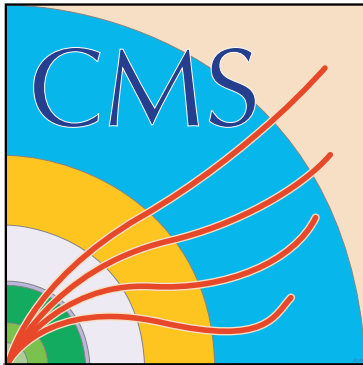


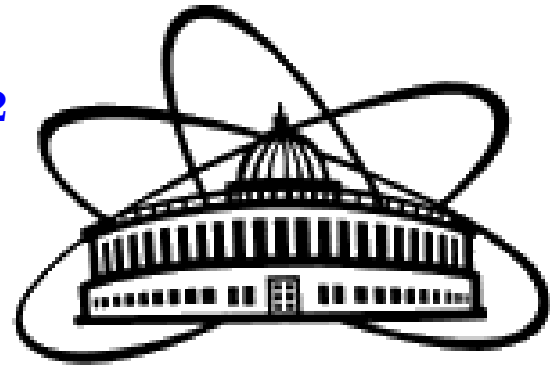
CMS overview: Results of Searches for Higgs Boson and New Physics at LHC

Alexander Lanyov (JINR)
on behalf of the CMS Collaboration

The XXI International Baldin Seminar
on High Energy Physics Problems, JINR, Dubna



10–15 September 2012





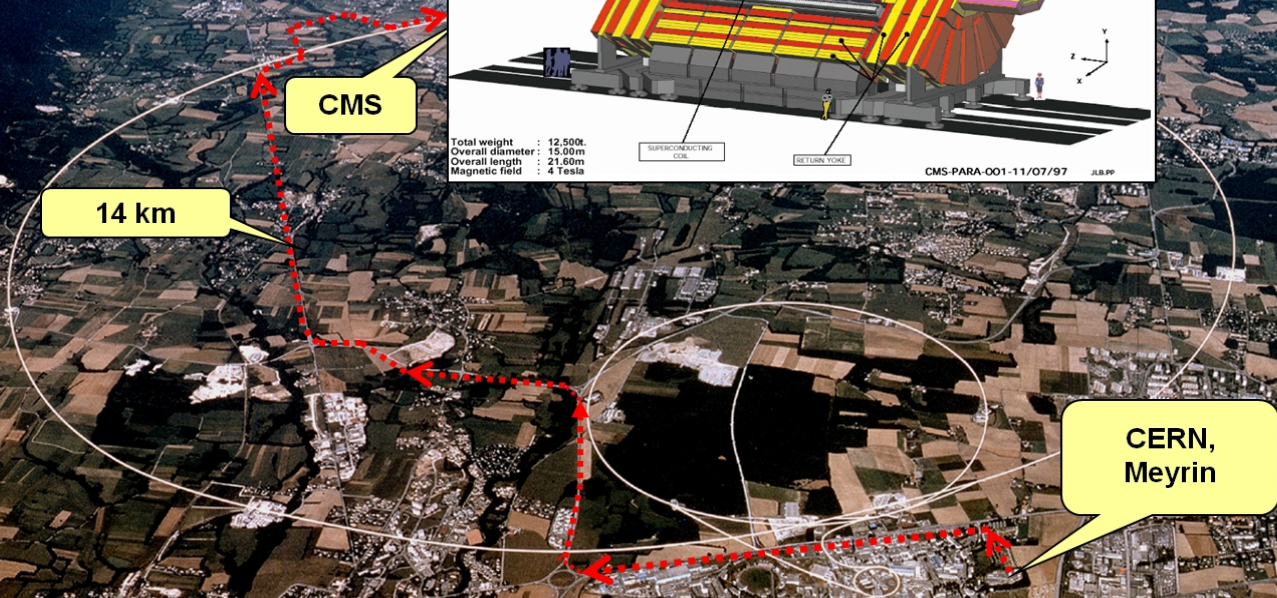
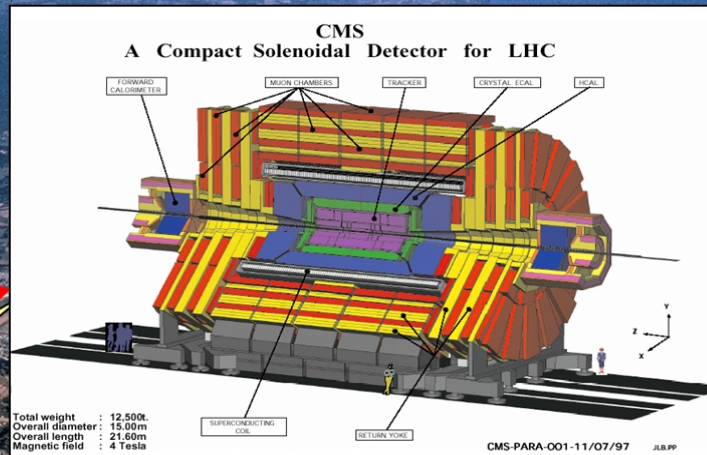
CMS Public Physics Results:

<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults>

Outline:

- CMS Experiment
- Studies of Electroweak and QCD processes
- Results of searches for Higgs boson
- Searches for New Physics
- Heavy-ion physics
- Conclusions

CMS Detector



Pixels
 Tracker
 ECAL
 HCAL
 Solenoid
 Steel Yoke
 Muons

SILICON TRACKER
 Pixels ($100 \times 150 \mu\text{m}^2$)
 ~1m² 66M channels
 Microstrips (50-100 μm)
 ~210m² 9.6M channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
 76k scintillating PbWO₃ crystals

PRESHOWER
 Silicon strips
 ~16m² 137k channels

STEEL RETURN YOKE
 ~13000 tonnes

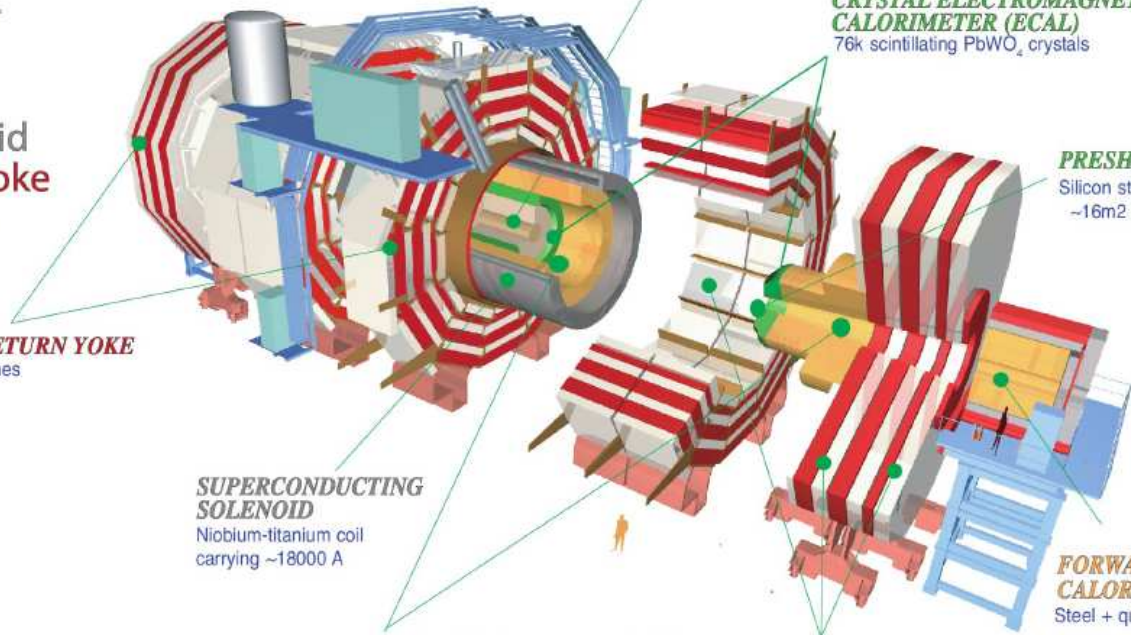
SUPERCONDUCTING SOLENOID
 Niobium-titanium coil
 carrying ~18000 A

HADRON CALORIMETER (HCAL)
 Brass + plastic scintillator

FORWARD CALORIMETER
 Steel + quartz fibres

Total weight : 14000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

MUON CHAMBERS
 Barrel: 250 Drift Tube & 500 Resistive Plate Chambers
 Endcaps: 450 Cathode Strip & 400 Resistive Plate Chambers

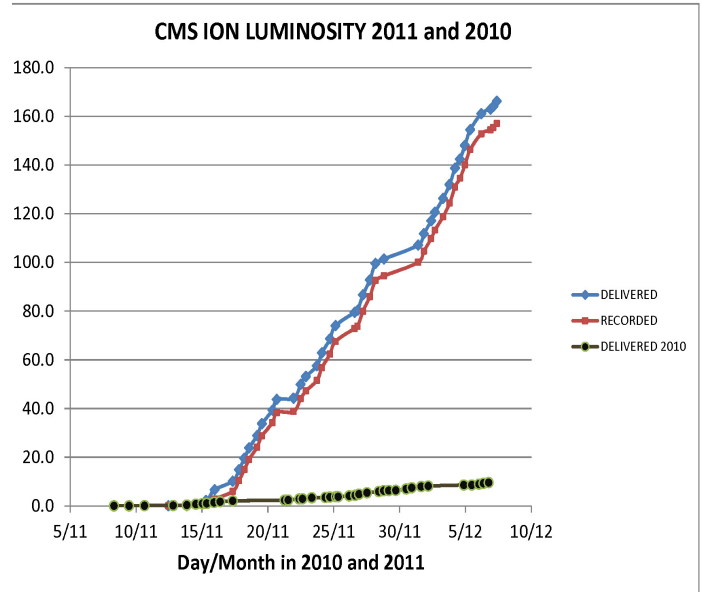
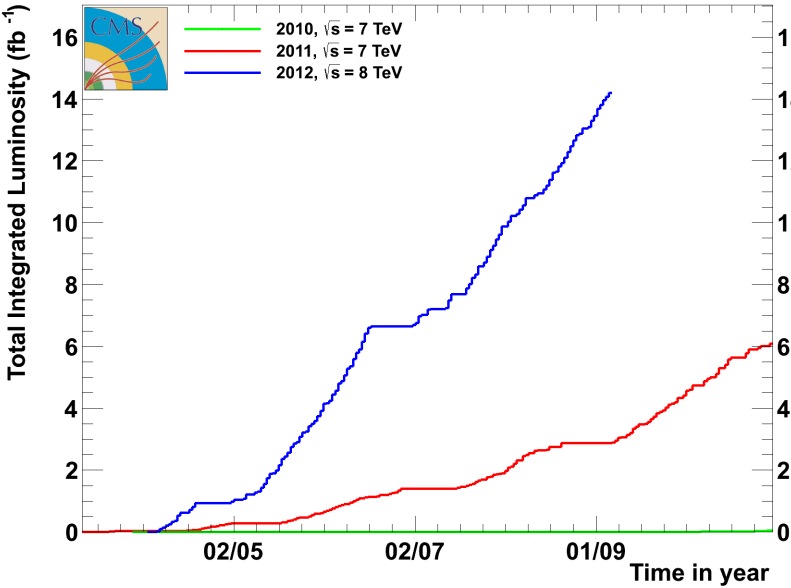




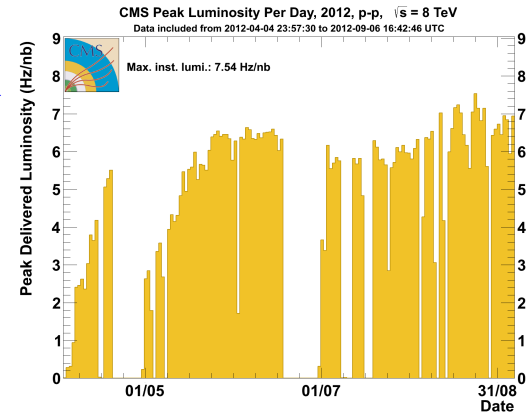
Statistics of Integrated Luminosity



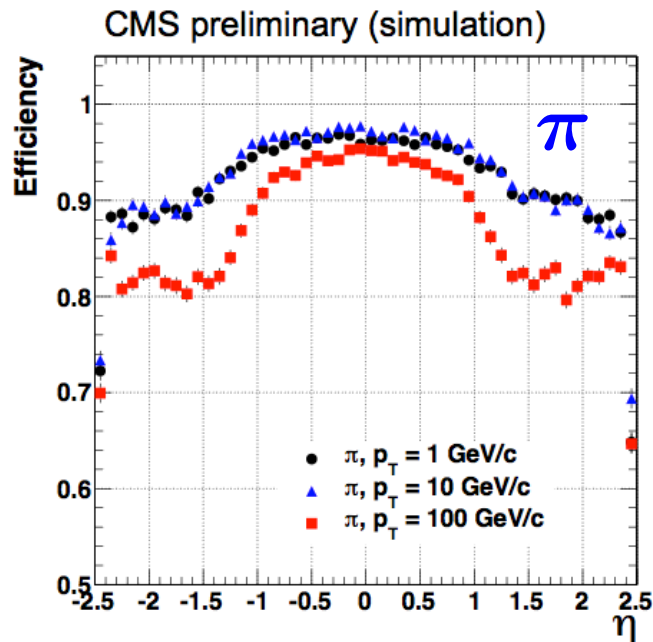
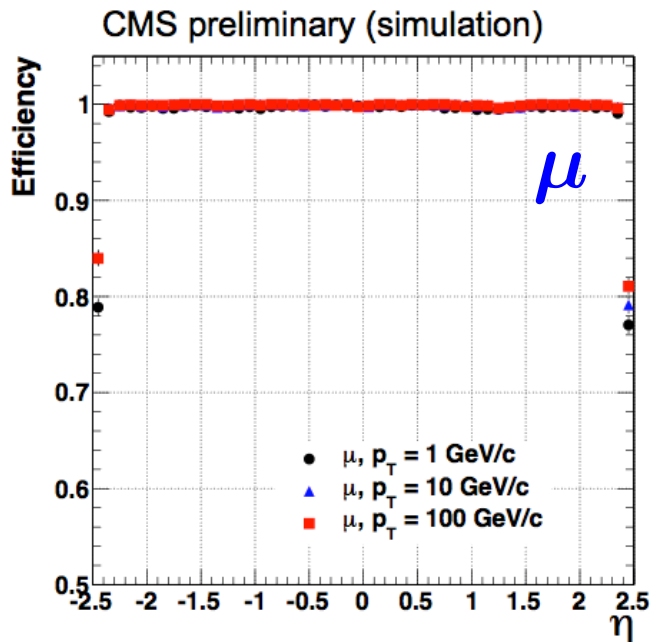
CMS Total Integrated Luminosity, p-p



- Excellent performance of LHC and CMS in 2011 and 2012
- $\int \mathcal{L} dt \approx 20 \text{ fb}^{-1}$ in pp collisions collected at $\sqrt{s} = 7$ and 8 TeV
- Until the summer conferences 2012 — analyzed $\sim 10 \text{ fb}^{-1}$
- Peak luminosity $7.6 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$
- Data taking efficiency $> 90\%$
- Plans: to get $\sim 30 \text{ fb}^{-1}$ before end of 2012

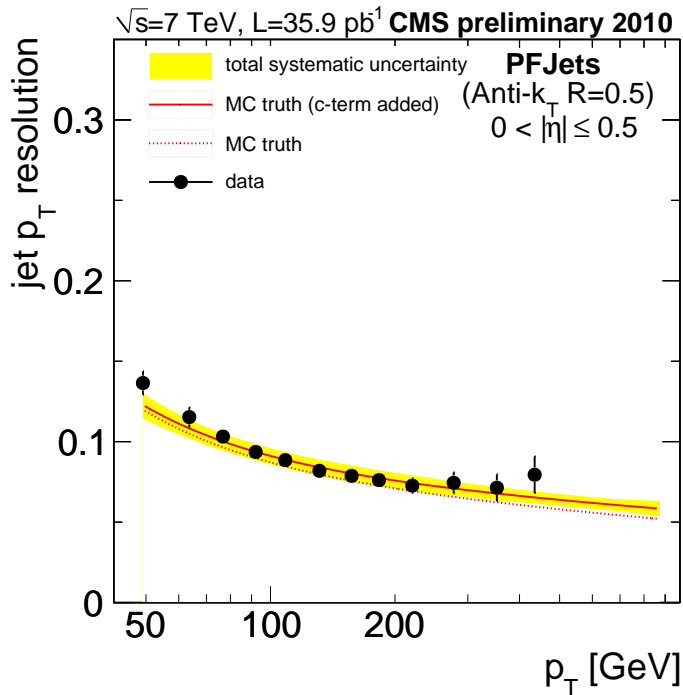


Track reconstruction efficiency for single muons as a function of pseudorapidity η



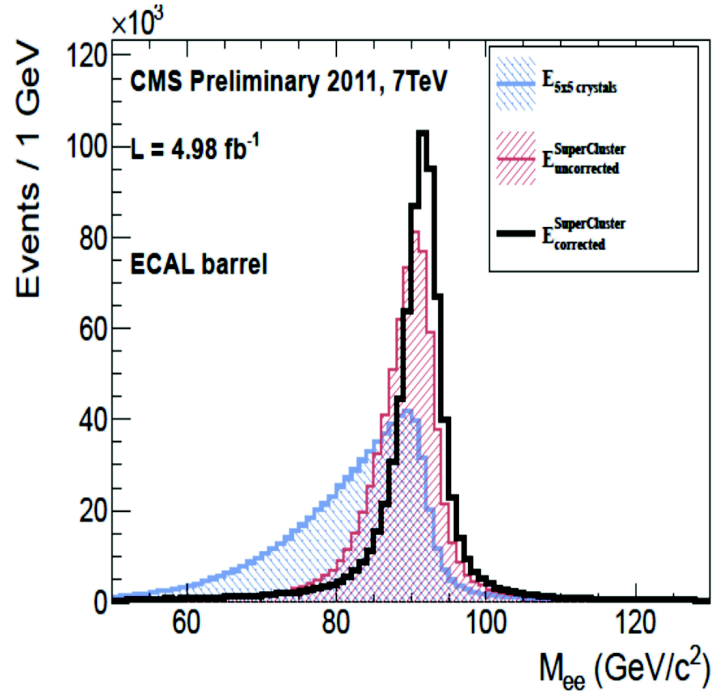
$$\frac{\sigma(p_T)}{p_T} \approx 10^{-4} \cdot p_T \oplus 0.005$$

PF Jet p_T resolution



$$\frac{\sigma(E)}{E} \approx \frac{1.0}{\sqrt{E}} \oplus 0.05$$

ECAL Clustering and Bremsstrahlung Corrections



$$\frac{\sigma(E)}{E} \approx \frac{0.03}{\sqrt{E}} \oplus 0.003$$

July 2011
EPS

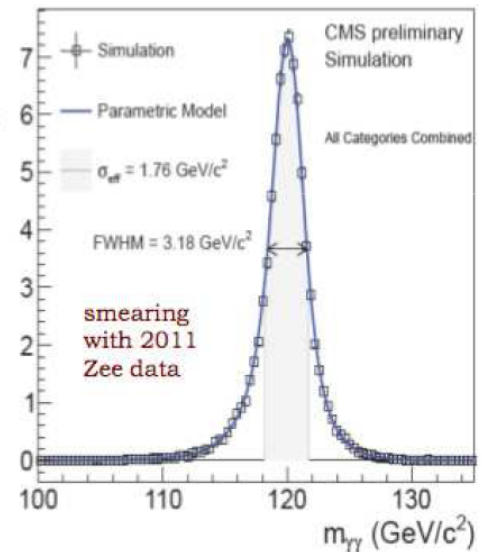
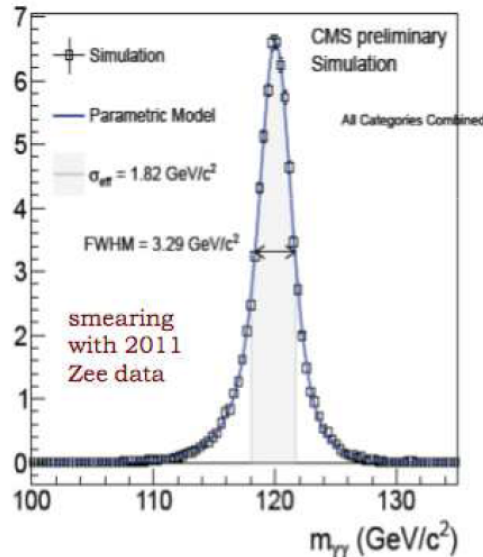
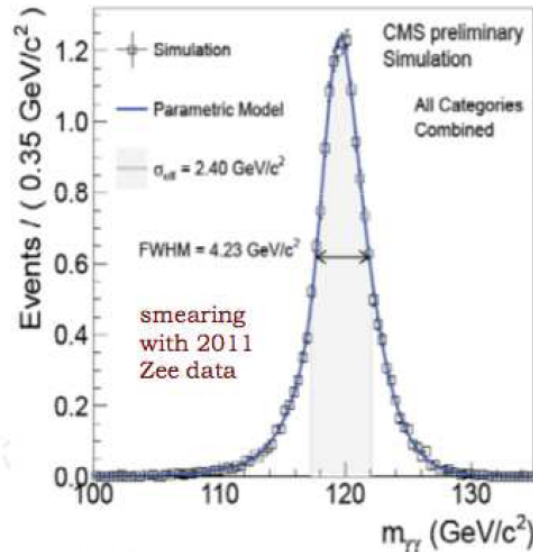
March 2012
Moriond

July 2012
ICHEP

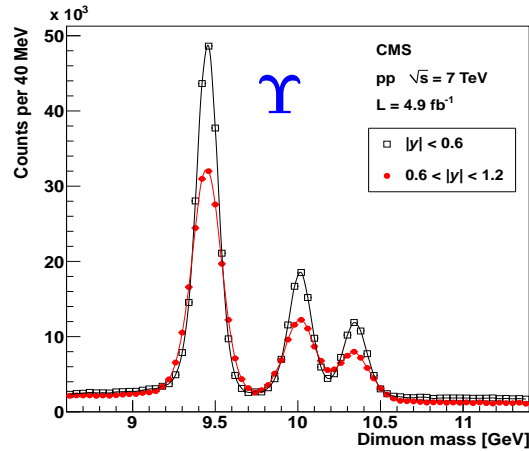
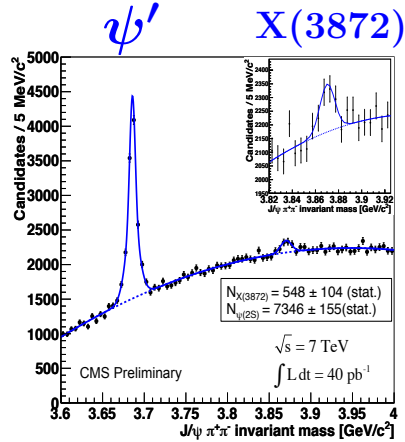
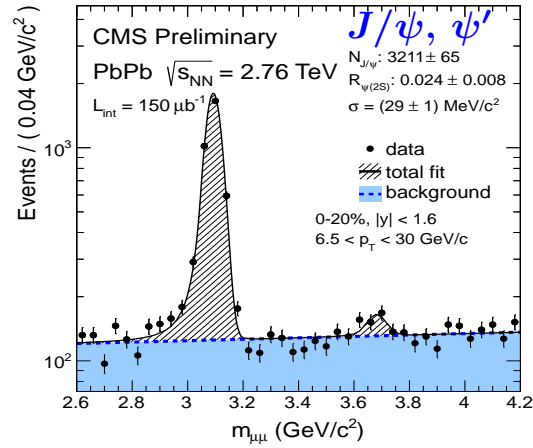
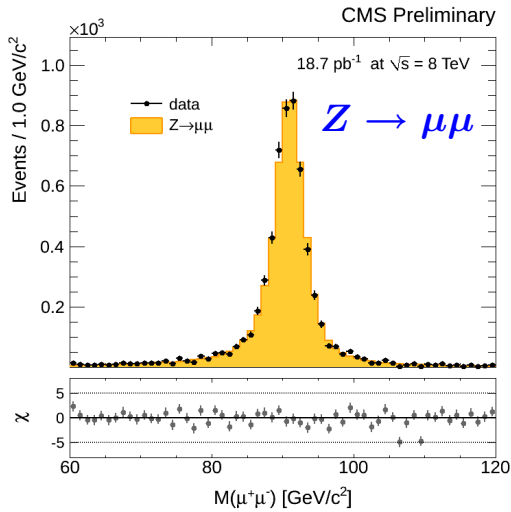
$\text{FWHM}/2.35 =$
1.80 GeV (1.50%)

$\text{FWHM}/2.35 =$
1.40 GeV (1.17%)

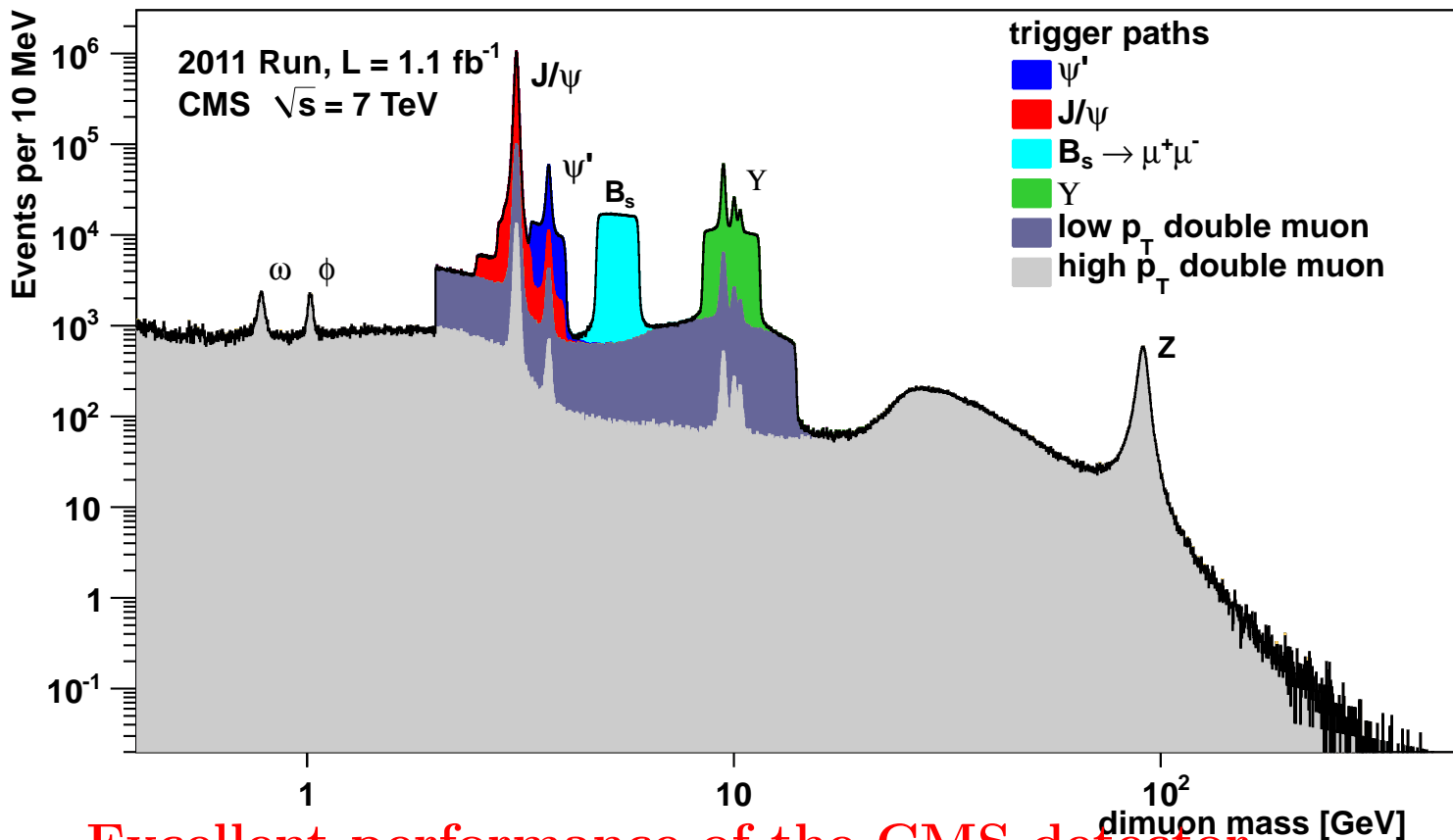
$\text{FWHM}/2.35 =$
1.35 GeV (1.13%)



For the golden categories, both photons in the barrel and no conversions:
 $\text{FWHM}/2.35 = 1.04 \text{ GeV} (0.87\%)$ approaching the nominal value.



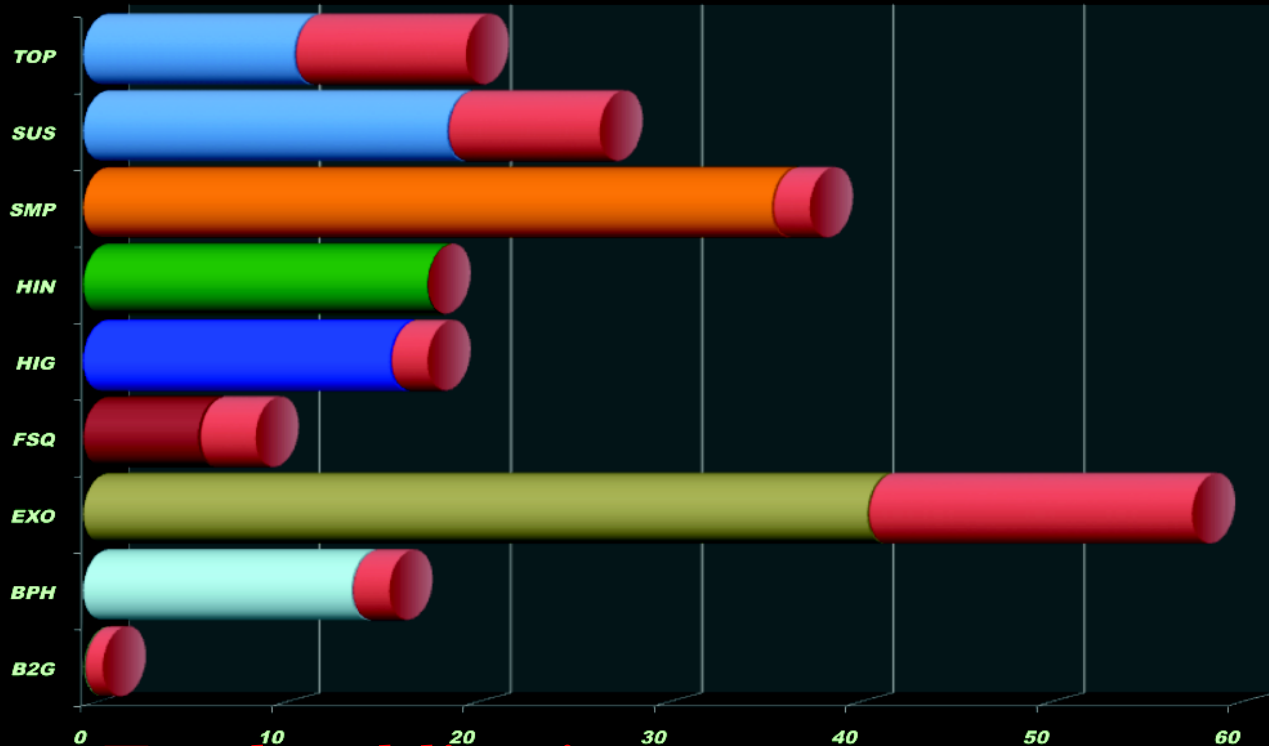
Dimuon mass distribution from several trigger paths



Excellent performance of the CMS detector

Published, submitted or in CWR

CMS Physics Publications

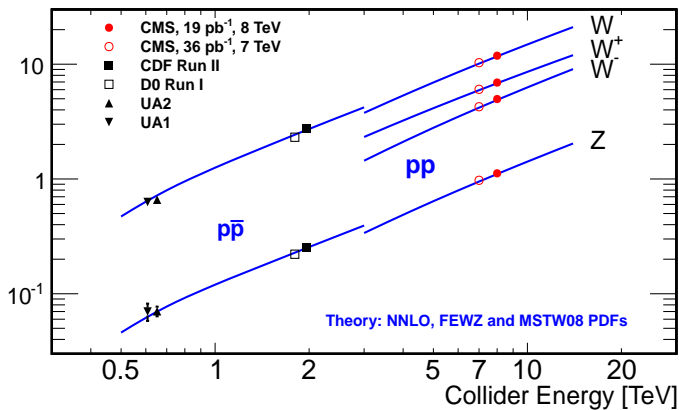
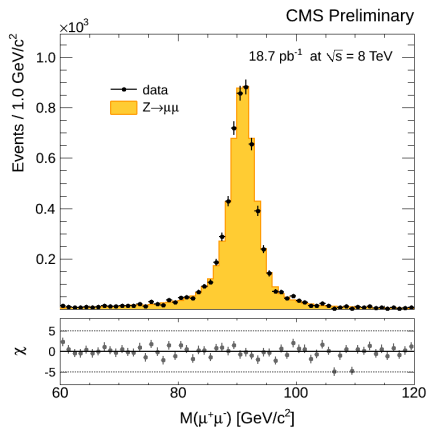
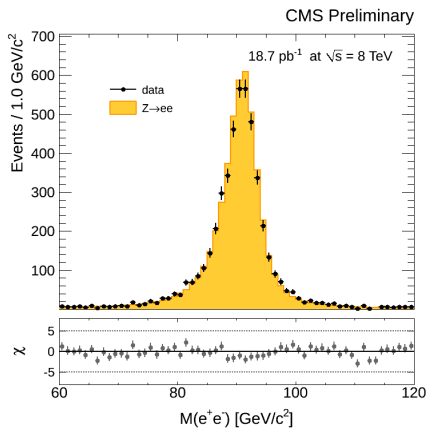


Total publications: ~ 200 papers

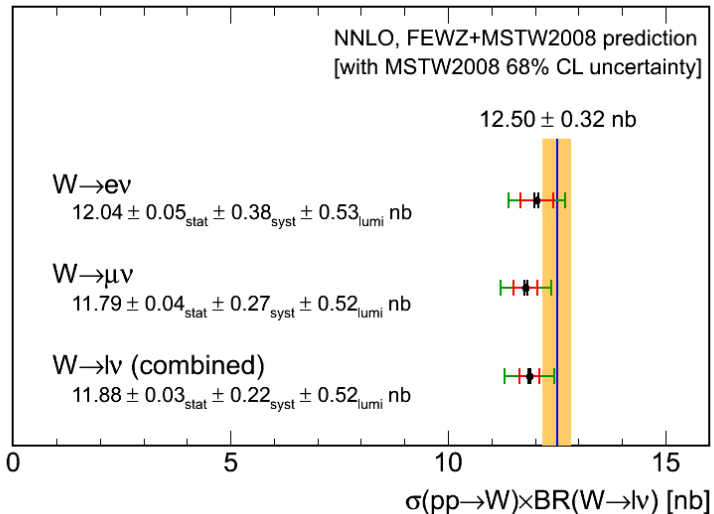
Standard Model (Electroweak & QCD)



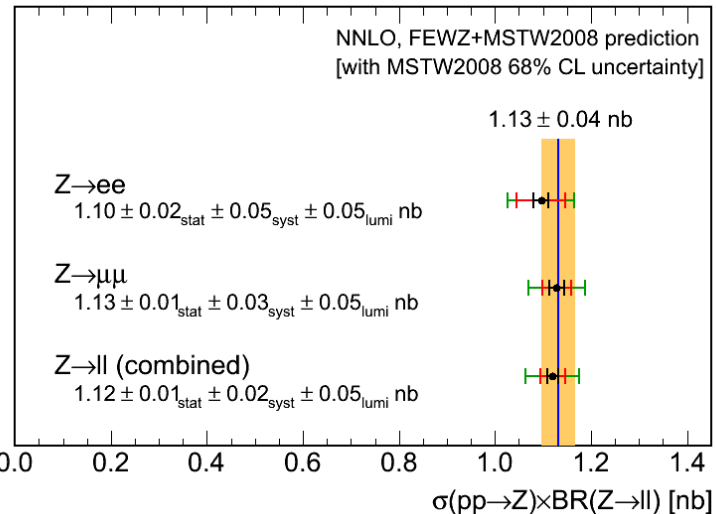
Inclusive W and Z boson cross sections at $\sqrt{s} = 8$ TeV (SMP-12-011)



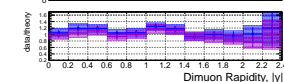
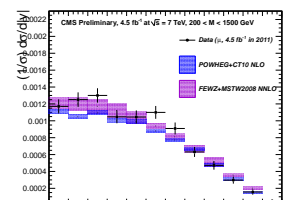
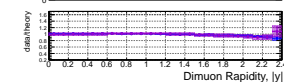
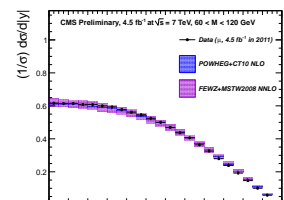
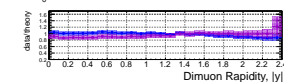
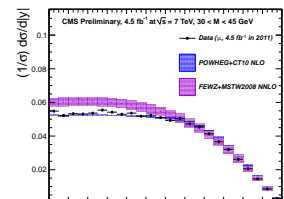
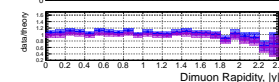
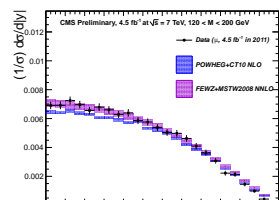
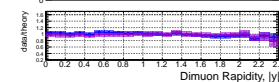
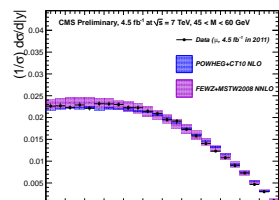
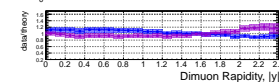
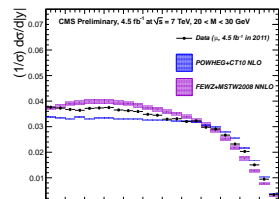
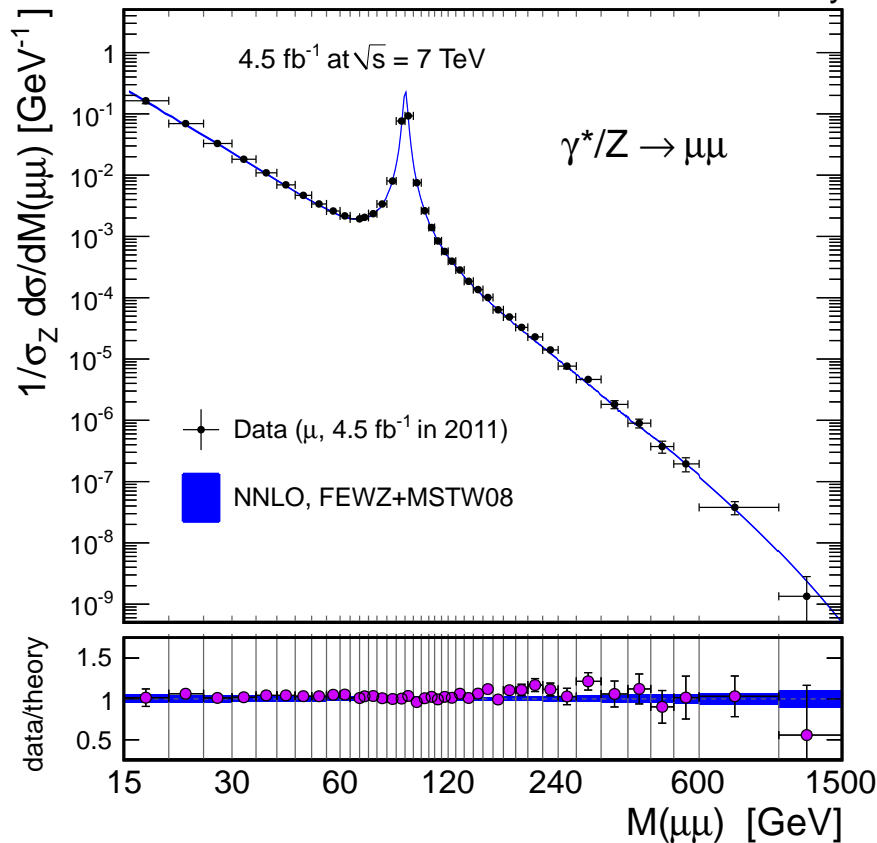
CMS Preliminary 18.7 pb⁻¹ at $\sqrt{s} = 8$ TeV



CMS Preliminary 18.7 pb⁻¹ at $\sqrt{s} = 8$ TeV

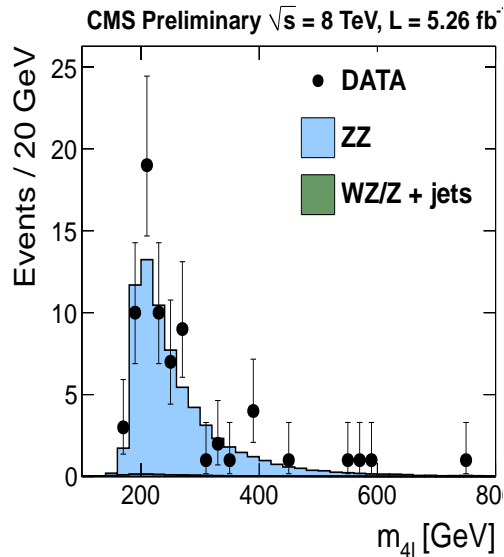


CMS Preliminary

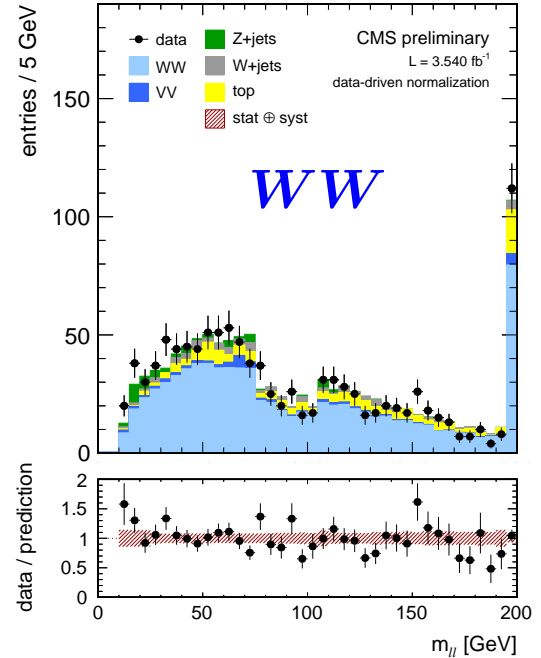
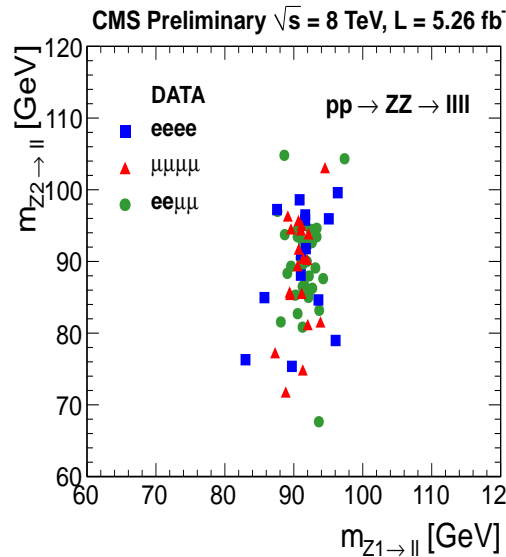


Generally good agreement between data and theory (NNLO calculation with FEWZ)
 2D differential distributions $d^2\sigma/dM dy$ also measured

ZZ



ZZ

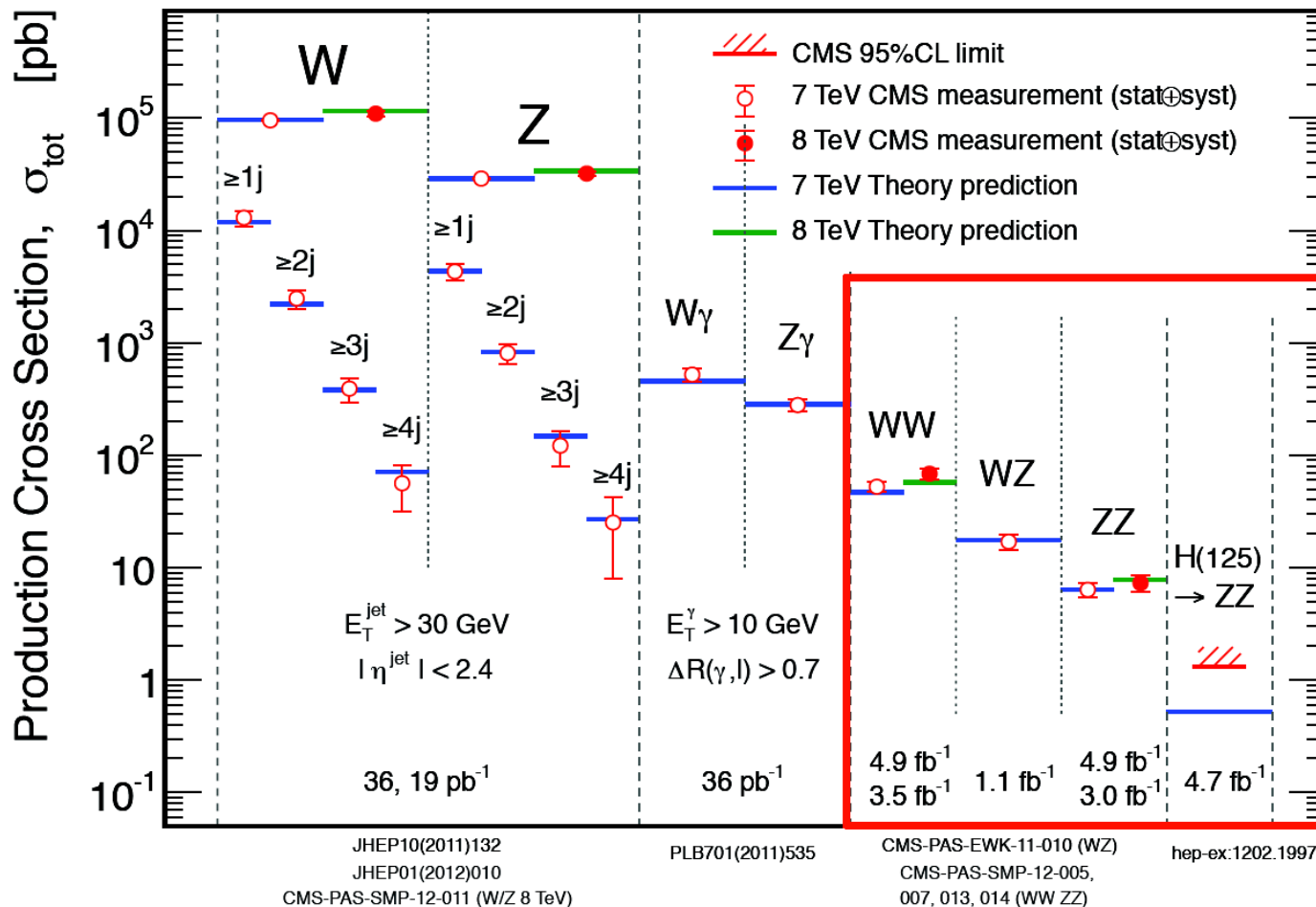


Measured cross sections:

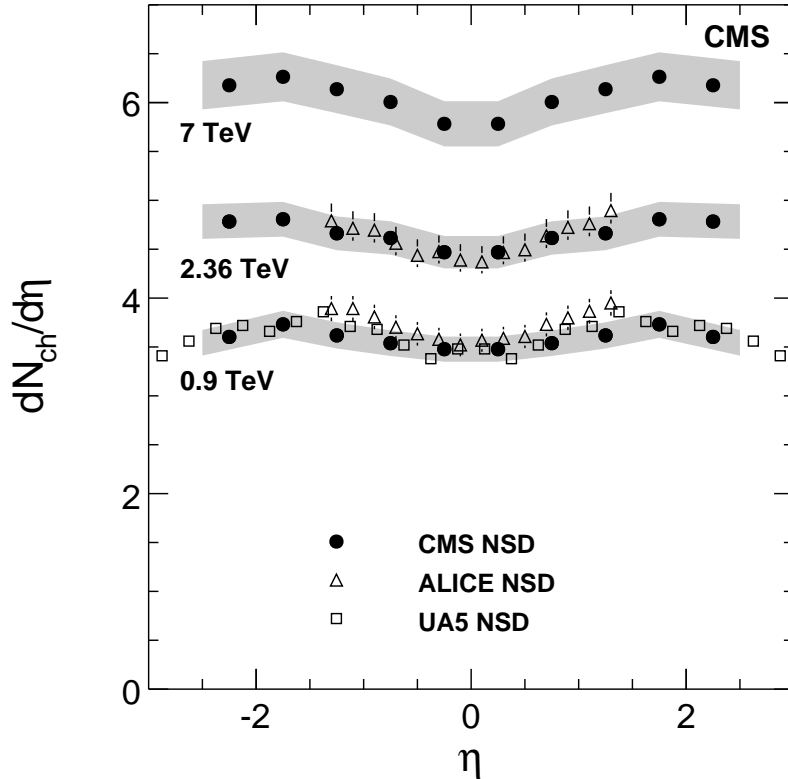
$\sigma(pp \rightarrow ZZ) = 8.4 \pm 1.0(\text{stat.}) \pm 0.7(\text{syst.}) \pm 0.4(\text{lumi.}) \text{ pb}$ (for $m_Z \in [60, 120] \text{ GeV}$)
 $\sigma(pp \rightarrow WW) = 69.9 \pm 2.8 (\text{stat.}) \pm 5.6 (\text{syst.}) \pm 3.1 (\text{lumi.}) \text{ pb}$

Consistent with the standard model prediction.

Summary of Electroweak Physics Results

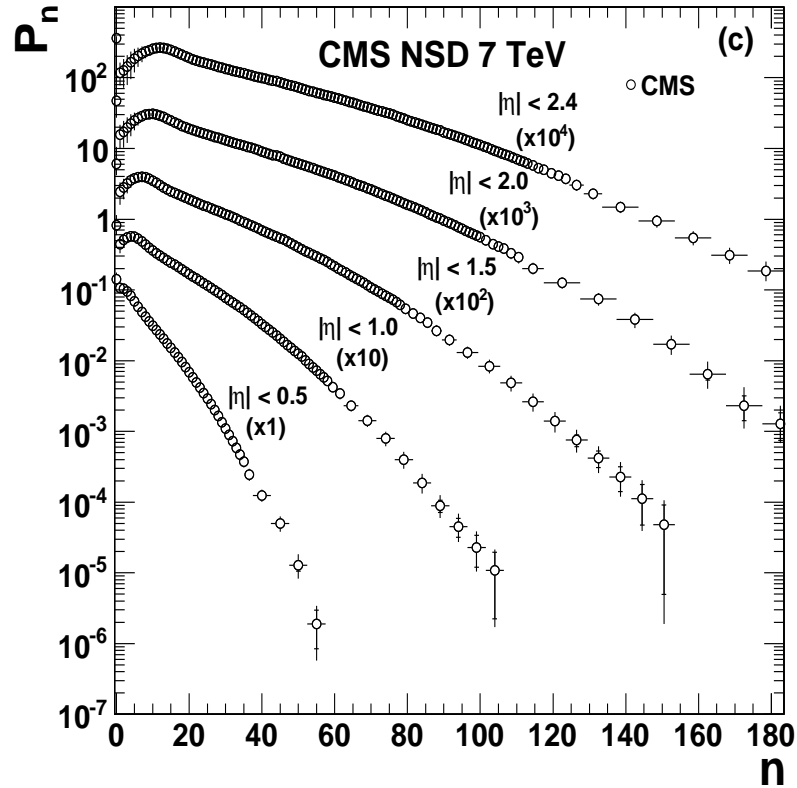


$dN_{\text{Charged}}/d\eta$



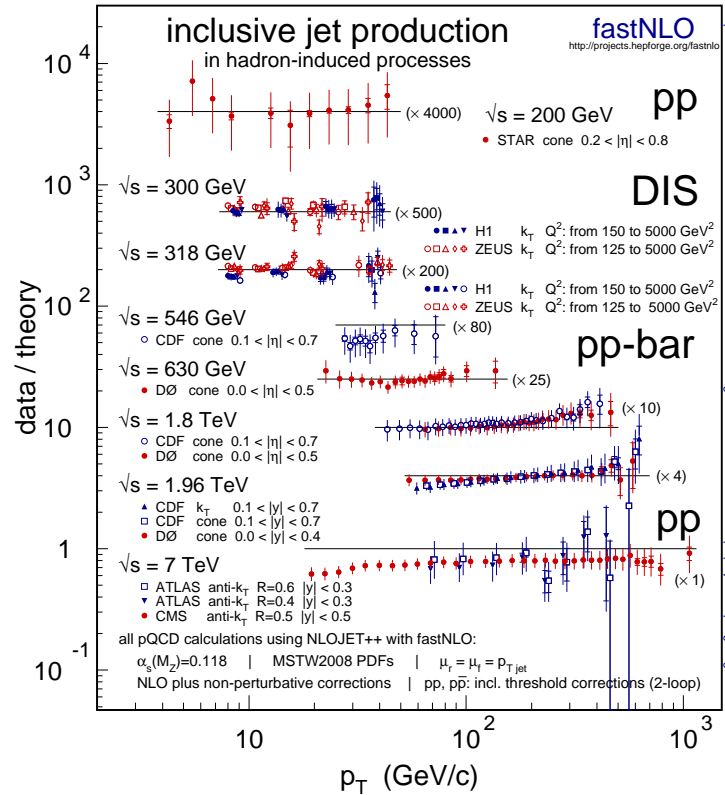
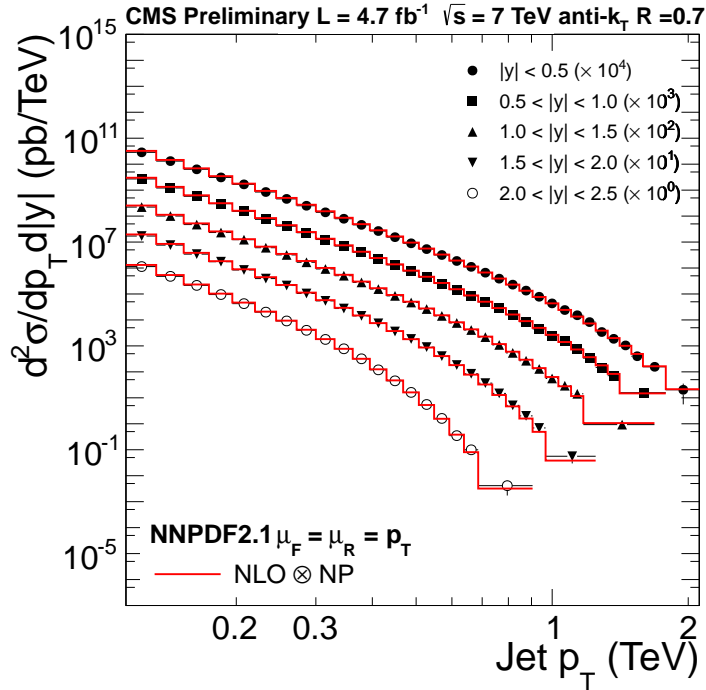
QCD-10-006

dP_n



QCD-10-004

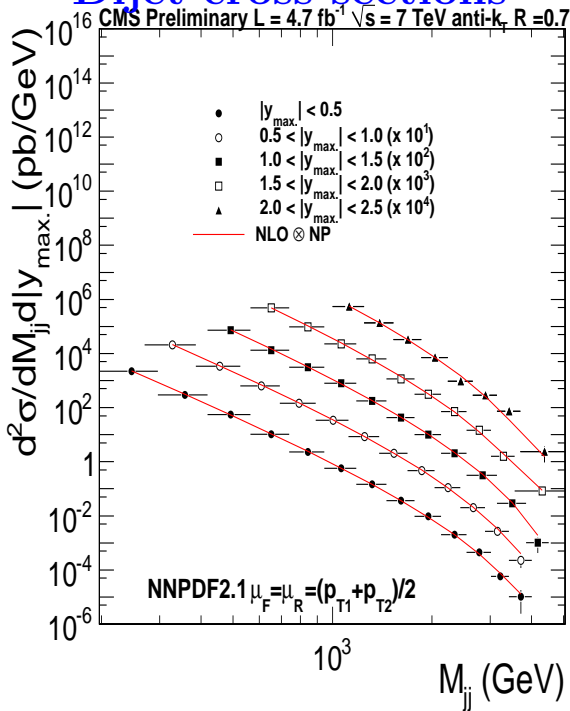
Inclusive jet cross sections



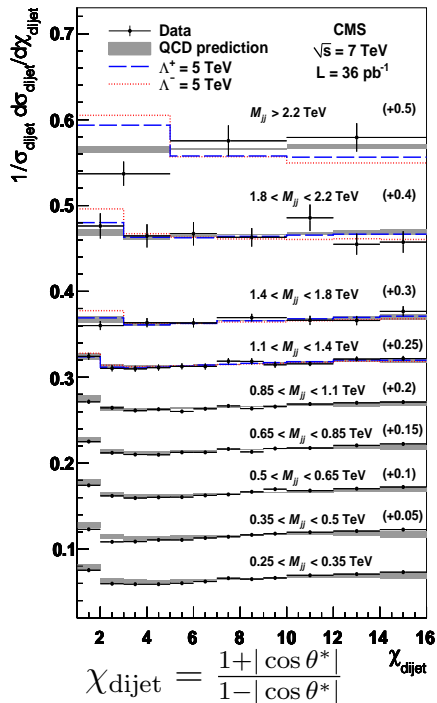
Results are in good agreement with NLO pQCD until jet $p_T \sim 2$ TeV.

Used in general fits of collider data by fastNLO Collaboration (ArXiv:1109.1310).

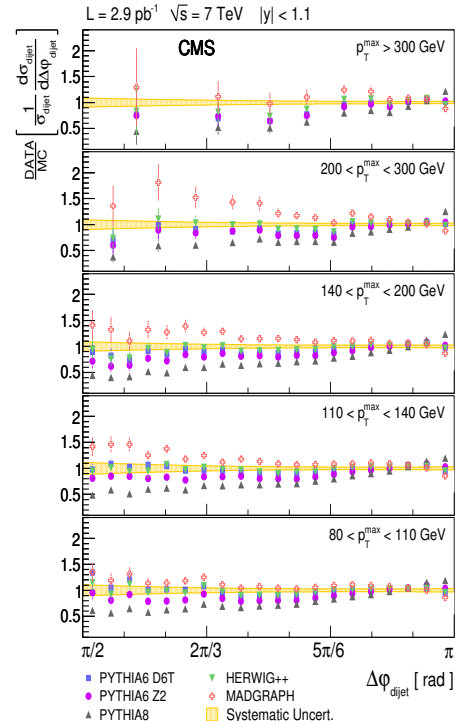
Dijet cross sections



Dijet angular distributions



Dijet azimuthal decorrelations

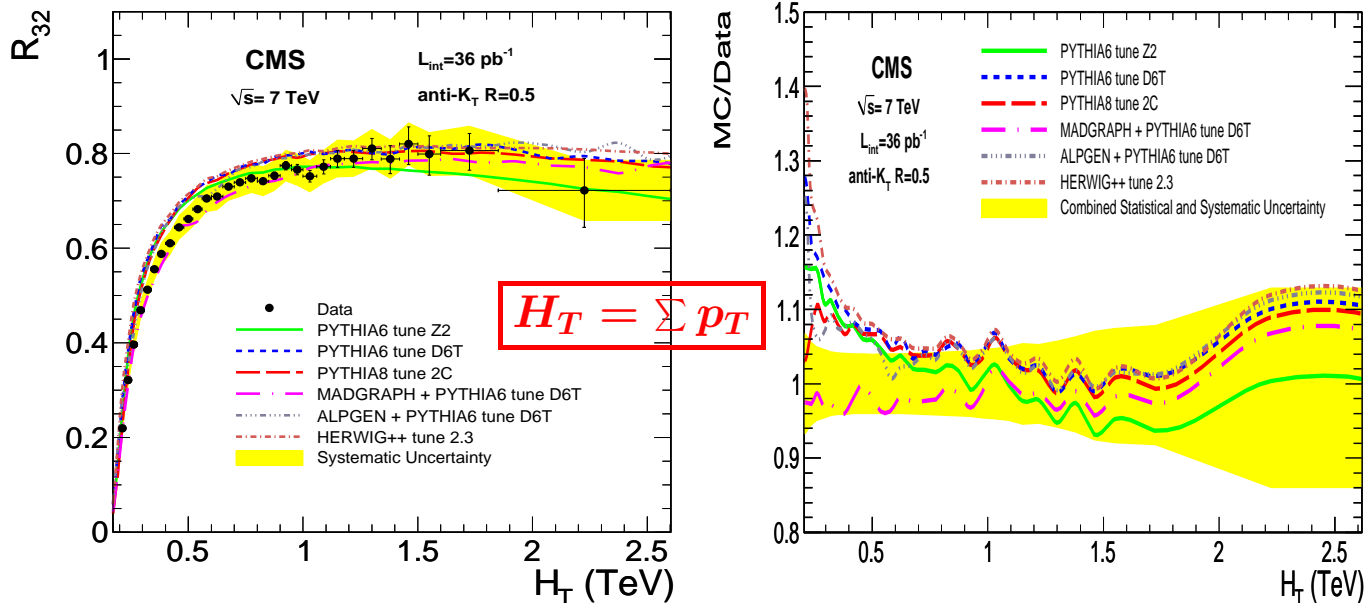


Results are in good agreement with NLO pQCD until invariant dijet mass 5 TeV.

Quark compositeness: lower limit on the contact interaction scale:

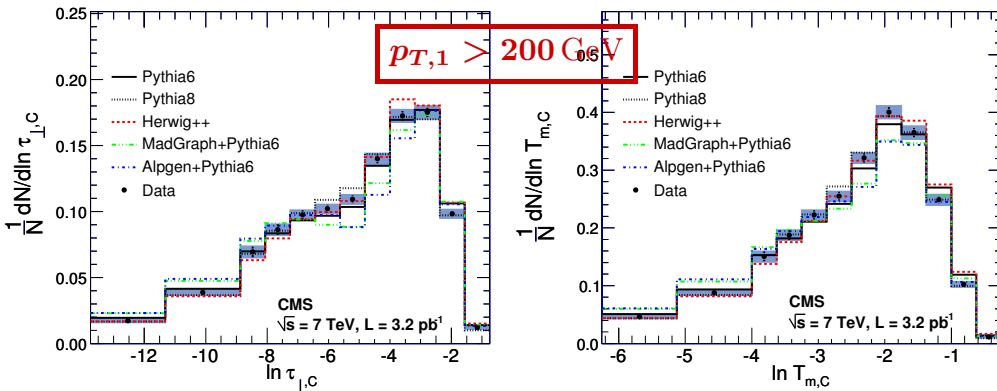
$\Lambda^+ = 5.6 \text{ TeV}$, $\Lambda^- = 6.7 \text{ TeV}$ at 95% confidence level.

Ratio of the 3-jet to 2-jet Cross Sections (QCD-10-012)



Results for ratio of the inclusive 3-jet to 2-jet cross sections are in good agreement with SM for all values H_T between from 0.5 to 2.5 TeV (extending to an H_T range that has not been explored before).

Event shapes provide information about the properties of hadronic final states



Event-shape variables:

Central transverse thrust

$$\tau_{\perp,C} \equiv 1 - \max_{\hat{n}_T} \frac{\sum_i |\vec{p}_{\perp,i} \cdot \hat{n}_T|}{\sum_i p_{\perp,i}}$$

Central thrust minor

$$T_{m,C} \equiv \frac{\sum_i |\vec{p}_{\perp,i} \times \hat{n}_{T,C}|}{\sum_i p_{\perp,i}}$$

3 bins for leading jet $p_{T,1}$:
(90–125, 125–200, > 200 GeV)

Pythia6 and Herwig++ predictions agree with the measurements in all three momentum bins, ALPGEN, MADGRAPH and Pythia8 curves have some deviations from the data.

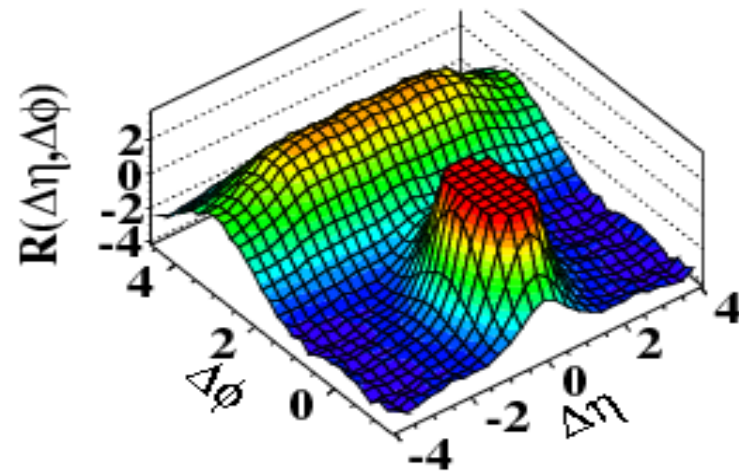
These measurements provide input for improvement of currently available models of QCD multijet production.



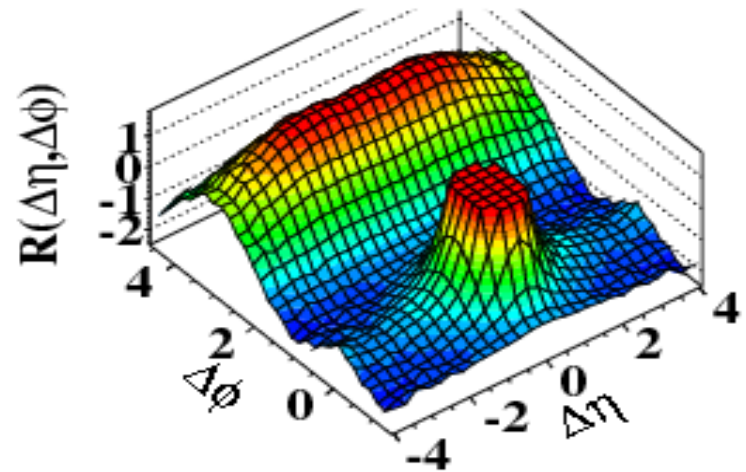
“Ridge effect” observed for the first time in pp collisions.

Particle correlations: wide $\Delta\eta$ region, narrow $\Delta\phi \approx 0$ region

(c) CMS $N \geq 110$, $p_T > 0.1 \text{ GeV}/c$



(d) CMS $N \geq 110$, $1.0 \text{ GeV}/c < p_T < 3.0 \text{ GeV}/c$

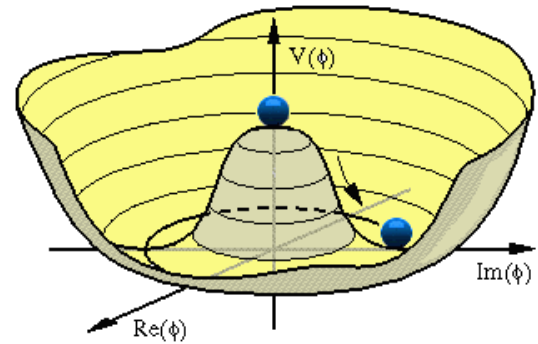
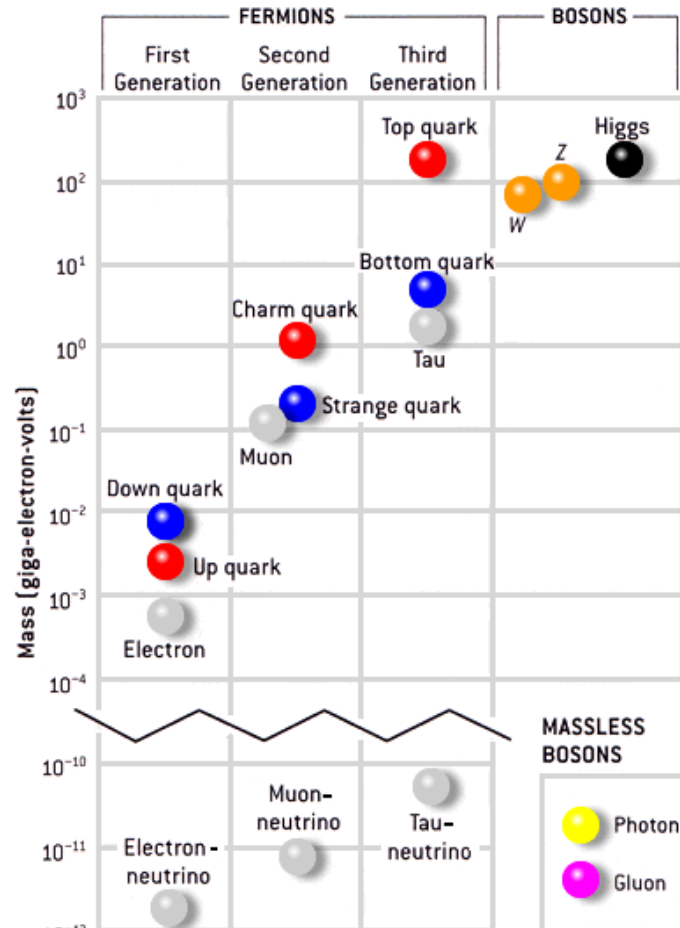


Pronounced structure at large $\Delta\eta$ around $\Delta\phi \approx 0$!

Experimental manifestation of the new coherent effects in proton-proton collisions

⇒ Flow of possible explanations using different mechanisms

Higgs boson searches



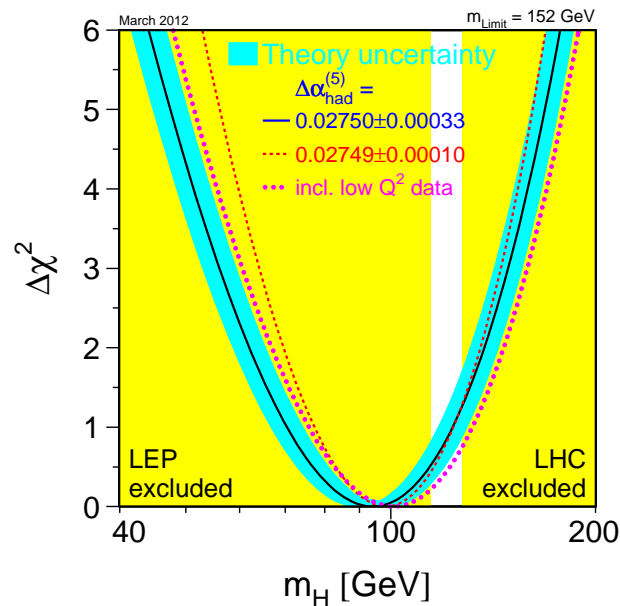




Timeline for Higgs Searches at CERN & 2011+2012 Analyses by CMS



- LEP excluded $M_H < 114$ GeV (2003)
- LHC exclusion, using 2011 data — 127-600 GeV 3σ peak at ~ 125 GeV (CMS-PAS-HIG-12-008)
- Fit of precision electroweak measurements (March 2012)
- On July 4, 2012, CMS and ATLAS reported 5σ observation (each) of a new boson with mass about 125 GeV, consistent with the SM Higgs boson.
- Papers submitted to publication on July 31: Phys. Lett. B716 (2012) 1; 30.

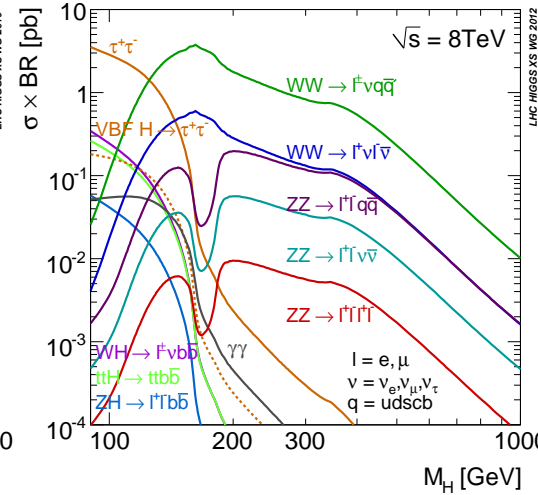
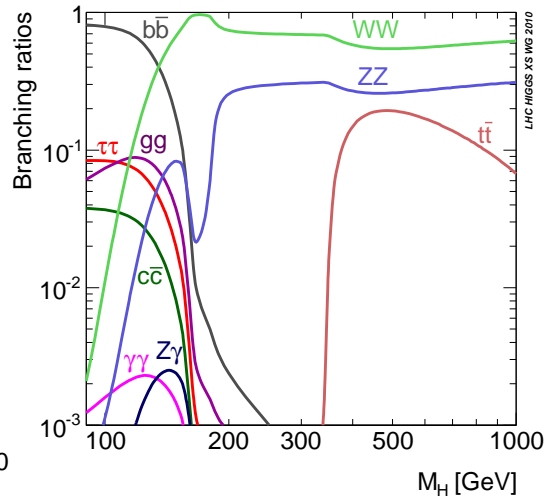
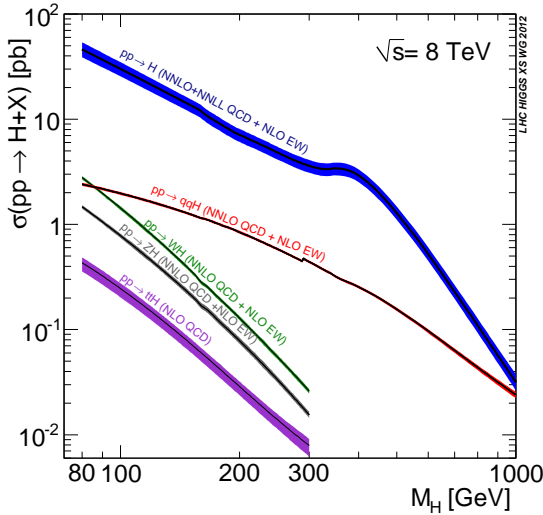




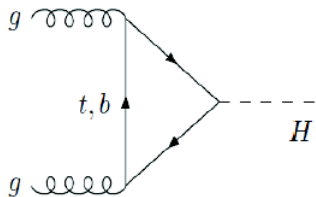
SM Higgs: Cross sections & Branchings



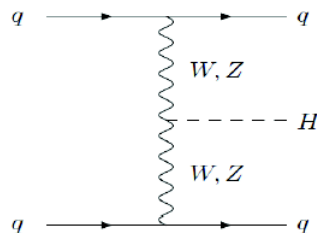
Expected cross sections for SM Higgs boson



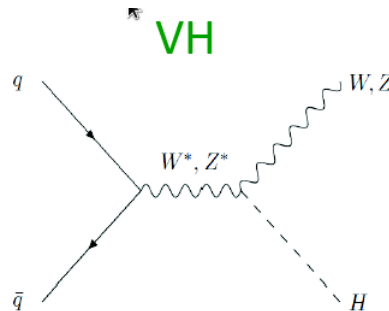
ggH



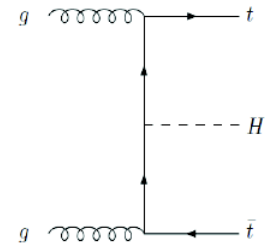
VBF



VH



ttH



5 main channels:

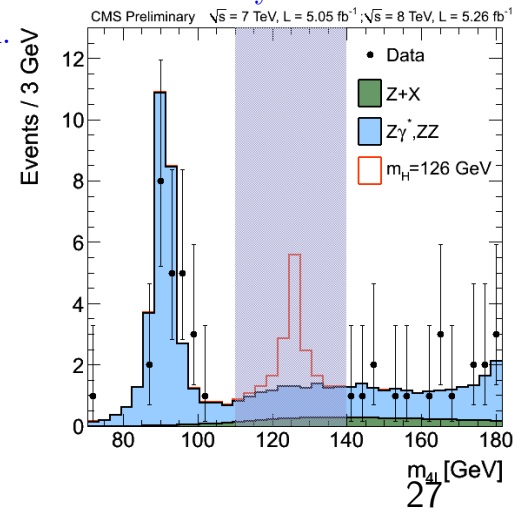
Summary of the subchannels, or categories, used in the analysis of each decay mode.

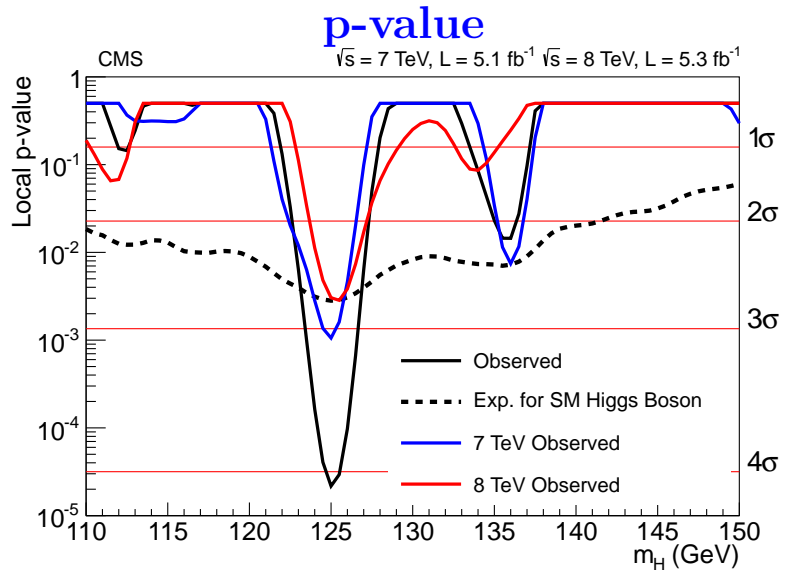
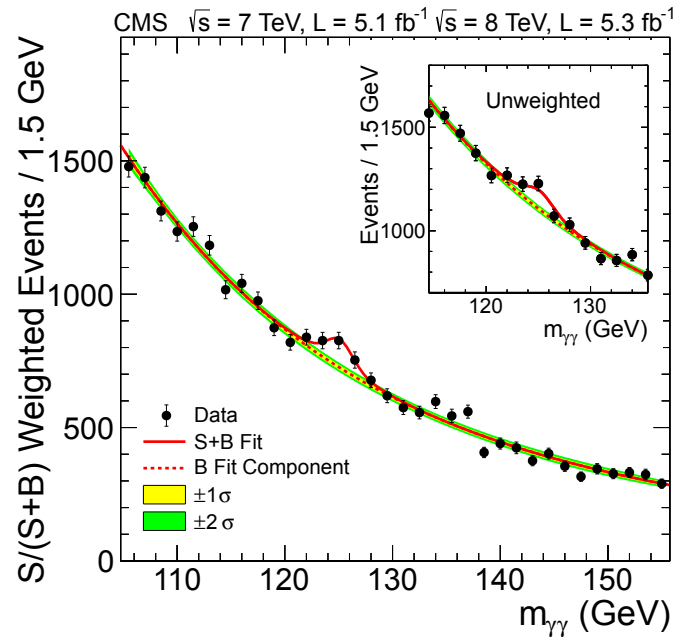
Decay mode	Production tagging	No. of subchannels	m_H range (GeV)	Int. Lum. (fb^{-1})	
				7 TeV	8 TeV
$\gamma\gamma$	untagged	4	110–150	5.1	5.3
	dijet (VBF)	1 or 2			
ZZ	untagged	3	110–600	5.1	5.3
WW	untagged	4	110–600	4.9	5.1
	dijet (VBF)	1 or 2			
$\tau\tau$	untagged	16	110–145	4.9	5.1
	dijet (VBF)	4			
bb	lepton, E_T^{miss} (VH)	10	110–135	5.0	5.1

} Excellent mass resolution
 1–2%

} Worst mass resolution
 Largest cross section

- All 2012 analyses were “blind”: analyses were fixed before looking at the signal region. In order to avoid the possibility of an unintended bias, all selection criteria in the analyses of the 2011 and 2012 data were fixed before looking at the result in the signal region.
- Most of analyses have been re-optimized compared to 2011.





- Significance: 4.1σ (expected 2.8σ)
- Excess at $\sim 125 \text{ GeV}$
- Very consistent between 2011 and 2012
- Resulting strength at 125.6 GeV : $\mu = \sigma/\sigma_{SM} = 1.6 \pm 0.4$
- $\gamma\gamma$ alone excludes almost full mass region
- Cross-checked with two alternative analyses (simple cuts and MVA) \implies Compatible results



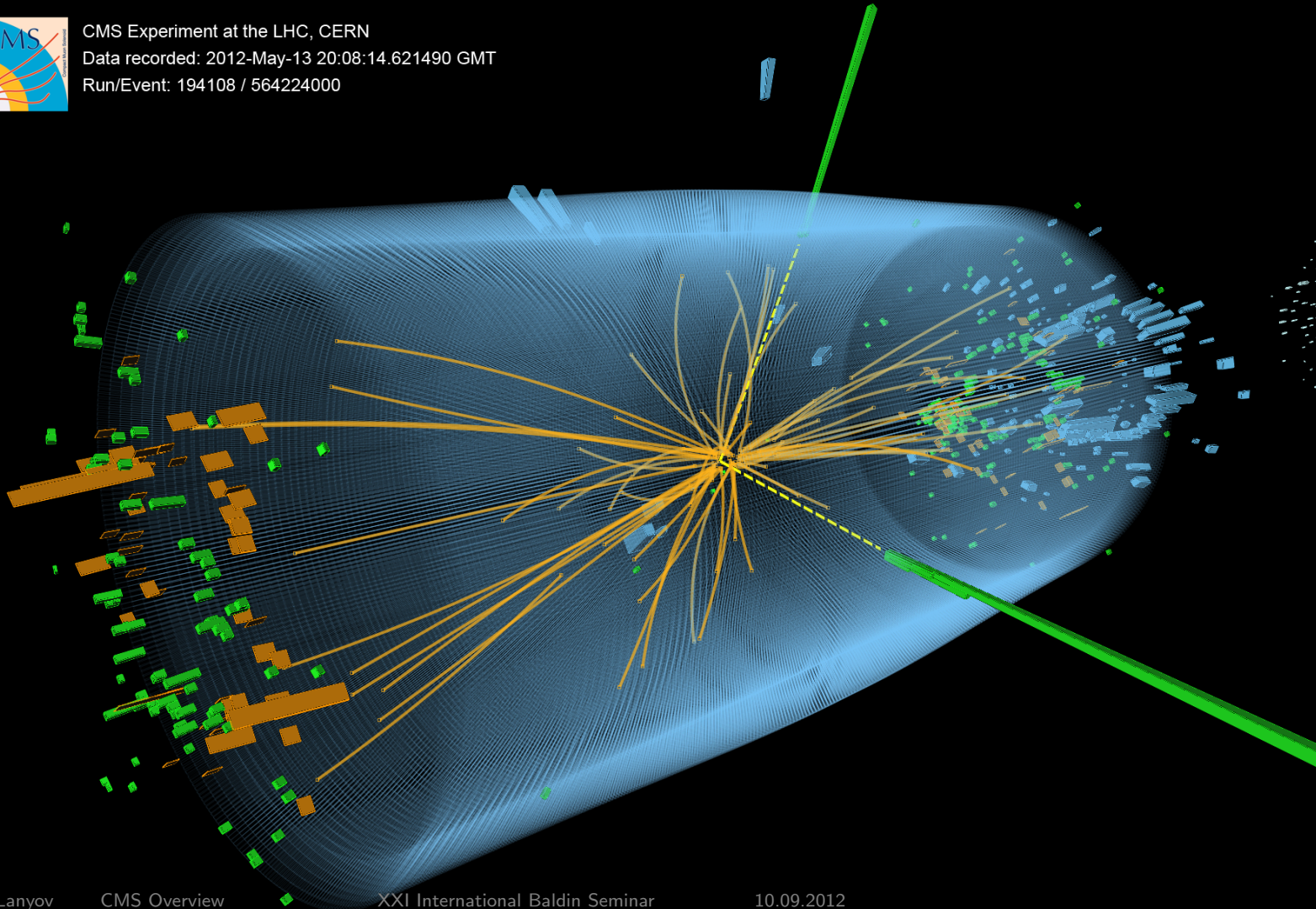
Event display for Higgs $\rightarrow \gamma\gamma$



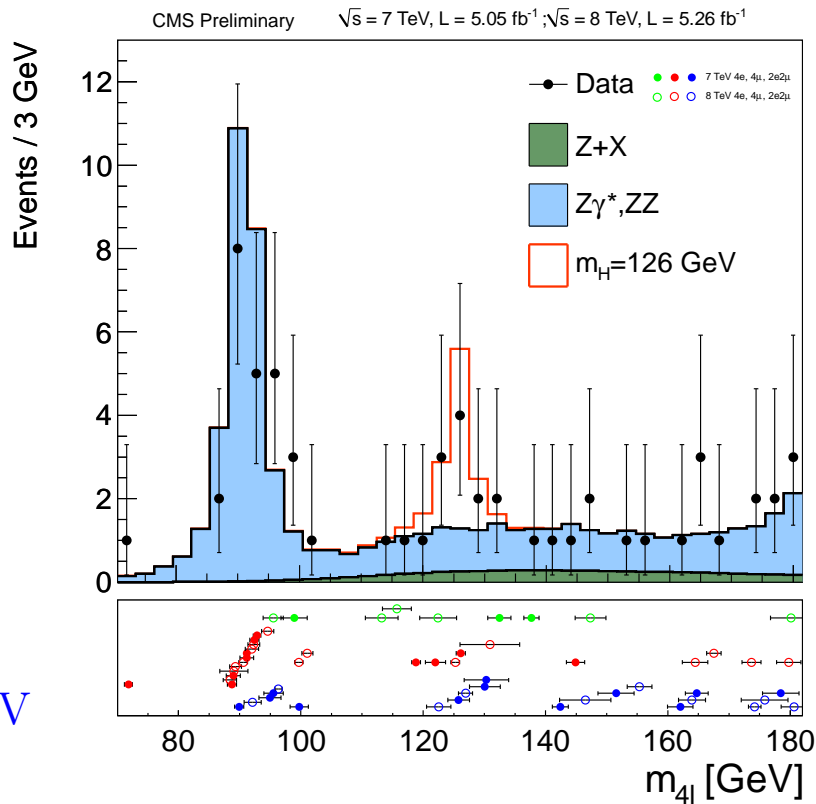
CMS Experiment at the LHC, CERN

Data recorded: 2012-May-13 20:08:14.621490 GMT

Run/Event: 194108 / 564224000



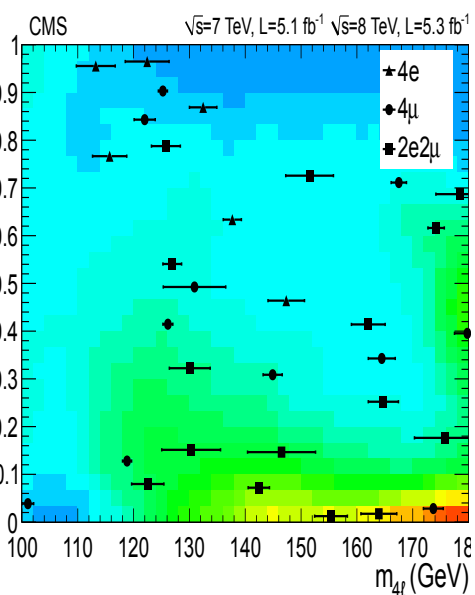
- Clean channel:
2 high-mass pairs of opposite-sign isolated electrons or muons coming from Primary vertex
- Narrow mass peak:
Very good mass resolution 1–2%
- Background:
 - irreducible: ZZ
 - reducible: $Z + \text{jets}$, $Zb\bar{b}$, $t\bar{t}$, WZ
- Small Branching $\sim 10^{-3}$ at 125 GeV



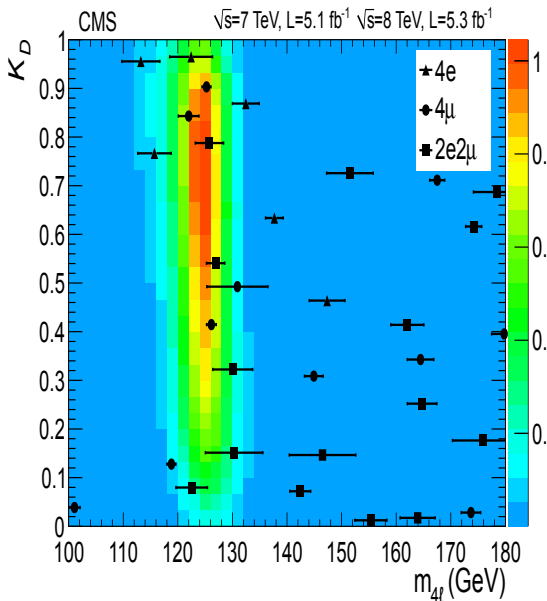
MELA (Matrix Element Likelihood Approach):
Analytical likelihood built from angular distributions

$$\text{MELA} = \frac{P_{\text{Sig}}}{P_{\text{Sig}} + P_{\text{bkg}}}$$

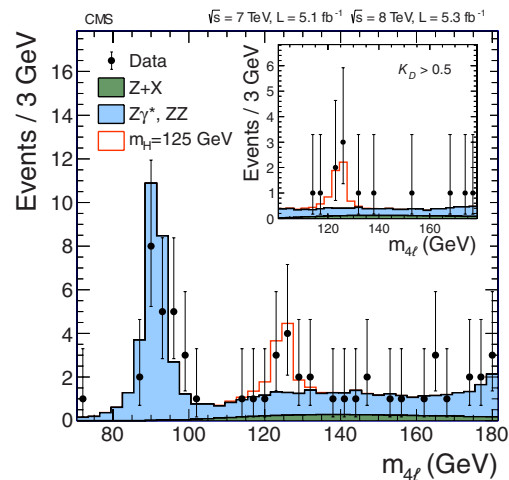
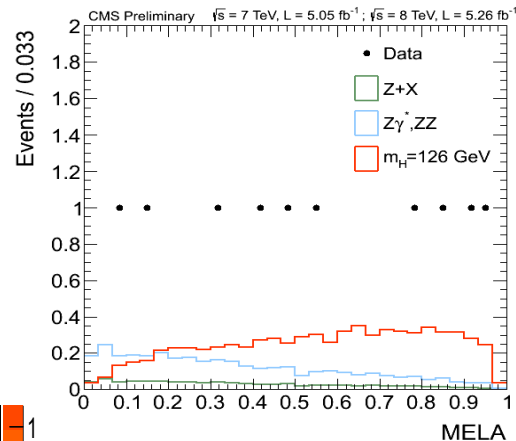
Background hypothesis



SM Higgs hypothesis



MELA distribution



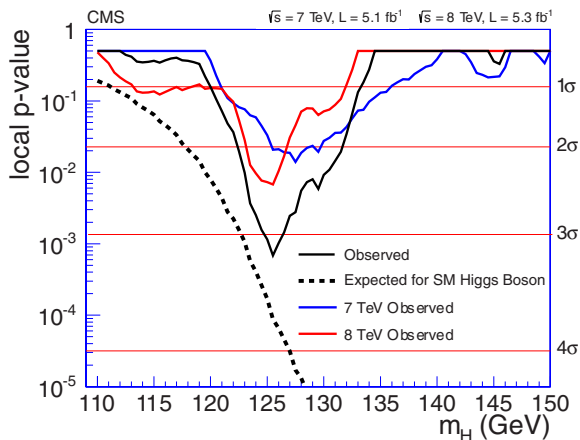


Higgs $\rightarrow ZZ \rightarrow 4\ell$ (HIG-12-016)



Number of selected events and background (mass range 110–160 GeV)

Channel	4e	4 μ	2e2 μ	4 ℓ
ZZ background	2.7 ± 0.3	5.7 ± 0.6	7.2 ± 0.8	15.6 ± 1.4
Z + X	$1.2^{+1.1}_{-0.8}$	$0.9^{+0.7}_{-0.6}$	$2.3^{+1.8}_{-1.4}$	$4.4^{+2.2}_{-1.7}$
All backgrounds (110 < $m_{4\ell}$ < 160 GeV)	4.0 ± 1.0	6.6 ± 0.9	9.7 ± 1.8	20 ± 3
Observed (110 < $m_{4\ell}$ < 160 GeV)	6	6	9	21
Signal ($m_H = 125$ GeV)	1.36 ± 0.22	2.74 ± 0.32	3.44 ± 0.44	7.54 ± 0.78
All backgrounds (signal region)	0.7 ± 0.2	1.3 ± 0.1	1.9 ± 0.3	3.8 ± 0.5
Observed (signal region)	1	3	5	9



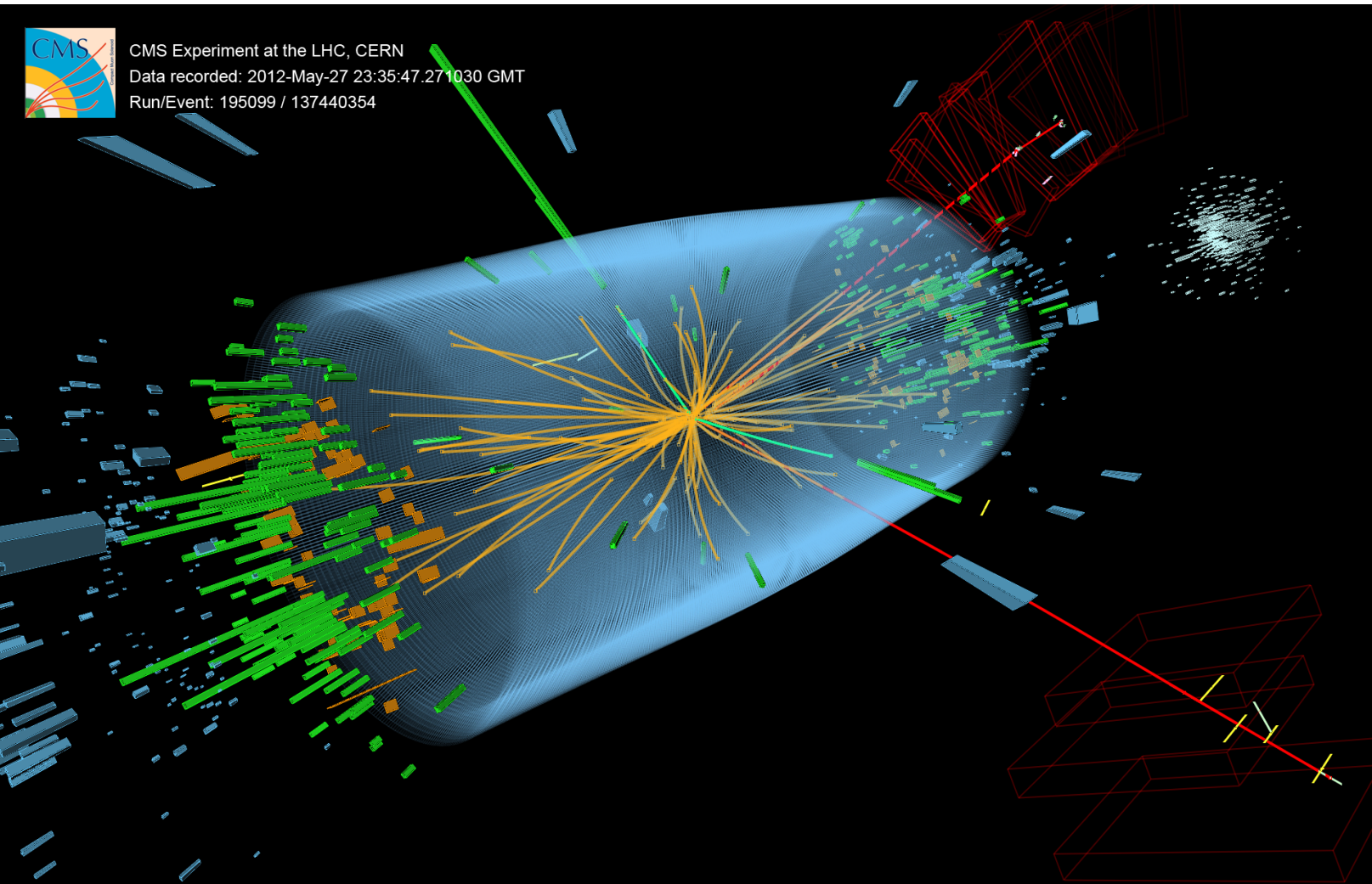
- Significance: 3.1σ (expected 3.6σ)
- Excess at ~ 125.6 GeV
- Resulting strength: $\mu = \sigma/\sigma_{SM} = 0.7^{+0.4}_{-0.3}$
- ZZ alone excludes almost full mass region

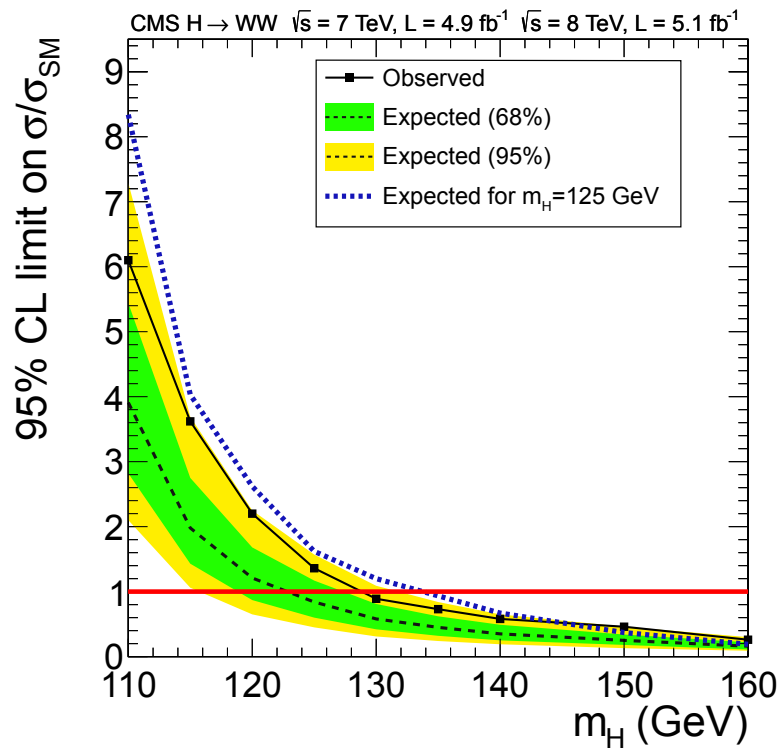
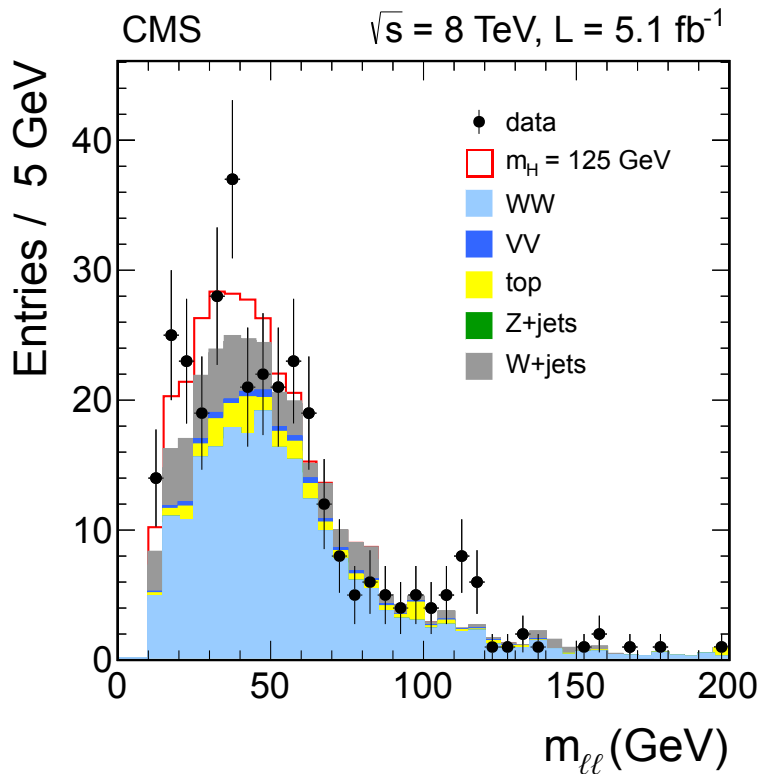


Event display for Higgs $\rightarrow ZZ \rightarrow 2\mu 2e$

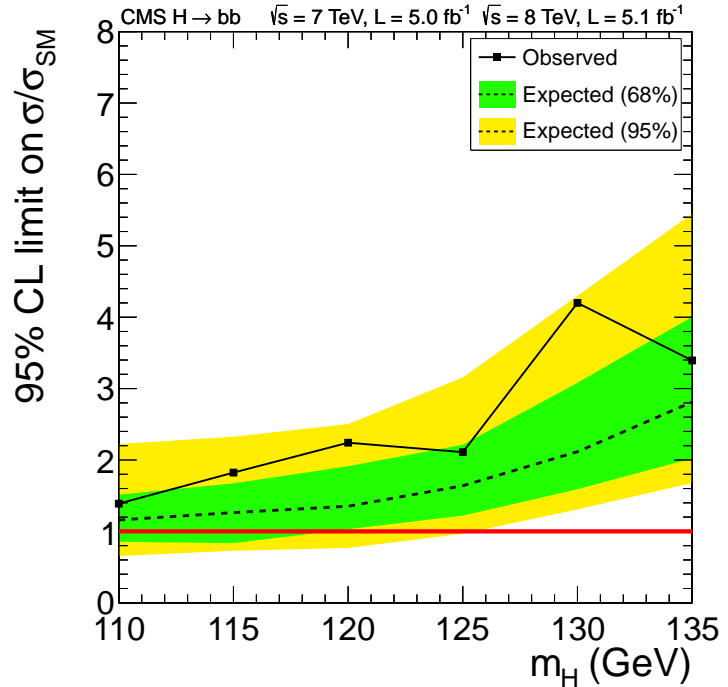
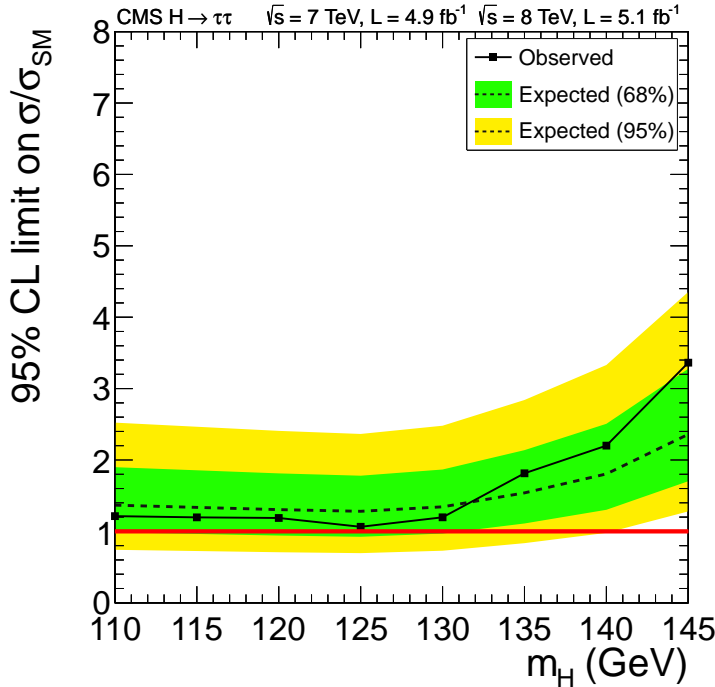


CMS Experiment at the LHC, CERN
Data recorded: 2012-May-27 23:35:47.271030 GMT
Run/Event: 195099 / 137440354

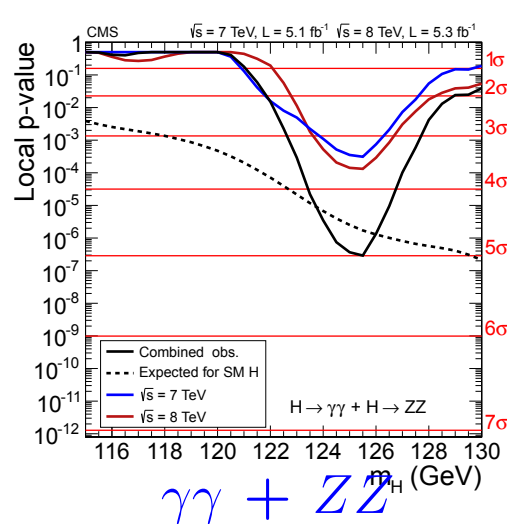
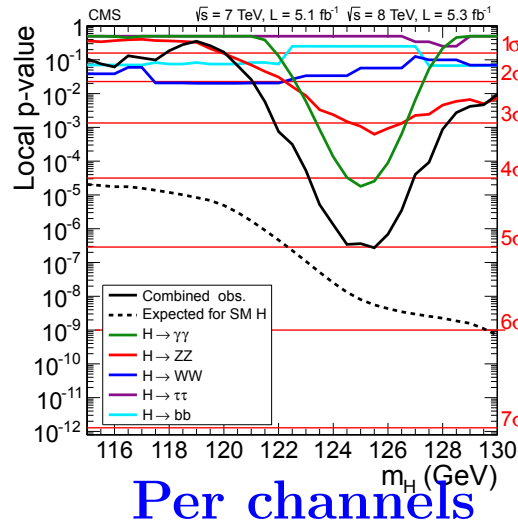
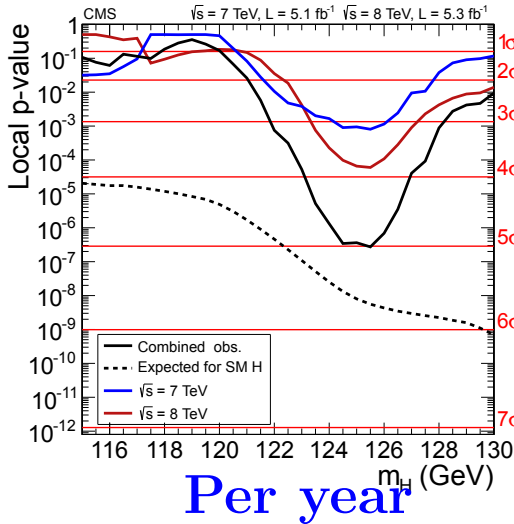




- Broad excess compatible with presence of 1 x SM Higgs

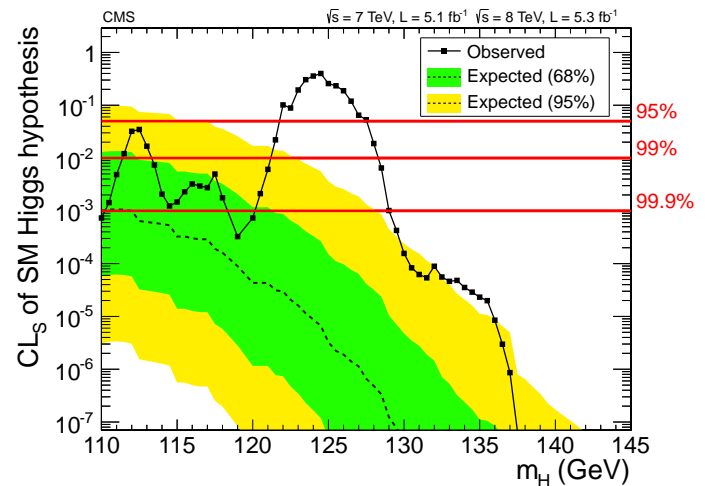


- $\tau\tau$ — No significant excess wrt SM background
 Sensitivity close to 1 x SM Higgs (improved by about 70% wrt 2011)
- bb — Two b-jets, large background is reduced by requiring an associated vector boson
 Analysis improvements wrt 2011 $\sim 50\%$ in sensitivity
 Results: broad excess compatible with presence of 1 x SM Higgs

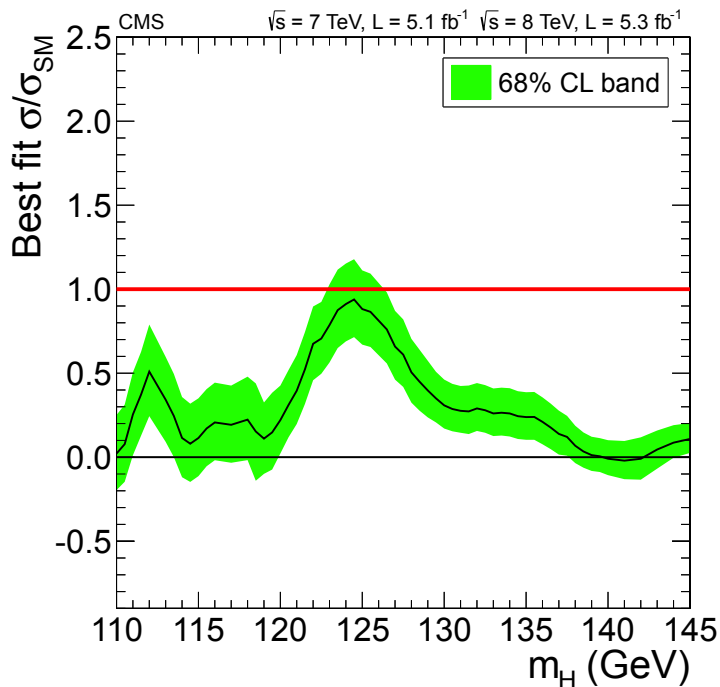


Expected and observed local p -values for $m_H = 125.5$ GeV (expressed in corresponding number of standard deviations of the observed excess from the background-only hypothesis)

Decay mode/combination	Expected (σ)	Observed (σ)
$\gamma\gamma$	2.8	4.1
ZZ	3.6	3.1
$\tau\tau + bb$	2.4	0.4
$\gamma\gamma + ZZ$	4.7	5.0
$\gamma\gamma + ZZ + WW$	5.2	5.1
$\gamma\gamma + ZZ + WW + \tau\tau + bb$	5.8	5.0

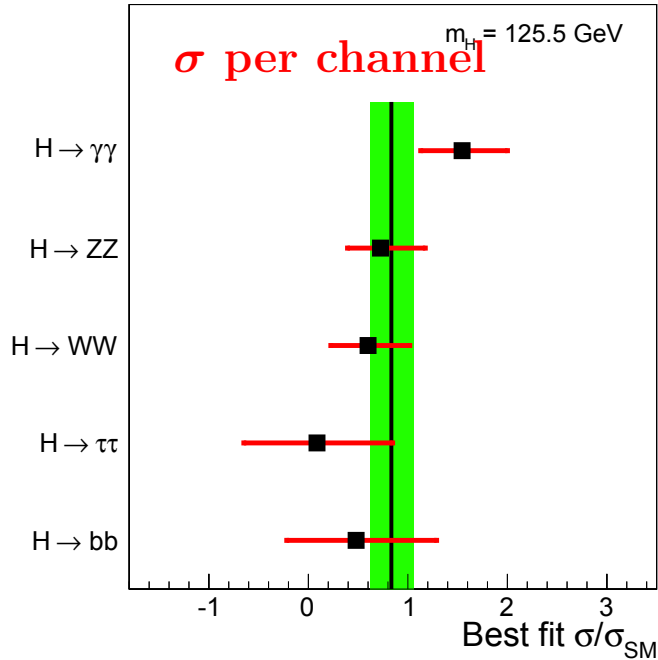


σ / σ_{SM}



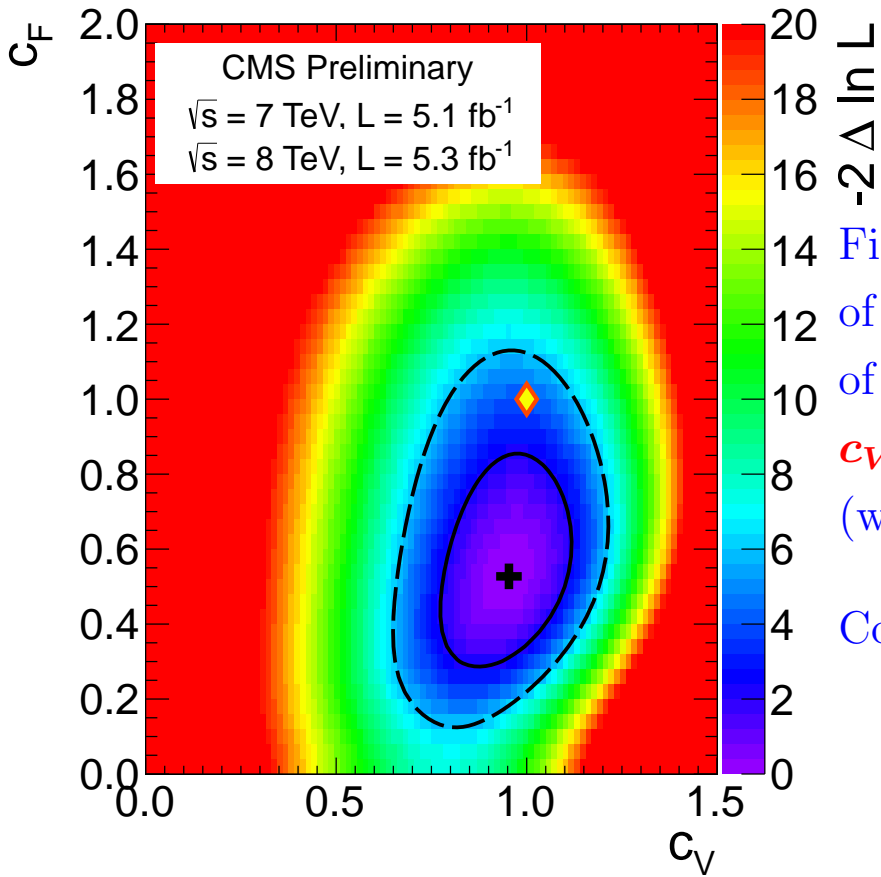
CMS $\sqrt{s} = 7 \text{ TeV}, L = 5.1 \text{ fb}^{-1}$ $\sqrt{s} = 8 \text{ TeV}, L = 5.3 \text{ fb}^{-1}$

σ per channel

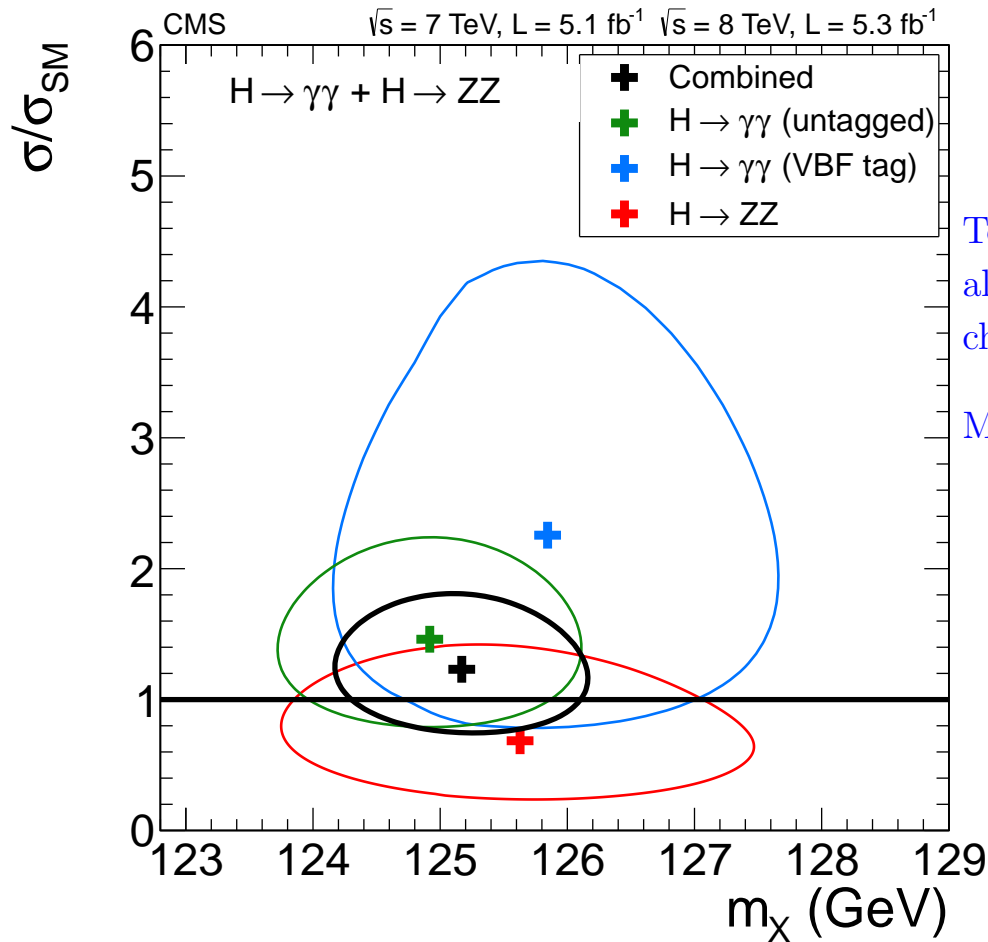


The fitted σ of the excess near 125 GeV is consistent with the SM scalar boson expectation: $\frac{\sigma}{\sigma_{SM}} = 0.87 \pm 0.23$

Signal strengths in 7 and 8 TeV data are consistent.



First measurement of the scaling
 of fermion vs vector couplings
 of the new boson
 $C_V \sim 1, C_F \sim 0.5$
 (when interpreted as a Higgs boson)
 Consistent with the SM Higgs boson.



To reduce model dependence, allow for free cross section in three channels and fit for the common mass.

Measurement dominated by $H \rightarrow \gamma\gamma$

$$M_X = 125.3 \pm 0.4(\text{stat.}) \pm 0.5(\text{syst.}) \text{ GeV}$$

- Not yet really sensitive with the analyzed dataset.

No public results yet using the data

- Only known that the observation of $\gamma\gamma$ channel

excludes the spin 1 hypothesis

(Landau-Yang theorem)

- Spin 2 and Parity could be probed

using angular distributions

- $H \rightarrow ZZ \rightarrow 4\ell$ projections:

using MELA Discriminator

we can discriminate

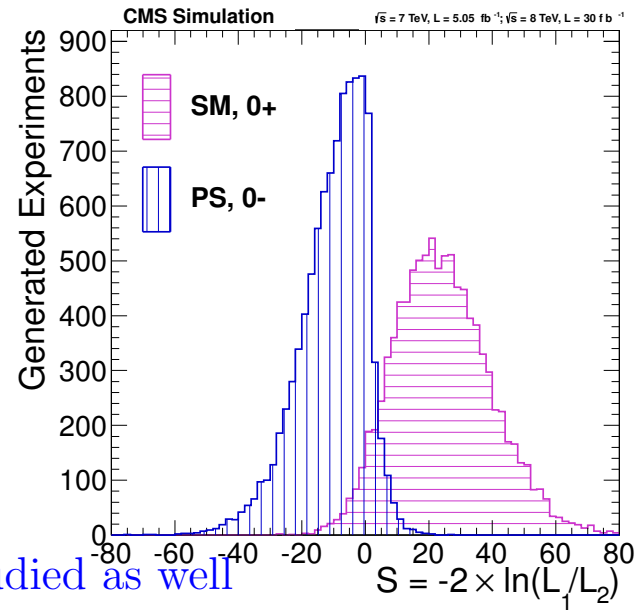
between scalar and pseudo-scalar

at 3σ level with 30 fb^{-1} at 8 TeV

(assuming SM cross section)

- Other channels (WW , $\gamma\gamma$) are being studied as well

Generated experiments ZZ , 30 fb^{-1} at 8 TeV





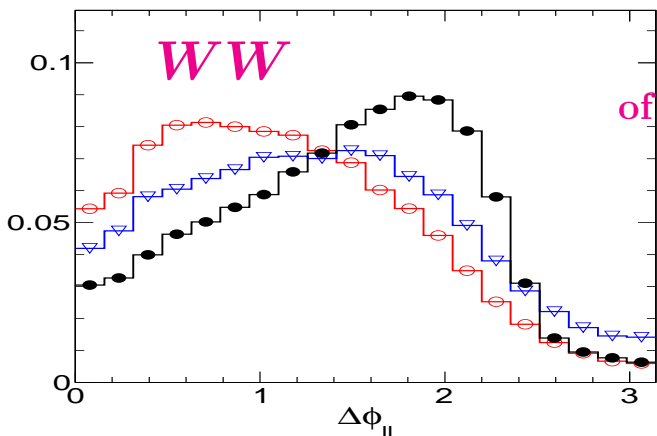
Spin/Parity Measurements in WW and $\gamma\gamma$ Channels



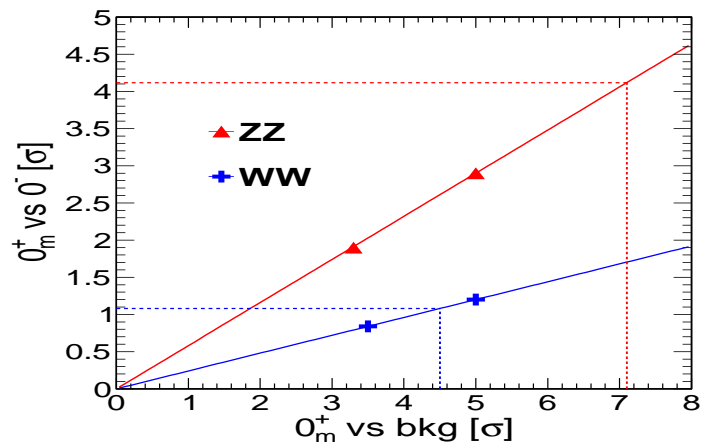
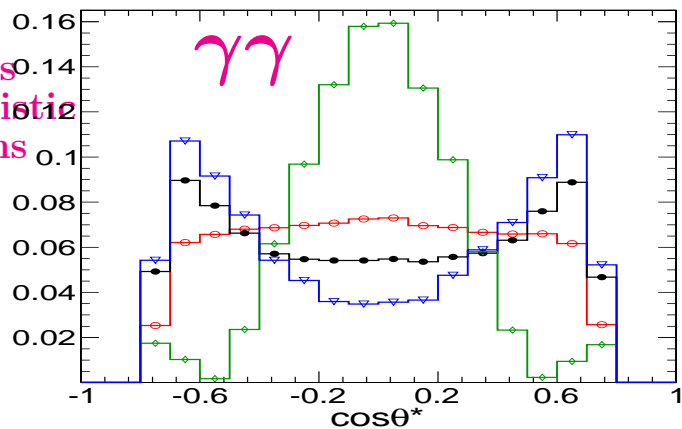
Y. Gao, A. Gritsan, Z. Guo, et al., Phys.Rev. D81 (2010) 075022 — considered separation in ZZ channel



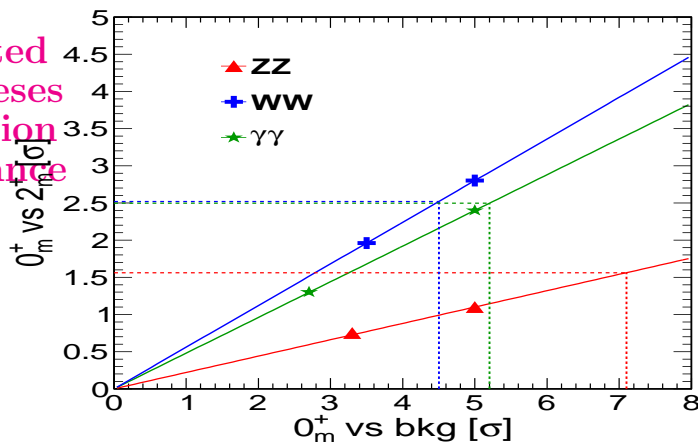
S. Bolognesi, Y. Gao, A. Gritsan, et al., arXiv:1208.4018 — added WW and $\gamma\gamma$ channels (see also ICHEP'2012)



2 Examples of 2 characteristic distributions



Expected hypotheses separation significance



Scalar vs Pseudoscalar —

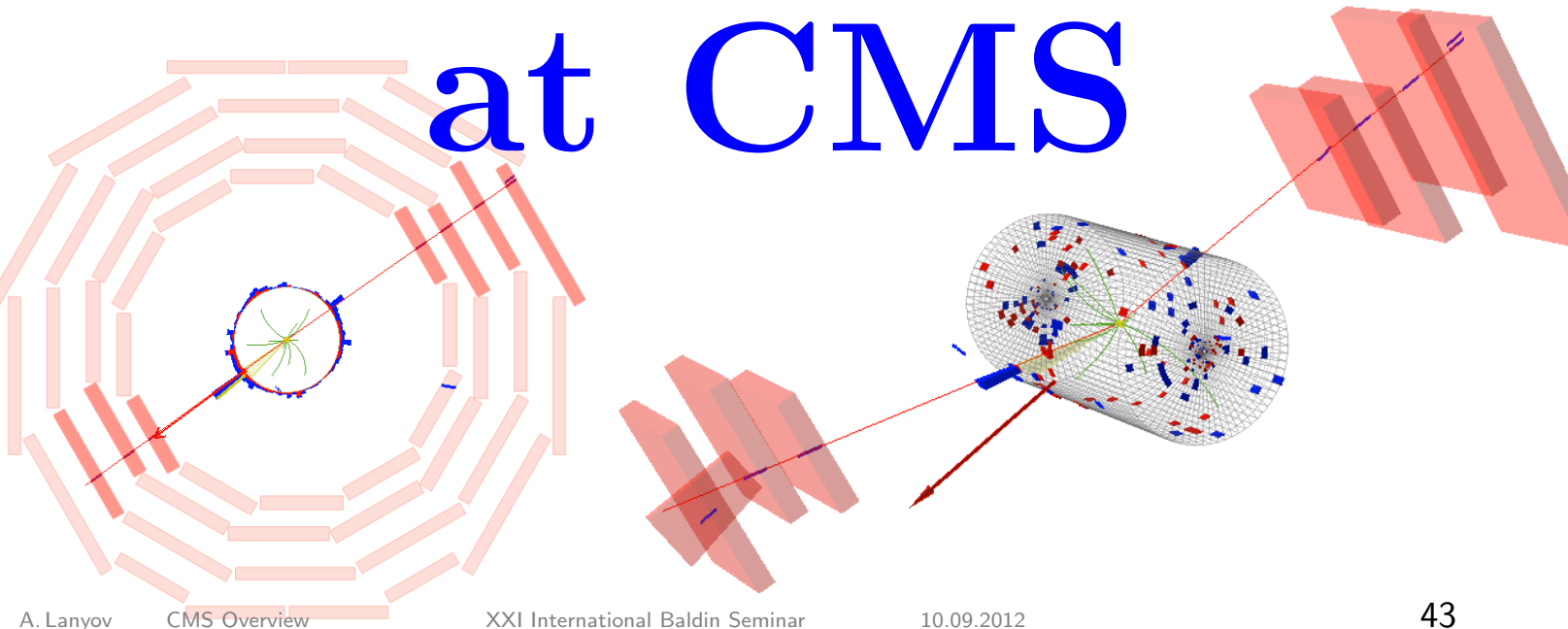
Scalar vs Spin 2 —

ZZ : Expected 4.1σ at 35 fb^{-1}

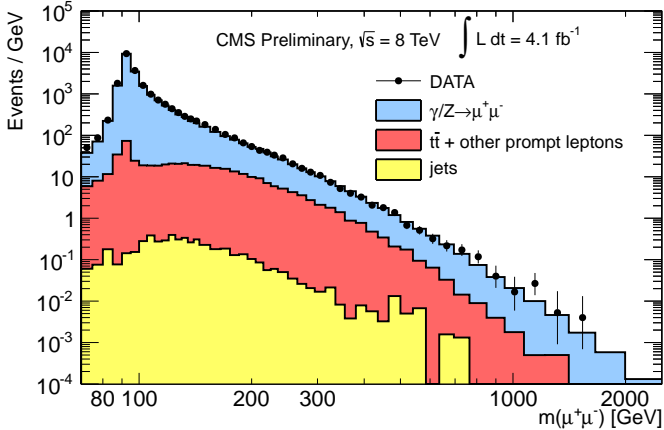
WW & $\gamma\gamma$: Expected 2.5σ at 35 fb^{-1}

- CMS observed a new boson consistent with a SM-like Higgs boson, more prominently in $\gamma\gamma$ and $ZZ \rightarrow 4\ell$ channels
 - Used data corresponding to up to 5.1 fb^{-1} at 7 TeV and 5.3 fb^{-1} at 8 TeV.
 - 5 decay modes: $\gamma\gamma$, ZZ , W^+W^- , $\tau^+\tau^-$ and $b\bar{b}$.
 - Excess observed: local significance of 5.0σ (expected 5.8σ)
 - Fit gives $M = 125.3 \pm 0.4$ (stat.) ± 0.5 (syst.) GeV.
 - Results are consistent (within uncertainties) with expectations for a SM Higgs boson.
 - A new era starts for the measurements of its properties, including also spin and parity determination.
- All the remaining mass range from 115 to 600 GeV is excluded at 99% CL.
- No evidence of BSM Higgs bosons and improved limits are obtained in different scenarios.
- CMS and LHC are on track to get a total of $\sim 30 \text{ fb}^{-1}$ by the end of 2012.

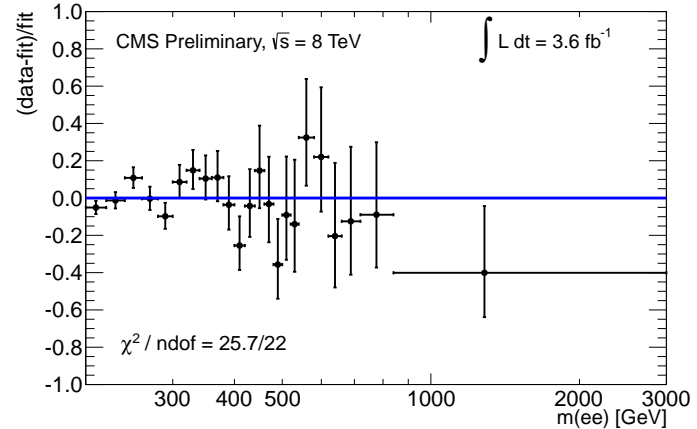
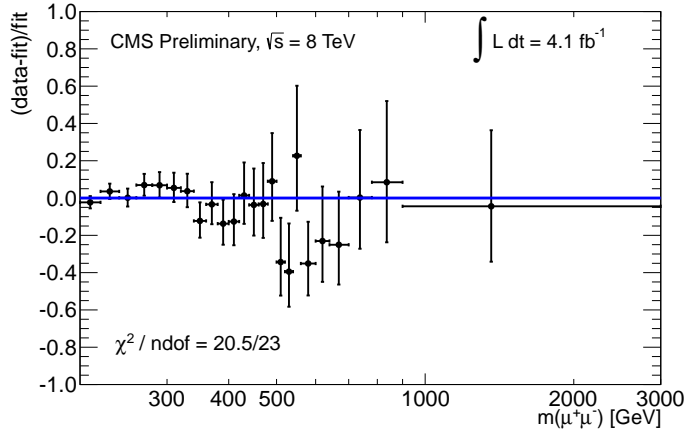
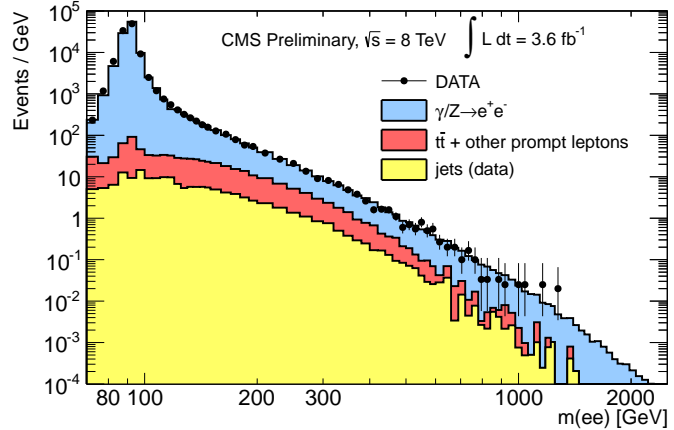
Search for Exotica (BSM) at CMS

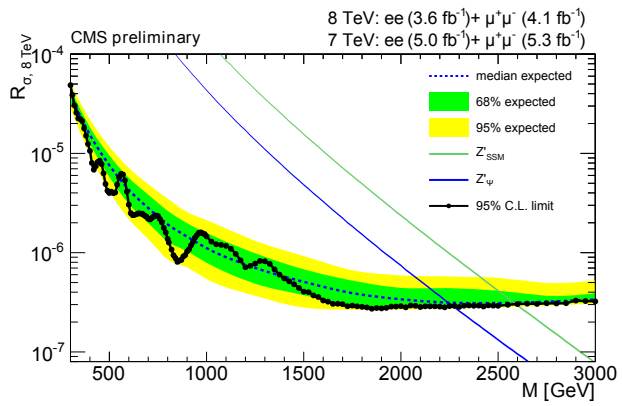
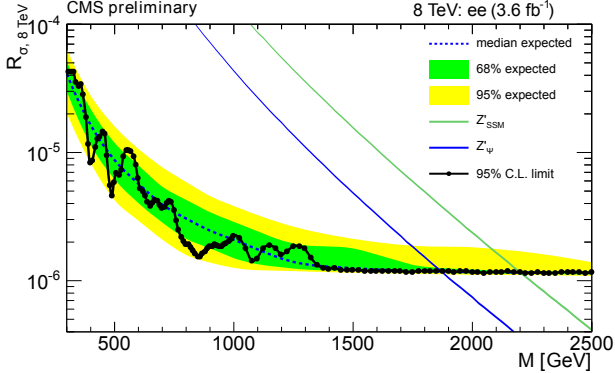
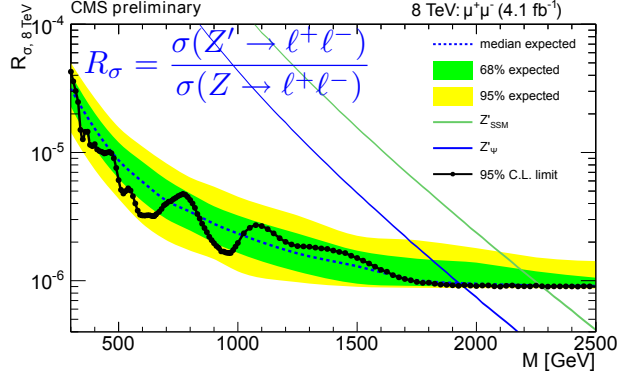


$\mu^+\mu^-$



e^+e^-



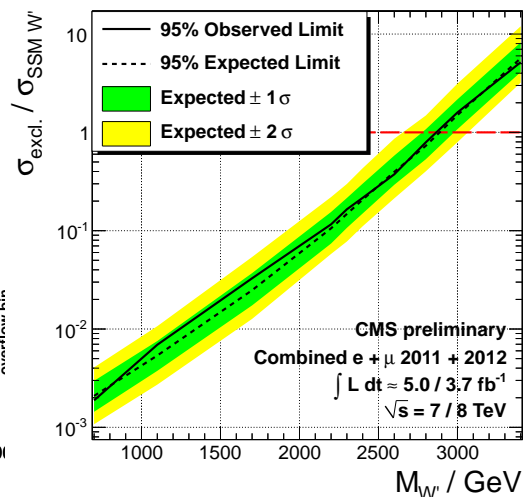
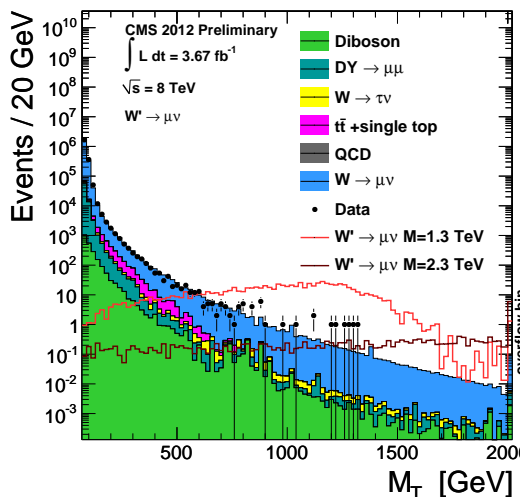
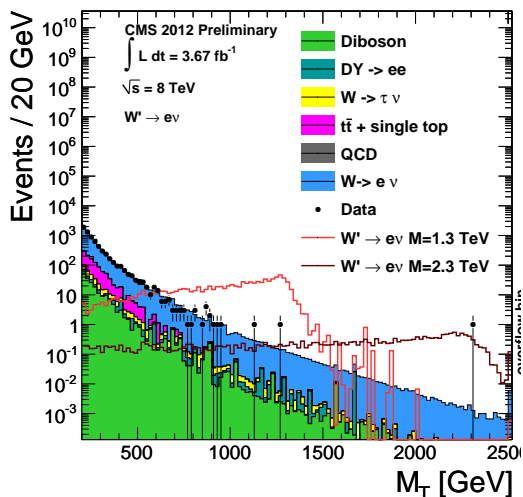


The lower dilepton mass limits at 95% CL:
 2590 GeV — Z'_{SSM} model
 2260 GeV — Z'_ψ model

CMS limits are more restrictive than those previously obtained with similar direct searches by the Tevatron experiments or indirect searches by LEP-II experiments.

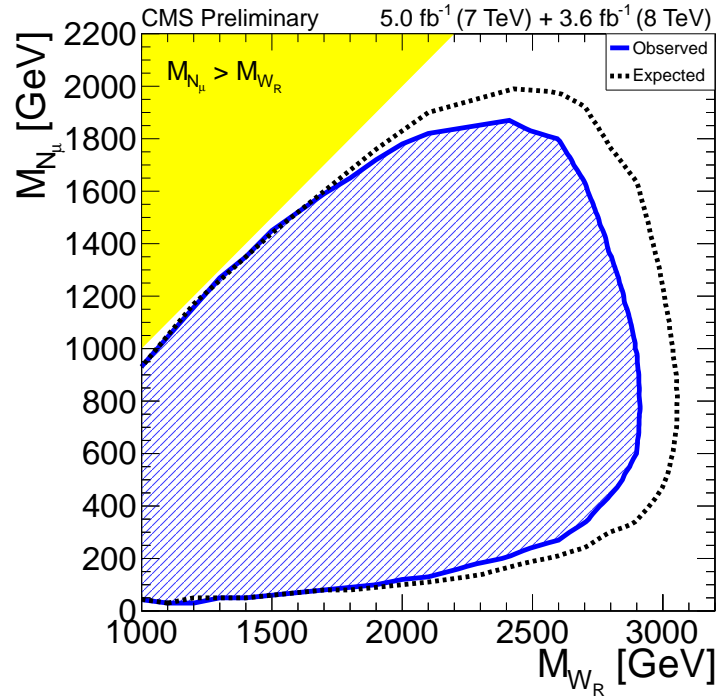
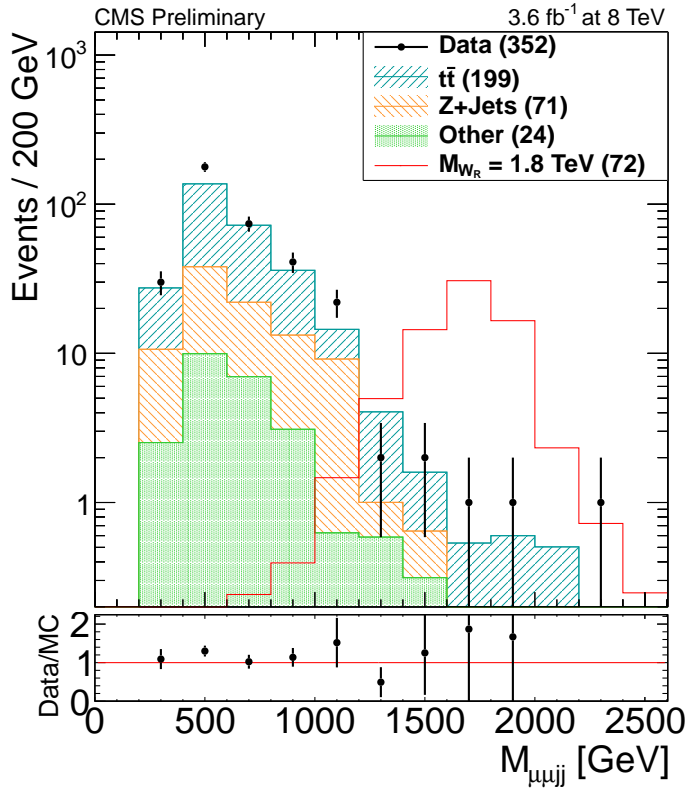
$W' \rightarrow \ell\nu$ Lepton-MET system: $M_T = \sqrt{2 \cdot p_T^\ell \cdot E_T^{\text{Miss}} \cdot (1 - \cos \Delta\phi_{\ell,\nu})}$

Integrated luminosity of 3.7 fb^{-1} at 8 TeV



A SSM W' with $M < 2.85 \text{ TeV}$ was excluded at 95% CL (with 3.5 fb^{-1} $\sqrt{s} = 8 \text{ TeV}$ data).

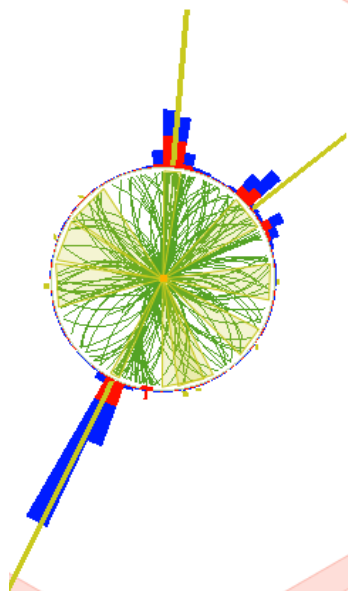
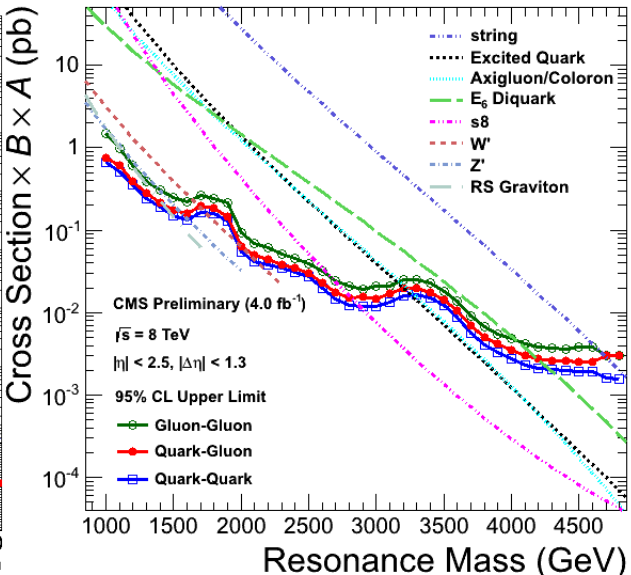
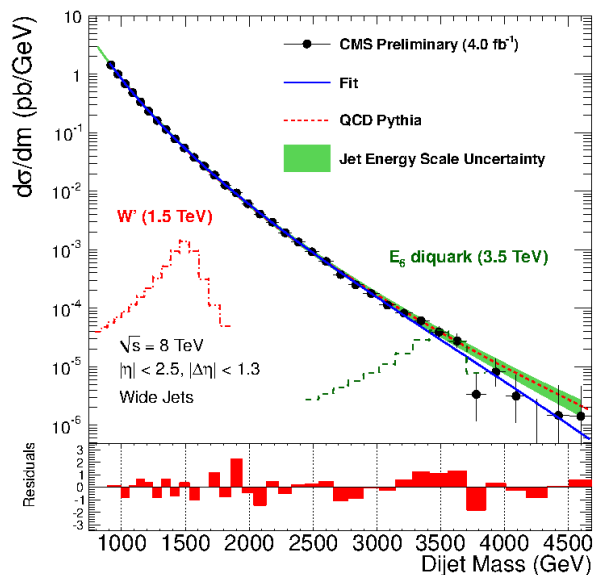
Combining 2011+2012 results does not improve further.



No excess over expectations from standard model processes is observed.

Combining 7 + 8 TeV data and electron + muon channels,

We exclude the region in the two-dimensional parameter (M_{W_R}, M_{N_ℓ}) space that extends beyond $M_{W_R} = 2.9$ TeV.



Lower limits on the masses of different types of exotic resonances are set in the range 1–4.7 TeV. Many of them extend the previous exclusions from the dijet mass search.

Model	Final State	Obs. Mass Excl. [TeV]	Exp. Mass Excl. [TeV]
String Resonance (S)	qg	[1.0, 4.69]	[1.0,4.69]
Excited Quark (Q*)	qg	[1.0, 3.19]	[1.0,3.48]
E ₆ Diquark (D)	qq	[1.0, 4.28]	[1.0,4.18]
Axigluon (A)/Coloron (C)	q \bar{q}	[1.0, 3.28]	[1.0,3.59]
s8 Resonance	gg	[1.0, 2.67]	[1.0,2.66]
W' Boson (W')	q \bar{q}	[1.0, 1.74]	[1.0,1.97]
Z' Boson (Z')	q \bar{q}	[1.97, 2.12]	[1.0,1.58]
RS Graviton (RSG)	q \bar{q} +gg	[1.0, 1.36]	[1.0,1.30]

Microscopic Black Holes can manifest themselves as multiparticle final state with large $S_T = \sum E_T$

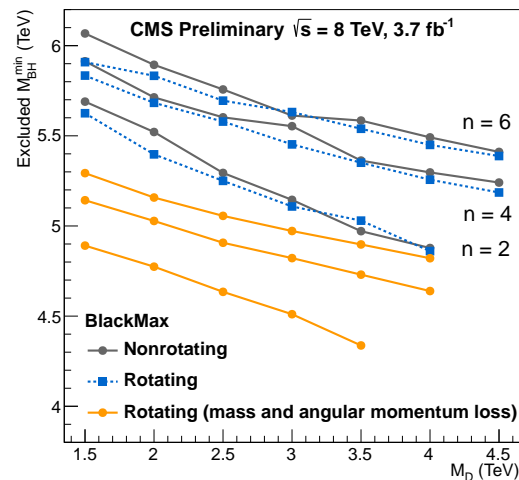
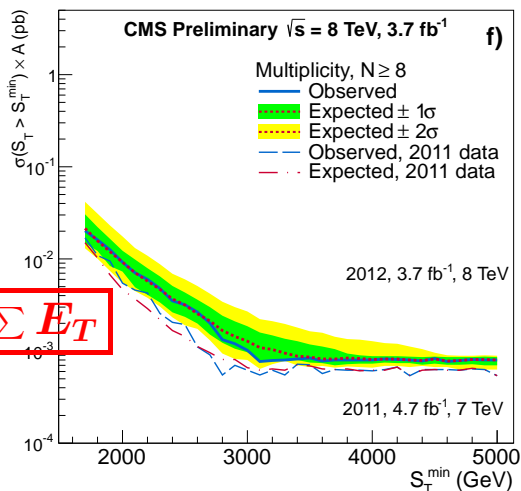
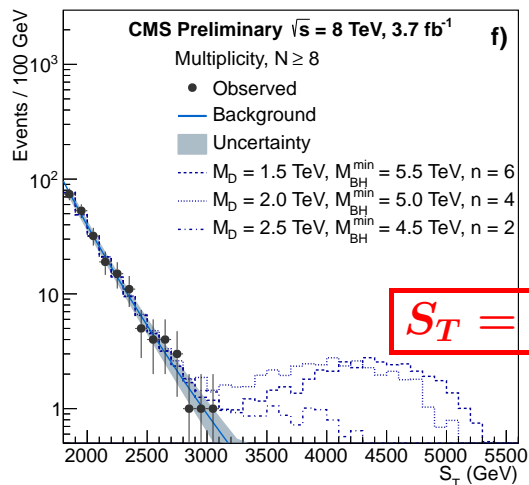
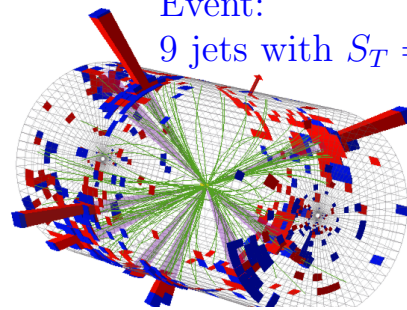
The CMS analyses:

2010, 35 pb⁻¹ at 7 TeV: Phys. Lett. B697 (2011) 434;

2011, 4.7 fb⁻¹ at 7 TeV: JHEP 1204 (2012) 061;

NEW 2012, 3.7 fb⁻¹ at 8 TeV: CMS-PAS-EXO-12-009

Event:
9 jets with $S_T = 2.6$ TeV

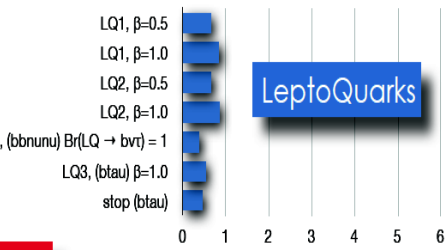
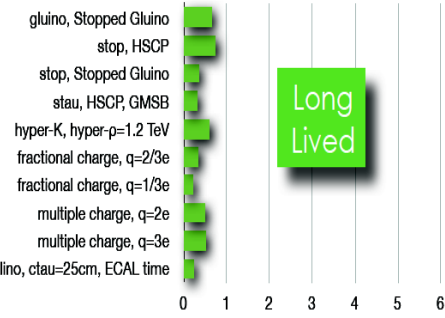
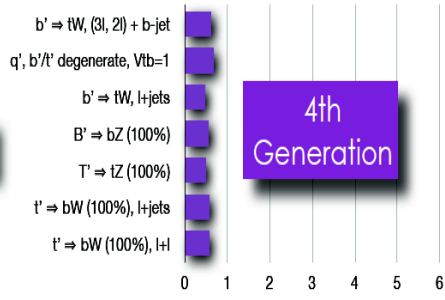
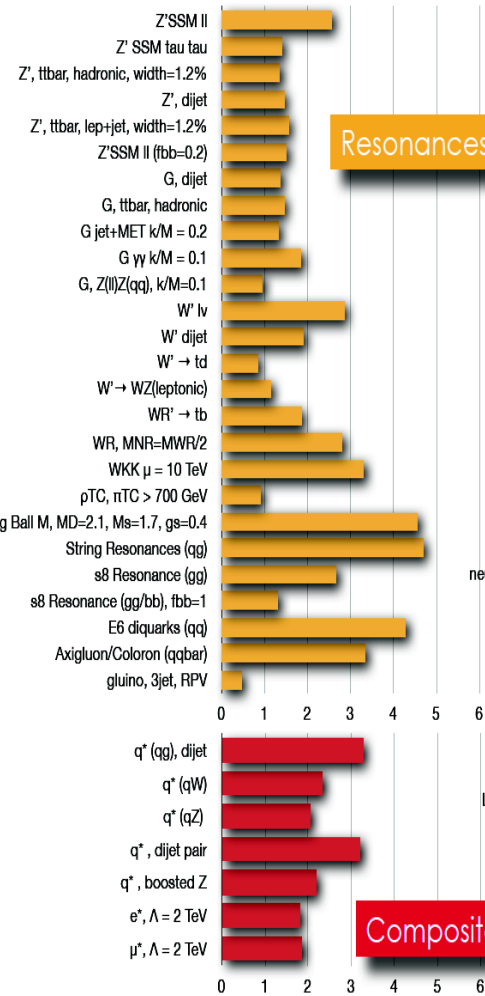


CMS set limits on the minimum Black Hole mass of 4.1–6.1 TeV.

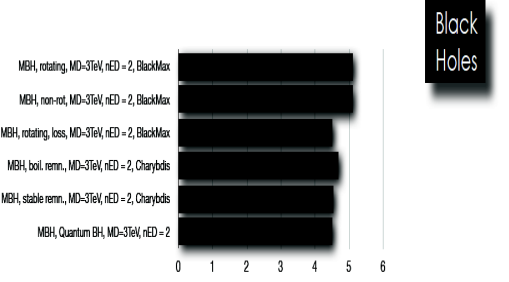
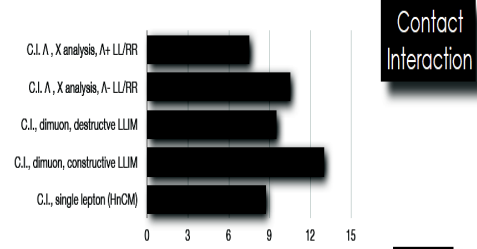
The last analysis at $\sqrt{s} = 8$ TeV has a substantially increased sensitivity compared to previous searches.



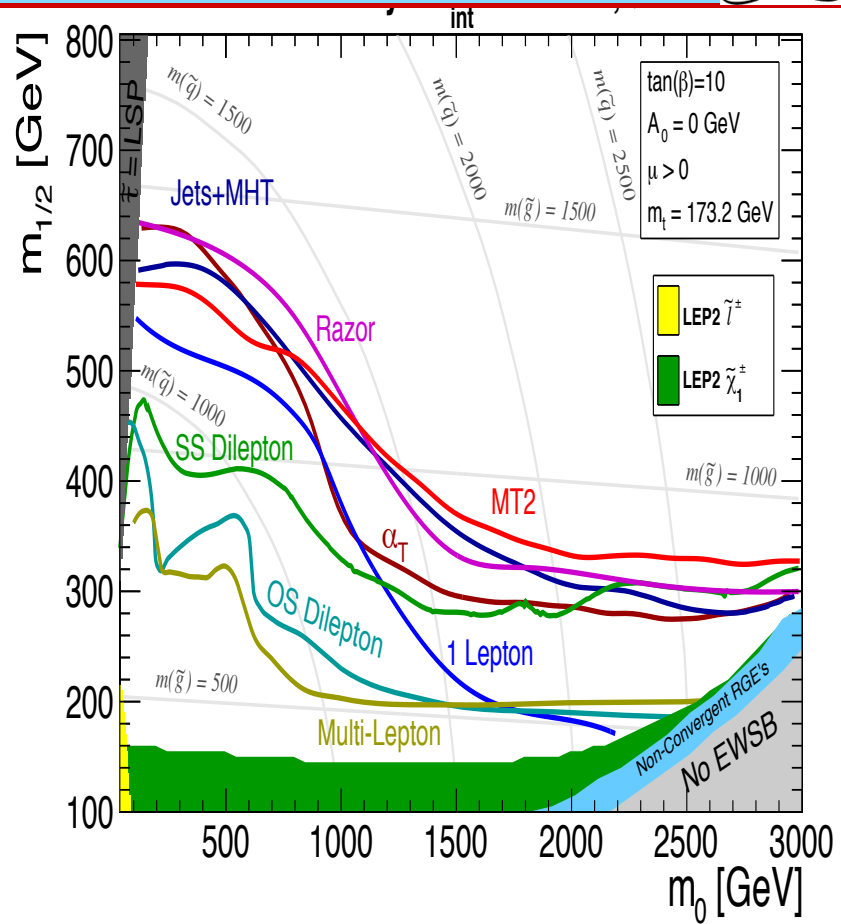
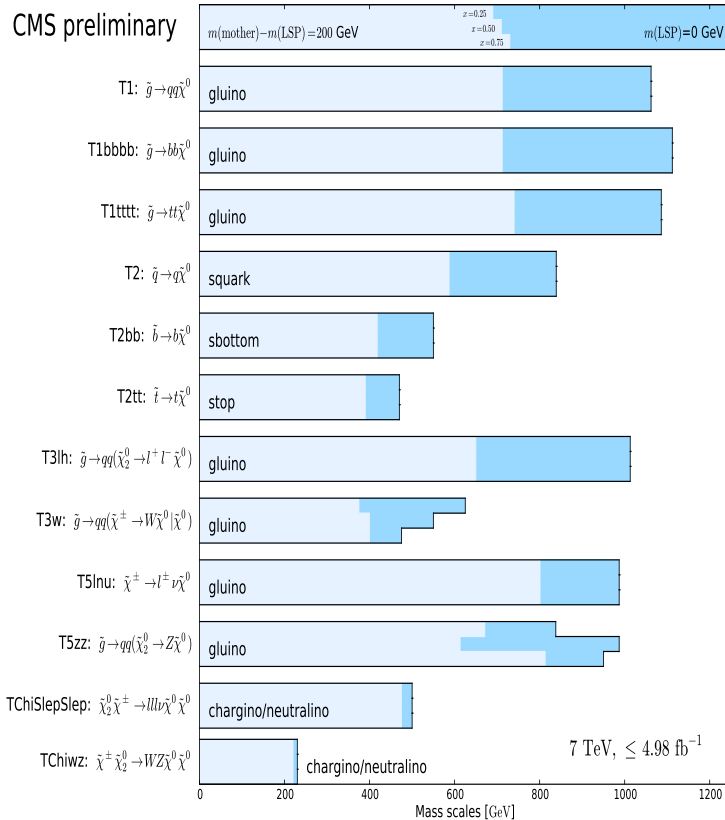
Exotica 95% CL Limits



Many other searches of Exotica at CMS has been performed. Limits have been set.

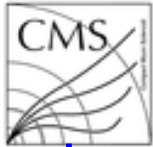


CMS preliminary



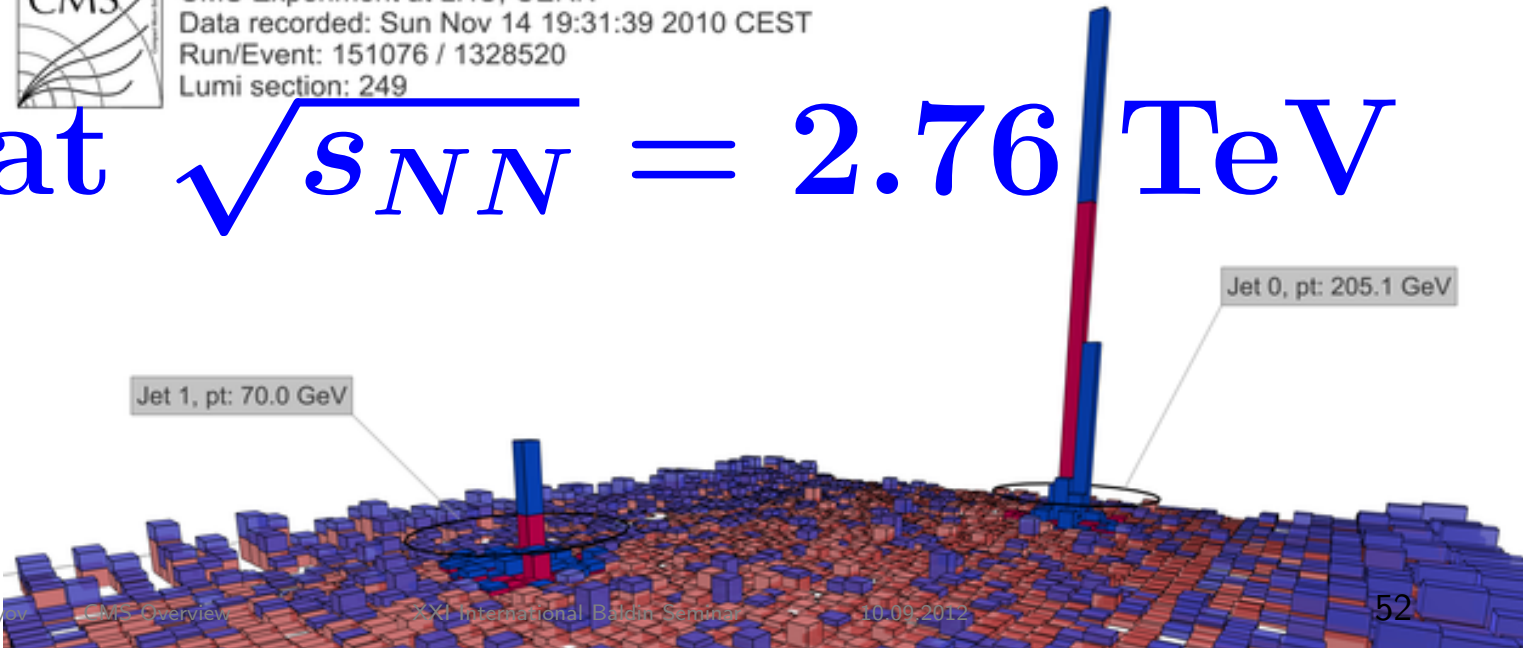
Many searches of Supersymmetry at CMS has been performed.
Limits have been set.

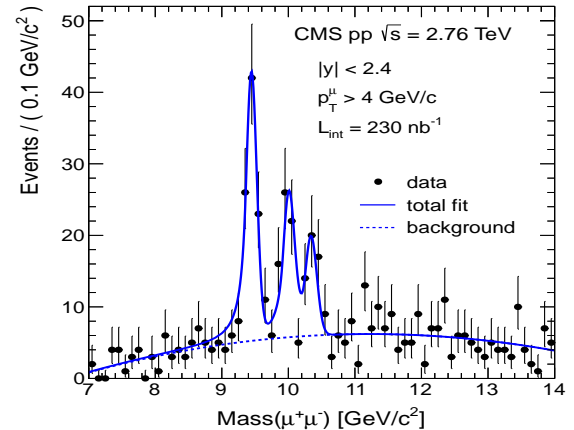
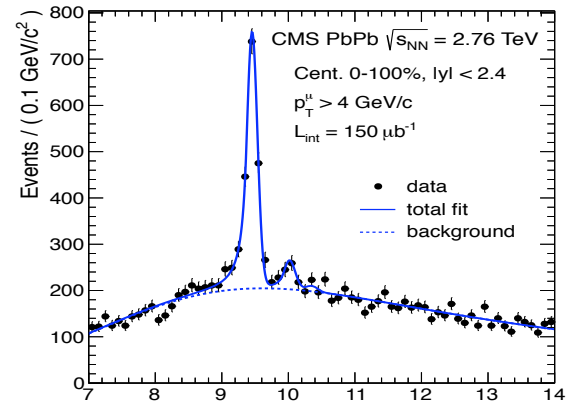
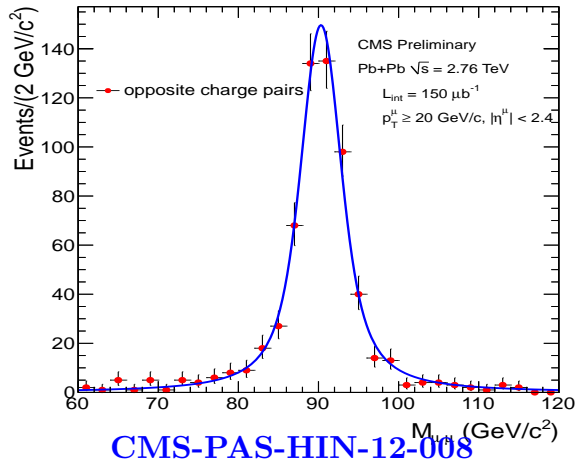
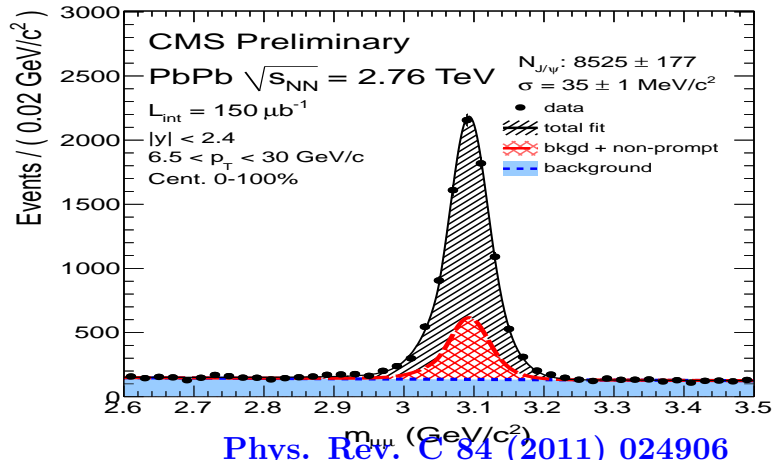
Heavy Ion Collisions



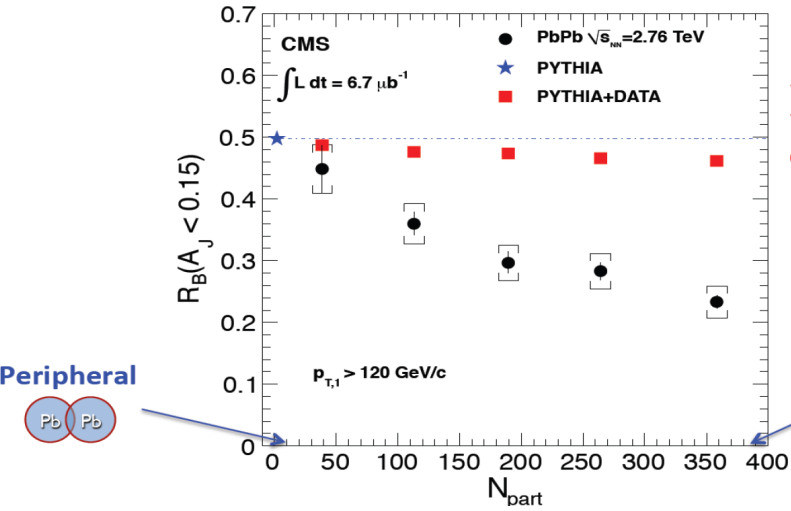
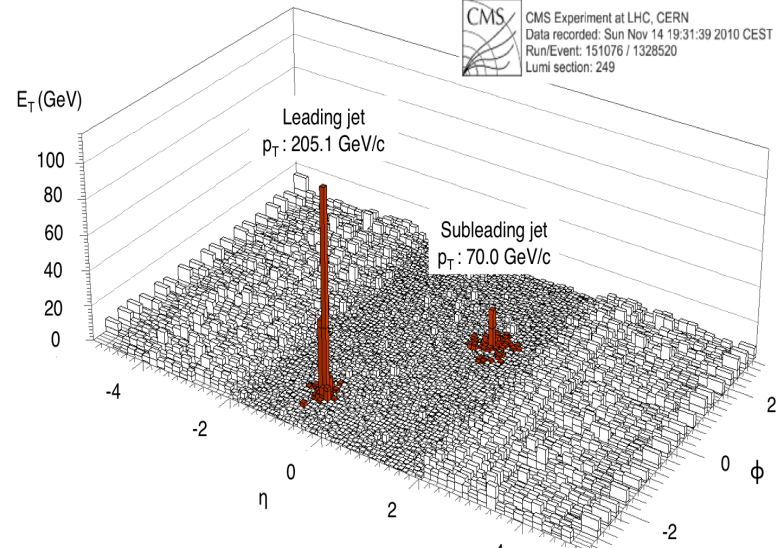
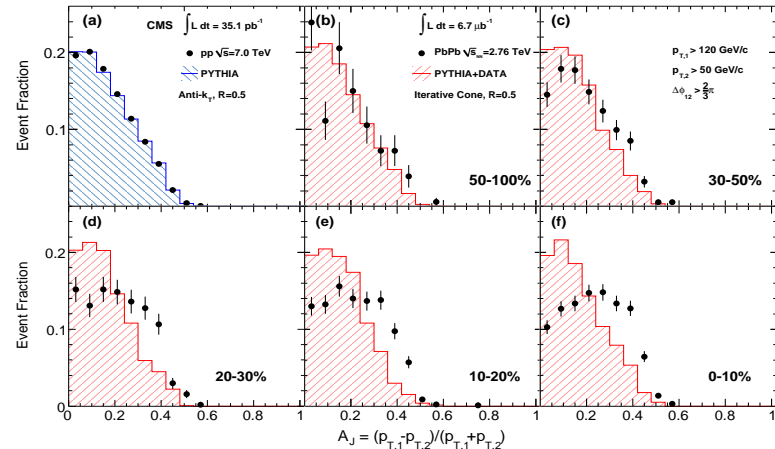
CMS Experiment at LHC, CERN
Data recorded: Sun Nov 14 19:31:39 2010 CEST
Run/Event: 151076 / 1328520
Lumi section: 249

at $\sqrt{s_{NN}} = 2.76 \text{ TeV}$





Suppression of excited states $f \approx 3$
arXiv:1208.2826 = CMS-HIN-11-011



Large jet quenching has been observed by CMS and ATLAS
 Phys. Rev. C84 (2011) 024906,
 "Observation and studies of jet quenching in PbPb collisions at $\sqrt{s_{NN}} = 2.76 \text{ TeV}$ "

- CMS detector performance is excellent, new results are produced at very high rate.
- Impressive agreement of the data with the Standard Model.
- ...even very impressive: A new boson is found around 125 GeV with 5.0σ , compatible with Higgs boson.
- Spin/parity determination of this boson is expected with 30 fb^{-1} .
- Many papers at CMS – $O(200)$, impossible to mention all analyses in a talk.

- Looking back:
What were the projections at the start of the LHC run?
- What has Nature prepared for us?
- Stay tuned for next results

Possible projections — from CERN Courier, Dec. 2009
Now we have it! © (One of the items...)
What's next?



Next CMS run ..?

We are here

Thank you