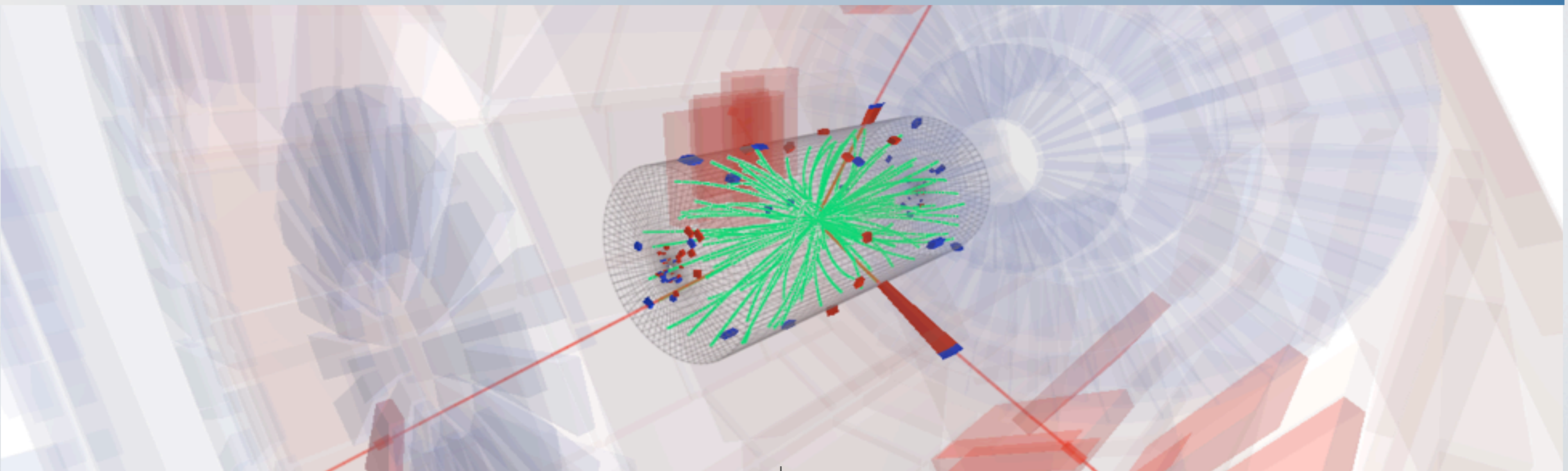
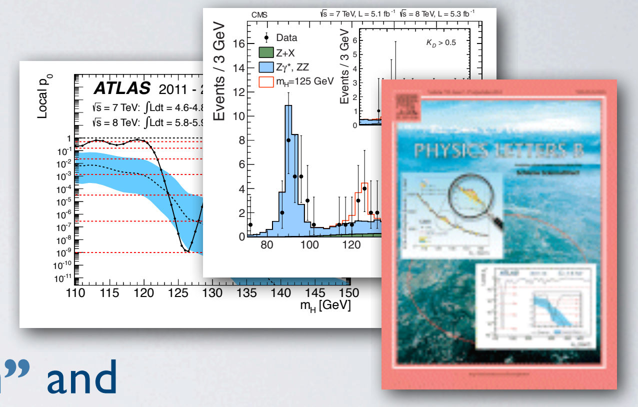
OBSERVATION AND PROPERTIES OF THE HIGGS-LIKE BOSON IN $H \to ZZ \to 4L$ DECAYS WITH CMS DETECTOR

Higgs Hunting 2013, Orsay, France

Predrag Milenović
(University of Florida)
on behalf of the CMS collaboration



Prelude...



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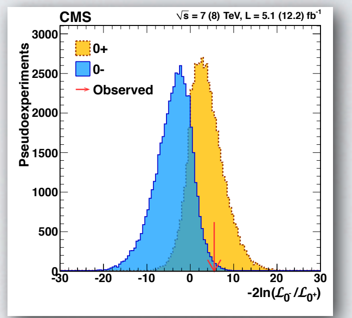


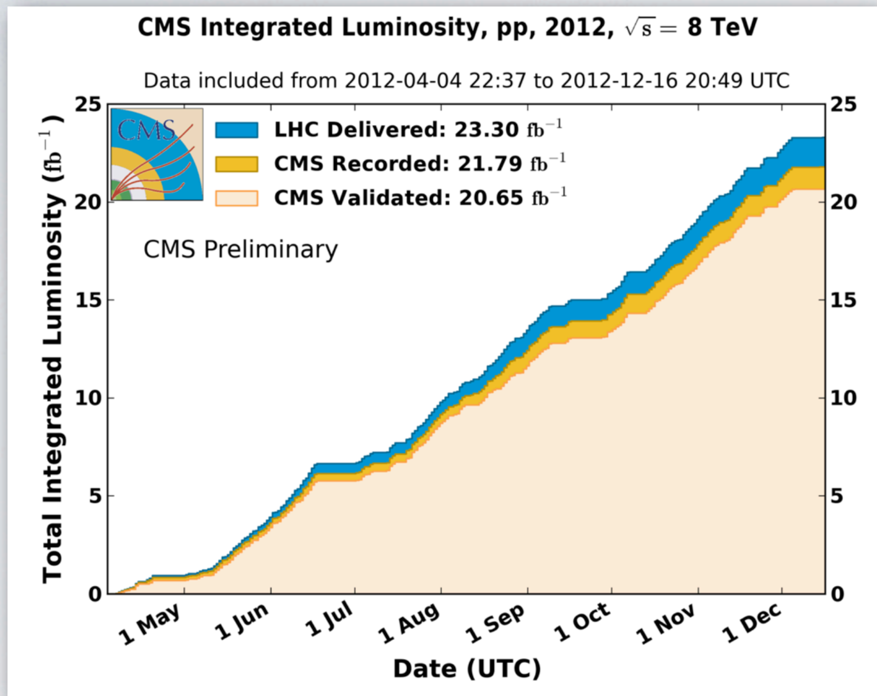
Phys. Rev. Lett. 110, 081803 (2013)

- **On July 4th 2012** the ATLAS and CMS collaborations announced **the discovery of a new boson!**
- Followed by several updates of results by two experiments with focus on answering:
  - if the new boson is **"the Standard Model Higgs boson"** and
  - if there are **any hints for the physics beyond SM?**
  - Example: Study of mass and spin-parity in H → ZZ → 4l (Dec 2012)
- In general answers provided as experimental:
  - measurements of the properties of the new boson and
  - searches for additional Higgs-like boson in a wide m_H range
- CMS analyzed full set of 7 TeV and 8 TeV data and updated several public results in March 2013
  - including study of the Higgs-Like boson in its H → ZZ → 4l decay mode (PAS HIG-13-002)

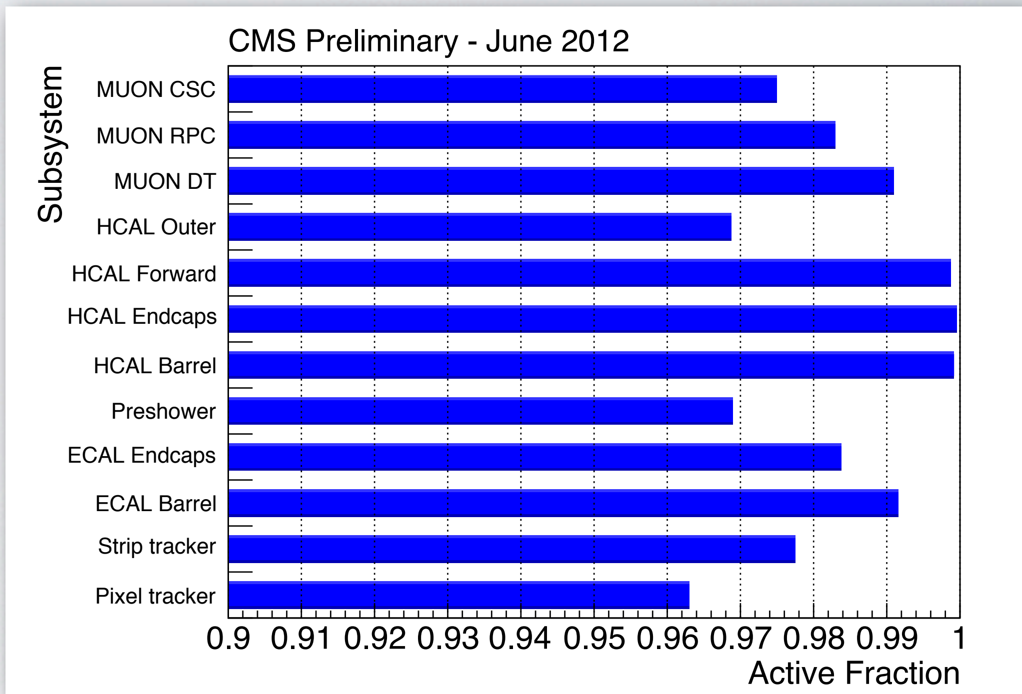
Data taking and detector performance

Extraordinary performance of LHC enabled significant physics results!

Luminosity @ CMS



Detector performance



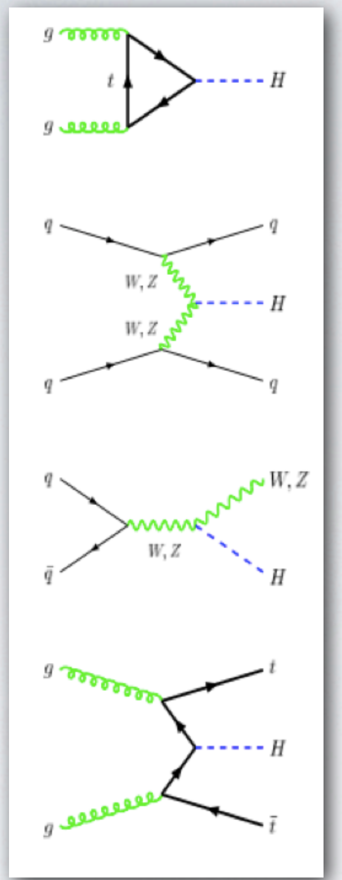
CMS data available for physics: ~25 fb^{-1}

(5 fb^{-1} at 7 TeV, 20 fb^{-1} at 8 TeV)

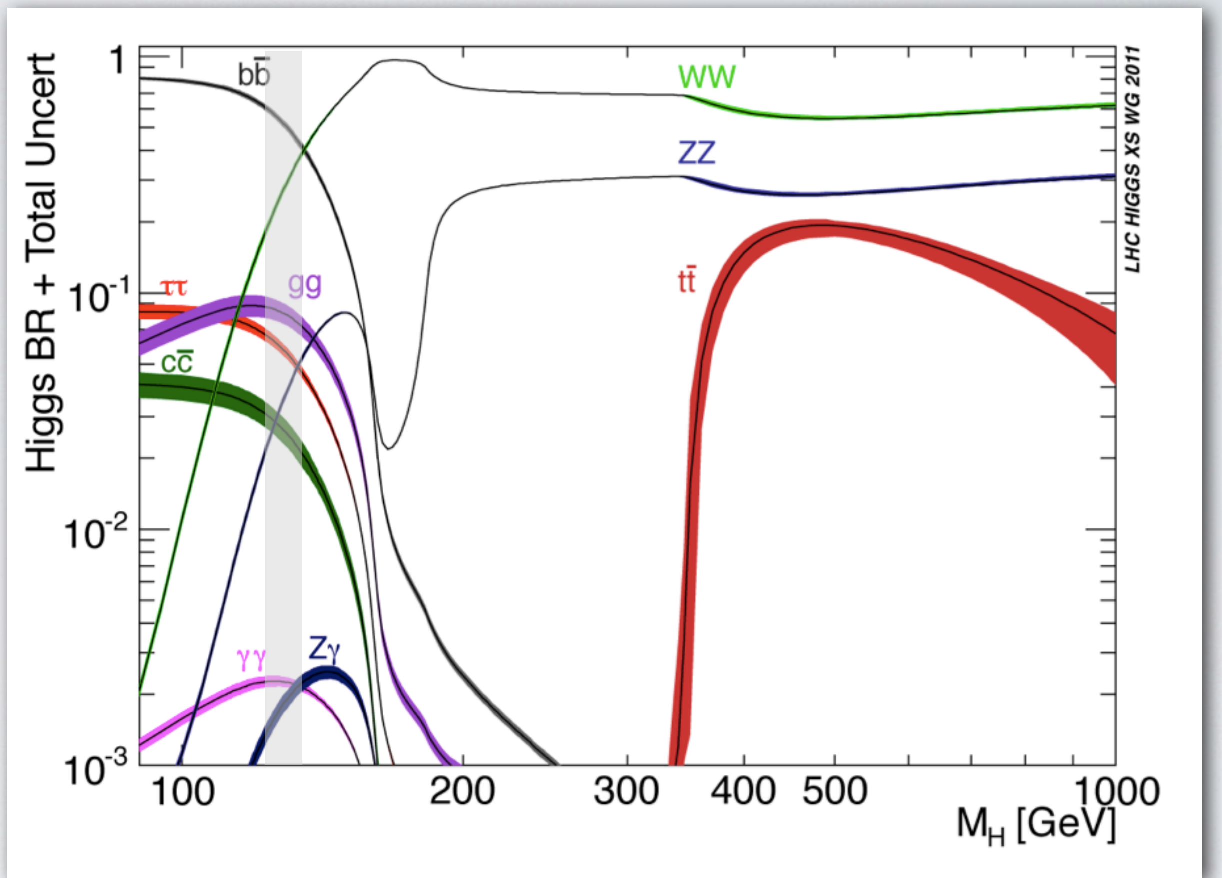
fraction of the total delivered data: ~90%

Higgs production and decay modes

Production



Decay modes and branching ratios



LHC Higgs XS WG:
arXiv:1101.0593,
arXiv:1201.3084,
arXiv:1209.0040

common inputs to experiments

Main contributions:

Low mass: **H→γγ, H→ZZ (also H→WW)**

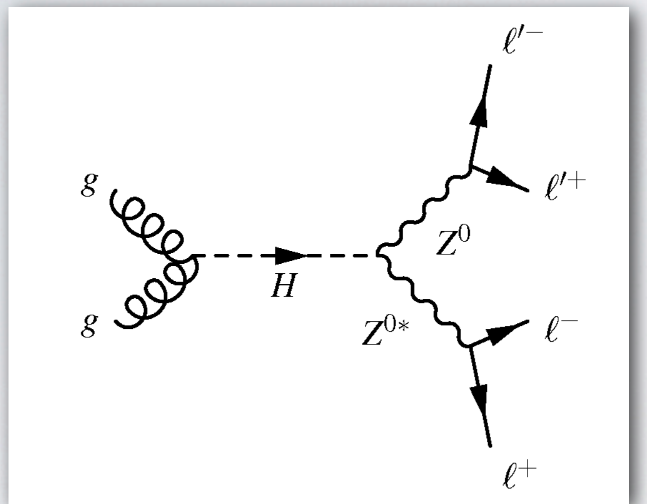
Intermediate/high mass: **H→WW, H→ZZ**

H → ZZ → 4l

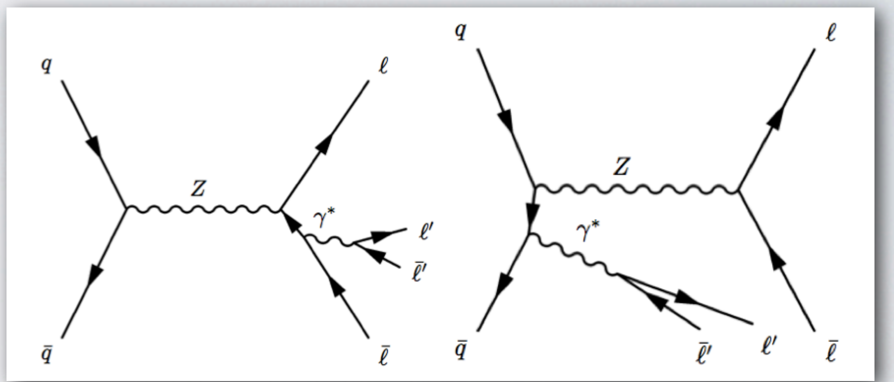
- Golden channel - clean experimental signature

➡ benefits from excellent lepton resolution

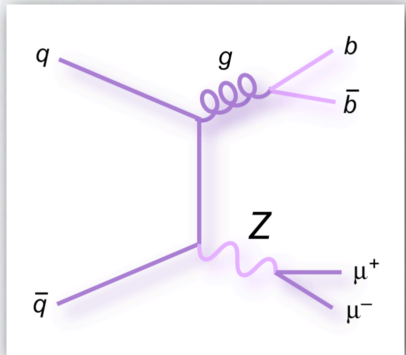
process H → ZZ → 4l

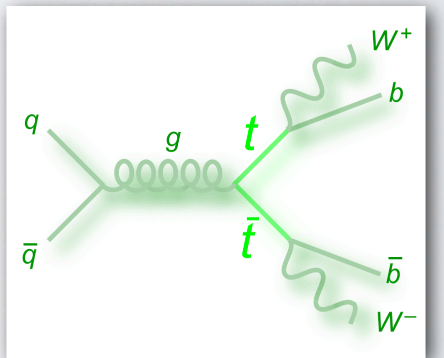


irreducible background
(qq → Zγ*, qq → ZZ, gg → ZZ)



instrumental background ("Z+X")





(Z + jets, ttbar, Z + γ + jets, WZ + jets, ...)

- Crucial aspects of the analysis
  - Highly efficient lepton reconstruction/ID
  - Excellent precision in lepton measurement
  - Good background estimation
  - Optimal use of kinematic information

H → ZZ → 4l

- Golden channel - clean experimental signature
  - benefits from excellent lepton resolution

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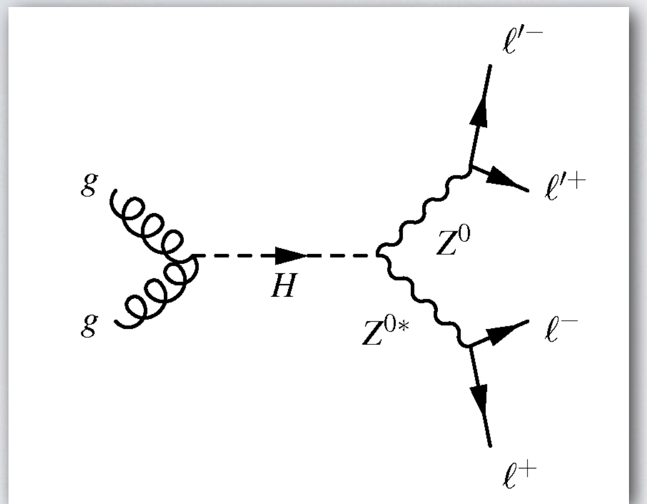
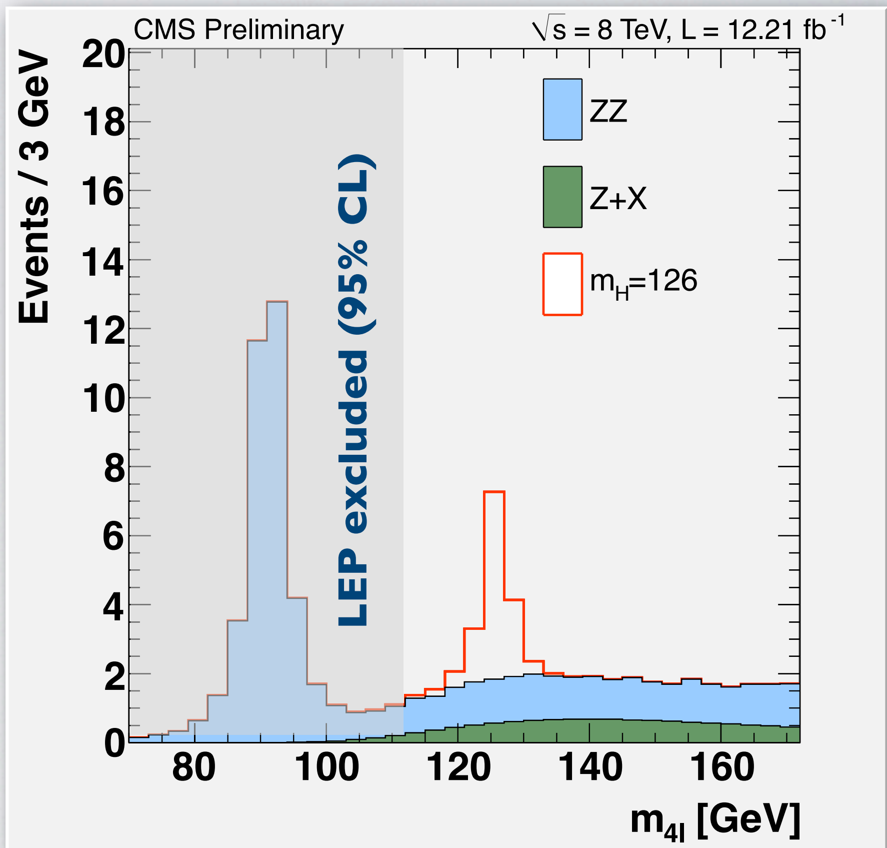


Narrow resonance in 4 lepton mass spectrum



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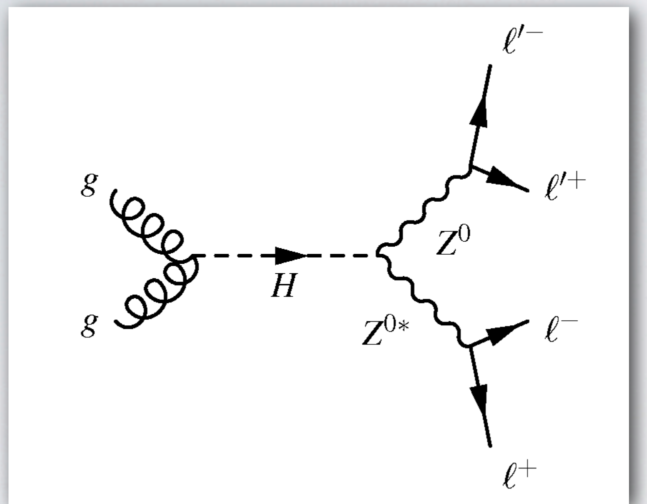
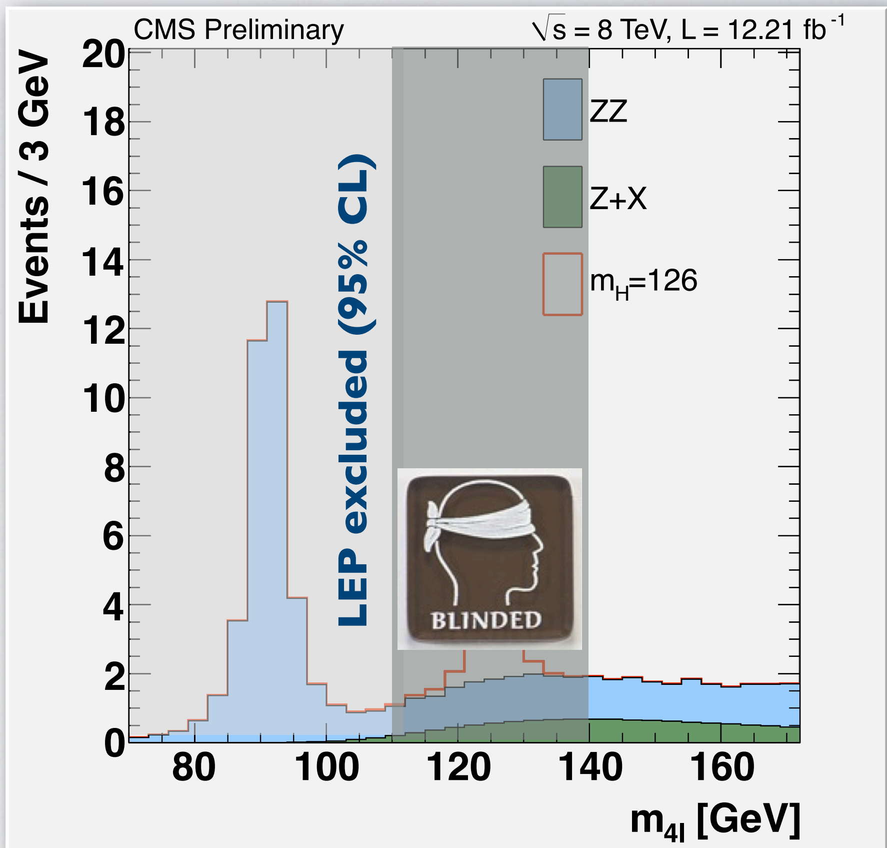


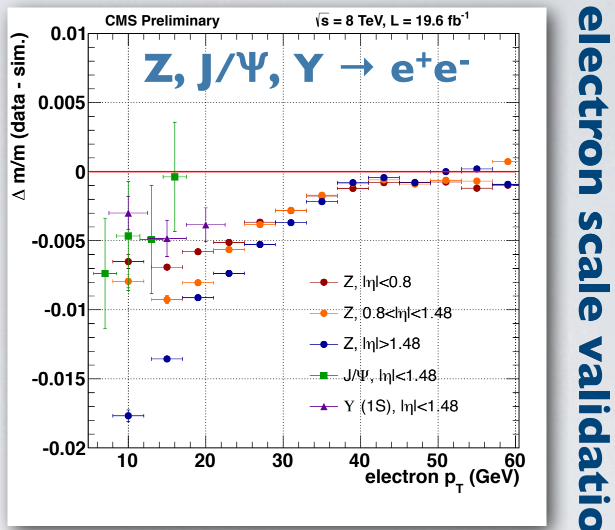
Narrow resonance in 4 lepton mass spectrum



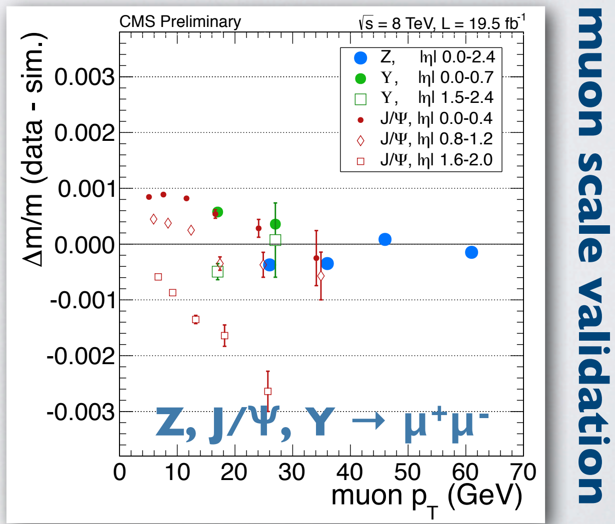
- Crucial aspects of the analysis
  - Highly efficient lepton reconstruction/ID
  - Excellent precision in lepton measurement
  - Good background estimation
  - Optimal use of kinematic information

Lepton reconstruction and identification

- Electron reconstruction and identification from the Tracker and ECAL information
  - momentum from **E-p combination** (MVA regression),
  - MVA identification,
  - Calibration of residual differences in scale and resolution,
  - **p_T > 7 GeV, |*eta*| < 2.5**
  - **validated using Z, J/Ψ, Υ → e^+e^- (data/MC)**
  - uncertainty on m_{4l} scale **0.3% (0.1%)** for 4e (2e2μ)
  - uncertainty on m_{4l} resolution **~20%**



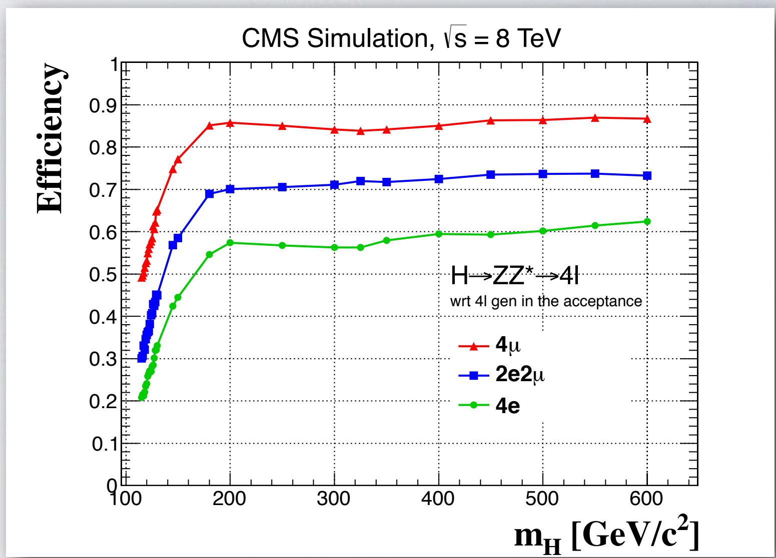
- Muon reconstruction and identification from the Tracker and Muon spectrometer
  - Calibration of residual differences in scale and resolution,
  - **p_T > 5 GeV, |*eta*| < 2.4**
  - **validated using Z, J/Ψ, Υ → $\mu^+\mu^-$ (data/MC)**
  - uncertainty on m_{4l} scale **0.1%**
  - uncertainty on m_{4l} resolution **~20%**

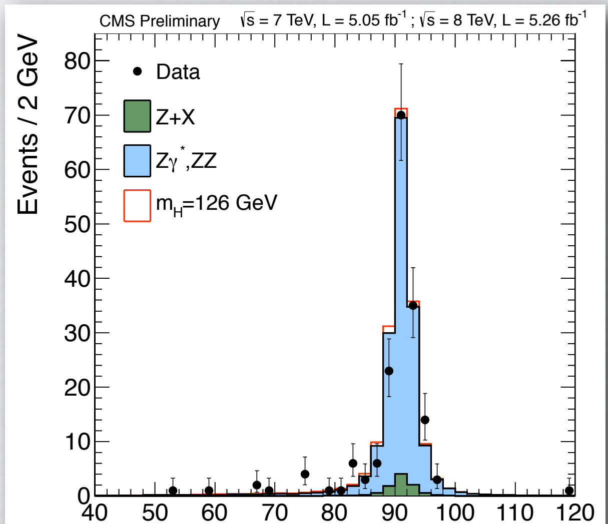


Event selection

- Trigger:
  - di(tri)-lepton signatures (ee, eμ or μμ)
- Leptons
  - **muons**: p_T > 5 GeV, isolated, compatible with PV
  - **electrons**: p_T > 7 GeV, isolated, compatible with PV
  - at least one lepton pair with p_T > 20/10 GeV
- First Z candidate (Z_1)
  - built from OSSF lepton pair with m_{2l} closest to m_Z
  - require: **$40 < m_{2l} < 120$ GeV**
- Second Z candidate (Z_2)
  - built from remaining OSSF highest p_T lepton pair
  - require: **$12 < m_{2l} < 120$ GeV**
- FSR correction for all three channels
  - FSR photons removed from isolation cones of all leptons
- m_{2l} > 4 GeV for OSAF pairs (QCD rejection)
- Mass selection: **m_{4l} > 100 GeV**

selection efficiency for 4e, 4μ, 2e2μ



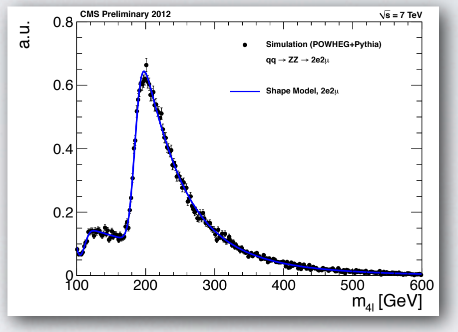


m_{Z1} spectrum

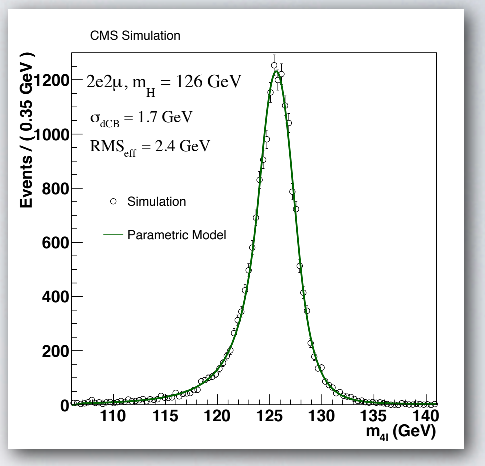
Signal and background models

- Signal model
  - Empirical param. shapes from simulation
  - Corrected for data/simulation scale
- Irreducible background
  - Empirical param. shapes from simulation
  - Corrected for data/simulation scale

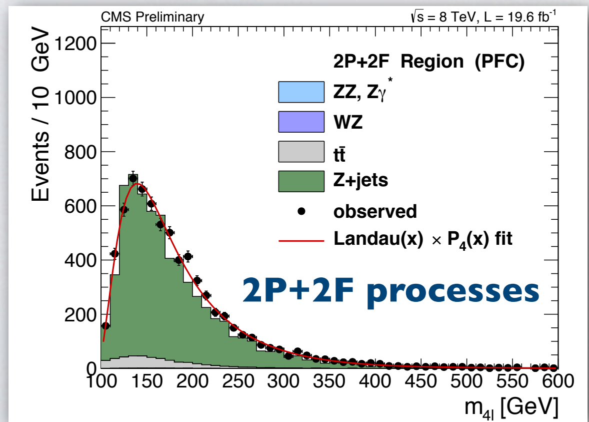
qq → ZZ → 2e2μ

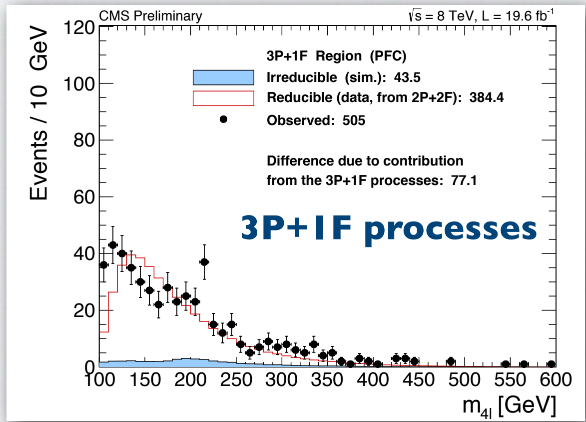


qq → H → ZZ → 2e2μ

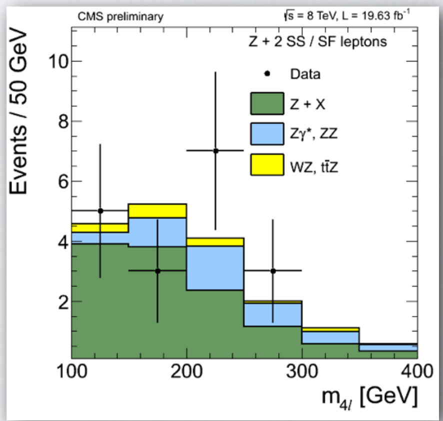


- Instrumental backgrounds estimated from data
  - Extrapolation from samples enriched with misidentified leptons (iso+ID) - 2 independent methods
    AA) **2P+2F** (2 pass + 2 fail) sample, dedicated correction for γ conversions in Z+γ+jets
    A) **2P+2F** & **3P+1F** (3 pass + 1 fail) sample, measures contributions from Z+γ+jets & WZ+jets
  - Total uncertainty ~40% (statistics, systematics of method/shape)



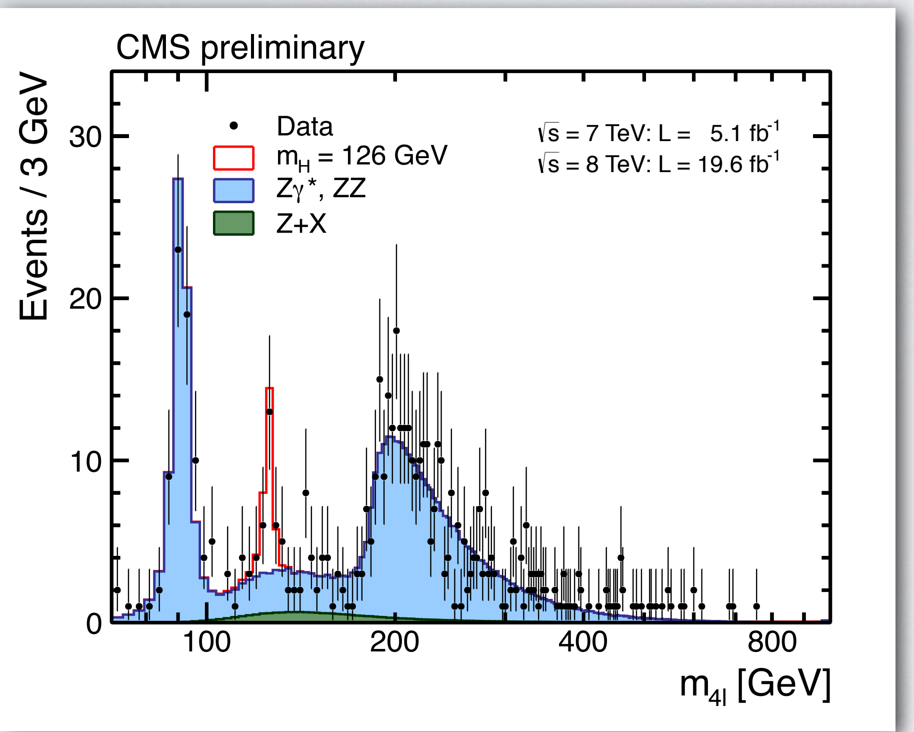


Validation in data (Z+SS/SF)

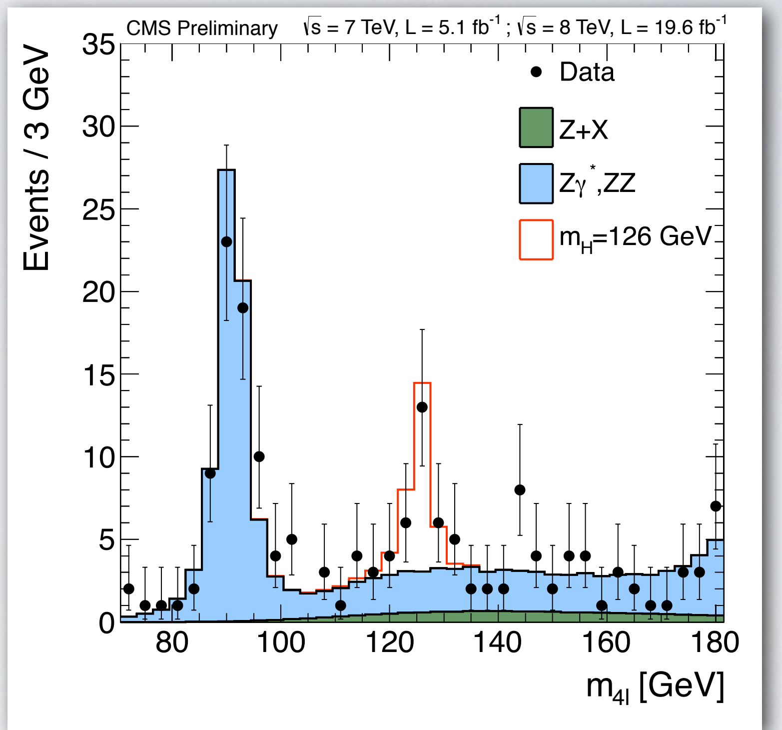


4 lepton mass spectrum

High-mass range



Low-mass range



- Good agreement with SM expectations
- Good agreement for the near-by resonance $Z \to 4l$ (normalization, shape)
- **Excess of events around 126 GeV** according to the SM Higgs expectations

$121.5 < m_{4l} < 130.5$ GeV	
H (126 GeV)	18.6
ZZ	7.4
Z+X	2.0
Total expected	28.0
Data	25

Expected S/B ≈ 2.0

Kinematic Discriminants

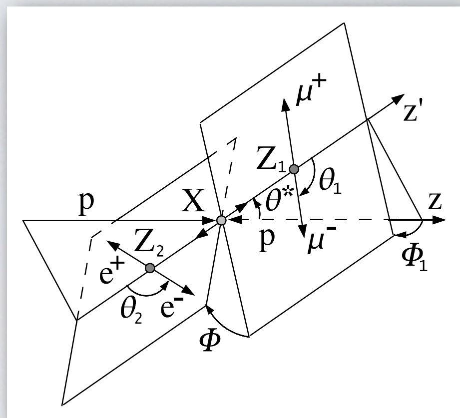
- Use the ratio of **LO** matrix elements to build kinematic discriminants
  - do not use system $\mathbf{p_T}$ and rapidity **Y** (NLO effects, PDFs)

Discriminator *KD* to separate SM Higgs from backgrounds:

$$KD = \left[1 + \frac{\mathcal{P}_{\rm BKG}(\vec{p}_i)}{\mathcal{P}_{\rm Higgs}(\vec{p}_i)}\right]^{-1}$$

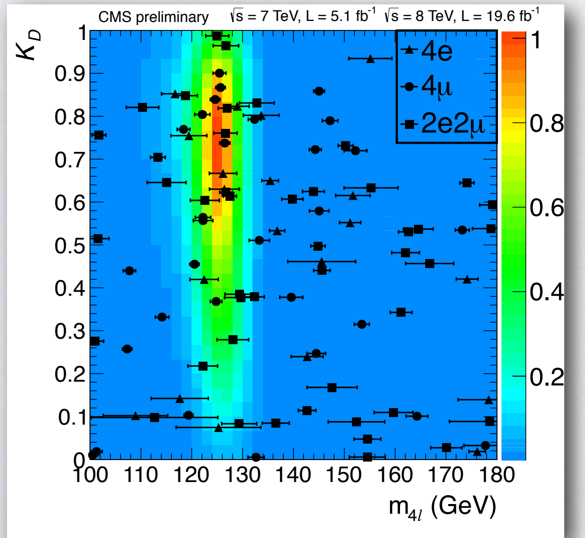
Probabilities $\mathcal{P}$ defined by the LO matrix elements for each value of m_{4l}.

Use kinematics of 4l system

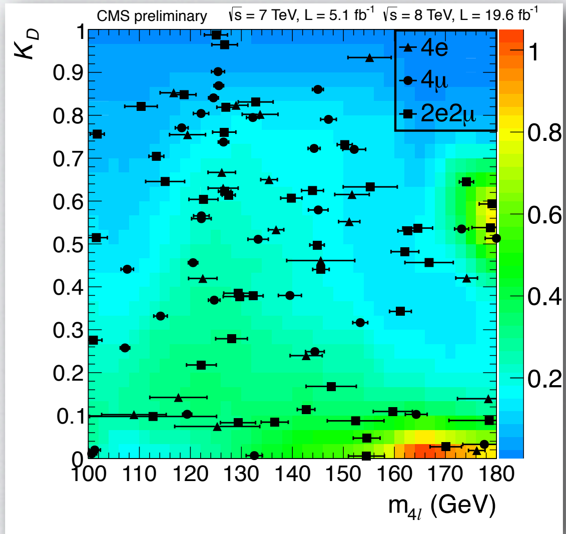


- Matrix elements computed using **MELA (JHUGen & MCFM)**
  - validated with **analytical MELA** and **MEKD (Madgraph+FeynRules)**, also **BDT/BNN**.

Higgs signal



ZZ background

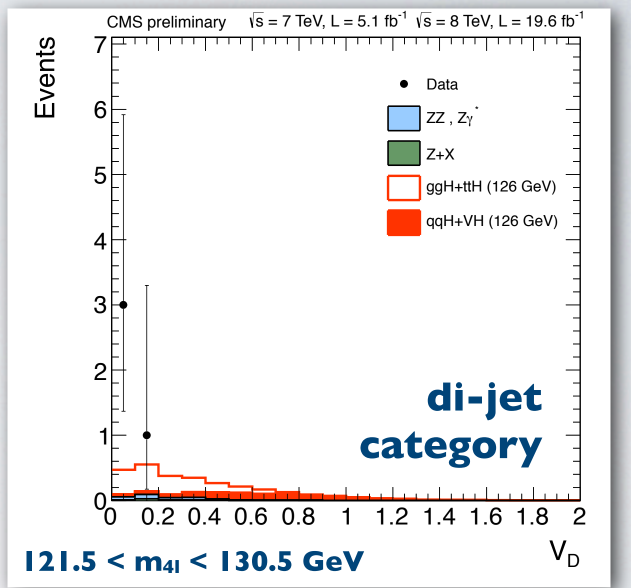


arXiv 1001.3396
arXiv 1108.2274
arXiv 1208.4018
arXiv 1210.0896
arXiv 1211.1959

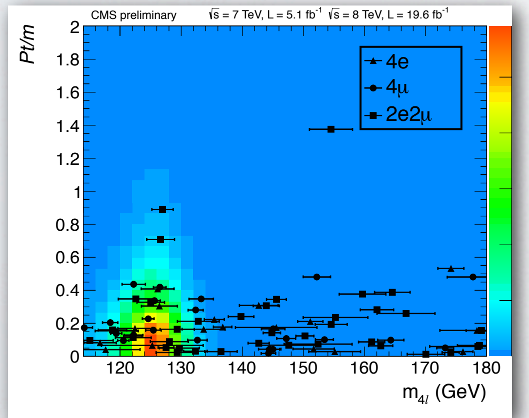
Event categories in the analysis

- The event sample is split into two categories:
  - **Category I:** Events with $\mathbf{N_{JETS} < 2}$. **(5% VBF)**
  - **Category II:** Events with $\mathbf{N_{JETS} \geq 2}$. **(20% VBF)**
- Discriminate production mechanisms (fermion- vs. vector-boson-induced):
  - **Cat. I:** using discriminant: $\mathbf{p_T/m_{4l}}$
  - **Cat. II:** using linear discriminant: $\mathbf{V_D = \alpha\,\Delta\eta_{jj} + \beta\,m_{jj}}$
- Analysis based on correlated 3D distributions:
  - **Cat. I:** $\mathcal{P}(m_{4l}) \times \mathcal{P}(KD \mid m_{4l}) \times \mathcal{P}(p_T/m_{4l} \mid m_{4l})$
  - **Cat. II:** $\mathcal{P}(m_{4l}) \times \mathcal{P}(KD \mid m_{4l}) \times \mathcal{P}(V_D \mid m_{4l})$

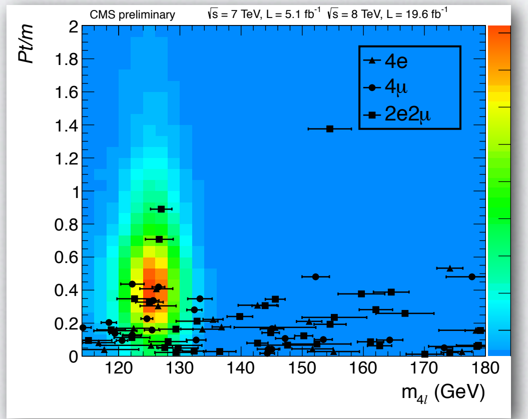
V_D distribution



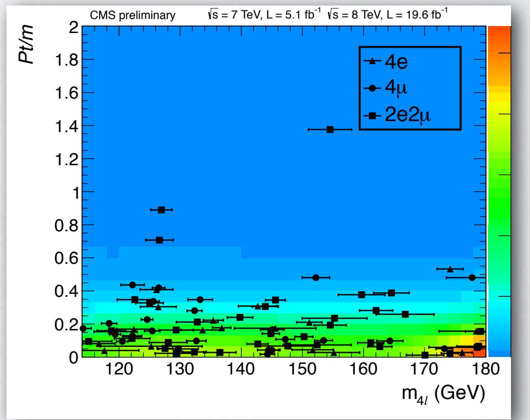
gg → H



VBF

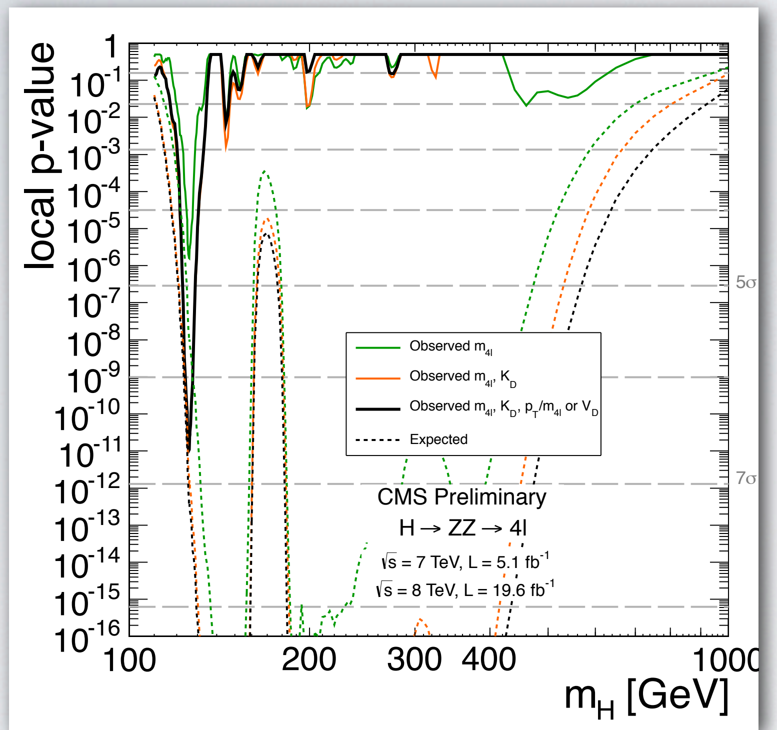


qq → ZZ

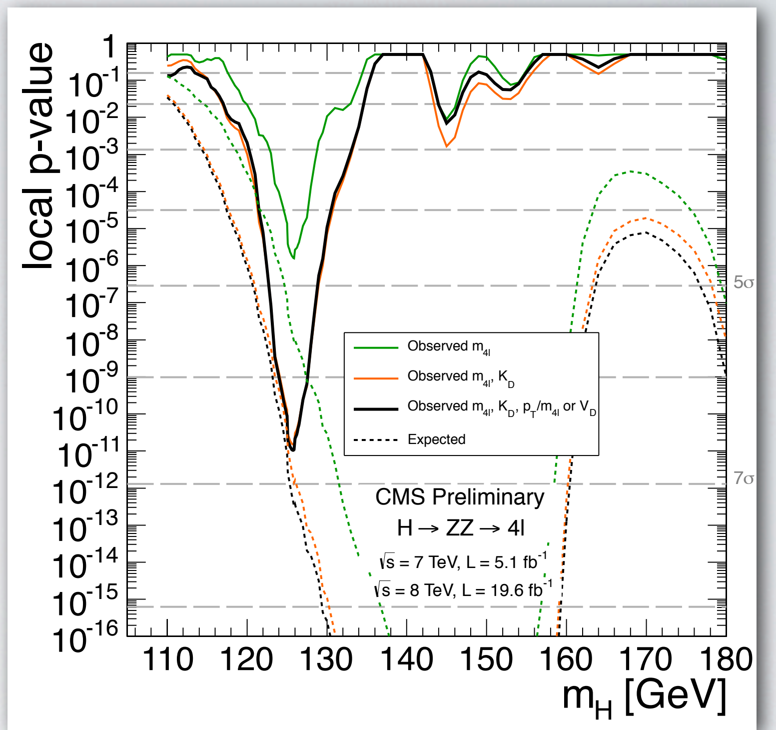


Excess characterization

High-mass region



Low-mass region



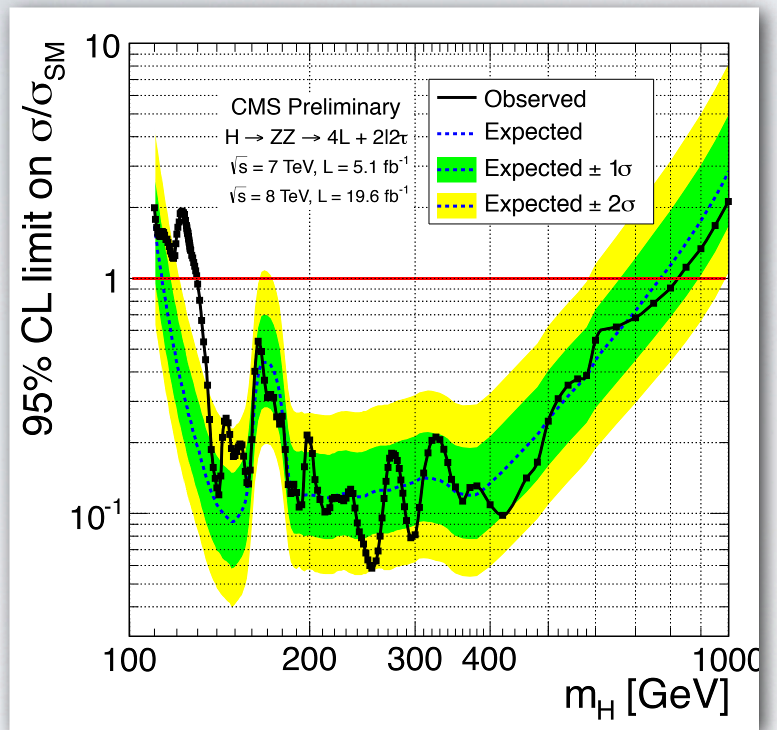
Observed and expected stat. significance for excess at 125.8 GeV

@ m_{4l} = 125.8 GeV	m_{4l}	m_{4l}, K_D	m_{4l}, K_D, p_T/m_{4l} or V_D
p-value (observed/expected)	4.7σ / 5.6σ	6.6σ / 6.9σ	6.7σ / 7.2σ

➡ **Sensitivity improved significantly by exploiting full kinematics**

Excess characterization

High-mass region



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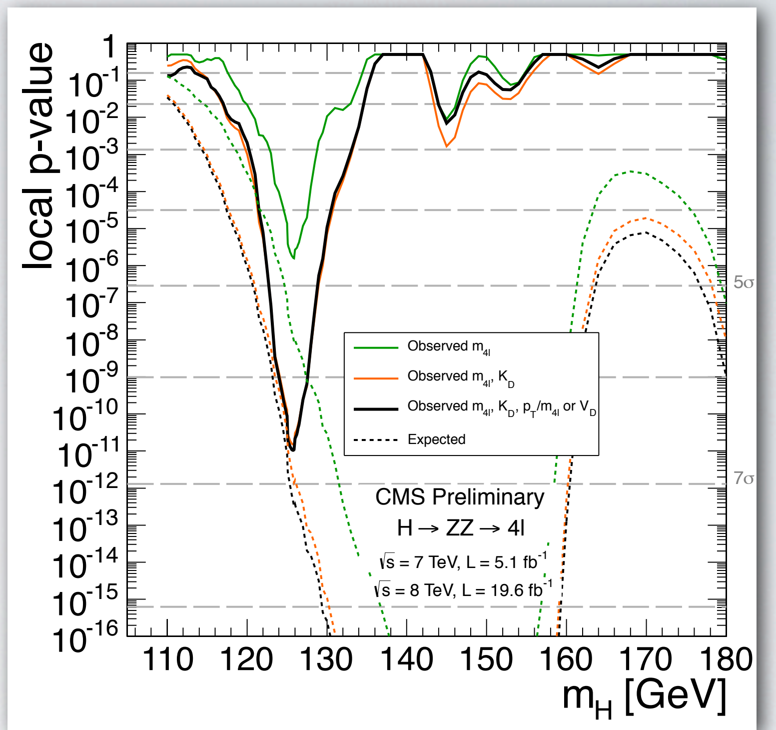

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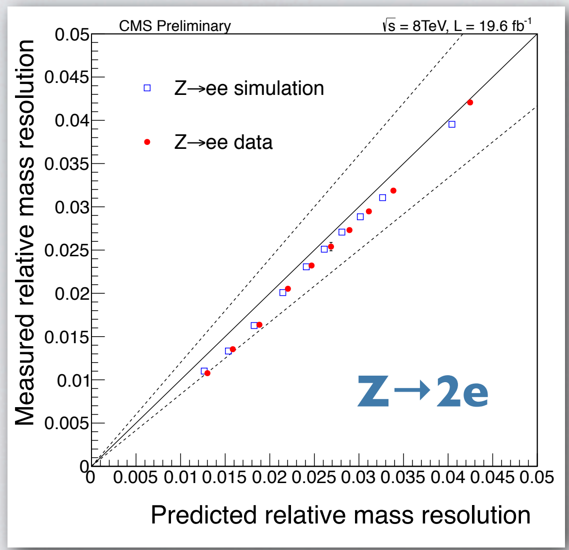
Sensitivity improved significantly by exploiting full kinematics

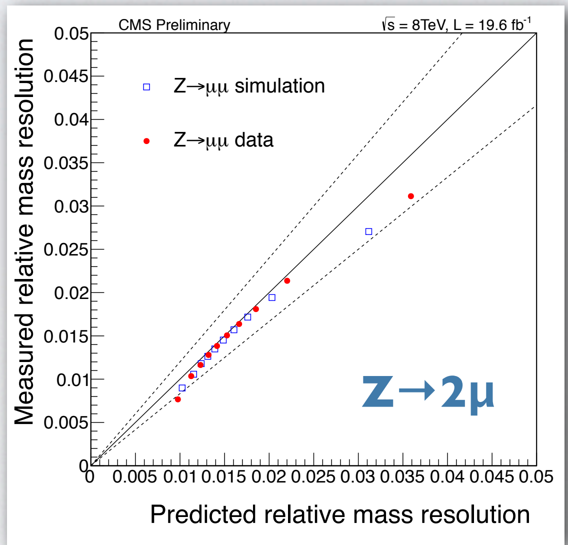
Excluded SM Higgs hypothesis @95% CL: [130, 827] GeV (4l + 2l2τ)

Even-by-event mass uncertainties

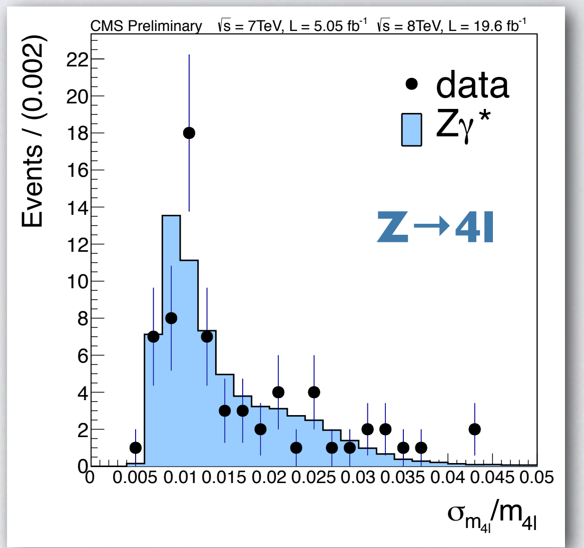
- Weight individual events in the mass fit according to their mass uncertainties **δm_{4l}**
- Estimate per-event m_{4l} uncertainties from individual lepton momentum errors:
  - **muons:** using the full error matrix obtained from the muon track fit,
  - **electrons:** estimated from the combination of the ECAL and tracker measurements.
  - calibrated in data, validated using $Z\to 2e$, $Z\to 2\mu$ and $Z\to 4l$ (assigned **20% uncertainty**)

predicted vs. measured δm_{4l} in Z events





relative δm_{4l} in $Z\to 4l$

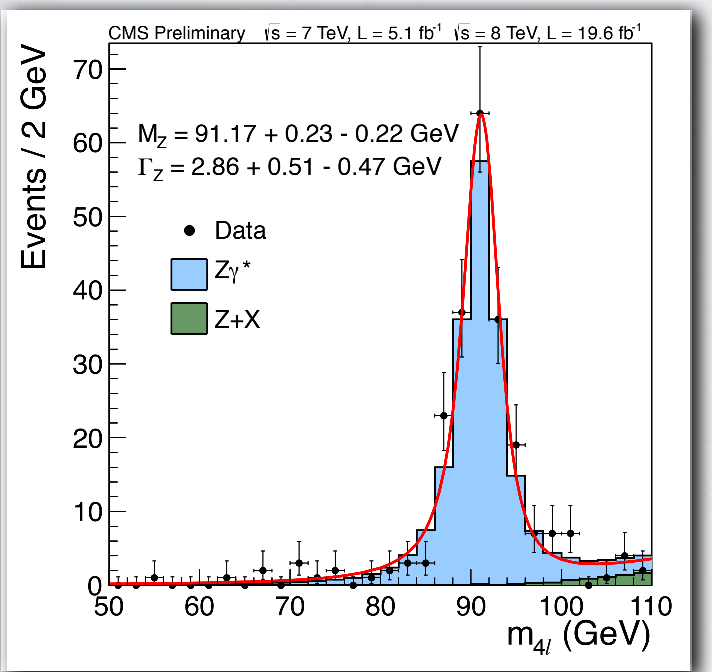


average expected improvement of 8%
on the measured mass uncertainty.

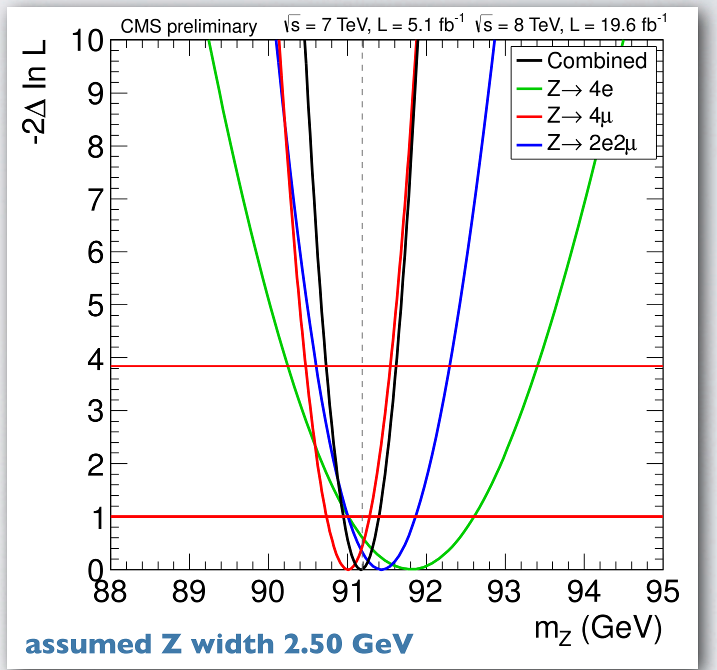
Mass measurement validation with Z → 4l

- Perform the mass measurement of the near-by Z → 4l resonance
  - **identical procedure** as for the new boson mass measurement (without δm_{4l} and *KD*),
  - **relaxed phase space** due to the limited statistics (m_{Z2} > 4 GeV)

fit for Z mass/width in Z → 4l events



likelihood scans for 4e, 4μ, 2e2μ

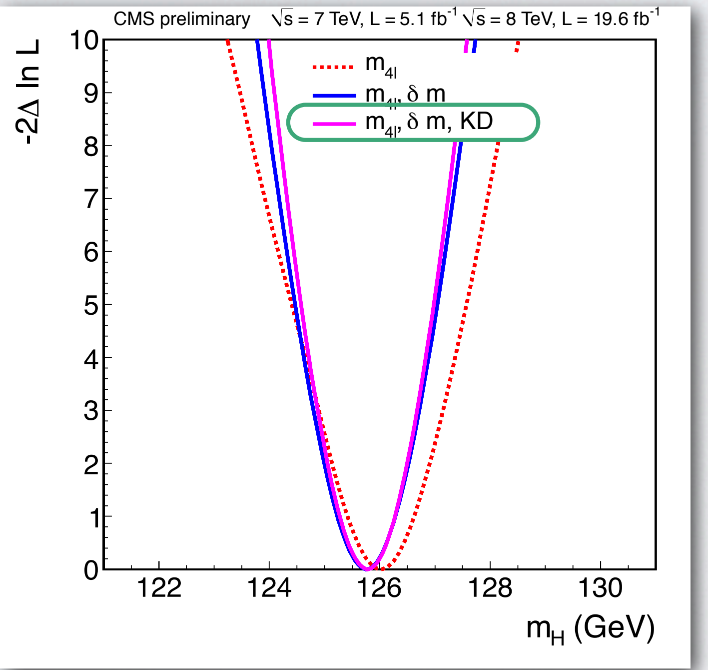


Compatible with the PDG values within uncertainties.

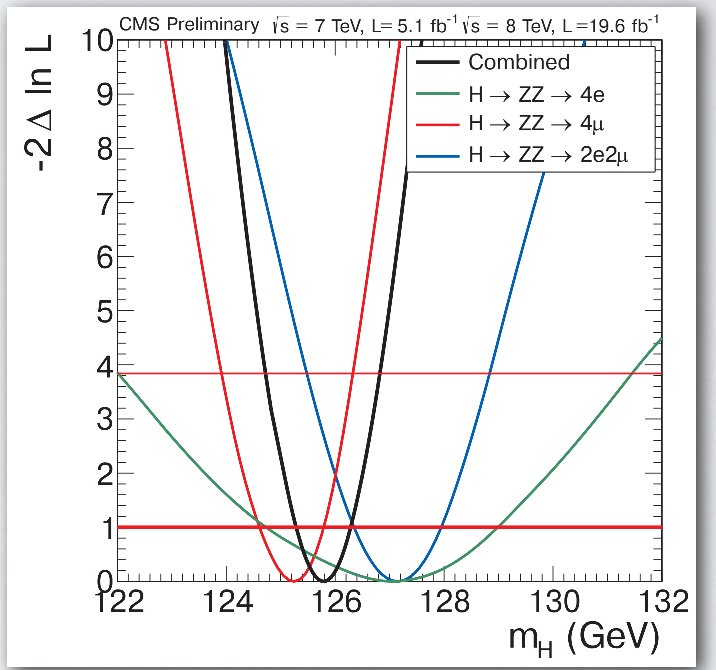
Mass measurement

- Mass measurement performed with a **3D fit** using for each event:
  - four-lepton invariant mass $\mathbf{m_{4l}}$,
  - associated **per-event mass uncertainty $\boldsymbol{\delta m_{4l}}$**,
  - kinematic discriminant **KD**.

profiled likelihood scan for 4l



profiled likelihoods for 4e, 4μ, 2e2μ



Mass of the newly observed boson:

$\mathbf{m_{4l} = 125.8 \pm 0.5_{stat} \pm 0.2_{syst}}$ **GeV**

Signal strengths and production mechanisms

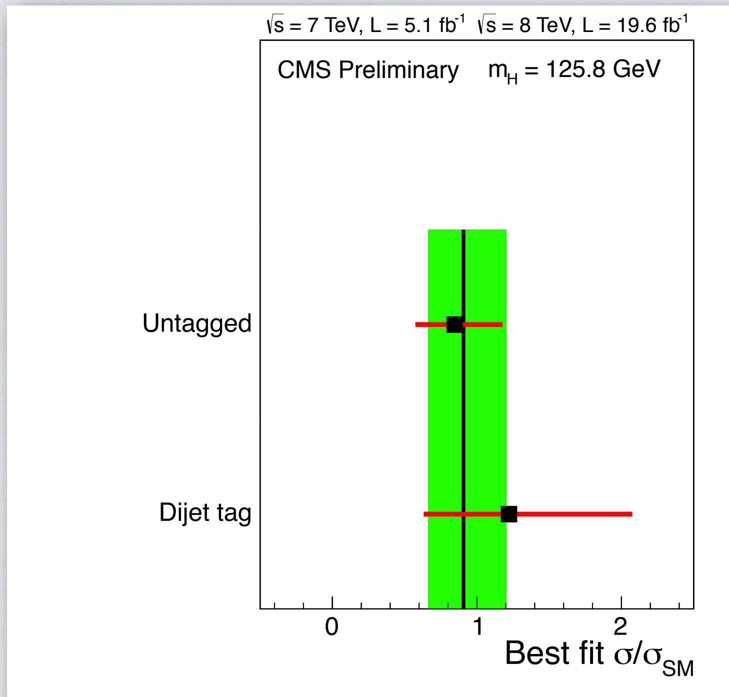
- Signal strength measured for each of the two categories (relative to the SM expectation)

signal strengths (modifiers): $\mu_I = 0.85 \pm 0.32$ (Cat. I)

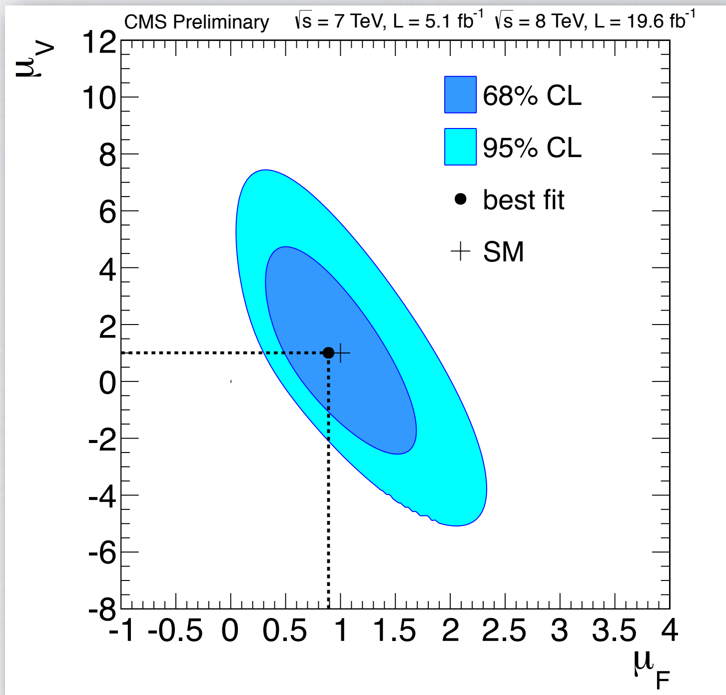
$\mu_{II} = 1.22 \pm 0.84$ (Cat. II)

total: $\mu = 0.91 \pm 0.30$

Measured signal strength



signal strength modifiers μ_V, μ_F



- Signal strength modifiers for classes of V-induced and F-induced production mechanisms:

signal strengths (modifiers): $\mu_V = 1.0 \pm 2.4$ (VBF, VH)

$\mu_F = 0.9 \pm 0.5$ (ggH, ttH)

Alternative J^{CP} hypotheses testing

- Perform the test of the compatibility of the new boson with alternative hypotheses
  - test a few reasonably well motivated J^P hypotheses ("pure" states only)
  - no full consensus on the choice of models in the TH community

J^P	production	description
0^+	$gg \to X$	SM Higgs boson
0^-	$gg \to X$	pseudoscalar
0_h^+	$gg \to X$	BSM scalar with higher dim operators in decay amplitude
2_{mgg}^+	$gg \to X$	KK Graviton-like with minimal couplings
$2_{mq\bar{q}}^+$	$q\bar{q} \to X$	KK Graviton-like with minimal couplings
1^-	$q\bar{q} \to X$	exotic vector
1^+	$q\bar{q} \to X$	exotic pseudovector

- Fit for the fractional presence of CP-odd contribution in case of the scalar hypothesis

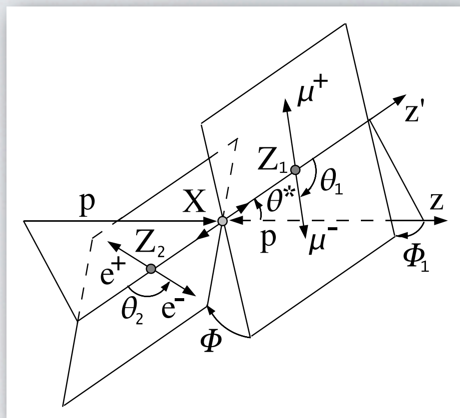
Kinematic Discriminants

- Use the ratio of **LO** matrix elements to build kinematic discriminants

Discriminator D_{J^P} to separate SM from an alternative J^P hypothesis:

$$D_{J^P} = \left[1 + \frac{\mathcal{P}_{\mathrm{J^P}}(\vec{p}_i)}{\mathcal{P}_{\mathrm{Higgs}}(\vec{p}_i)}\right]^{-1}$$

Use kinematics of the 4l system

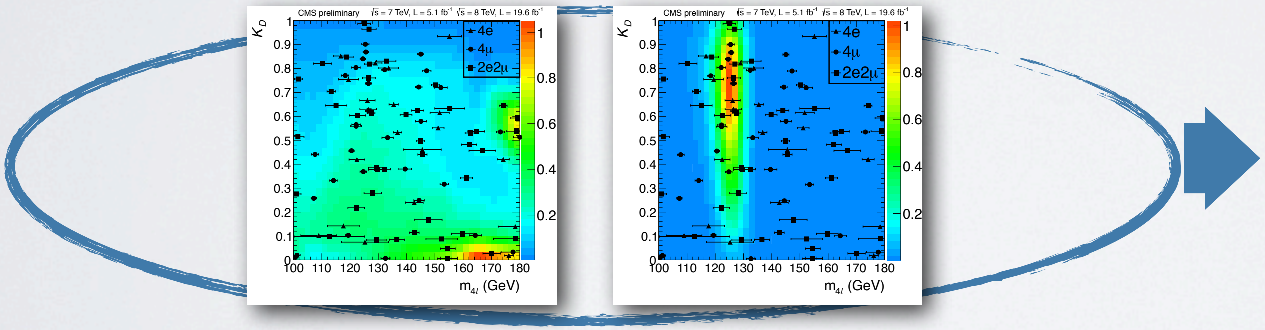


Discriminator D_{BKG} to separate SM Higgs from backgrounds:

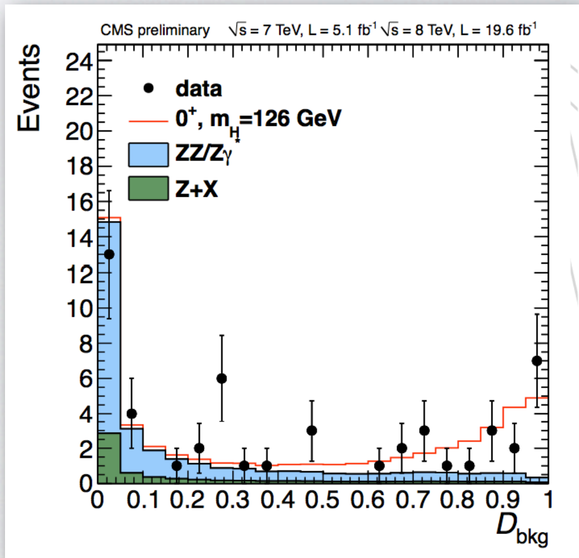
$$D_{\mathrm{BKG}} = \left[1 + \frac{\mathcal{P}_{\mathrm{BKG}}(\vec{p}_i) \cdot \mathcal{P}(m_{4\ell}|\mathrm{BKG})}{\mathcal{P}_{\mathrm{Higgs}}(\vec{p}_i) \cdot \mathcal{P}(m_{4\ell}|\mathrm{Higgs})}\right]^{-1}$$

Probabilities $\mathcal{P}$ defined by the LO matrix elements for each value of m_{4l}.

Combined kinematics and m_{4l} information into one discriminant



106 < m_{4l} < 141 GeV

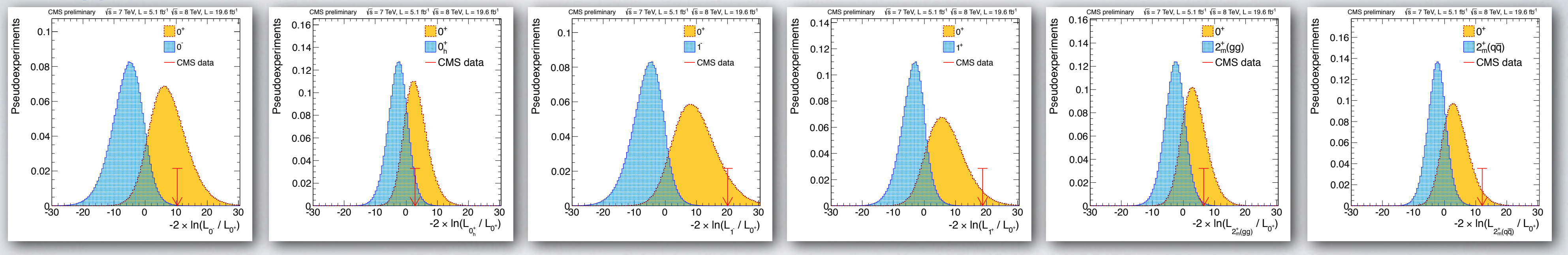


- Statistical analysis based on 2D distributions $\mathcal{P}$**(D_{J^P} , D_{BKG})**

Alternative J^{CP} hypotheses testing

- Test statistics for the separation between J^P hypotheses (expected and observed):

$gg \to 0^-$ **$gg \to 0_h^+$** **$qq \to 1^-$** **$qq \to 1^+$** **$gg \to 2_m^+$** **$qq \to 2_m^+$**



- Expected separation between J^P hypotheses and the observed results with the data:

J^P	production	comment	expect (μ=1)	obs. 0^+	obs. J^P	CL_s
0^-	$gg \to X$	pseudoscalar	2.6σ (2.8σ)	0.5σ	3.3σ	0.16%
0_h^+	$gg \to X$	higher dim operators	1.7σ (1.8σ)	0.0σ	1.7σ	8.1%
2^+_{mgg}	$gg \to X$	minimal couplings	1.8σ (1.9σ)	0.8σ	2.7σ	1.5%
$2^+_{mq\bar{q}}$	$q\bar{q} \to X$	minimal couplings	1.7σ (1.9σ)	1.8σ	4.0σ	<0.1%
1^-	$q\bar{q} \to X$	exotic vector	2.8σ (3.1σ)	1.4σ	$>4.0\sigma$	<0.1%
1^+	$q\bar{q} \to X$	exotic pseudovector	2.3σ (2.6σ)	1.7σ	$>4.0\sigma$	<0.1%

in case a hypothesis is disfavoured with large confidence we quote > 4.0σ,

All tested alternative hypotheses (except 0_h^+) excluded with at least 95% C.L.

Fraction of a CP-odd contribution

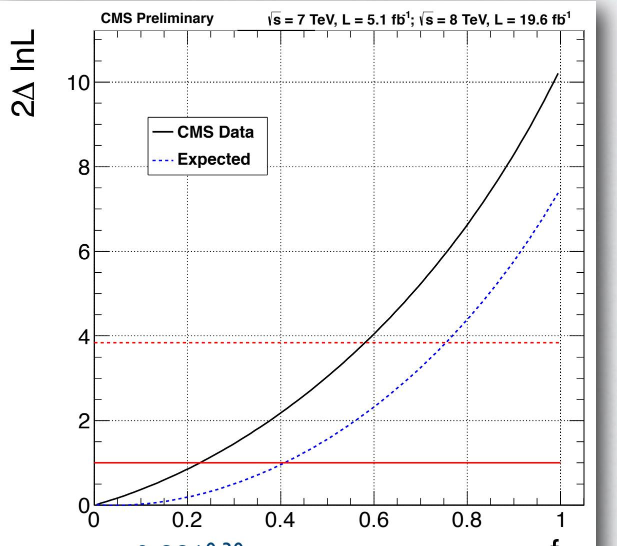
- Asses a fractional presence of the CP-odd contribution (0^-) in the scalar decays:

$$f_{a3} = \frac{\sigma_{0^-}}{\sigma_{0_m^+} + \sigma_{0^-}}$$

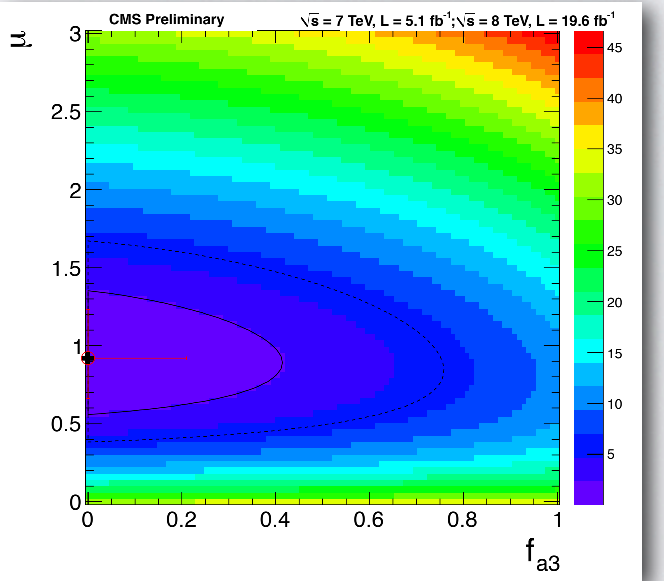
$$A(X \to VV) = v^{-1}\epsilon_1^{*\mu}\epsilon_2^{*\nu}\left(a_1 g_{\mu\nu} m_H^2 + a_2 q_\mu q_\nu + a_3 \epsilon_{\mu\nu\alpha\beta} q_1^\alpha q_2^\beta\right) = A_1 + A_2 + A_3$$

A_2 contribution assumed to be 0

  - **0_m^+** decays governed by the **A_1** amplitude (cross-section **σ_{0-}**),
  - **0^-** decays governed by the **A_3** amplitude (cross-section **σ_{0m+}**),
- Take separate 2D templates for SM Higgs (0_m^+) and 0^- states and fit the data for their relative presence (total events yields taken from data)



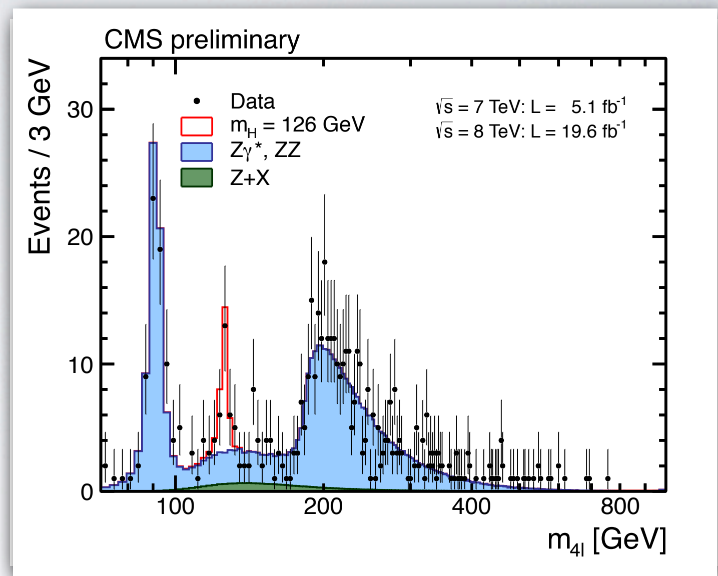
$\mu_{profiled} = 0.92^{+0.30}_{-0.27}$



- Measurement of the f_{a3} fraction in data: $\boldsymbol{f_{a3} = 0.00^{+0.23}_{-0.00}}$, $\boldsymbol{f_{a3} < 0.56}$ (@95%CL)

Conclusions

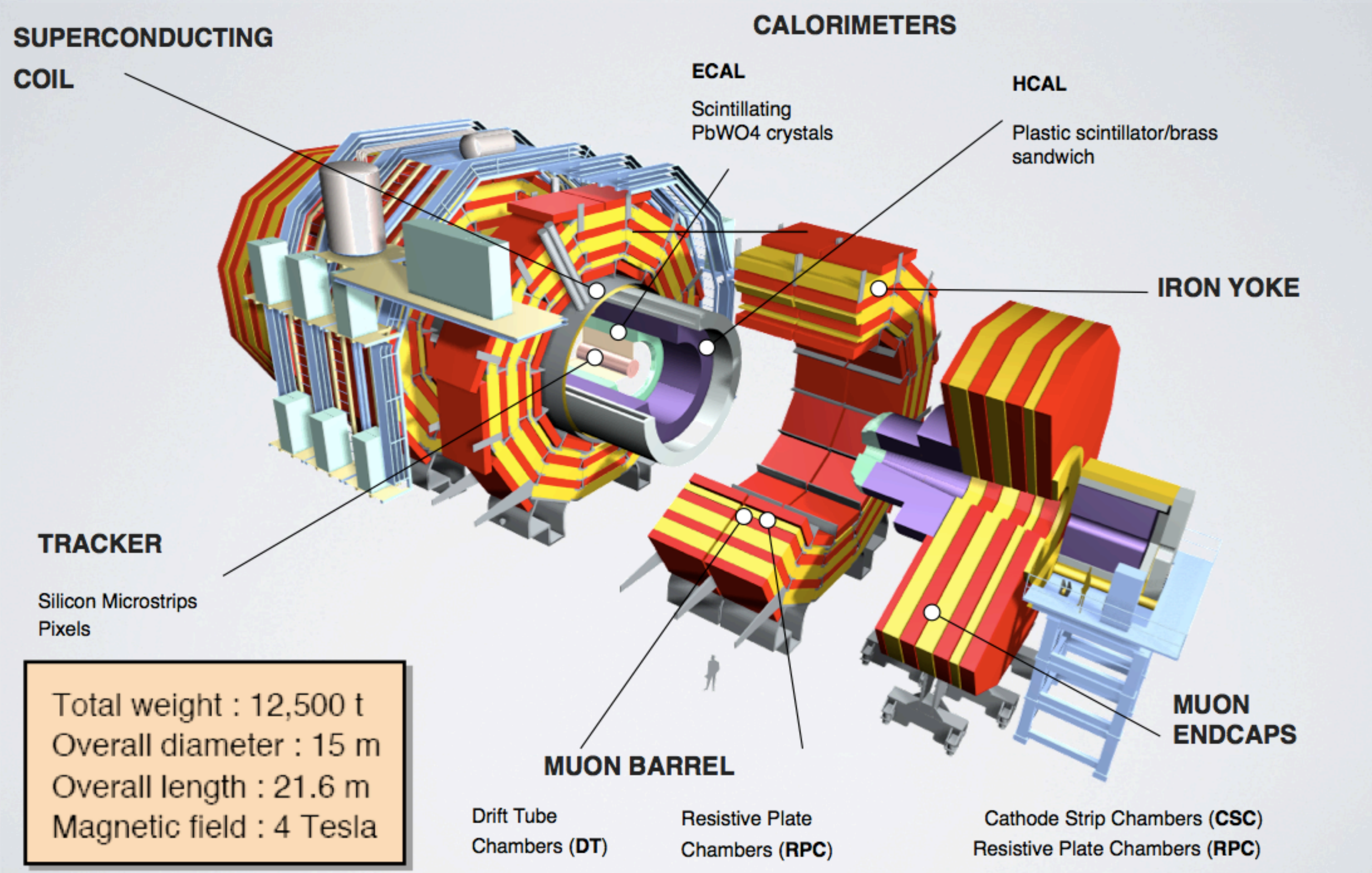
- LHC and its experiments delivered **impressive results** on a short timescale!
- CMS established presence of the Higgs-like boson in $H \rightarrow ZZ \rightarrow 4l$ decay mode with local **stat. significance 6.7σ**



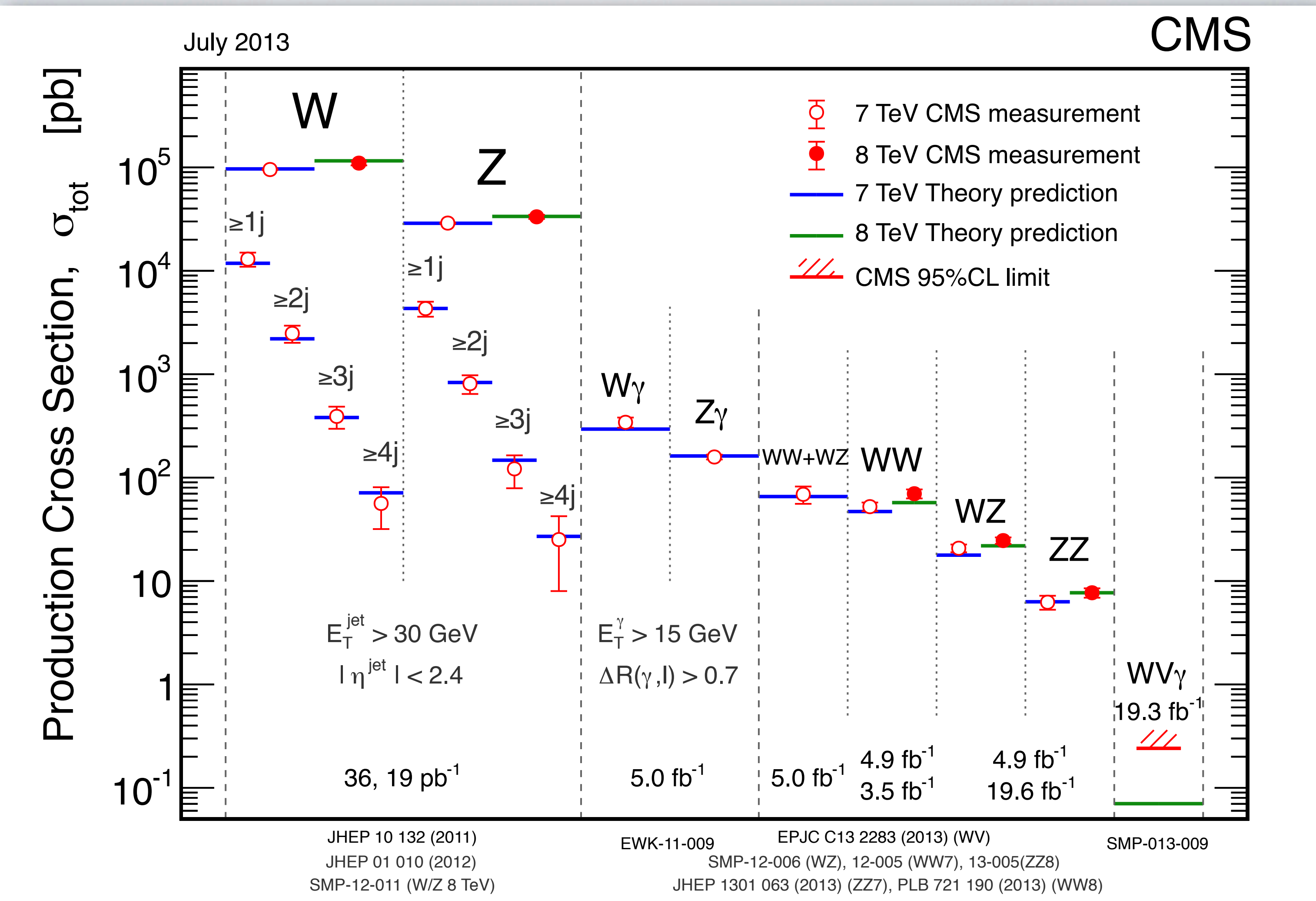
- Boson mass measured at the 4 per mil level:
  $125.8 \pm 0.5_{stat} \pm 0.2_{syst}$ GeV
- The observed boson is **consistent with the SM**:
  - Signal strength, production mechanisms,
  - its scalar nature,
  - Additional SM Higgs-like boson excluded in [130, 827] GeV.
- Legacy paper with reanalyzed 25 fb^{-1} of 7+8 TeV data to be published soon
- A new era is opening in front of us with the LHC in 2015 and beyond:
  - Precise measurements of boson properties with increased E_{CM} and higher luminosity...
  - ...and **challenging of the SM predictions!**

Backup slides

Compact Muon Solenoid



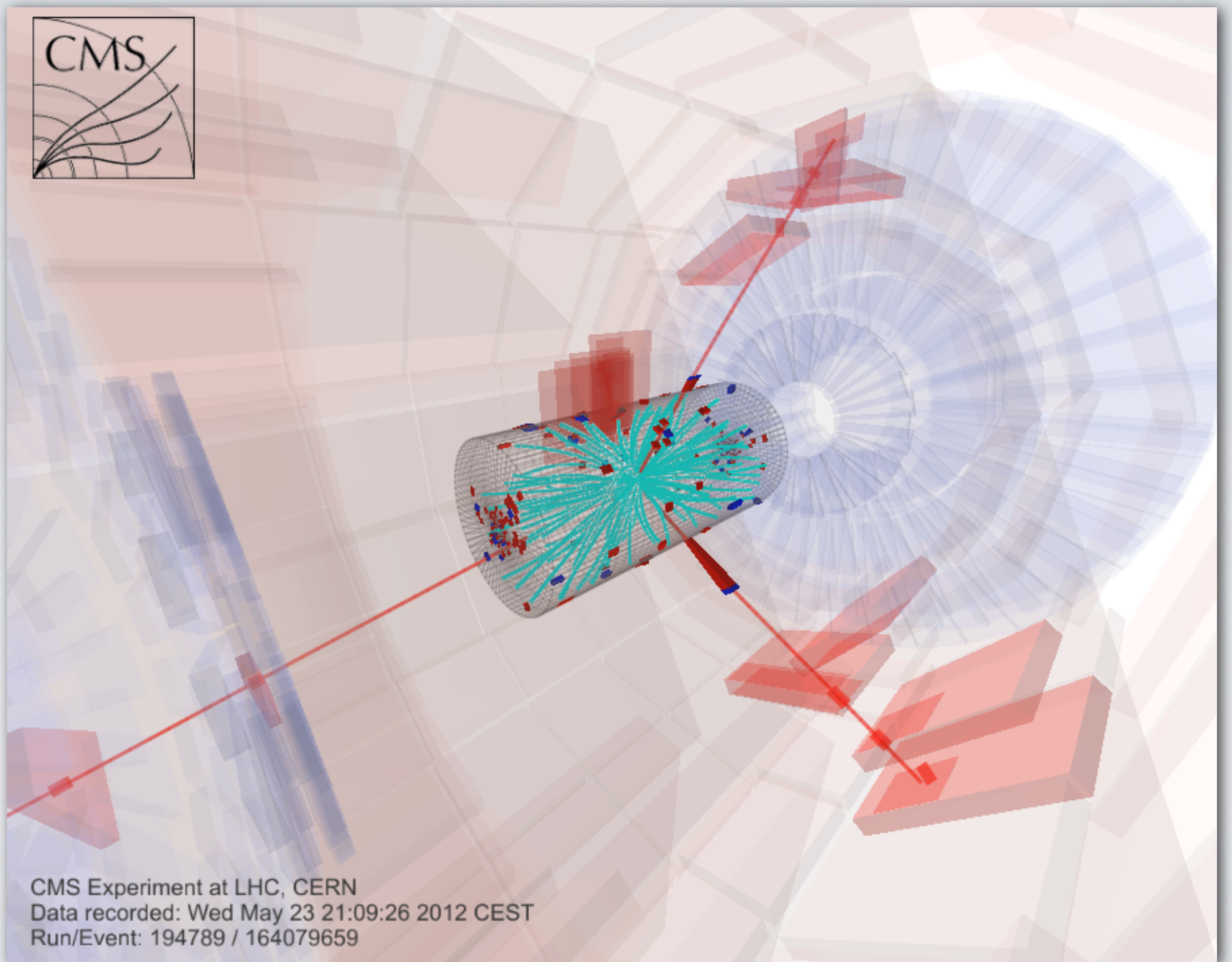
Precise SM (EWK) measurements



Good understanding of the detector & accurate SM predictions:

- Precise measurements of the SM processes
- Good understanding of the background for Higgs searches

A "H → ZZ → 4μ" event



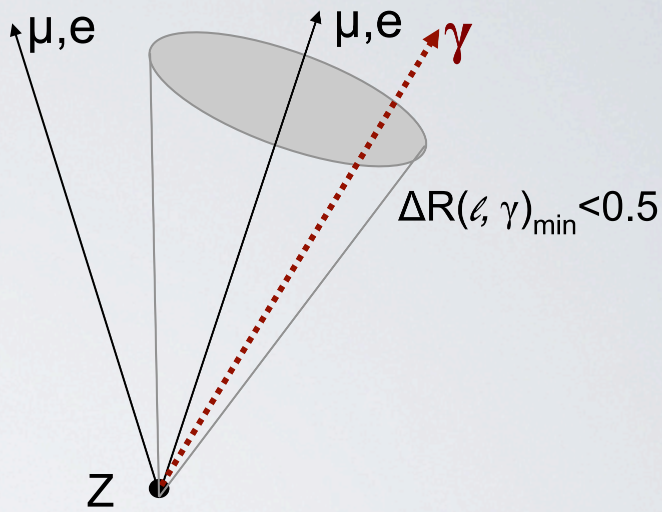
Final State Radiation recovery (CMS)

- Recovery algorithm
  - Applied on each Z for photons near the leptons (isolated photons, E_T > 2 GeV)
  - Associates photon with Z if:

    $$M_{2l+\gamma} < 100 \text{ GeV}$$

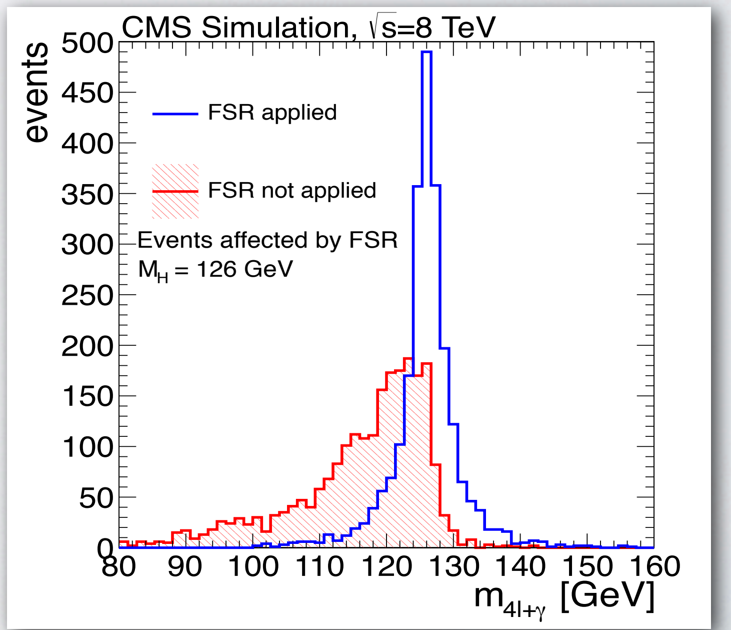
    $$| M_{2l+\gamma} - M_Z | < | M_{2l} - M_Z |$$

  - Removes associated photons from lepton isolation calculation



- Expected Performance for Higgs at 126 GeV
  - 6% of events affected
  - Average purity of 80%

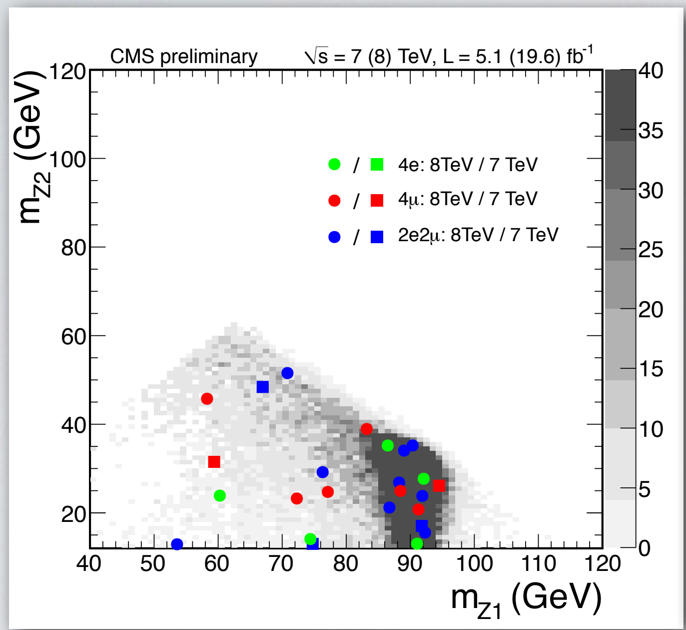
➡ **2% gain in the efficiency**



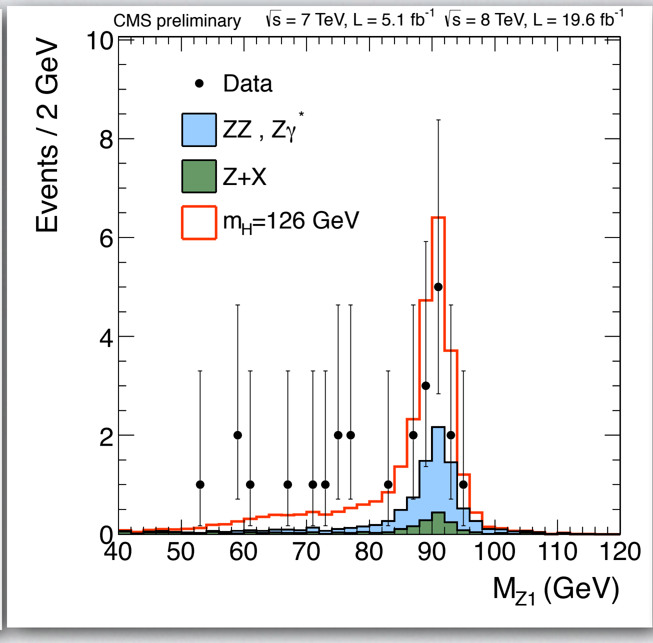
Dilepton masses

- Distributions of di-lepton masses for events with **$121.5 < m_{4l} < 130.5$ GeV**

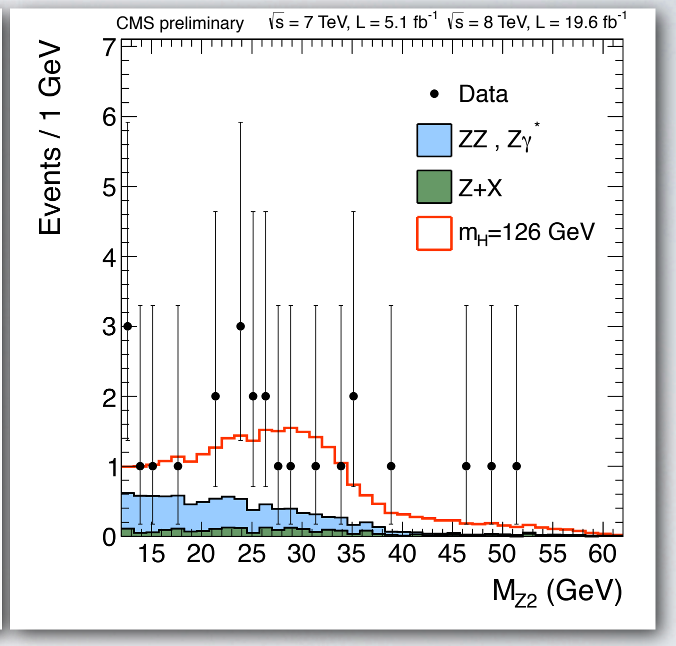
m_{Z1} vs. m_{Z2}



m_{Z1}



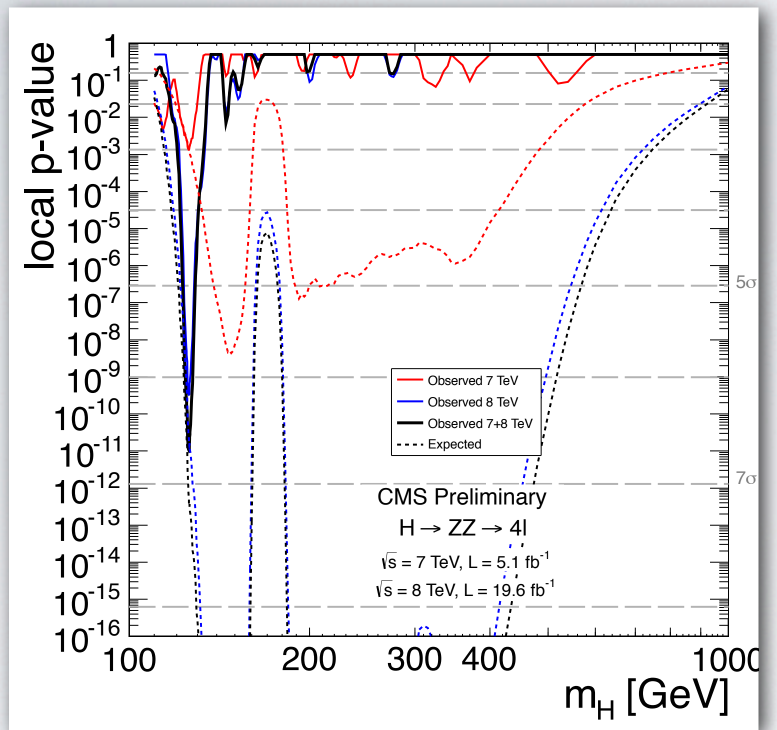
m_{Z2}



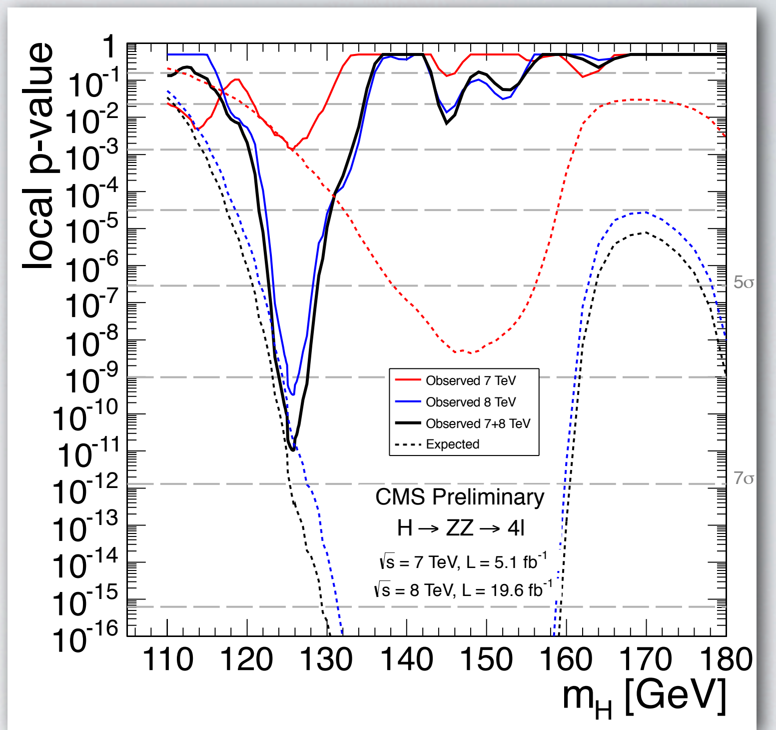
Masses m_{Z1} and m_{Z2} for candidate events around 125/126 GeV according to the SM expectations

Excess characterization

High-mass region



Low-mass region



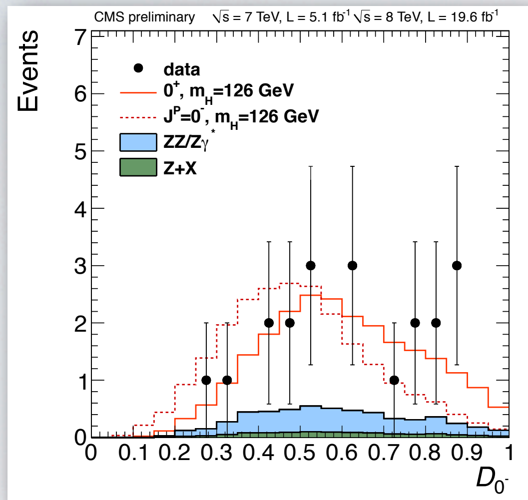
➡ Observed (expected) excess at 125.8 GeV
corresponding stat. significance: **~6.7σ (~7.2σ)**

Compatible/complementary excesses at 7 TeV and 8 TeV

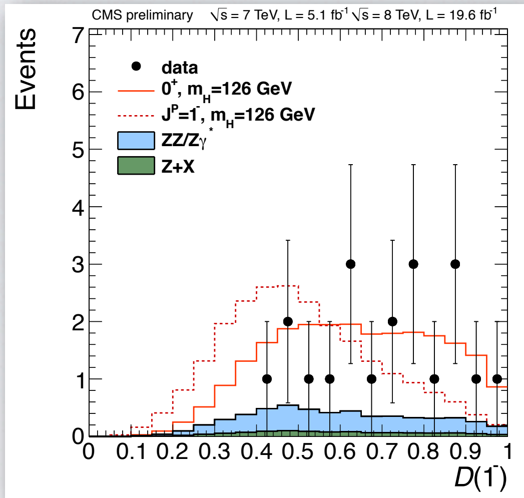
Discriminator D_{J^P} (D_{BKG} >0.5)

- D_{BKG} > 0.5 cut is just for illustration

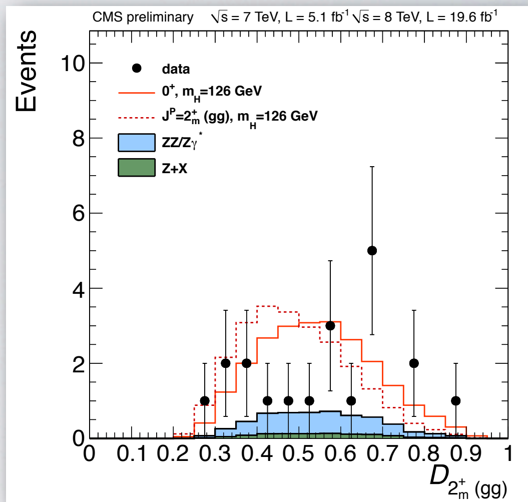
gg → 0⁻



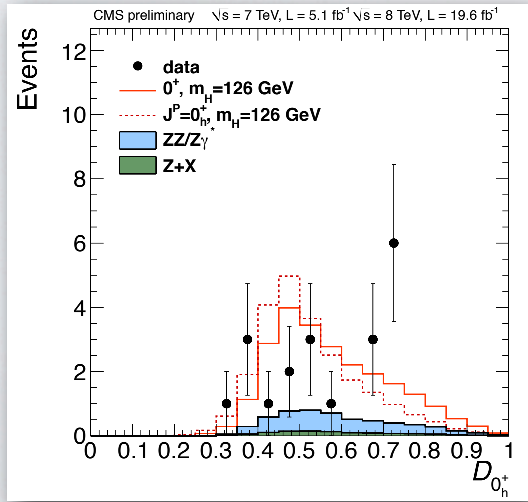
qq → 1⁻



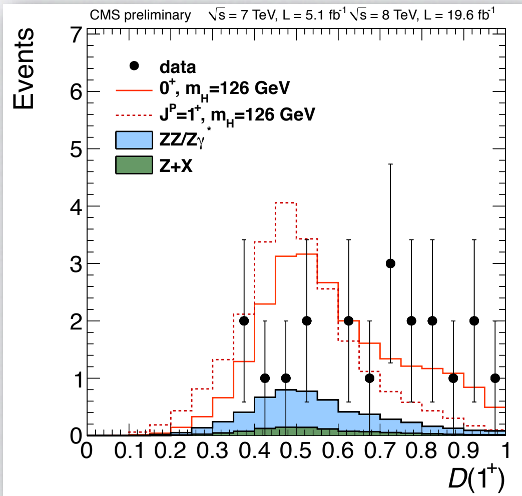
gg → 2m⁺



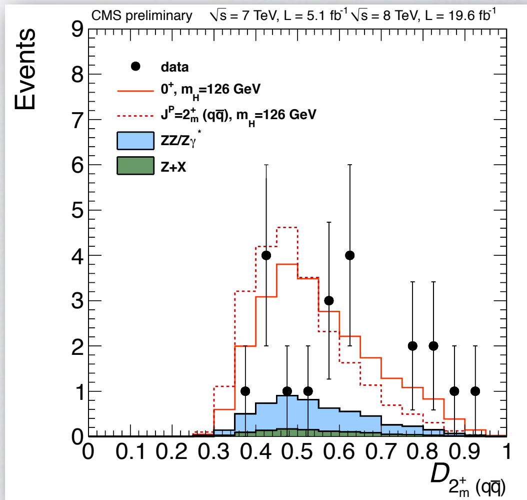
gg → 0h⁺



qq → 1⁺



qq → 2m⁺



Alternative J^{CP} hypotheses testing

- Expected separation between J^P hypotheses and the observed results with the data: