A Discovery in the Search for the Elusive Higgs Boson at CMS

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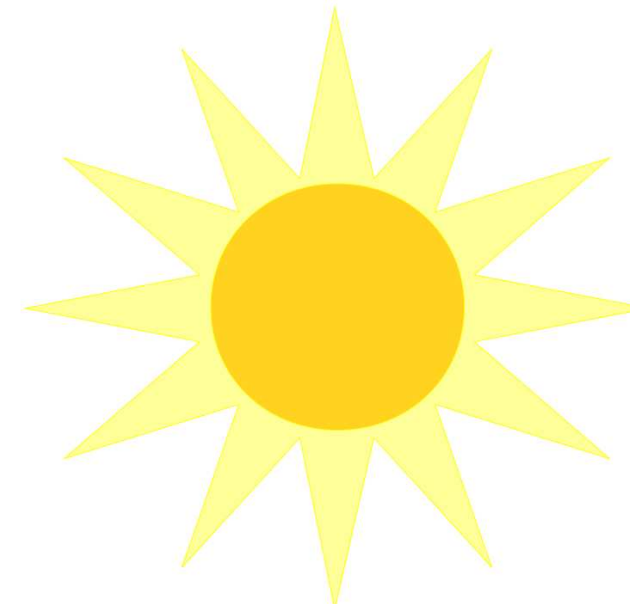
for the CMS Collaboration

17 July 2012

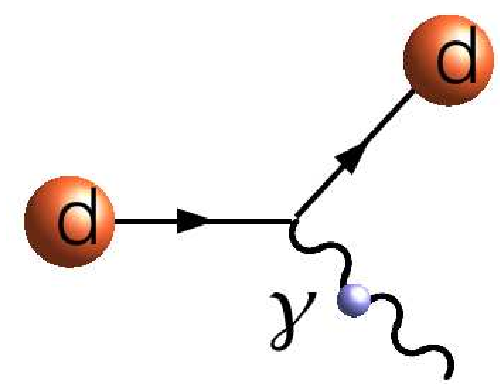
LBNL Research Progress Meeting

Why Search for the Higgs Boson



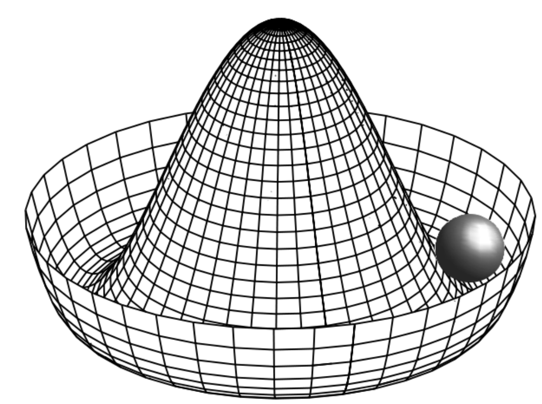
- we know 12 bosons: γ, Z^0, W^+, W^-, 8 gluons
  - carry force, spin=$\hbar$=1
- in early Universe: all massless, forces unify
- as Universe cools down
  - symmetry spontaneously breaks

$$|\gamma\rangle \ = \cos\theta_W |B^0\rangle + \sin\theta_W |W^0\rangle \quad \text{light}$$
$$|Z^0\rangle = \sin\theta_W |B^0\rangle + \cos\theta_W |W^0\rangle \quad \text{heavy}$$



  - weak interactions become weak (Z^0, $W^\pm$ mass)
  - Higgs field in vacuum – possible mechanism

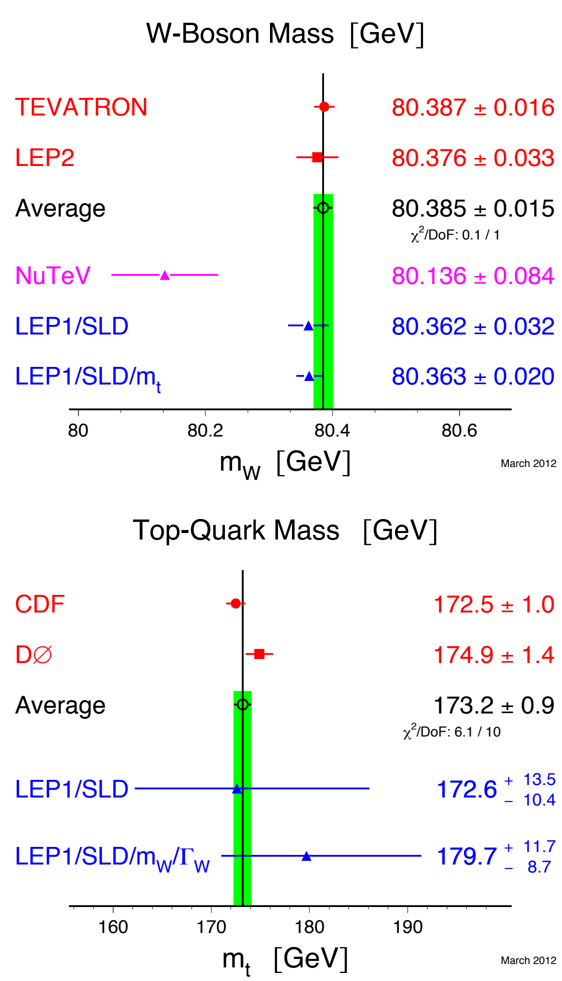
  $\Rightarrow$ look for its excitation, the Higgs boson

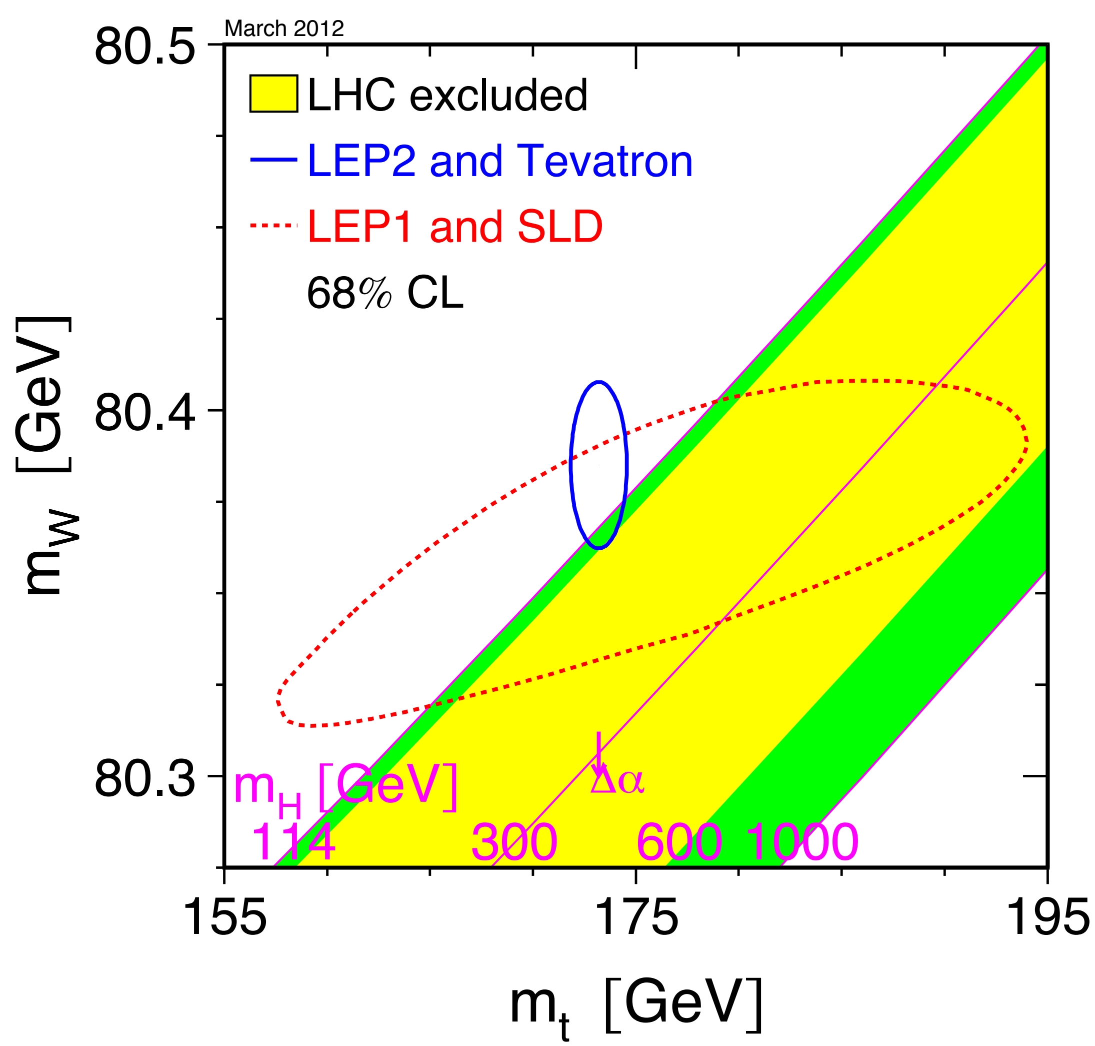


- is vacuum stable $\Rightarrow$ fate of the Universe?

Constraints on the SM Higgs Boson

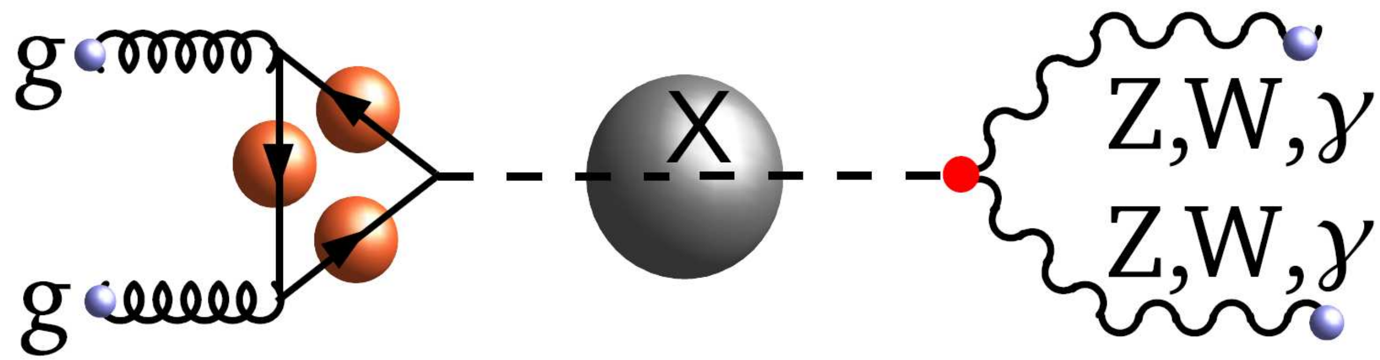
- SM Higgs boson mass m_H unknown; constraints:
  - indirectly due to m_W, m_t at Tevatron, LEP/SLD
    m_W related to m_t (quadratic) and m_H (log) from loop corrections
  - directly due to LHC, LEP, Tevatron
    open $115 < m_H < 127$ GeV

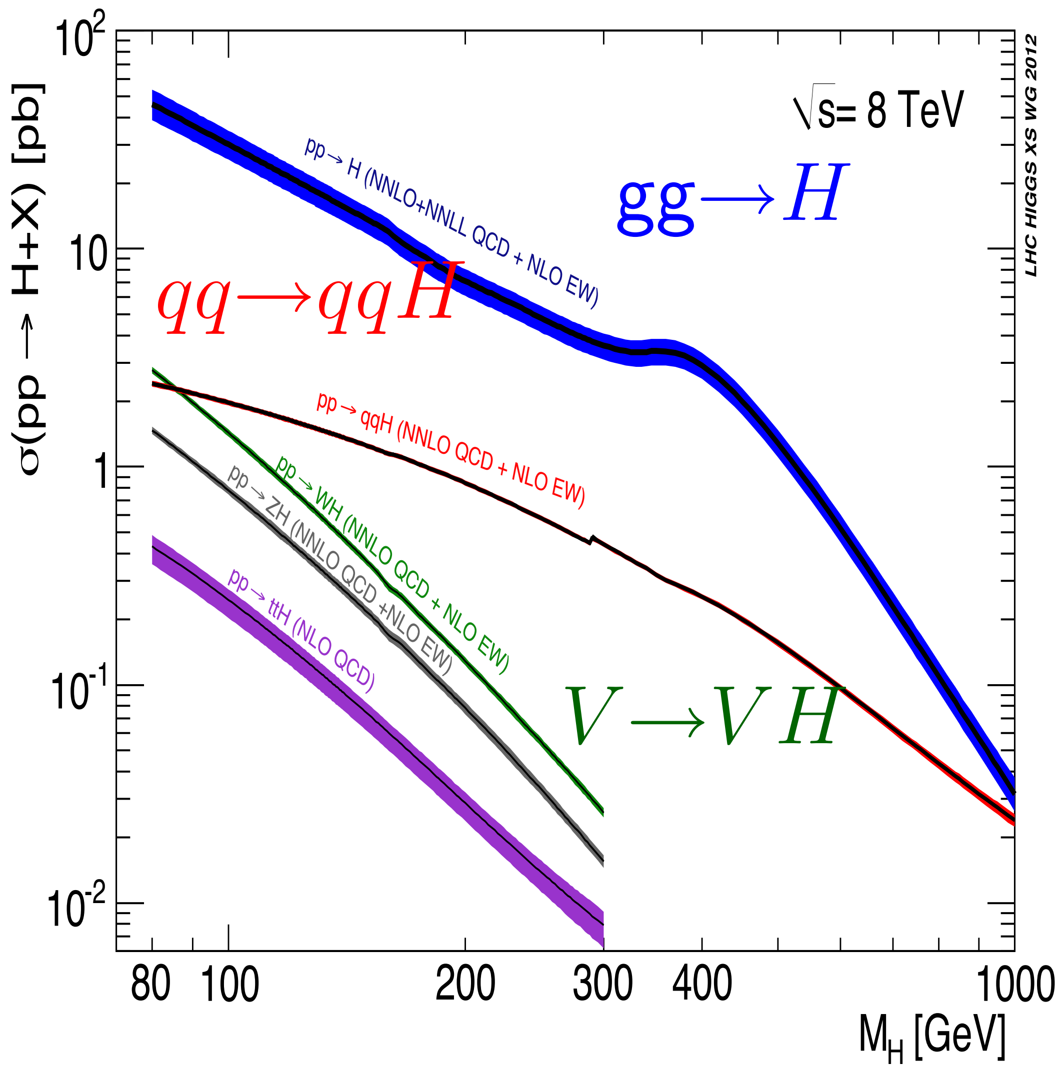


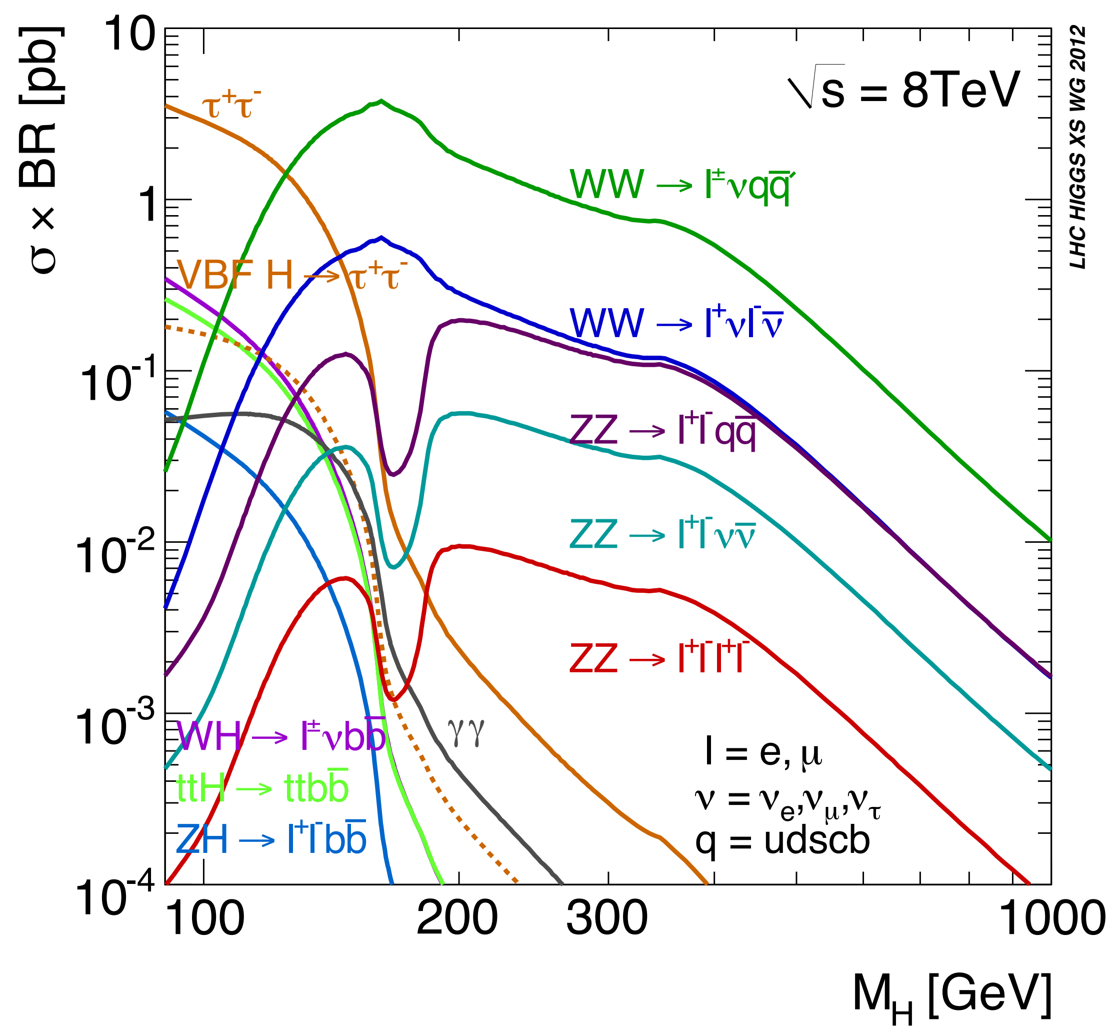


The Hunt for the Higgs Boson

- Excite vacuum: gg, VBF,.. $\rightarrow H \rightarrow ZZ^{(*)}, WW^{(*)}, \gamma\gamma, \tau^+\tau^-, b\bar{b}$,..



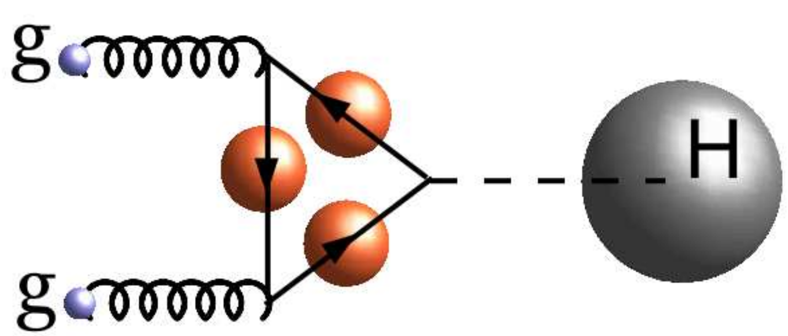




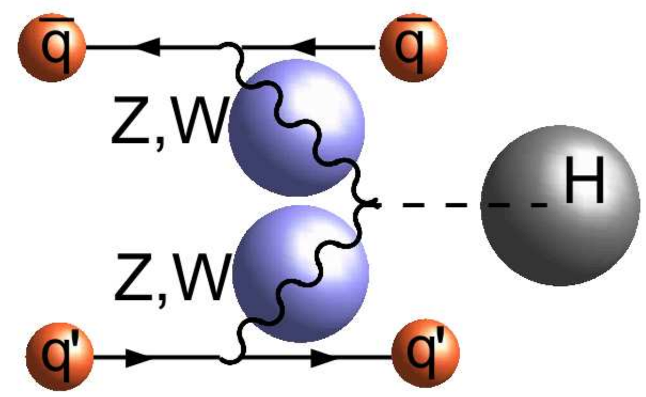
The Challenge is Background

- At LHC might have produced > 100000 Higgs bosons / experiment

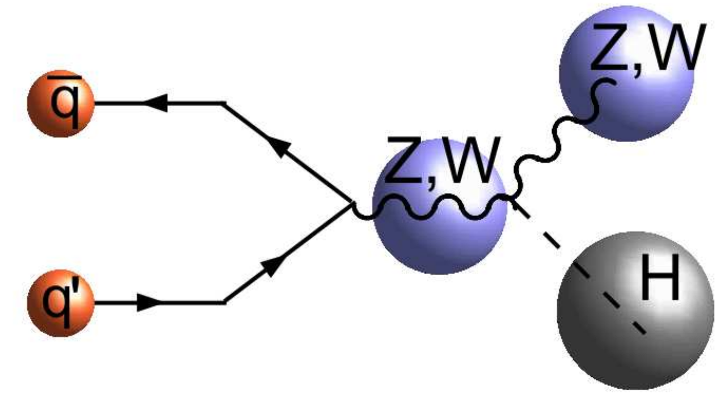
gluon fusion



weak boson fusion

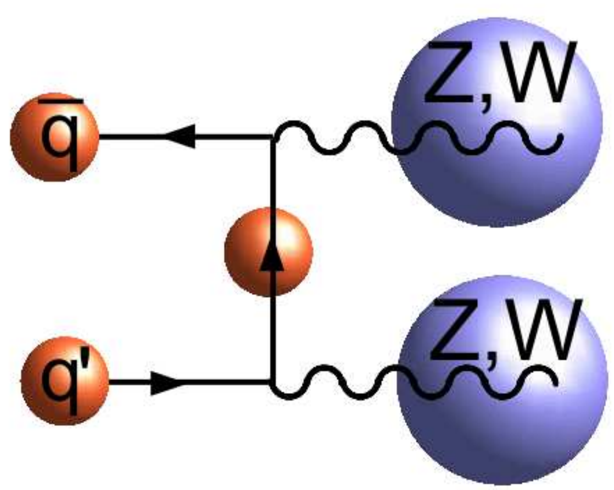


associated production

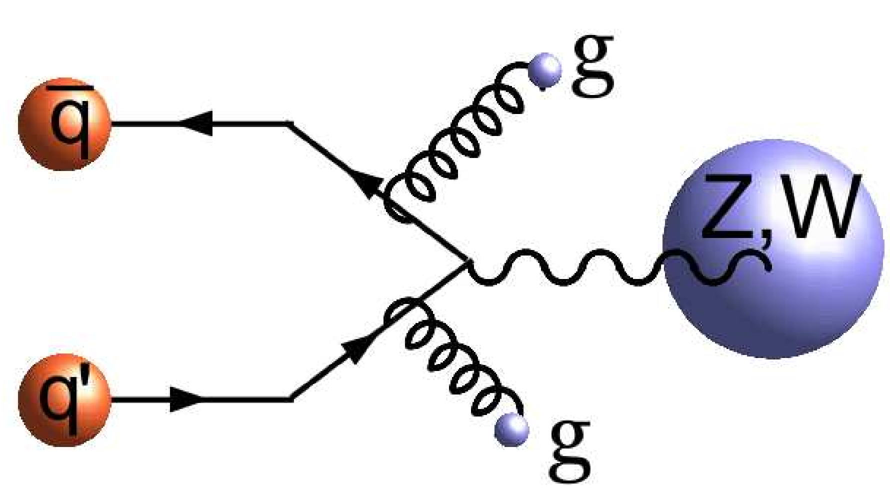


- The challenge is to distinguish signal from backgrounds, examples:

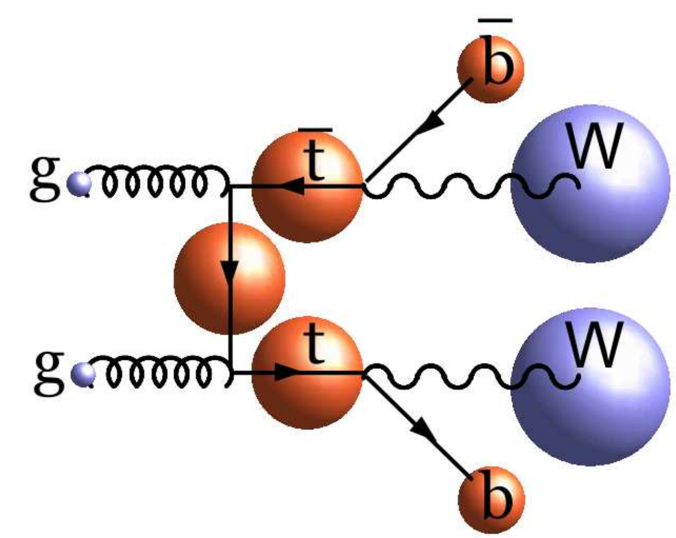
$q\bar{q} \to ZZ^{(*)}(\gamma^{(*)})$



$q\bar{q} \to Z(\gamma)$+jets

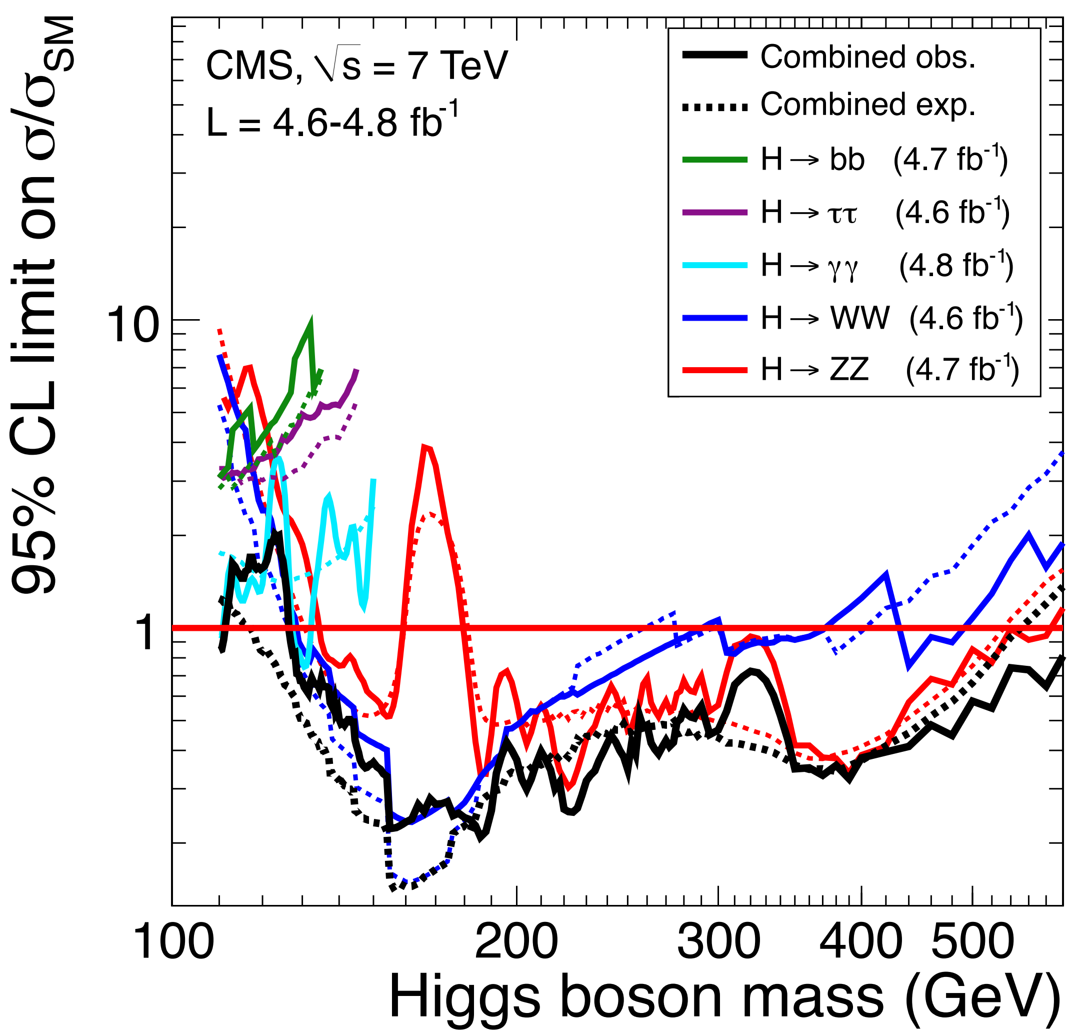


gg$\to t\bar{t}$

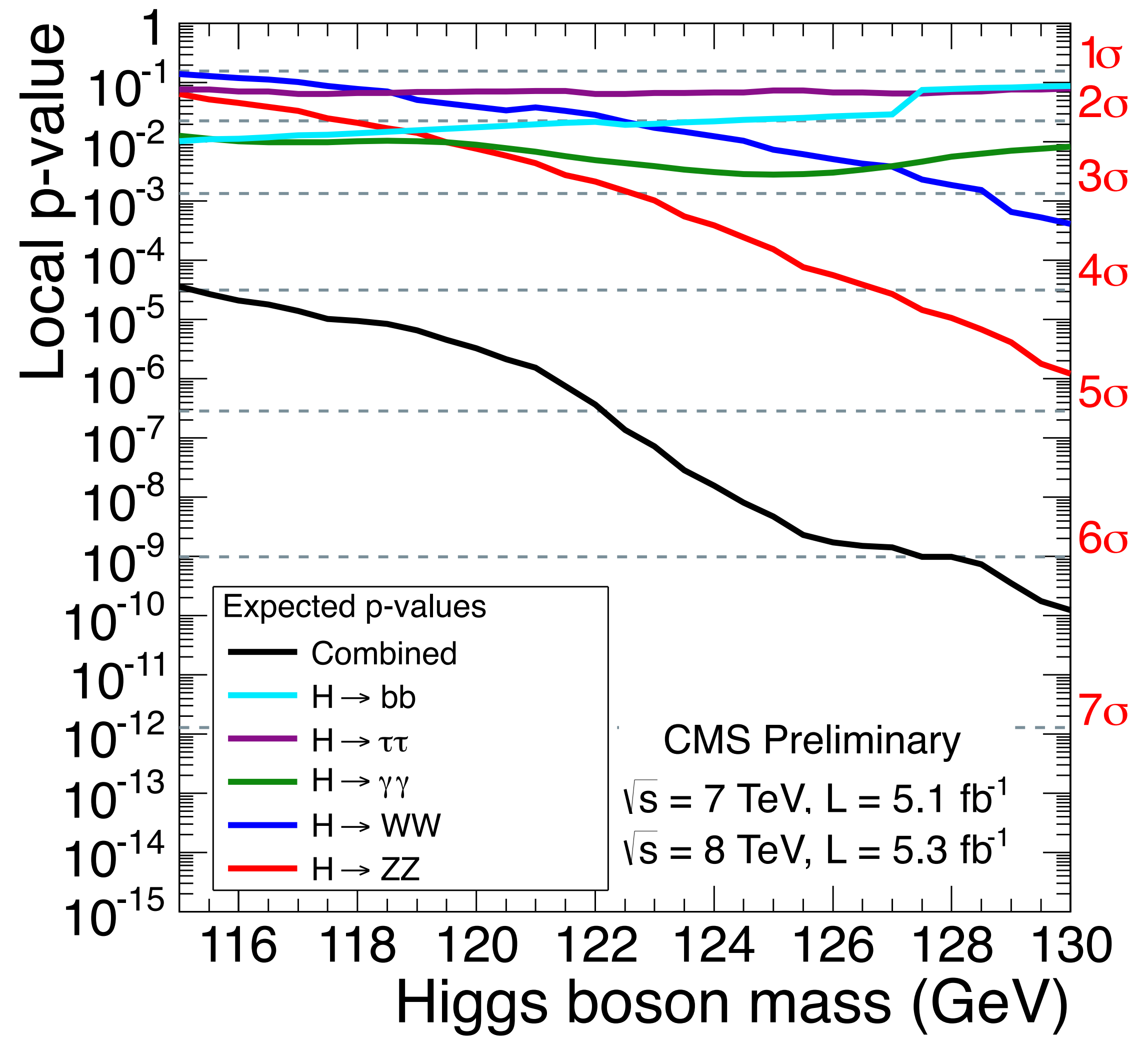


CMS on Track for Discovery

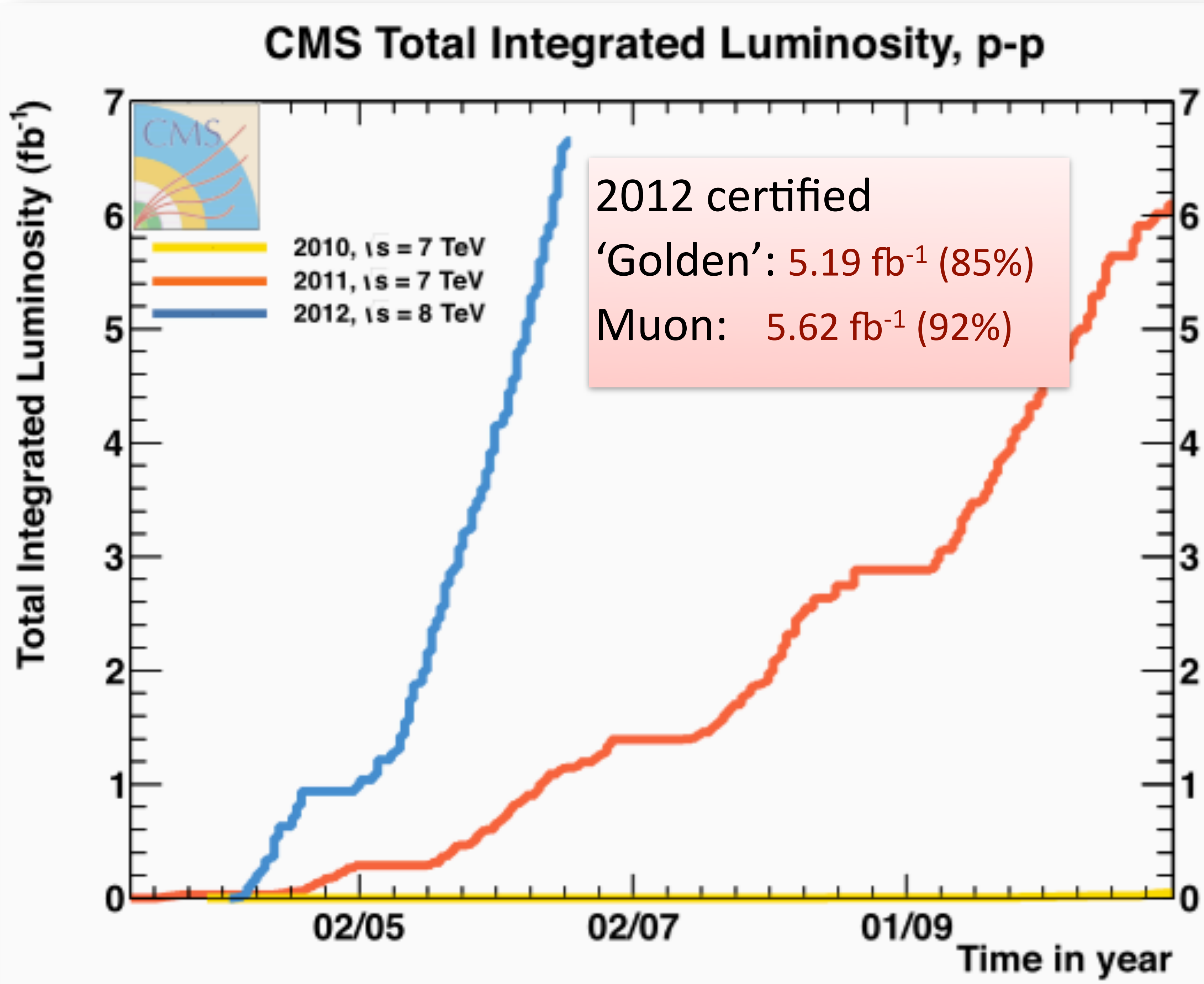
- In December 2011
  excluded SM Higgs
  $127 < m_H < 600$ GeV
  tantalizing hint $m_H \sim 125$ GeV



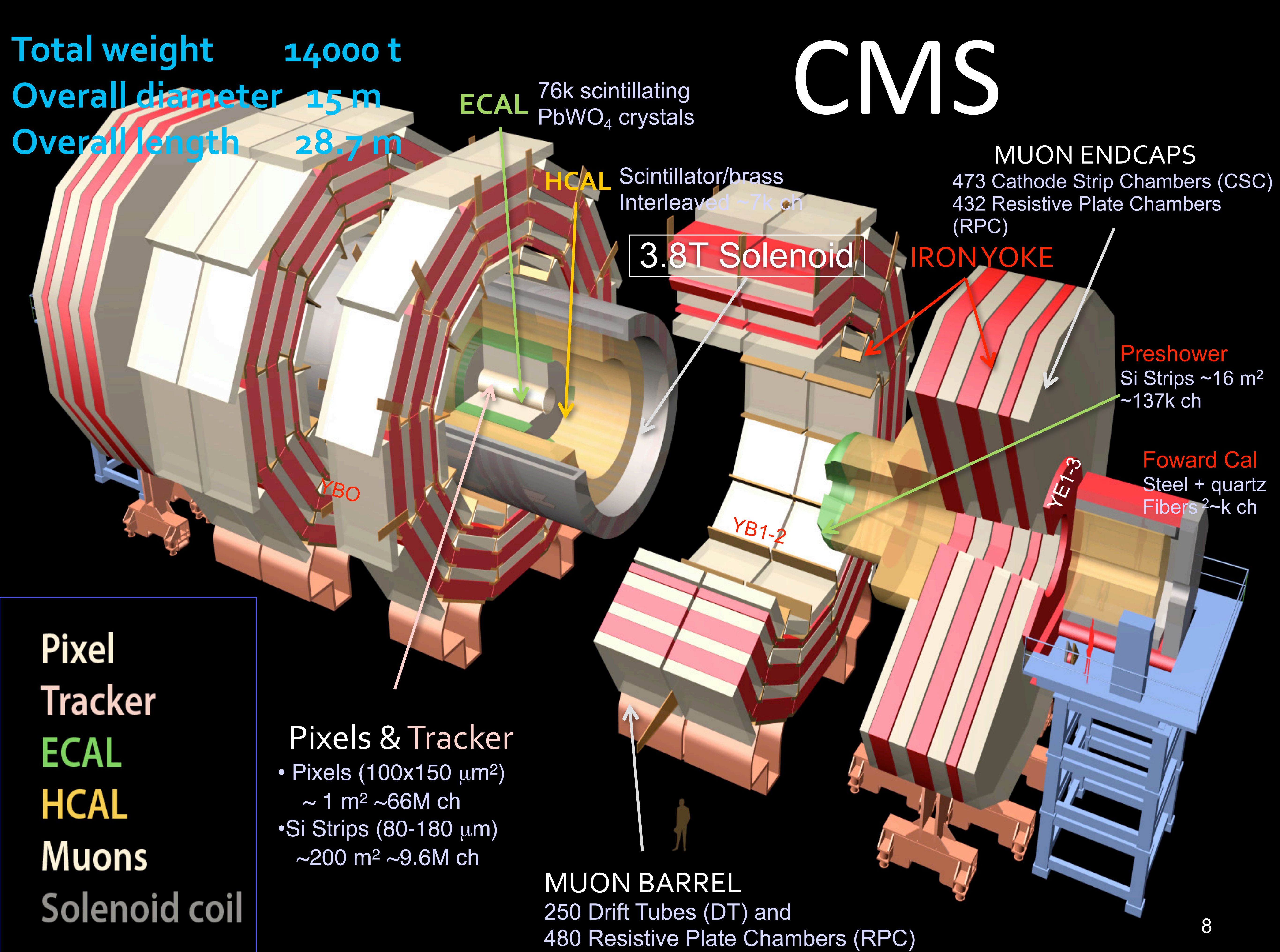
- In July 2012
  expect for SM Higgs
  up to 6σ observation
  $H \to ZZ^{(*)}, \gamma\gamma, WW^{(*)}, b\bar{b}, \tau\tau$



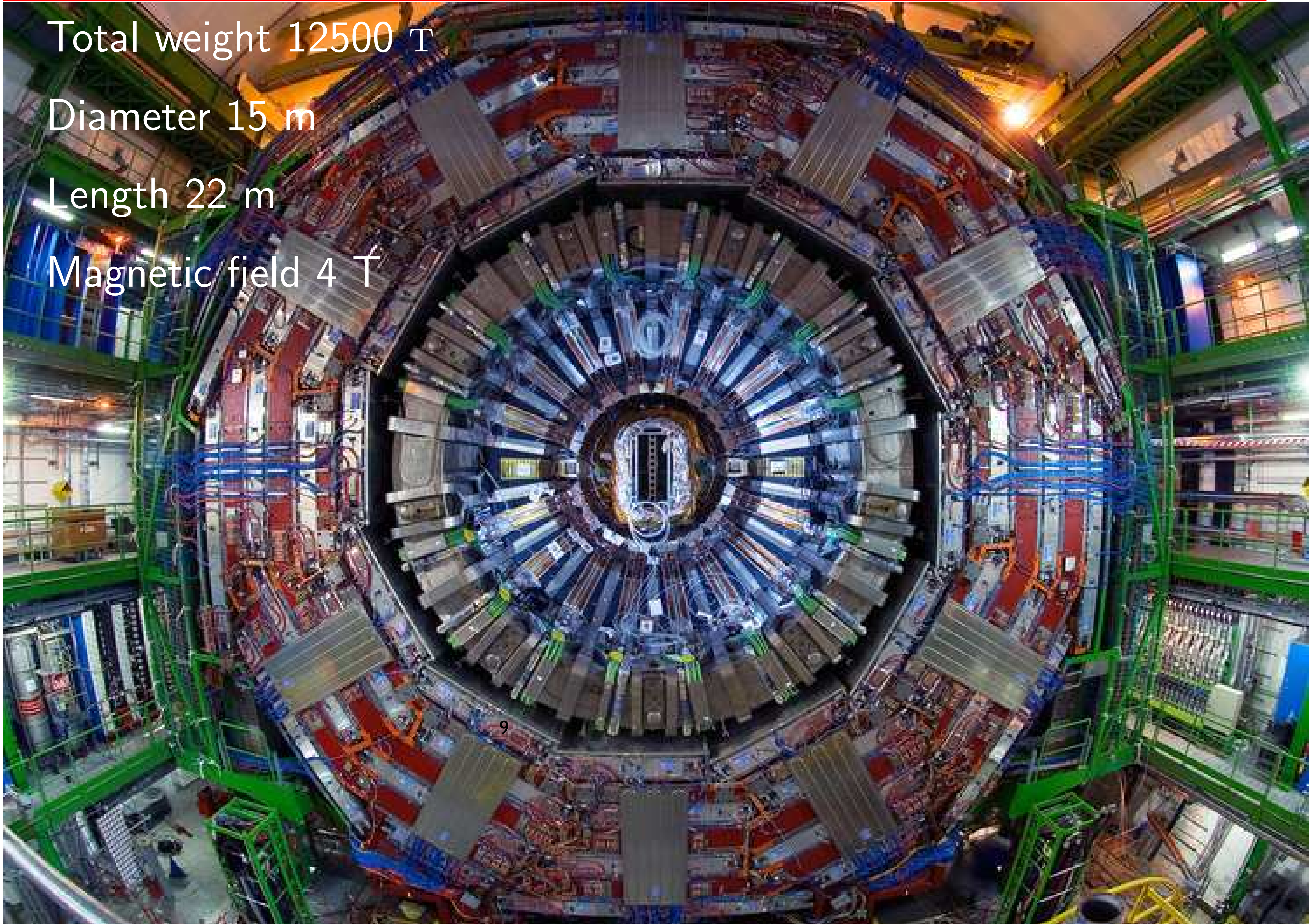
Thanks to excellent LHC performance



Excellent performance of the LHC


CMS
Total weight 14000 t
Overall diameter 15 m
Overall length 28.7 m
ECAL
76k scintillating $PbWO_4$ crystals
HCAL
Scintillator/brass Interleaved ~7k ch
3.8T Solenoid
MUON ENDCAPS
473 Cathode Strip Chambers (CSC)
432 Resistive Plate Chambers (RPC)
IRON YOKE
Preshower
Si Strips ~16 m^2
~137k ch
Foward Cal
Steel + quartz
Fibers 2~k ch
YE1-3
YBO
YB1-2
Pixel
Tracker
ECAL
HCAL
Muons
Solenoid coil
Pixels & Tracker
• Pixels (100x150 μm^2)
~ 1 m^2 ~66M ch
•Si Strips (80-180 μm)
~200 m^2 ~9.6M ch
MUON BARREL
250 Drift Tubes (DT) and
480 Resistive Plate Chambers (RPC)

The CMS Detector



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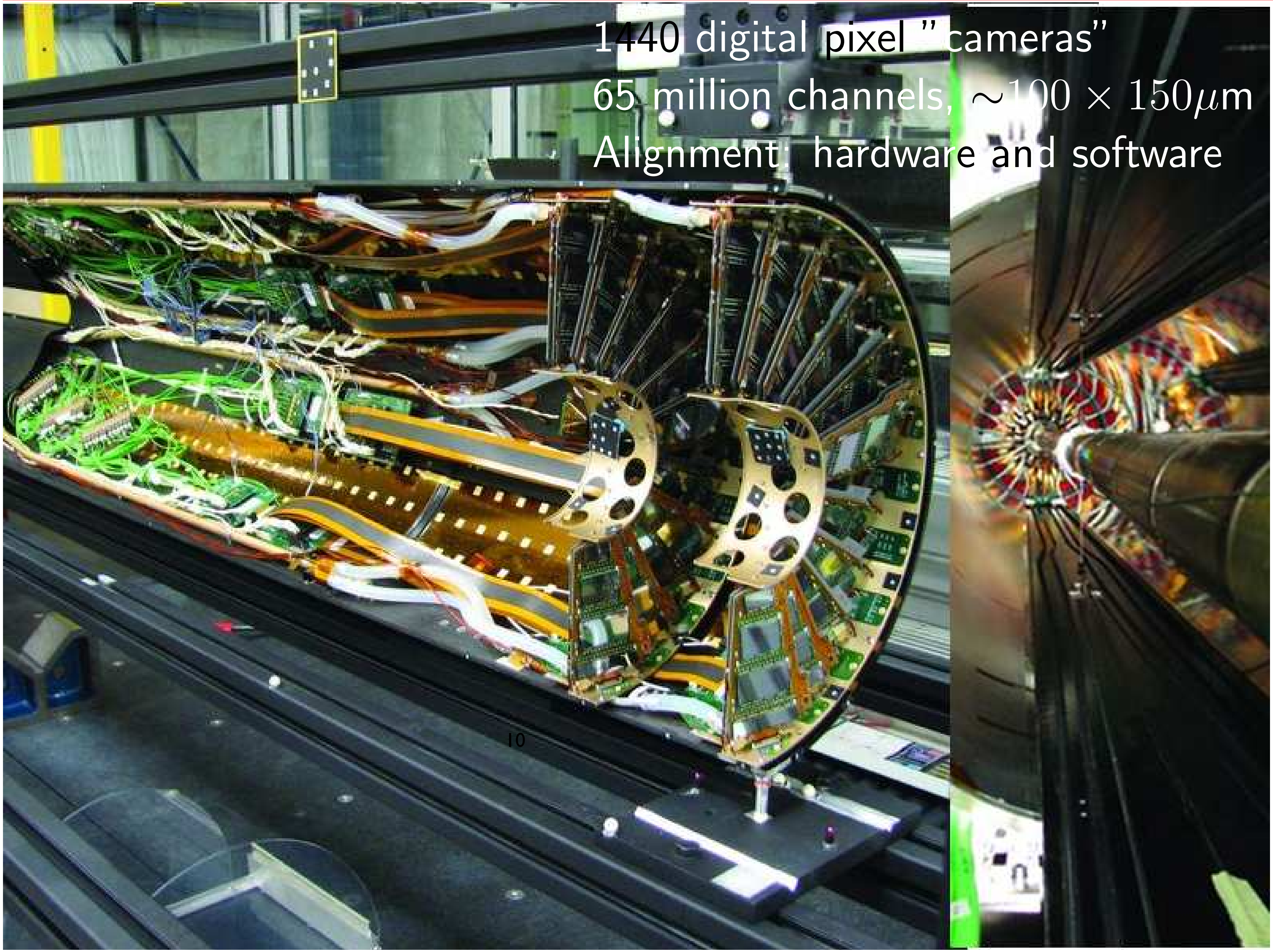
The Silicon Pixel Detector



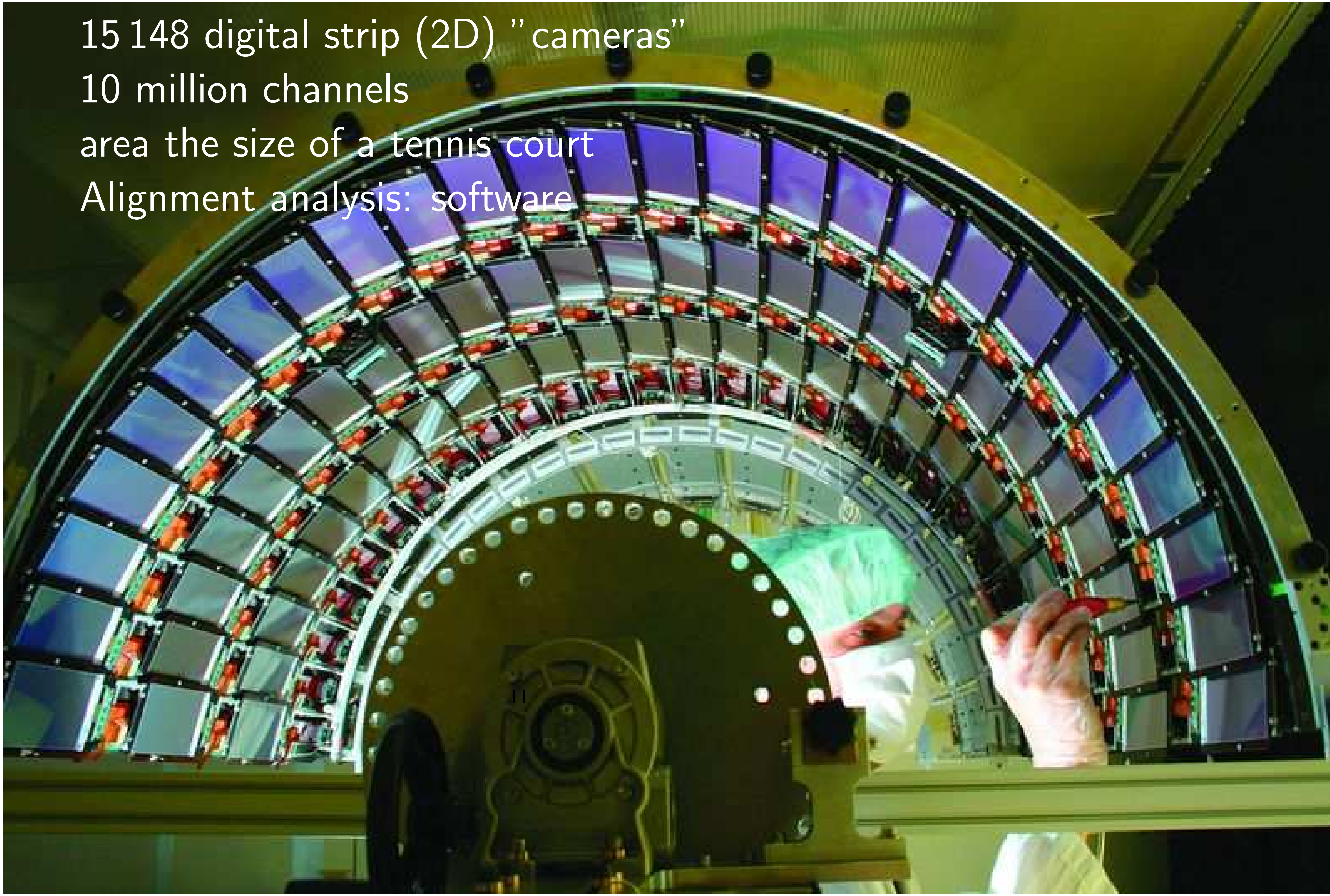
1440 digital pixel "cameras"

65 million channels, $\sim 100 \times 150 \mu$m

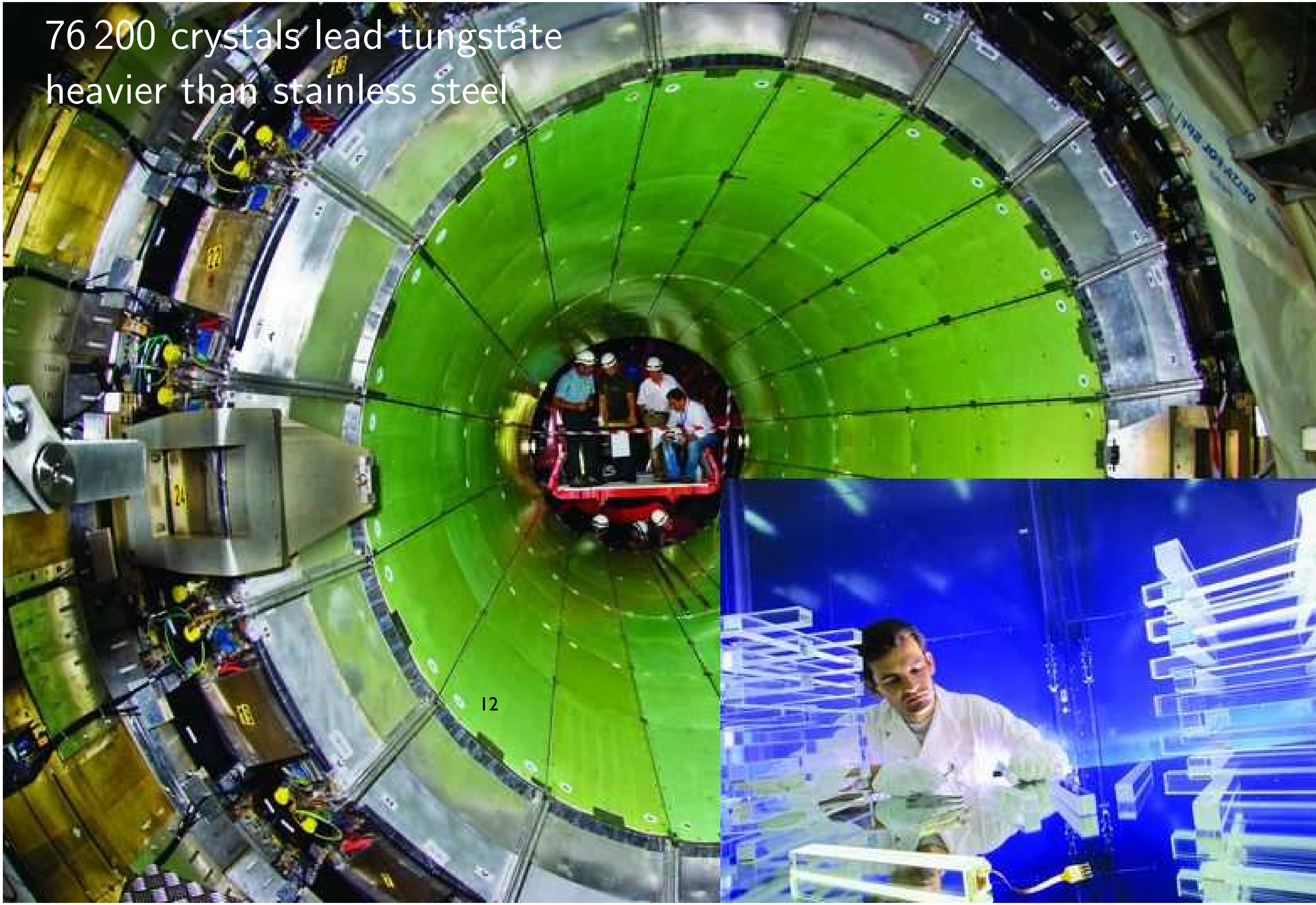
Alignment: hardware and software

The Silicon Strip Detector

15 148 digital strip (2D) "cameras"
10 million channels
area the size of a tennis court
Alignment analysis: software



Electromagnetic Calorimeter



Hadronic Calorimeter and Muon System

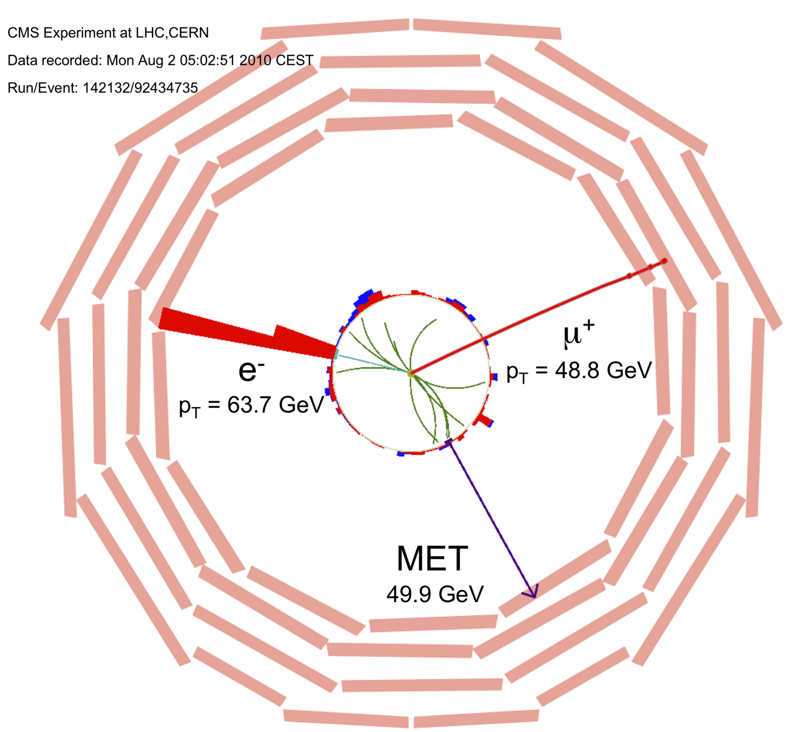
>1 million WWII brass shells $\Rightarrow$ HCAL absorber

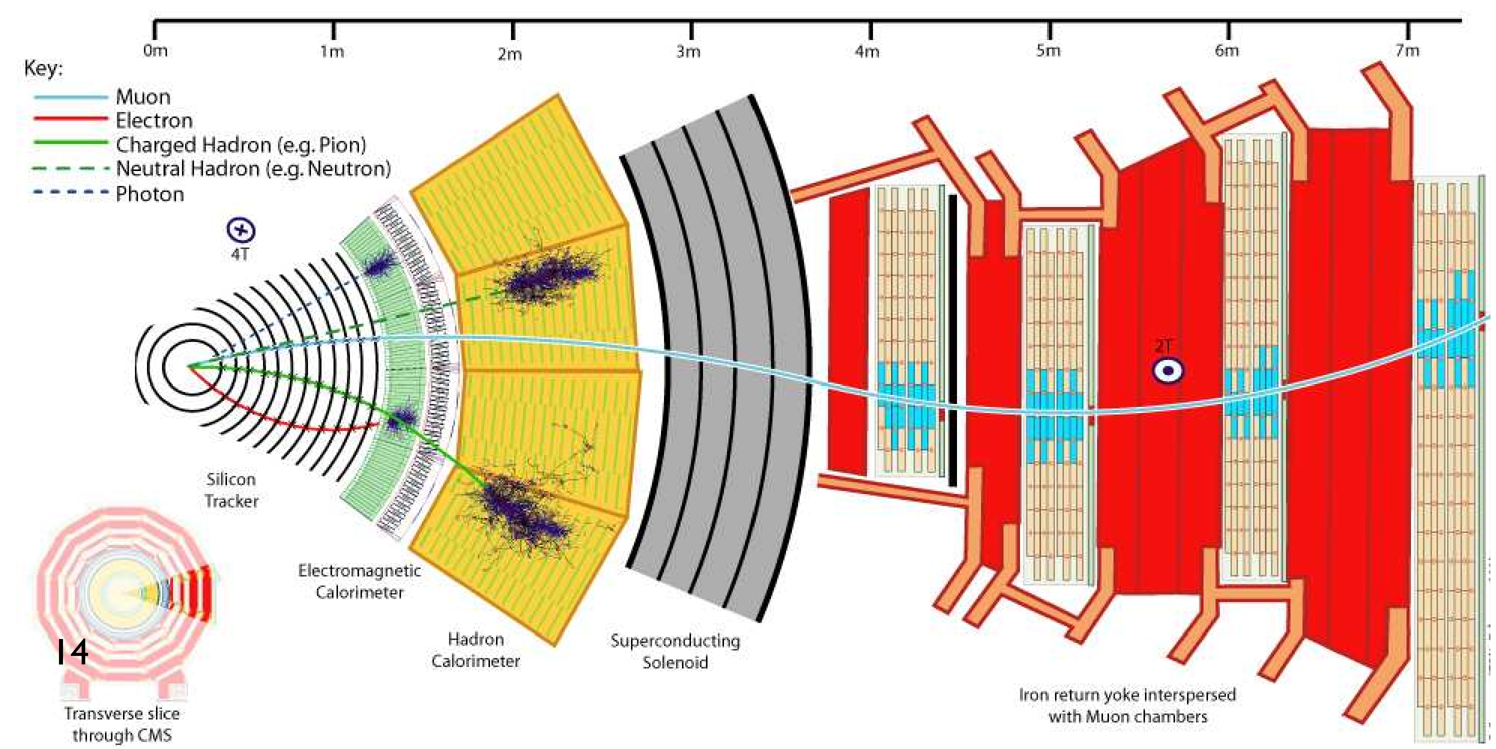
HCAL scintillator $\Rightarrow$ light signal

1400 Muon chambers in iron "return yoke," 2 million wires

Global Event Description: Particle Flow

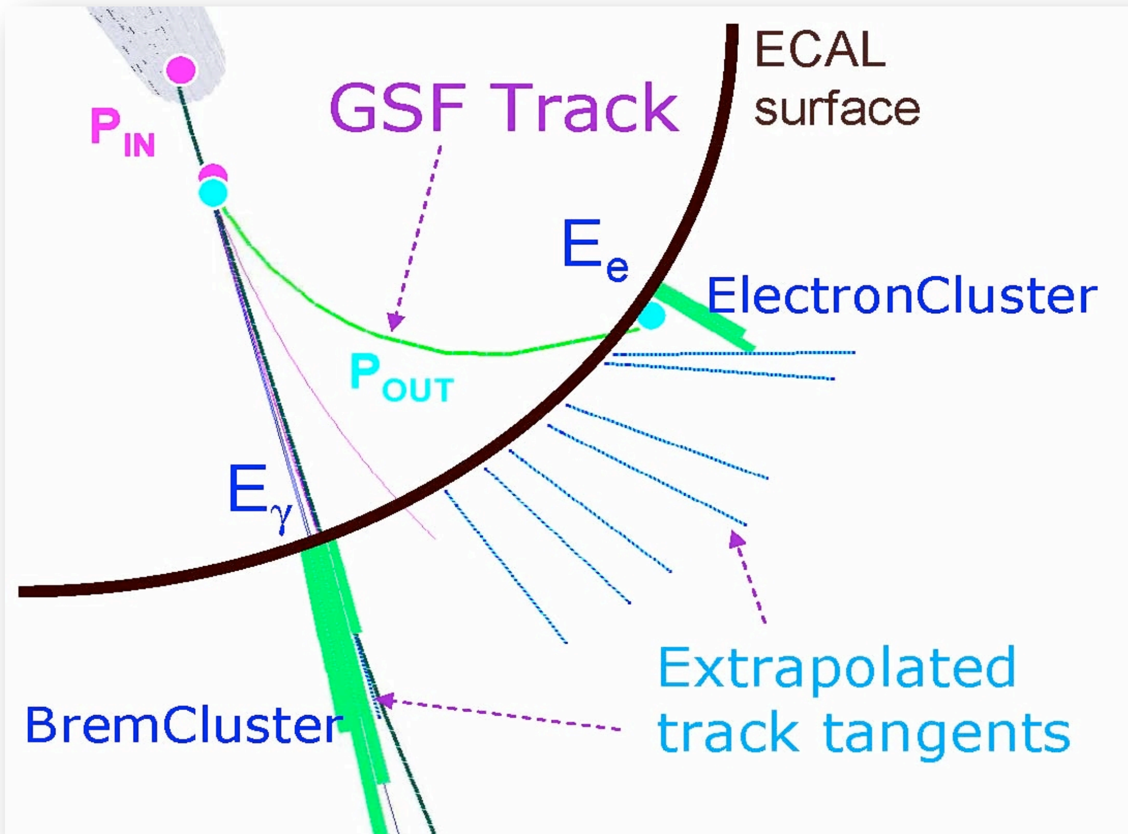
- Leptons: $\ell^{\pm}$ in Si Tracker: $e^{\pm}$ (EM Calorimeter), $\mu^{\pm}$ (Muon System)
- Photons: γ (EM Calorimeter)
- Charged and neutral hadrons thru Hadronic Calorimer
- Build jets, τ, MET; use in isolation and pileup correction

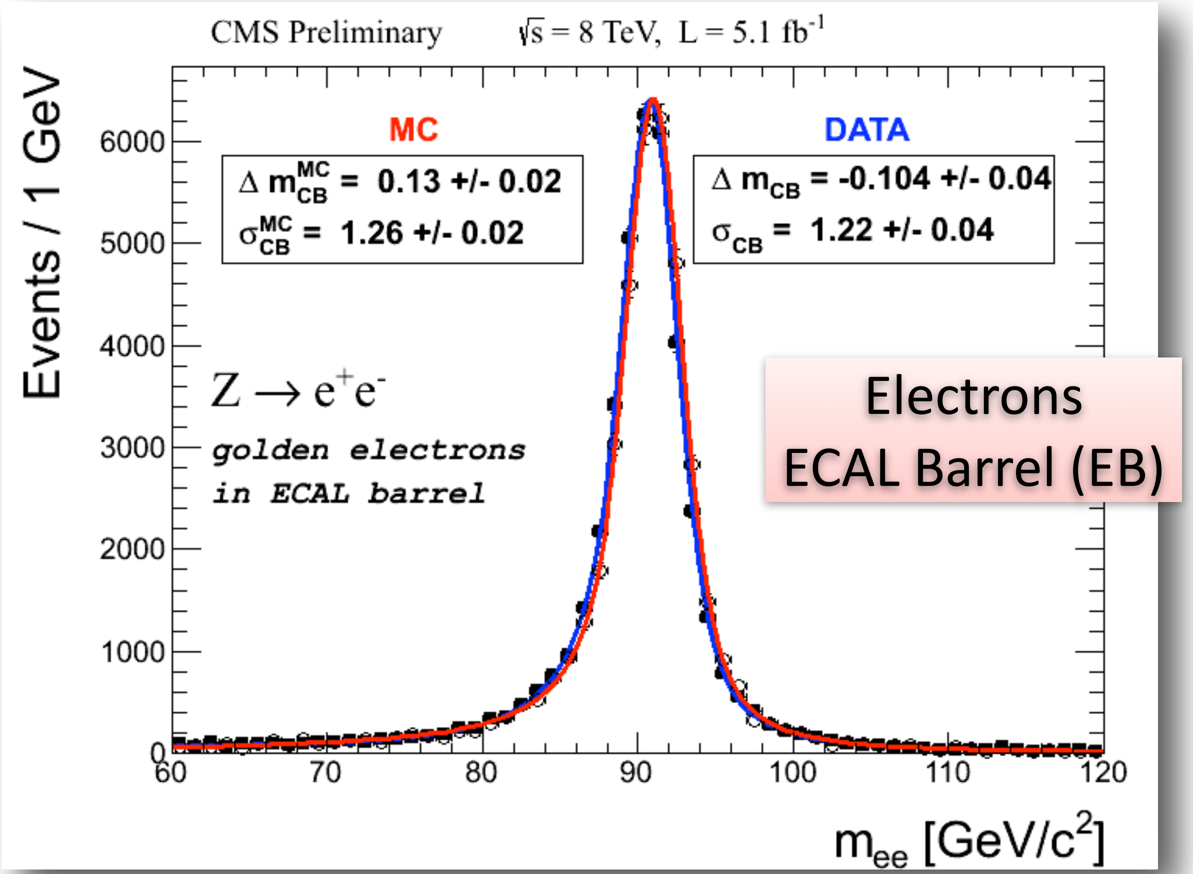




$$WW \to (e^-\bar{\nu})(\mu^+\nu)$$

Electron/Photon reconstruction

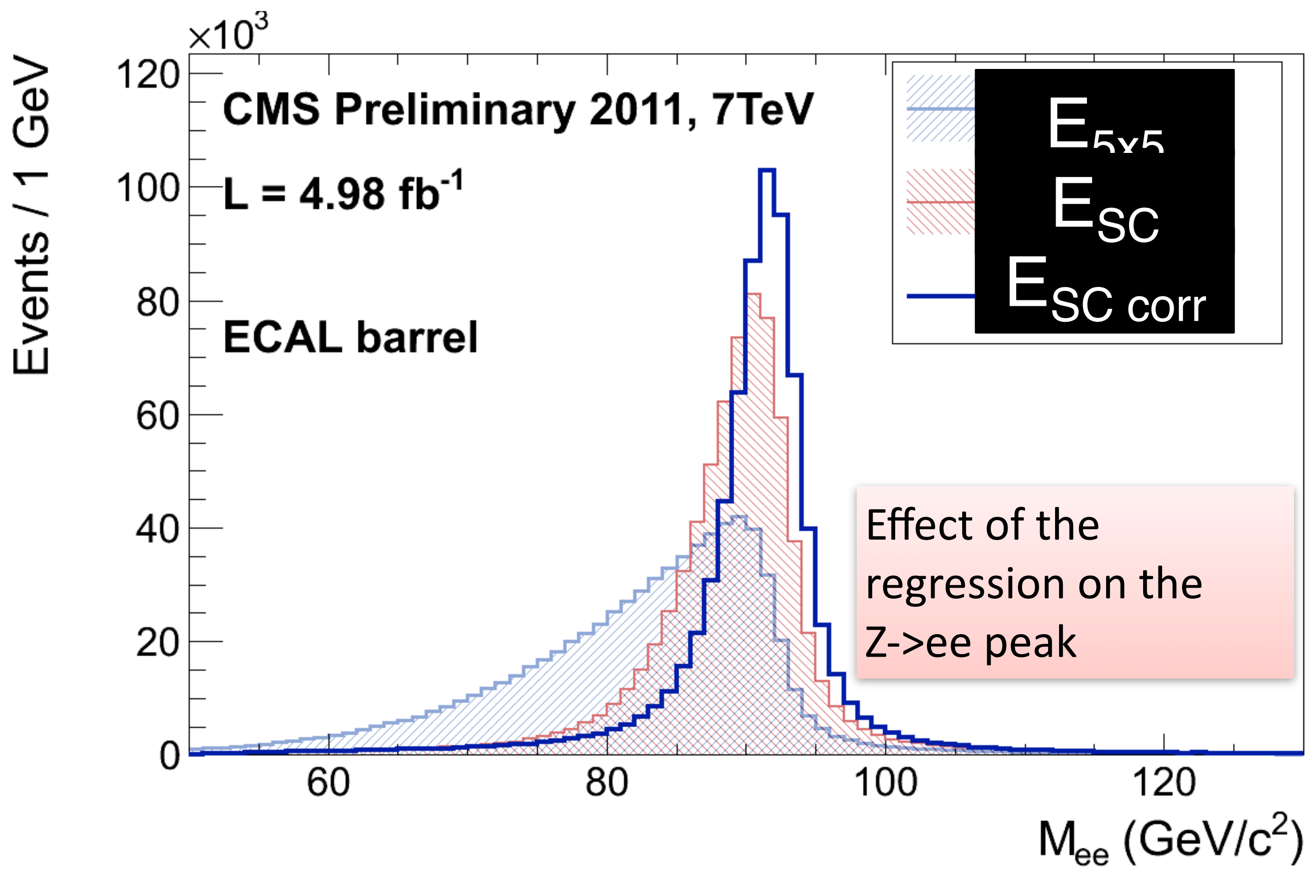


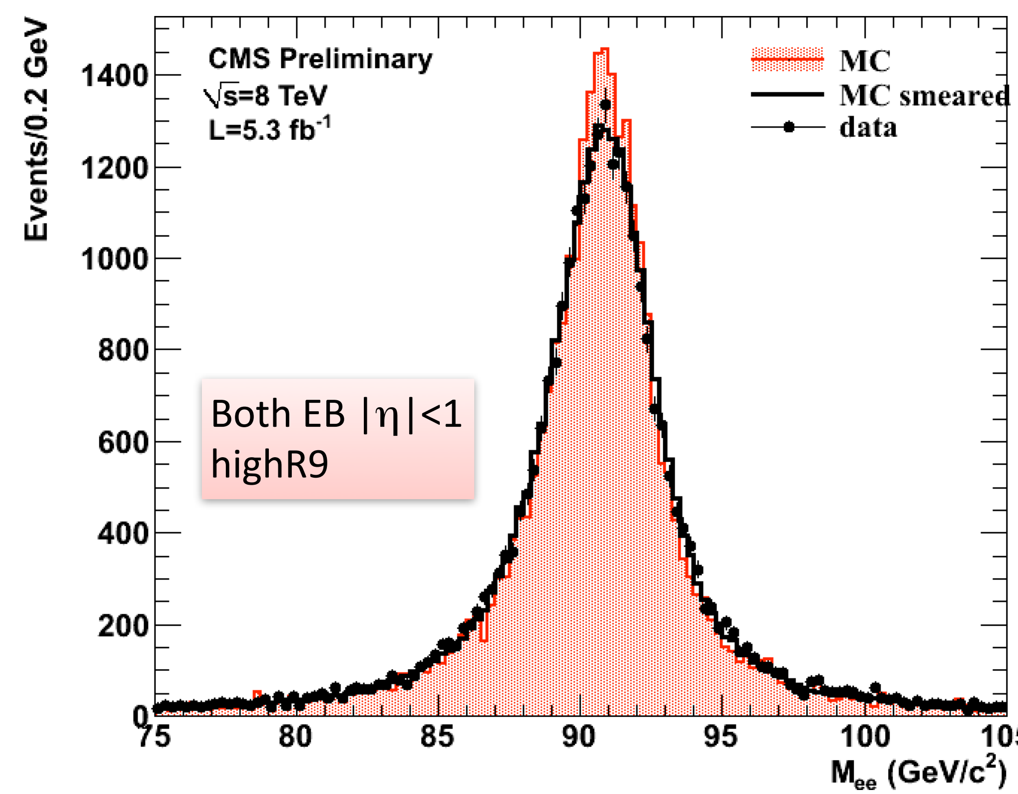


- Cluster reconstruction in ECAL
  - Common for both electrons and photons (Electrons also reconstructed as photons)
  - Designed to collect bremsstrahlung and conversions in extended phi region
- Dedicated track reconstruction for electrons
  - Gaussian Sum Filter allows for tracks w/large bremsstrahlung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

Photon Energy Scale and Resolution

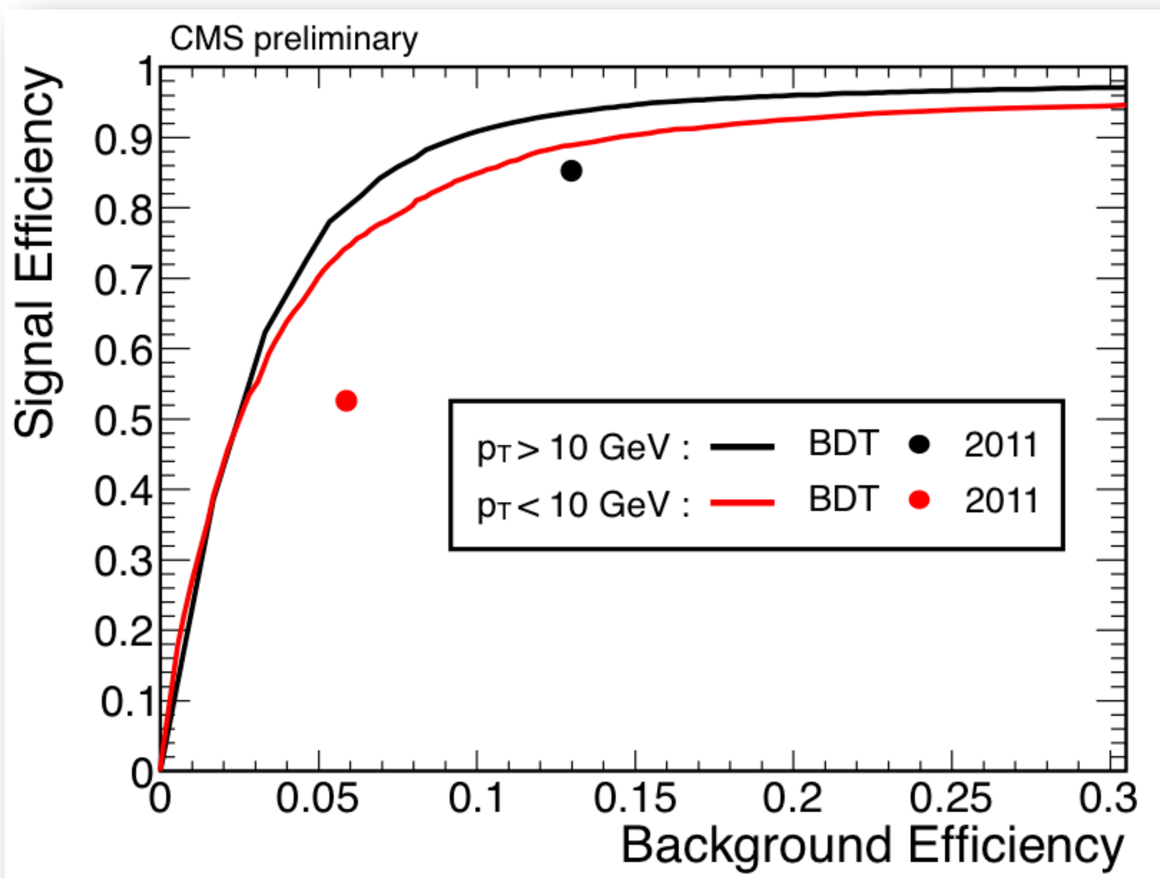
- ECAL cluster energies corrected using a MC trained multivariate regression
  - Improves resolution and restores flat response of energy scale versus pileup
    - Inputs: Raw cluster energies and positions, lateral and longitudinal shower shape variables, local shower positions w.r.t. crystal geometry,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





Electron identification

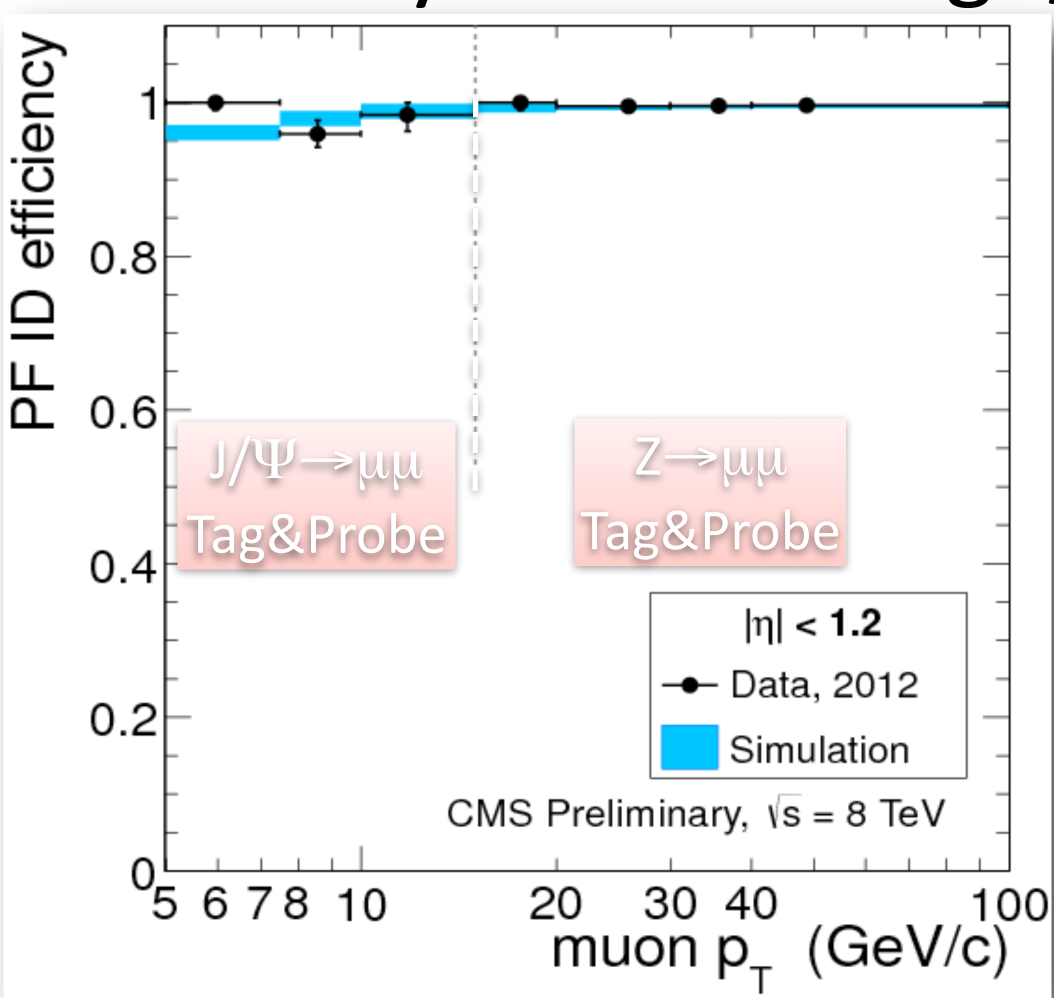
- Multivariate e identification in 2012
  - ECAL, tracker, ECAL-tracker-HCAL matching, impact parameter
  - 30% efficiency improvement in $H \rightarrow ZZ \rightarrow 4e$ wrt cut based ID
- Multivariate training against background in data

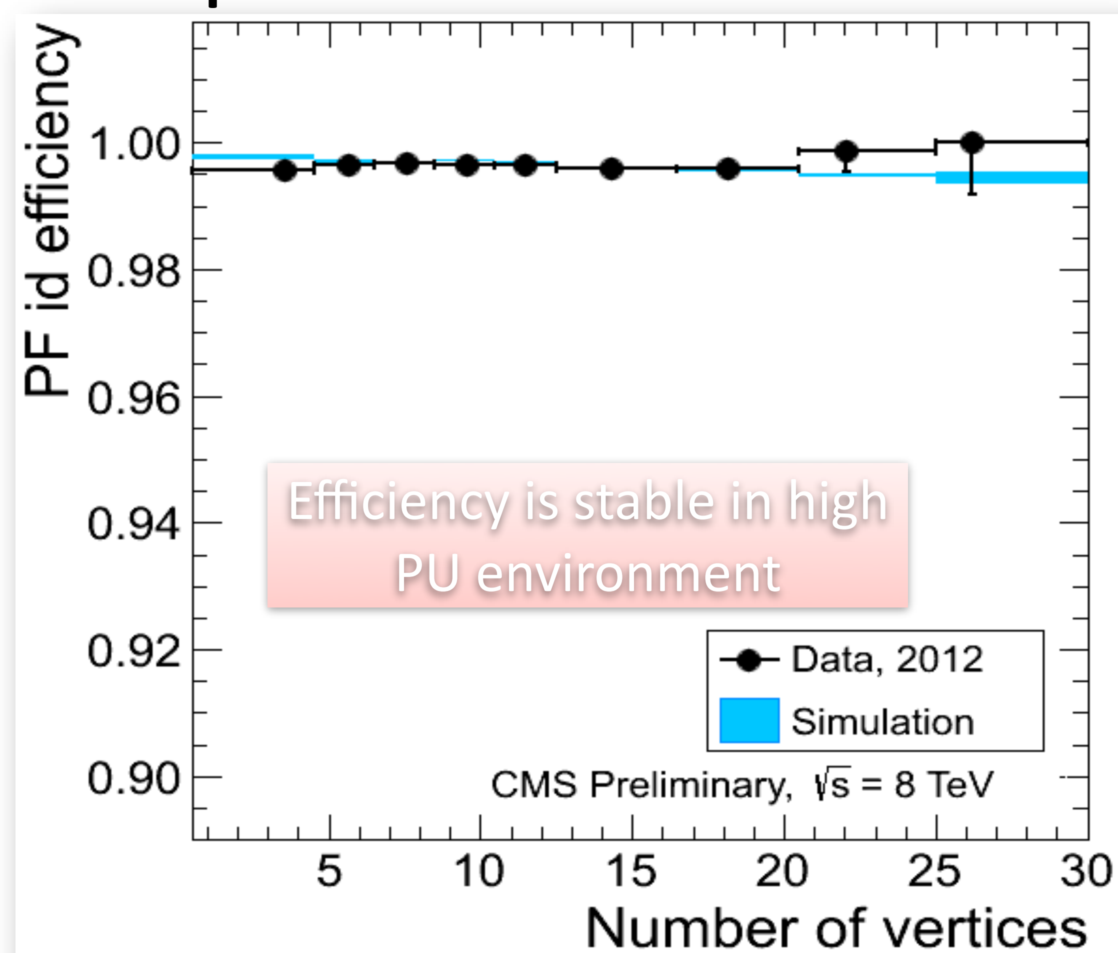


Cut Based vs MVA ID

Muon reconstruction and identification

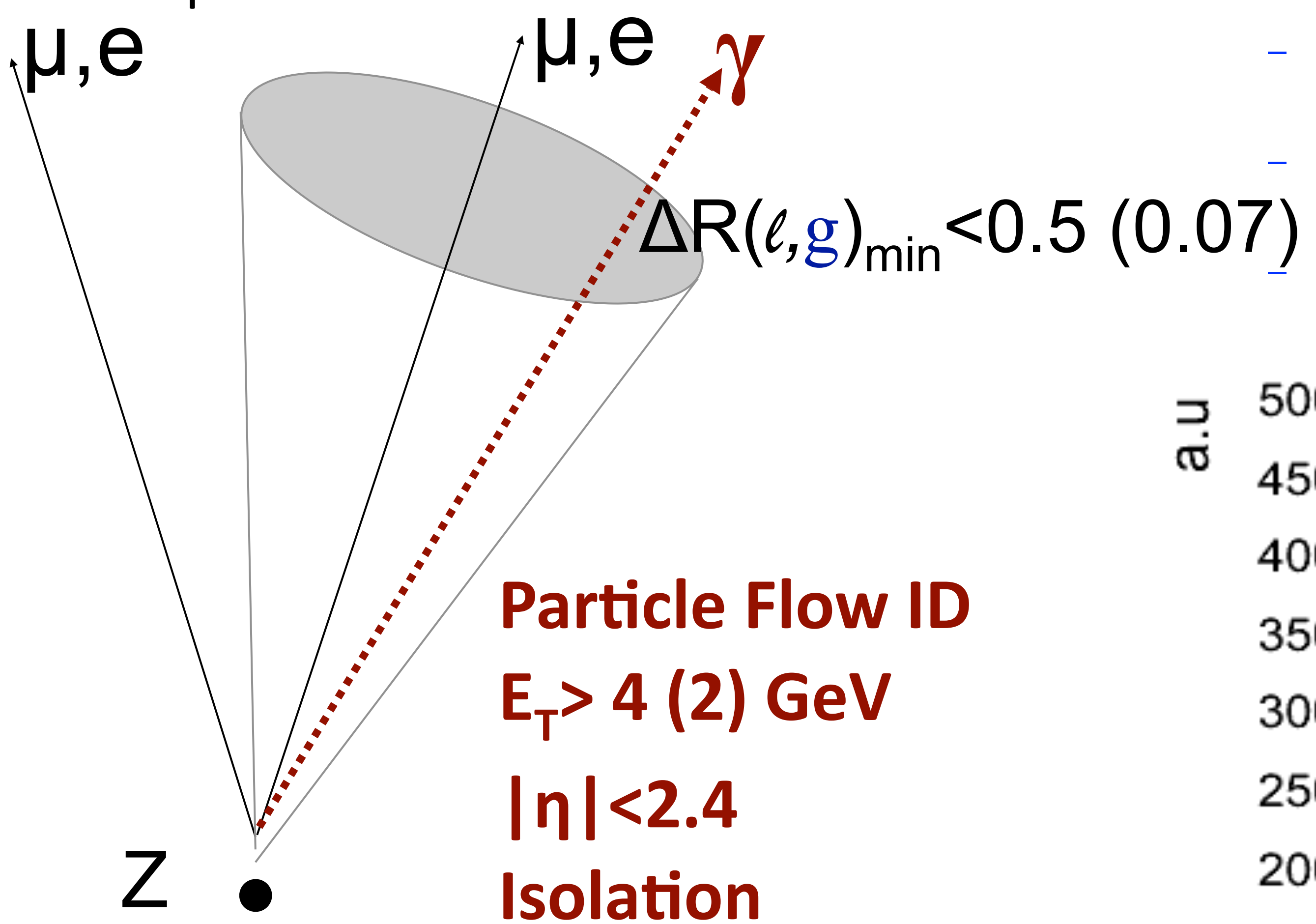
- Start with particle flow muons
- Efficiency above 96% down to $p_T = 5$ GeV
  - Above 99% efficiency for $p_T > 10$ GeV
  - Efficiency in data using J/Ψ and Z peak





Final State Radiation recovery Z->ll

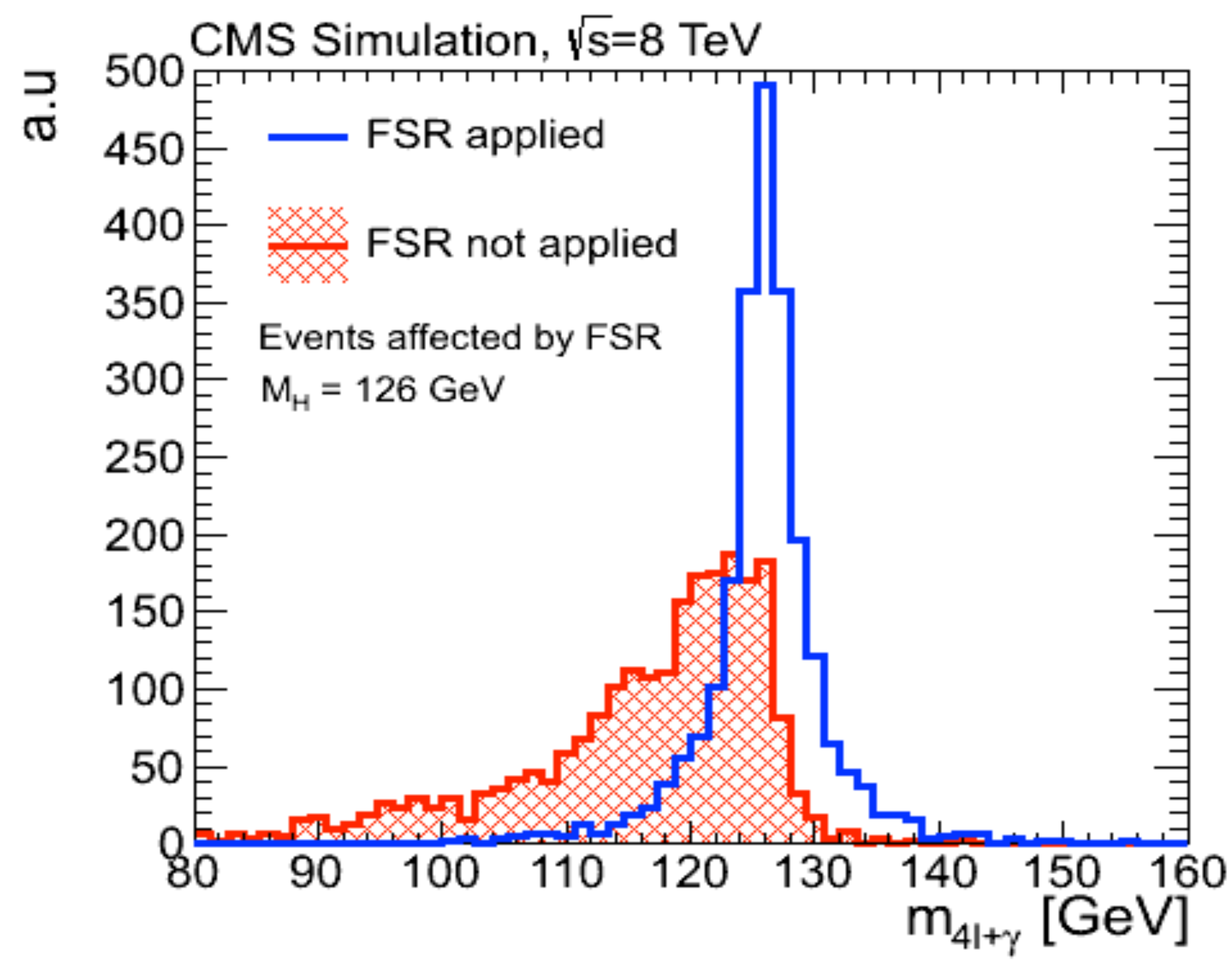
- Applied on each Z for photons near the leptons



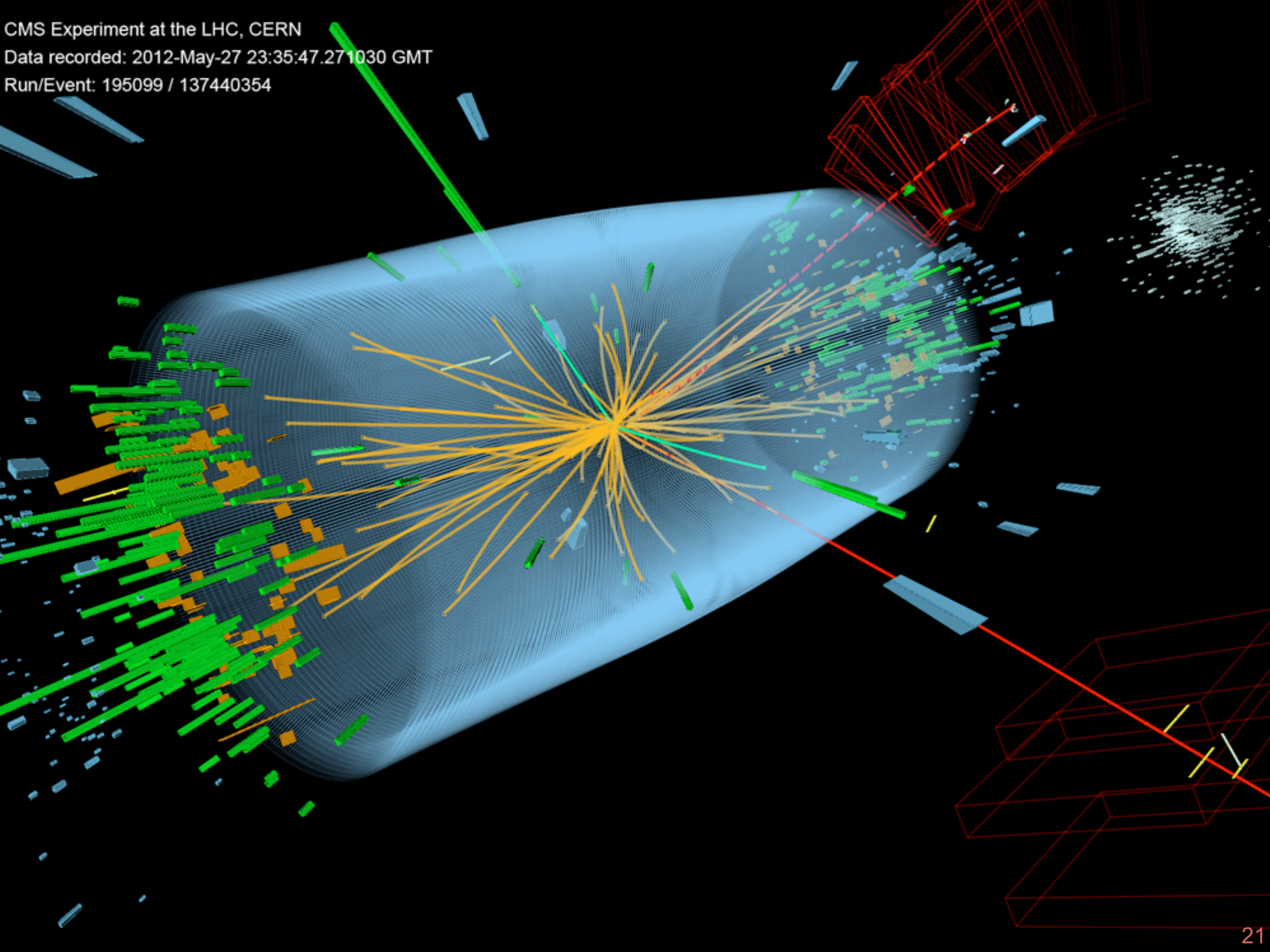
Particle Flow ID
E_T> 4 (2) GeV
|η|<2.4
Isolation

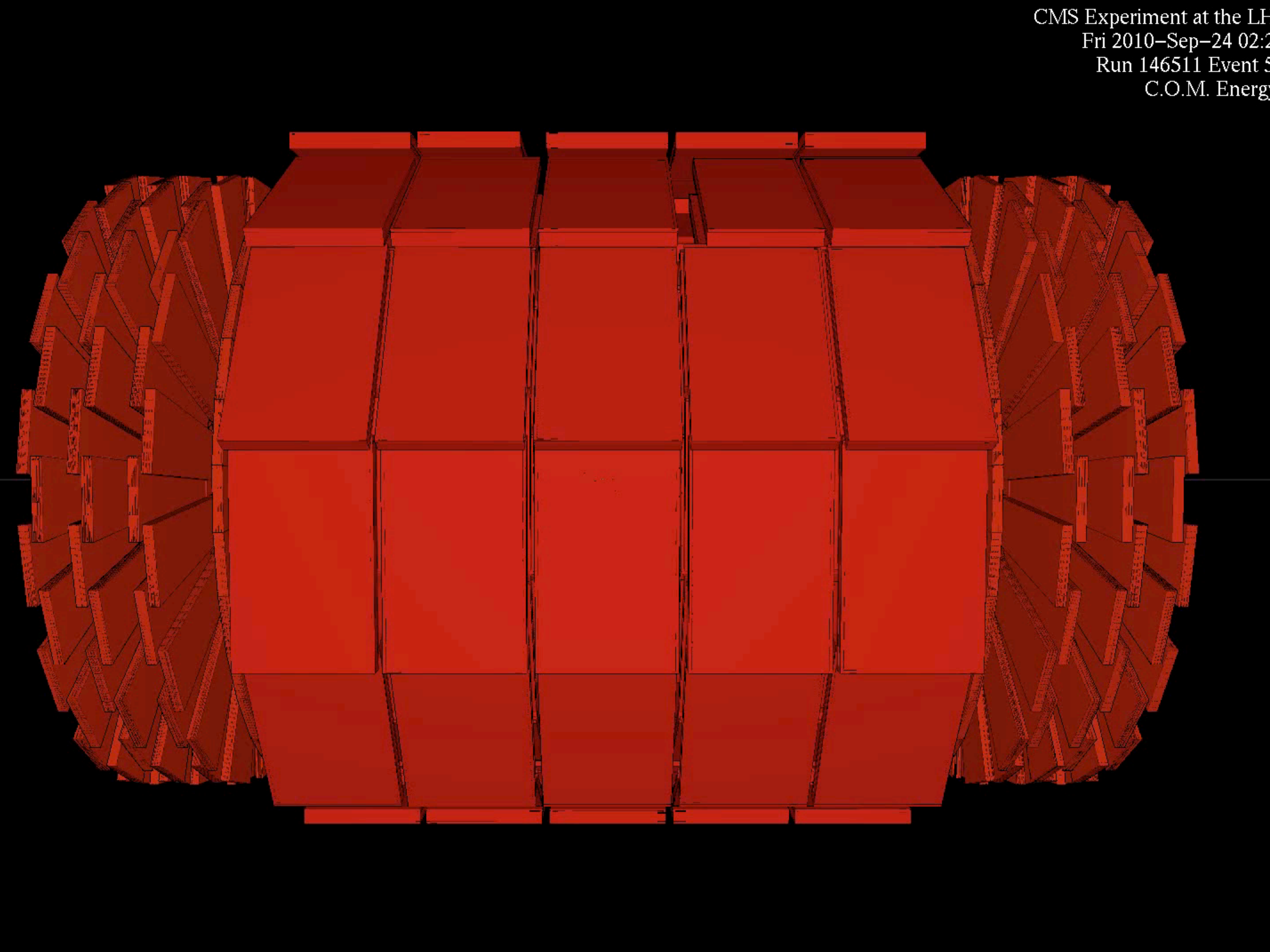
- Associates photon with Z if:
  - M(*ll*+γ)< 100 GeV
  - $|M(ll+\gamma)-M_Z|<|M(ll)-M_Z|$

- Expected Performance for M_H=126 GeV
  - 6% of events affected
  - Average purity of 80%
  - 2% added in analysis



$$H \rightarrow Z^{(*)}Z^{(*)}$$

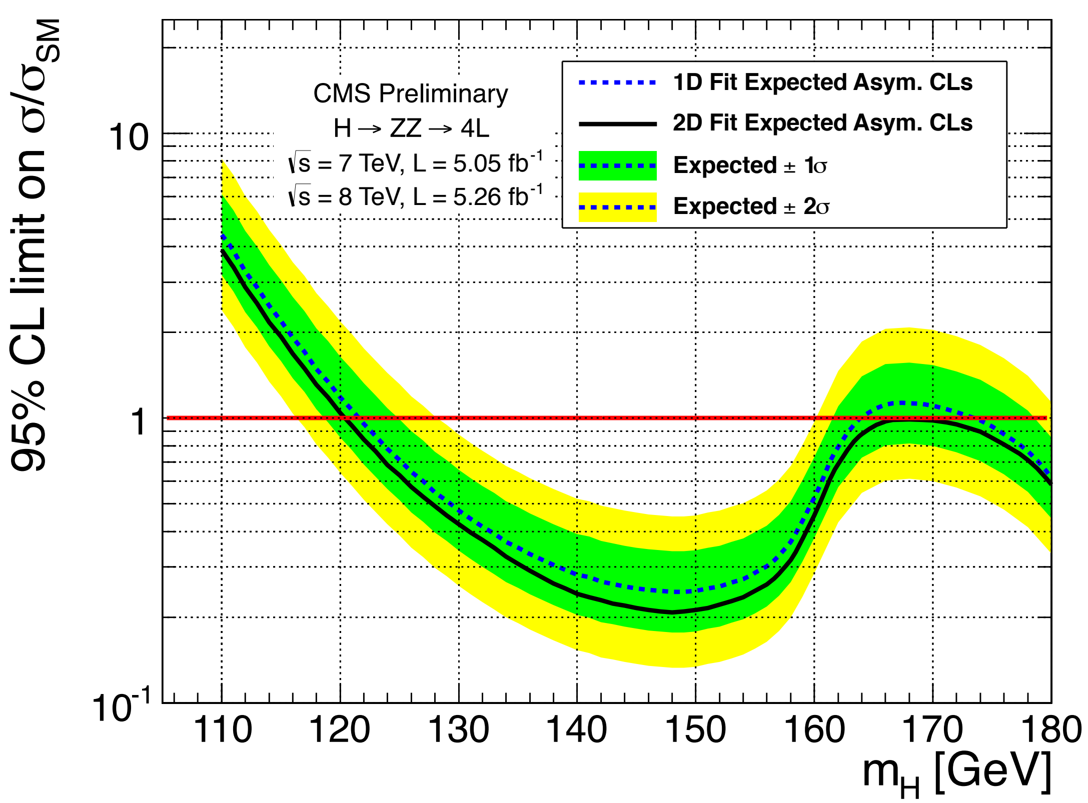

CMS Experiment at the LHC, CERN
Data recorded: 2012-May-27 23:35:47.271030 GMT
Run/Event: 195099 / 137440354

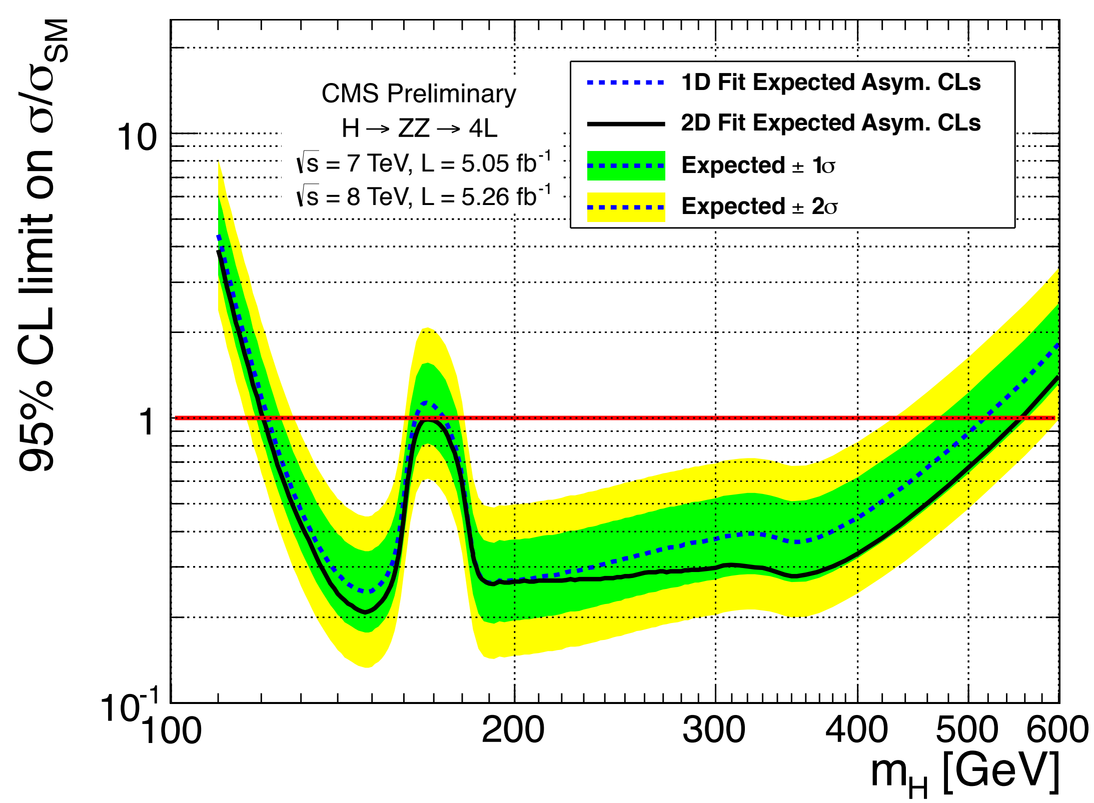

CMS Experiment at the LH
Fri 2010–Sep–24 02:2
Run 146511 Event 5
C.O.M. Energ

$H \to Z^{(*)}Z^{(*)} \to 4\ell$

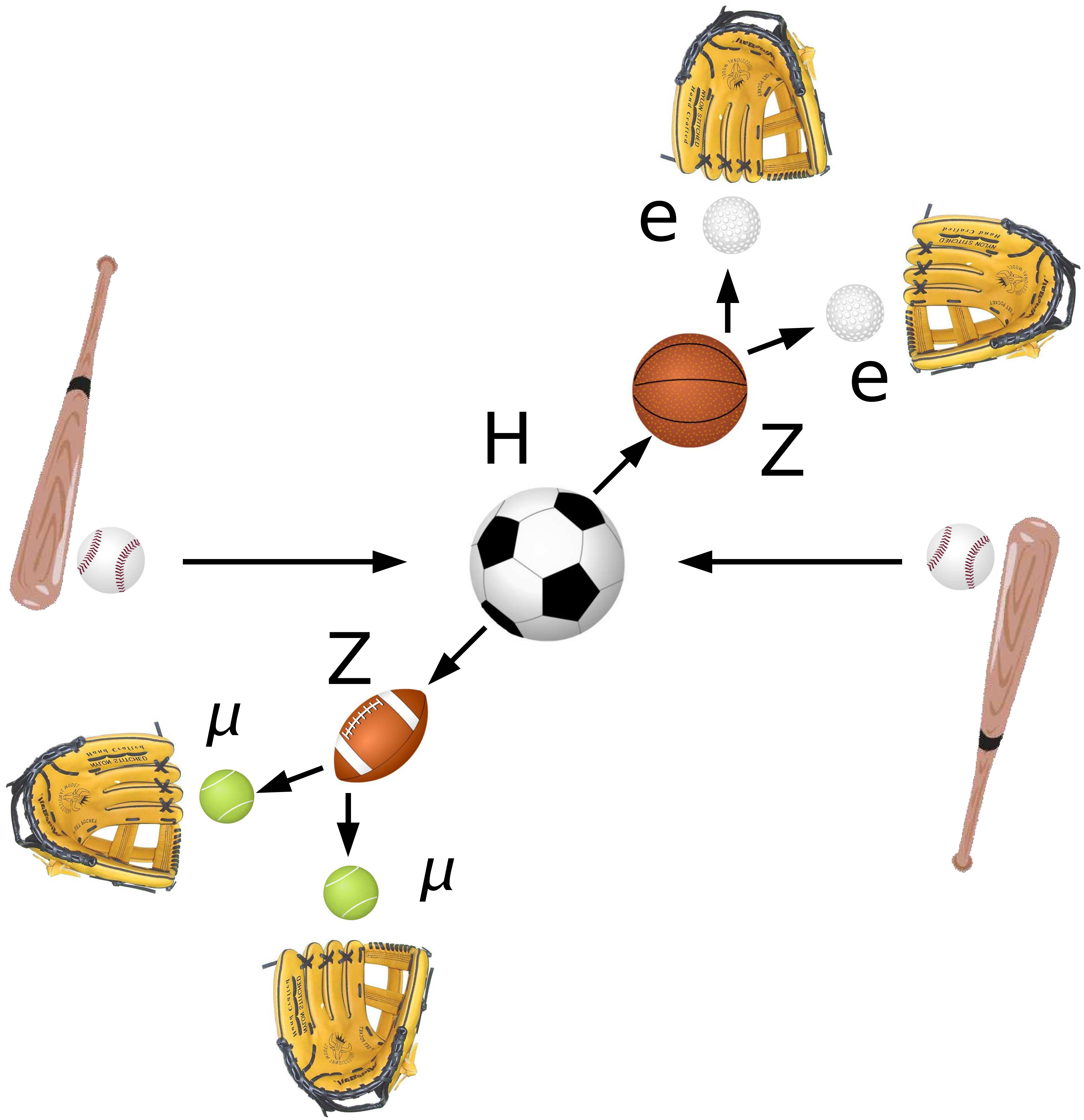
- Significant improvements since 2011, apply to both 7 and 8 TeV data
  - electron identification and isolation
  - muon identification and isolation
  - FSR recovery
  - full kinematics (MELA)
  - 2D statistical analysis ($m_{4\ell}$ + kinematics)

expected signif. $\sim 2.7\sigma \to 3.8\sigma$

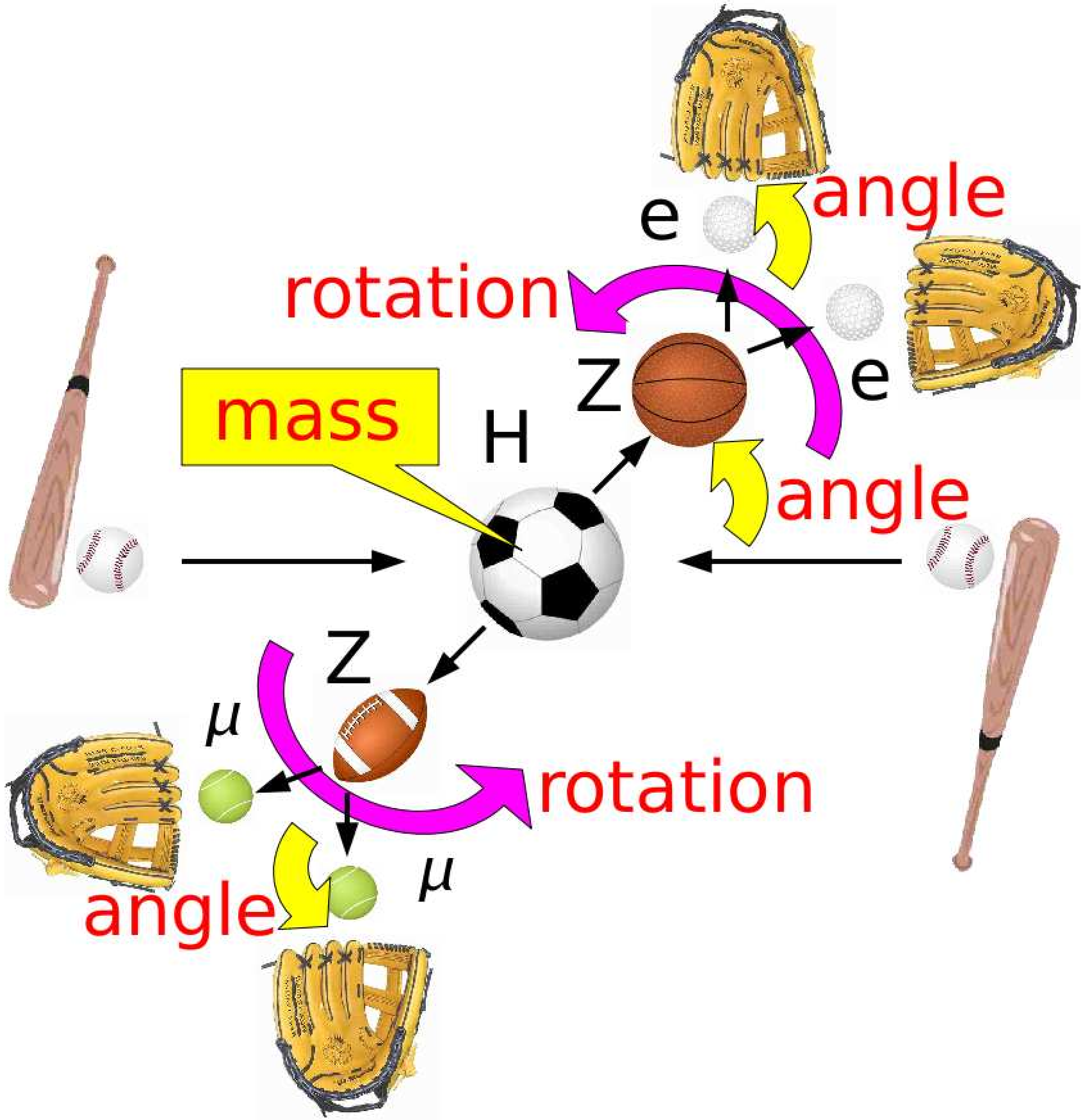




Kinematics in $H \rightarrow Z^{(*)}Z^{(*)}$

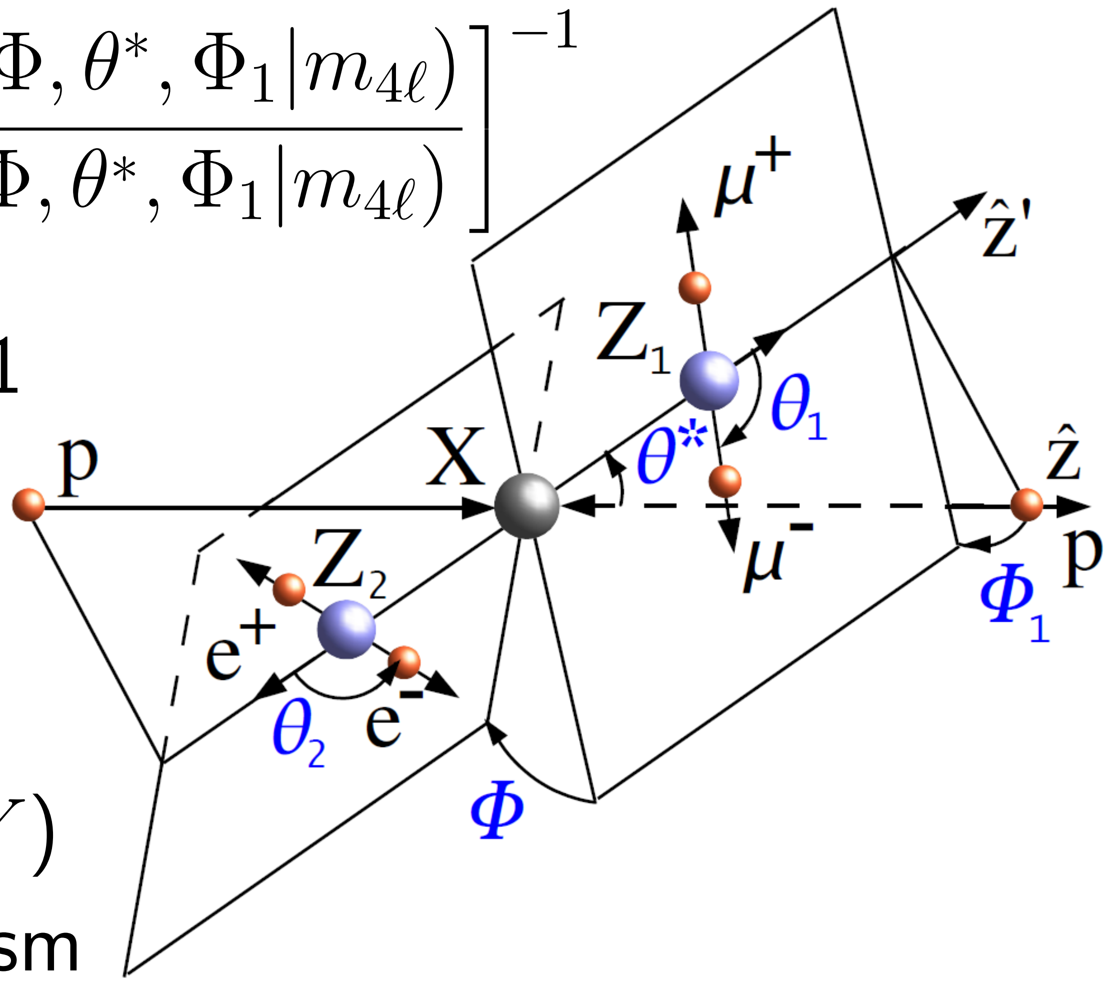


Kinematics in $H \to Z^{(*)}Z^{(*)}$



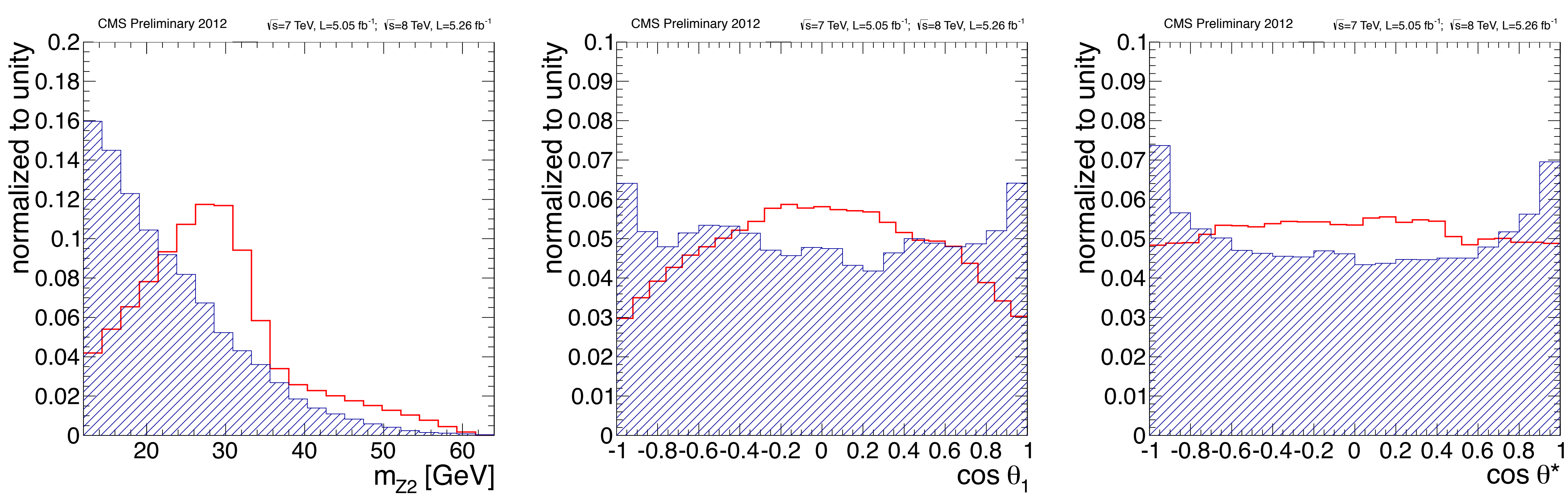
Matrix Element Likelihood Analysis (MELA)

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



- Used in $H \to ZZ^{(*)} \to 2q2\ell$ in 2011
  JHEP04(2012)036
  from PRD81,075022(2010)

- Discriminate signal vs background
  – QCD effects suppressed (no p_T, Y)
  independent of production mechanism



MELA Probability Distributions

- $\mathcal{P}_{\rm bkg} \propto$ POWHEG template ($m_{4\ell} < 180$ GeV): dominant $q\bar{q} \to Z\gamma^*$
  $\propto$ JHEP11(2011)027 ($m_{4\ell} > 180$ GeV): dominant $q\bar{q} \to ZZ$
- $\mathcal{P}_{\rm sig} \propto$ PRD81,075022(2010)

$$F^J_{00}(\theta^*) \times \Big\{ 4\, f_{00}\, \sin^2\theta_1 \sin^2\theta_2 + (f_{++} + f_{--}) \left((1+\cos^2\theta_1)(1+\cos^2\theta_2) + 4R_1R_2\cos\theta_1\cos\theta_2 \right)$$
$$- 2\,(f_{++} - f_{--}) \left(R_1\cos\theta_1 (1+\cos^2\theta_2) + R_2(1+\cos^2\theta_1)\cos\theta_2 \right)$$
$$+ 4\sqrt{f_{++}f_{00}}\,(R_1 - \cos\theta_1)\sin\theta_1 (R_2 - \cos\theta_2)\sin\theta_2 \cos(\Phi + \phi_{++})$$
$$+ 4\sqrt{f_{--}f_{00}}\,(R_1 + \cos\theta_1)\sin\theta_1 (R_2 + \cos\theta_2)\sin\theta_2 \cos(\Phi - \phi_{--})$$
$$+ 2\sqrt{f_{++}f_{--}}\,\sin^2\theta_1 \sin^2\theta_2 \cos(2\Phi + \phi_{++} - \phi_{--}) \Big\}$$

spin $= 0$ & ≥ 2

$$+4F^J_{11}(\theta^*) \times \Big\{ (f_{+0} + f_{0-})(1 - \cos^2\theta_1\cos^2\theta_2) - (f_{+0} - f_{0-})(R_1\cos\theta_1\sin^2\theta_2 + R_2\sin^2\theta_1\cos\theta_2)$$
$$+ 2\sqrt{f_{+0}f_{0-}}\,\sin\theta_1\sin\theta_2 (R_1R_2 - \cos\theta_1\cos\theta_2)\cos(\Phi + \phi_{+0} - \phi_{0-}) \Big\}$$
$$+4F^J_{-11}(\theta^*) \times (-1)^J \times \Big\{ (f_{+0} + f_{0-})(R_1R_2 + \cos\theta_1\cos\theta_2) - (f_{+0} - f_{0-})(R_1\cos\theta_2 + R_2\cos\theta_1)$$
$$+ 2\sqrt{f_{+0}f_{0-}}\,\sin\theta_1\sin\theta_2\cos(\Phi + \phi_{+0} - \phi_{0-}) \Big\} \sin\theta_1\sin\theta_2\cos(2\Psi)$$

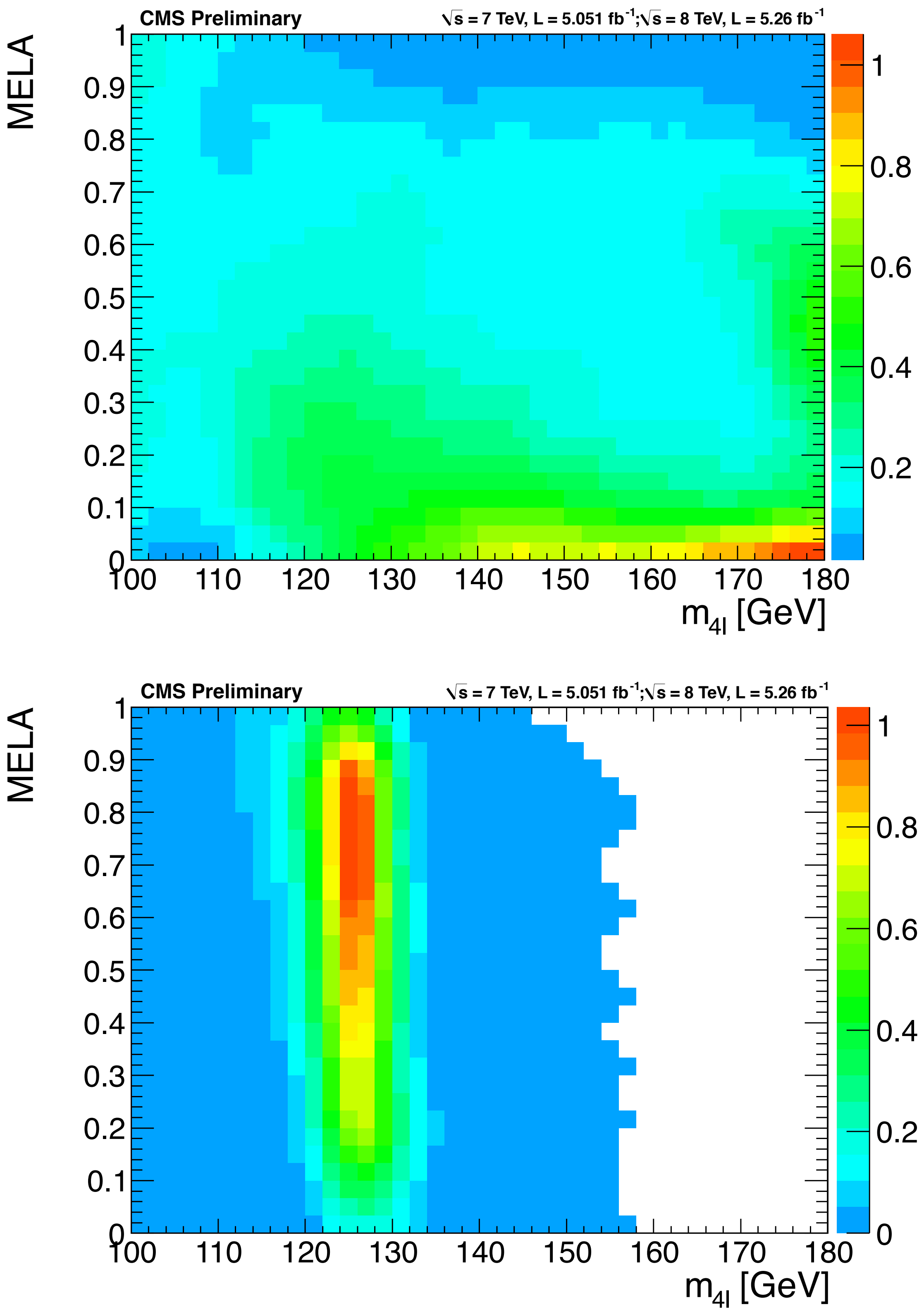
spin $= 1$ & ≥ 2

$$+2F^J_{22}(\theta^*) \times f_{+-} \Big\{ (1+\cos^2\theta_1)(1+\cos^2\theta_2) - 4R_1R_2\cos\theta_1\cos\theta_2 \Big\}$$
$$+2F^J_{-22}(\theta^*) \times (-1)^J \times f_{+-}\,\sin^2\theta_1\sin^2\theta_2\cos(4\Psi)$$

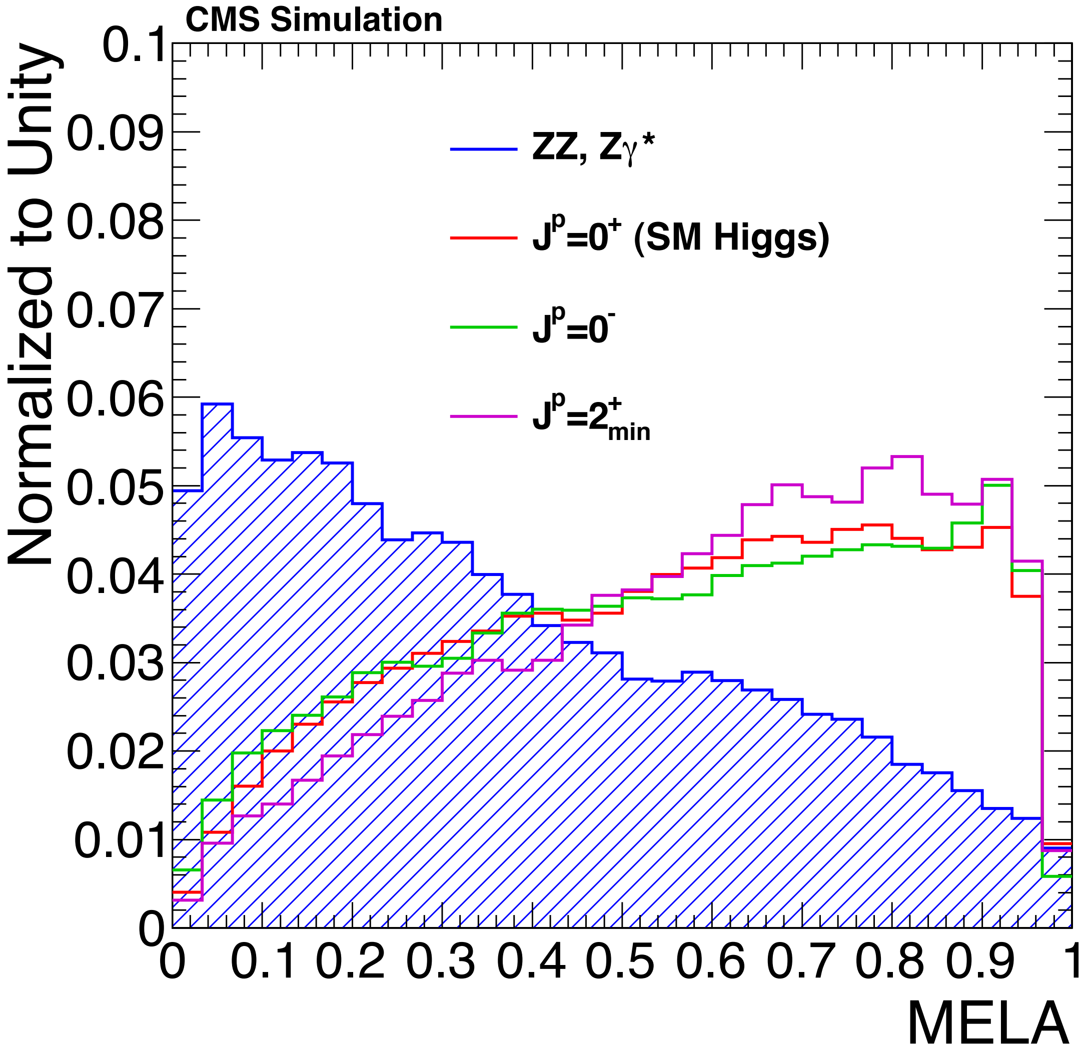
spin ≥ 2 unique

$+$ ...interference terms

2D analysis MELA vs $m_{4\ell}$

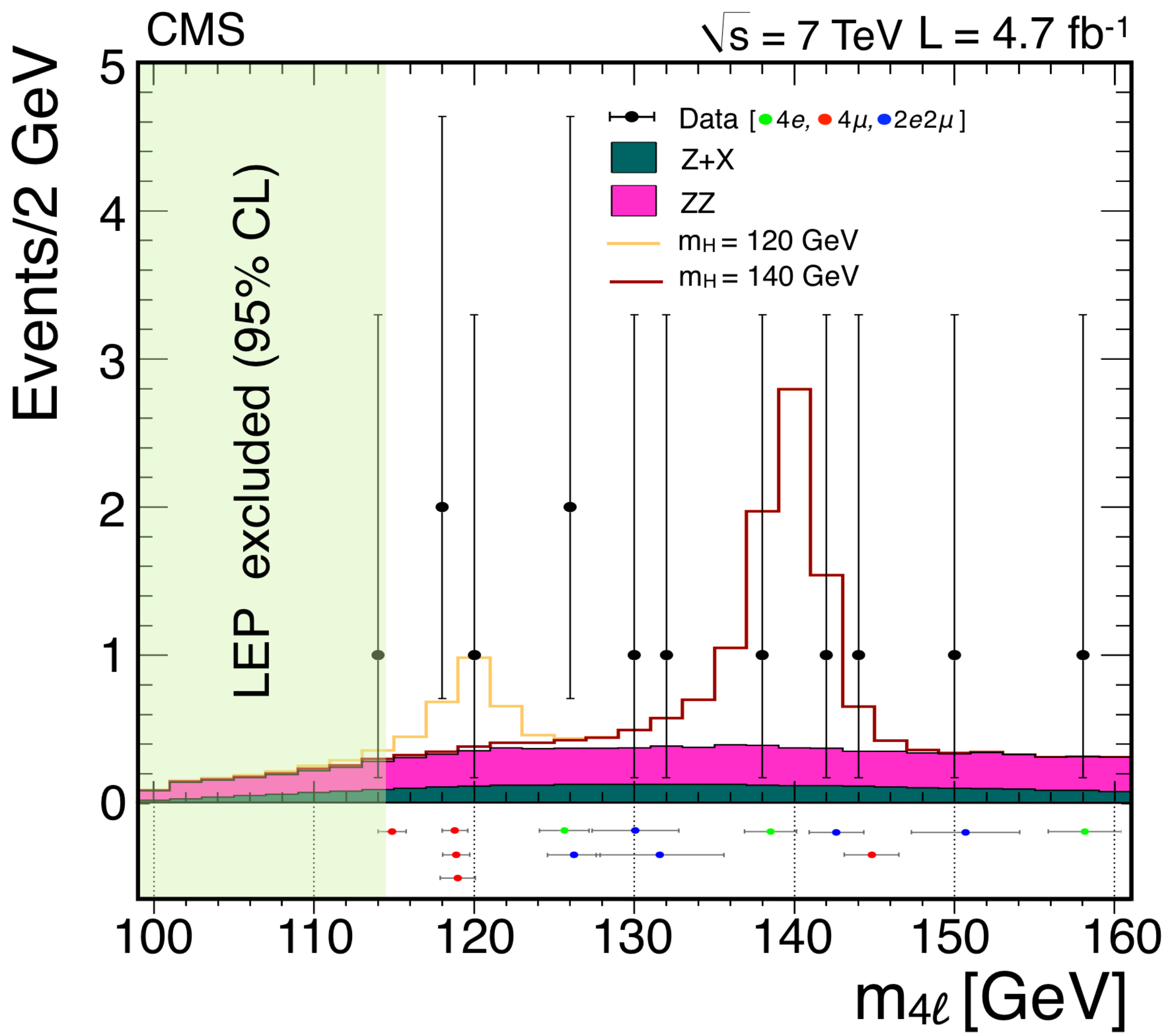


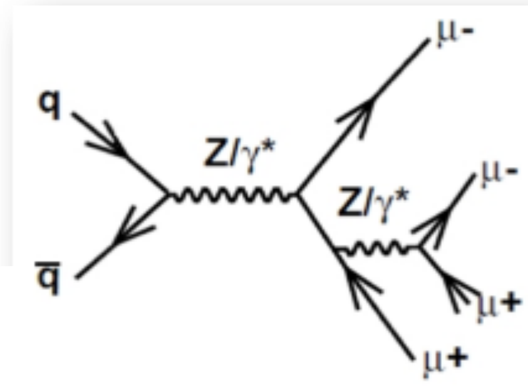
- Model with full simulation
  - include interference
  - powerful sig.-bkg. separation
  - little model-dependence



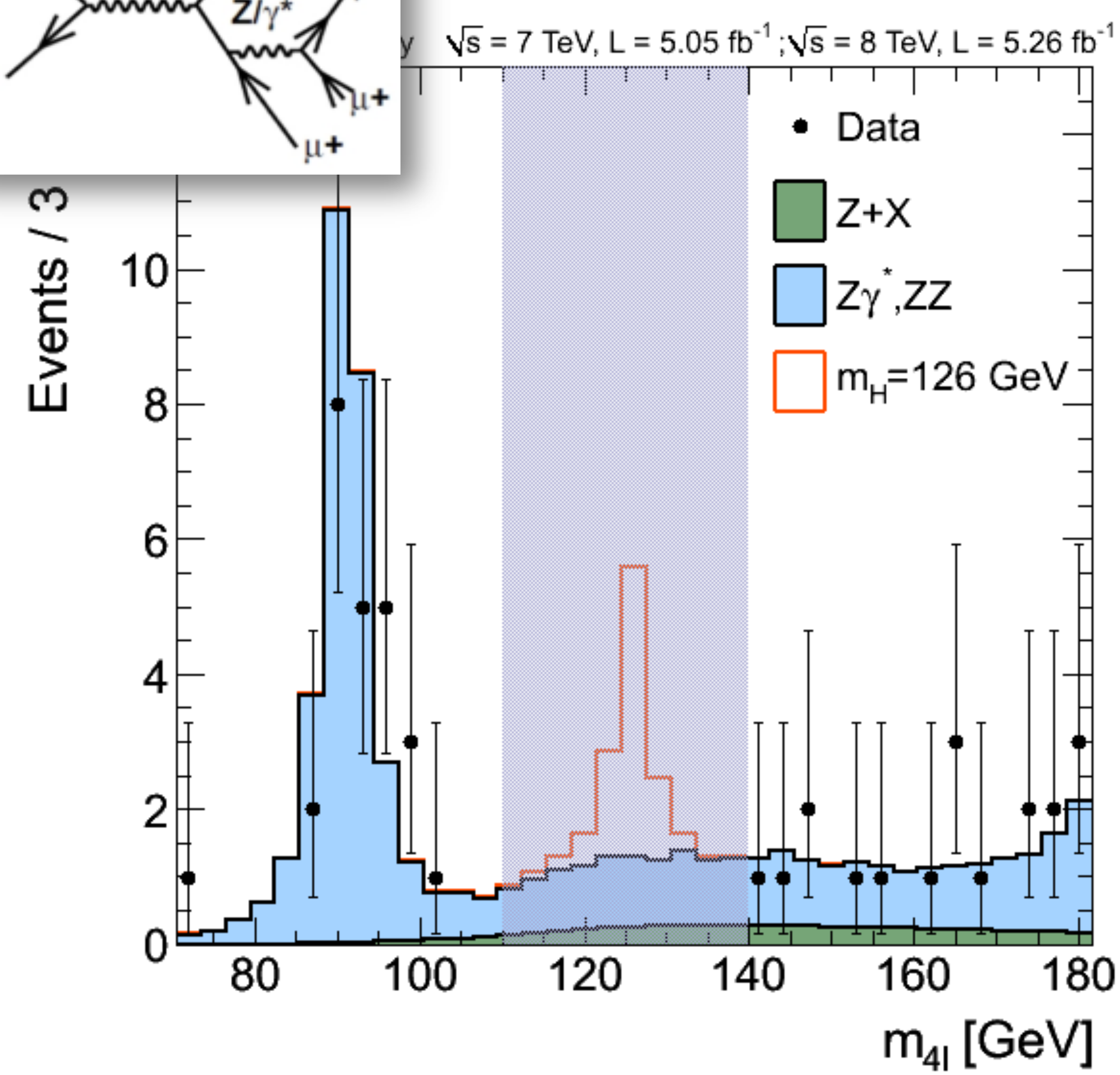
Analysis performed "blind"

Last year



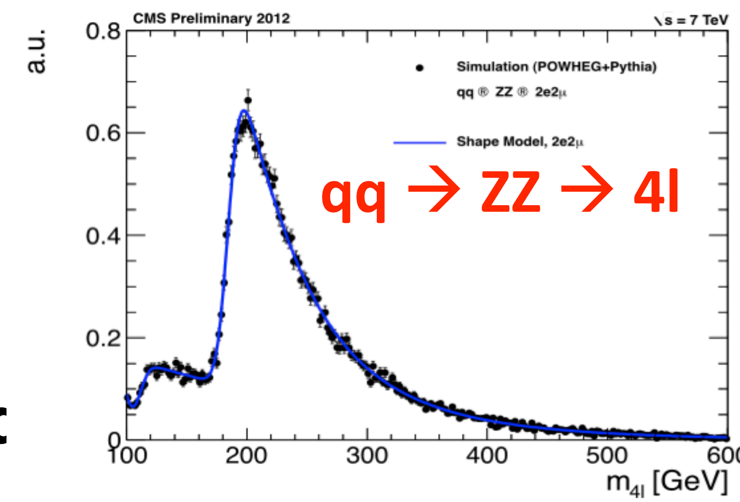


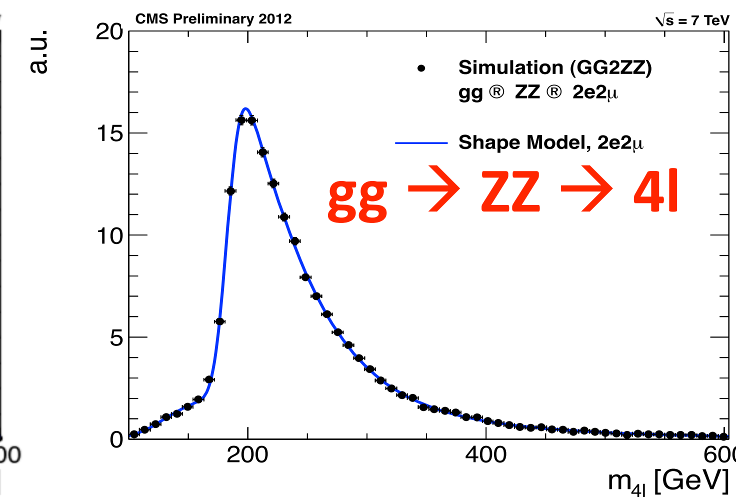
This year



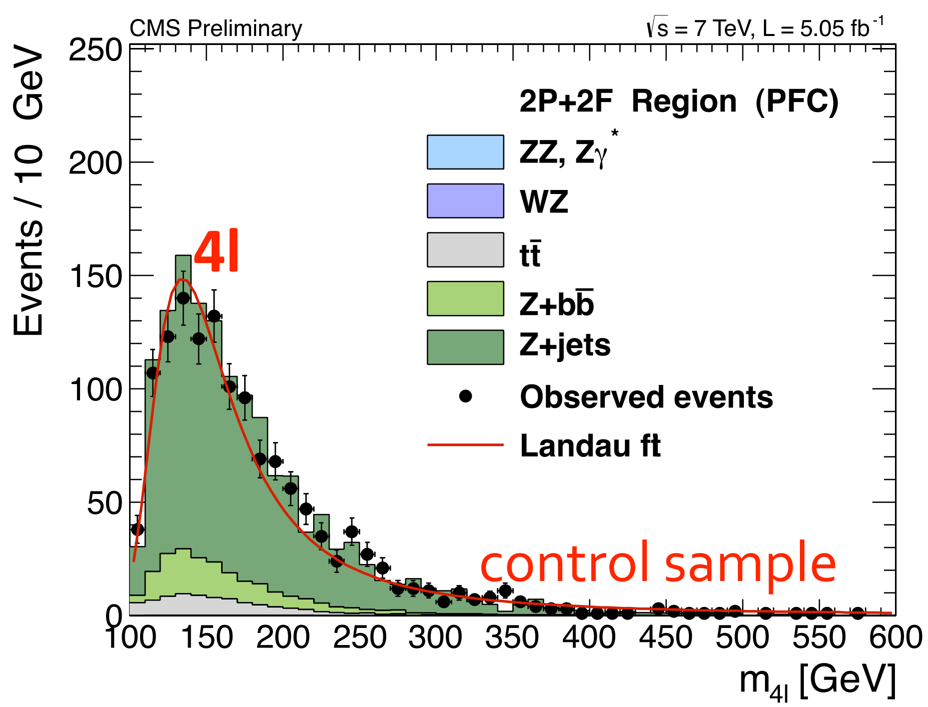
Background models

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

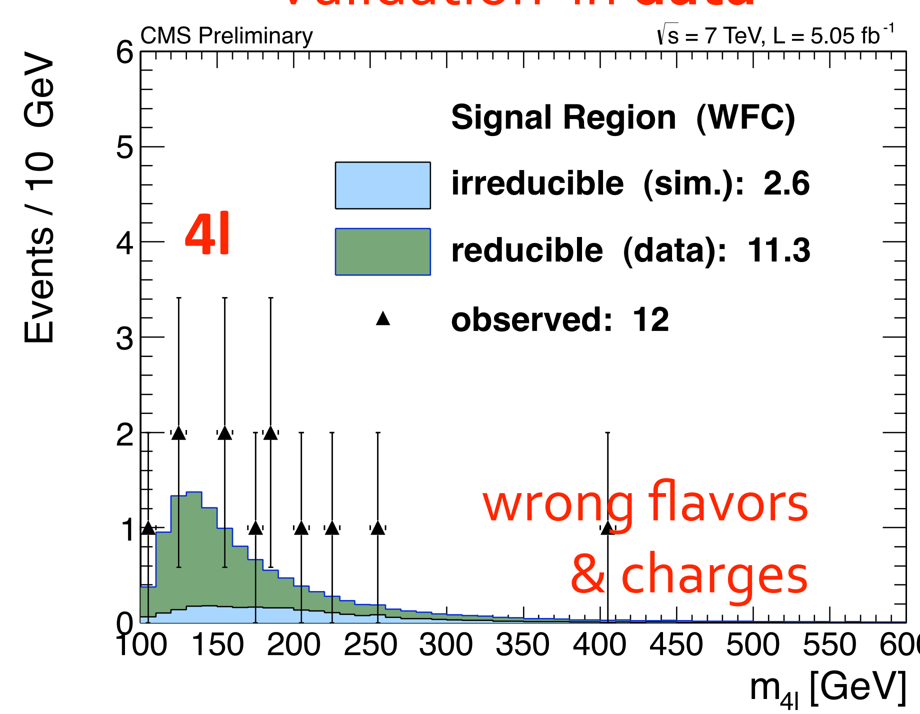




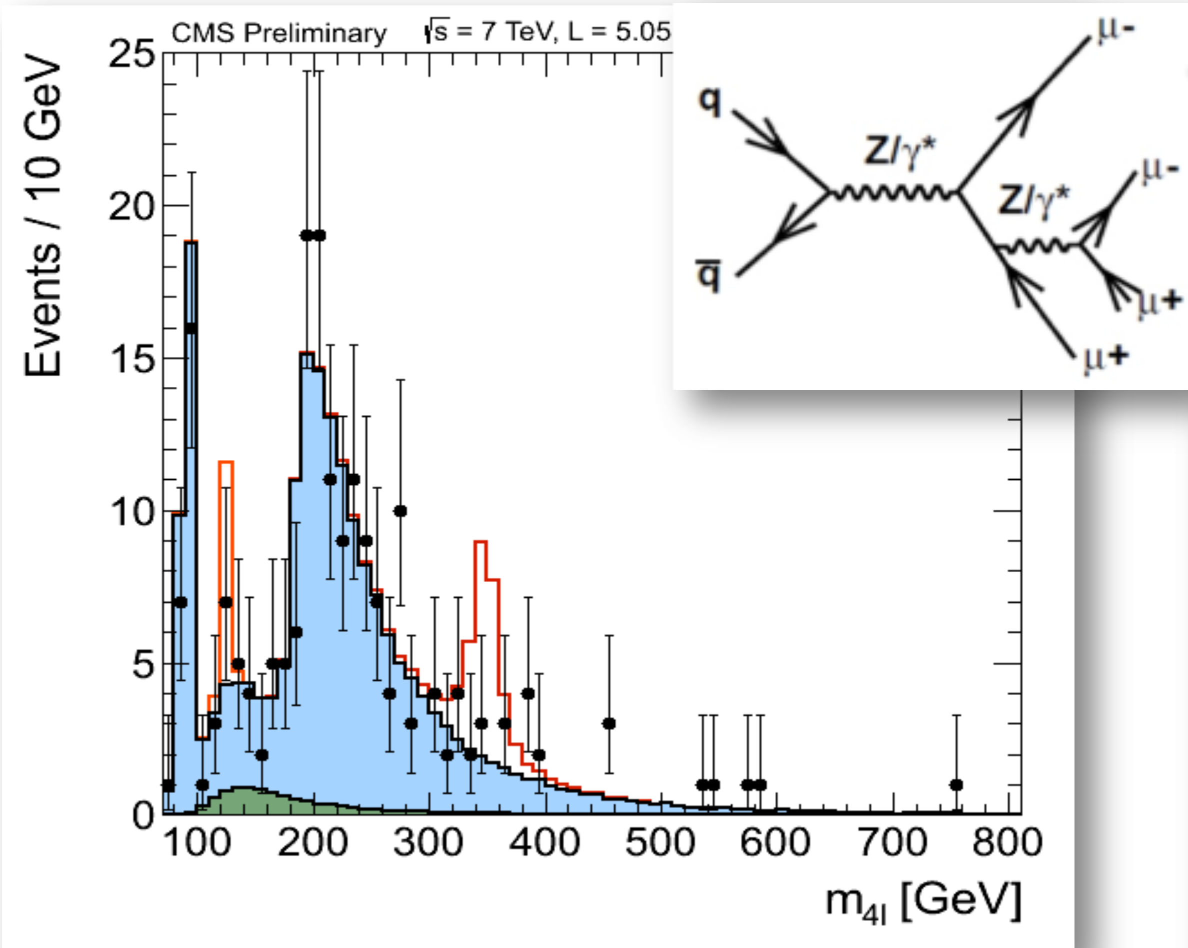
- **Reducible backgrounds estimatec**
  - Extrapolation from control samples enriched with misidentified leptons
  - Total uncertainty ~50%

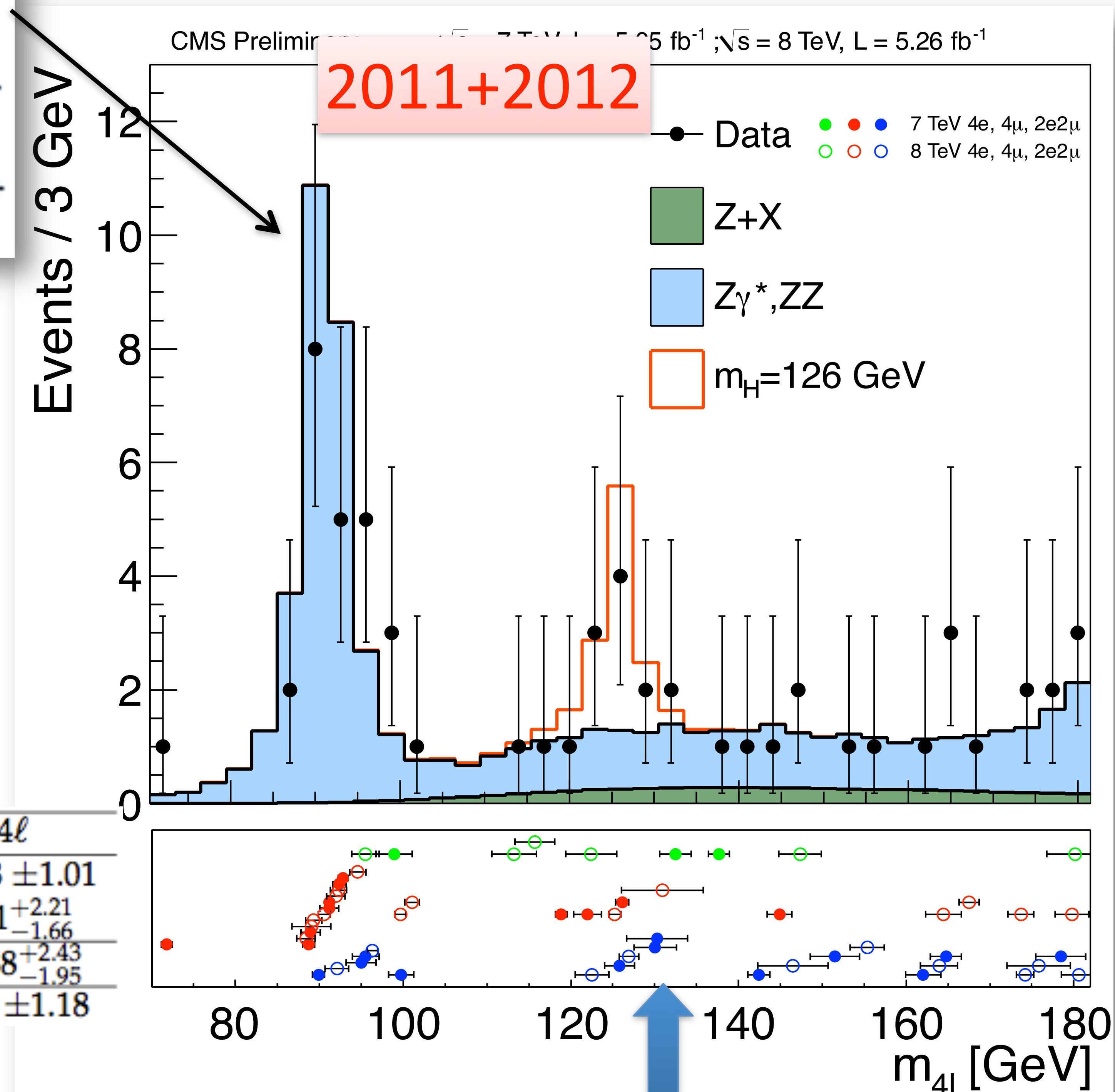


Validation in **data**



Results: m(4l) spectrum





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

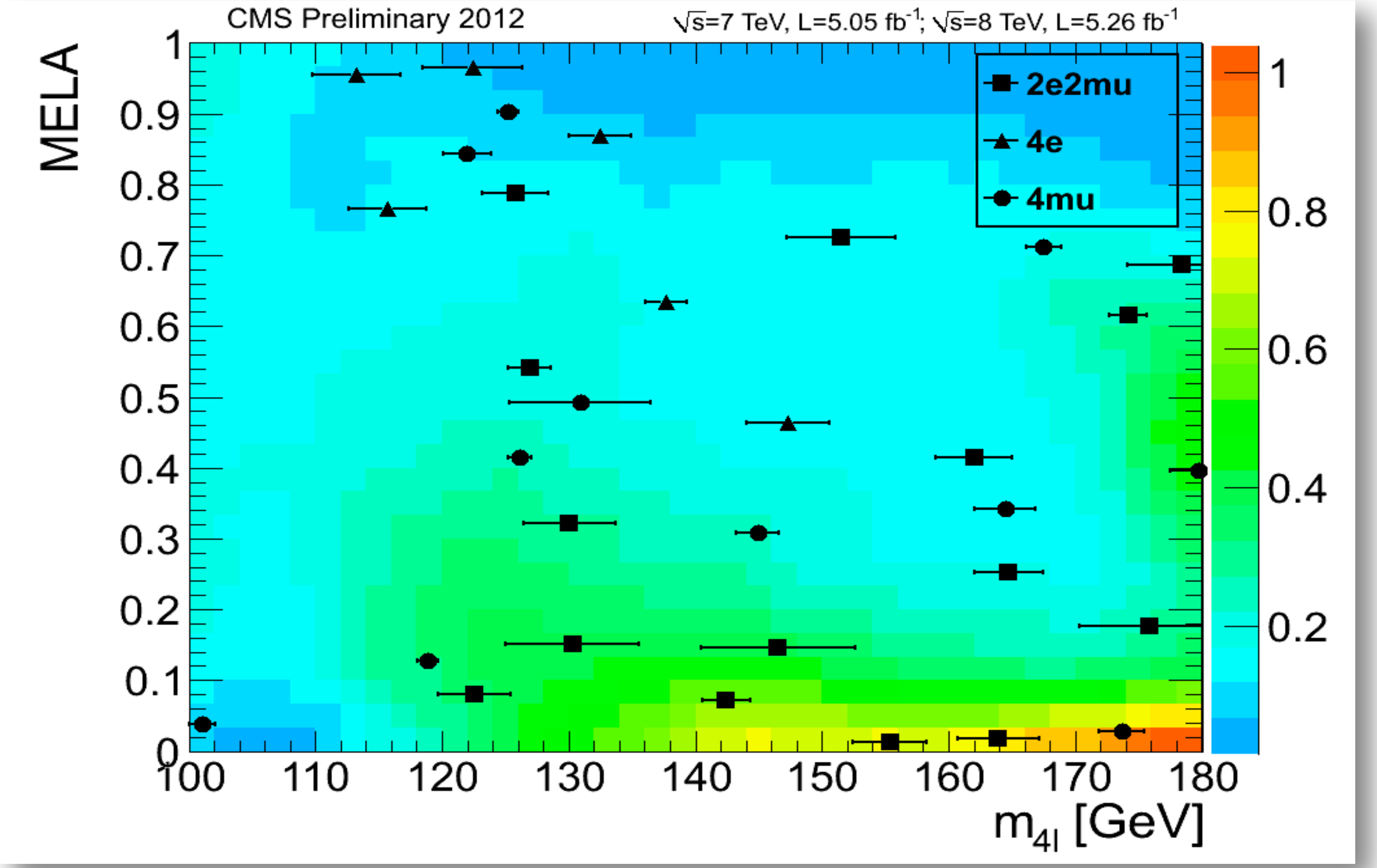
Channel	4e	4μ	2e2μ	4ℓ
ZZ background	2.65 ±0.31	5.65 ±0.59	7.17 ±0.76	15.48 ±1.01
Z+X	$1.20^{+1.08}_{-0.78}$	$0.92^{+0.65}_{-0.55}$	$2.29^{+1.81}_{-1.36}$	$4.41^{+2.21}_{-1.66}$
All backgrounds	$3.85^{+1.12}_{-0.84}$	$6.58^{+0.88}_{-0.81}$	$9.46^{+1.96}_{-1.56}$	$19.88^{+2.43}_{-1.95}$
$m_H = 126$ GeV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

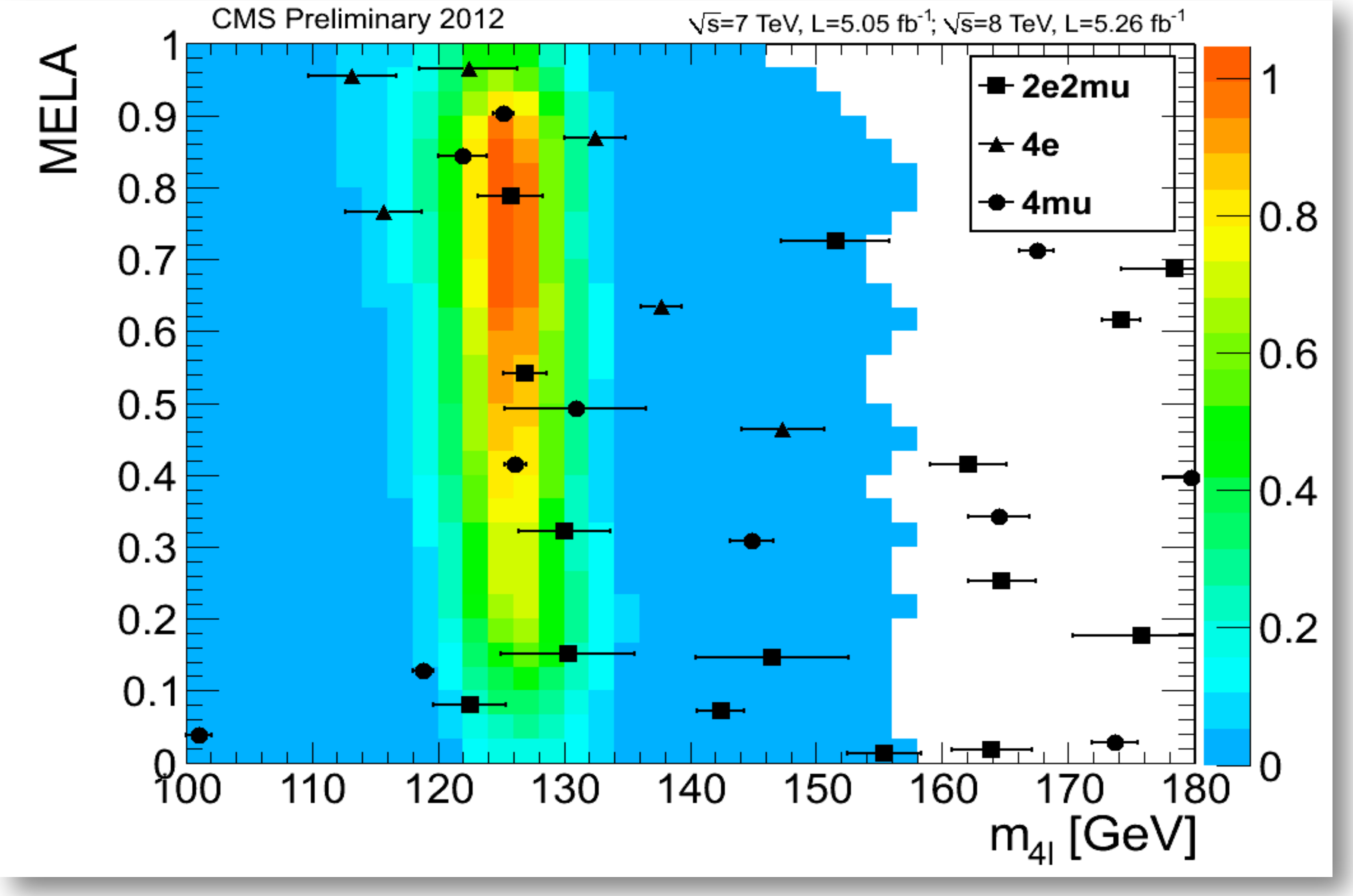


Data w.r.t. background expectation

Results: MELA 2D plots

Perform 2D fit

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

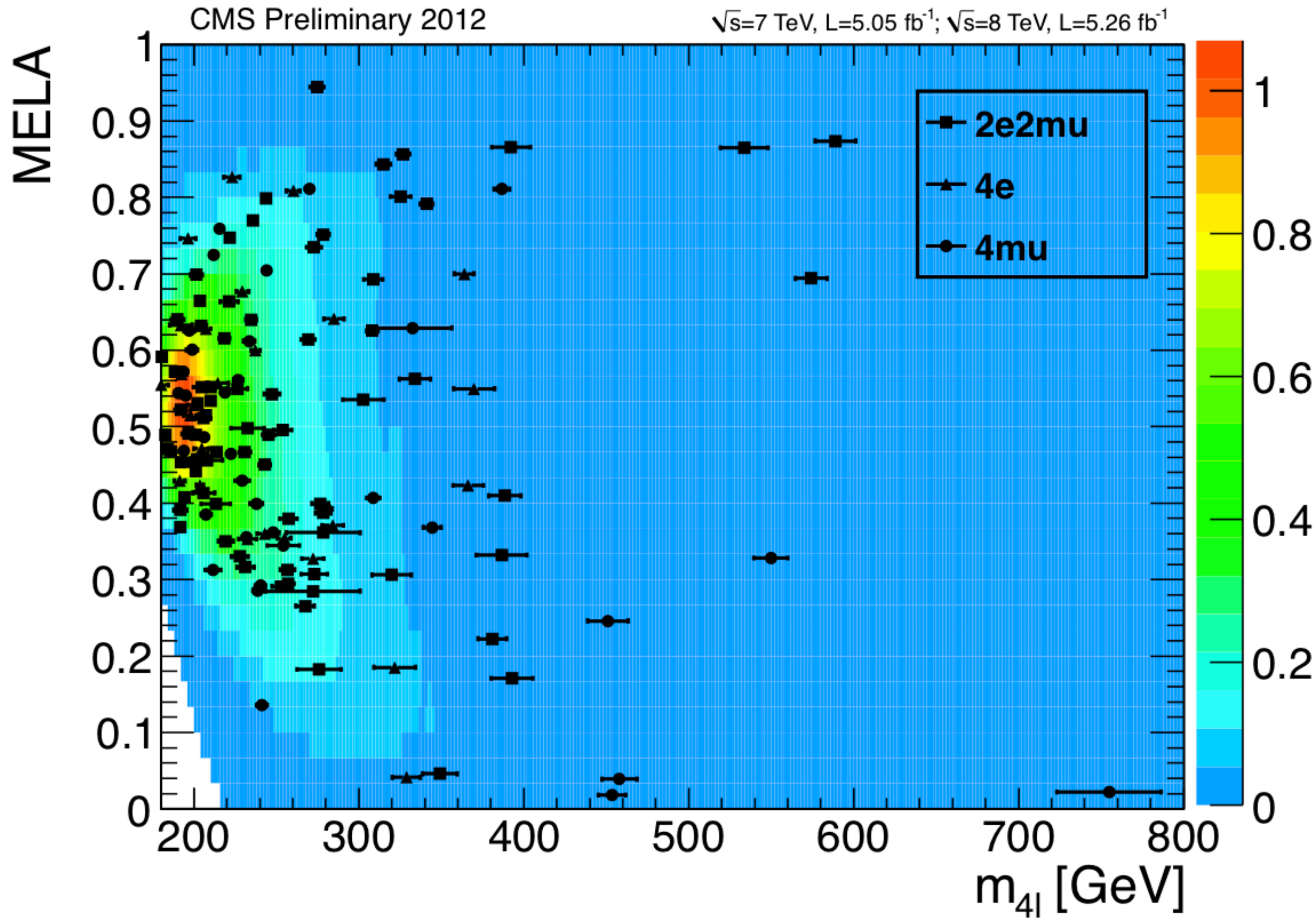


Data w.r.t 126 GeV Higgs Expectation

Results: MELA 2D plots: high mass

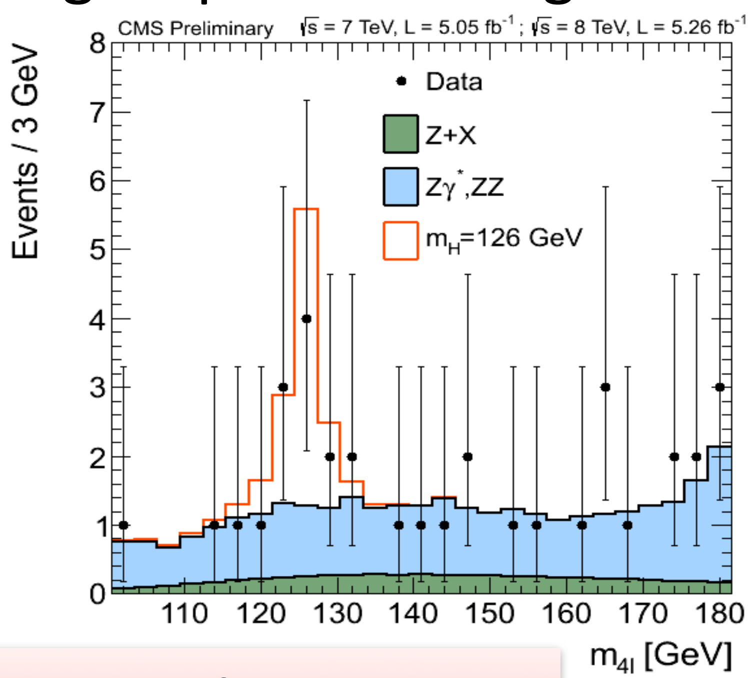
Perform 2D fit

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

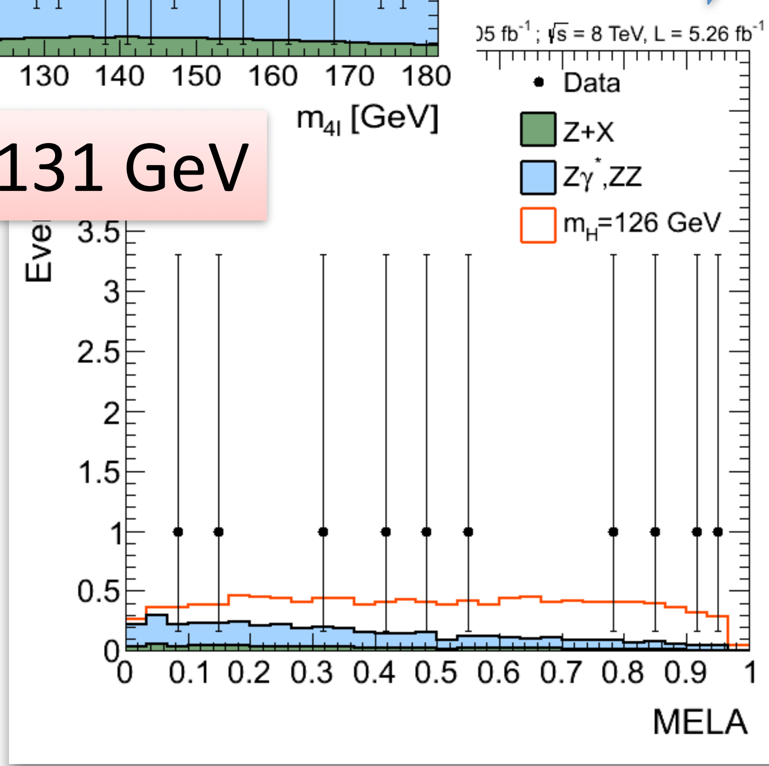


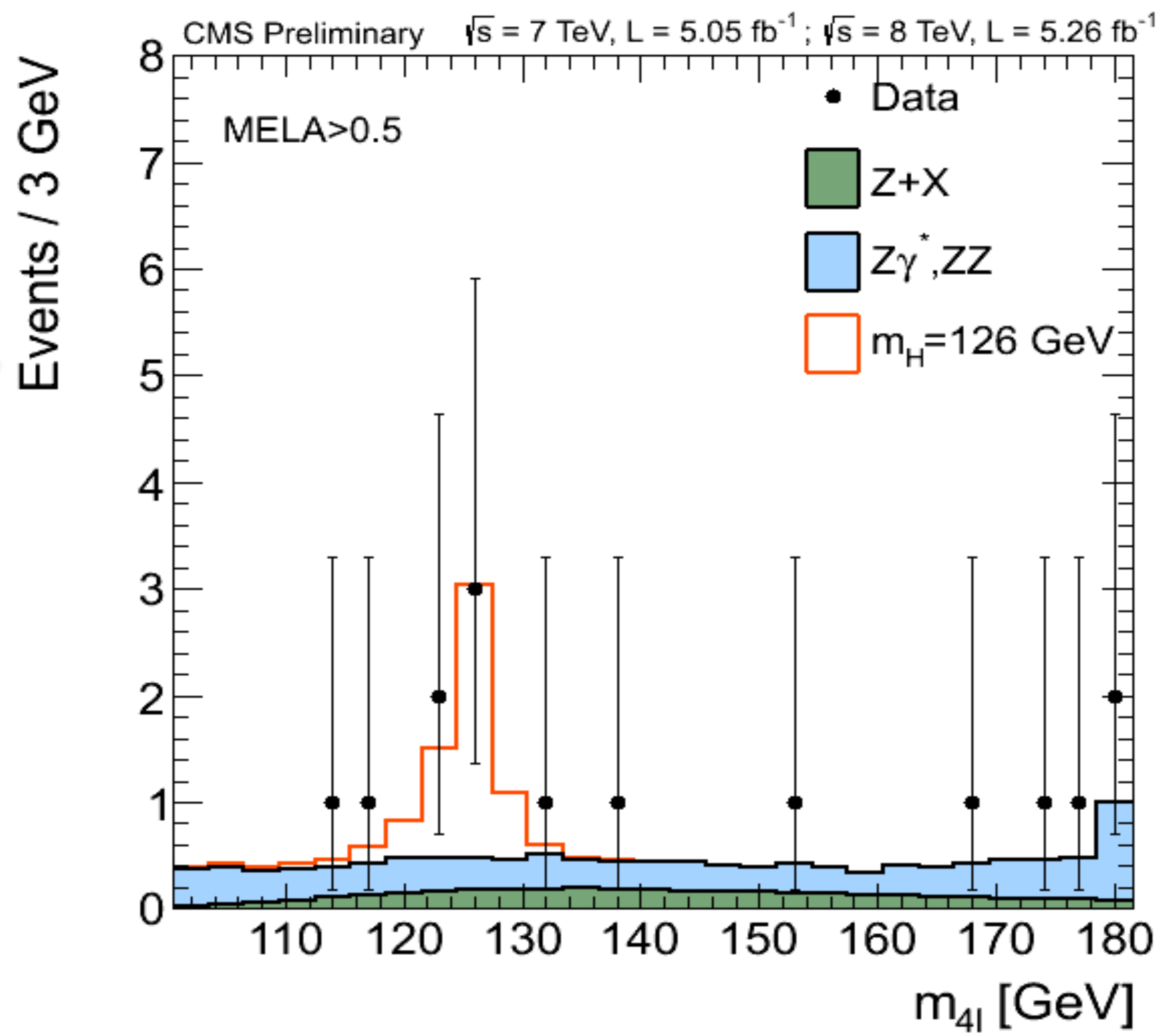
Low mass region with MELA cut

- Enrich the signal MELA > 0.5
- Cut value chosen such that
- signal prob. > background prob.



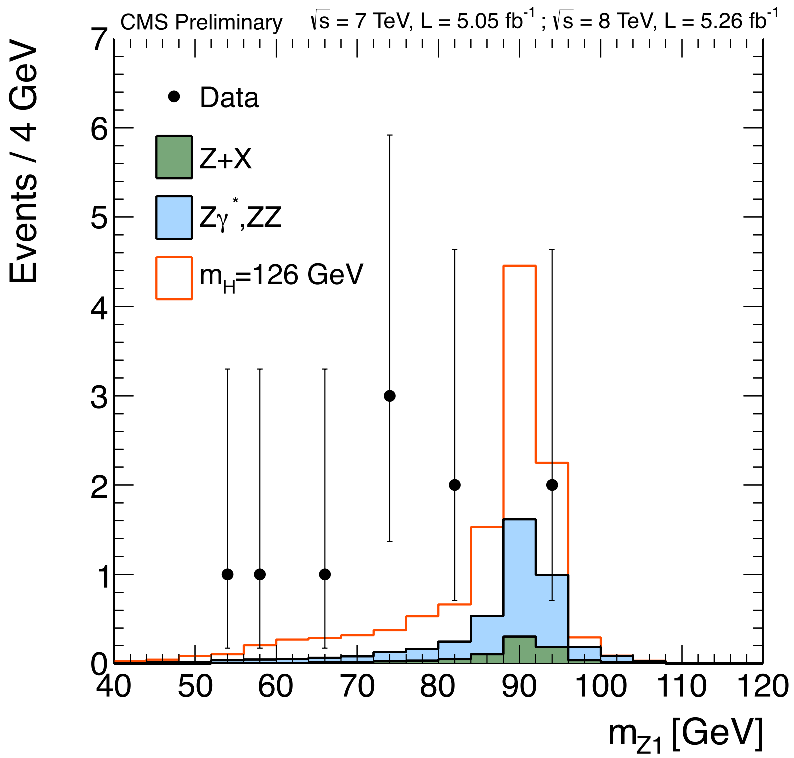
121< m4l <131 GeV

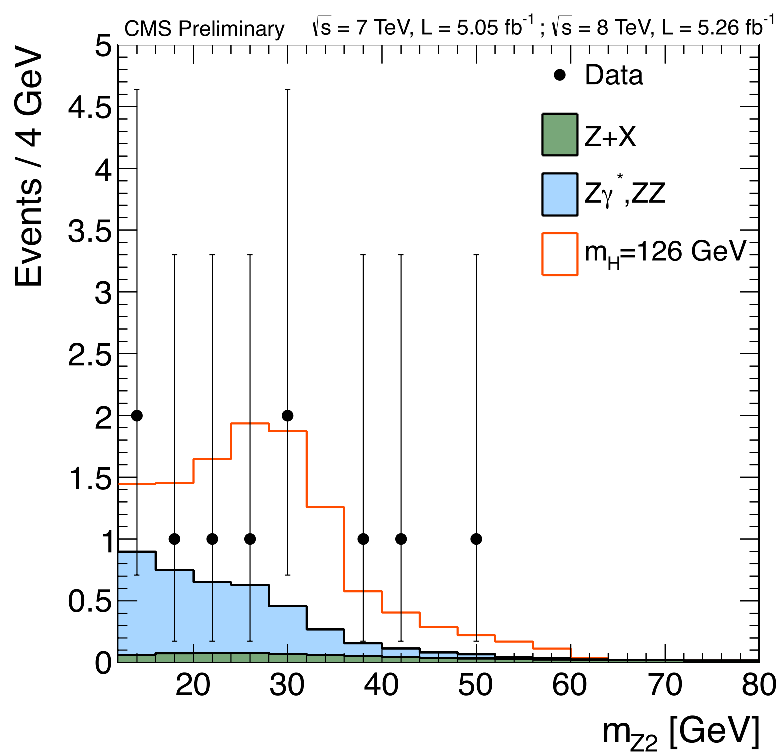


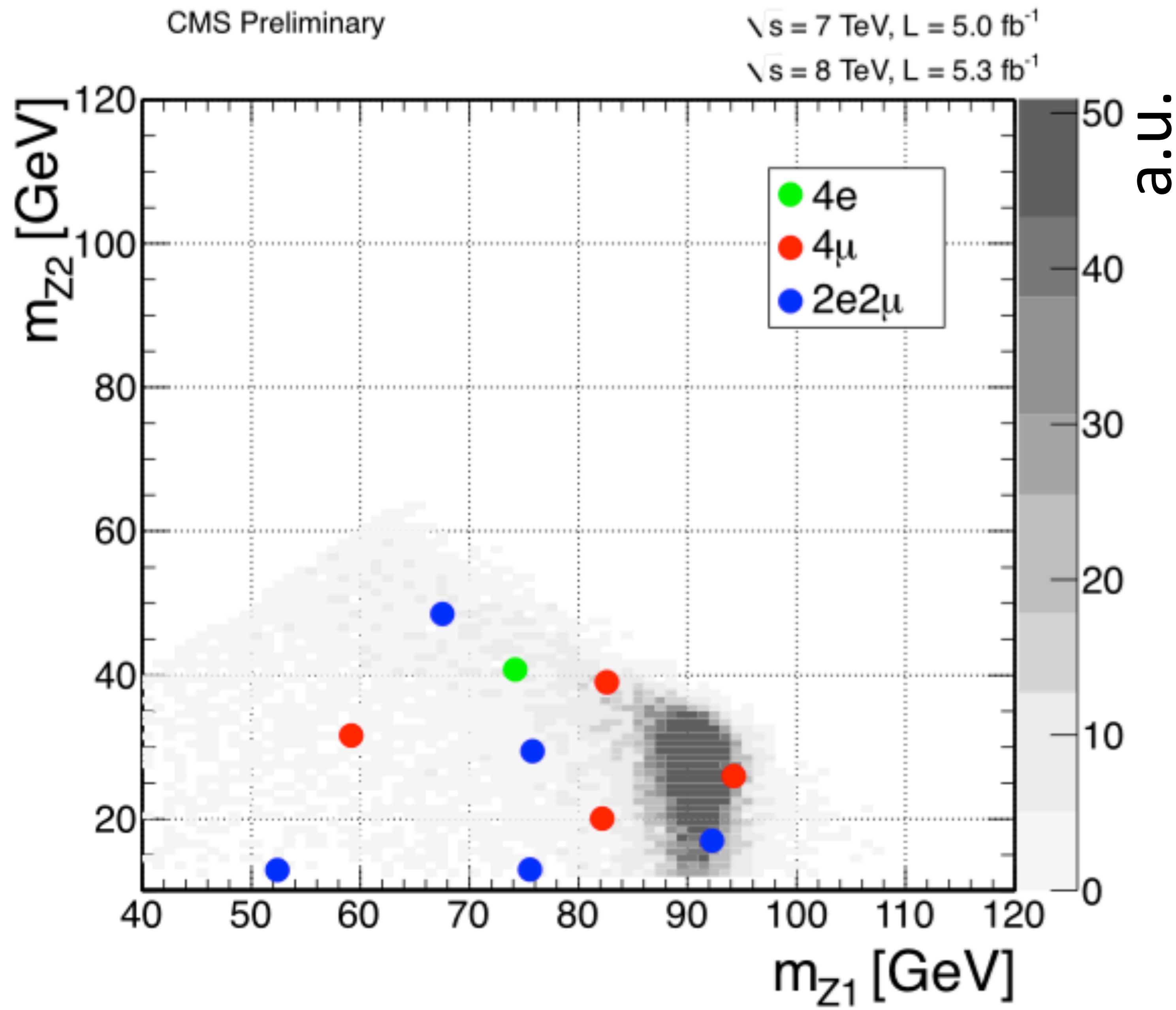


Two-lepton invariant mass plots

121< m4l <131 GeV

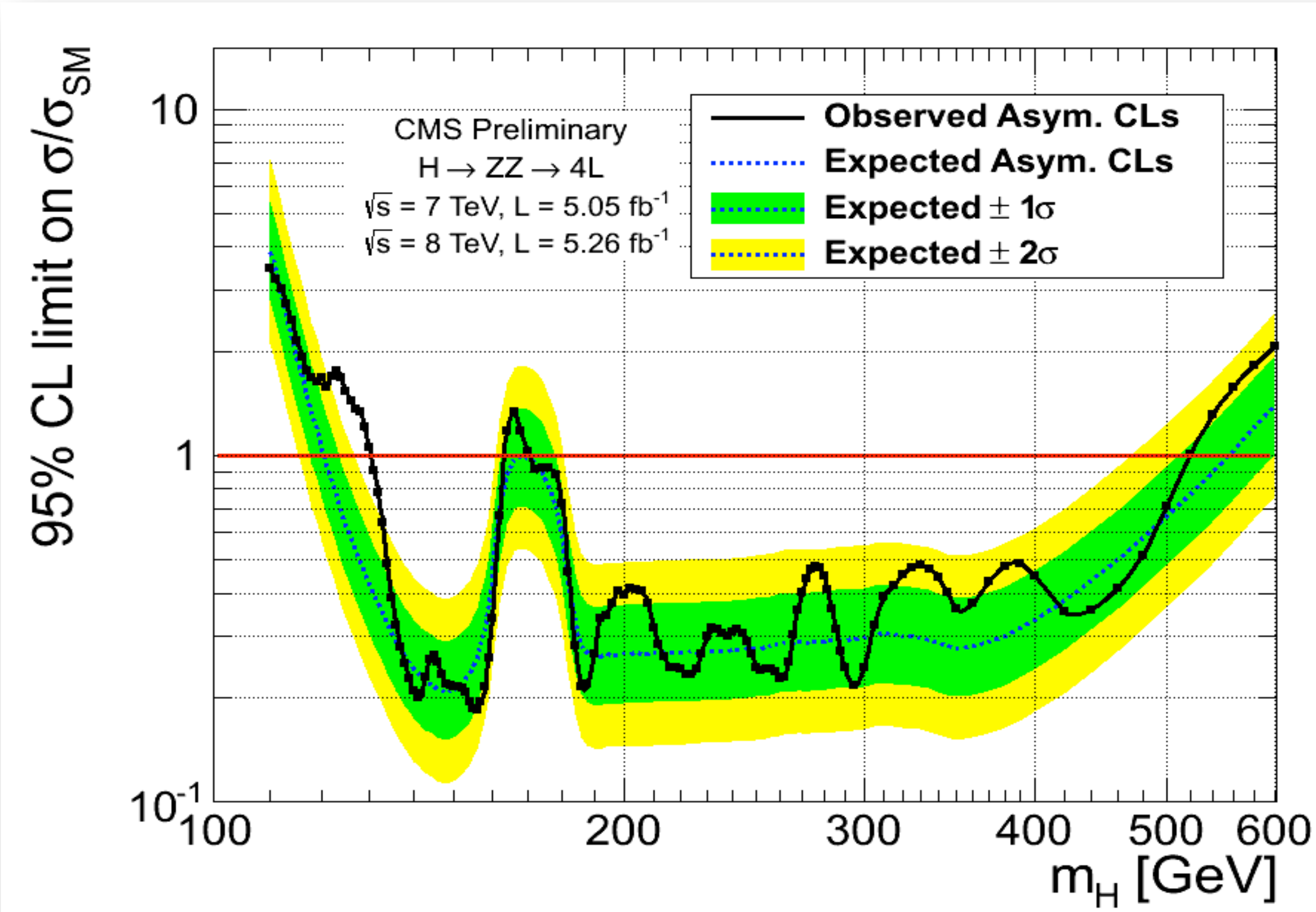


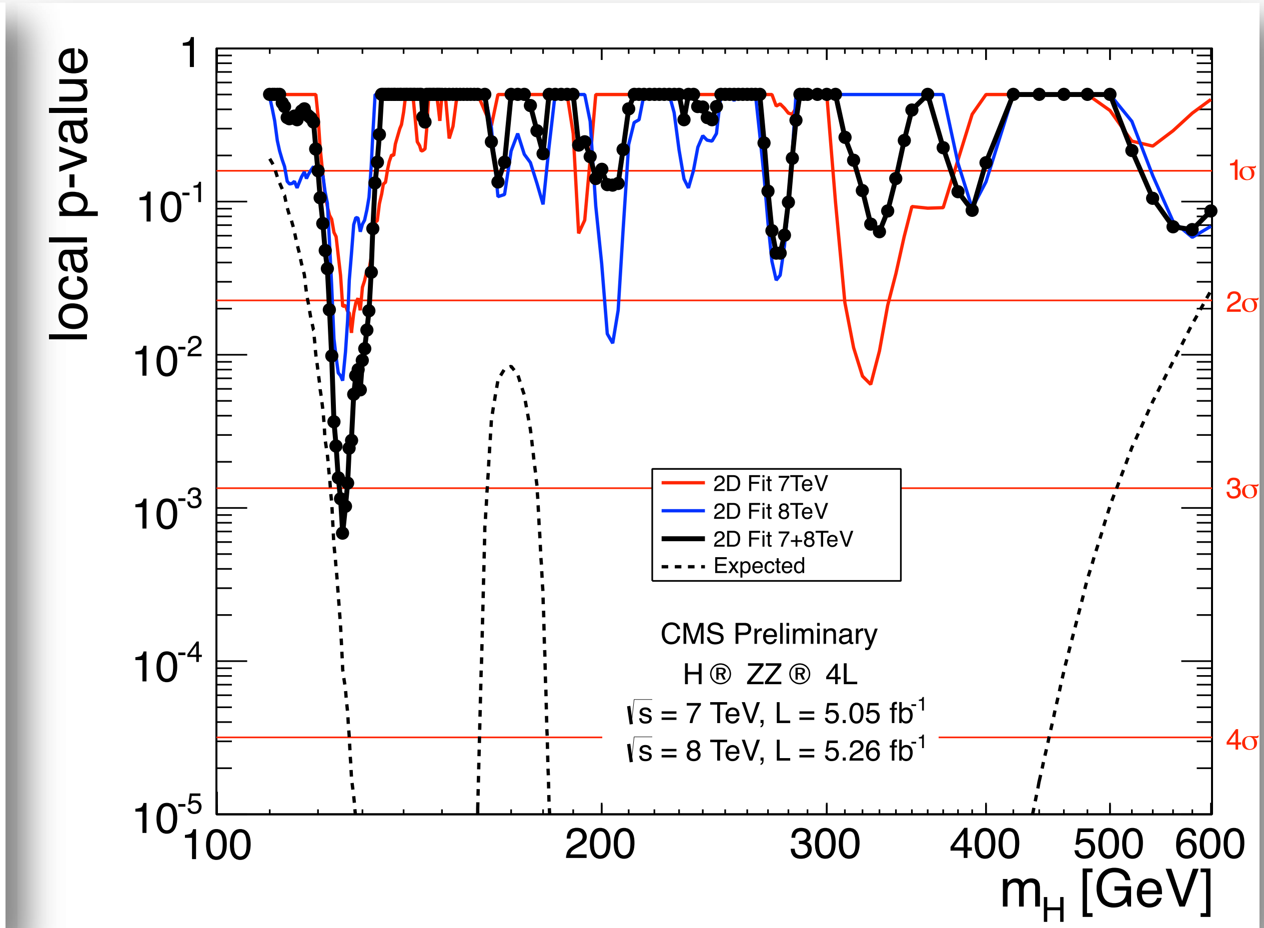




Grey – is simulation (expectation) for Higgs (126 GeV)

Limits and p-values

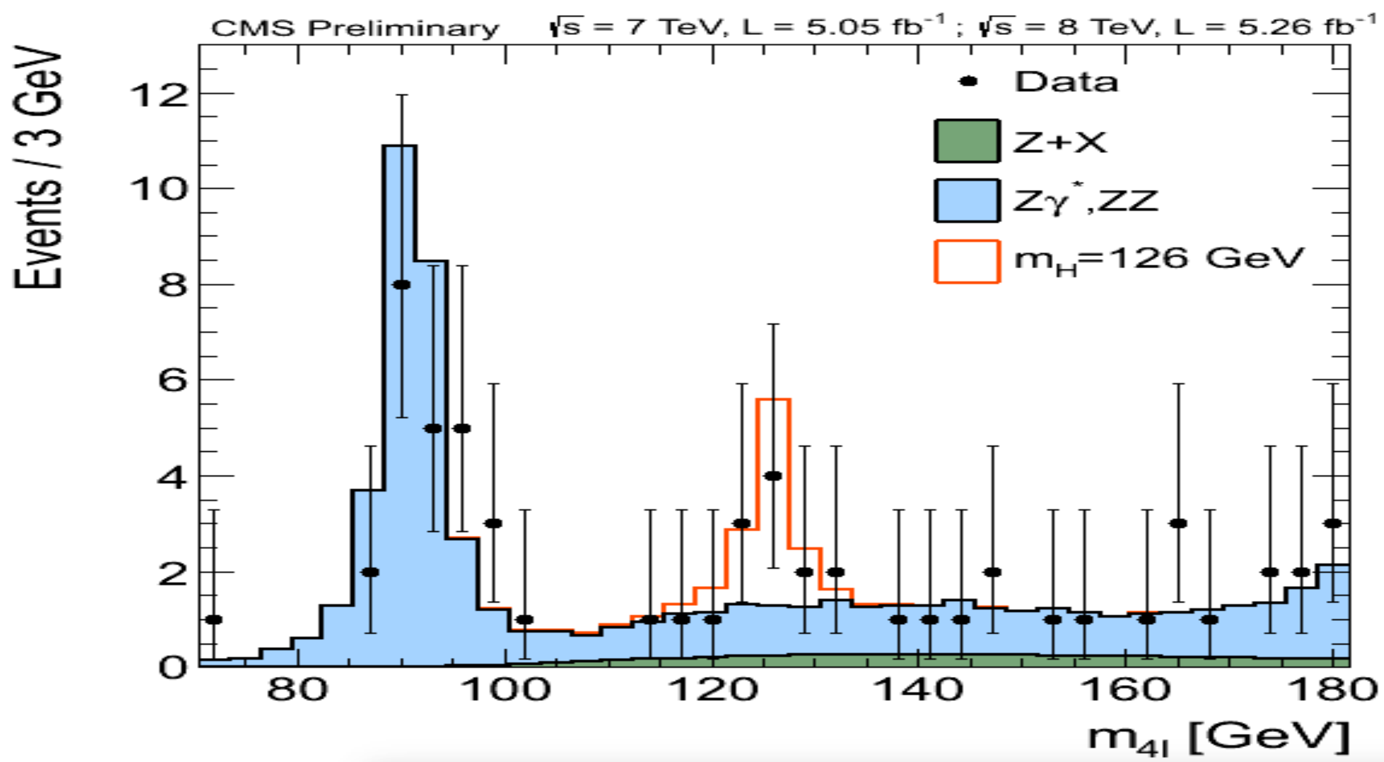


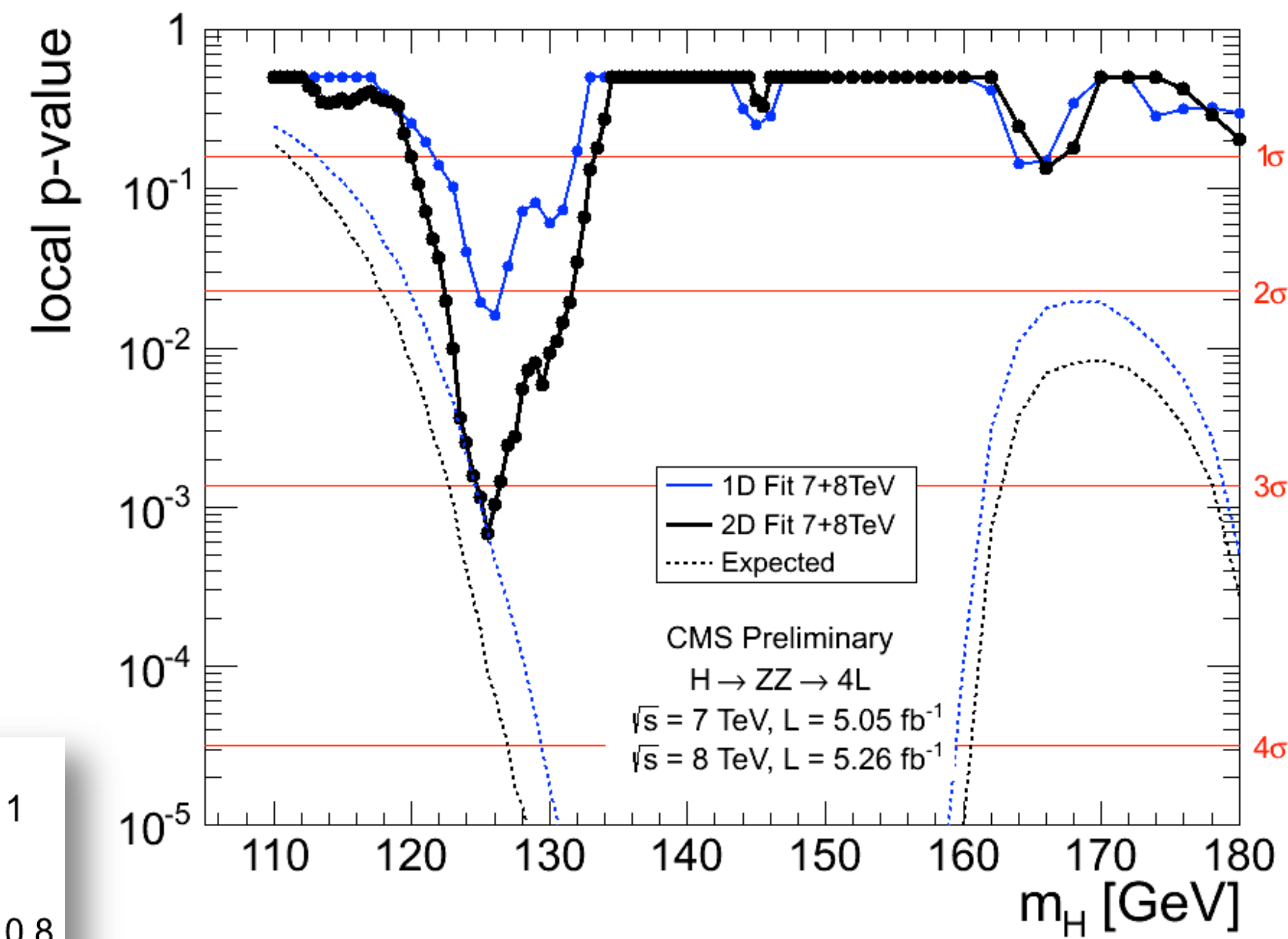


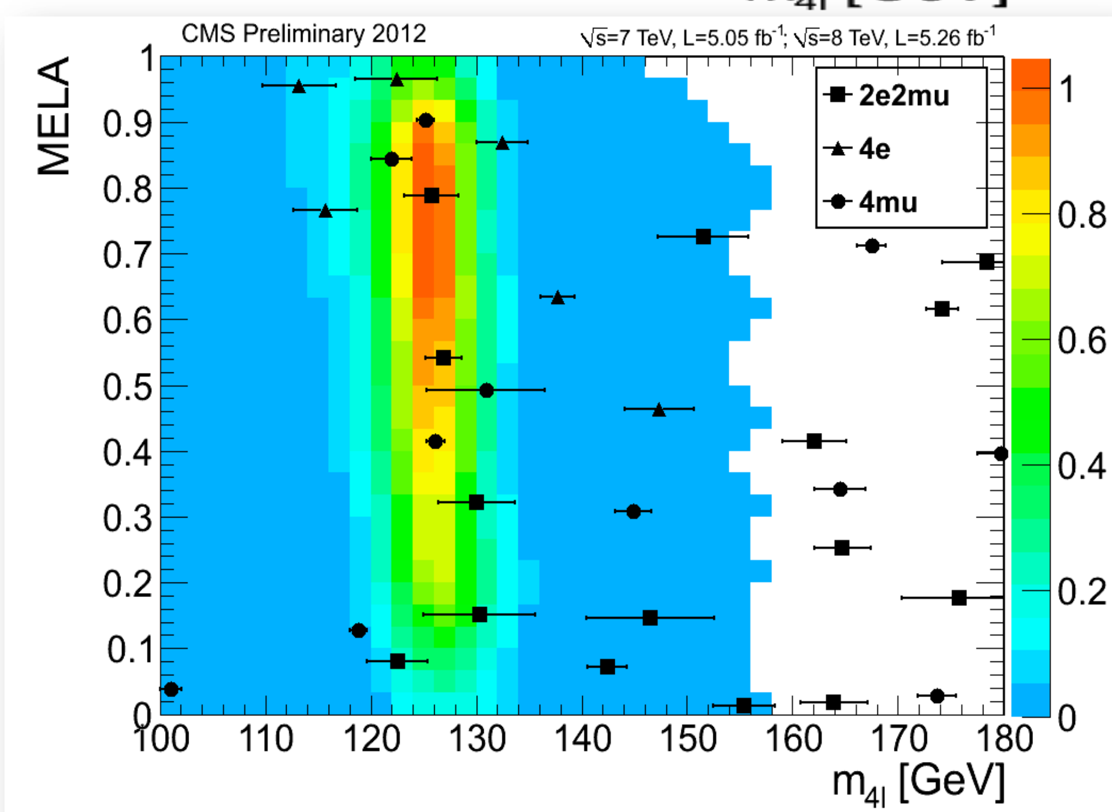
Expected exclusion at 95% CL :
121-550 GeV
Observed exclusion at 95% CL :
131-162 GeV and 172-530 GeV

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

Observed local excess of events







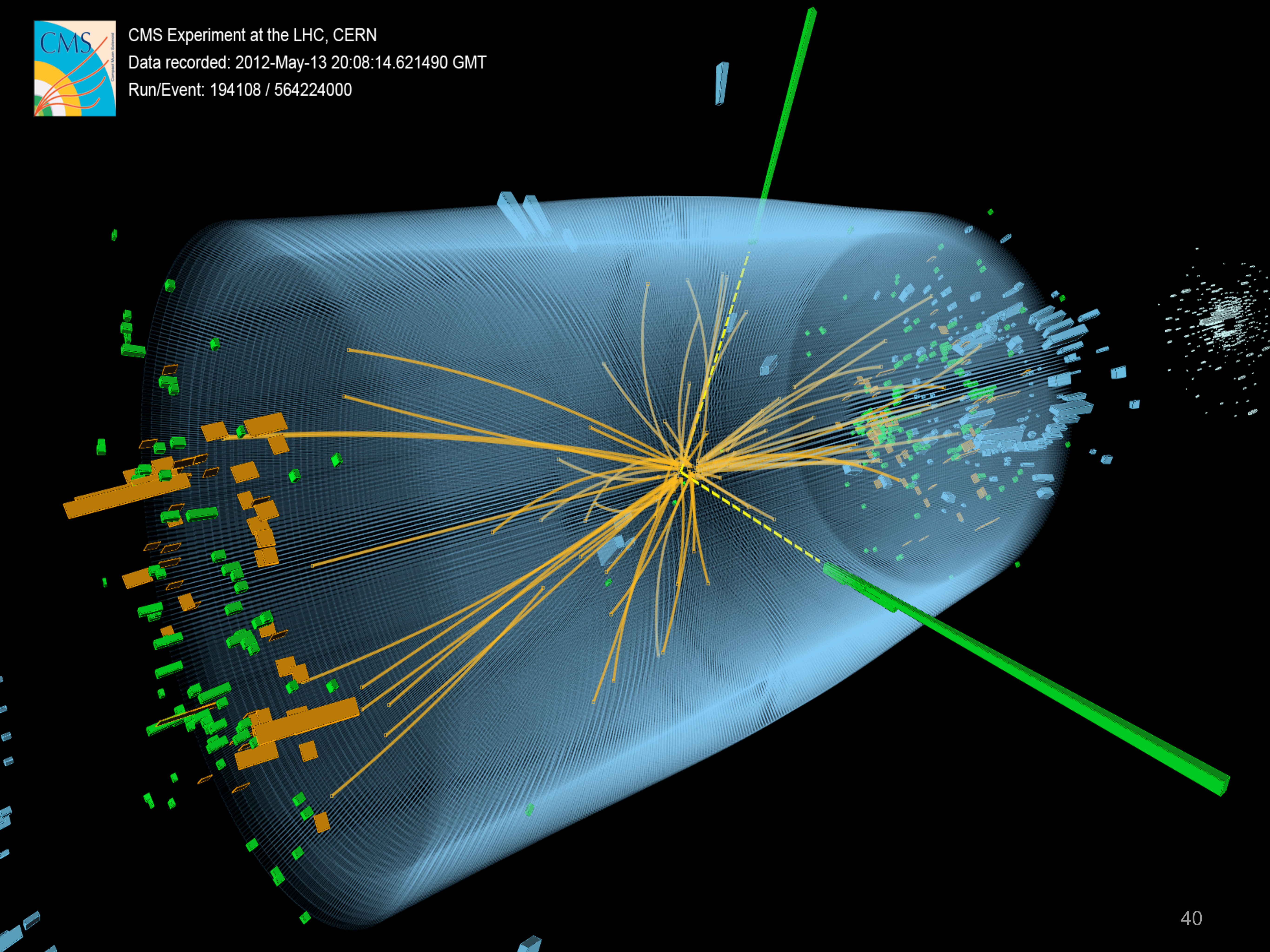
Expected significance at 125.5 GeV :

3.8 σ

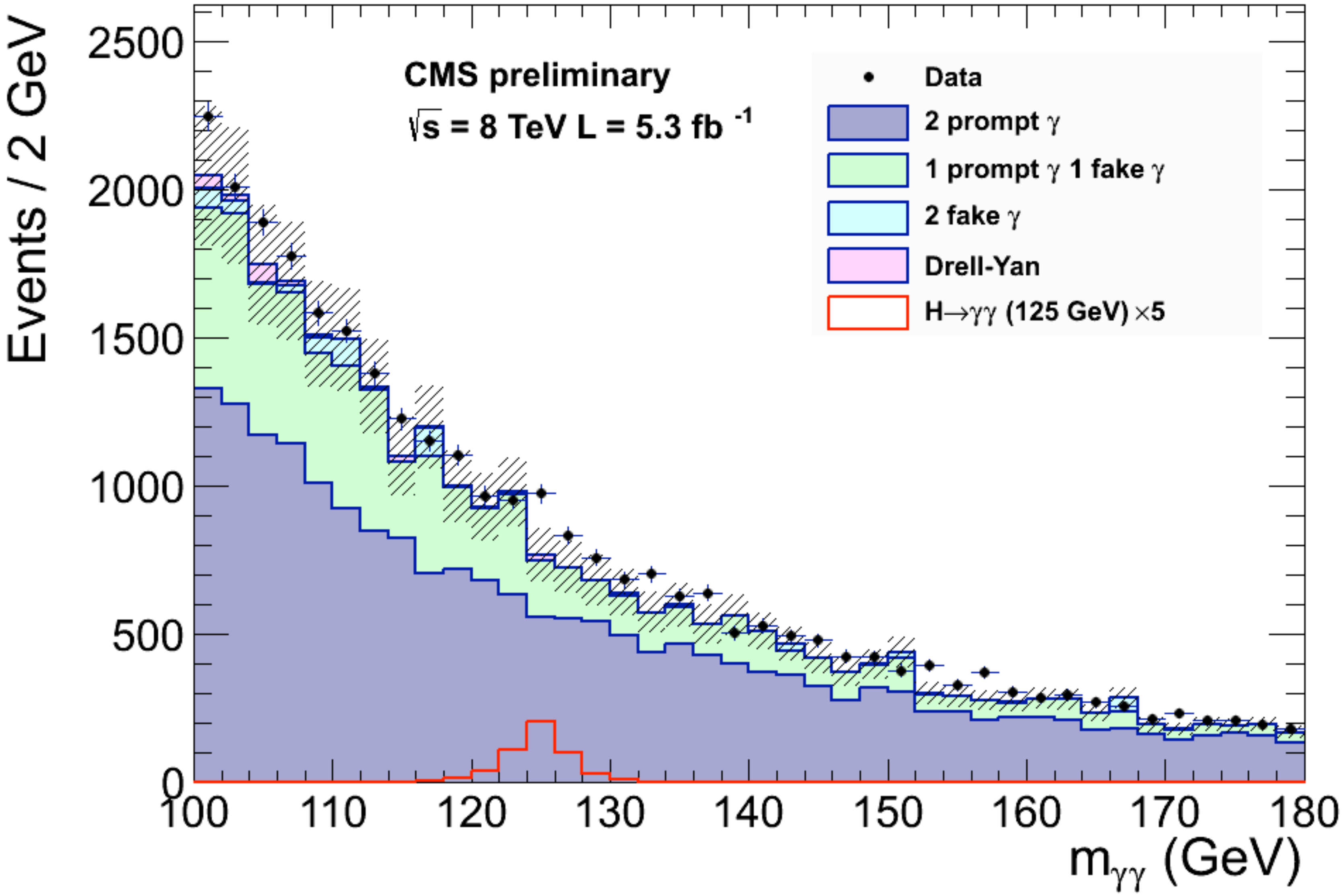
Observed significance at 125.5 GeV:

3.2 σ

$$H \to \gamma\gamma$$


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

Search for a di-photon mass peak

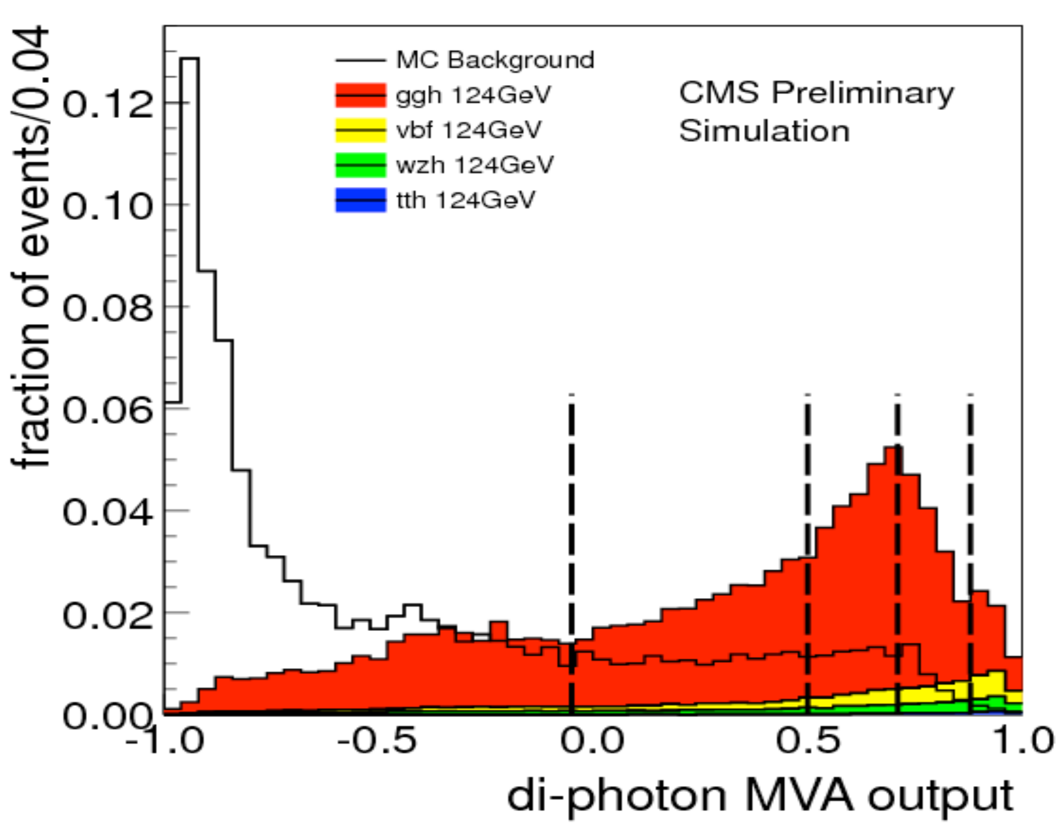


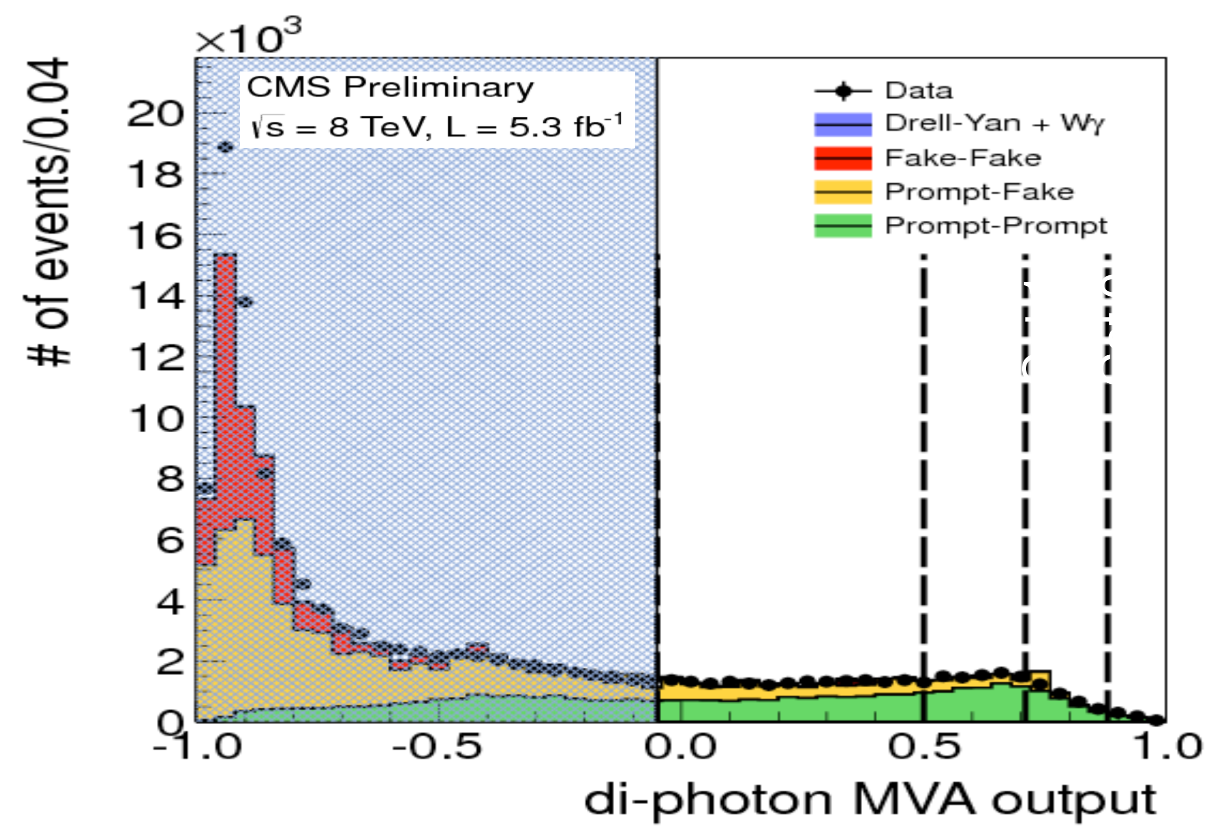
- Blind analysis in 2012
- Re-reco 2011 data into unchanged 2011 analysis
- Background MC only used for analysis optimization,
- Z->ee also to measure photon efficiencies and resolution with data

- 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

Diphoton Multivariate Analysis

- 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 bkg. discrimination (aside from $m_{\gamma\gamma}$ itself) into a single di-photon MVA output to first order independent of $m_{\gamma\gamma}$)



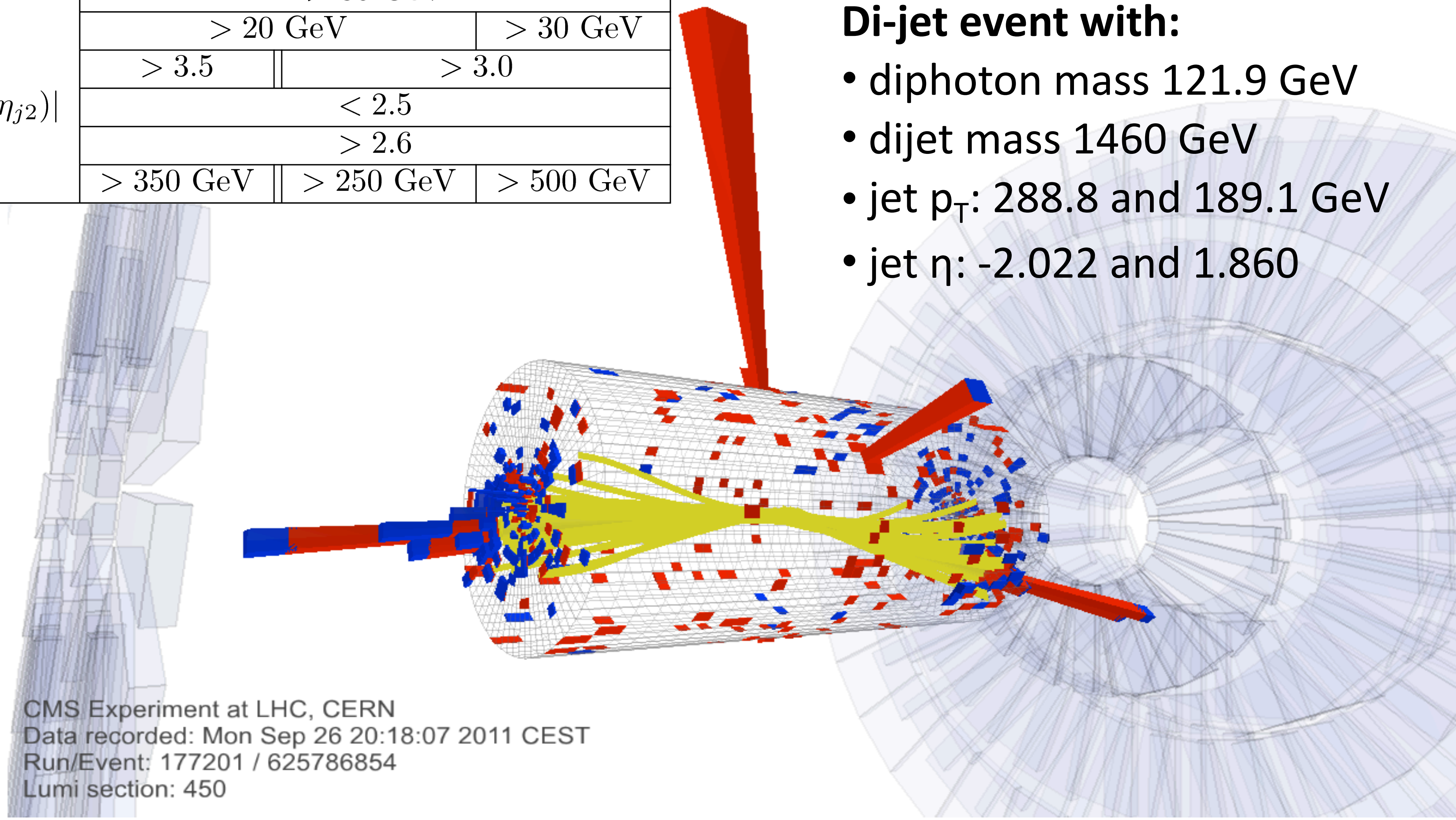


Di-jet tagging

Variable	2011	2012 Loose	2012 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

Di-jet event with:

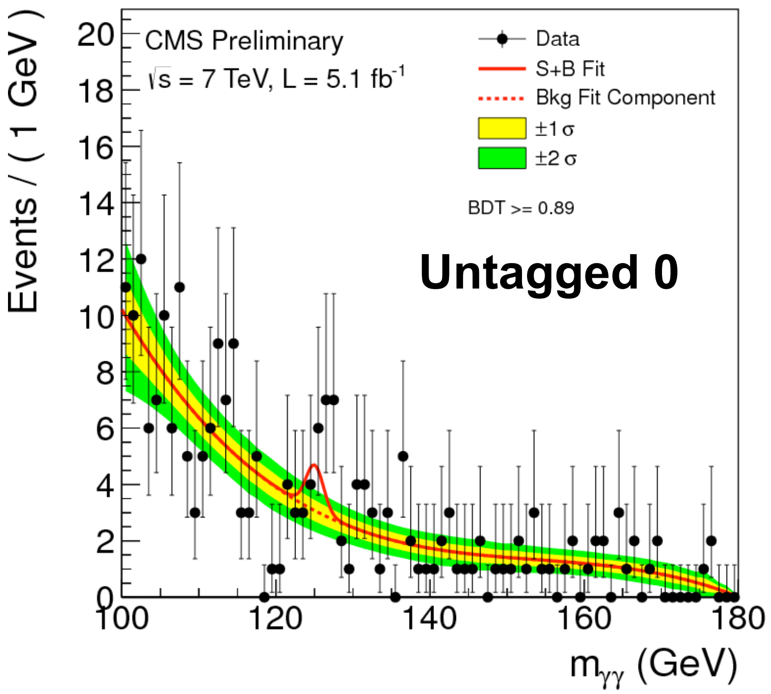
- diphoton mass 121.9 GeV
- dijet mass 1460 GeV
- jet p_T: 288.8 and 189.1 GeV
- jet η: -2.022 and 1.860

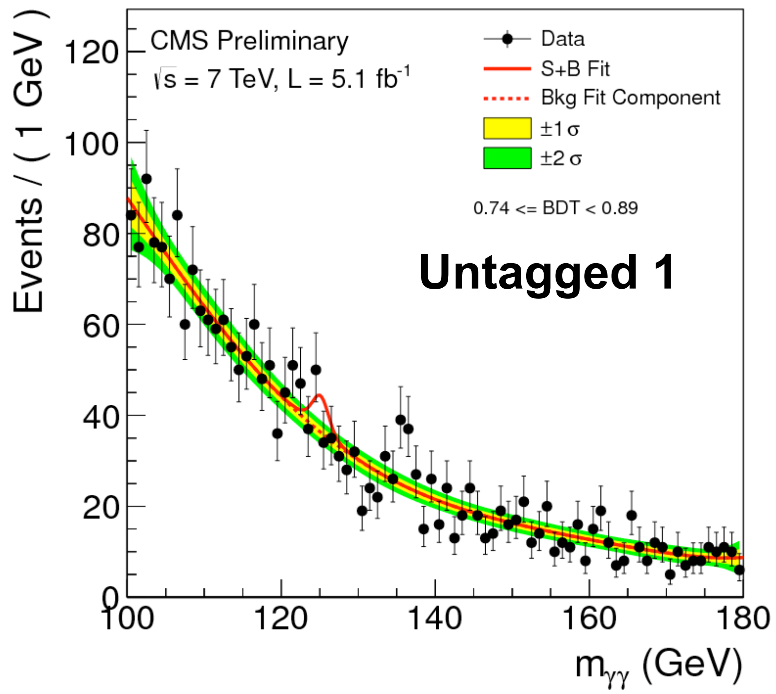


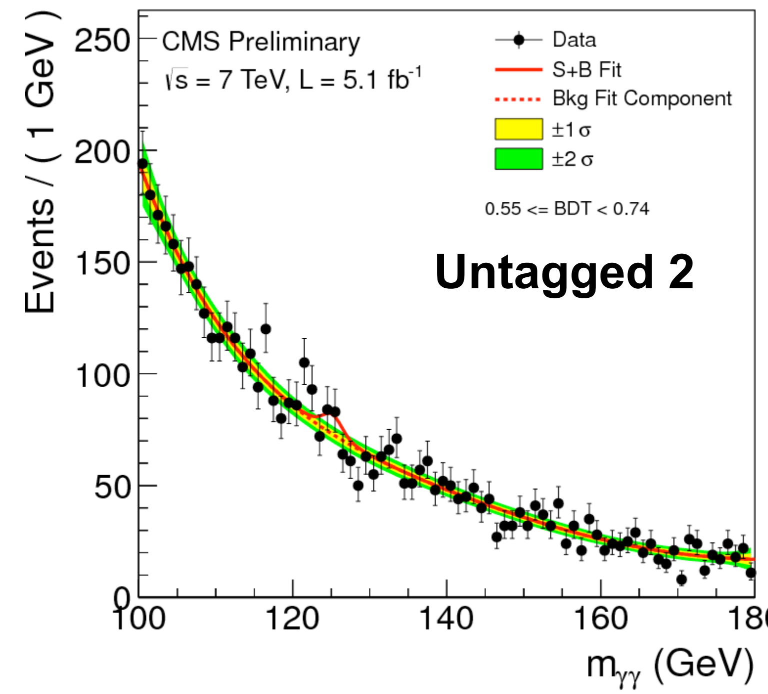
Category Performance

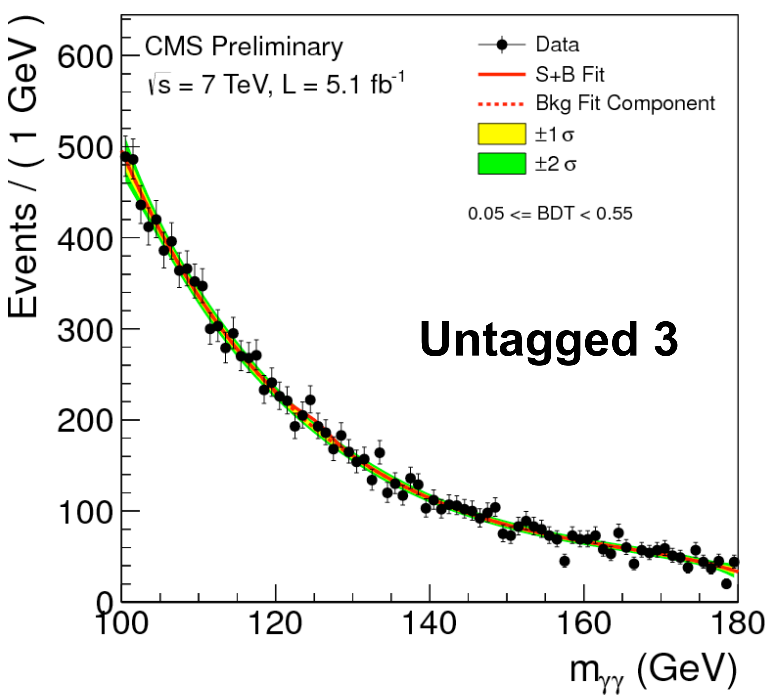
Expected signal and estimated background									
Event classes		SM Higgs boson expected signal (m_H=125 GeV)							Background $m_{\gamma\gamma} = 125$ GeV (ev./GeV)
		Total	ggH	VBF	VH	ttH	σ_{eff} (GeV)	FWHM/2.35 (GeV)	
7 TeV 5.1 fb^{-1}	Untagged 0	3.2	61%	17%	19%	3%	1.21	1.14	3.3 $\pm$ 0.4
	Untagged 1	16.3	88%	6%	6%	1%	1.26	1.08	37.5 $\pm$ 1.3
	Untagged 2	21.5	91%	4%	4%	–	1.59	1.32	74.8 $\pm$ 1.9
	Untagged 3	32.8	91%	4%	4%	–	2.47	2.07	193.6 $\pm$ 3.0
	Dijet tag	2.9	27%	73%	1%	–	1.73	1.37	1.7 $\pm$ 0.2
8 TeV 5.3 fb^{-1}	Untagged 0	6.1	68%	12%	16%	4%	1.38	1.23	7.4 $\pm$ 0.6
	Untagged 1	21.0	88%	6%	6%	1%	1.53	1.31	54.7 $\pm$ 1.5
	Untagged 2	30.2	92%	4%	3%	–	1.94	1.55	115.2 $\pm$ 2.3
	Untagged 3	40.0	92%	4%	4%	–	2.86	2.35	256.5 $\pm$ 3.4
	Dijet tight	2.6	23%	77%	–	–	2.06	1.57	1.3 $\pm$ 0.2
	Dijet loose	3.0	53%	45%	2%	–	1.95	1.48	3.7 $\pm$ 0.4

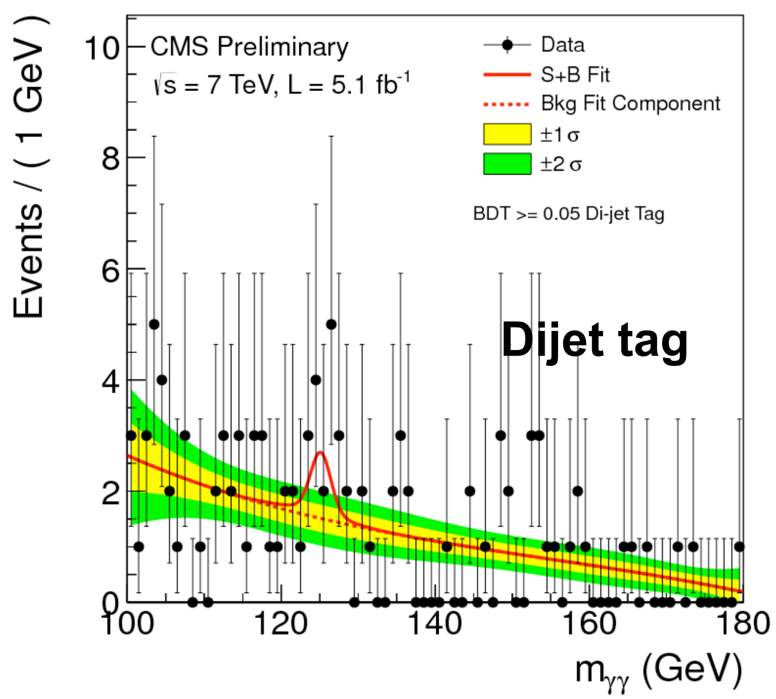
7 TeV Mass Distribution in Categories





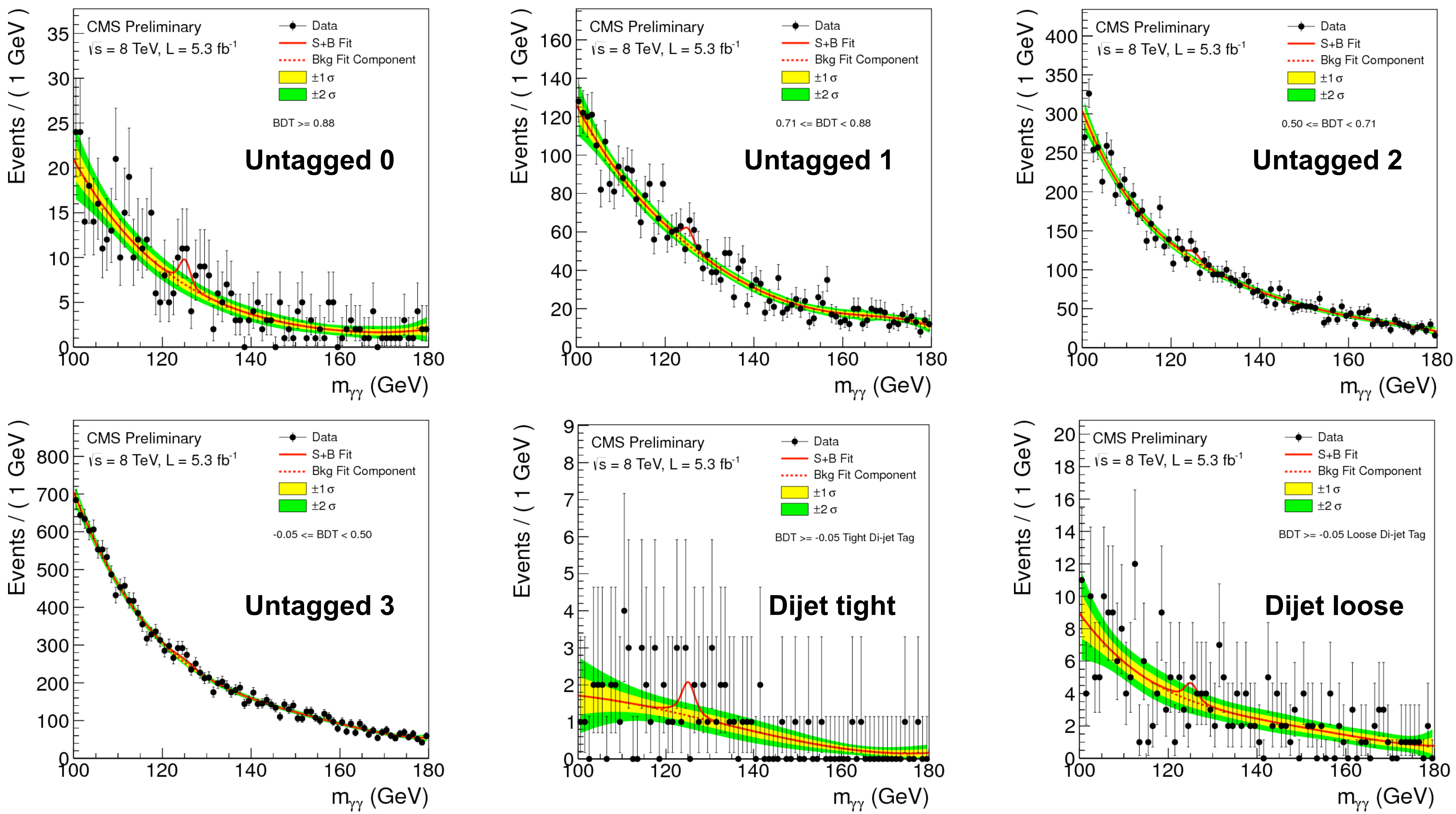




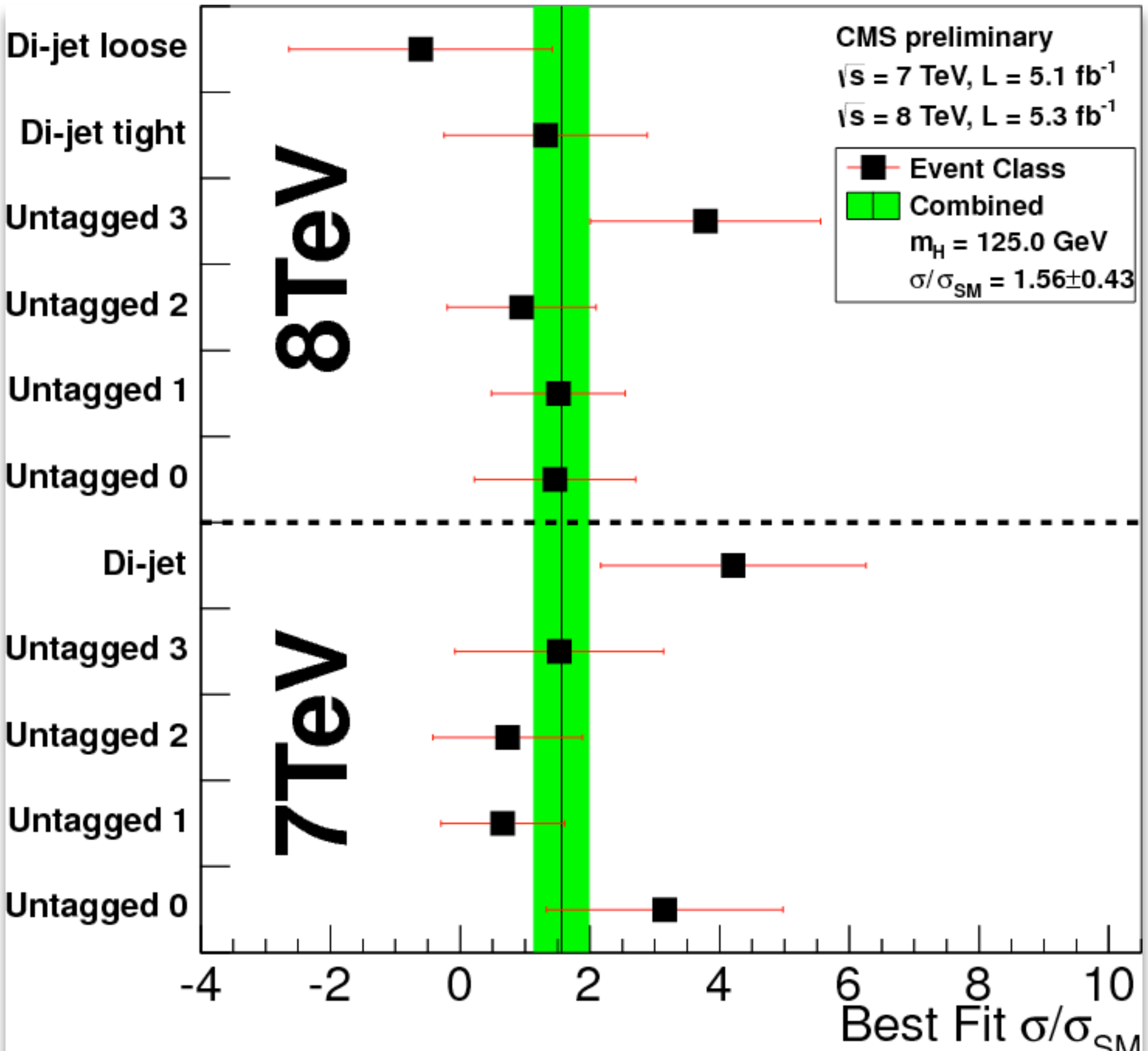


- Background model is entirely from data.
- Fit to mass distribution in each category with polynomial functions (3rd to 5th degree)
  - keep bias below 20% of fit error.
  - causes some loss of performance due to number of parameters in fit function.

8 TeV Mass Distribution in Categories

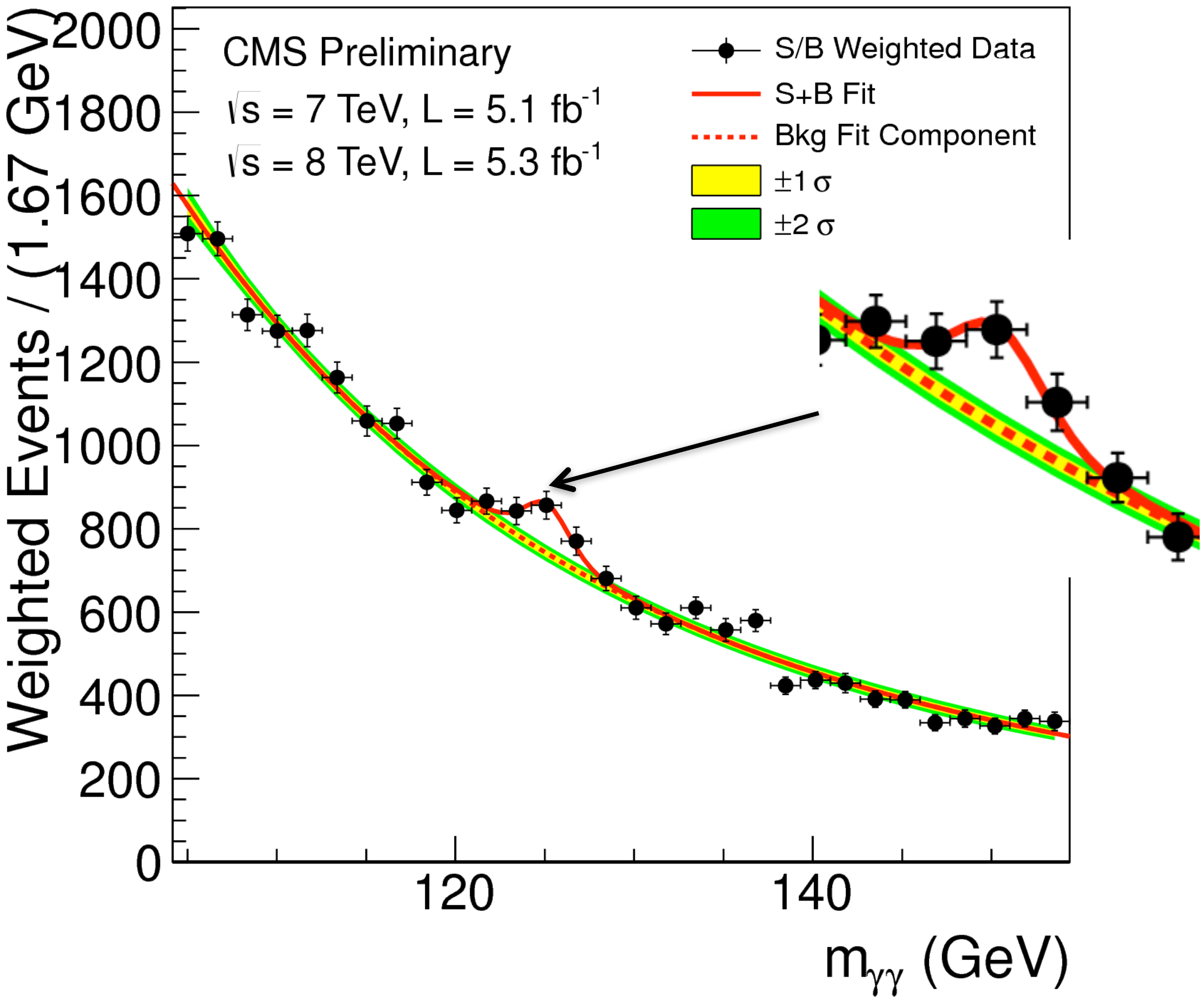


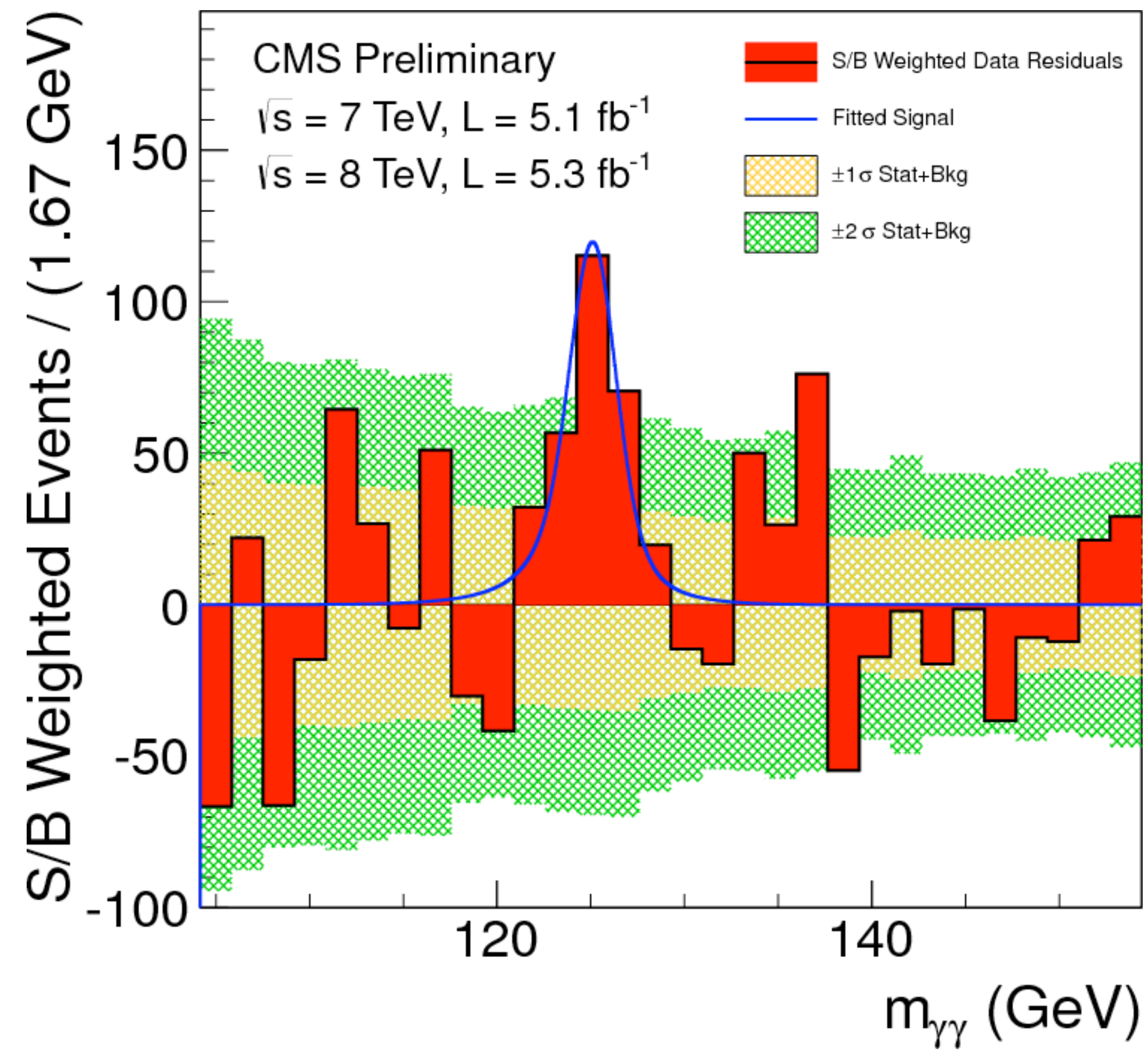
Fit Results in Categories



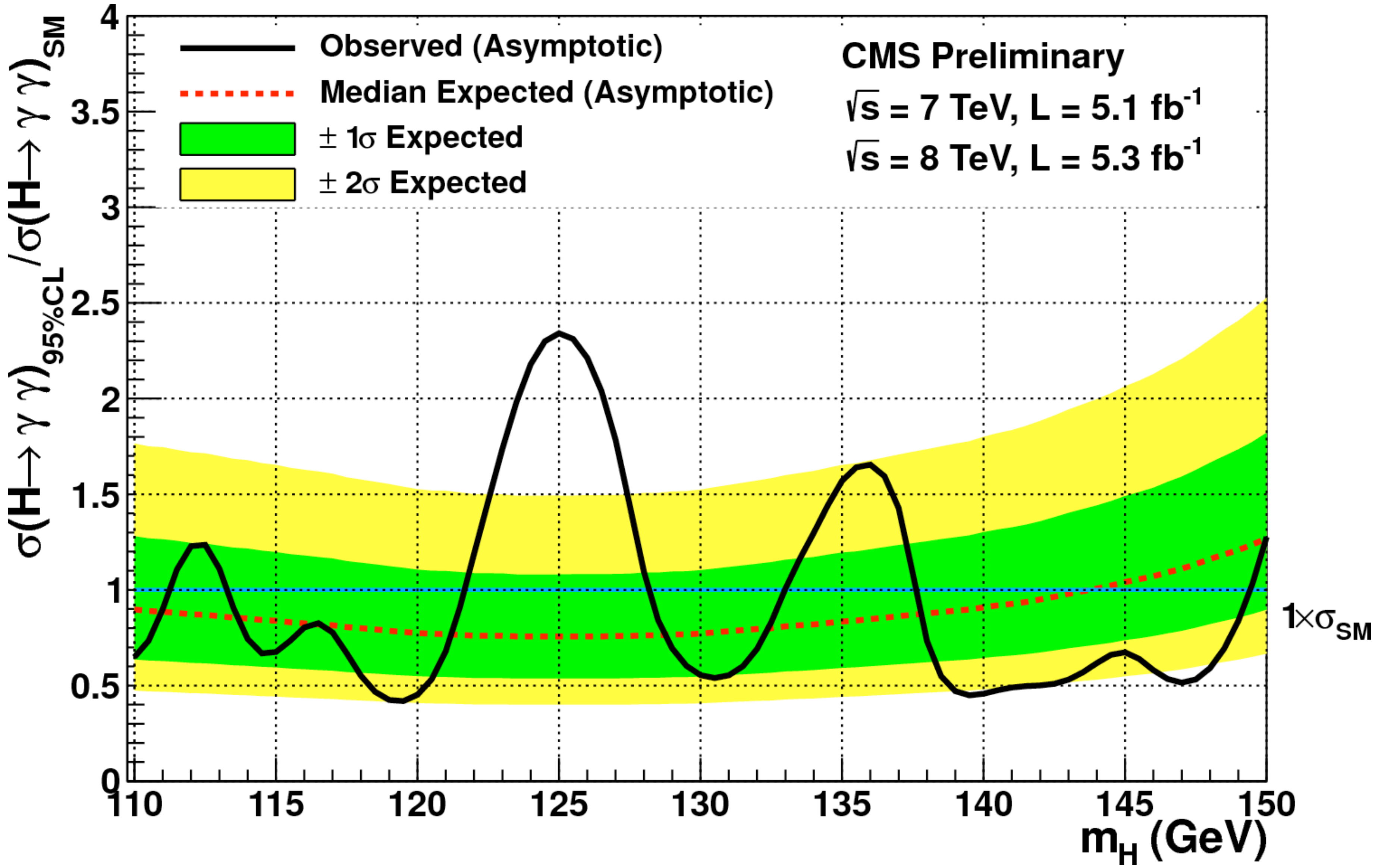
S/B Weighted Mass Distribution

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



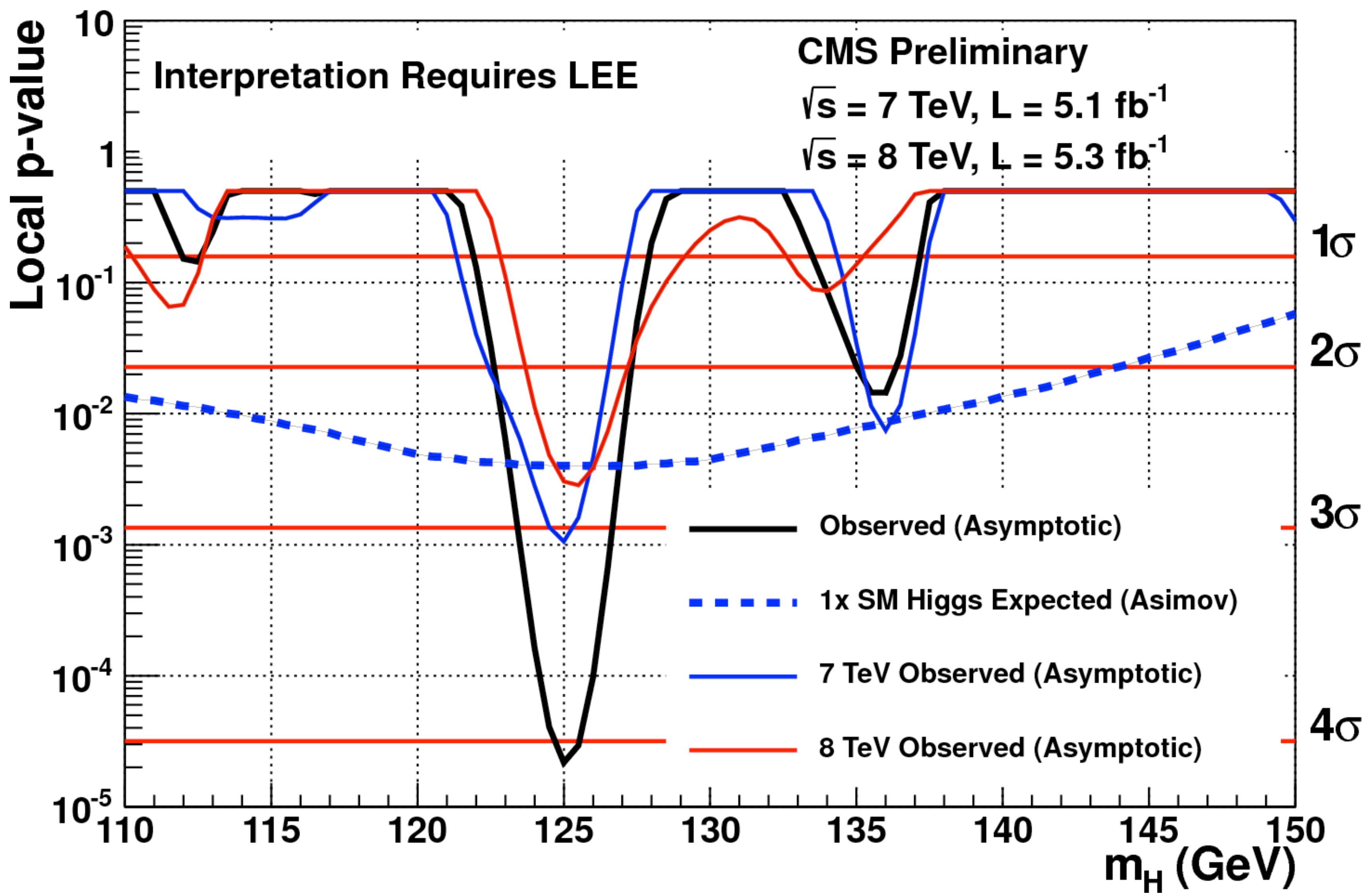


95% CL Exclusion for SM Higgs



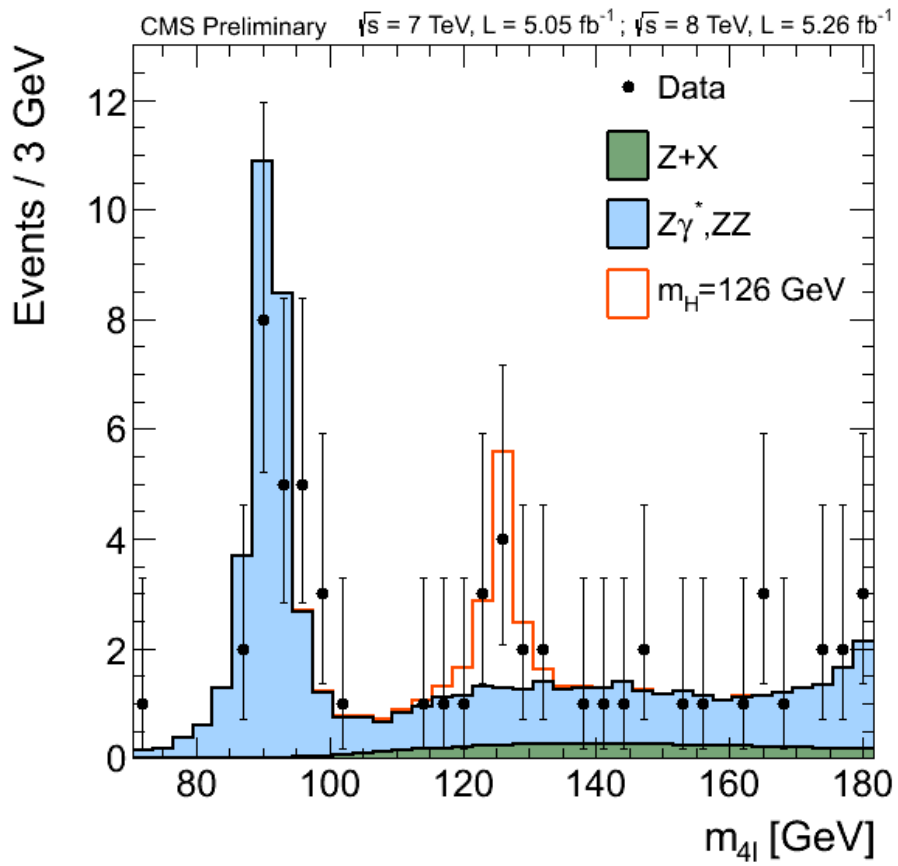
- Expected 95% CL exclusion 0.76 times SM at 125 GeV
- Large range with expected excusion below σ_{SM}

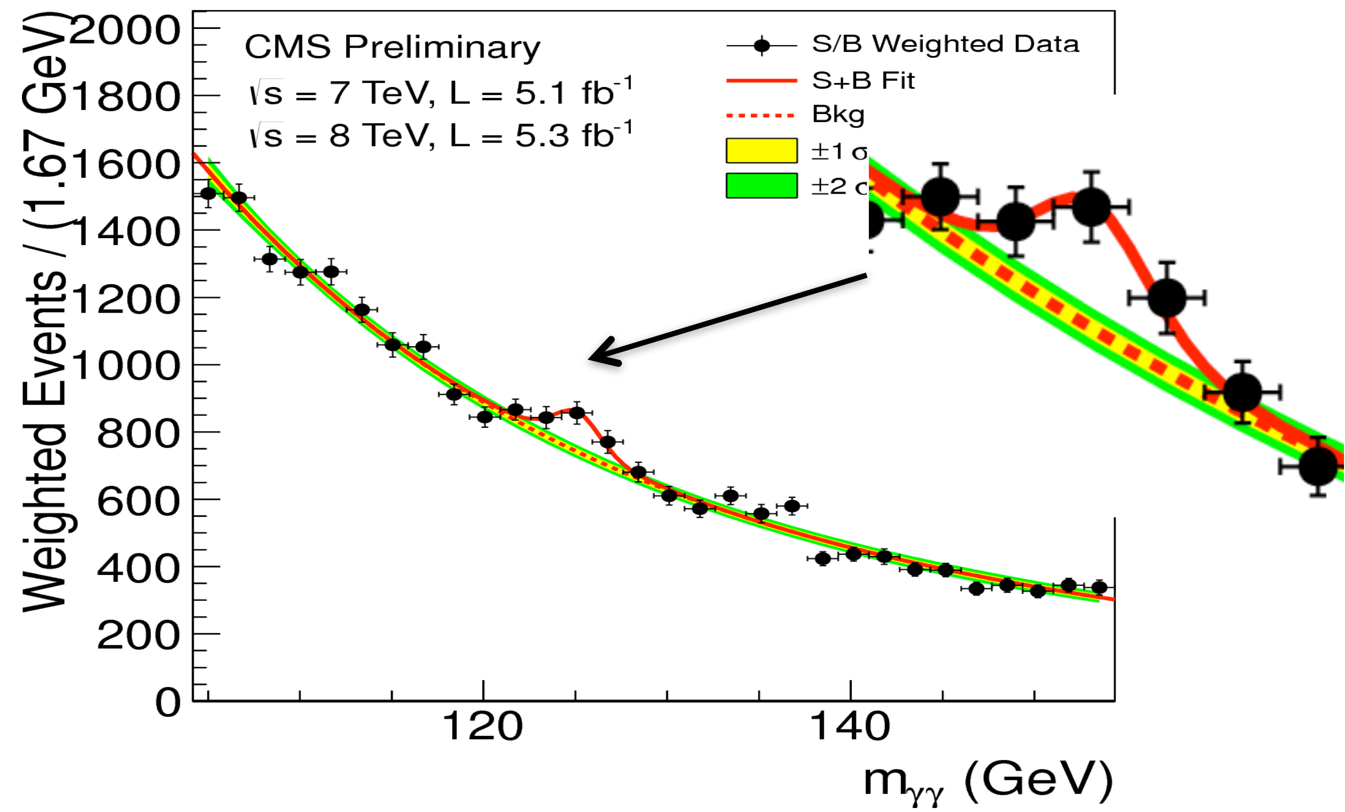
P-Values

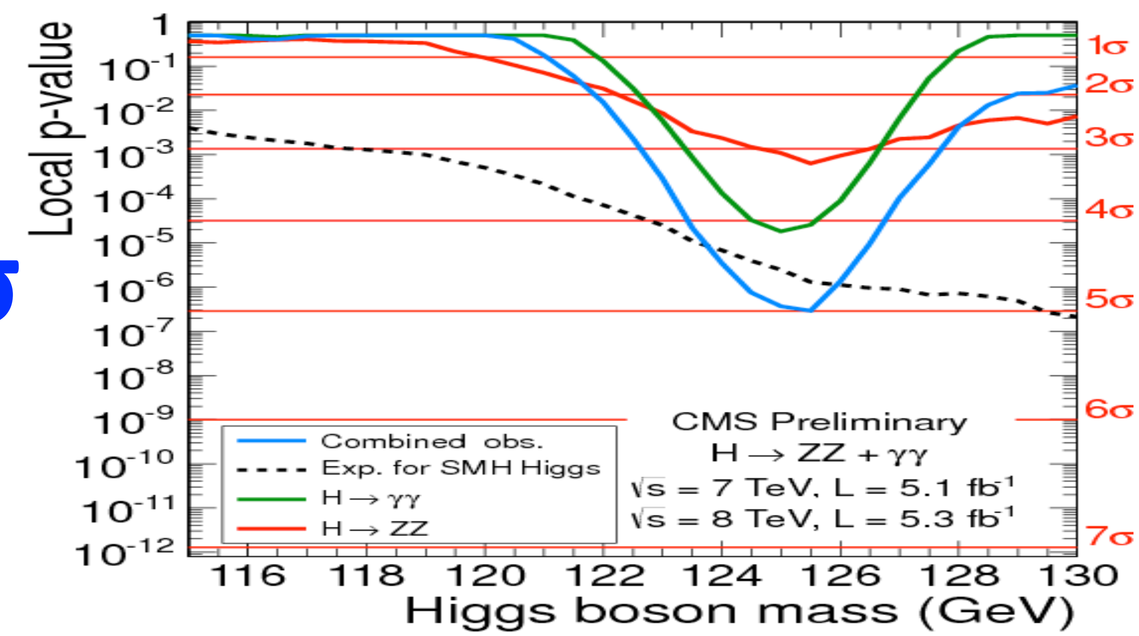


- Minimum local p-value at 125 GeV with significance of 4.1 σ

Two channels ZZ and 2gamma combined

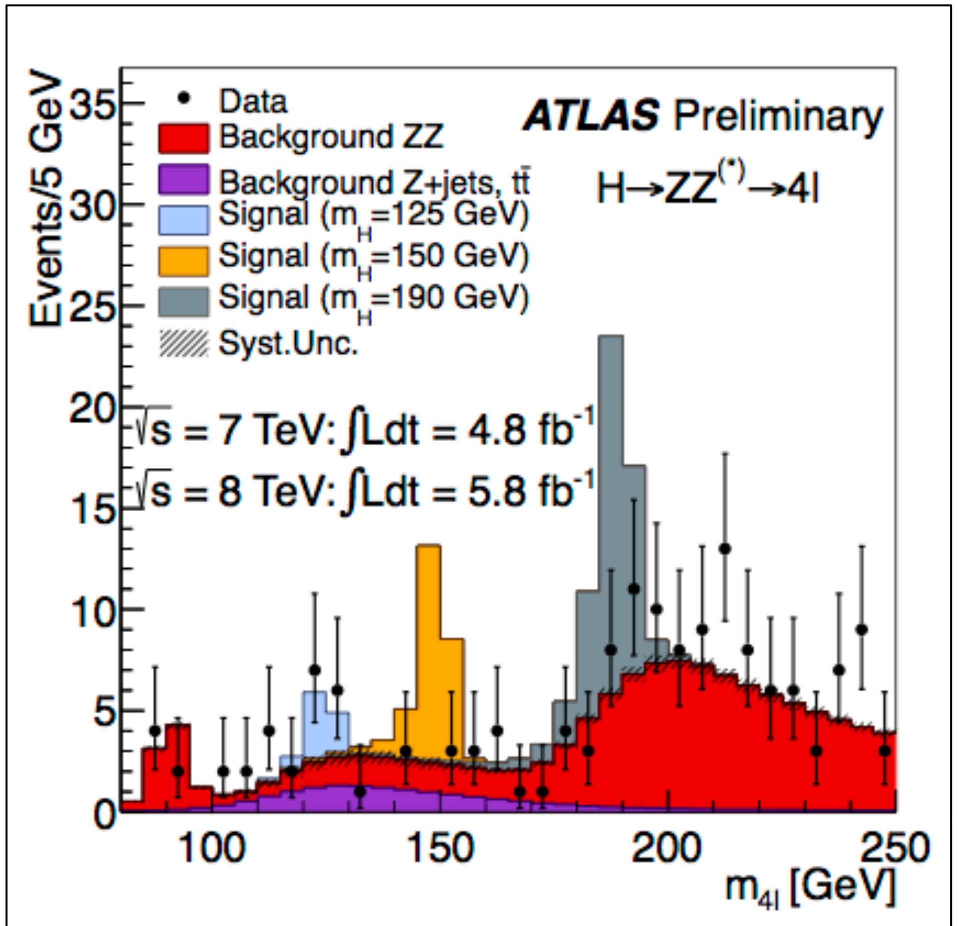


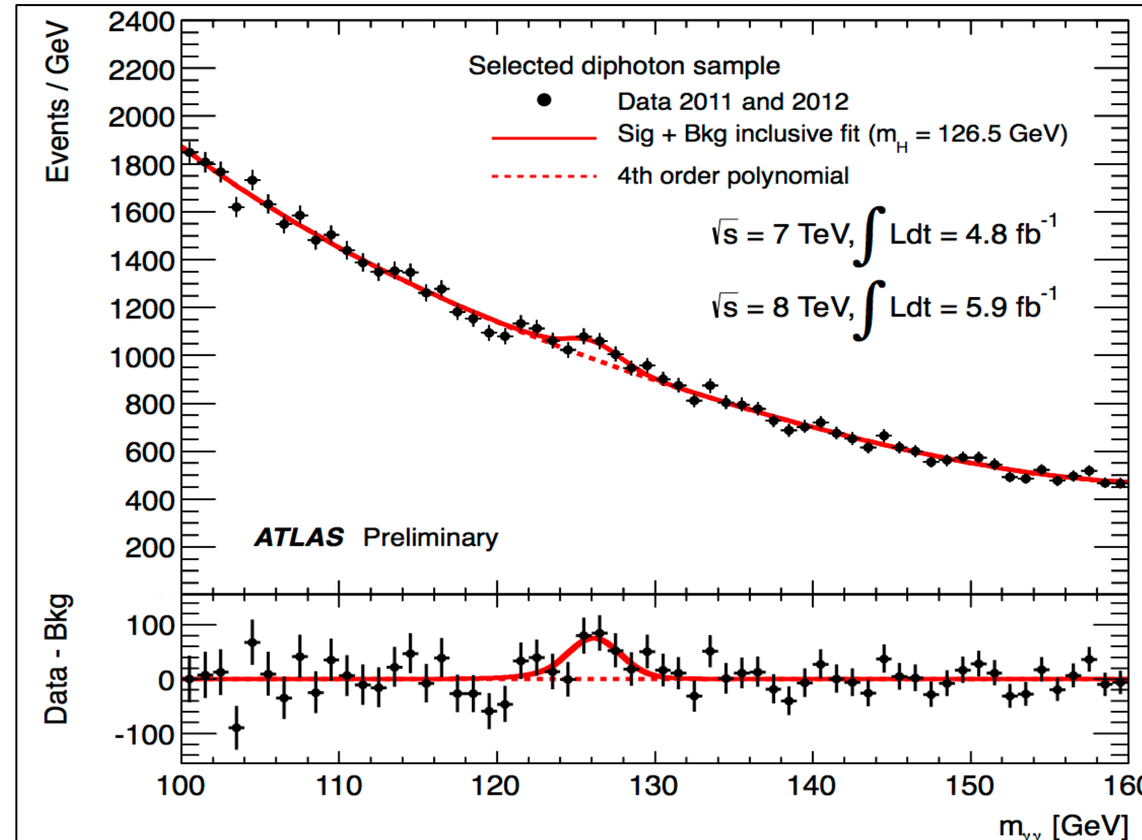


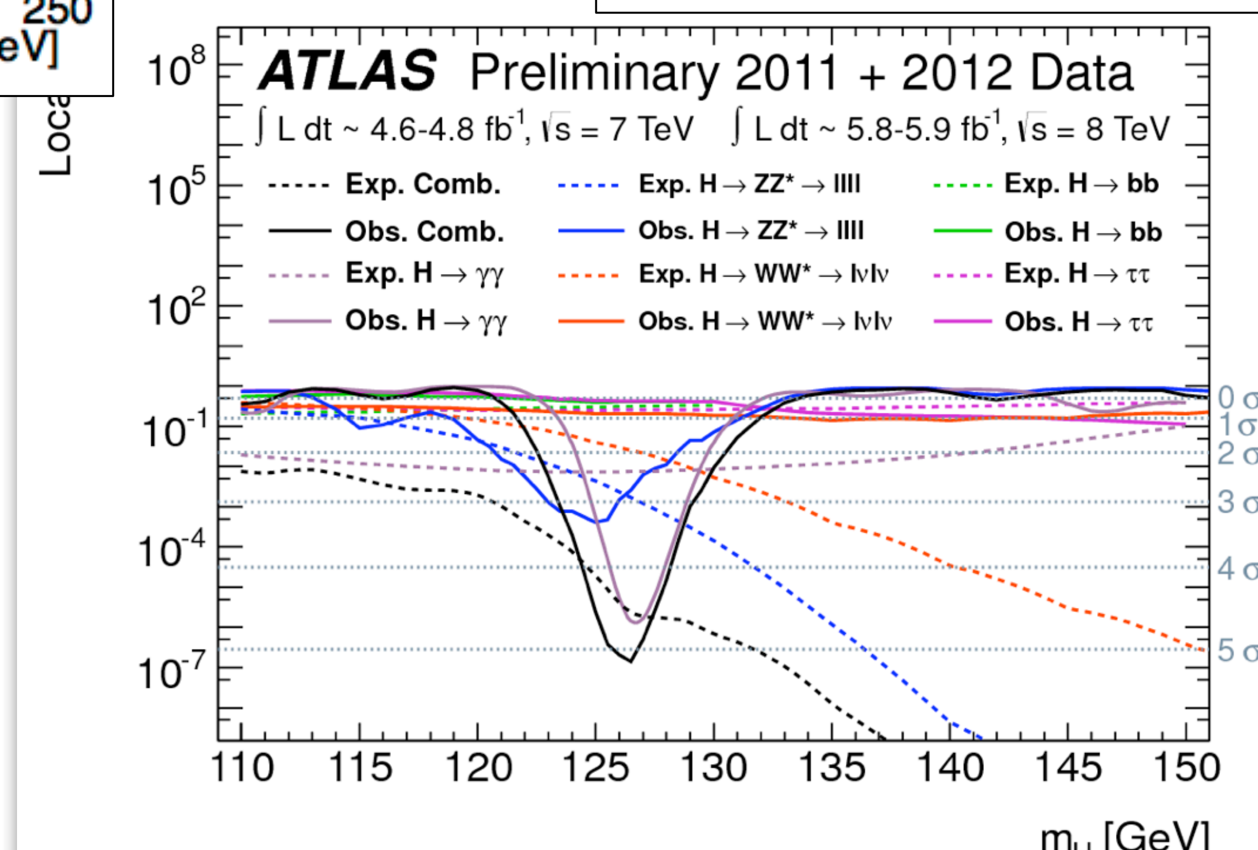


- **Comb. significance: 5.0 σ**
- **Expected 4.7 σ**

ATLAS has it too: talk by Ian Hinchliffe







"All the News That's Fit to Print"

The New York Times

Late Edition

Today, sunny to partly cloudy, rather hot, high 92. **Tonight,** mostly clear, low 72. **Tomorrow,** mostly sunny, hot and humid, high 90. Weather map appears on Page B16.

VOL. CLXI . . No. 55,823 — © 2012 The New York Times — NEW YORK, THURSDAY, JULY 5, 2012 — $2.50

Physicists Find Elusive Particle Seen as Key to Universe

Scientists in Geneva on Wednesday applauded the discovery of a subatomic particle that looks like the Higgs boson.

Oil Backed Up, Iranians Put It On Idled Ships

Subterfuge at Tankers as Embargo Tightens

By THOMAS ERDBRINK and CLIFFORD KRAUSS

BANDAR ABBAS, Iran — The hulking tanker Neptune was floating aimlessly this week in the warm waters of the Persian Gulf, a fresh coat of black paint barely concealing its true identity as an Iranian ship loaded with hundreds of thousands of barrels of oil that no one is willing to buy.

The ship's real name was Iran Astaneh, and it was part of a fleet of about 65 Iranian tankers serving as floating storage facilities for Iranian oil, each one given a nautical makeover to conceal its origin and make a buyer easier to find. The Neptune had been floating there for a month, and local fishermen said there were two even larger tankers anchored nearby.

Iran, faced with increasingly stringent economic sanctions imposed by the international community to force it to abandon any ambitions to develop nuclear weapons, has been reluctant to reduce its oil production, fearing that doing so could damage its wells. But Iran has insufficient space to store the crude it cannot sell. So while it furiously works to build storage capacity on shore, it has turned to mothballing at sea.

"We have never seen so many just waiting around," said Ros-

ROMNEY NOW SAYS HEALTH MANDATE BY OBAMA IS A TAX

SHIFT RENEWS CRITICISM

Move Aligns Him With Conservative Voices Within His Party

By JEREMY W. PETERS

WOLFEBORO, N.H. — Mitt Romney declared on Wednesday that President Obama's health care mandate was in fact a tax, shifting his campaign's characterization of the law and aligning himself with the conservative voices in his party.

Mr. Romney's remarks, made in a hastily arranged interview with CBS News on a national holiday, prompted renewed criticisms that he was willing to adjust his views for political expediency. Two days earlier, his chief spokesman and senior strategist had said that Mr. Romney did not believe the mandate should be called a tax.

Mr. Romney was already in the uncomfortable position of standing at odds with the dominant Republican Party message on health care: that President Obama was imposing a burdensome new tax on the middle class by requiring health insurance. His latest statement, while carrying the short-term risk of allowing his opponent to brand him a flip-

Date Night at the Zoo, if Rare Species Play Along

By LESLIE KAUFMAN

THE ANIMAL LIFEBOAT
Barriers to Breeding

FRONT ROYAL, Va. — After cautiously sniffing the grass, three male cheetahs at the animal-breeding center here suddenly began running in frenzied circles. It was a sign that a female cheetah that normally lives in the yard was in heat.

Then one of the males let out a

fore they mate. It turns out that familiarity can be a turnoff for cheetahs, too.

Finally, it was time to bring in the female. She seemed mystified by the male cheetah's eagerness and failed to assume a mating po-

thing but.

Eighty-three percent of those species in North American zoos are not meeting the targets set for maintaining their genetic diversity, the Association of Zoos and Aquariums reports. In the case of cheetahs, fewer than 20 percent of those in North American zoos have been able to reproduce.

Zoos must figure out how to

'I Think We Have It' Is Cheer of Day at Home of Search

By DENNIS OVERBYE

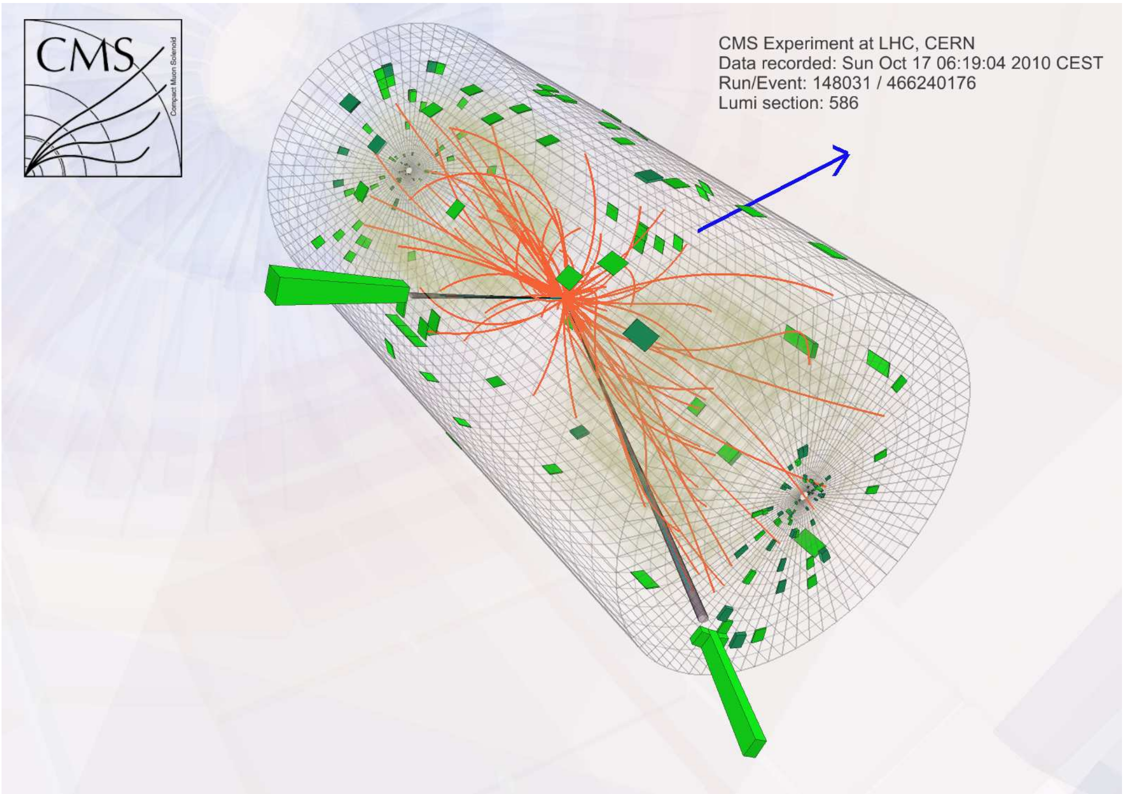
ASPEN, Colo. — Signaling a likely end to one of the longest, most expensive searches in the history of science, physicists said Wednesday that they had discovered a new subatomic particle

CMS Collaboration Party

Seminar at CERN on July 4, 2012

$$H \to WW^{(*)}$$

Higgs $\rightarrow WW^{(*)} \rightarrow (\ell_1^- \bar{\nu})(\ell_2^+ \nu)$



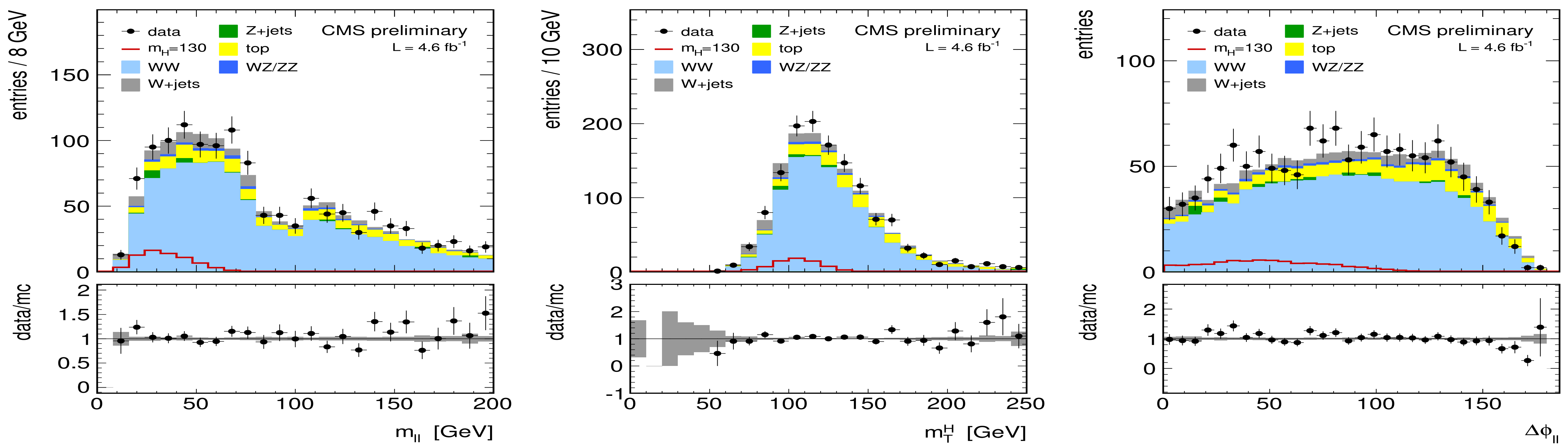
- Partial reconstruction

$|m_{\ell\ell} - m_Z| > 15$ GeV

projected ($\perp \ell$) MET >40 GeV ($\ell\ell$)
>20 GeV ($e\mu$)

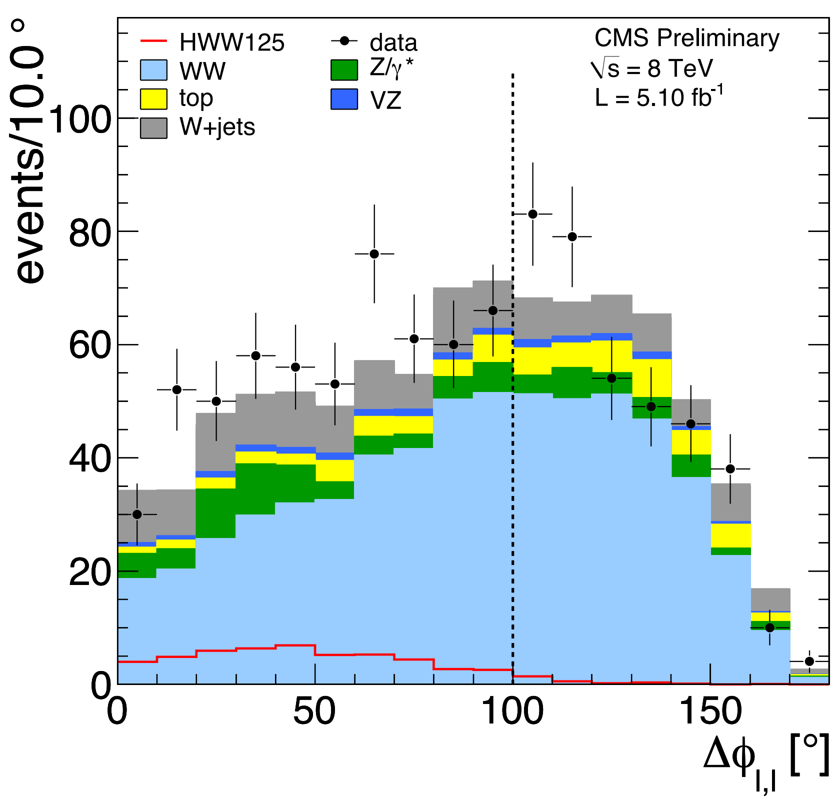
- Require 0, 1, and 2 (VBF) jets
- Reject top: soft μ and b-tag veto

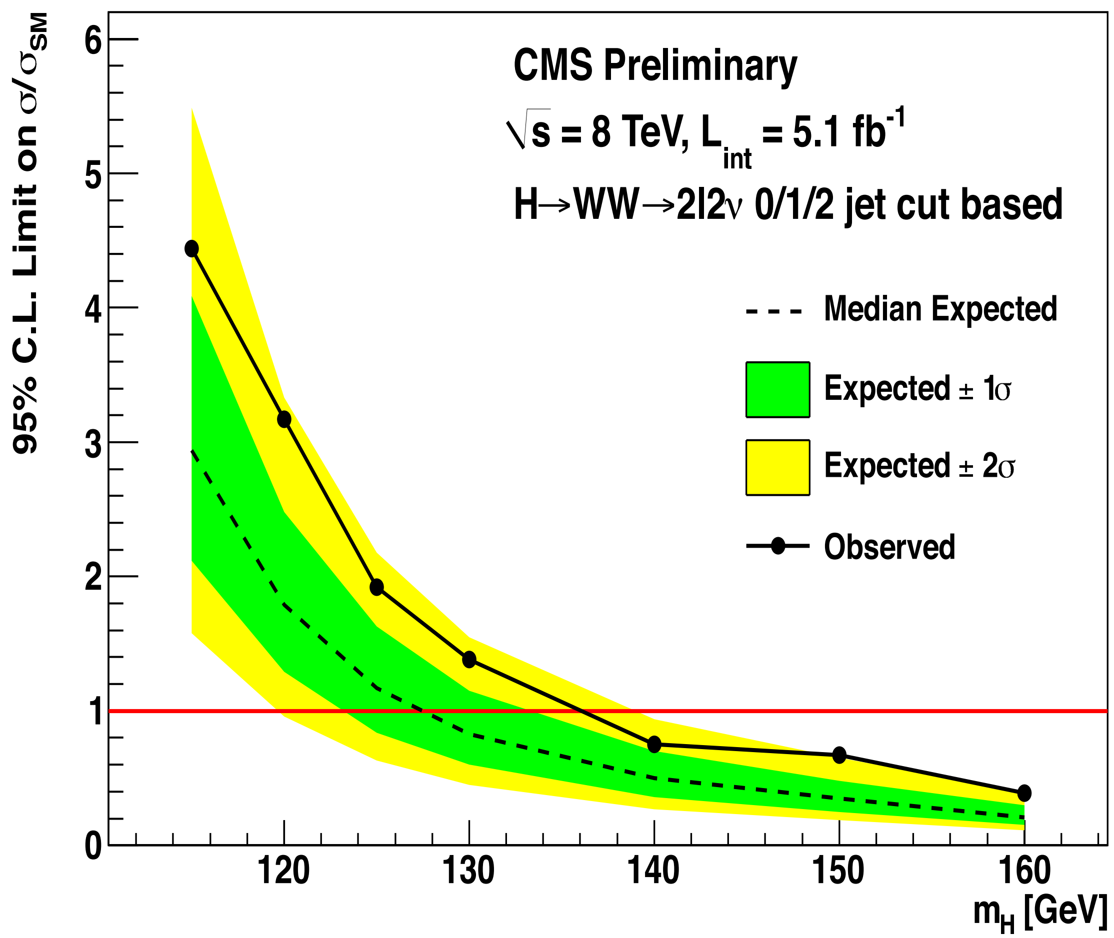
130 GeV: $m_{\ell\ell}$<45 GeV   80<m_T<125 GeV $\Delta\phi_{\ell\ell}<\pi/2$



Higgs $\rightarrow WW^{(*)} \rightarrow (\ell^-\bar{\nu})(\ell^+\nu)$

- 7 TeV data analysis unchanged (BDT, shape)
- 8 TeV data analysis – cut based
  - shape fit in development
  - excess consistent with ZZ



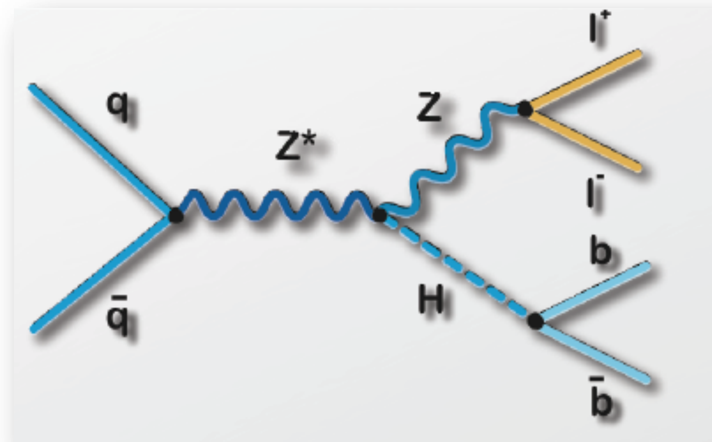


- $R_{WW/ZZ} = 0.9^{+1.1}_{-0.6}$

$$H \to b\bar{b}$$

Analysis Strategy

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



5 channels

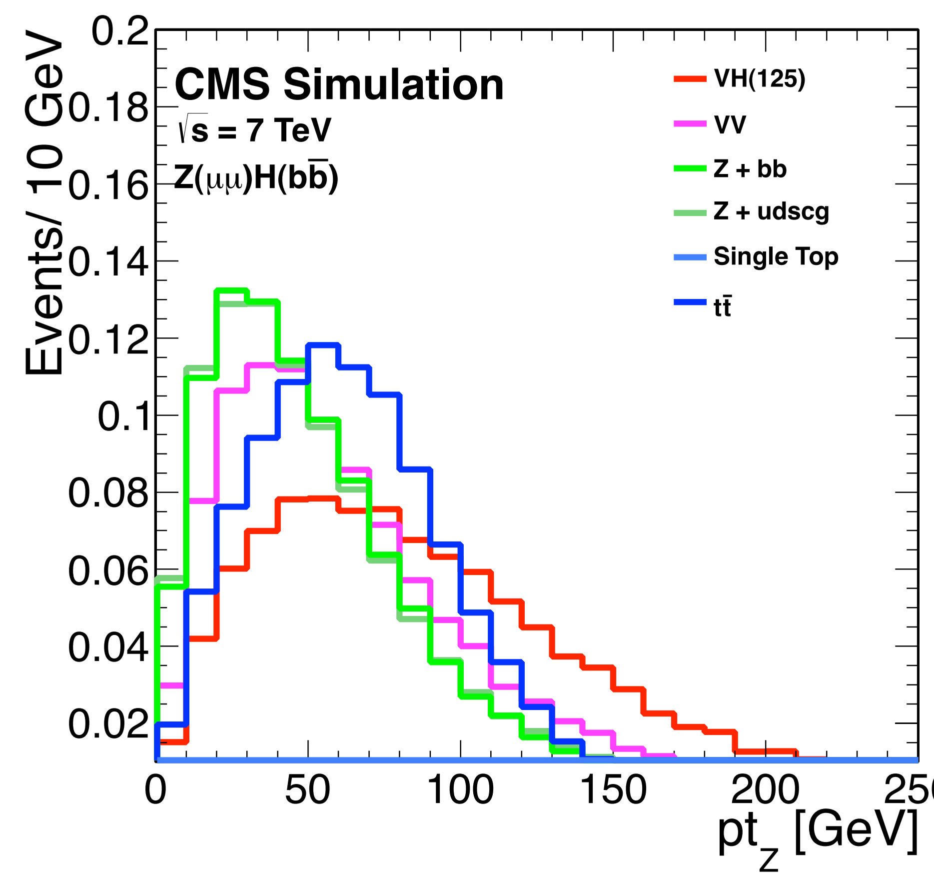
- Z(ll)H(bb)
- Z(νν)H(bb)
- W(lν)H(bb)

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

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

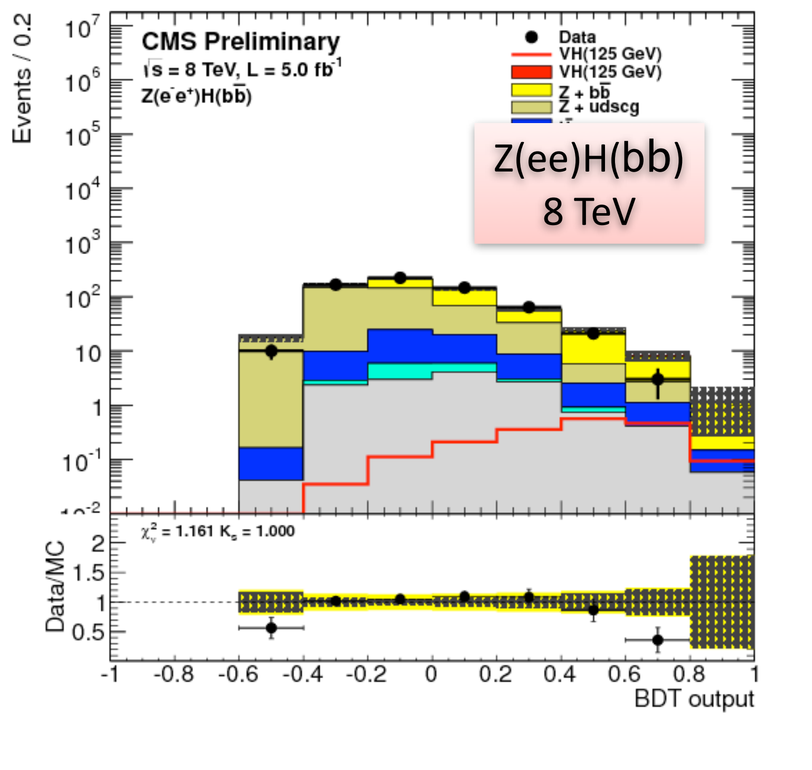
Boosted vector bosons:
$p_T(V)$ -> 2 ranges
2 b-tagged jets (H->bb)
Back-to-back V and H,
reconstruct m_{bb}

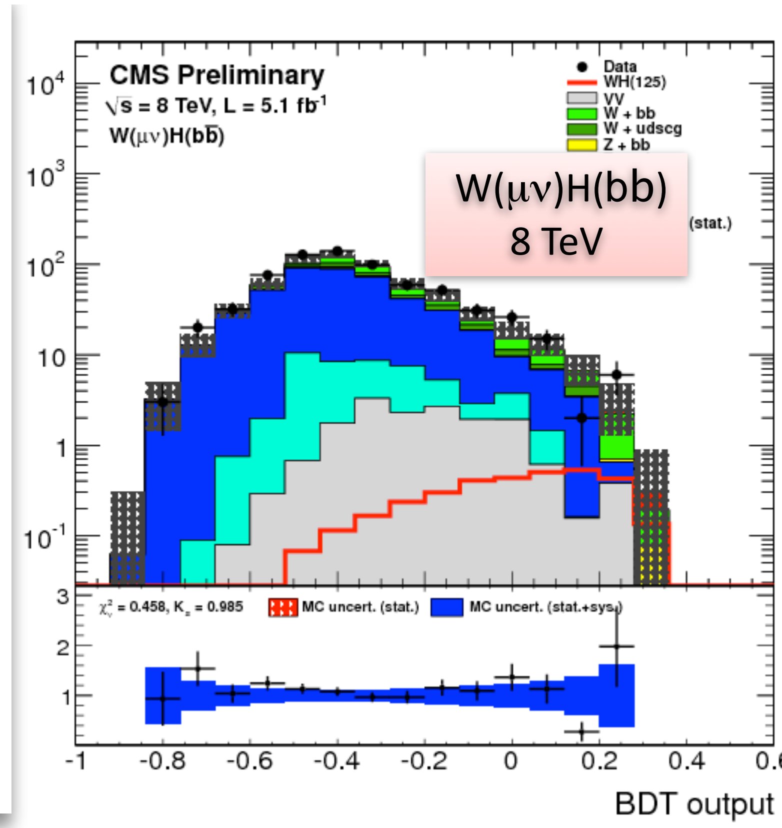
Main backgrounds estimated from data in control regions (scales)

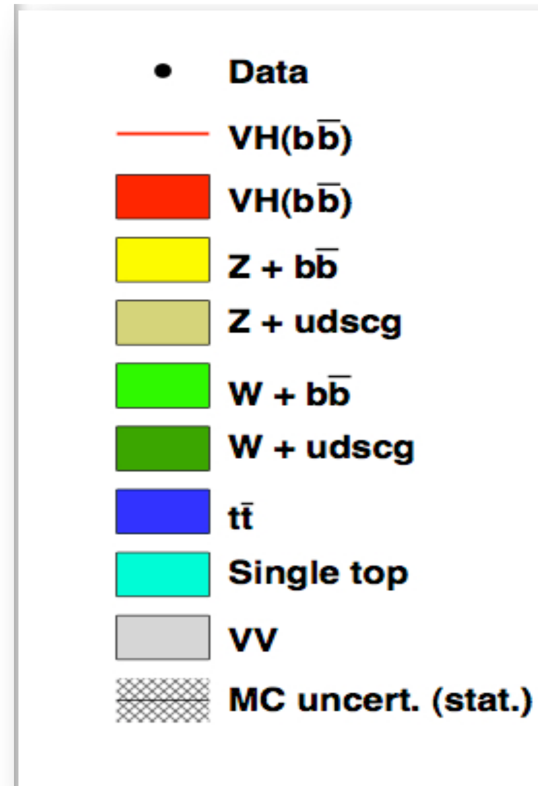


Examples of final MVA distributions

H->bb







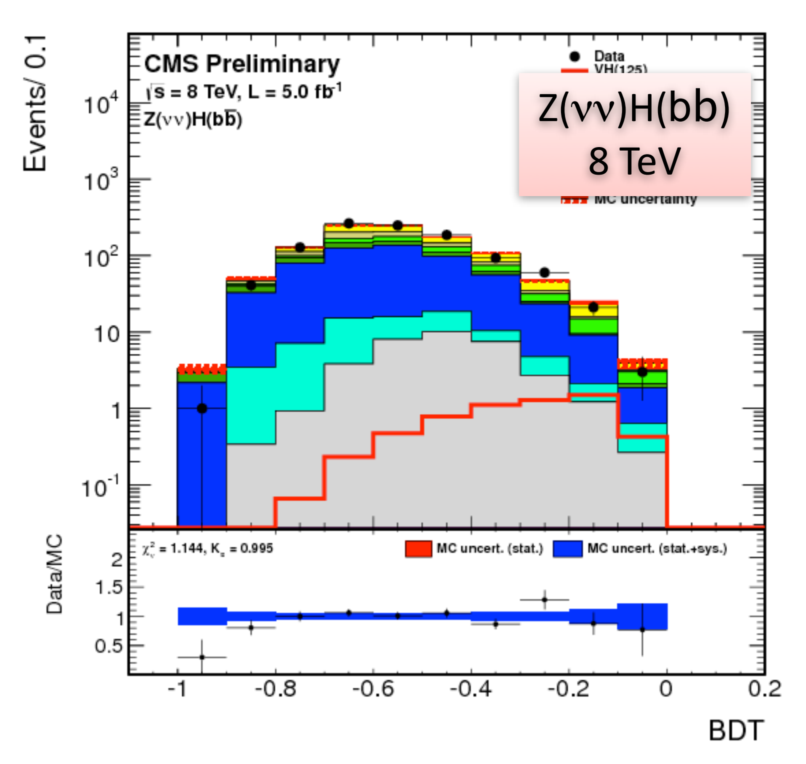
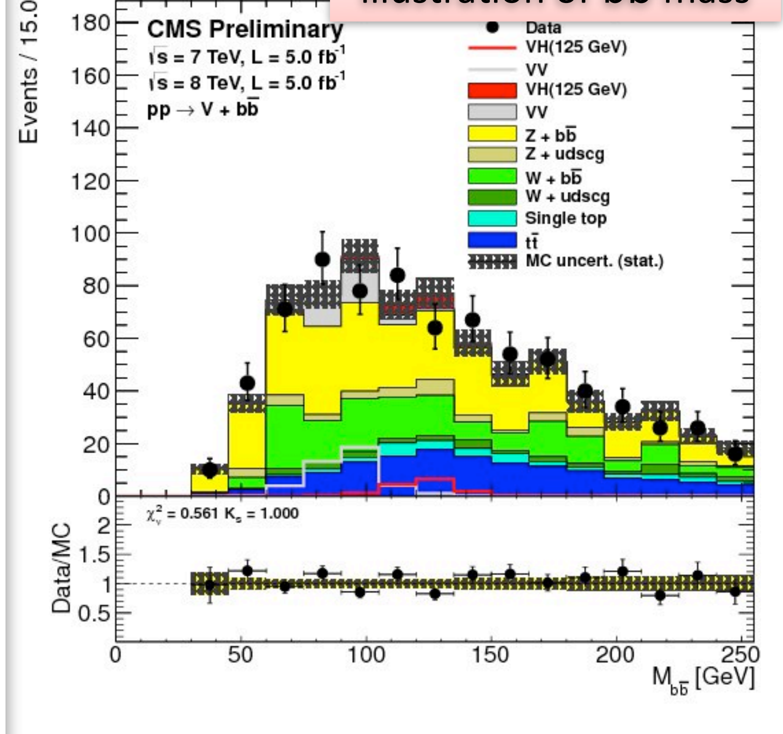
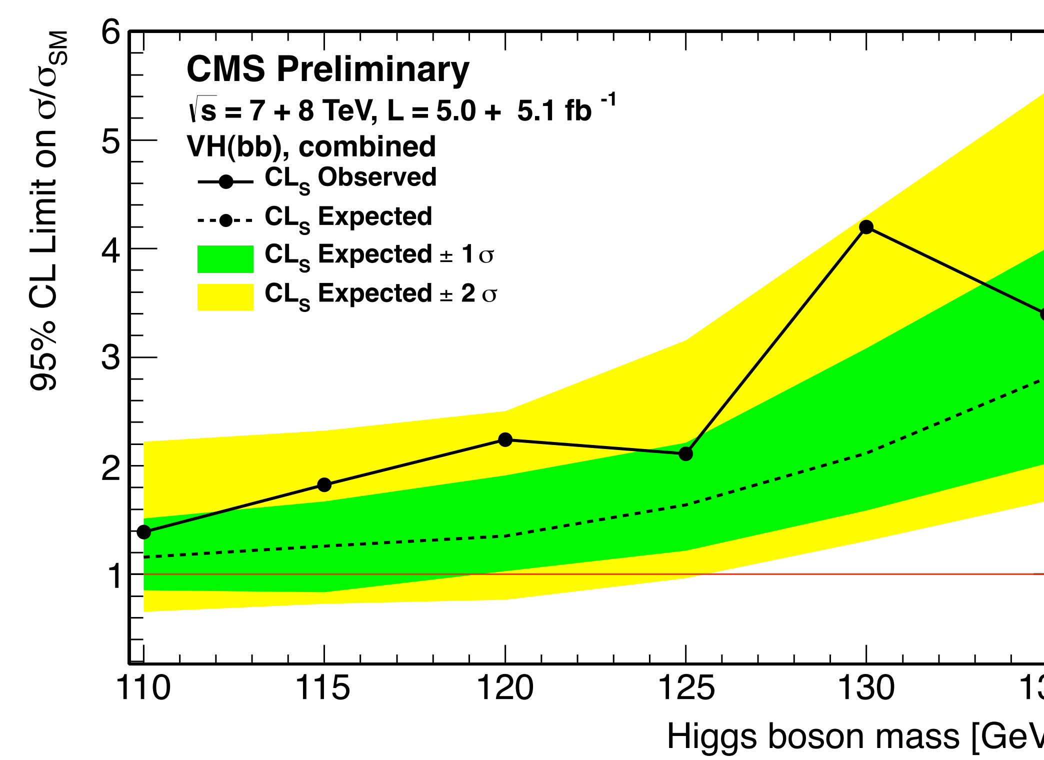


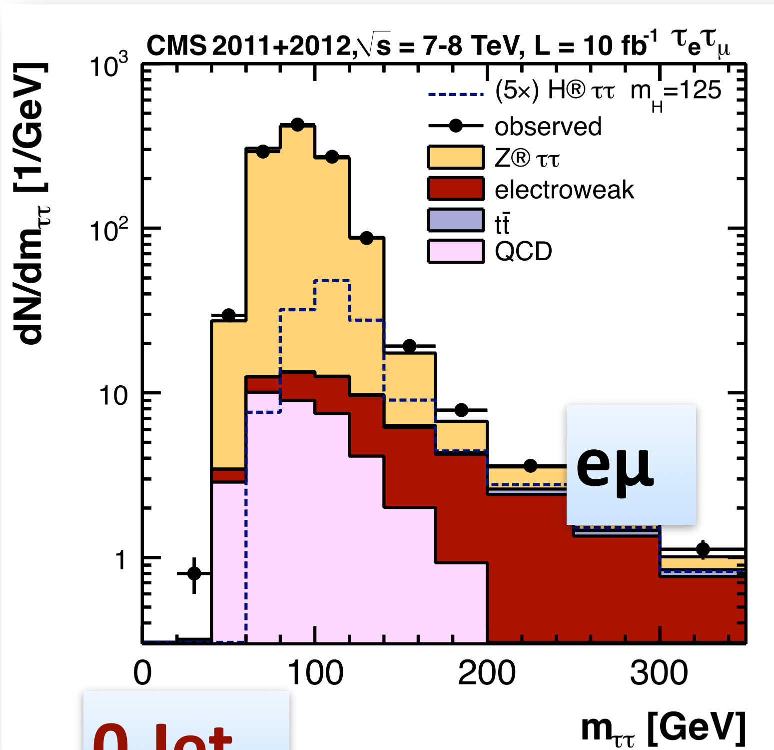
illustration of bb mass





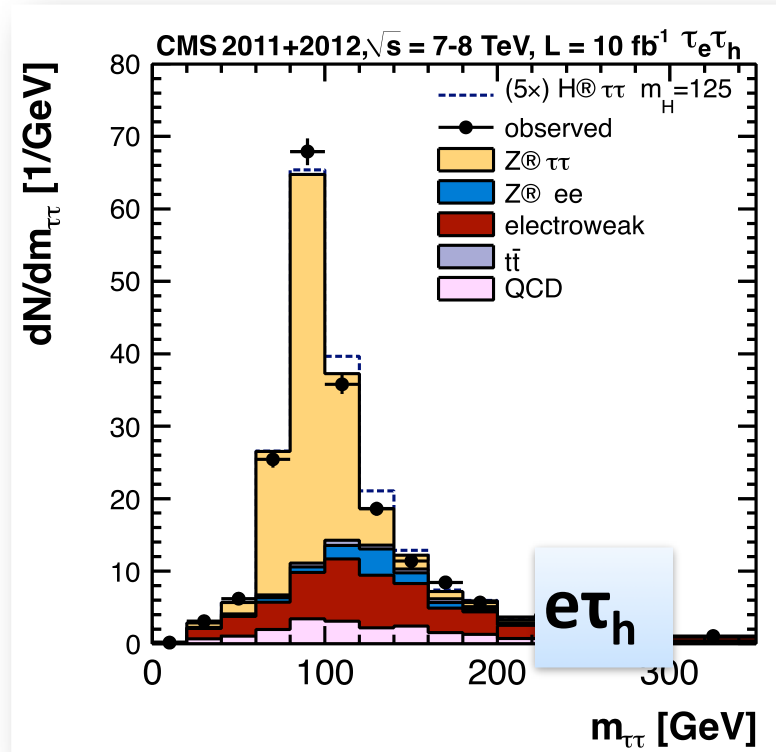
$$H \to \tau^+\tau^-$$

Mass Distributions in Event



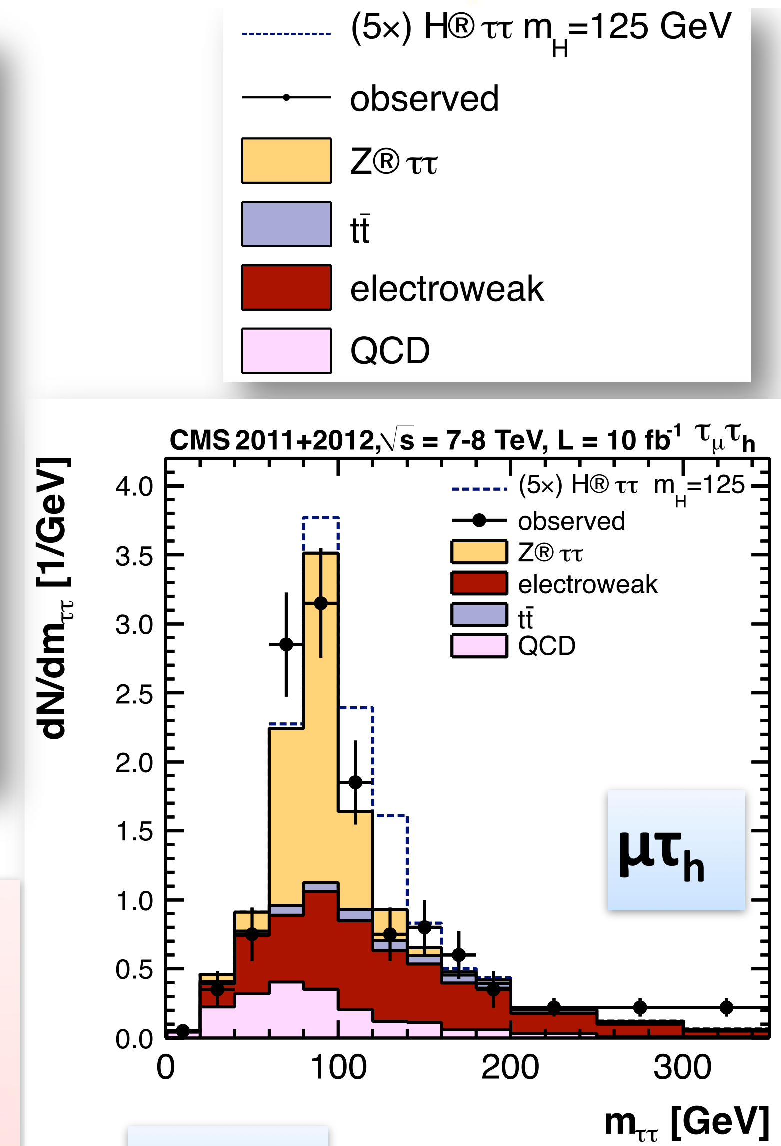
0 Jet

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



Boosted

- Enhanced sensitivity to gluon fusion
  - Improved mass resolution
  - Sensitivity boosted by low/high p_T split

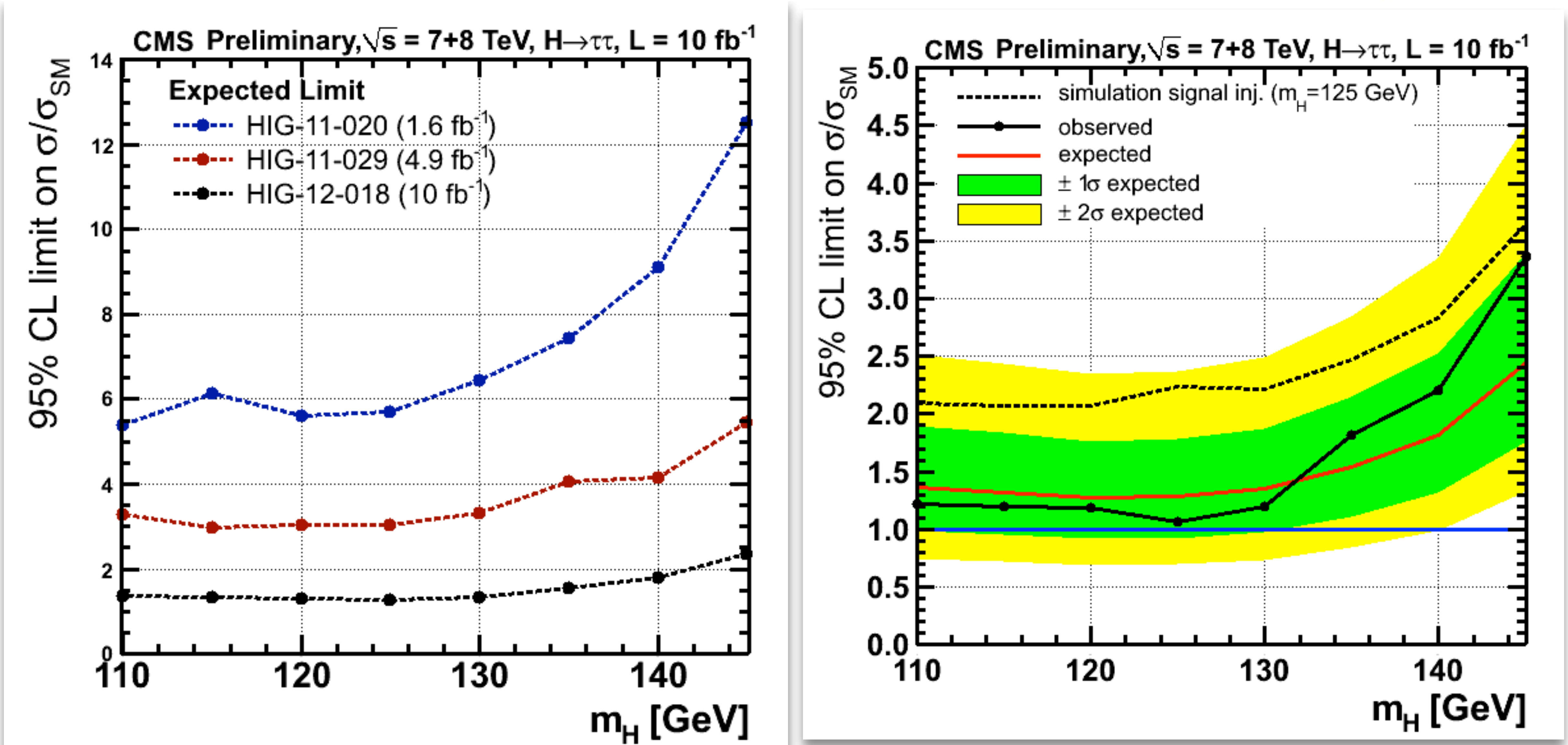


VBF

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

4x5 channels

Results for H→ττ



- ~2x improvement in sensitivity
  - => 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 (expected 1.28)

SM Higgs: High Mass

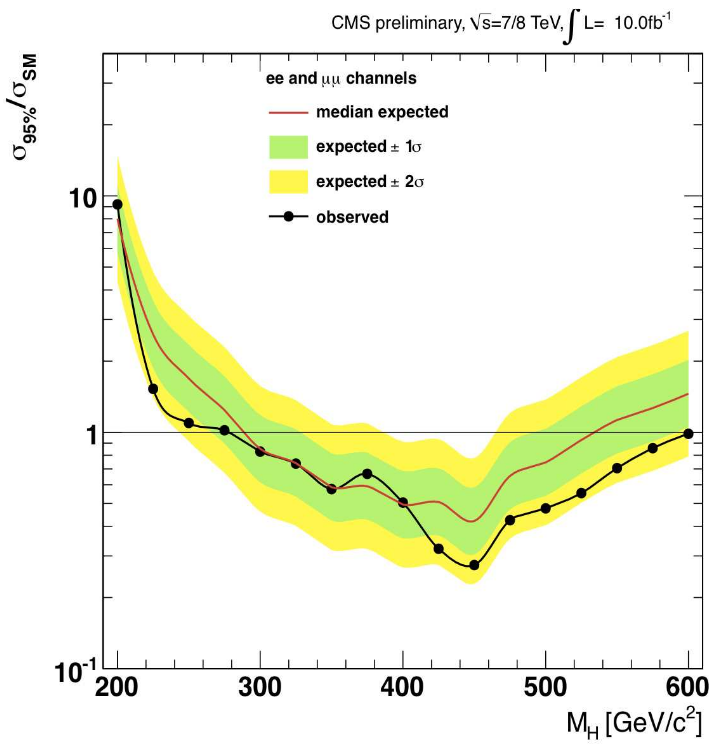
- Extensive effort across the full mass range:

$$H \to ZZ \to \quad 4\ell, \quad 2\ell 2\tau, \quad 2\ell 2q, \quad 2\ell 2\nu$$

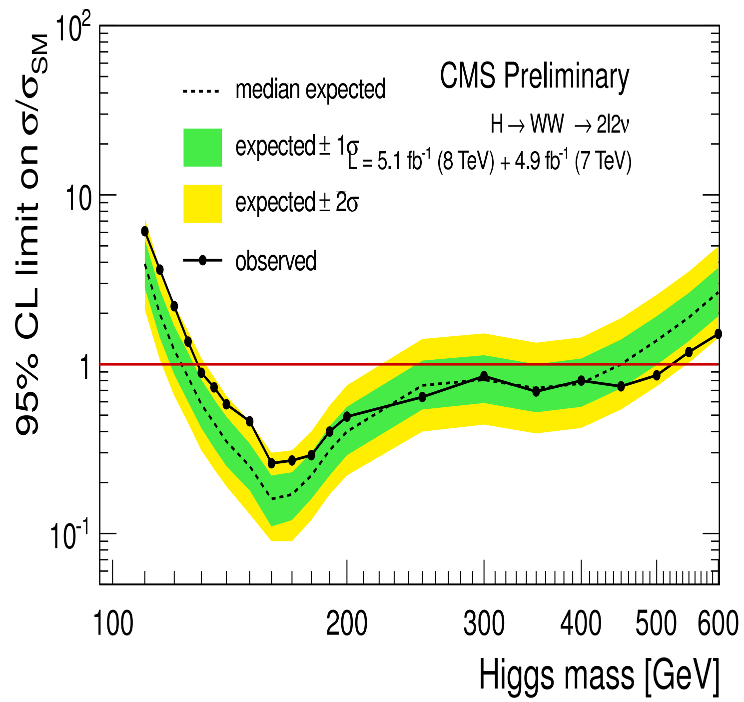
$$H \to WW \to \quad 2\ell 2\nu, \quad 2q\ell\nu$$

- Recent updates:

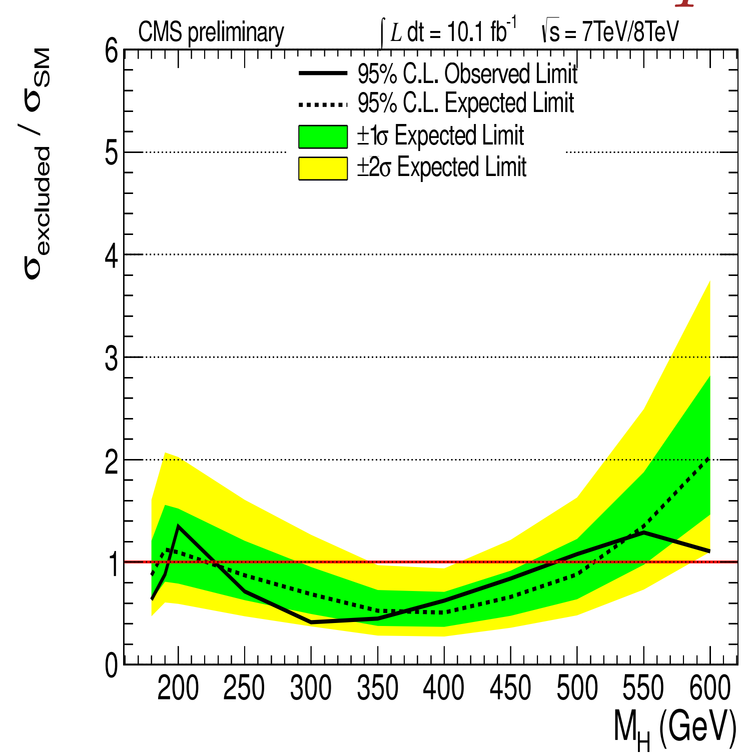
$H \to ZZ \to 2\ell 2\nu$



$H \to WW \to 2\ell 2\nu$

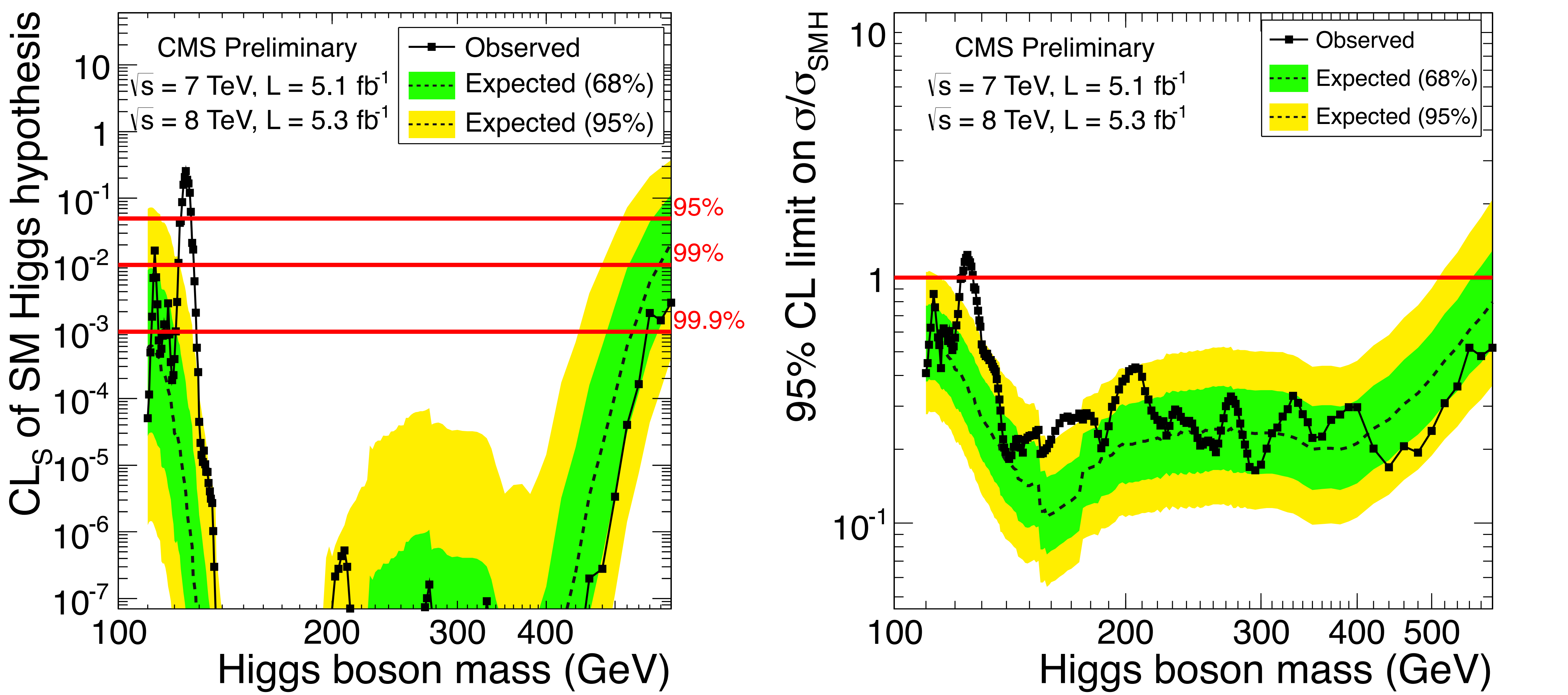


$H \to WW \to 2q\ell\nu$

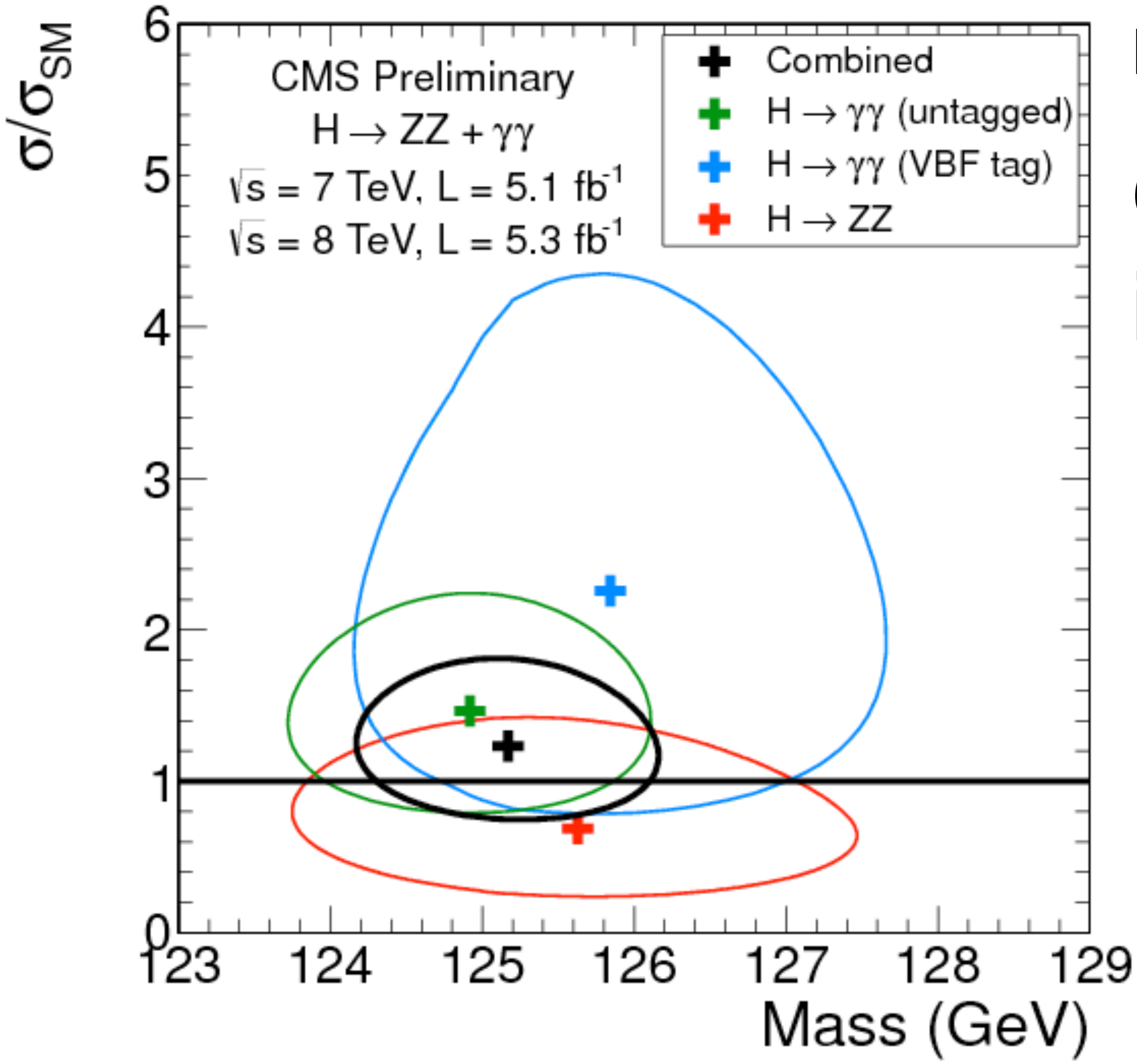


SM Higgs Exclusion

- Excluded SM Higgs in the full search range
  - except for a narrow range around 125 GeV



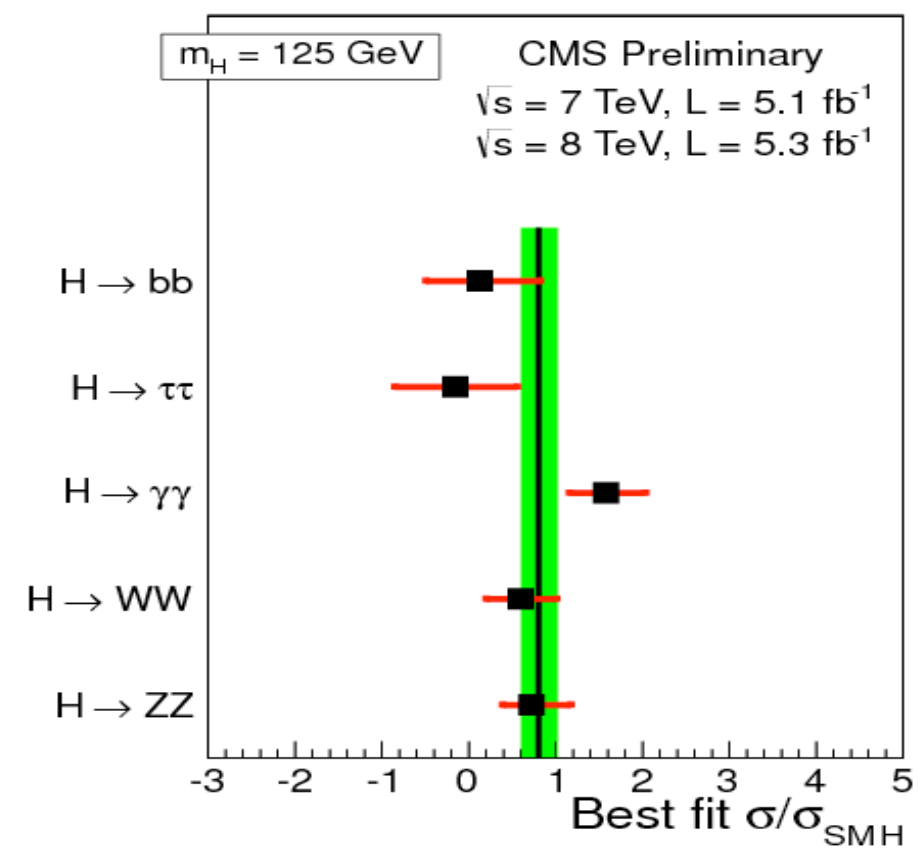
Characterization of the excess



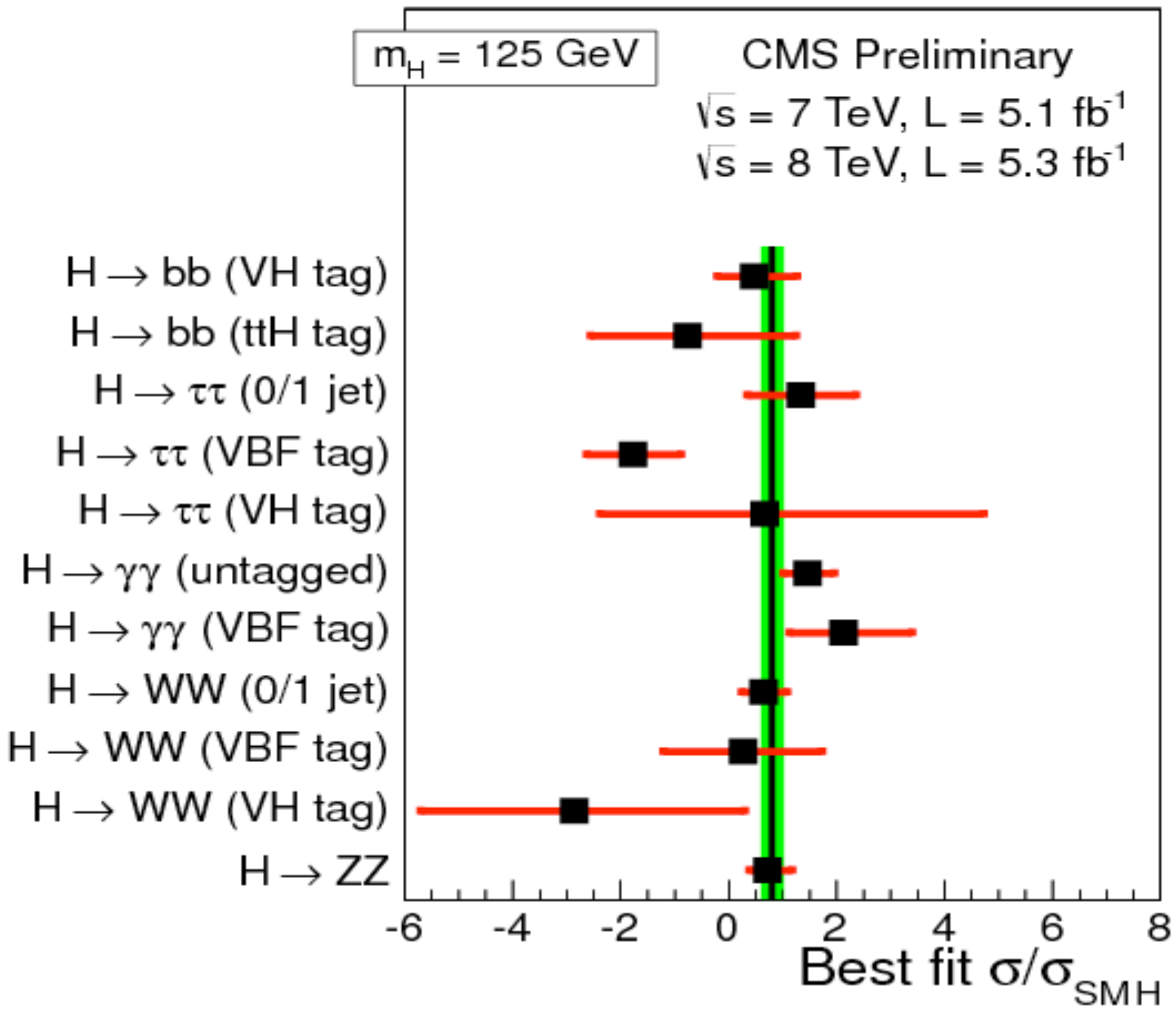
The observed state has mass near 125.3 ± 0.4 ± 0.5 GeV

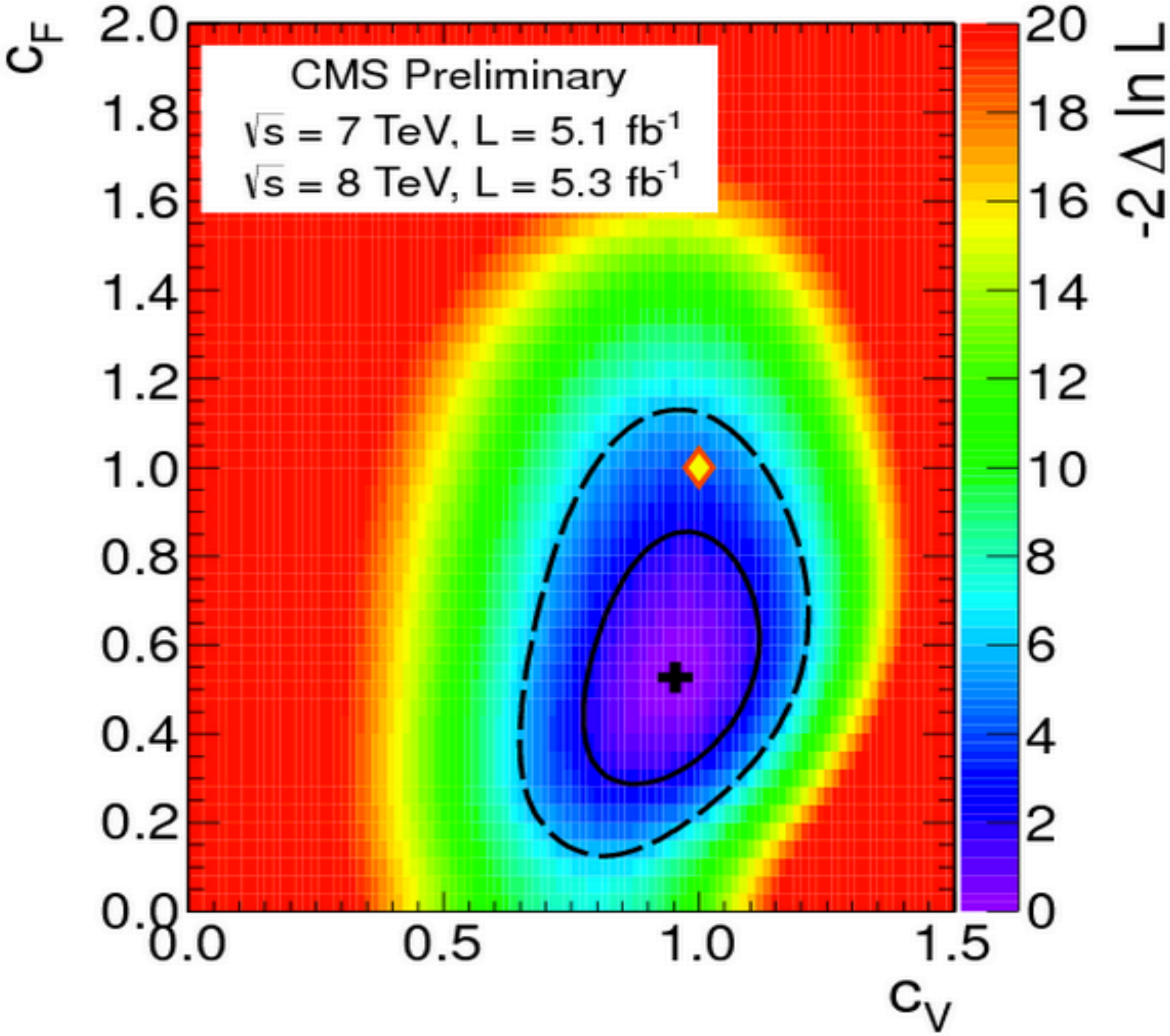
Overall best-fit signal strength in the combination:

σ/σ_{SM} = 0.80±0.22



Fit Boson and Fermion couplings





- In agreement with SM within 95% CL

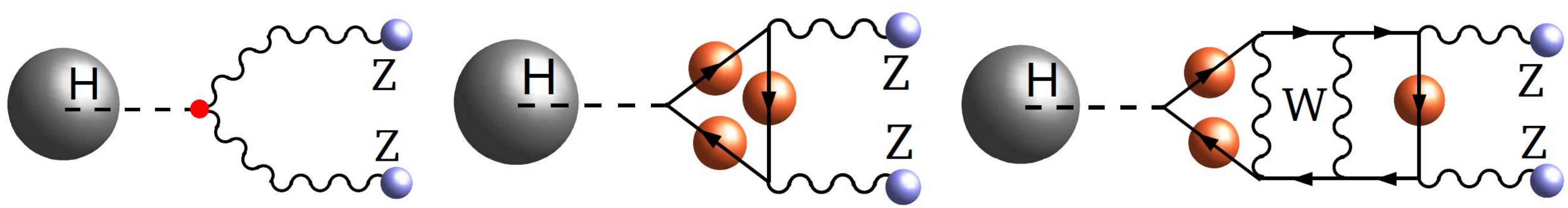
Measuring Tensor Structure of Interactions

- Amplitude for $X_{J=0} \to ZZ$ or WW (see RPM May 6, 2010)

http://www-physics.lbl.gov/seminars/old/Gritsan2010.pdf

$$A = v^{-1} \epsilon_1^{*\mu} \epsilon_2^{*\nu} \left(a_1 g_{\mu\nu} M_X^2 + a_2\, q_\mu q_\nu + a_3 \epsilon_{\mu\nu\alpha\beta}\, q_1^\alpha q_2^\beta \right)$$

- SM Higgs 0^+: (a_1) CP $\sim$few% (a_2) CP $\sim 10^{-10}$? (a_3) $\not{C}\not{P}$



(or beyond SM) (or beyond SM)

- 3 amplitudes ("experiment") $\Leftrightarrow$ 3 coupling constants ("theory")

$$A_{00} = -\frac{M_X^2}{v} \left(a_1 x + a_2 \frac{M_{V_1} M_{V_2}}{M_X^2} (x^2 - 1) \right)$$

$$A_{\pm\pm} = +\frac{M_X^2}{v} \left(a_1 \pm i a_3 \frac{M_{V_1} M_{V_2}}{M_X^2} \sqrt{x^2 - 1} \right)$$

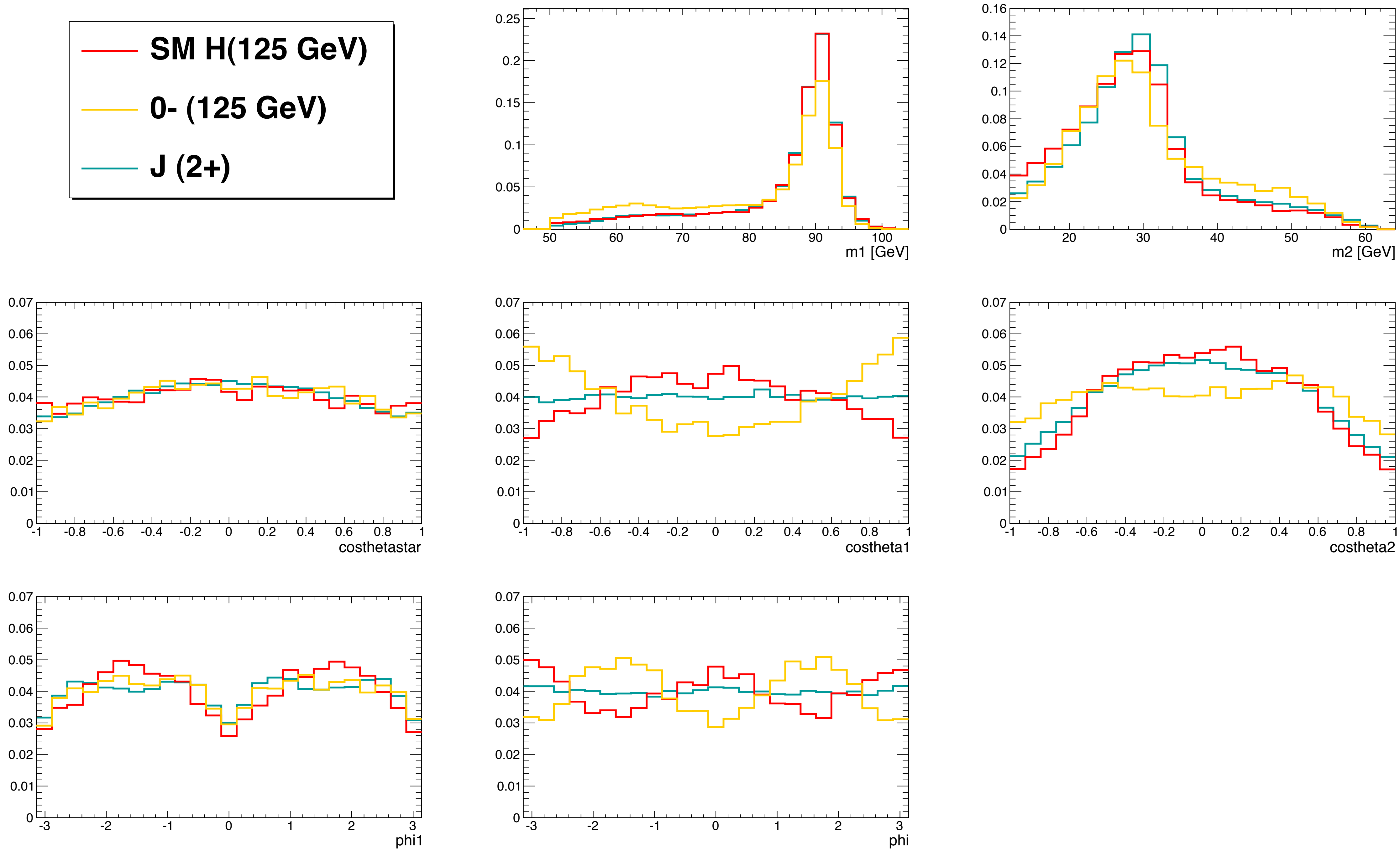
$$x = \frac{M_X^2 - M_{V_1}^2 - M_{V_2}^2}{2 M_{V_1} M_{V_2}}$$

Angular / Mass Distributions

- JHU generator: http://www.pha.jhu.edu/spin ($H \to ZZ, WW, \gamma\gamma$)

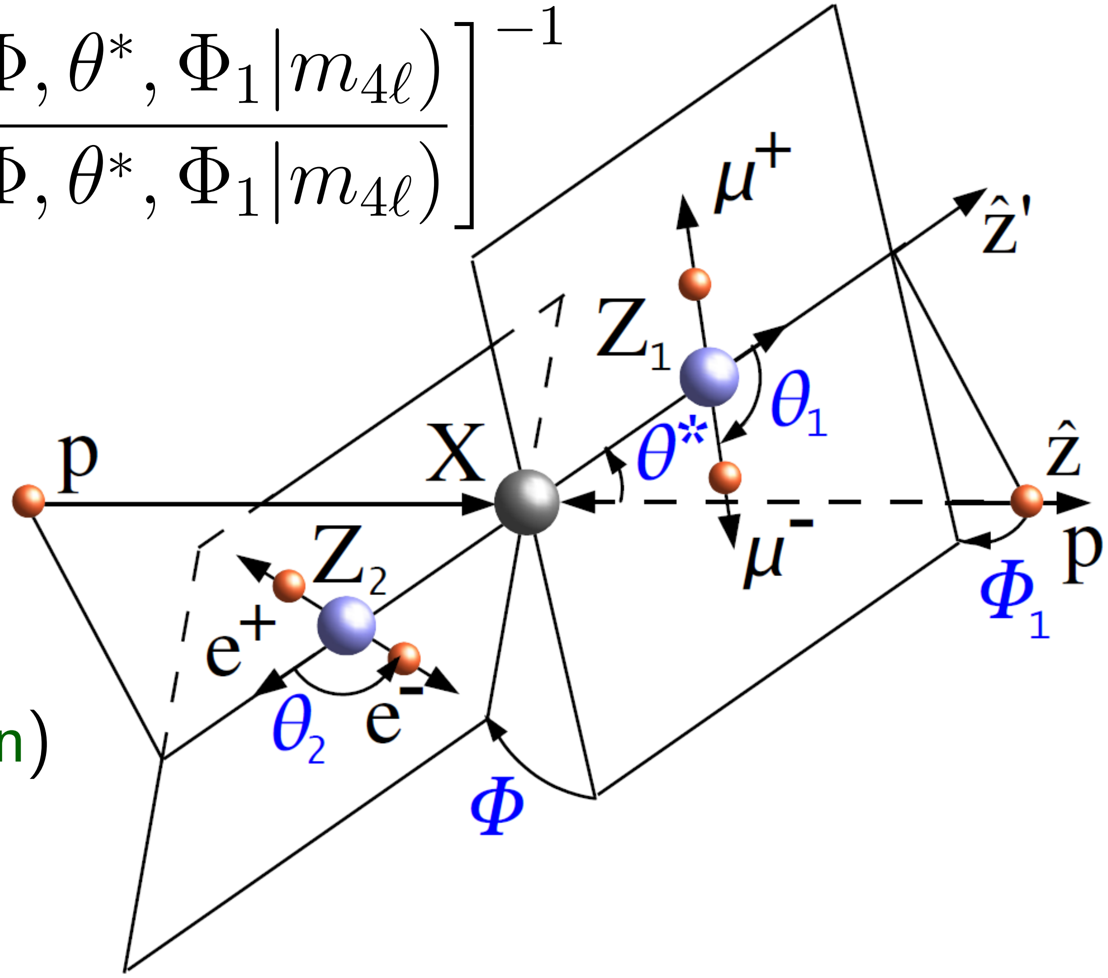
See also ICHEP talk "Determination of properties of a Higgs–like resonance at LHC"

https://indico.cern.ch/getFile.py/access?contribId=473&sessionId=53&resId=0&materialId=slides&confId=181298

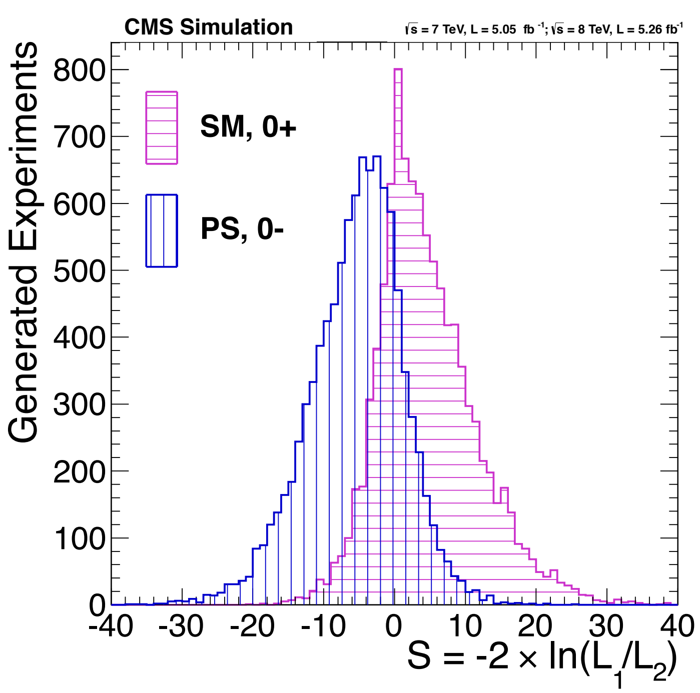


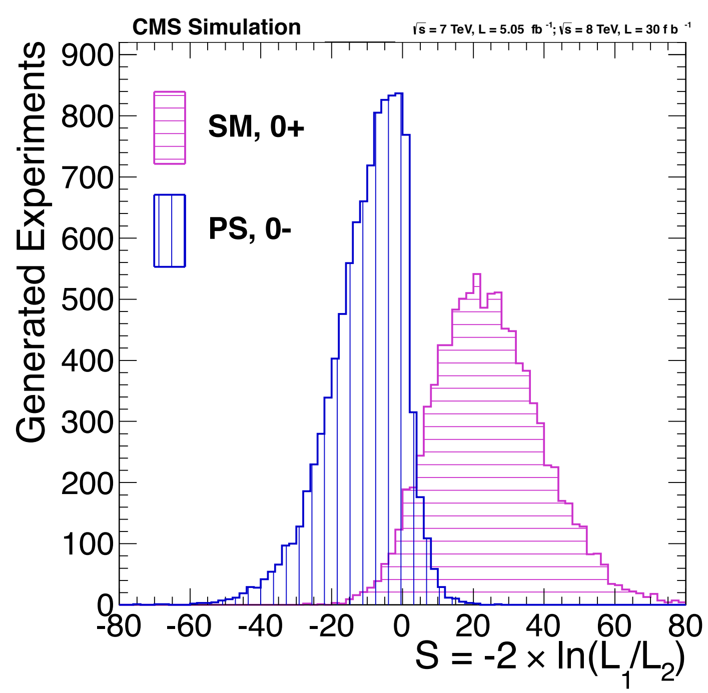
MELA for Spin / Parity

$$\text{psMELA} = \left[1 + \frac{\mathcal{P}_{0^-}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}{\mathcal{P}_{0^+}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}\right]^{-1}$$



- Hypothesis testing
  - scalar (0^+) vs pseudoscalar (0^-)
  - may include any other model
- Simulation (http://www.pha.jhu.edu/spin)
  - expected separation 1.6σ now
  - 3.1σ with 5+30 fb^{-1}

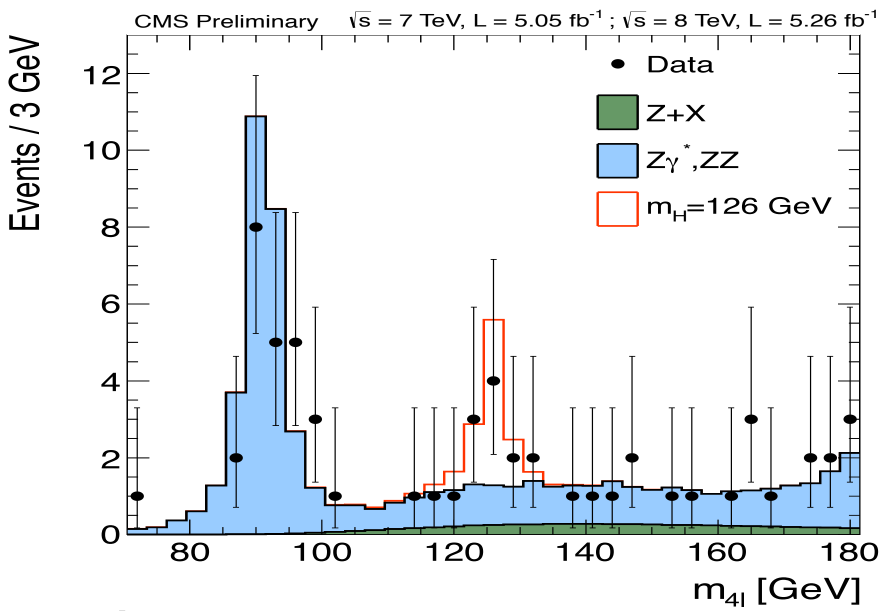


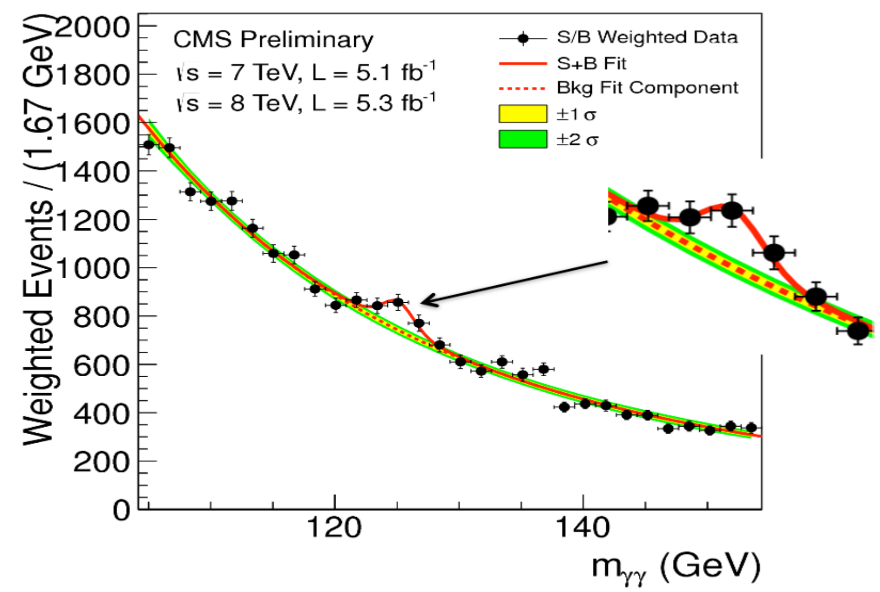


Observation of a New Boson

- Observation of a New Boson on CMS: 5σ excess

$$X \rightarrow Z^{(*)} Z^{(*)} \qquad\qquad X \rightarrow \gamma\gamma$$





- What we know:
  - it is a boson, spin$\neq$1 $\Rightarrow$ spin $=$ 0 or 2... (nothing like this before)
  - it couples to vector bosons

- What we do not know:
  - if it is the Higgs boson, if couples to Fermions (matter)
  - expect it to be elementary, if not $\Rightarrow$ even more interesting...
  - if it is a tip of an iceberg of new exciting states of matter / energy

CMS collaboration