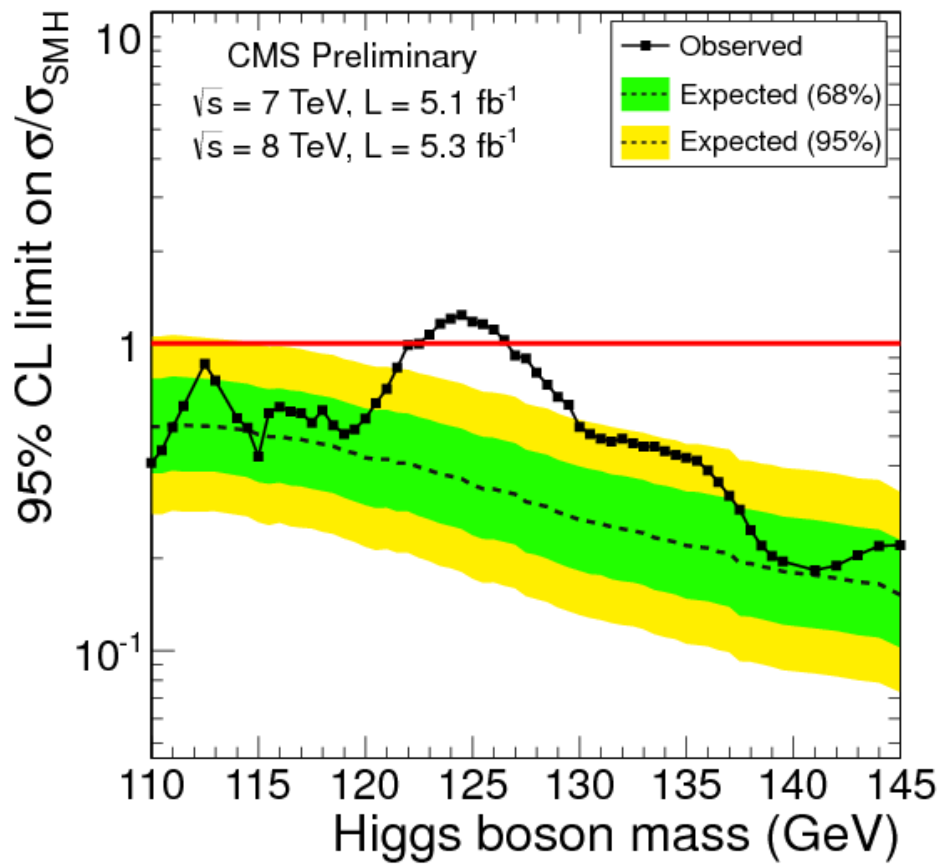


Observed: 110 – 122.5 [...] 127 – 600 GeV at 95% CL

110—112 .. 113 – 121.5 [...] 128 – 600 GeV at 99% CL

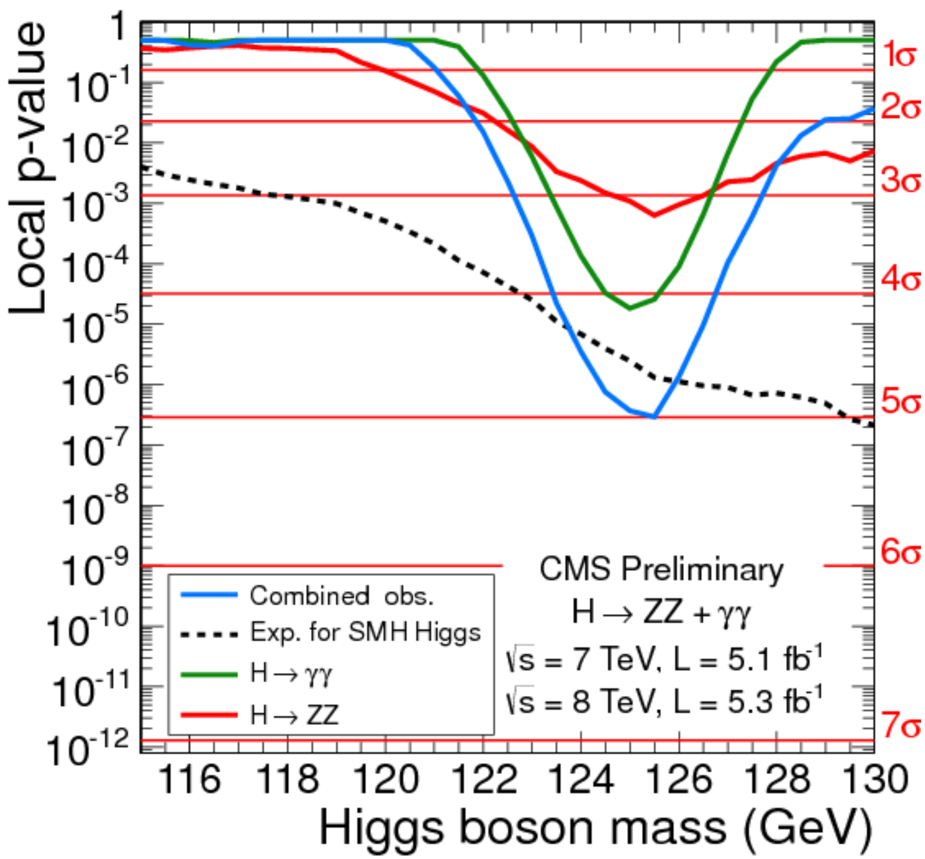
SM Higgs exclusion: signal strength





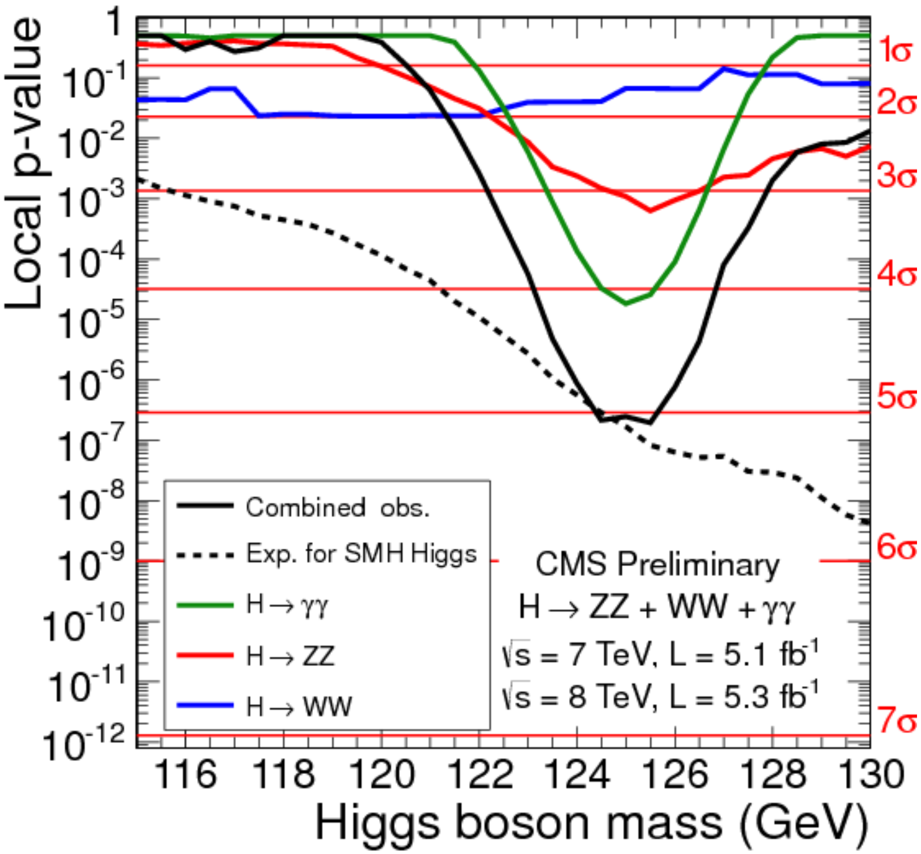
Observed: 110 – 122.5 …. 127 – 600 GeV at 95% CL

Characterization of excess near 125 GeV



- **high sensitivity, high mass resolution channels: γγ+4l**
  - **γγ: 4.1 σ excess**
  - **4 leptons: 3.2 σ excess**
  - **near the same mass 125 GeV**
- **comb. significance: 5.0 σ**
- **expected significance for SM Higgs: 4.7 σ**

Characterization of excess near 125 GeV

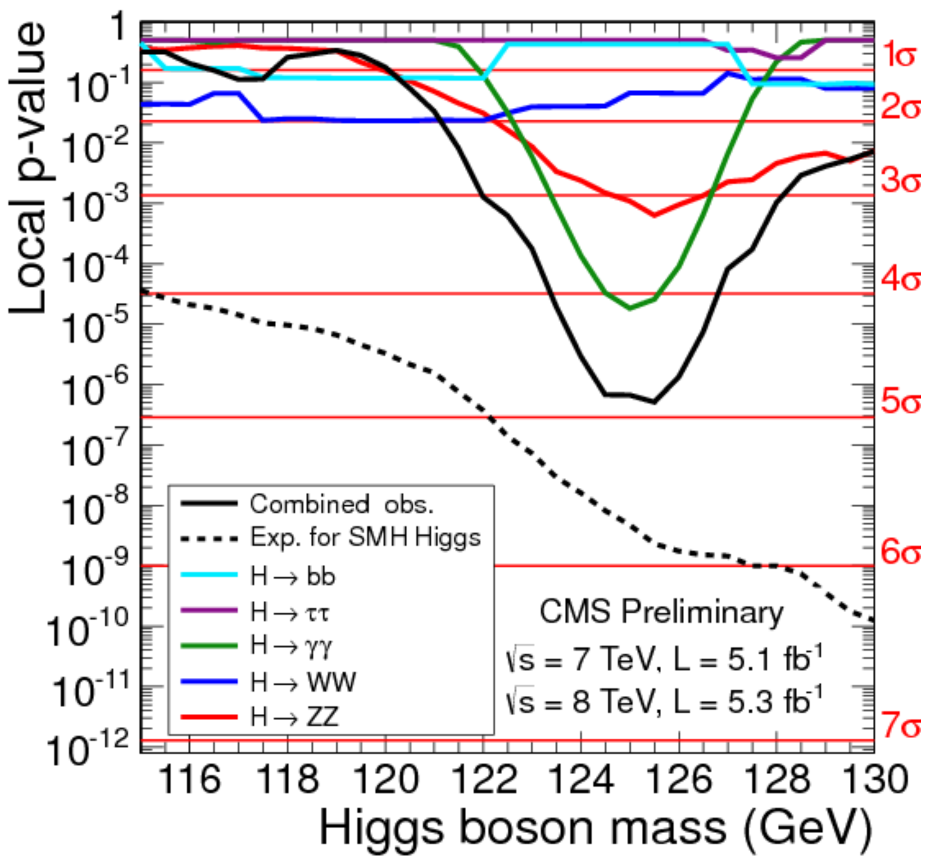


adding high sensitivity, but low mass resolution WW

comb. significance: 5.1 σ

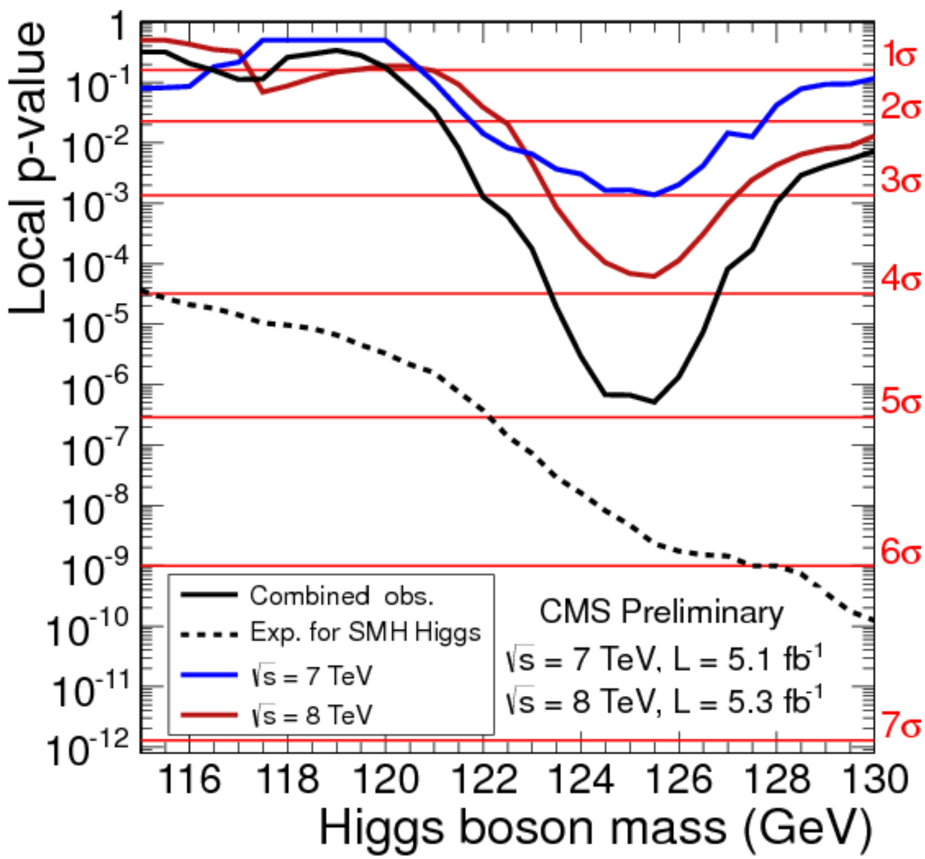
expected significance for SM Higgs: 5.2 σ

Characterization of excess near 125 GeV



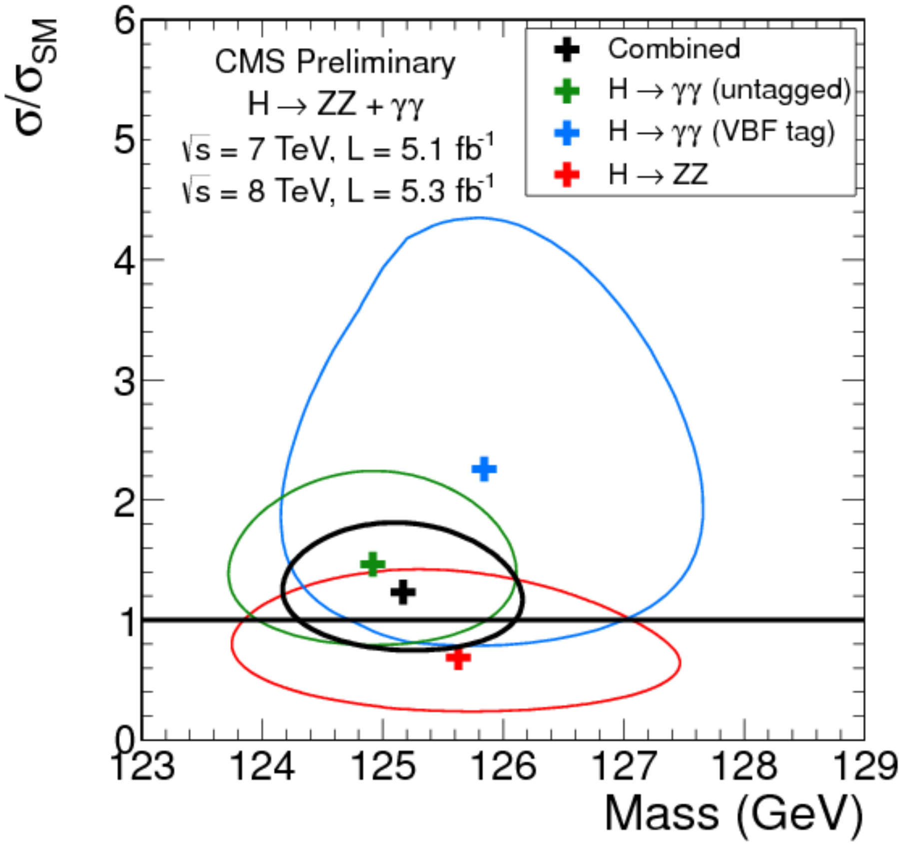
- **all channels together: comb. significance: 4.9 σ**
- **expected significance for SM Higgs: 5.9 σ**

Characterization of excess near 125 GeV



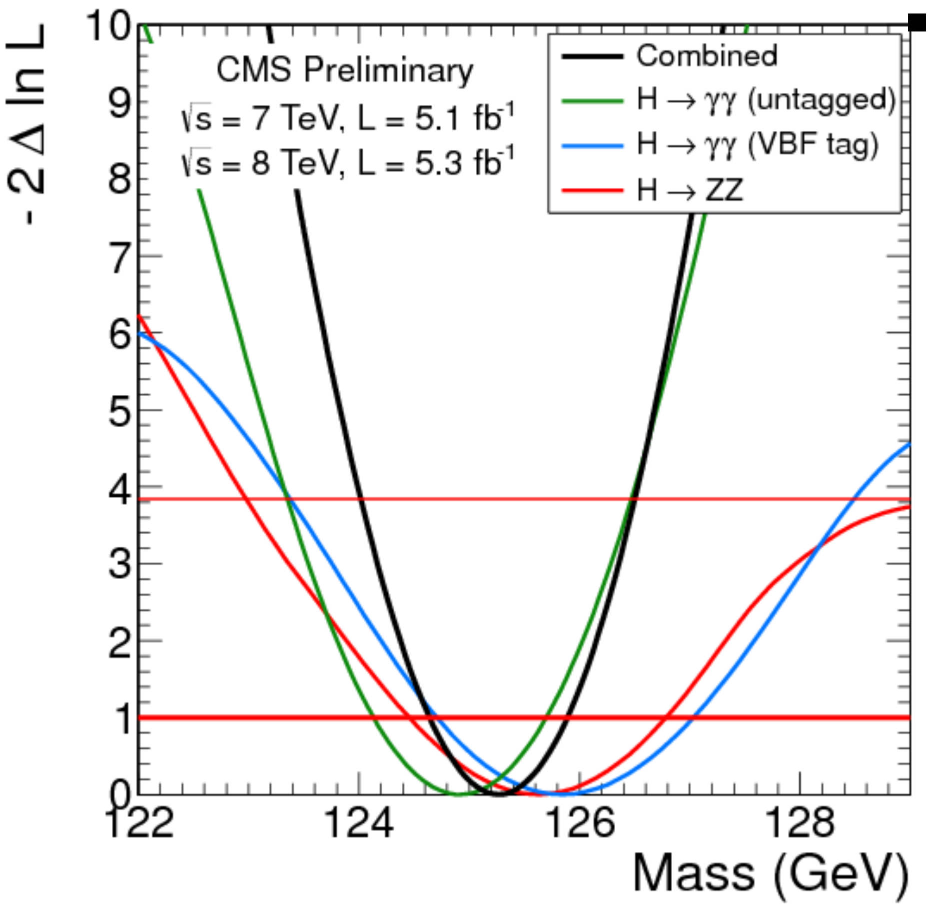
- **Observed significance: 4.9 σ**
- **Excess seen in both**
  - **7 TeV data (3.0 σ)**
  - **8 TeV data (3.8 σ)**
  - **near the same mass 125 GeV**

Characterization of the excess: mass



- Likelihood scan for mass and signal strength in three high mass resolution channels
- results are self-consistent and can be combined

Characterization of the excess: mass



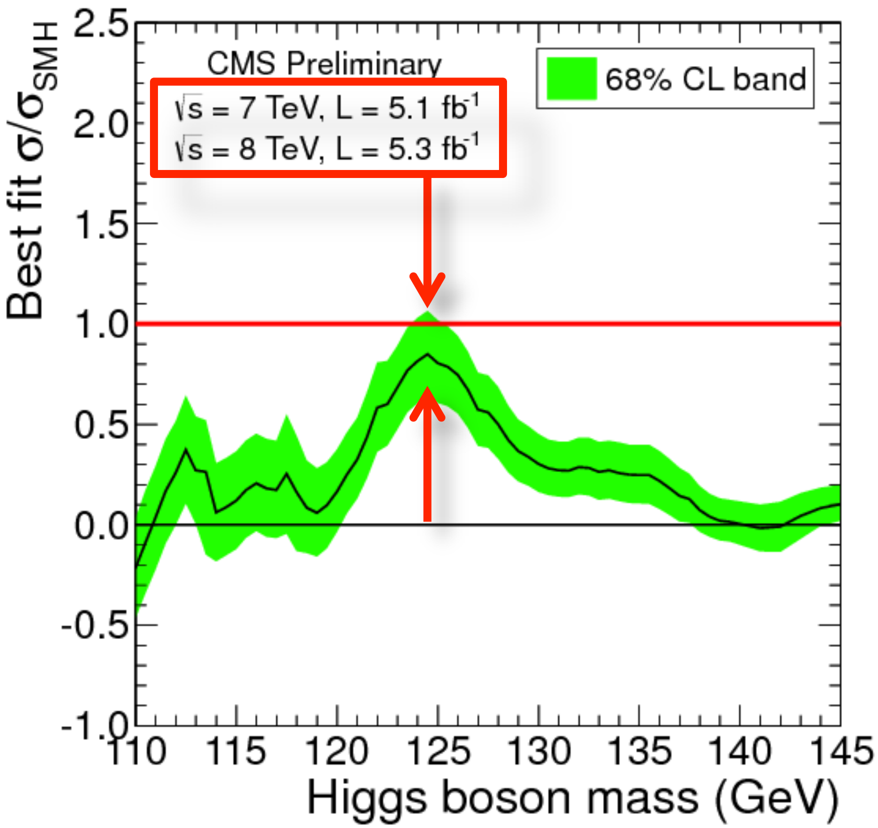
- To reduce model dependence, allow for free cross sections in three channels and fit for the common mass:

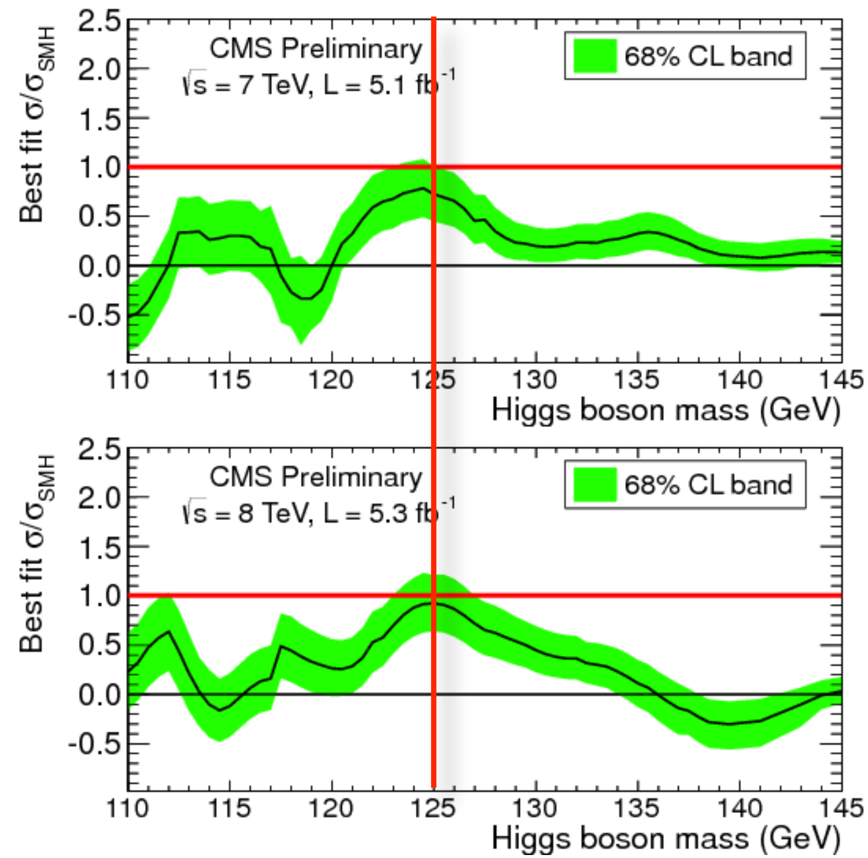
m_X = 125.3 ± 0.6 GeV

- We have observed a state decaying to di-photon and four-lepton final state with statistical significance of 5 σ
- The observed state has mass near 125.3 ± 0.6 GeV
- Next we look at the extent to which the observed state is compatible, within the current uncertainties, with the SM Higgs boson

Compatibility with SM Higgs boson

Signal strength





- Overall best-fit signal strength in the combination:

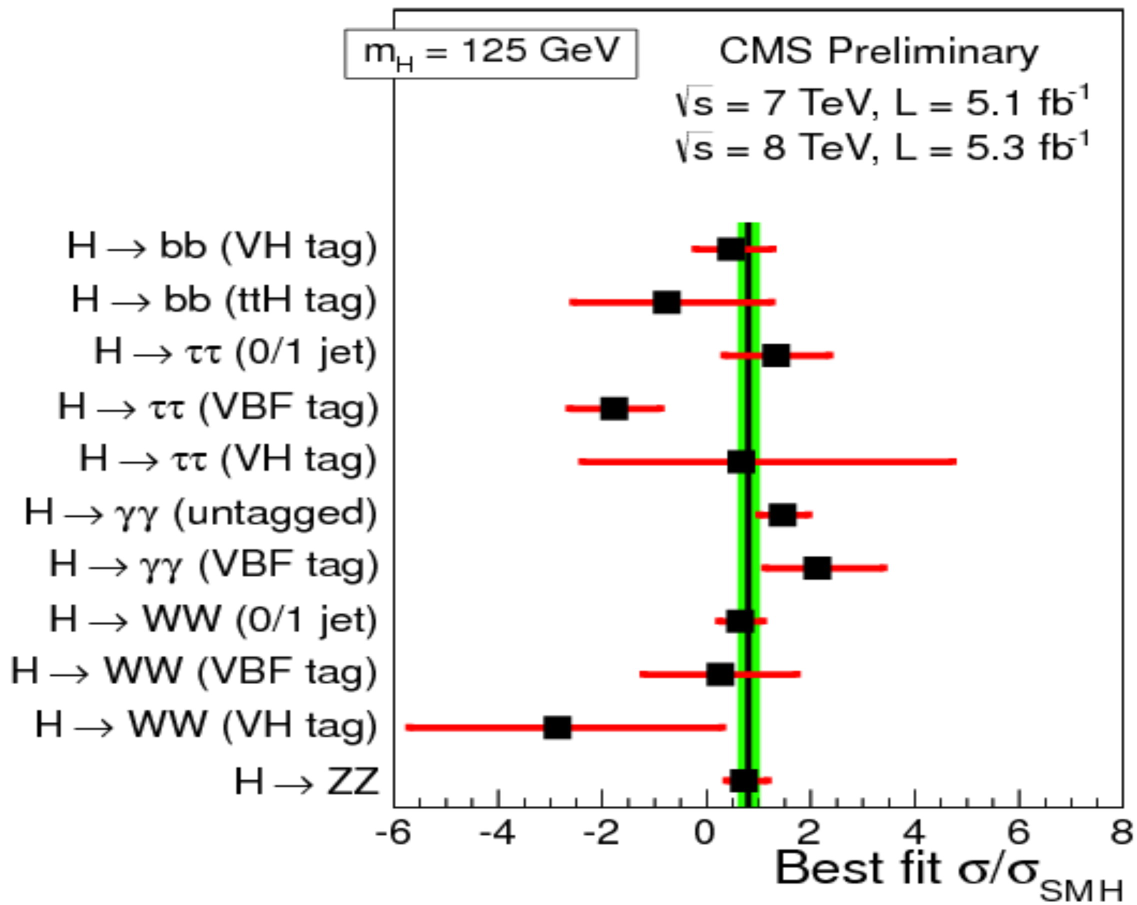
  σ/σ_{SM} = 0.80±0.22

- Signal strength in 7 and 8 TeV data are self-consistent

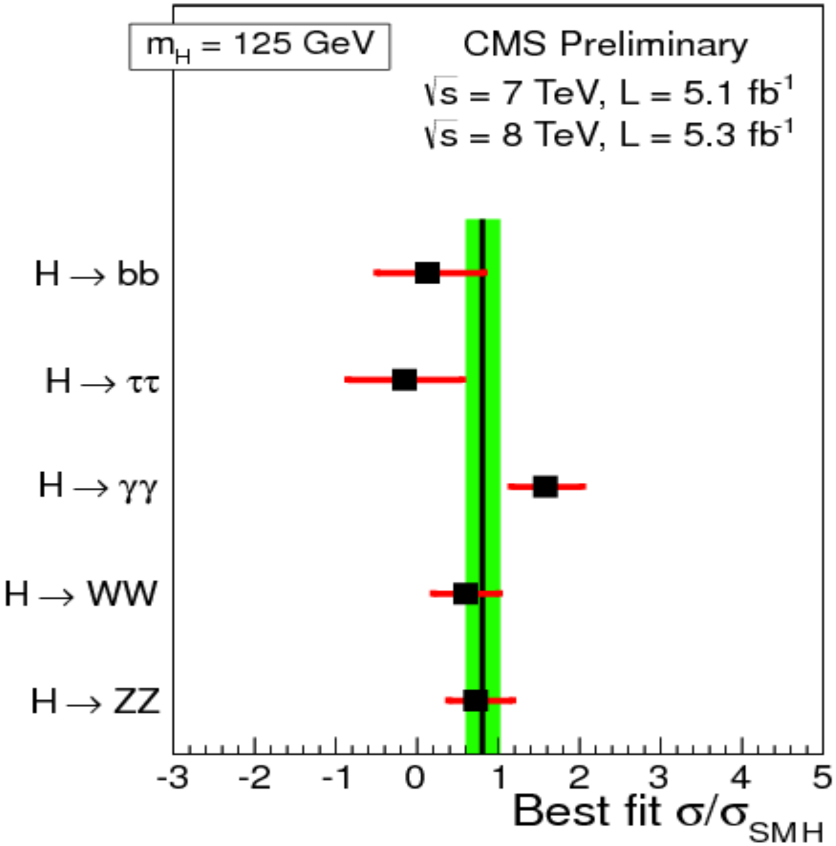
98

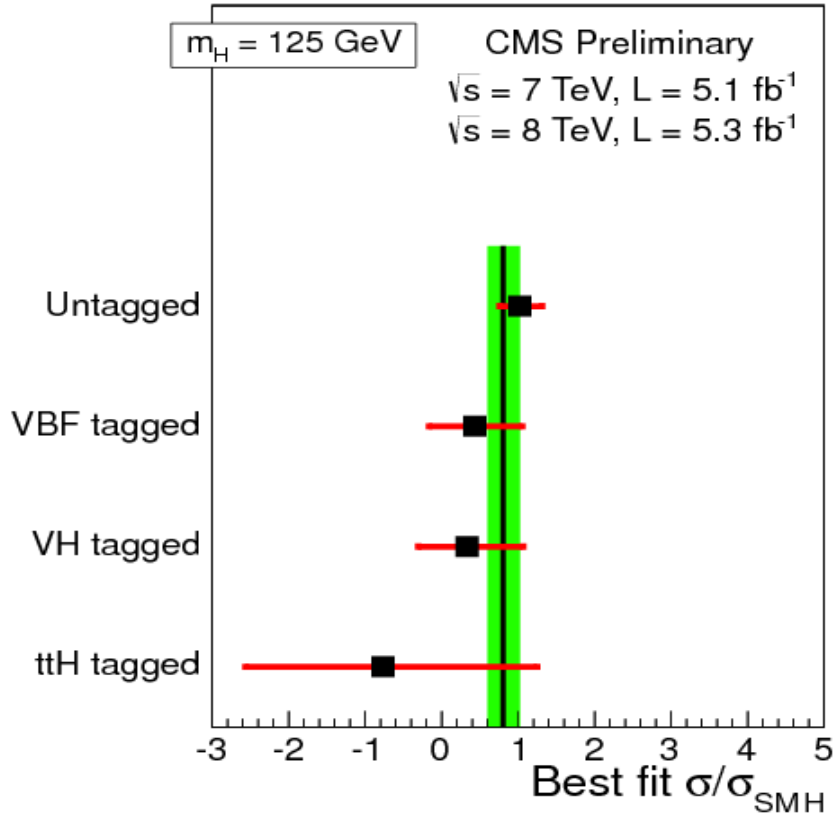
Compatibility with SM Higgs boson
event yields in different modes (1)

- Event yields in different production times decay modes are self-consistent
  - albeit many modes have not yet reached sensitivity to distinguish SM from Background



Compatibility with SM Higgs boson
event yields in different modes (2)





- Event yields in different decay modes are self-consistent
- Event yields in different production topologies are self-consistent

Compatibility with SM Higgs boson
custodial symmetry

- The measurement of the H→WW/H→ ZZ ratio is mostly driven by the ratio of the Higgs couplings to WW and ZZ, which is protected by custodial symmetry

- Combination of "inclusive" WW and ZZ yields gives

$$R_{WW/ZZ} = 0.9^{+1.1}_{-0.6}$$

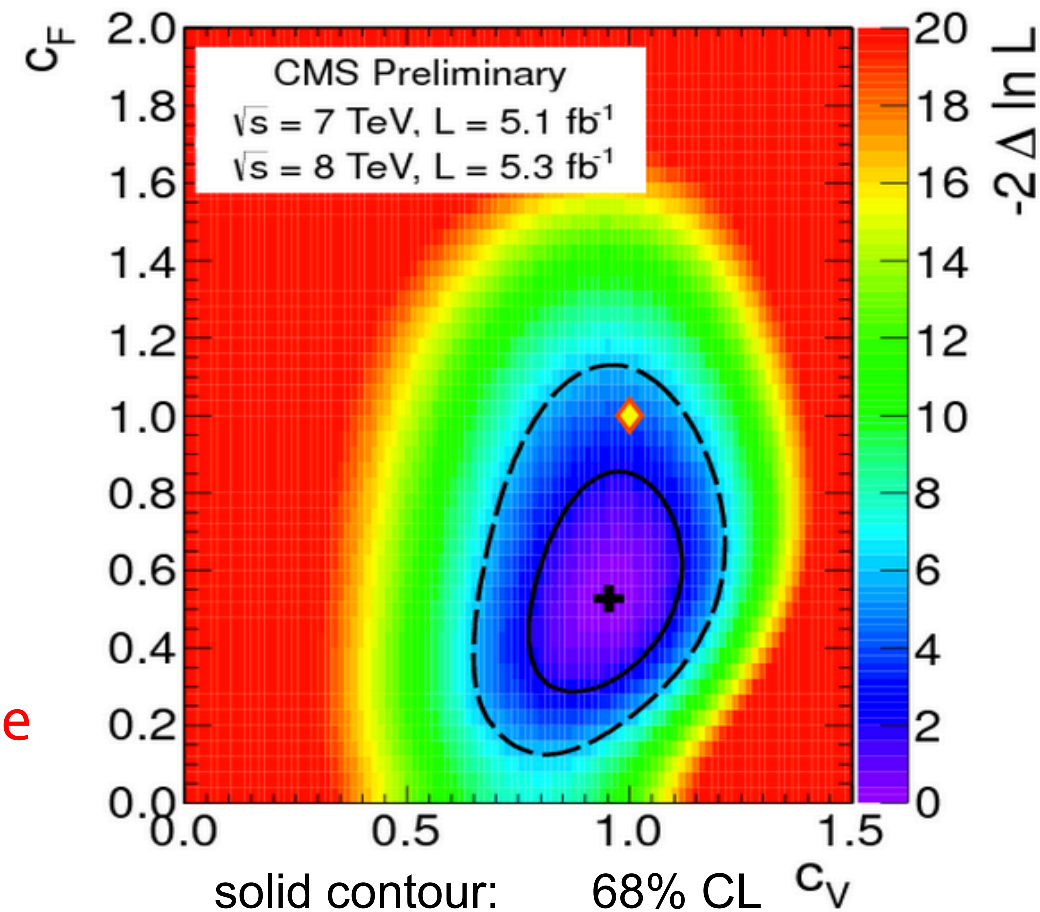
Fit to C_V and C_F

Group the Higgs couplings into "Vectorial" and "Fermionic" sets.

Attach a modifier to the SM prediction
to each of those (C_V and C_F).

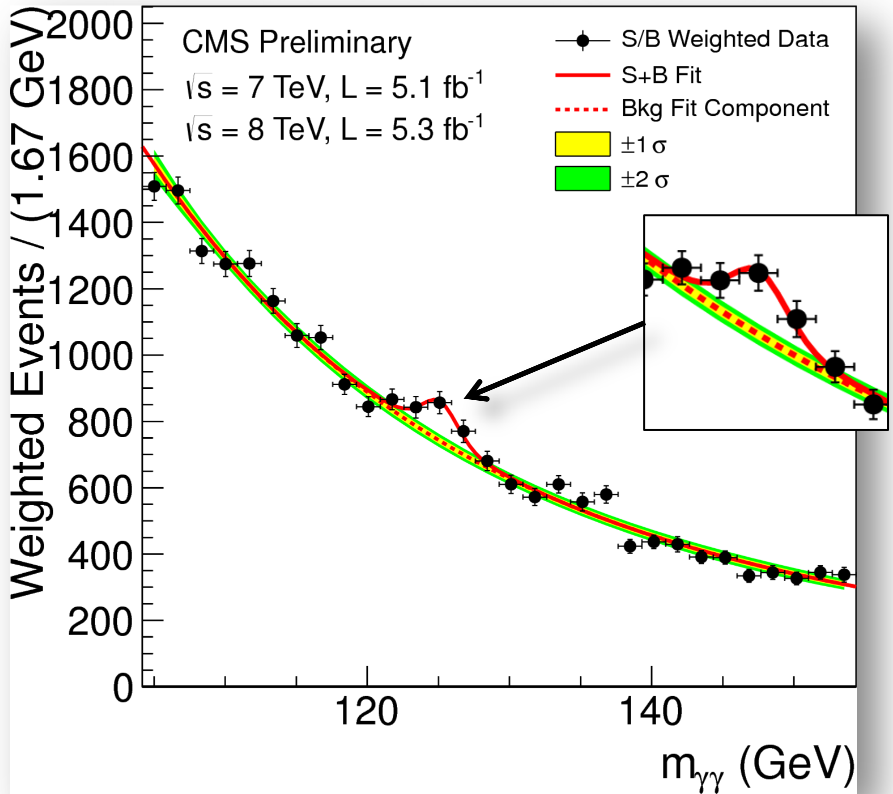
Use LO theoretical prediction for loop-induced $H \rightarrow \gamma\gamma$, $H \rightarrow gg$ couplings.

In agreement with the SM within the 95% confidence range
→ Need more data!

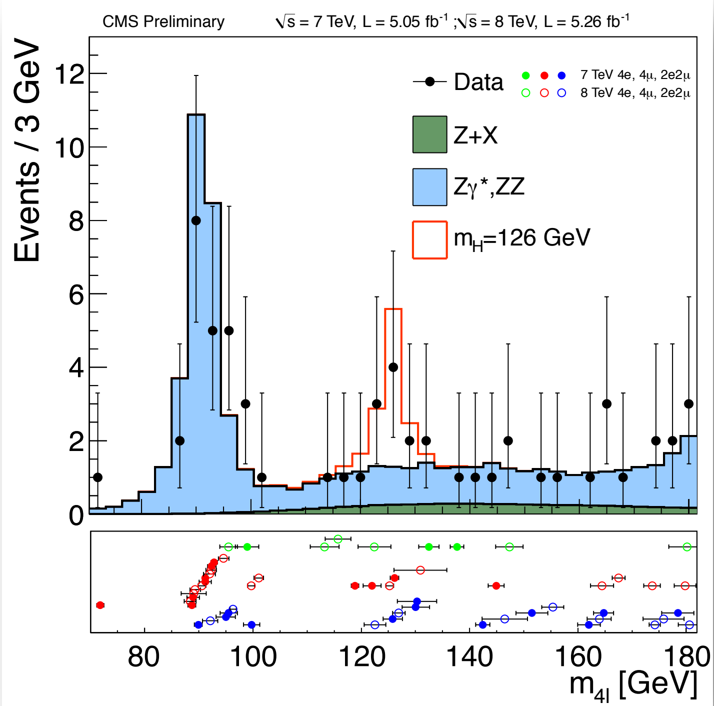


solid contour: 68% CL
dashed contour: 95% CL

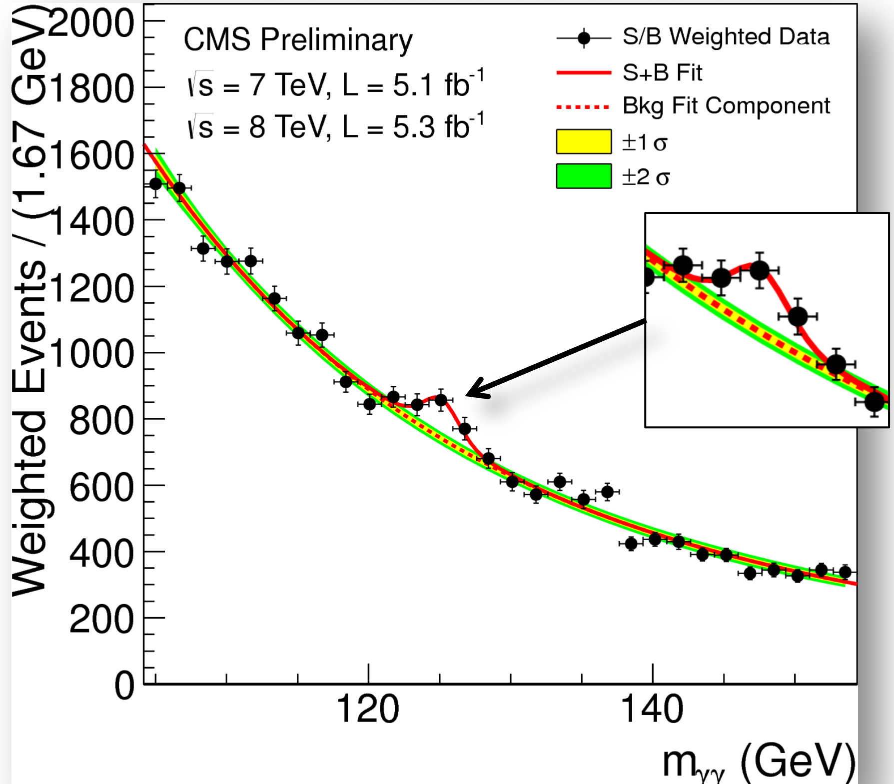
In summary


CMS Preliminary
√s = 7 TeV, L = 5.1 fb-1
√s = 8 TeV, L = 5.3 fb-1
S/B Weighted Data
S+B Fit
Bkg Fit Component
±1 σ
±2 σ
Weighted Events / (1.67 GeV)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
120
140
mγγ (GeV)

In summary



CMS Preliminary
√s = 7 TeV, L = 5.05 fb⁻¹ ;√s = 8 TeV, L = 5.26 fb⁻¹
Events / 3 GeV
Data
7 TeV 4e, 4μ, 2e2μ
8 TeV 4e, 4μ, 2e2μ
Z+X
Zγ*,ZZ
mH=126 GeV
m4l [GeV]



CMS Preliminary
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Bkg Fit Component
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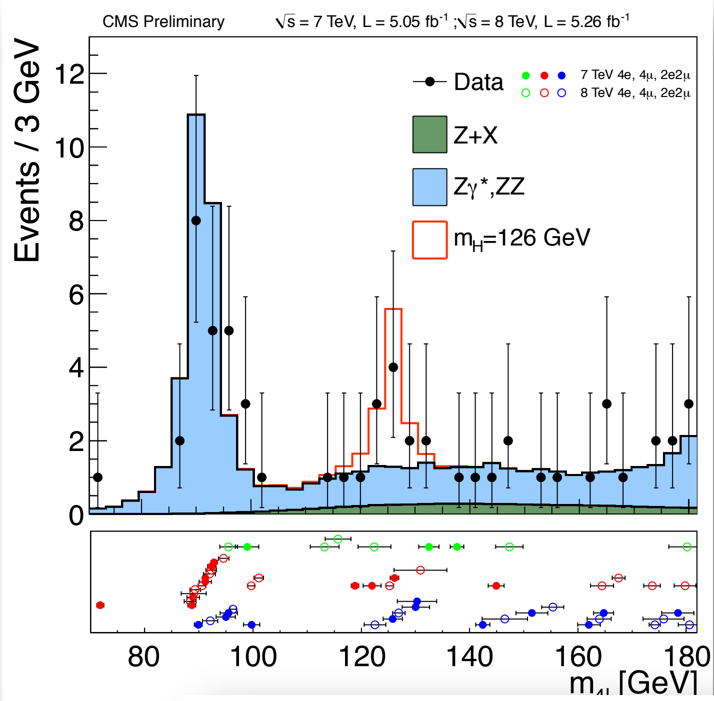
Weighted Events / (1.67 GeV)
mγγ (GeV)

In summary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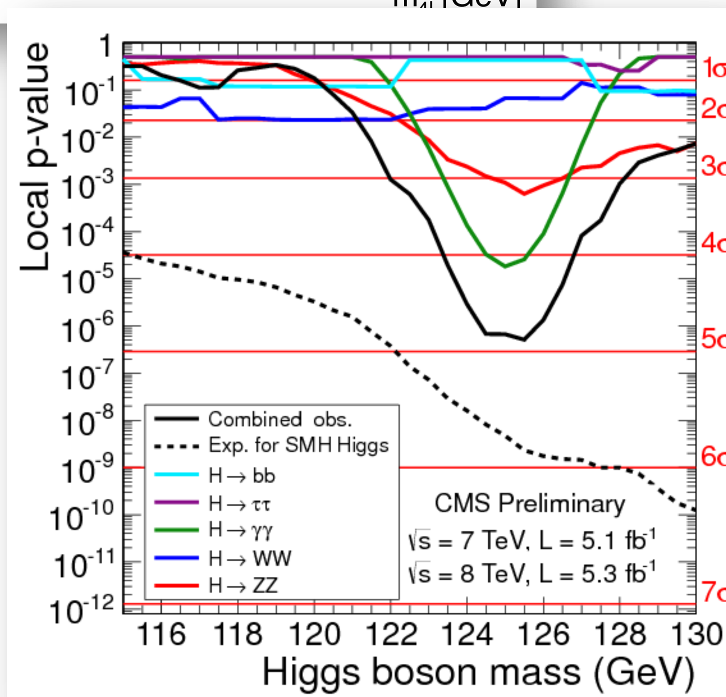
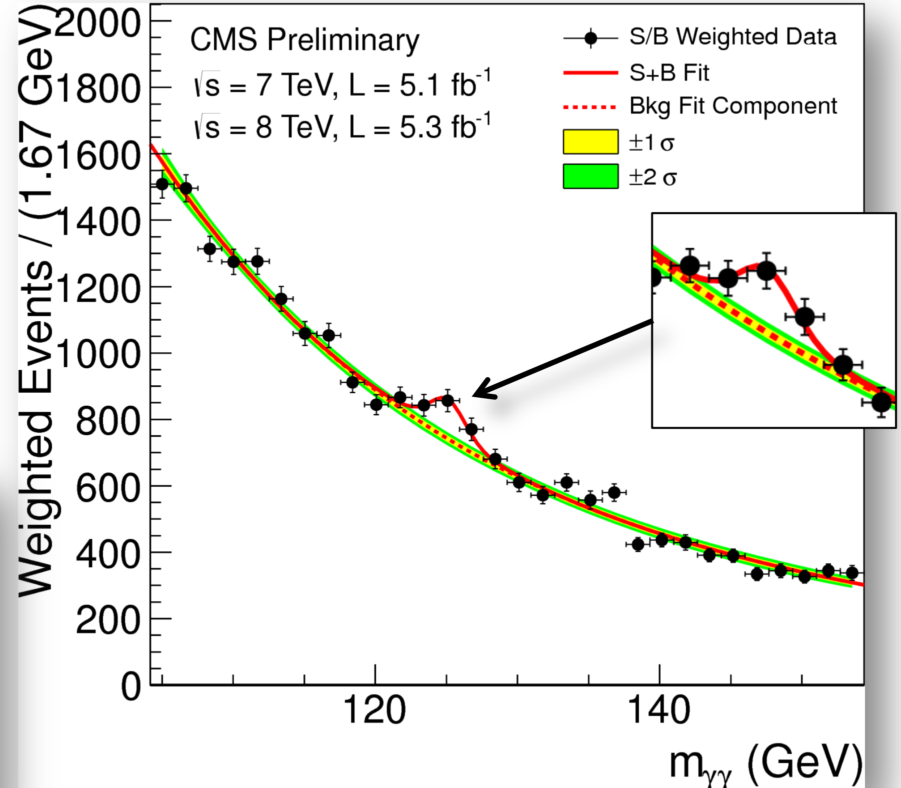

Local p-value
1σ
2σ
3σ
4σ
5σ
6σ
7σ
Combined obs.
Exp. for SMH Higgs
H→bb
H→ττ
H→γγ
H→WW
H→ZZ
CMS Preliminary
√s = 7 TeV, L = 5.1 fb⁻¹
√s = 8 TeV, L = 5.3 fb⁻¹
Higgs boson mass (GeV)


CMS Preliminary
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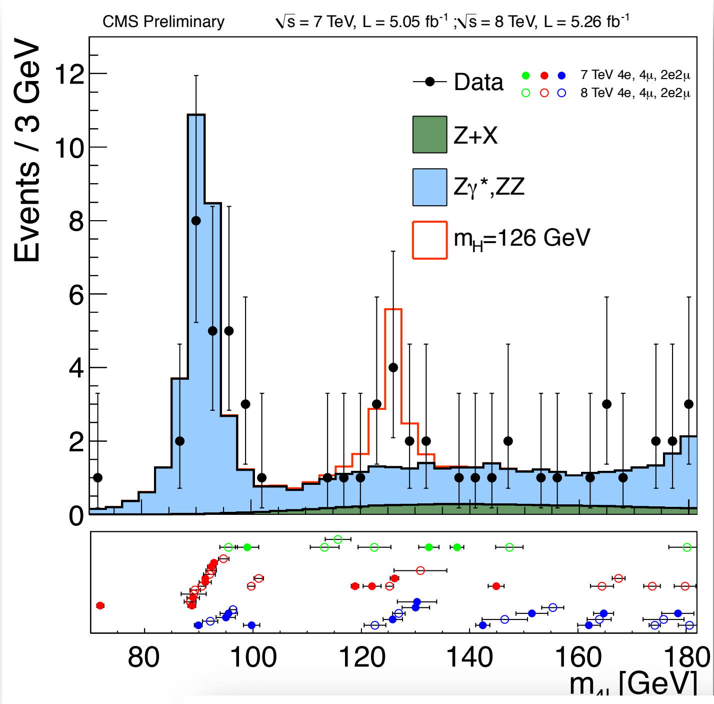
√s = 8 TeV, L = 5.3 fb⁻¹
S/B Weighted Data
S+B Fit
Bkg Fit Component
±1 σ
±2 σ
Weighted Events / (1.67 GeV)
mγγ (GeV)

In summary


CMS Preliminary
√s = 7 TeV, L = 5.05 fb-1 ;√s = 8 TeV, L = 5.26 fb-1
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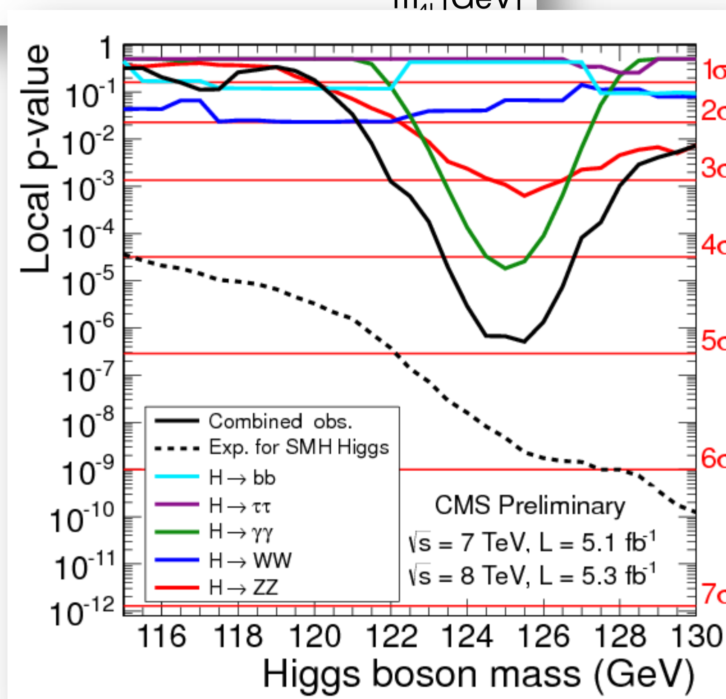
Local p-value
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2σ
3σ
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6σ
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Combined obs.
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H→ bb
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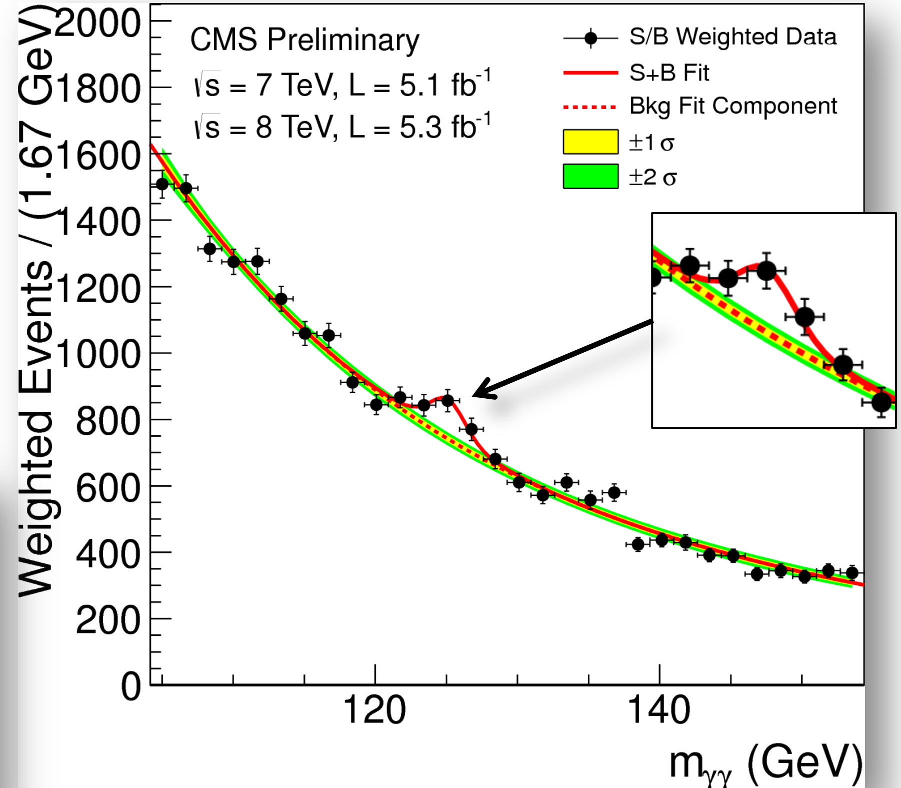
Higgs boson mass (GeV)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√s = 8 TeV, L = 5.3 fb-1
S/B Weighted Data
S+B Fit
Bkg Fit Component
±1 σ
±2 σ
Weighted Events / (1.67 GeV)
mγγ (GeV)

In summary

We have observed a new boson with a mass of

125.3 ± 0.6 GeV

at

4.9 σ significance !

Acknowledgements

Acknowledgements

- A very wide range of measurements have shown that SM predictions for known physics have been ~spot on.
  - A tribute to a large amount of work done by our theory colleagues along with the results from the other collider experiments at LEP, Tevatron, HERA, b-factories etc.
- And the Higgs cross section WG and all those theorists who prepared the way for today!

Electroweak Theory

[1] S. Glashow, Nucl. Phys. 22 (1961) 579, doi:10.1016/0029-5582(61)90469-2.
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Electroweak Symmetry Breaking

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[7] G. Guralnik, C. Hagen, T.W.B. Kibble, Phys. Rev. Lett. 13 (1964) 585, doi:10.1103/PhysRevLett.13.585.
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10 September 2008: LHC inauguration day

First (single) beams circulating in the machine

Six CERN DGs, from conception to physics:
Schopper, Rubbia, Llewellyn Smith, Maiani, Aymar, Heuer (from right to left) with 5-year terms!!

Acknowledgements

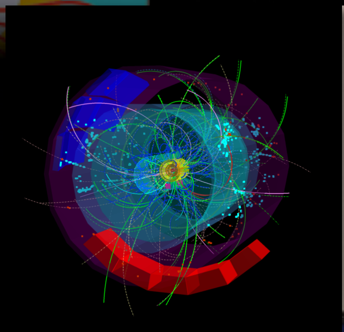
- The LHC Project (the accelerator, the experiments, and computing) have required a long and painstaking effort on a global scale encompassing the terms of 6 Director Generals, 3 LHC Project Leaders, and 6 Research Directors.

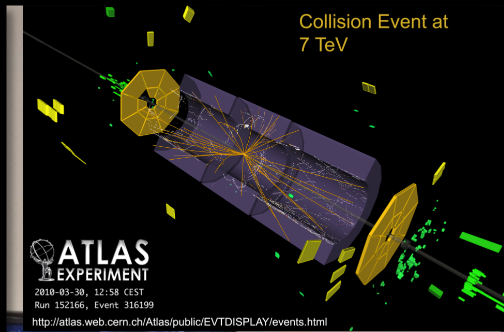
- The Project started in earnest in 1987 with Rubbia's Long Range Planning Committee recommending the LHC as the right choice for CERN's future.

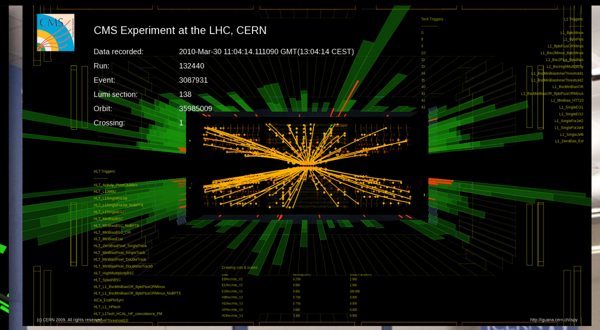
- Great appreciation of the work of teams that built and now operate the magnificent LHC accelerator

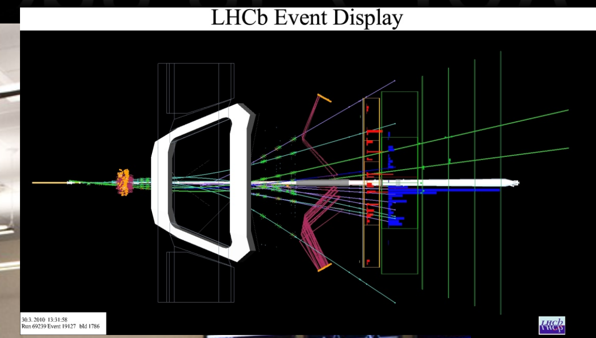
- The CMS experiment is a tribute to the vision of its founders, the dedication of all of its thousands of collaborators in constructing and preparing the experiment in terms of hardware, software, computing, and physics analysis, and now the ones who operate and analyze the data (mostly young scientists!).

March 30 2010: 1st Collisions at 7 TeV









A small fraction of the CMS Collaboration: June 2012

Thanks to all of the CMS institutes

AACHEN-1, AACHEN-3A, AACHEN-3B, ADANA-CUKUROVA, ALABAMA-UNIV, ANKARA-METU, ANTWERPEN, ATHENS, ATOMKI, AUCKLAND, BARI, BAYLOR-UNIV, BEIJING-IHEP, BOGAZICI, BOLOGNA, BOSTON-UNIV, BRISTOL, BROWN-UNIV, BRUNEL, BRUSSEL-VUB, BRUXELLES-ULB, BUDAPEST, CALTECH, CANTERBURY, CARNEGIE-MELLON, CATANIA, CCCS-UWE,CERN, CHANDIGARH, CHARLES-UNIV, CHEJU, CHICAGO, CHONNAM, CHUNGBUK, CHUNGLI-NCU, COLORADO, CORNELL, DEBRECEN-IEP, DELHI-UNIV, DEMOKRITOS, DESY, DONGSHIN, DUBLIN-UCD, DUBNA, EINDHOVEN, FAIRFIELD, FERMILAB, FIRENZE, FLORIDA-FIU, FLORIDA-STATE, FLORIDA-TECH, FLORIDA-UNIV, FRASCATI, GENOVA, GHENT, HAMBURG-UNIV, HEFEI-USTC, HELSINKI-HIP, HELSINKI-UNIV, HEPHY, IOANNINA, IOWA, IPM, ISLAMABAD-NCP, ISTANBUL-TECH, JOHNS-HOPKINS, KANGWON, KANSAS-STATE, KANSAS-UNIV, KARLSRUHE-IEKP, KHARKOV-ISC, KHARKOV-KIPT, KHARKOV-KSU, KONKUK-UNIV, KOREA-UNIV, KYUNGPOOK, LAPP, LAPPEENRANTA-LUT, LIP, LIVERMORE, LONDON-IC, LOUVAIN, LYON, LYON-CC, MADRID-CIEMAT, MADRID-UNIV, MARYLAND, MEXICO-IBEROAM, MEXICO-IPN, MEXICO-PUEBLA, MEXICO-UASLP, MILANO-BICOCCA, MINNESOTA, MINSK-INP, MINSK-NCPHEP, MINSK-RIAPP, MINSK-UNIV, MISSISSIPPI, MIT, MONS, MOSCOW-INR, MOSCOW-ITEP, MOSCOW-LEBEDEV, MOSCOW-MSU, MOSCOW-RDIPE, MUMBAI-BARC, MYASISHCHEV, NAPOLI, NEBRASKA, NICOSIA-UNIV, NORTHEASTERN, NORTHWESTERN, NOTRE DAME, NUST, OHIO-STATE, OVIEDO, PADOVA, PAVIA, PEKING-UNIV, PERUGIA, PISA, POLYTECHNIQUE, PRINCETON, PROTVINO, PSI, PUERTO RICO, PURDUE, PURDUE-CALUMET, RAL, RICE, RIE, RIO-CBPF, RIO-UERJ, ROCHESTER, ROCKEFELLER, ROMA-1, RUTGERS, SACLAY, SANTANDER, SAO PAULO, SEONAM, SEOUL-EDU, SEOUL-SNU, SINP, SHANGHAI-IC, SKK-UNIV, SOFIA-INRNE, SOFIA-ISER, SOFIA-UNIV, SPLIT-FESB, SPLIT-UNIV, ST-PETERSBURG, STRASBOURG, SUNY-BUFFALO, TAIPEI-NTU, TALLINN, TASHKENT, TBILISI-IHEPI, TBILISI-IPAS, TENNESSEE, TEXAS-TAMU, TEXAS-TECH, TIFR-EHEP, TIFR-HECR, TORINO, TRIESTE, UCDAVIS, UCLA, UCRIVERSIDE, UCSB, UCSD, UNIANDES, VANDERBILT, VILNIUS-ACADEMY, VILNIUS-UNIV, VINCA, VIRGINIA-TECH, VIRGINIA-UNIV, WARSAW-IEP, WARSAW-INS, WARSAW-ISE, WAYNE, WISCONSIN, WONKWANG, YEREVAN, ZAGREB-RUDJER, ZURICH-ETH, ZURICH-UNIV

June 2012: 193 Institutions with ~3300 scientists and engineers
~ 2000 Signing Authors (including students)

HUGE Thanks to CERN Staff and CMS Funding Agencies

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The End

Stay tuned