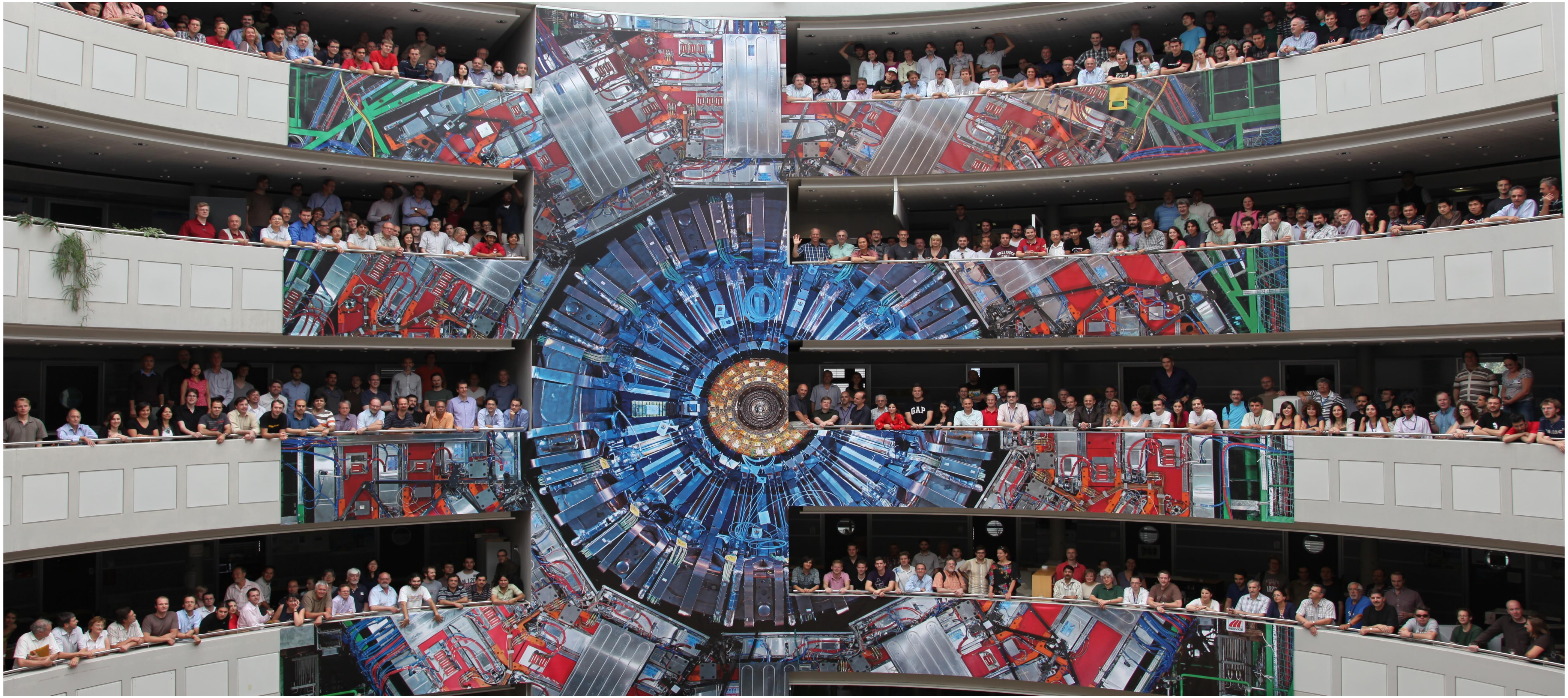
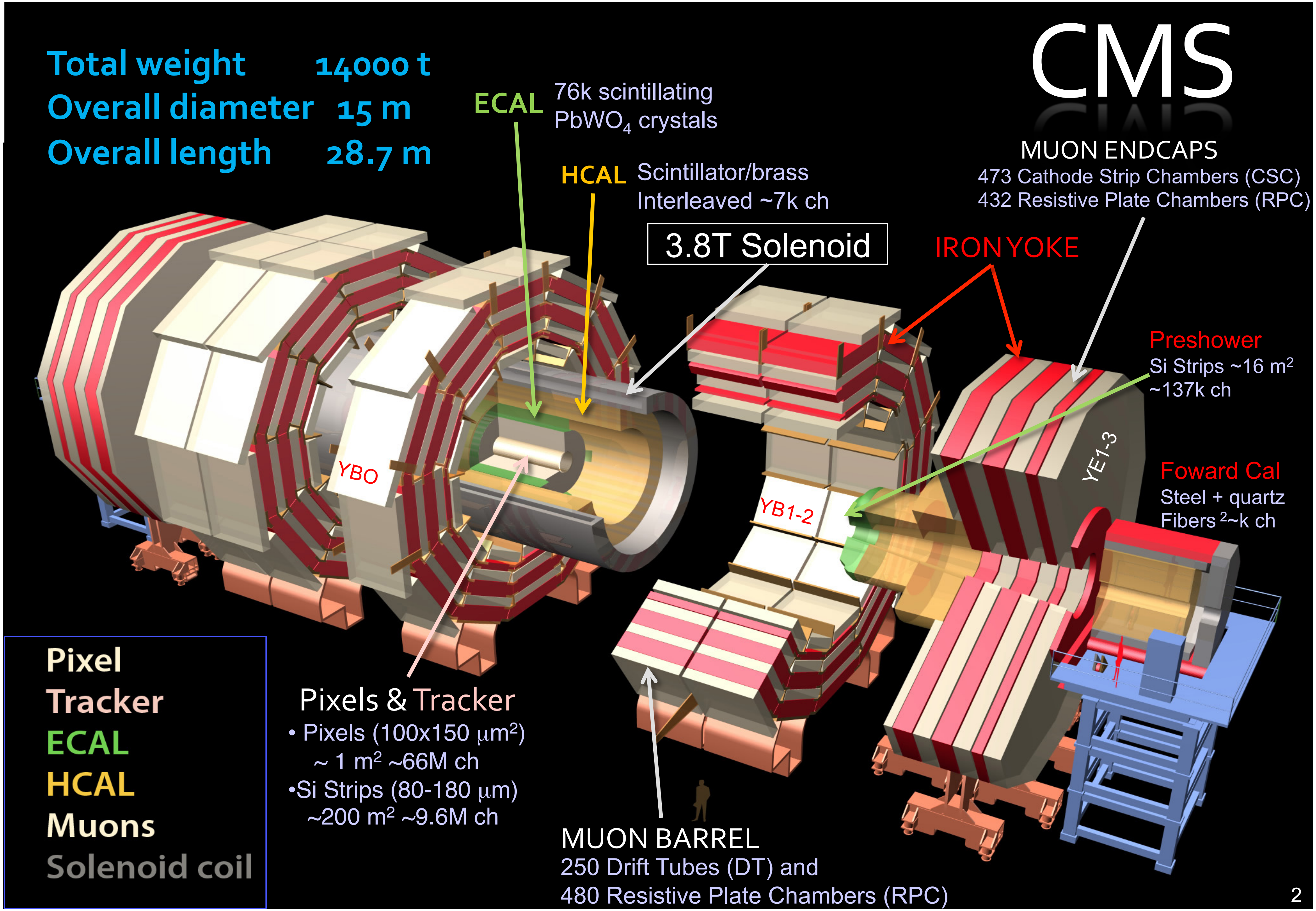


CMS Measurements of a New Boson in the H =>ZZ => Four Lepton Channel

Guenakh Mitselmakher
University of Florida

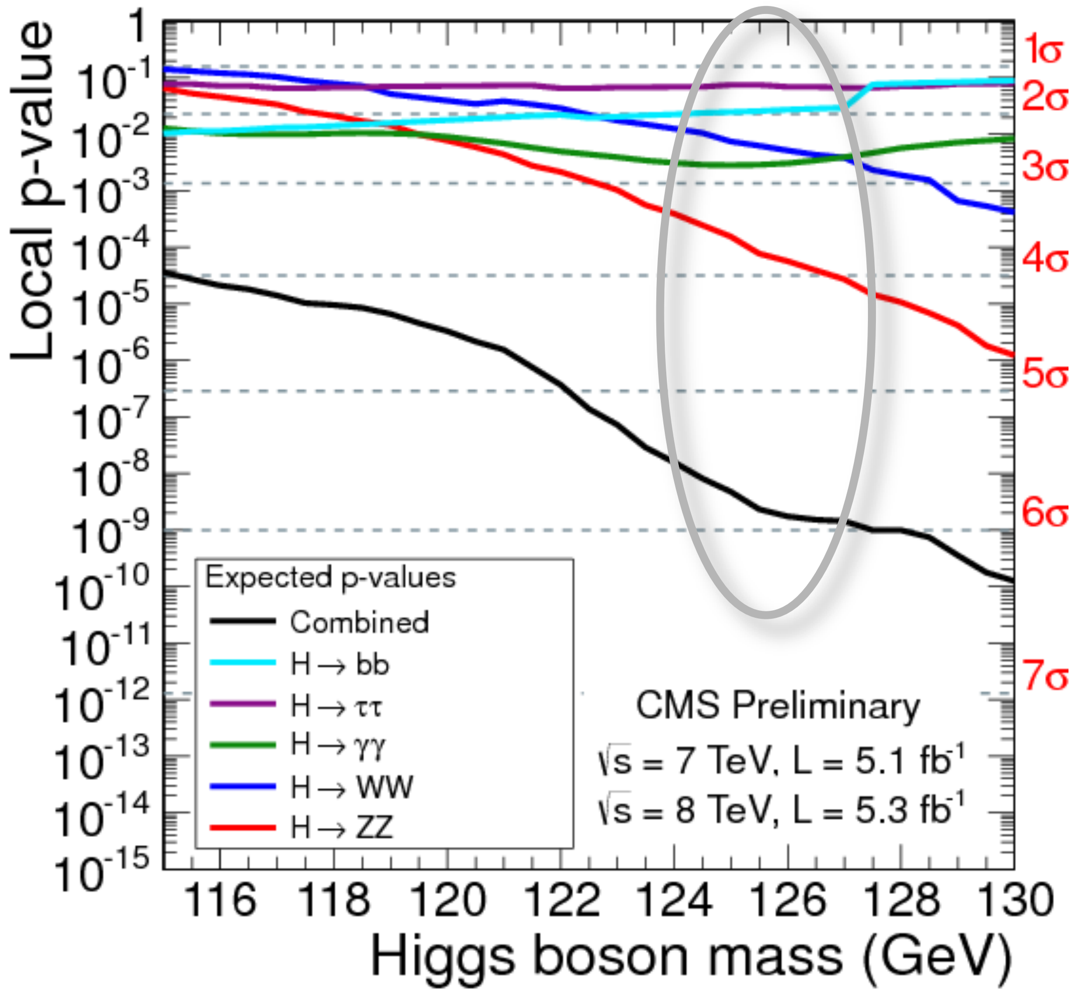


CMS
Total weight 14000 t
Overall diameter 15 m
Overall length 28.7 m
ECAL
76k scintillating
$PbWO_4$ crystals
HCAL
Scintillator/brass
Interleaved ~7k ch
3.8T Solenoid
IRON YOKE
MUON ENDCAPS
473 Cathode Strip Chambers (CSC)
432 Resistive Plate Chambers (RPC)
Preshower
Si Strips ~16 m^2
~137k ch
Foward Cal
Steel + quartz
Fibers ^{2}~k ch
YBO
YB1-2
YE1-3
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)

CMS Higgs Discovery potential (at the time of ICHEP-2012)

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.
- H→ZZ→4l potentially most sensitive channel
- Excellent prospects exploring properties

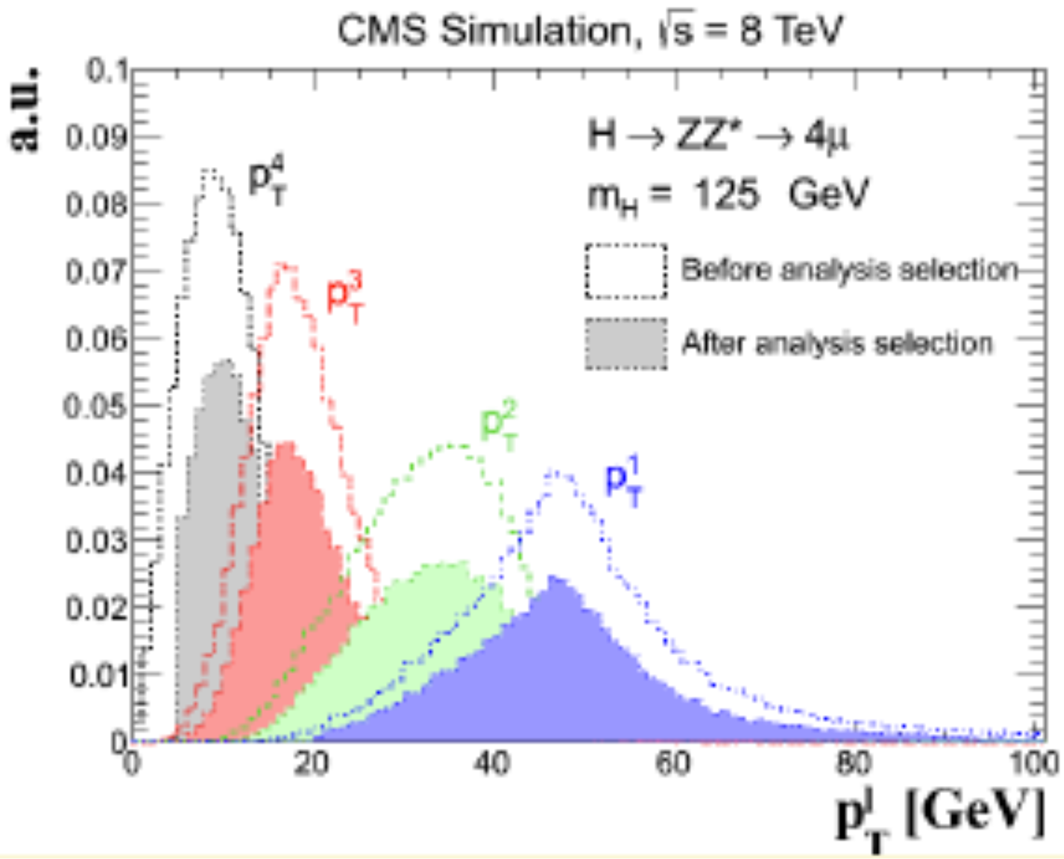


Triggers used in the 4l channel

- CMS Trigger requires the presence of at least a pair of leptons (electrons or muons). The minimal momenta of the first and second lepton are 17 and 8 GeV, respectively, for the double lepton triggers

- The trigger efficiency within the acceptance of this analysis is greater than 98% for a SM Higgs boson signal with mH > 120 GeV in the 4l channel

A challenge: 4 Leptons selection



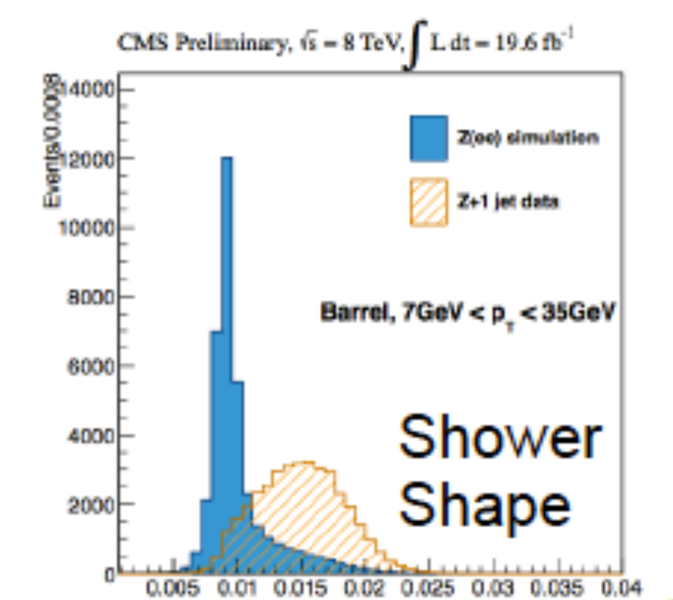
- Almost 50% of leptons from low mass Higgs →4l have pT less than 10 GeV
- A challenge for the lepton selection in the analysis
- Control of background rate is difficult at low pT
- Control of lepton selection efficiencies is also a challenge at low pT

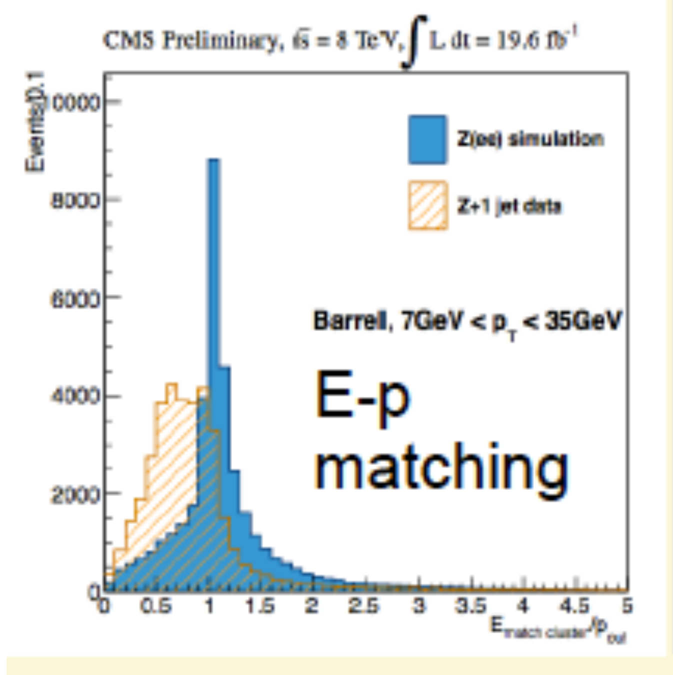
Multivariate Electron selection

- Improve discrimination power by combining multiple observables using a boosted-decision tree (BDT)

- BDT training is using signal simulation and W+Jets data sample

- Many checks and validations



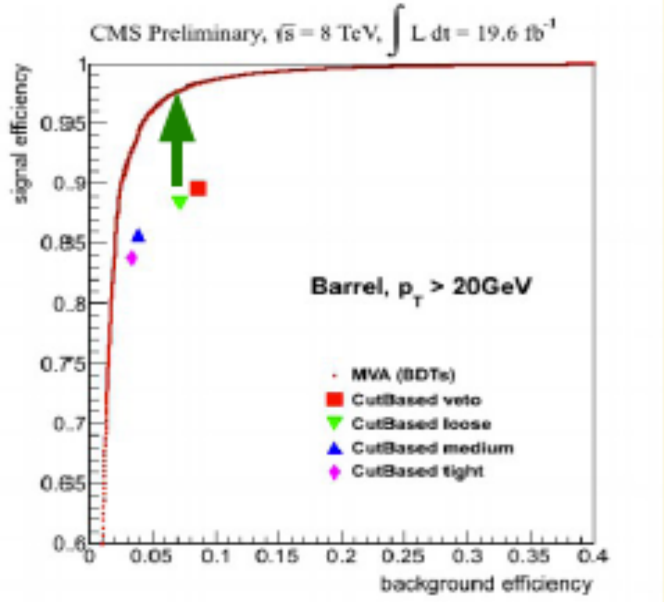


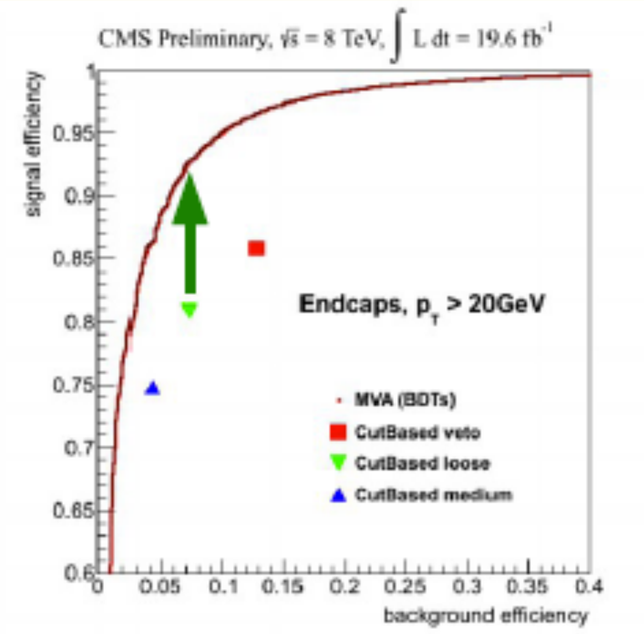
Multivariate Electron selection

- significant improvement:
  signal efficiency increased

- Barrel
  90% → 98% pT > 20 GeV
  70% → 85% pT < 20 GeV

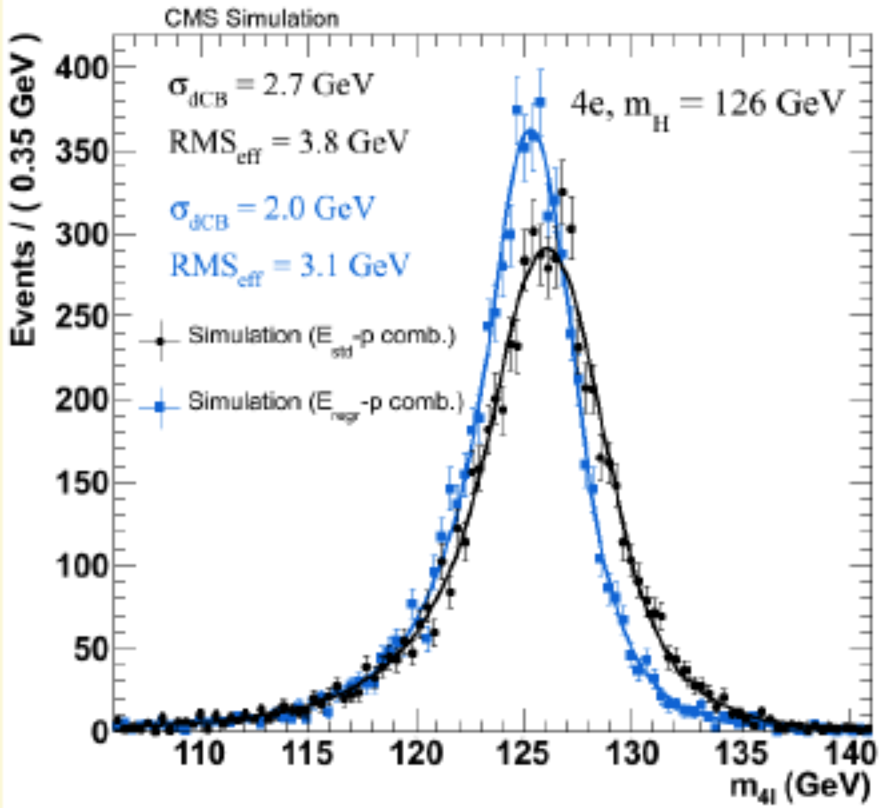
- Endcap
  85% → 95% pT > 20 GeV
  50% → 70% pT < 20 GeV





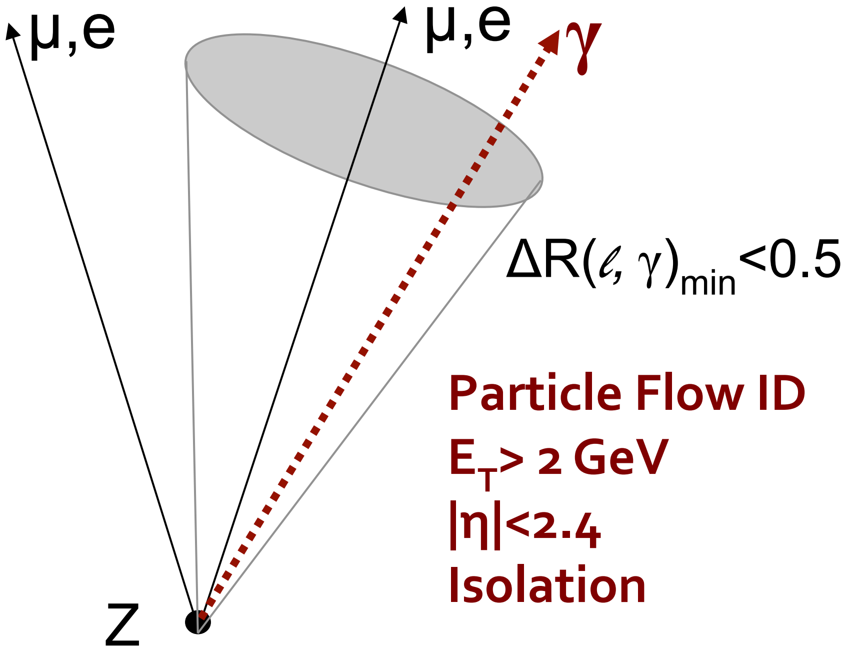
Electron Energy Regression

- Corrections applied using a multivariate regression trained with simulation
- Incorporate detailed information on shower shape & local geometry (gaps and crystal edges)
- **Significant Improvement in mass resolution for 4e channel: 25% better**



Final State Radiation recovery

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

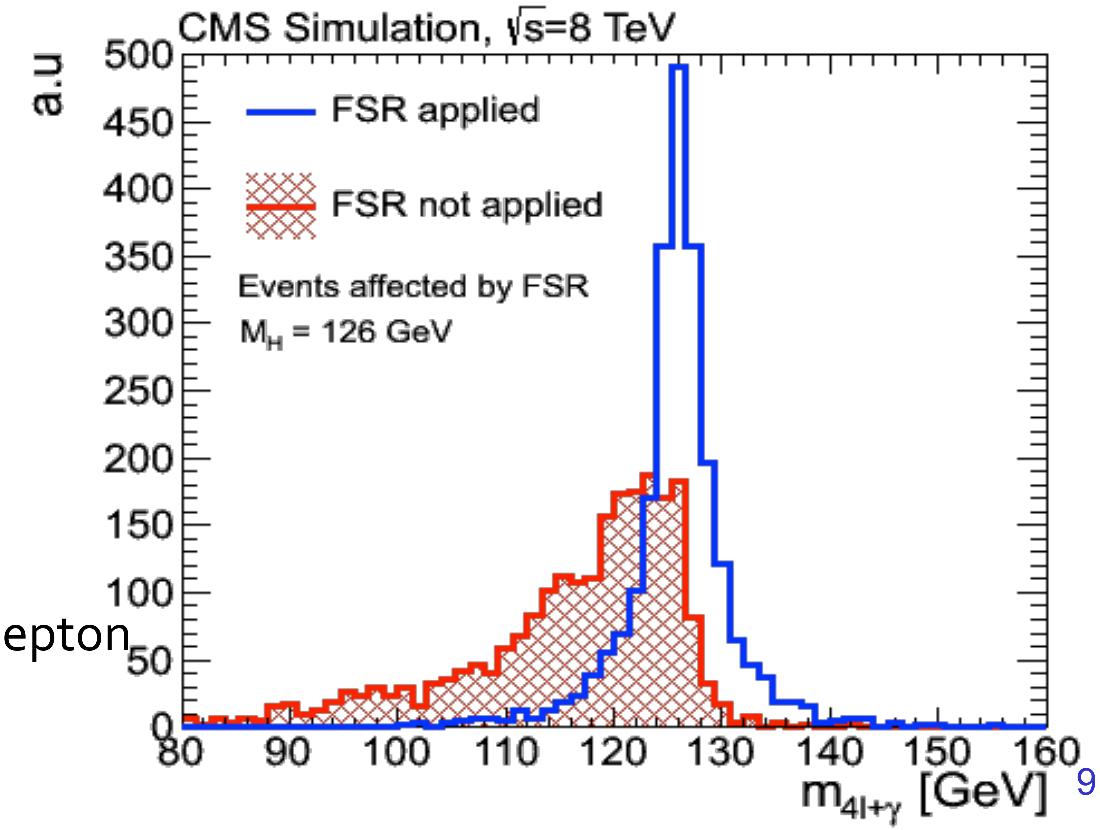


Particle Flow ID
E_T> 2 GeV
|η|<2.4
Isolation

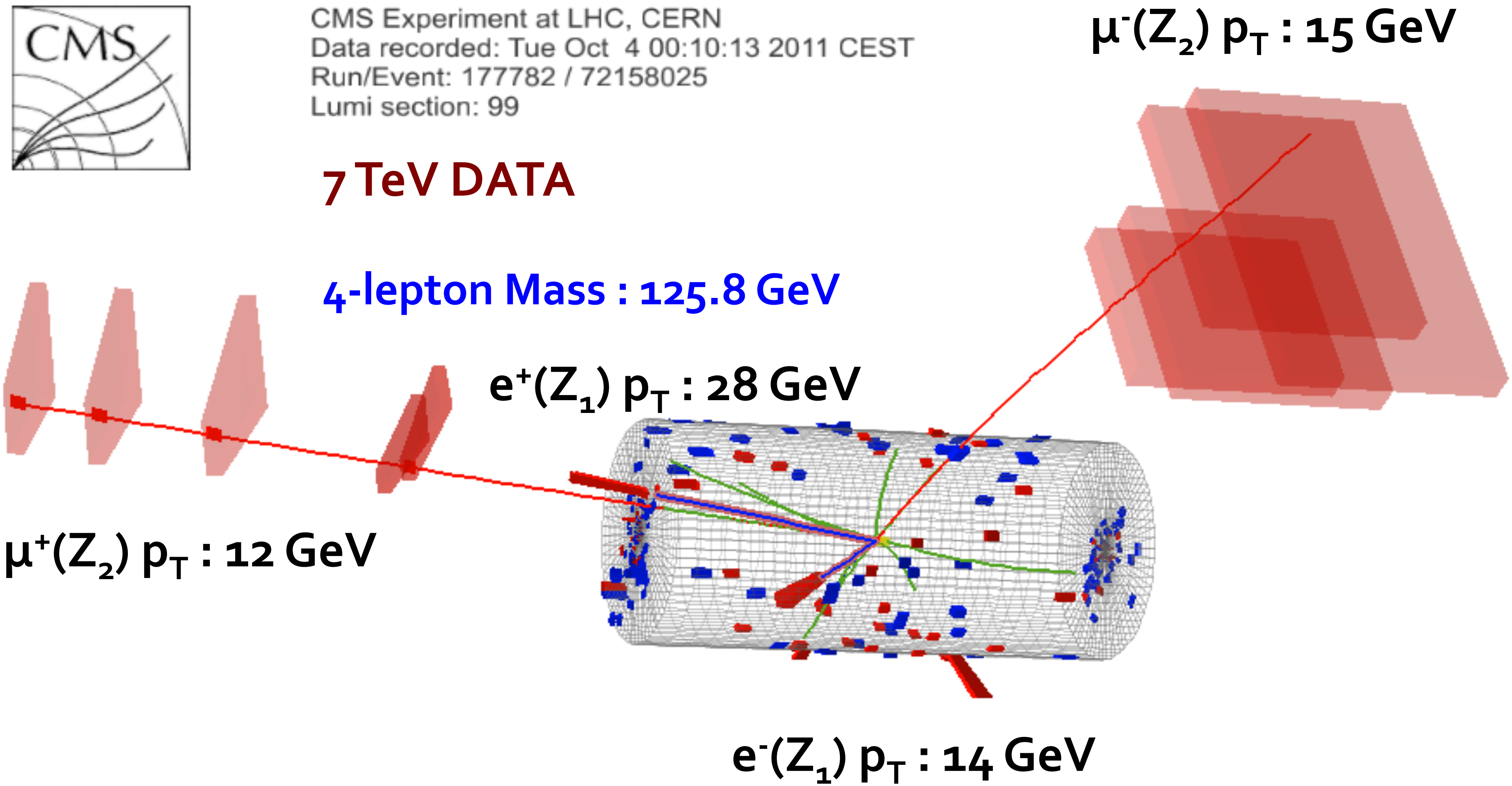
- Associates photon with Z
- Removes associated photons from lepton isolation calculation

Expected Performance for M_H=126 GeV

- ~ 6% of events affected
- 80% purity



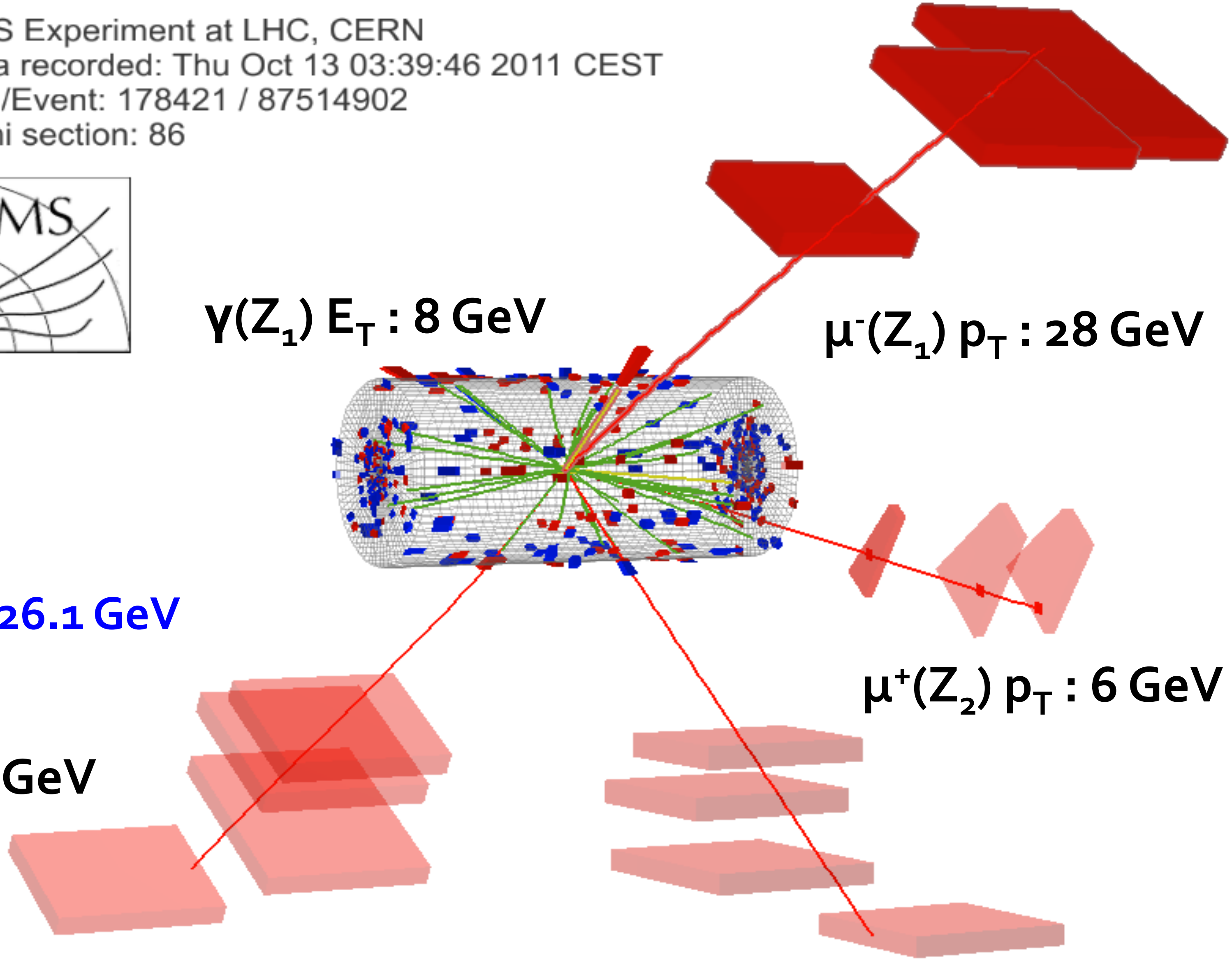
$2\mu + 2e$ event



CMS
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
$\mu^-(Z_2)$ p_T : 15 GeV
$e^+(Z_1)$ p_T : 28 GeV
$\mu^+(Z_2)$ p_T : 12 GeV
$e^-(Z_1)$ p_T : 14 GeV

4μ+γ event

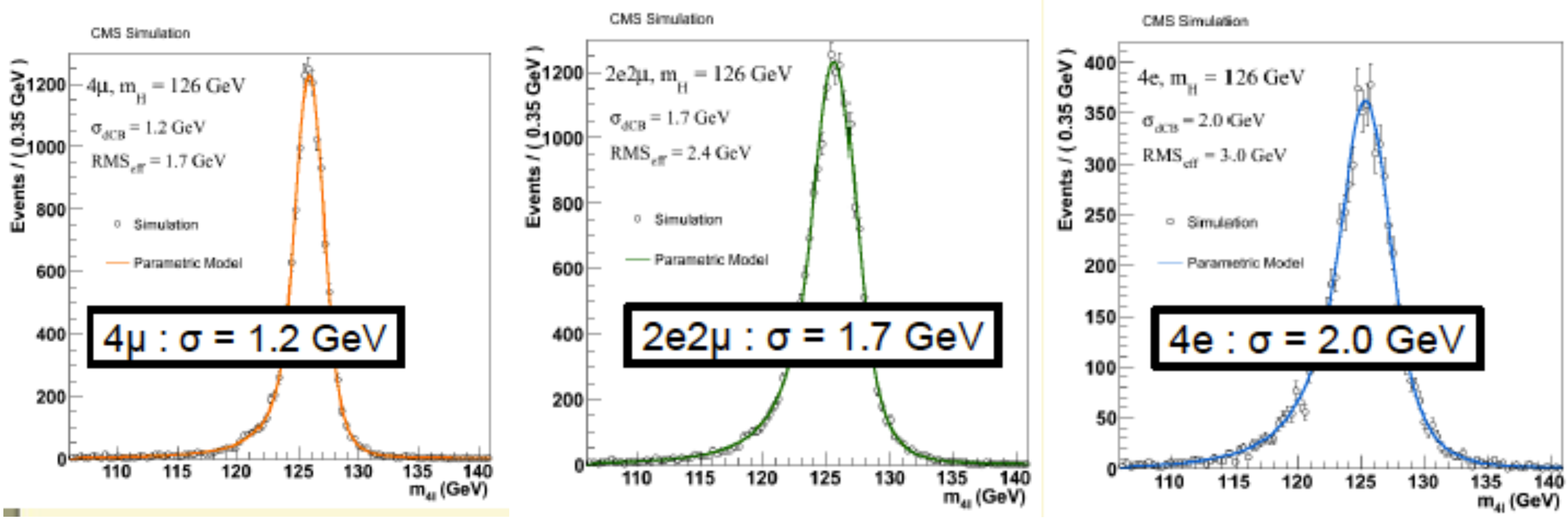
CMS Experiment at LHC, CERN
Data recorded: Thu Oct 13 03:39:46 2011 CEST
Run/Event: 178421 / 87514902
Lumi section: 86



7 TeV DATA

4μ+γ Mass : 126.1 GeV

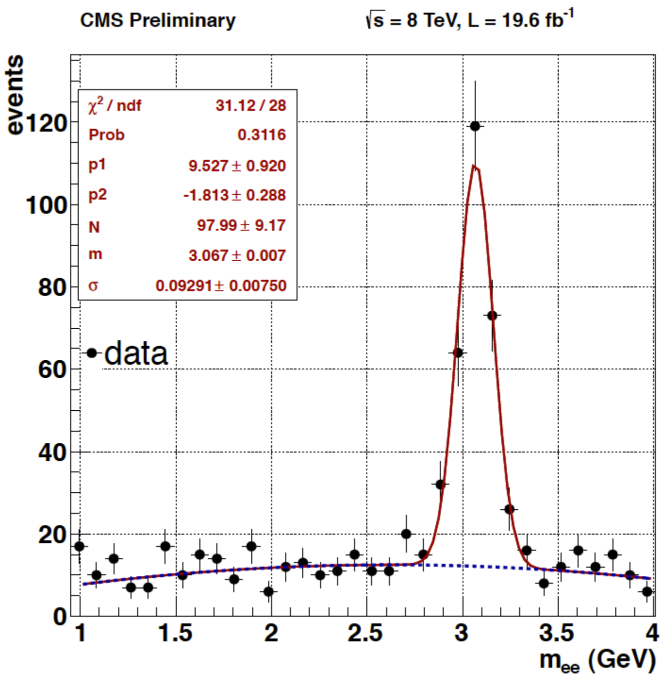
Higgs mass resolution simulation

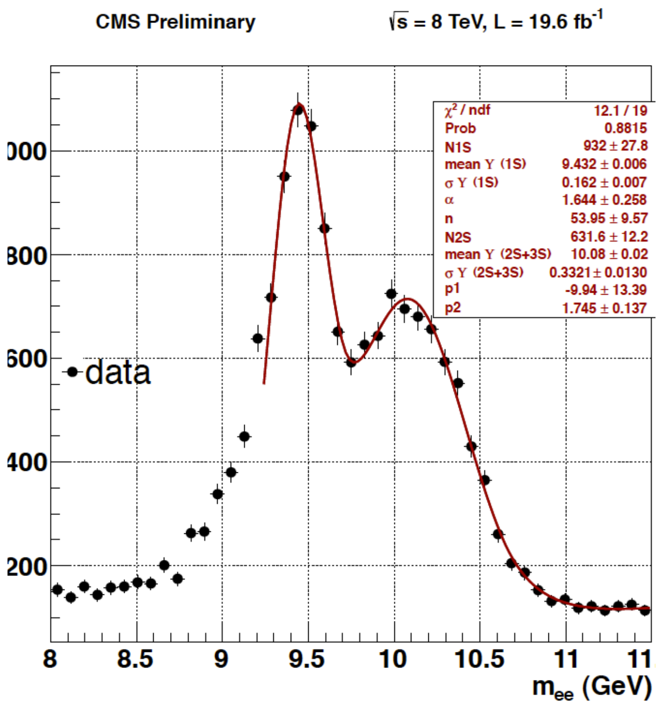


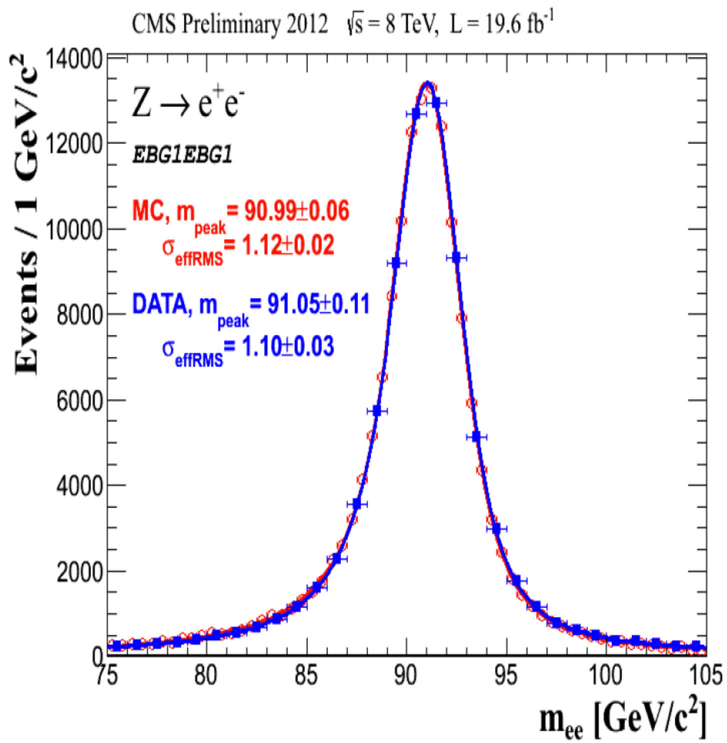
- Excellent momentum and mass resolution for muons
- Good resolution for electrons
- Helps to suppress backgrounds

Momentum scale and mass resolution control

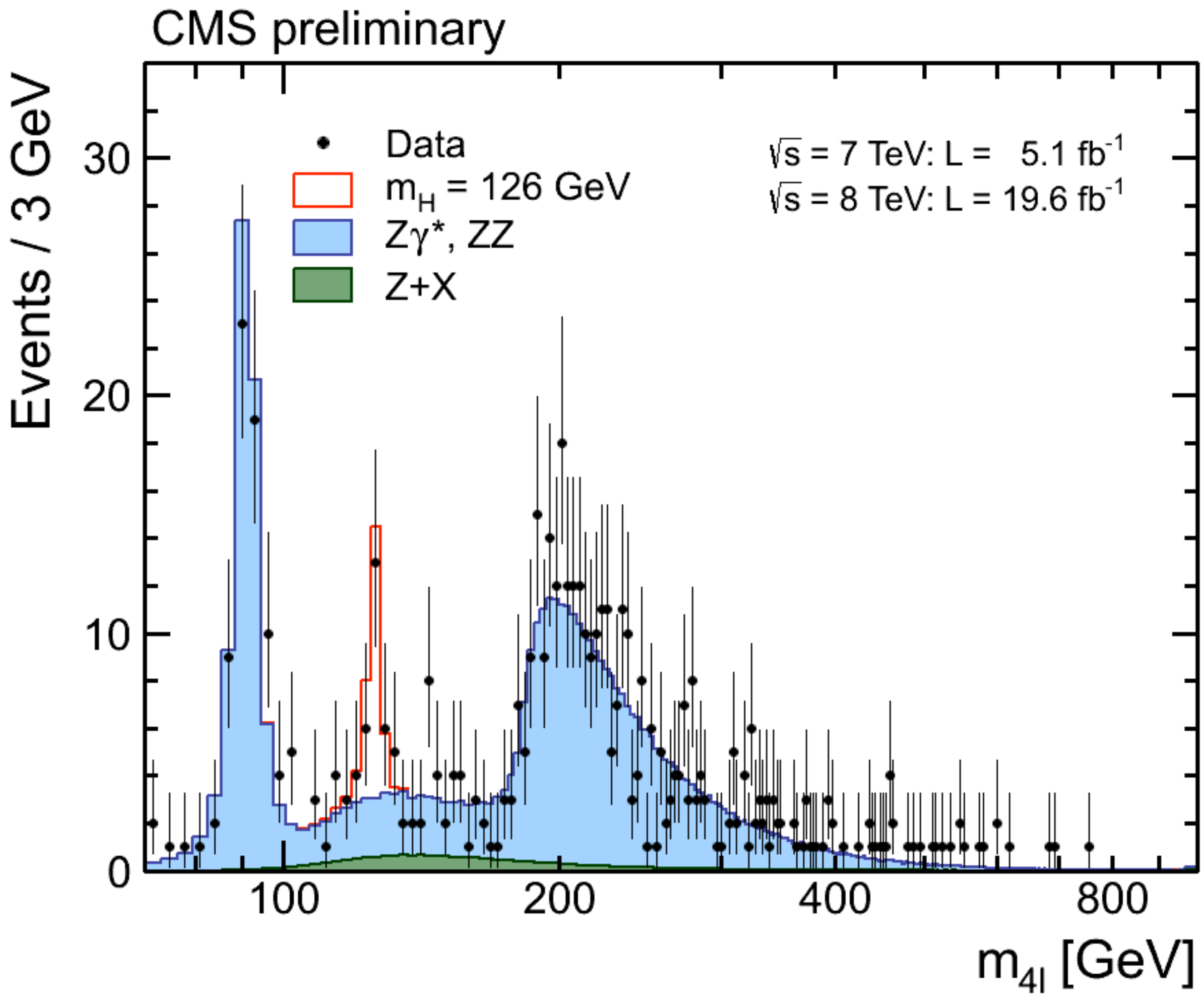
- J/ψ , ϒ & Z decays to ee and μμ used to control momentum scale and resolution across pT and η







Full statistics in 4l channel color-filled: SM background

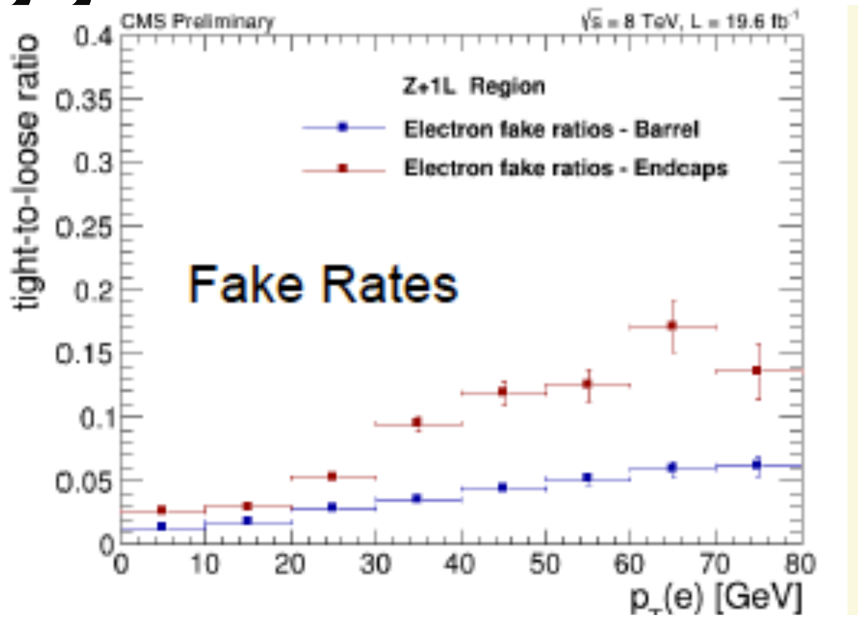


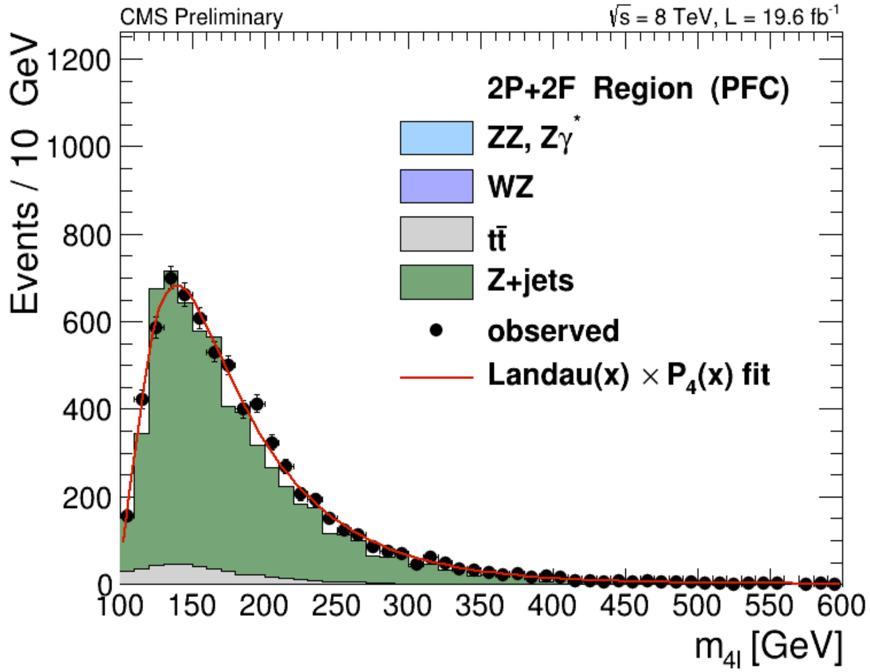
Backgrounds for Higgs search

- Backgrounds do not form a narrow peak

- Main background:
  ZZ* → 4l "irreducible"
  → shape from simulations,
  cross-section validated in data

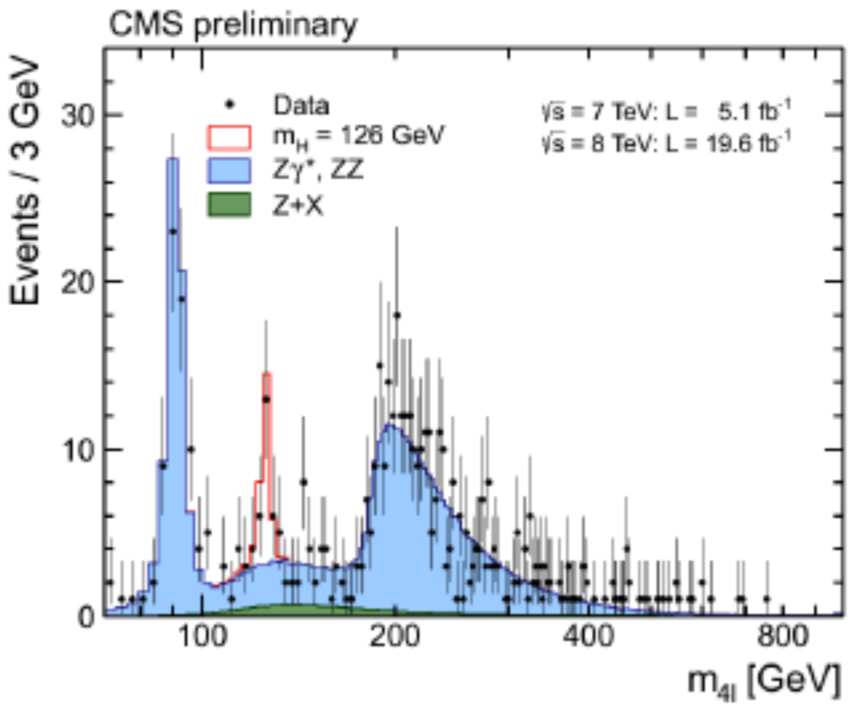
- Misidentified ("fake") isolated leptons "reducible" background (mainly Z+jets)
  → from control data:
  relaxing isolation
  and lepton ID

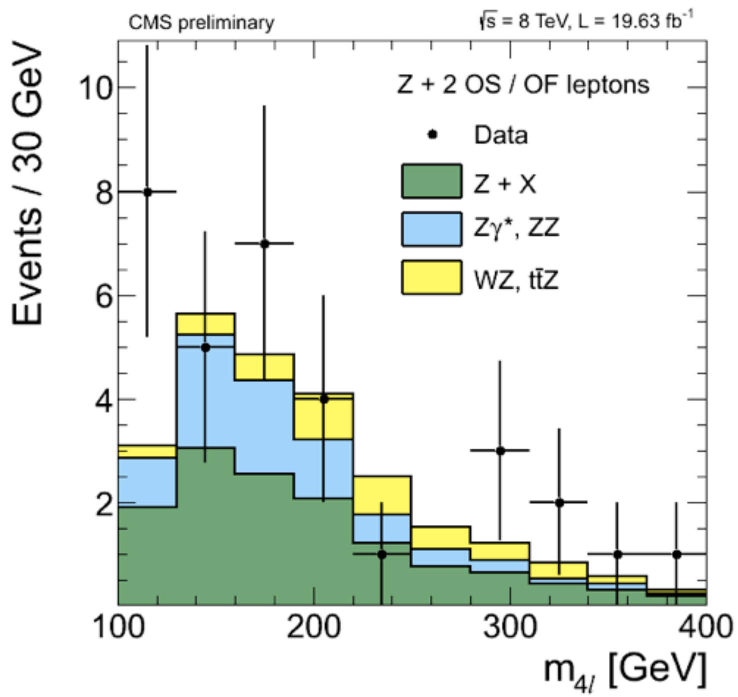




Backgrounds validation

- High Mass control region dominated by continuum ZZ background. Well reproduced by Monte Carlo simulation
- Z+2l control regions dominated by misidentified leptons background agree with data-driven estimates





Higgs →4l : Signal/Background ratio ~ 2:1 observed: 25 events total (S+B)

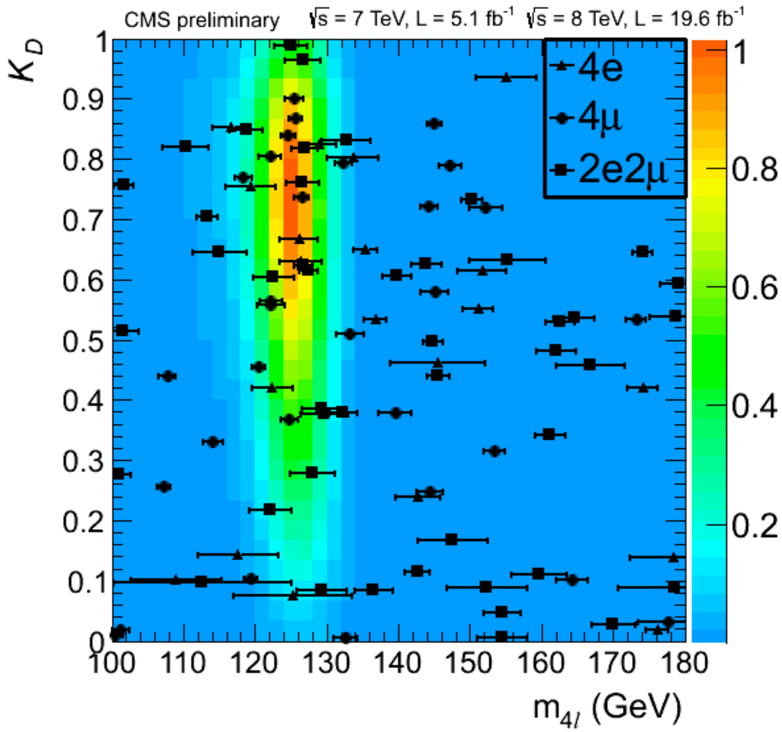
For 121.5 < m4l < 130.5 GeV

	4e	4μ	2e2μ
H(126) expected	3.0	6.7	8.9
ZZ expected	1.2	2.7	3.5
Z+X & top expected	0.6	0.5	0.9
Total Bkg	1.8	3.2	4.4
Signal+Bkg expected	4.8	9.9	13.3
Observed	5	8	12

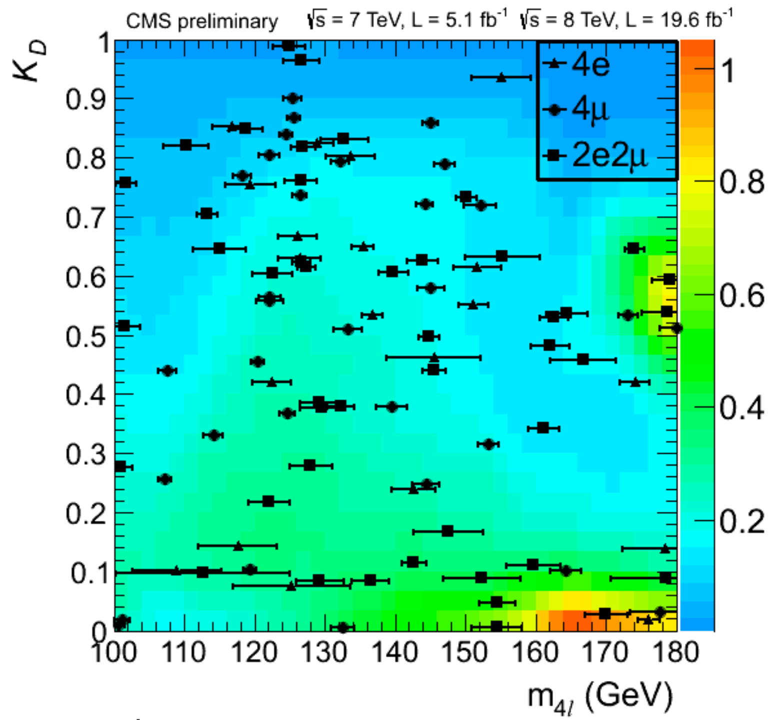
S/B improvement: Kinematic Discriminant

- To further improve signal to background ratio, we use a discriminant based on kinematic 4l information

$$\mathrm{KD} = \frac{\mathcal{P}_{\mathrm{sig}}}{\mathcal{P}_{\mathrm{sig}} + c \times \mathcal{P}_{\mathrm{bkg}}} = \left[1 + \frac{c \times \mathcal{P}_{\mathrm{bkg}}(m_1, m_2, \vec{\Omega}|m_{4\ell})}{\mathcal{P}_{\mathrm{sig}}(m_1, m_2, \vec{\Omega}|m_{4\ell})}\right]^{-1}$$



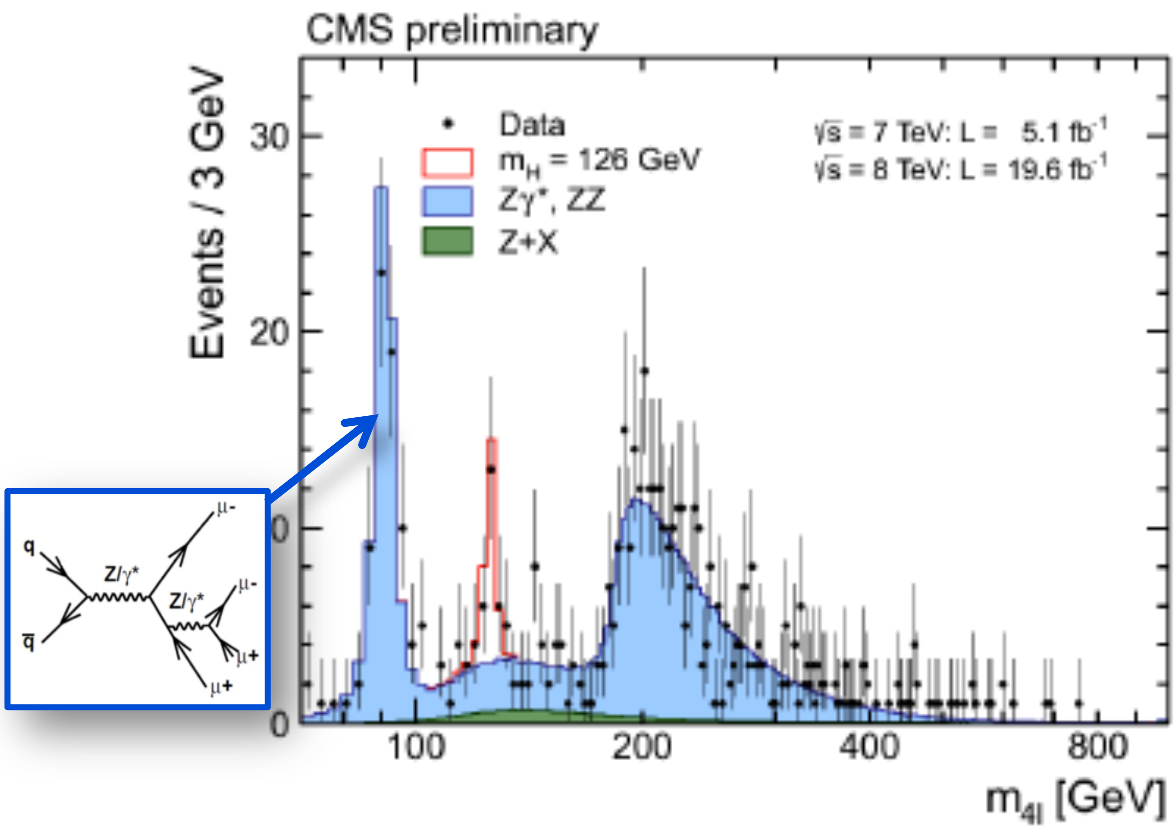
Higgs signal

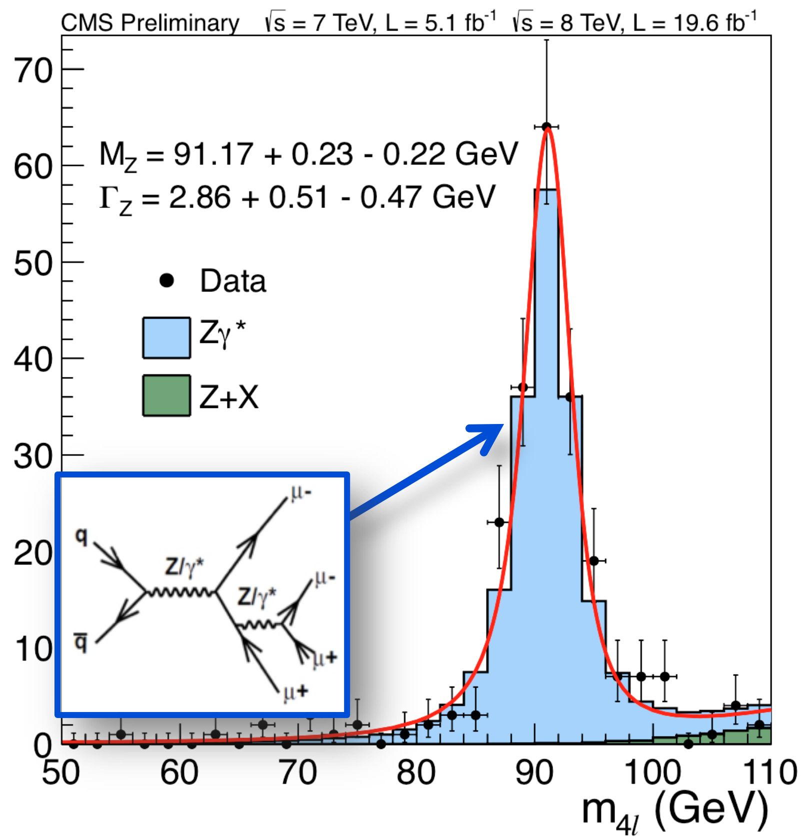


ZZ* background

“Standard Candle” for Higgs measurements : Z→4decay

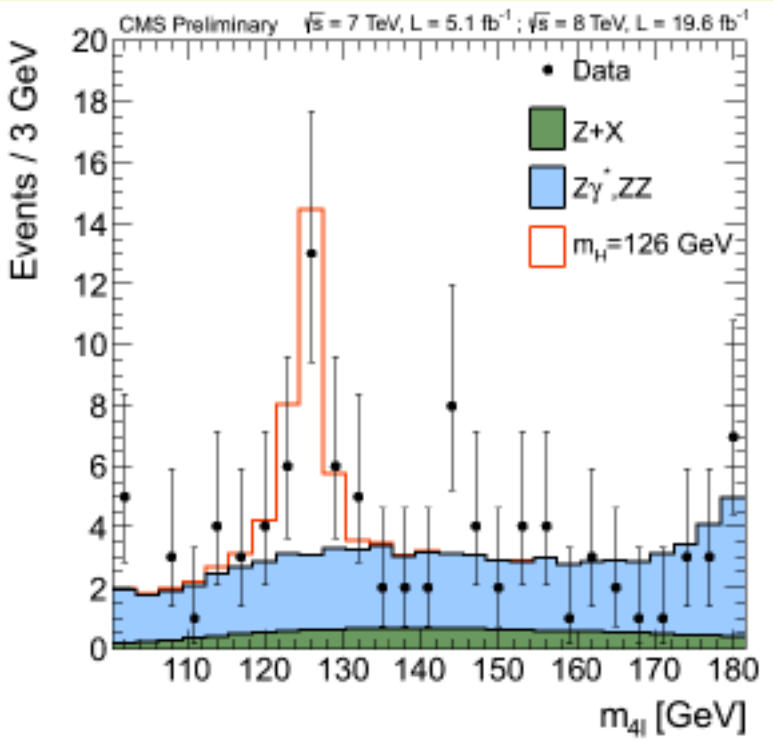
Z→4l decay is also a 4l narrow state with known properties, has more events than Higgs→4l: convenient for validation of resolution and momentum scale

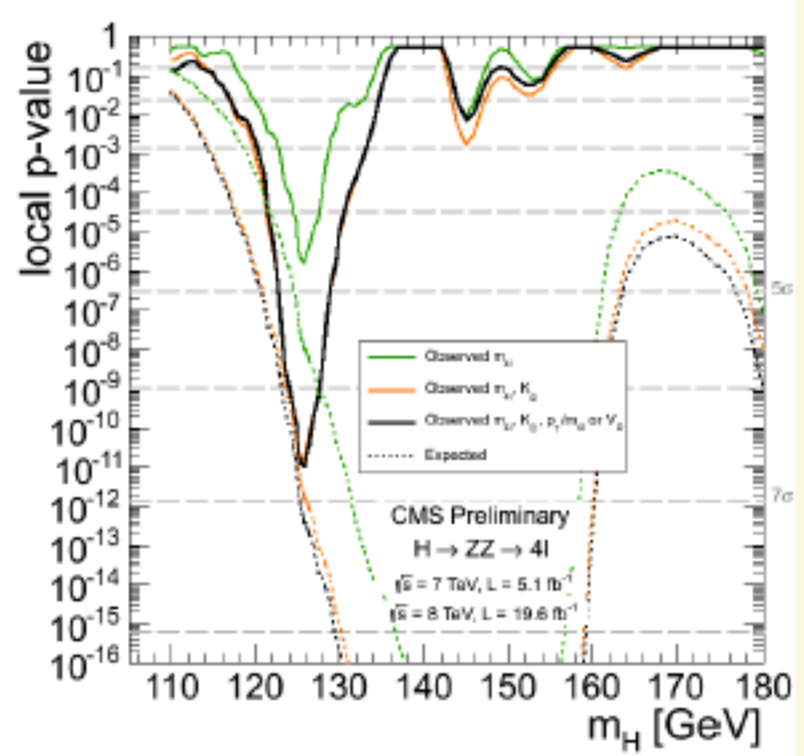




Statistical significance
of the peak of the new boson in 4l channel
(local p-value)

Statistical significance of 4l peak





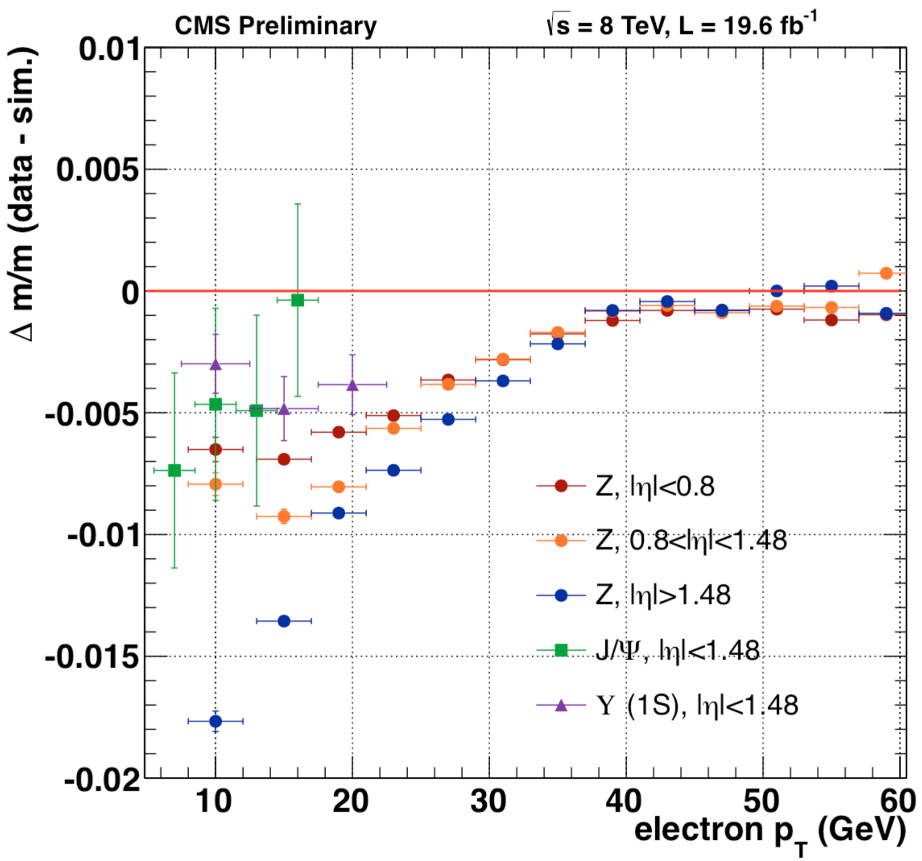
	Expected	Observed
3D (m_{4l}, K_D, V_D or p_T/m_{4l})	7.2 σ	6.7 σ
2D (m_{4l}, K_D)	6.9 σ	6.6 σ
1D (m_{4l})	5.6 σ	5.6 σ

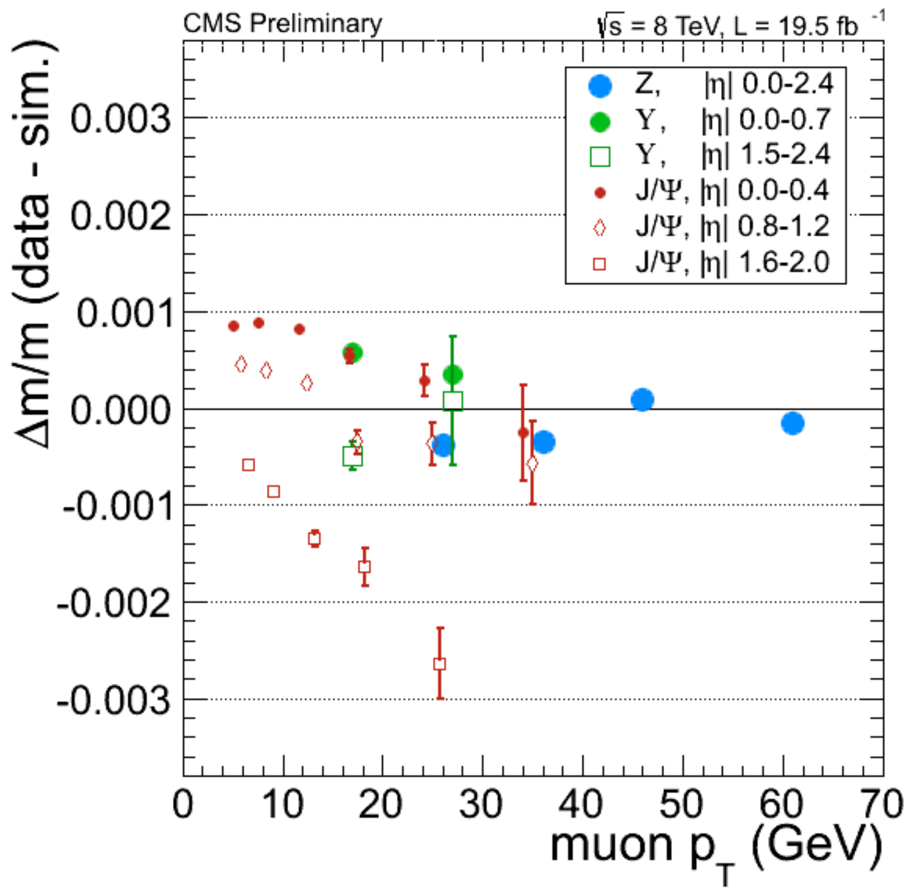
Statistical significance of the 4l peak is > 5 sigma and growing

New boson mass measurements

Lepton Momentum Scale

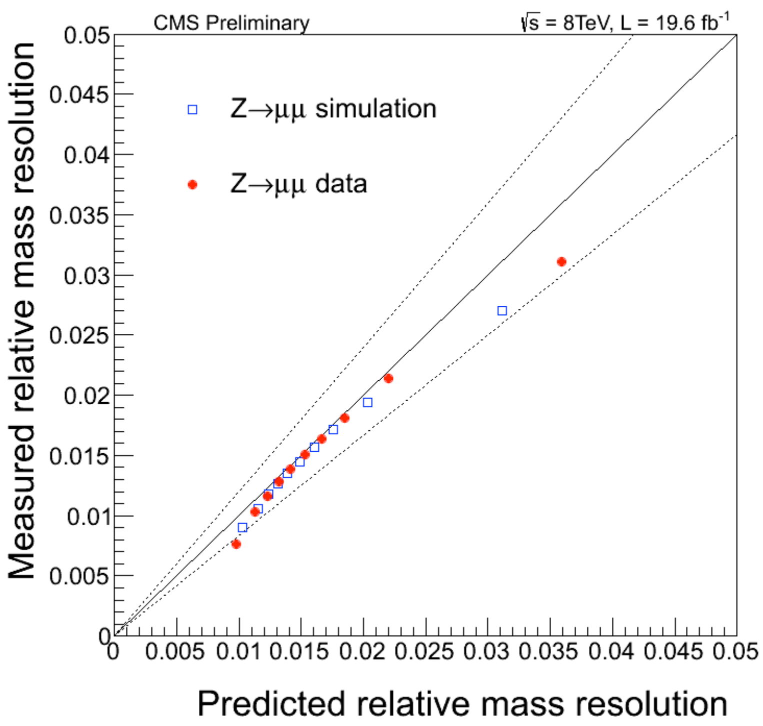
- Main systematic uncertainty for mass measurement
- Systematic on 4e/2e2mu mass scale is 0.3%, 4mu : 0.1%

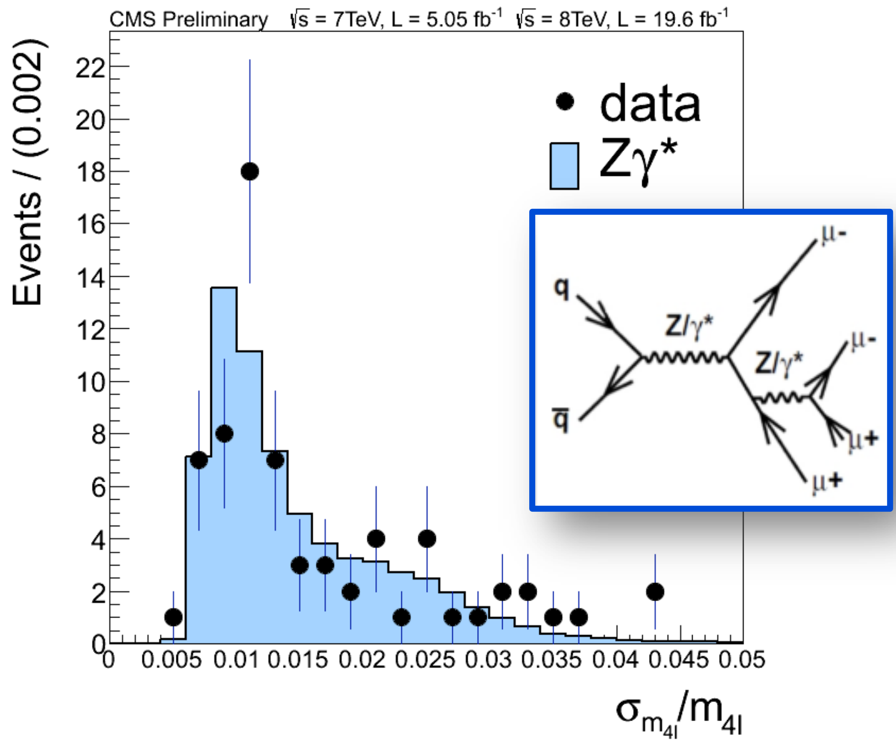




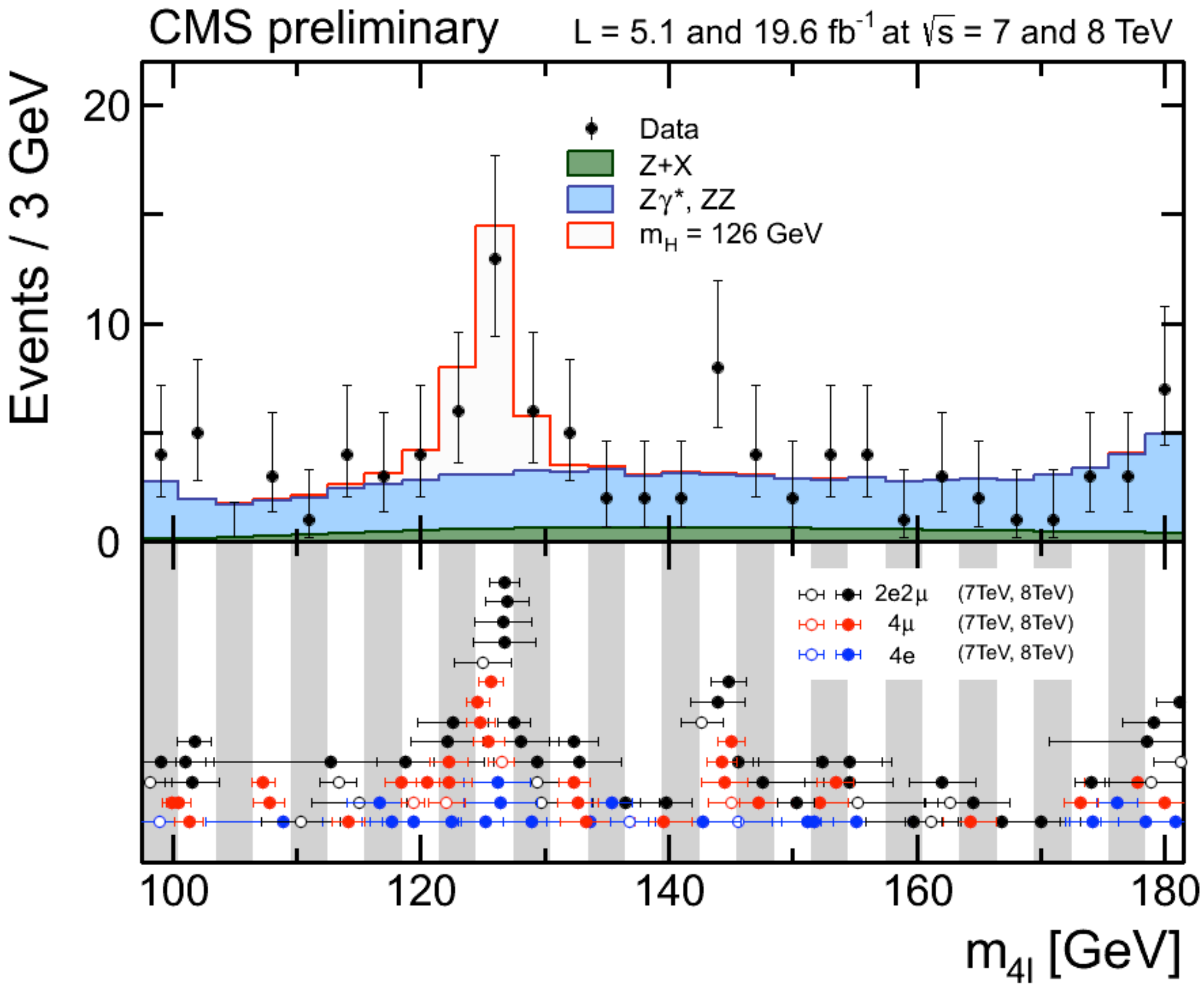
Per-event mass errors

- To improve precision of the mass measurement, we estimate per-event mass uncertainty and KD
- Per-event mass uncertainty validated using Z→ll data
- Additional cross-check performed using the Z→4l decays:

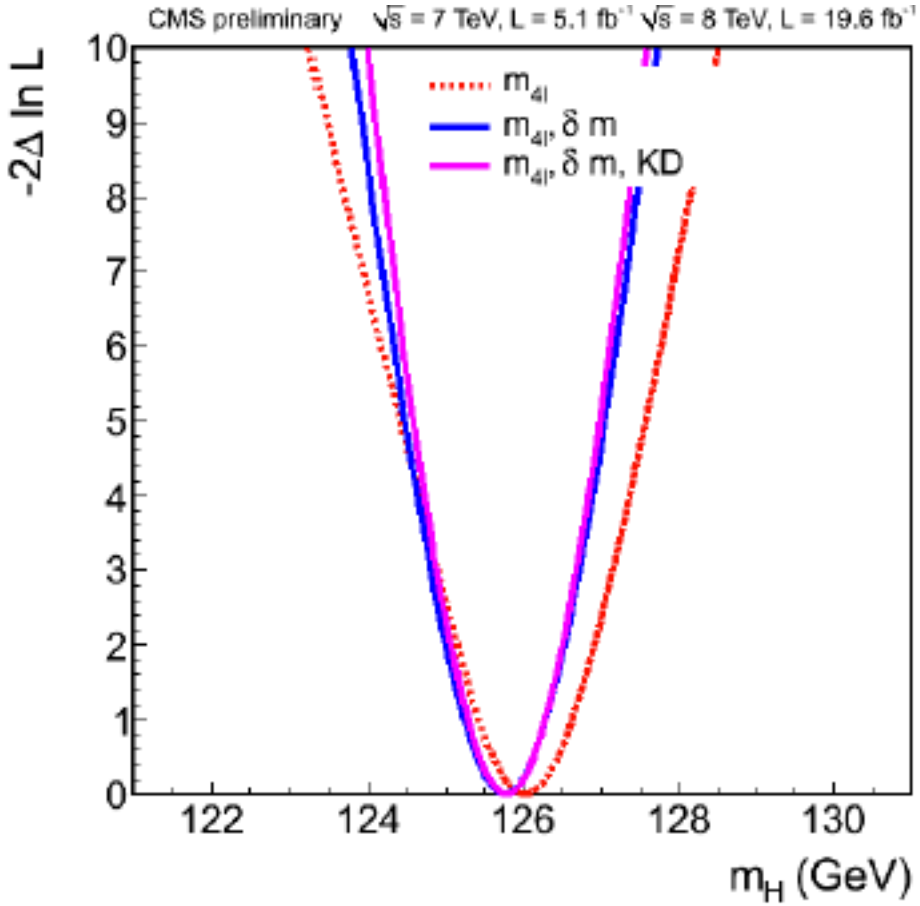




Mass distribution with individual events including per-event errors



New boson mass measurement



	Model	Mass
3D	$m_{4l}, \delta m_{4l}, K_D$	$125.80^{+0.50}_{-0.50}$
2D	$m_{4l}, \delta m_{4l}$	$125.76^{+0.52}_{-0.53}$
1D	m_{4l}	$126.02^{+0.60}_{-0.60}$

Mass = 125.8 ± 0.5 (stat) ± 0.2 (syst)

Tests of compatibility with the Standard Model Higgs predictions

- Given the mass, properties of the SM Higgs boson are all known theoretically
- Proceed to test data whether it's compatible with SM prediction on various properties

  - spin-parity
  - signal strength
  - couplings

Spin-parity studies

Spin and Parity J^P

- Use kinematic information to separate different spin-parity hypotheses J^P
- The following J^P considered (pure cases, no mixing):

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

:

Kinematic Discriminants for J^P separation

- Build two discriminants based on the complete Leading-Order Matrix Elements

  - one discriminant to separate signal from background, combined with mass information → D_{bkg}

$$D_{\mathrm{BKG}} = \left[1 + c_{\mathrm{bkg}} \cdot \frac{|\mathcal{M}_{\mathrm{BKG}}(\vec{p}_i)|^2 \cdot pdf(m_{4\ell}|\mathrm{BKG})}{|\mathcal{M}_{\mathrm{Higgs}}(\vec{p}_i)|^2 \cdot pdf(m_{4\ell}|\mathrm{Higgs})}\right]^{-1}$$

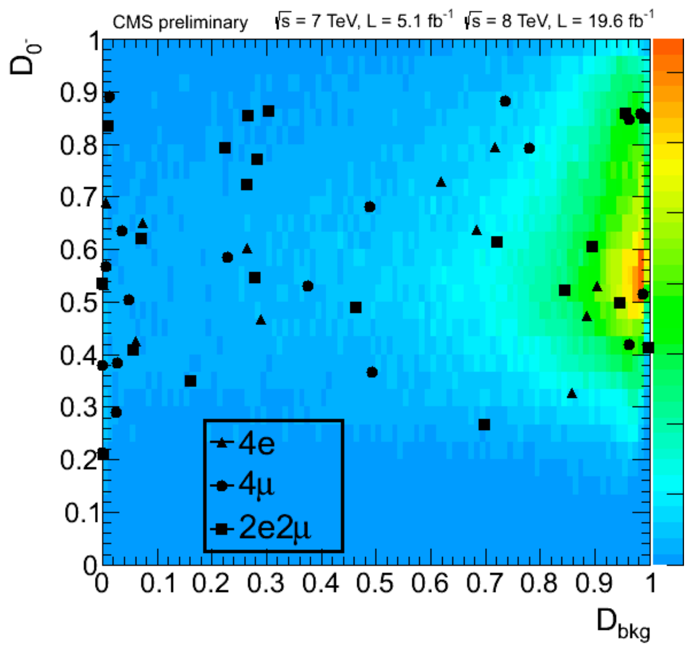
  - another discriminant to separate the SM Higgs from alternative J^P hypothesis → D_{JP}

$$D_{\mathrm{J^P}} = \left[1 + c_{\mathrm{j^P}} \cdot \frac{|\mathcal{M}_{\mathrm{J^P}}(\vec{p}_i)|^2}{|\mathcal{M}_{\mathrm{Higgs}}(\vec{p}_i)|^2}\right]^{-1}$$

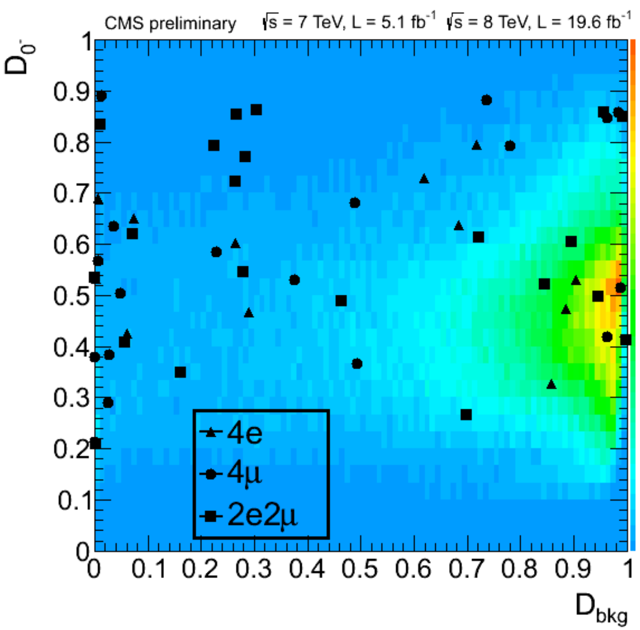
Example: comparison of 0^+ (Higgs) and 0^- (with ZZ bckg included)

- Expected two dimensional distributions of (D_{JP}, D_{bkg}) for: a) the SM Higgs 0^+, b) pseudoscalar 0^- and c) ZZ bkgd

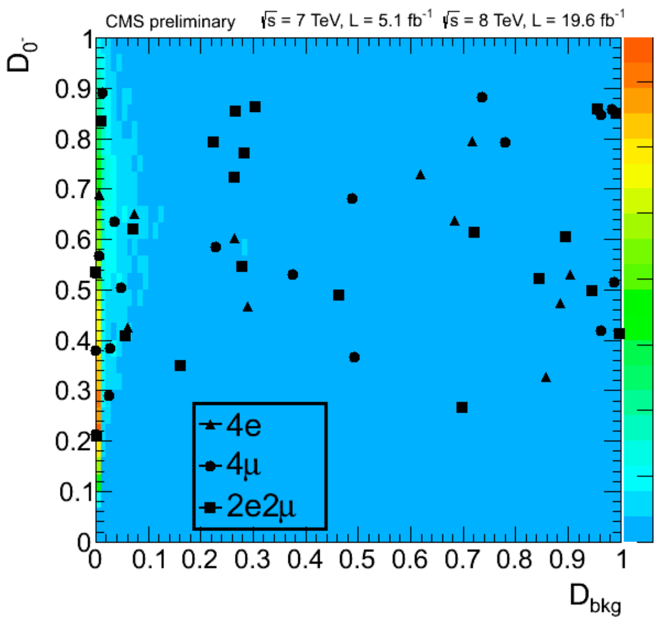
- distributions superimposed with the observed events



Higgs 0^+

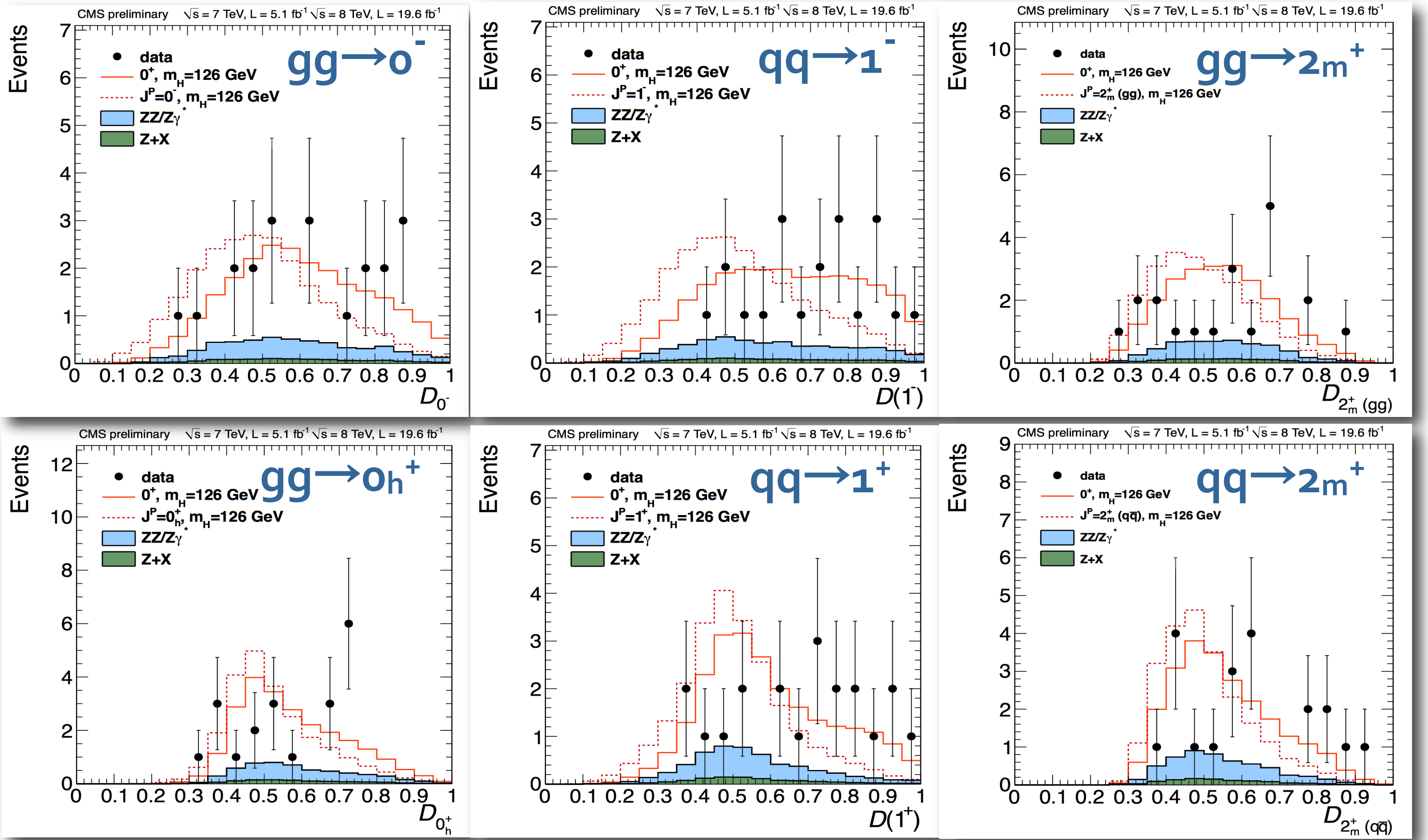


pseudoscalar 0^-

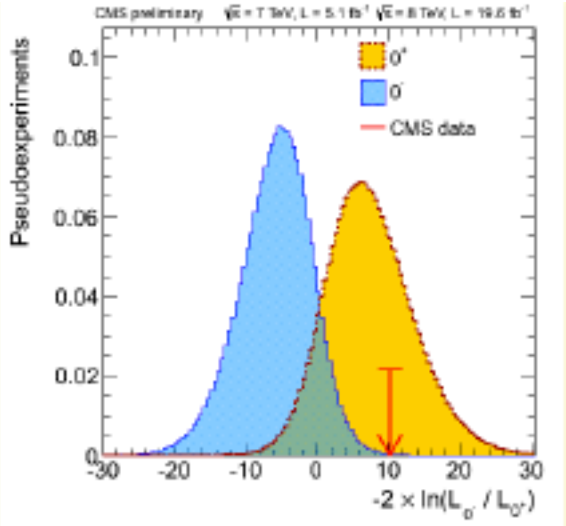


ZZ bkg

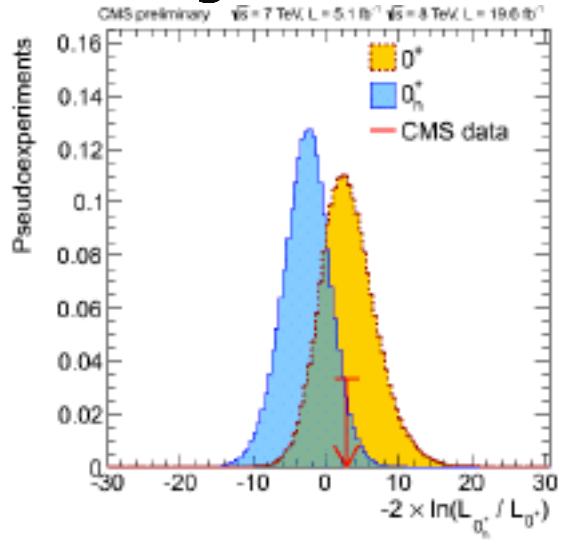
D_{JP} distributions (with D_{bkg}>0.5)



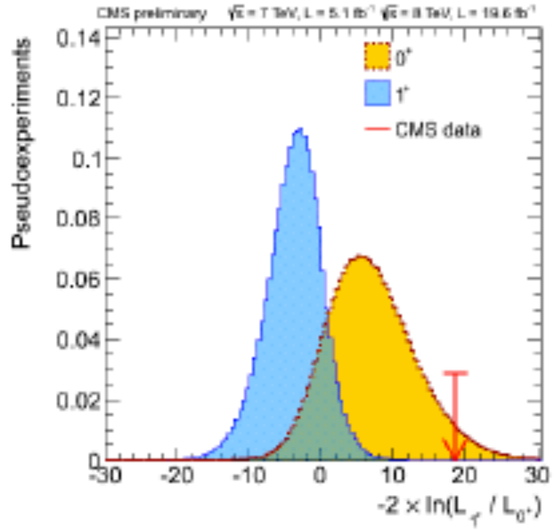
Confidence level (CL_s) : "exotic" J^P vs scalar



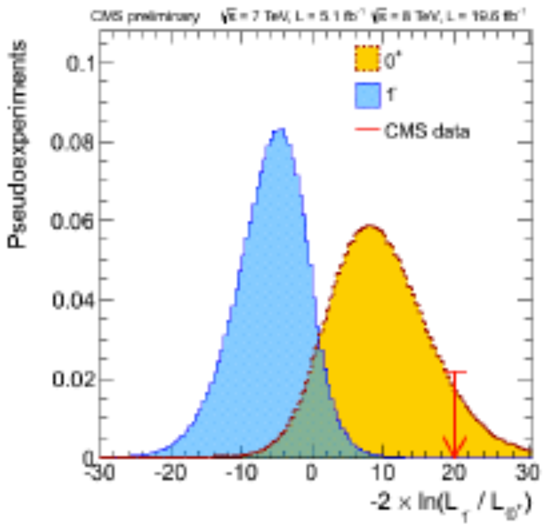
0^- : 0.16 %



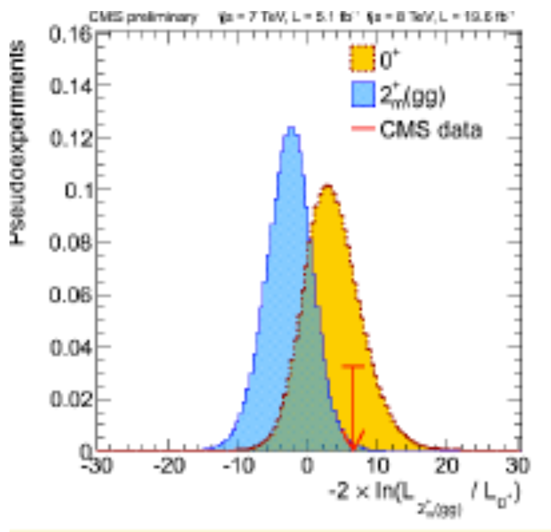
0^+_h : 8.1 %



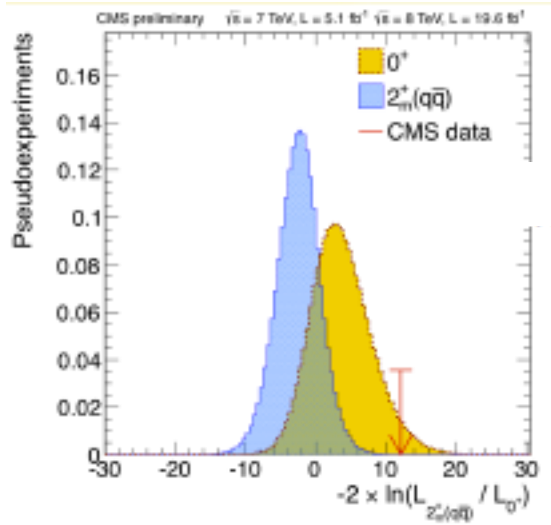
1^+ < 0.01 %



1^- < 0.01 %



2^+_{mgg} : 1.5 %



2^+_{mqq} < 0.1 %

Spin-parity: results

	Expected [σ]		Observed (μ from data)		
	μ=1	μ from data	P(q > Obs | alternative) [σ]	P(q > Obs | SM Higgs) [σ]	CLs [%]
$gg \rightarrow 0^-$	2.8	2.5	3.3	-0.5	0.16
$gg \rightarrow 0_h^+$	1.8	1.7	1.7	+0.0	8.12
$qq \rightarrow 1^+$	2.6	2.3	> 4.0	-1.7	< 0.01
$qq \rightarrow 1^-$	3.1	2.8	> 4.0	-1.4	< 0.01
$gg \rightarrow 2_m^+$	1.9	1.8	2.7	-0.8	1.46
$qq \rightarrow 2_m^+$	1.9	1.7	4.0	-1.8	0.09

The studied pseudo-scalar, spin-1 and spin-2 models are excluded at 95% CL or higher

Data is consistent with SM Higgs

Fit for CP-odd contribution

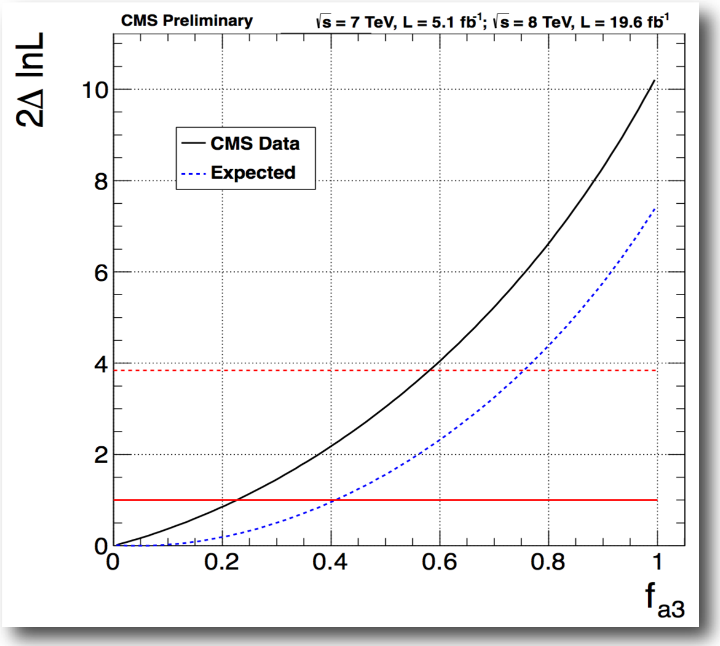
- Perform a fit for the fraction f_{a3} of a CP-odd contribution in the observed peak

$$f_{a3} = \frac{|A_3^2|}{|A_1^2| + |A_3^2|}$$

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

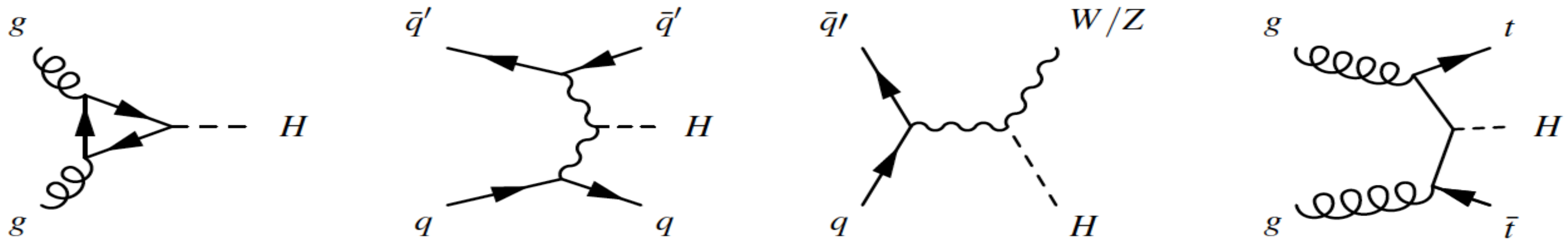
  - decays of state 0_m^+ governed by the A1 amplitude
  - decays of state 0^- governed by A3 amplitude

$$f_{a3} = 0.00^{+0.23}_{-0.00}$$



Signal strength,
couplings of the new particle
with bosons and fermions

Higgs Production mechanisms at LHC

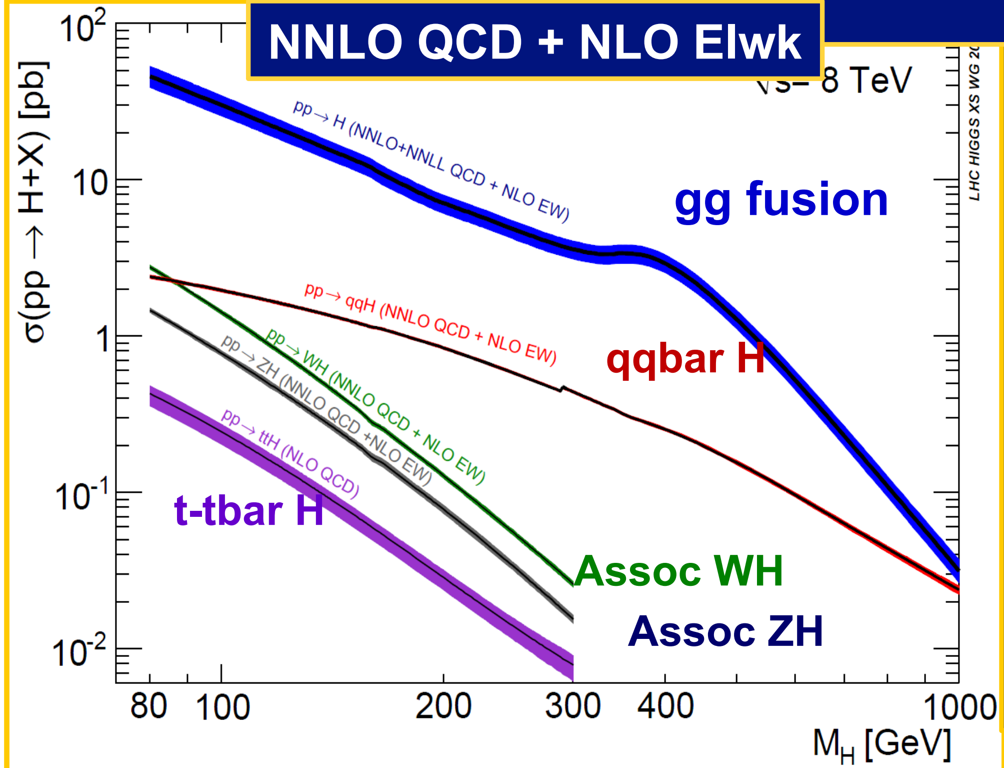


gg fusion: gg→ H

Vector Boson fusion

Assoc Prod: WH, ZH

Assoc. Prod: t-tbar, H



Dominant production at 125 GeV gg→ H

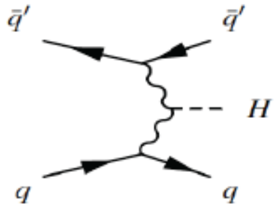
Subdominant, but with Larger S/B:

VBF: ~13X Less
WH + ZH: ~18X Less
ttH ~150X Less

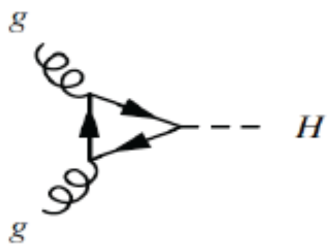
Tagging Vector-Boson Fusion

To have sensitivity to couplings of the new particle with vector bosons, as well as with fermions, we split events into two categories:

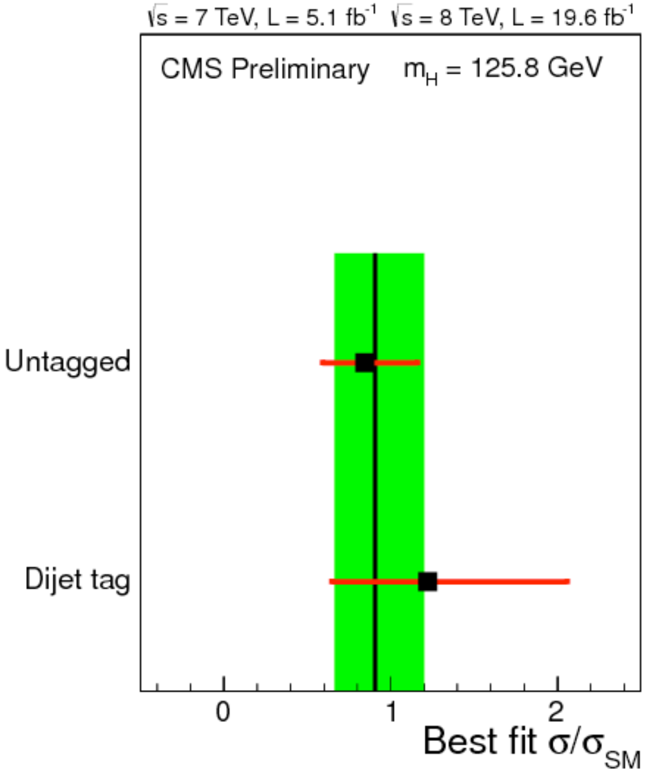
1) Di-jet tag (sensitive to coupling with vector bosons):
PT > 30 GeV, |n| < 4.7; Jet ID to reject fake jets from pileup

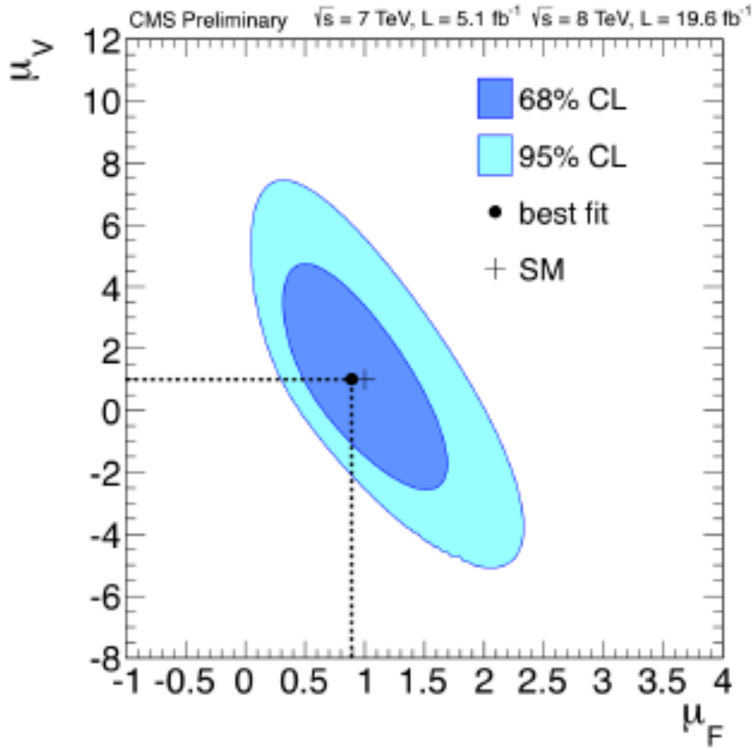


2) Untagged (majority of events, sensitive to couplings with fermions)



Signal strength, boson vs vector couplings





- Best fit signal strength: **μ=0.91+0.30-0.24** is compatible with the Standard Model **(μ=1).**
- Couplings with bosons and fermions also compatible with the SM
- Statistical precision needs to be improved (particularly of boson couplings, which are still compatible also with zero)

Summary: 4l "golden channel " results

4l channel by itself is > 5 sigma discovery of the new boson

Very convenient for properties measurements

- Mass : m = 125.8 ÷0.50 GeV,

best mass measurement of the new particle in a single channel

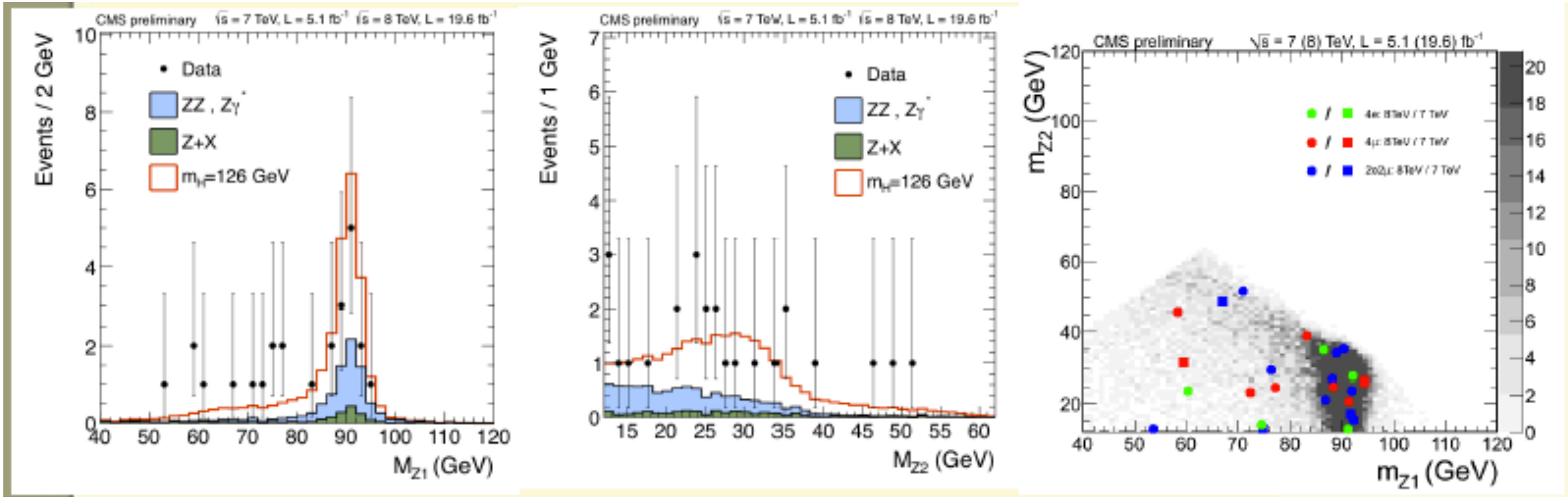
Looks more and more like SM Higgs scalar:

- Cross section : μ = 0.91+0.30 –0.24
- Several "exotic" non-SM J^P hypotheses excluded

All measurements in this channel are limited by statistics: significant improvements possible in the future

Backup

Sanity check:
MZ_1, MZ_2 distributions vs expected for SM Higgs



- **Event distributions for m4l in [121.5, 130.5]**

  MZ1 has a few more events off-shell compared to SM Higgs expectation, but difference is not statistically significant

Test statistics

Signal model parameters a (signal strength modifier μ can be one of them) are evaluated from a scan of the profile likelihood ratio $q(a)$:

$$q(a) = -2 \ln \frac{\mathcal{L}(\text{obs} \,|\, s(a) + b, \hat{\theta}_a)}{\mathcal{L}(\text{obs} \,|\, s(\hat{a}) + b, \hat{\theta})}, \tag{6}$$

Parameters $\hat{a}$ and $\hat{\theta}$ that maximize the likelihood, $\mathcal{L}(\text{obs} \,|\, s(\hat{a}) + b, \hat{\theta}) = \mathcal{L}_{\text{max}}$, are called the best-fit set. The 68% (95%) CL on a given parameter of interest a_i is evaluated from $q(a_i) = 1$ (3.84) with all other unconstrained model parameters treated in the same way as the nuisance parameters. The 2D 68% (95%) CL contours for pairs of parameters are derived from $q(a_i, a_j) = 2.3$ (6). One should keep in mind that boundaries of 2D confidence regions projected on either parameter axis are not identical to the 1D confidence interval for that parameter.