Status of the SM Scalar boson searches at CMS; New physics searches at the LHC

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On behalf of the
CMS and ATLAS Collaborations

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Plan of the talk

- CMS and ATLAS detectors
- LHC performance in 2011
- Physics objects

PART I. Search for the SM scalar boson at CMS

- Low mass channels : $H \rightarrow \gamma\gamma$, $H \rightarrow \tau\tau$
- Full mass range channels : $H \rightarrow WW \rightarrow l\nu l\nu$, $H \rightarrow ZZ \rightarrow 4l$
- Combination

PART II. New physics searches at the LHC

- Non-SM scalar boson searches
- some SUSY searches
- Some exotics searches

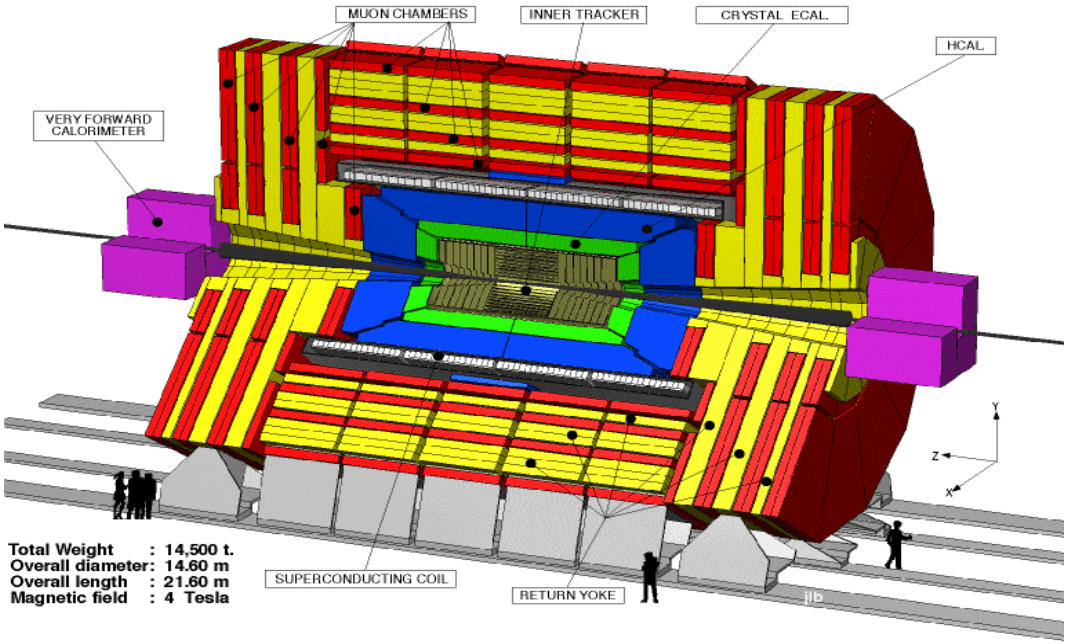
Public physics results :

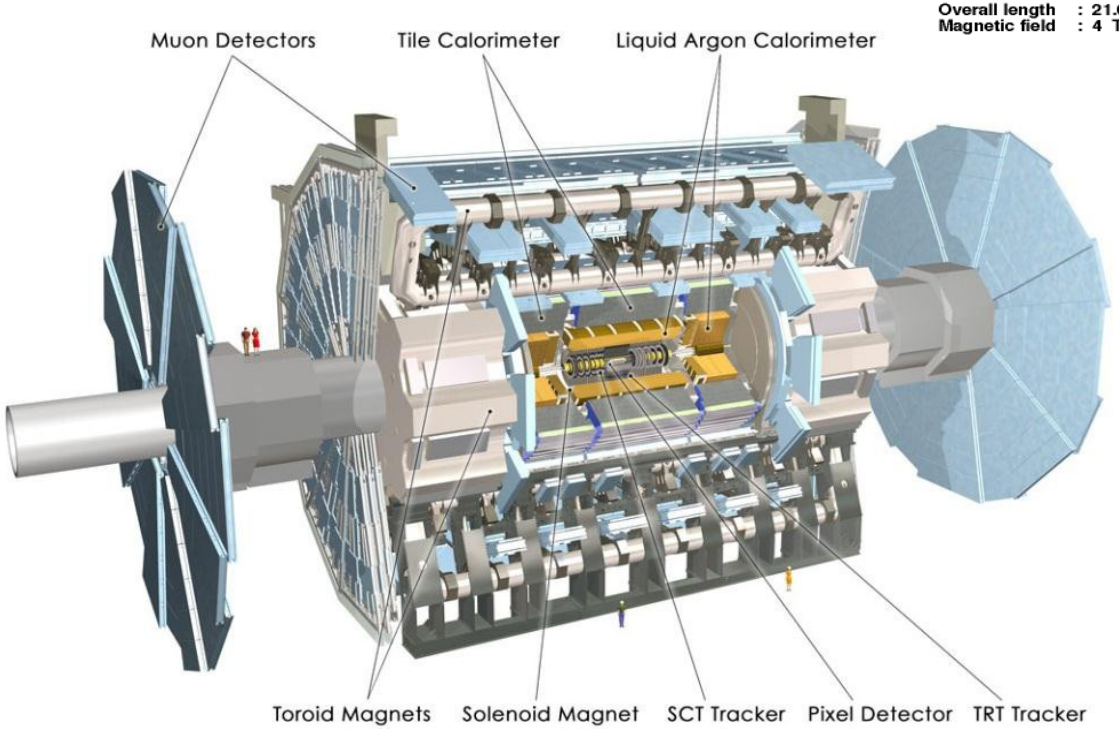
- CMS: https://twiki.cern.ch/twiki/bin/view/CMSPublic
- ATLAS : https://twiki.cern.ch/twiki/bin/view/AtlasPublic

CMS and ATLAS detectors

CMS : Compact Muon Solenoid

- r = 7.5 m, L = 29 m
- B = 4 T central solenoid
  Calorimeter inside





ATLAS : A Toroidal LHC ApparatuS

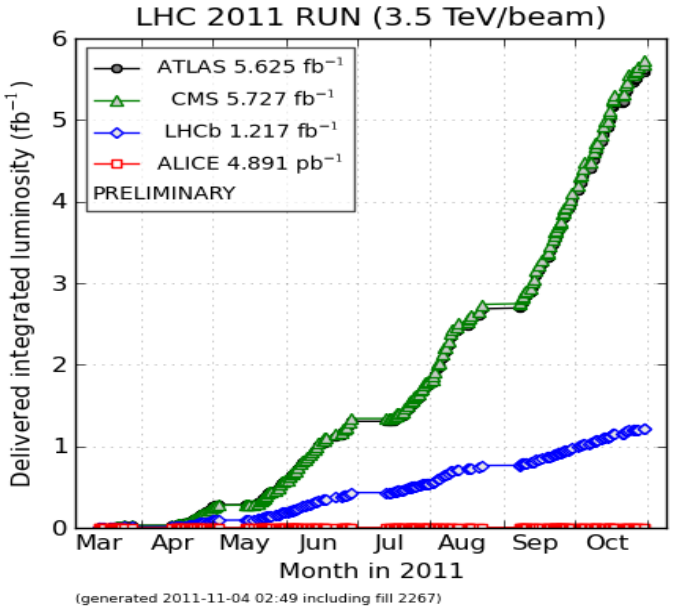
- r = 11 m, L = 45 m
- B = 2 T central solenoid
  and 3 outer toroids

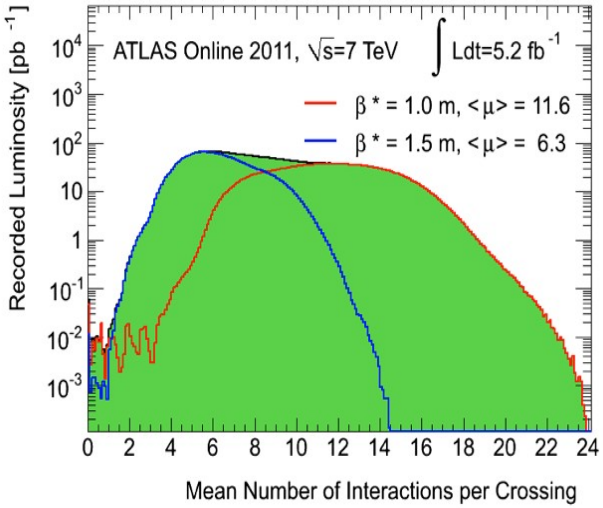
LHC performance

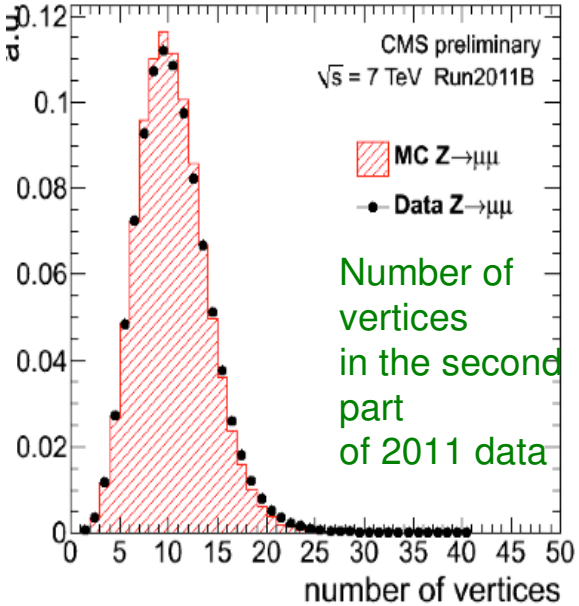
Excellent performance of LHC and CMS in 2011!

ATLAS and CMS results presented here :

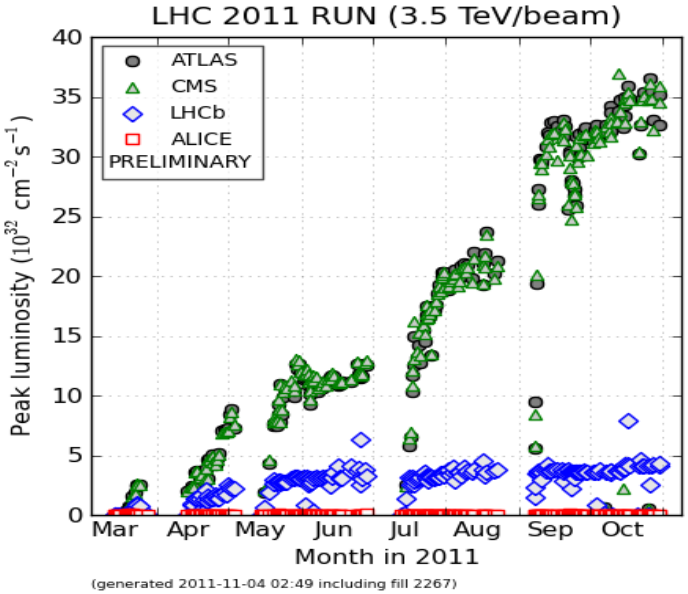
- based on the 7 TeV collisions recorded in 2011
- More than 5 fb^{-1} for each experiment
- Luminosity increased during the year :
  Maximum was 3.5×10^{33} cm^{-2} s^{-1}
- Multiple interactions per beam crossing :
  Average more than 10



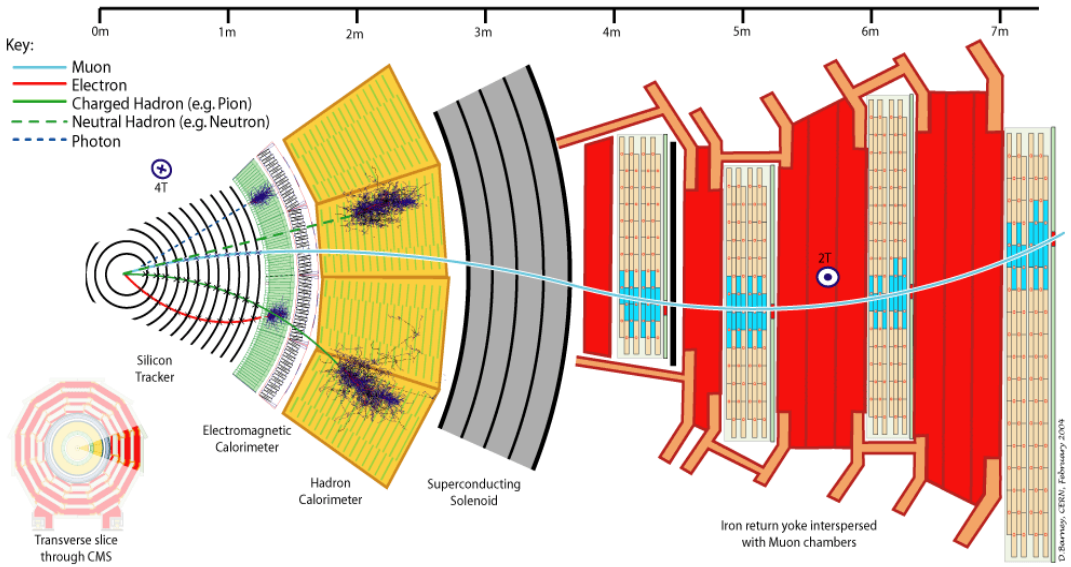




Number of vertices in the second part of 2011 data



Physics objects



Basic physics objects :

- Jet : Cluster in EM and hadronic calorimeters (and inner tracker)
- Photon : EM cluster without matching track
- Electron : EM cluster with matching track
- μ : Matching tracks in inner and μ trackers
- τ lepton : Narrow jet with matching track(s)
- MET : pT required to balance all of the above

Higher level objects :

- B-jet : Jet with displaced secondary vertex (or lepton tag)
- W-boson : ll+MET or dijet with m=80 GeV
- Z-boson : OS dilepton or dijet with m=90 GeV
- Top quark : W+b, m=173 GeV

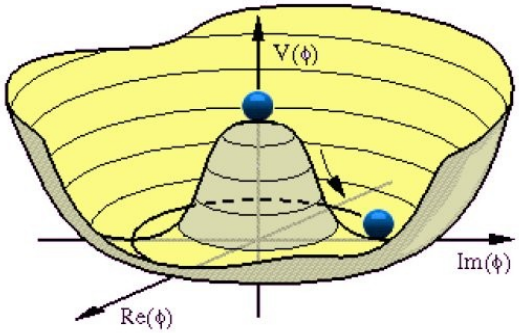
Particle flow algorithm (PF) : global event description in form of a list of particles and avoids double-counting - Large improvement in tau, jet, and MET

PART I :

Status of the SM Scalar boson searches at CMS;

How can we break the EW symmetry?
→The Brout-Englert-Higgs mechanism

- F. Englert and R. Brout, Phys. Rev. Lett. 13, 321 (1964)
- P. Higgs, Phys. Rev. Lett. 13, 508 (1964)
- G. Guralnik, C.R. Hagen, T.W.B. Kibble, Phys. Rev. Lett.13, 585 (1964)



SM scalar boson production at LHC

- Direct searches : LEP: M_H > 114.4 GeV excluded at 95% CL

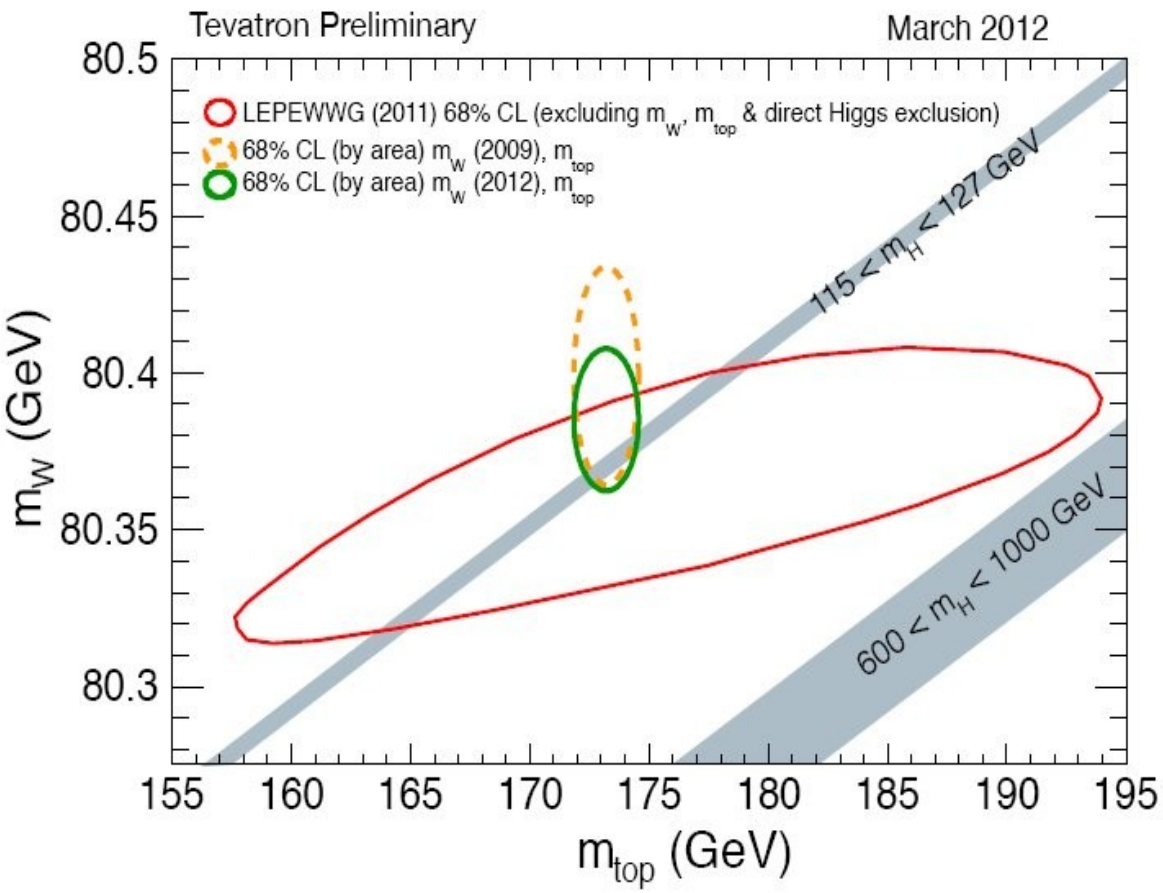
- Indirect constraints from precision EW measurements :

LEPEWWG/ZFitter
With M_W = 80399±23 MeV
M_H < 161 GeV at 95% CL

Including the new M_W tevatron measurement (Moriond 2012) :

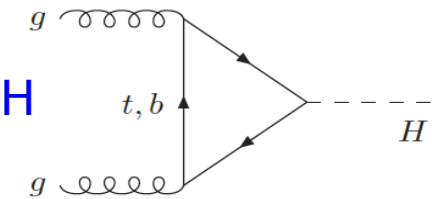
With M_W = 80385±15 MeV
M_H < 152 GeV at 95% CL

SM scalar boson favoured at low mass above the LEP limit

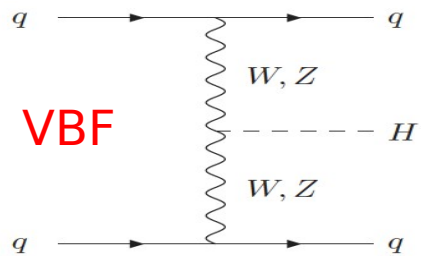


SM scalar boson production at LHC

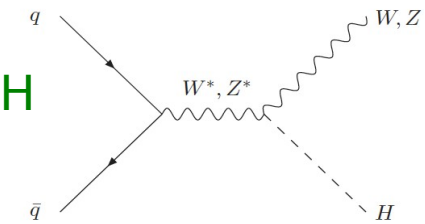
gg→H



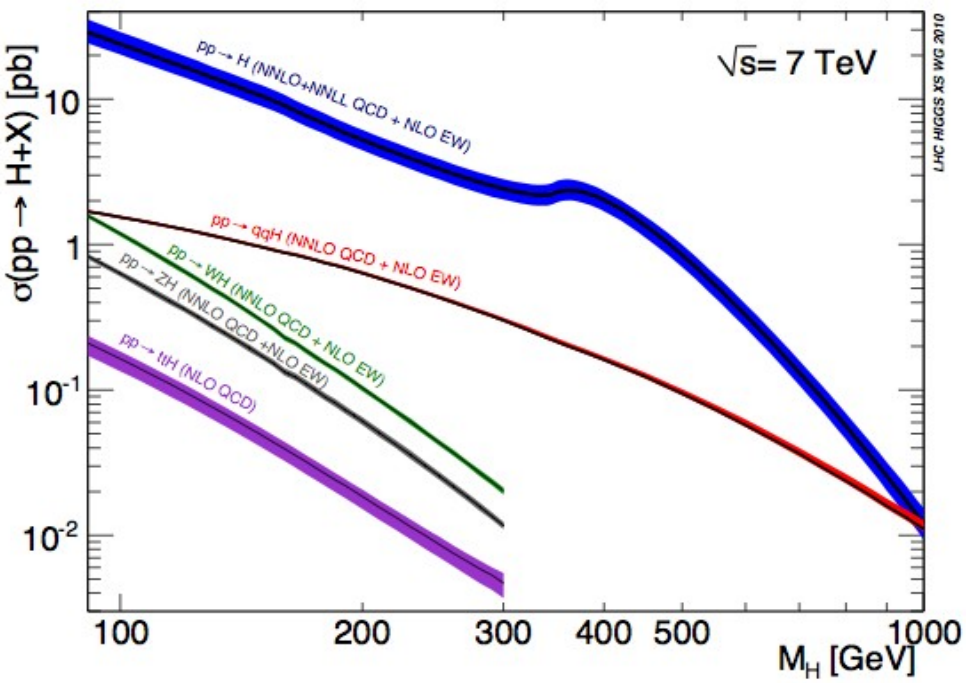
VBF



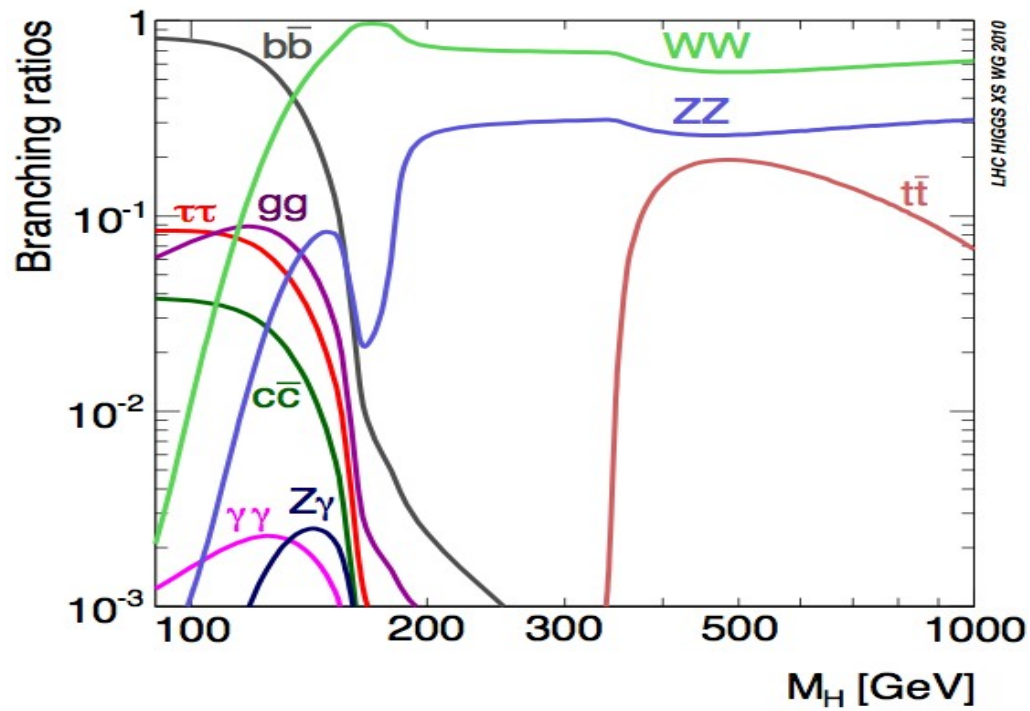
VH



Production



Decay



SM scalar boson channels at CMS

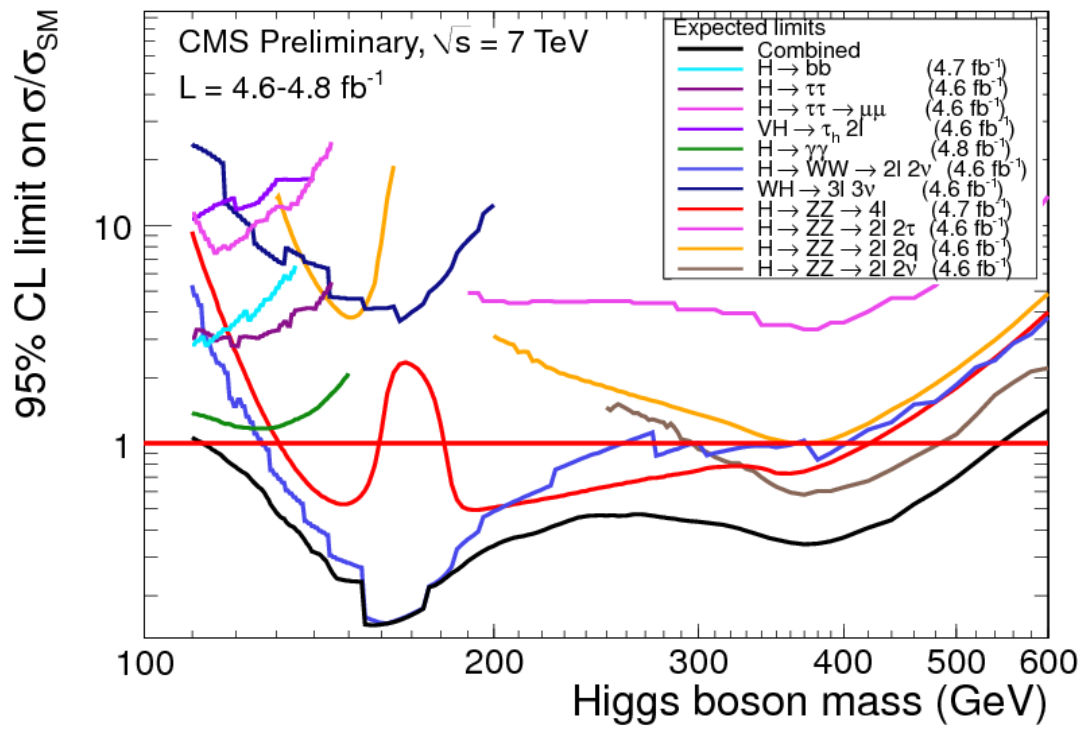
Low mass

High mass

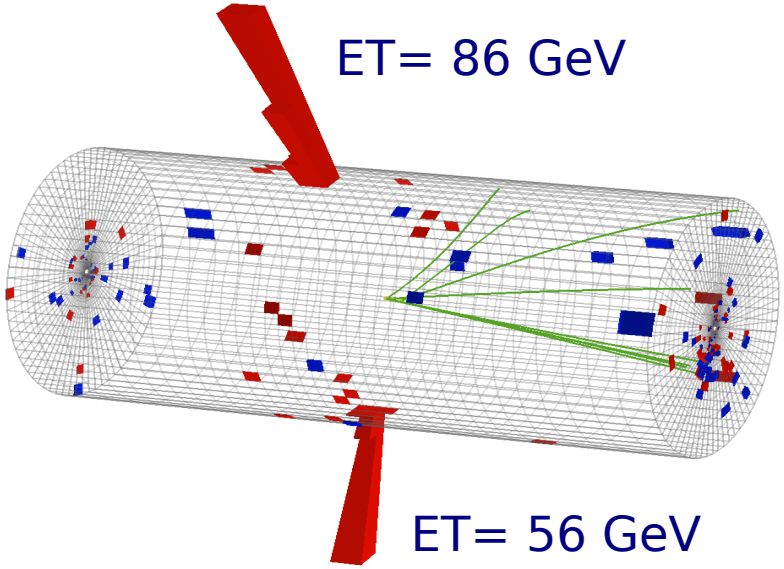
	Channel	m_H range (GeV)	Luminosity (fb^{-1})	Sub-channels	m_H resolution
new	$H \to \gamma\gamma$	110–150	4.8	2	1–2%
	$H \to \tau\tau \to e\tau_h/\mu\tau_h/e\mu + X$	110–145	4.6	9	20%
new	$H \to \tau\tau \to \mu\mu + X$	110–140	4.5	3	20%
new	$WH \to e\mu\tau_h/\mu\mu\tau_h + \nu$'s	100–140	4.7	2	20%
	$(W/Z)H \to (e\nu/\mu\nu/ee/\mu\mu/\nu\nu)(bb)$	110–135	4.7	5	10%
	$H \to WW^* \to 2\ell 2\nu$	110–600	4.6	5	20%
new	$WH \to W(WW^*) \to 3\ell 3\nu$	110–200	4.6	1	20%
	$H \to ZZ^{(*)} \to 4\ell$	110–600	4.7	3	1–2%
	$H \to ZZ^{(*)} \to 2\ell 2q$	130–164	4.6	6	3%
		200–600			3%
	$H \to ZZ \to 2\ell 2\tau$	190–600	4.7	8	10–15%
	$H \to ZZ \to 2\ell 2\nu$	250–600	4.6	2	7%

11 independent channel searches for mass range 110-600 GeV

Expected combined 95% exclusion : 114.5-543 GeV

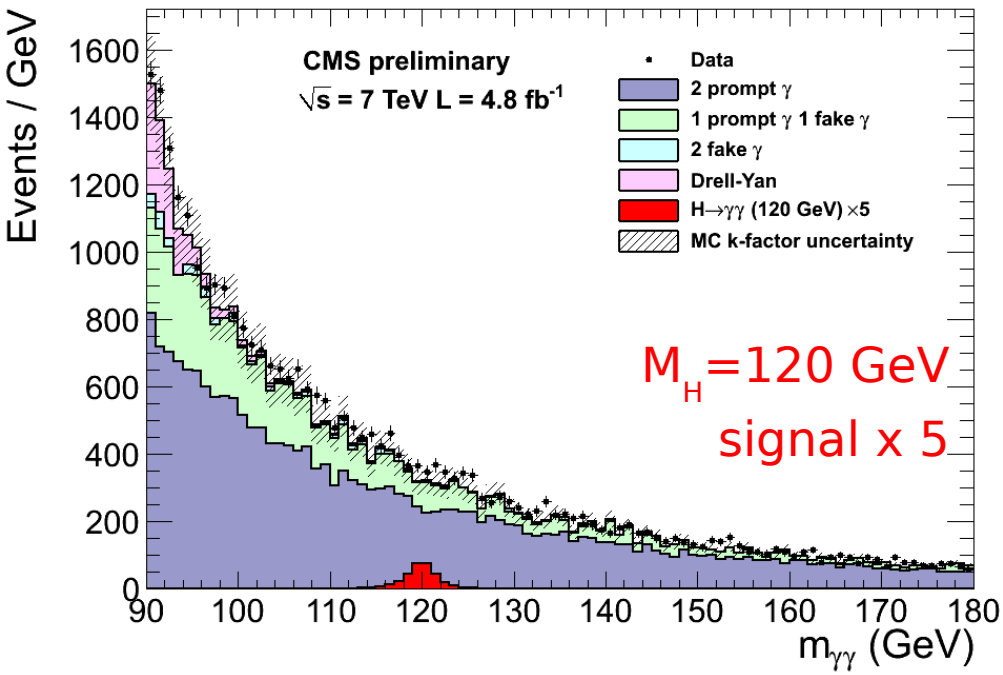


Low mass H→γγ channel



- Small BR: ~2×10^{-3}
- Two isolated high Et photons
- VBF channel has two additional jets from outgoing quarks
- Narrow mass peak : very good mass resolution 1-2%

bg MC only used for optimization



Signature: small mass peak over large smoothly decreasing background

Irreducible: 2γ QCD production
Reducible: γ+jet with one fake γ
DY with electrons faking photons

Studied mass range: 110-150 GeV

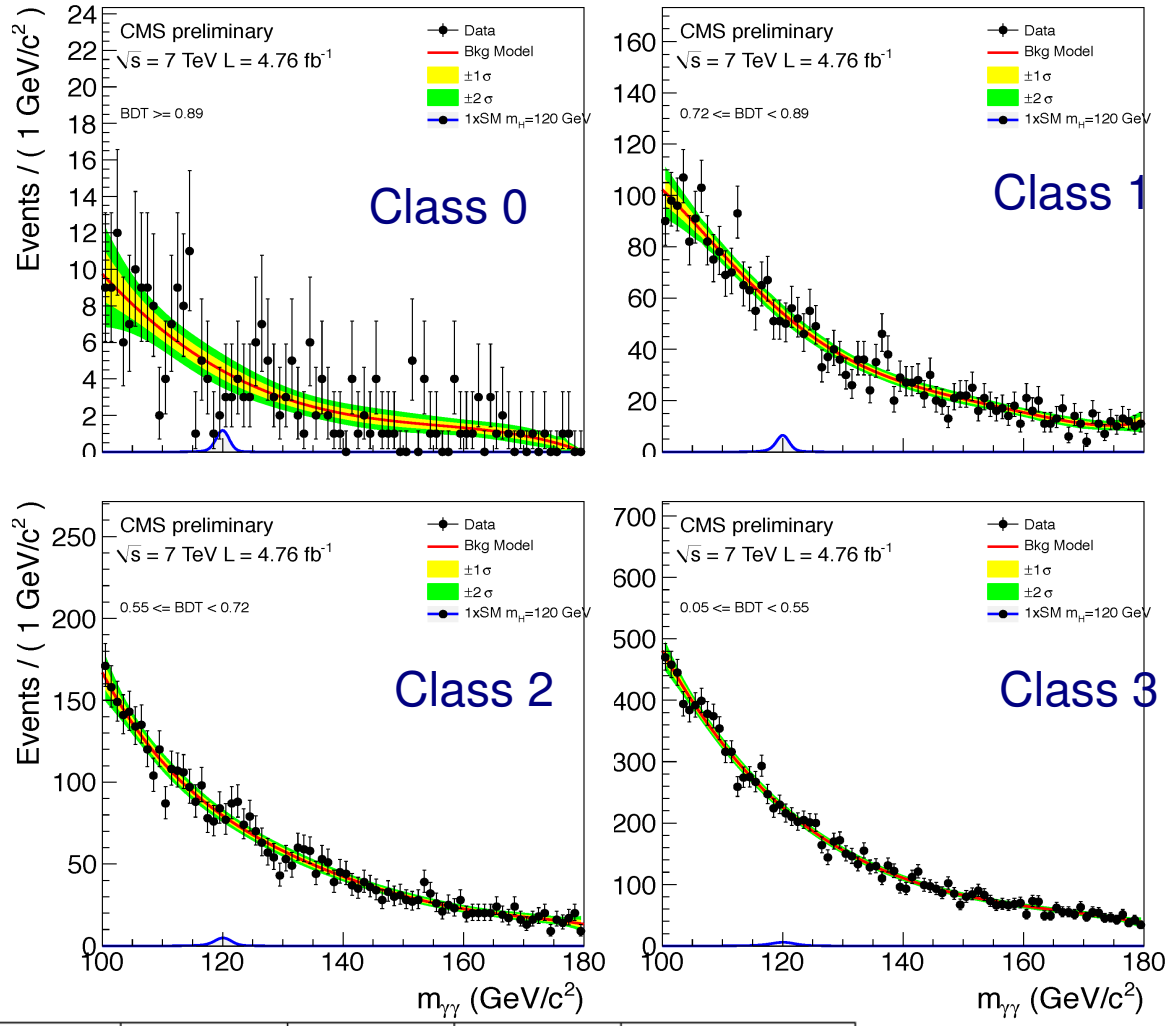
H→γγ (non VBF) MVA analysis

CMS HIG-12-001

- Multivariate (MVA) analysis
Event-by event mass resolution, photon id discriminant, di-photon kinematic variables and vertex probability combined using with boosted decision tree (BDT)

- 4 non-VBF event classes
split based on the diphoton BDT classifier output

- BG estimation
by fitting to a polynomial in the full mass range (3rd to 5th order)



m_H=120 GeV	class 0	class 1	class 2	class 3	Dijet class
Total signal expected events	3.4	19.3	18.7	33.0	2.8
Data (events/GeV)	4.5	55.1	81.3	229.1	2.1
resolution FWHM/2.35 (%)	0.9	0.9	1.2	1.7	1.1

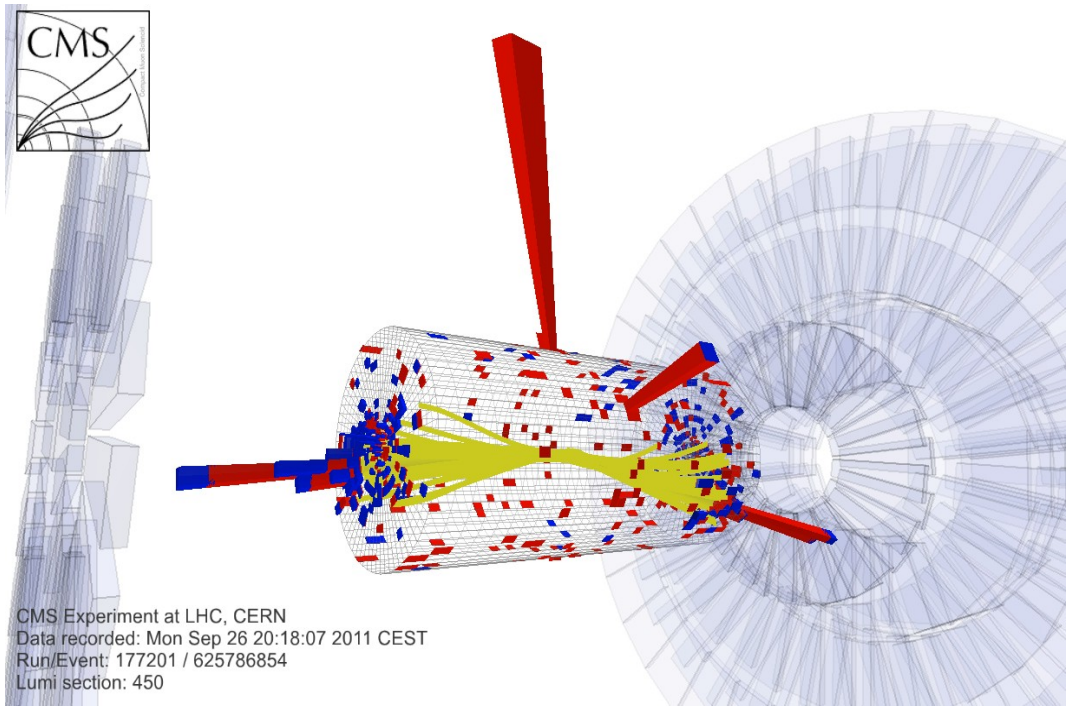
H→γγ (VBF) analysis

Dijet tag selection :exploits two additional VBF high pT jets at large rapidity

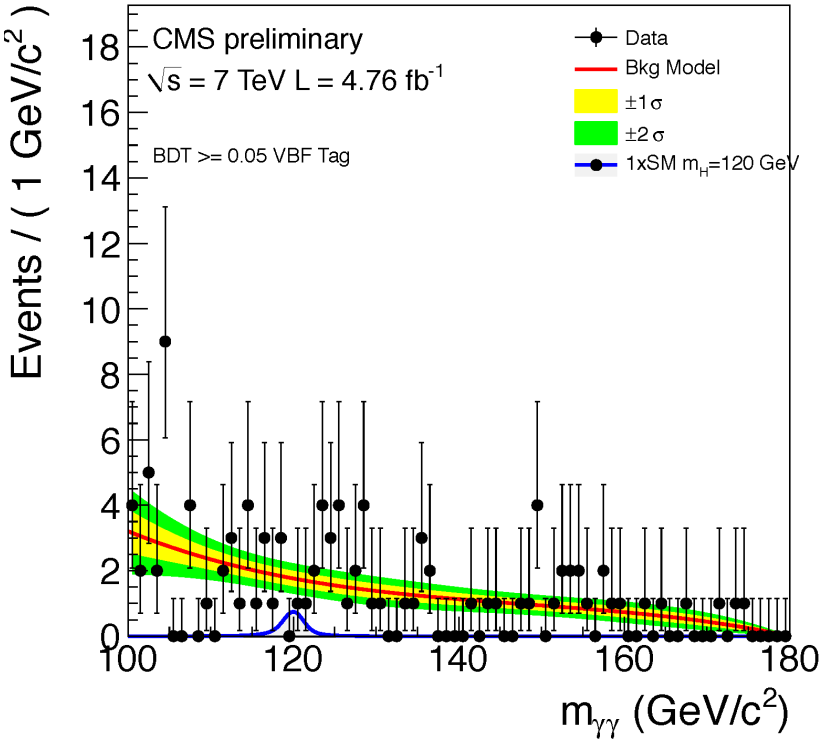
Exclusive dijet tag improves sensitivity by ~10%

Photon identification is the same

Tighter lead photon Et cut (Et lead/Myy > 55/120)



Dijet tag selection has high s/b, ~1/3

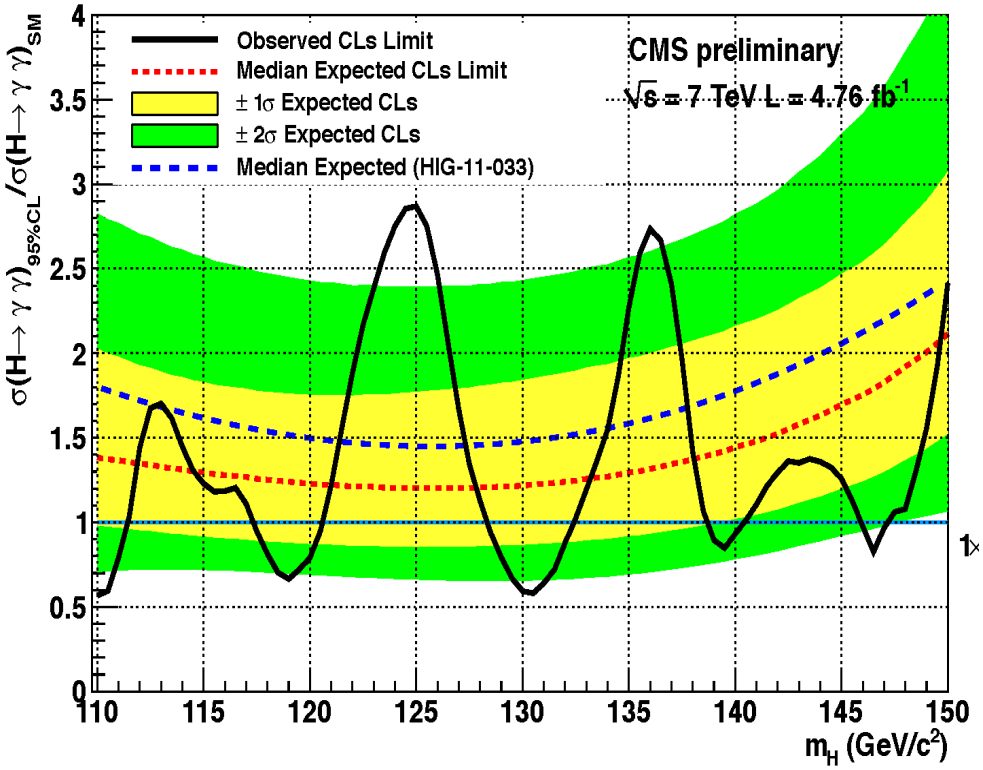


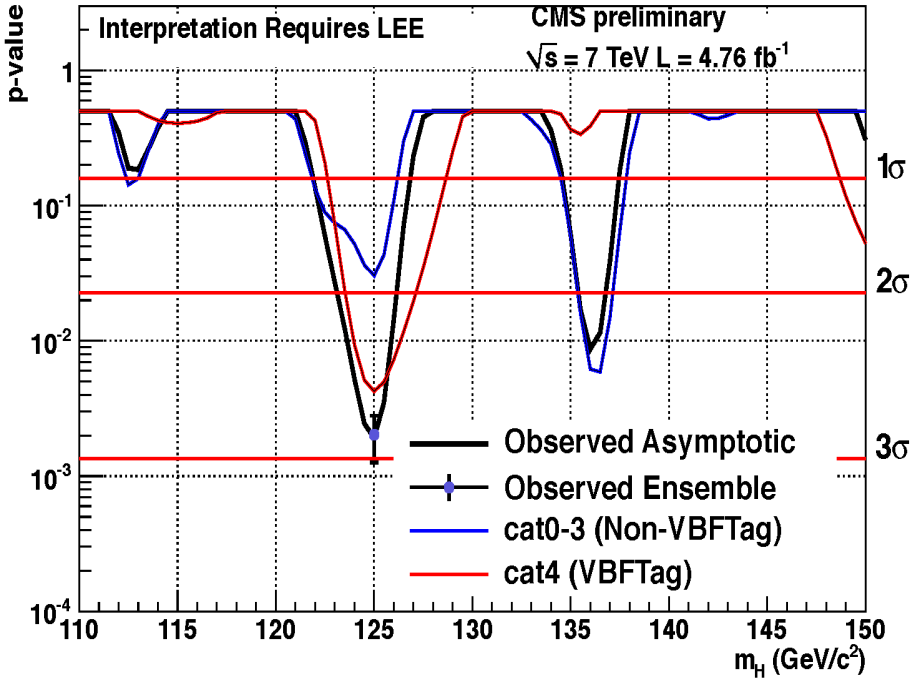
Mγγ = 121.9 GeV

Mjj = 1460 GeV

H→γγ results : limits

CMS HIG-12-001





Expected from MVA analysis
Improvement ~20%

P-value: probability that a bg only fluctuation is at least as large as the observation

Expected 95% CL exclusion: 1.2-2 x SM
Excluded at 95% CL:
110.0-111.0, 117.5-120.5, 128.5-132.0, 139.0-140.0, 146.0-147.0 GeV
Cut based analysis gives consistent results

Largest excess around 125 GeV
Local significance 2.9 σ
Global significance 1.6 σ

Low mass H→ττ channel

No narrow mass peak : σ(M) ~20%

Also important for MSSM

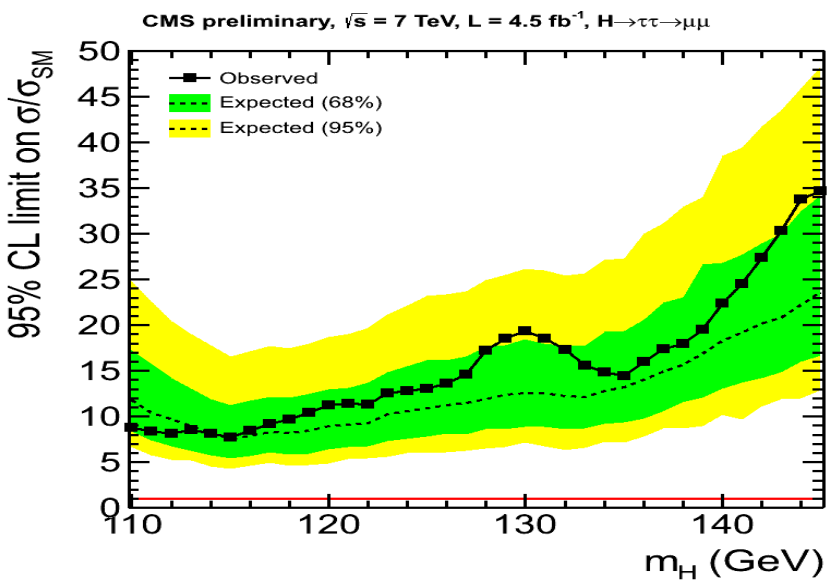
Search in 3 categories for SM:

- 0/1 jet case : no more than 1 jet p_t>15 GeV
- Boosted case: one jet with p_t>150 GeV
- VBF case : two additional forward jets

Two new channels added :

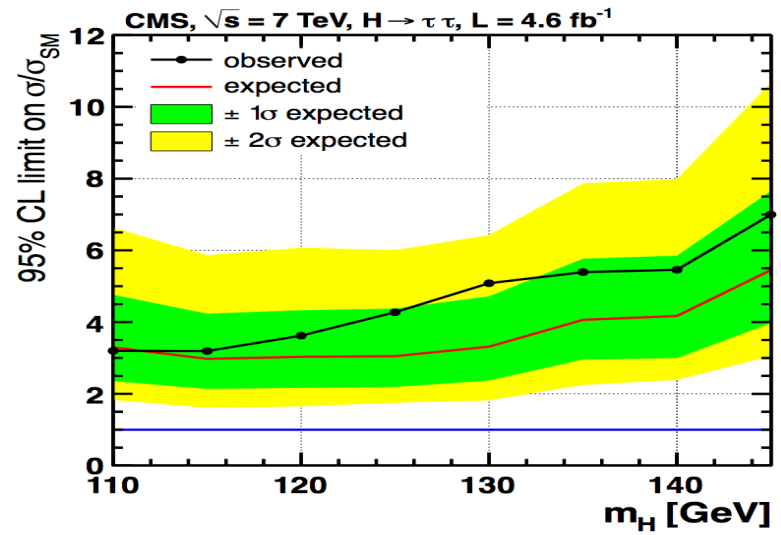
(1) H→ττ→μμ (VBF, or boosted H)

Large bg from DY Z→μμ,ττ



CMS HIG-12-007

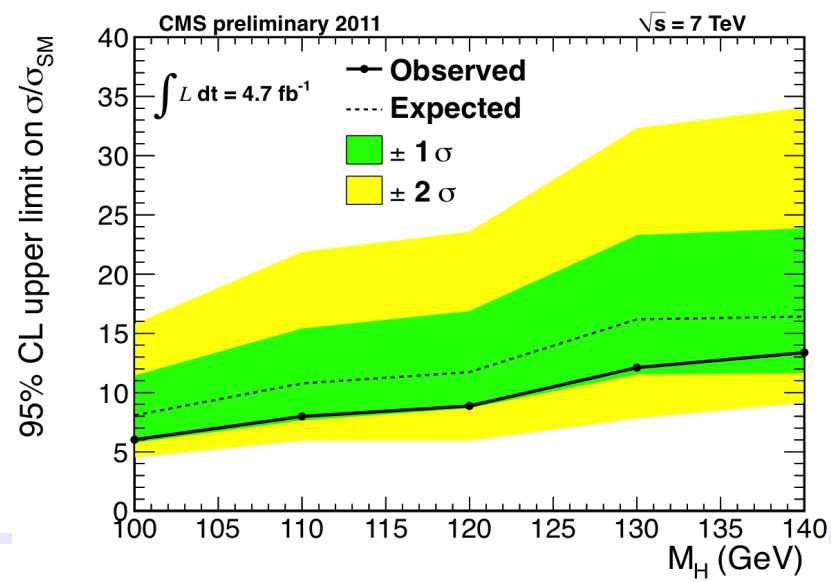
H→ττ→eτ$_h$, μτ$_h$, eμ



arXiv:1202.4083
Submitted to PLB

(2) WH→lττ→eμτ$_h$, μμτ$_h$

Same sign e and μ



CMS HIG-12-006

Full mass range : H→WW→lνlν

Channel sensitive in a large mass range!
Most sensitive channel around $2xM_W$

No narrow mass peak (mass resolution ~20%)

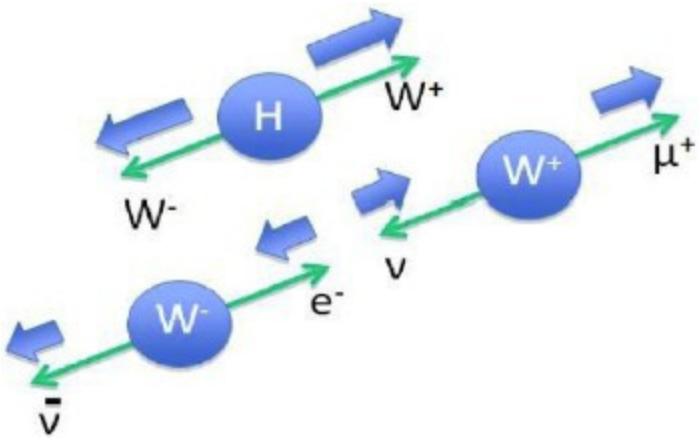
Two high p_t isolated leptons + MET

Main backgrounds

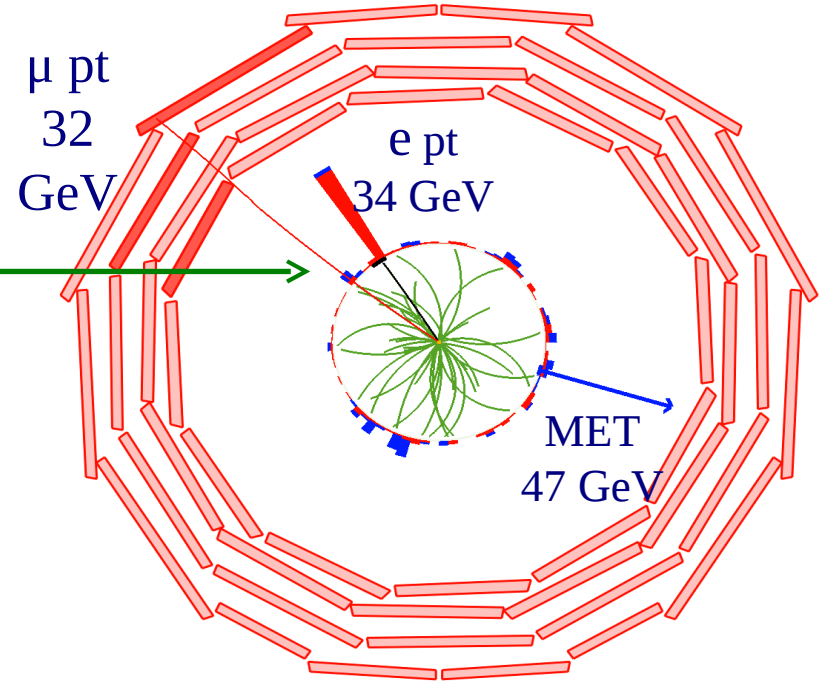
WW (irreducible)

Z+jets, WZ, ZZ, tt, W + jets

Main bg estimated from data



H→WW→eνμν candidate



Scalar boson + V-A structure of W decayfavours small opening angle between the 2 charged leptons

Full mass range : H→WW→lνlν

To improve signal sensitivity :

Analysis is performed in : jet multiplicities (0, 1, 2-jet bins) and flavour (ee, μμ, eμ)

- WW bg contributes more to the 0-jet bin
- tt bg contributes more to the 1 and 2-jet bins
- Z+jet and ZZ contribute more to same flavour (ee and μμ)
- 2 jet bin corresponds to VBF dijet ta

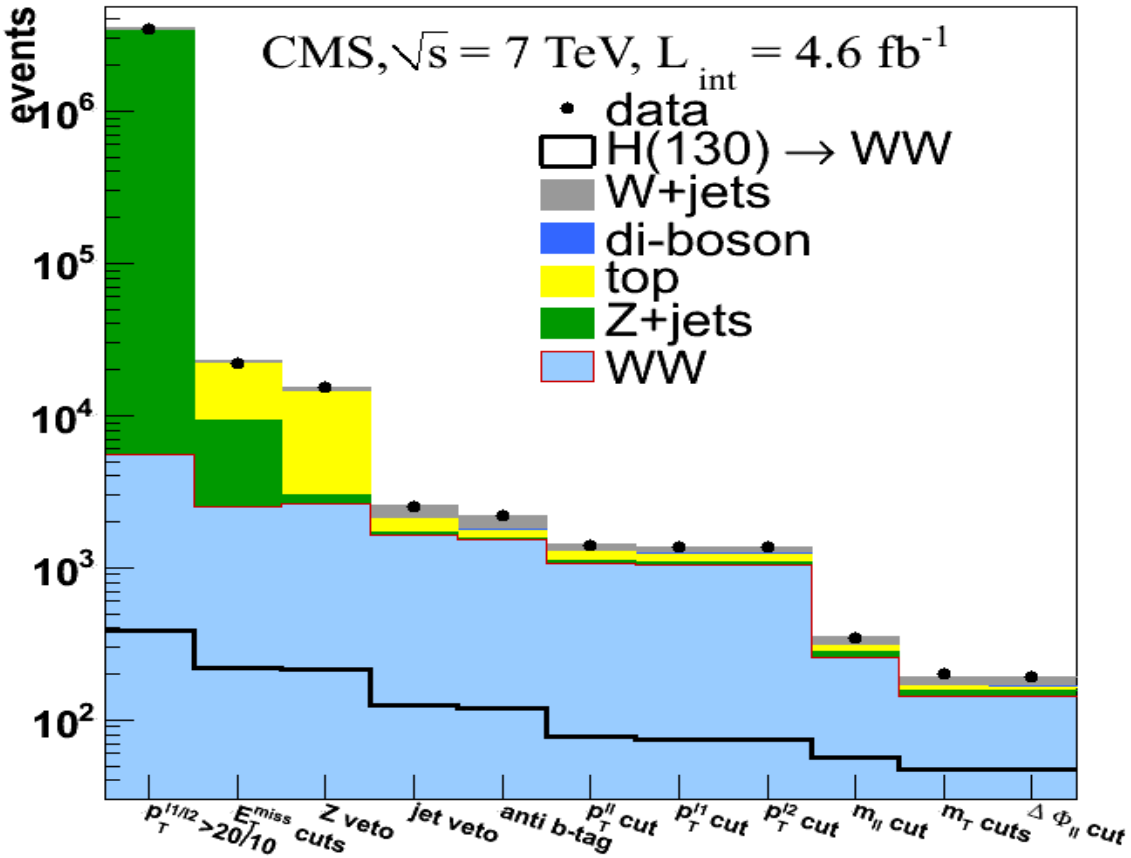
CMS arXiv:1202.1489

Two different analyses performed :

- Cut and count in 0, 1, 2-jet bins
- Multivariate in 0 and 1-jet bin

MET affected by pile-up
Special treatment
Z mass veto for ee, μμ channels

0-jet bin, M_H=130 GeV
Data-bg comparison after various cuts



MVA analysis: 0 and 1-jet bins

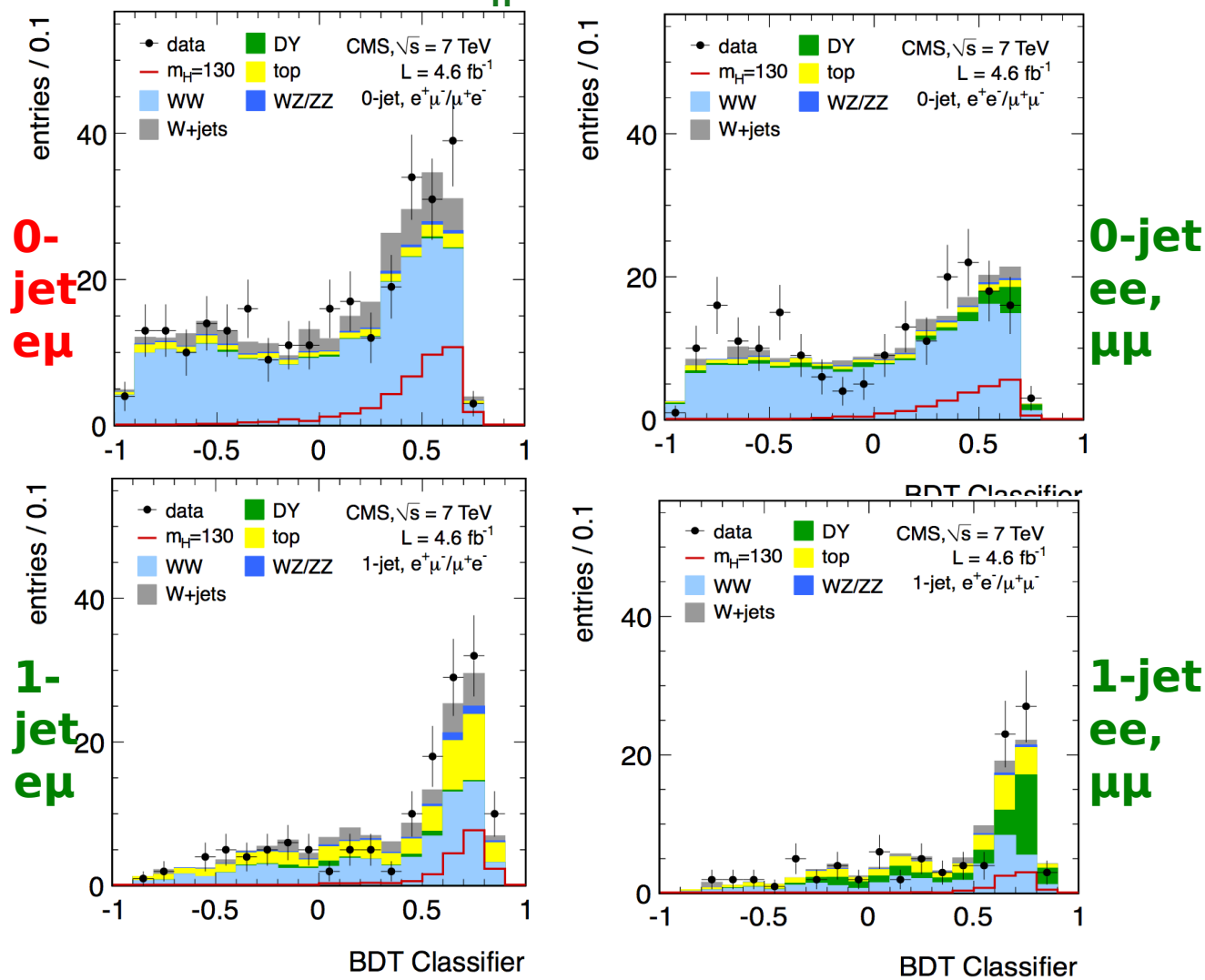
-Cut based analysis:
pt(max), pt(min),m(ll),Δφ(ll), mt(ll)

-MVA uses in addition :
Ptleptons, Mll, Δφll , ΔR(ll), Mt (for each lepton), lepton flavour

BDT trained at ≠ masses :
Using H→WW as signal and Non-resonant WW as bg

- Use BDT output classifier distribution for CL estimation

M_H=130 GeV

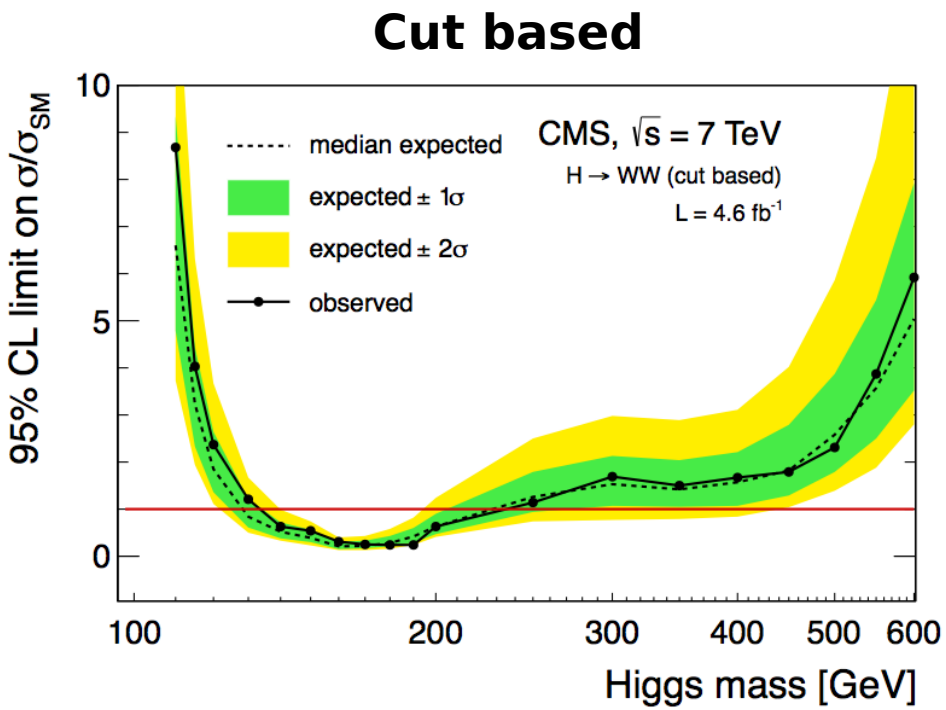


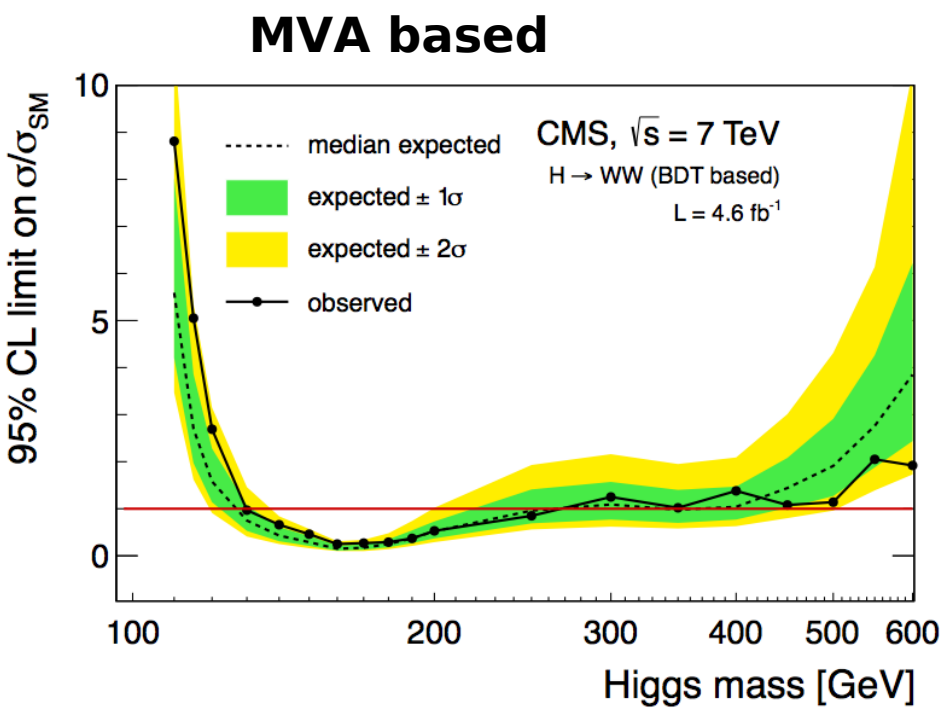
Most sensitive channel is eμ in 0-jet bin
higher s/b and smaller systematic errors

CMS arXiv:1202.1489

Full mass range : H→WW→lνlν

CMS arXiv:1202.1489





No significant excess in the full mass range
Multivariate analysis more sensitive, especially at low mass

95% C.L. expected exclusion for MH in [127-270] GeV
95% C.L. observed exclusion for MH in [129-270] GeV
Slight excess at low mass in BDT analysis

Full mass range : H→ZZ→4l

CMS arXiv:1202.1997

Clean channel: 2 high mass pairs of isolated electrons or muons

Narrow mass peak

Very good mass resolution 1-2 %

Small BR ~1E^{-3} at high mass

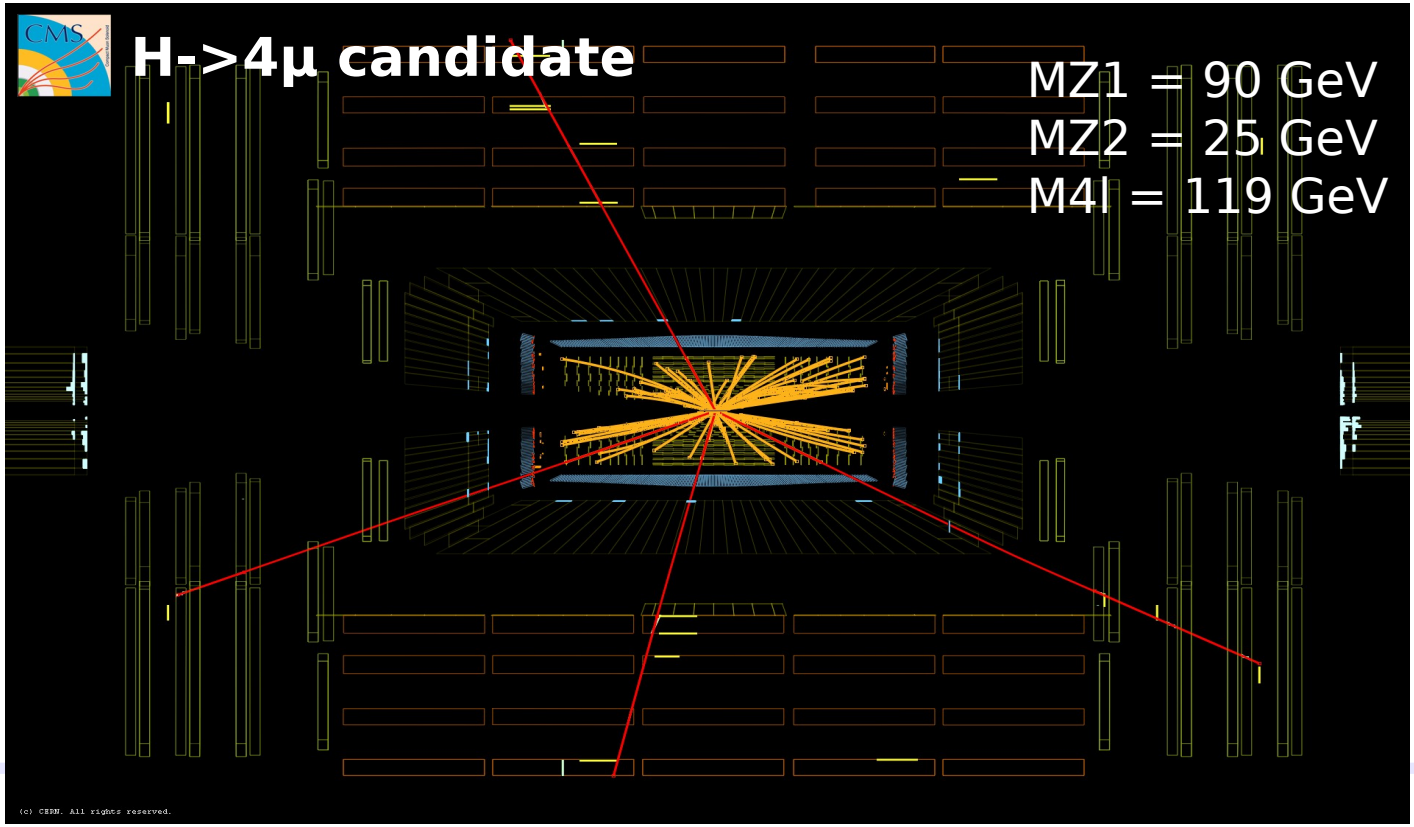
Need : Very good lepton id

Select down to very low Pt

Background

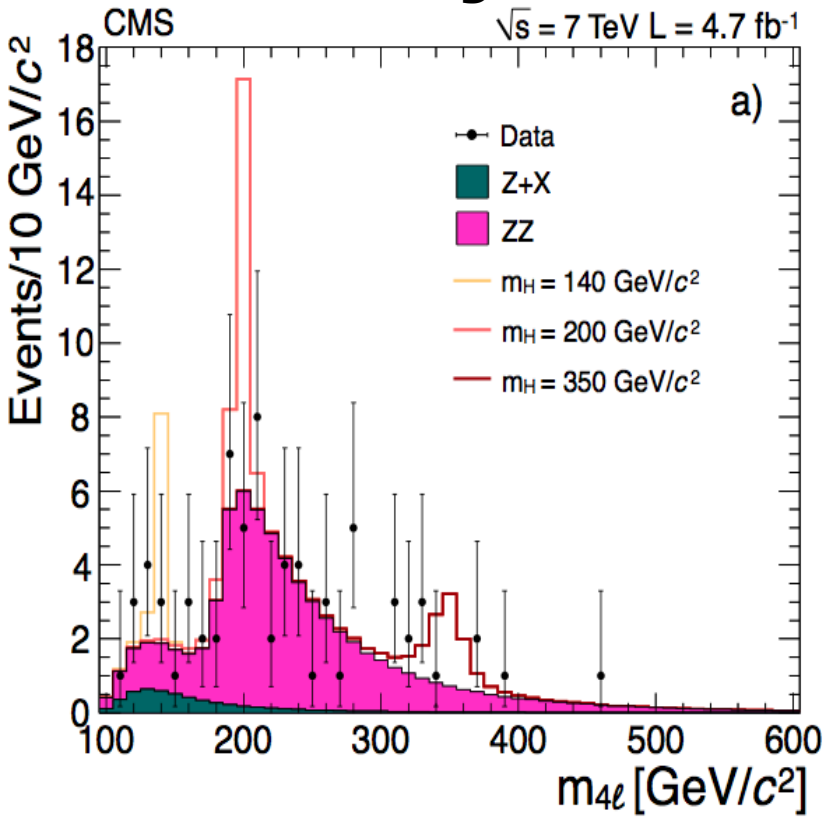
irreducible: ZZ,

Reducible: Z+jets, Zbb, tt, WZ

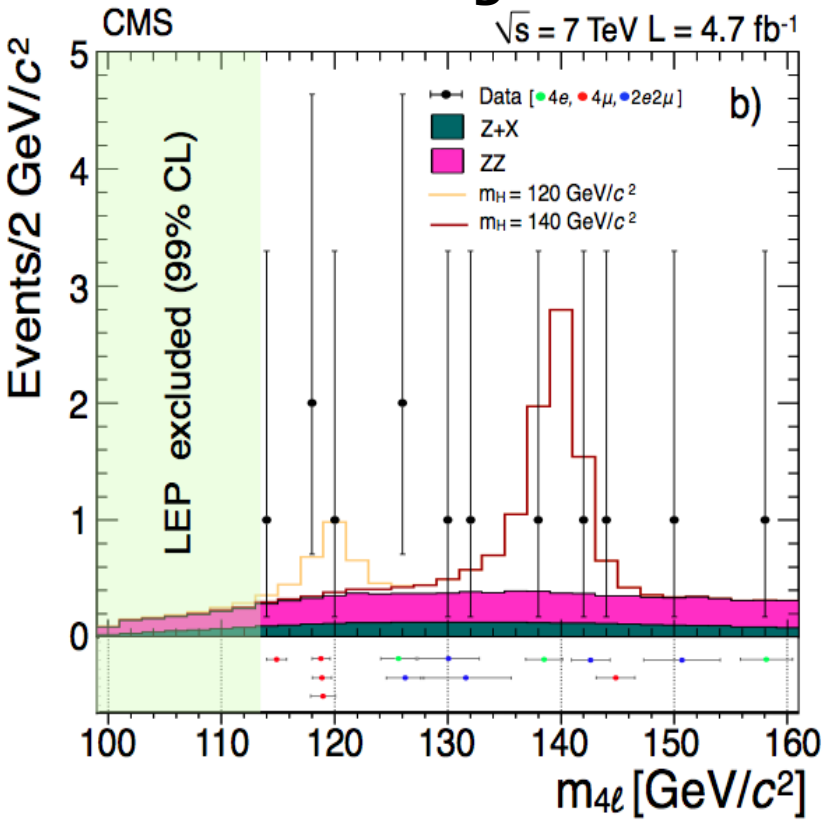


H->ZZ->4l : mass spectrum

Full mass range



Low mass range



bg exp.: 67±6
Data: 72

bg exp.: 9.5±1.3
Data: 13
In 100-160 GeV

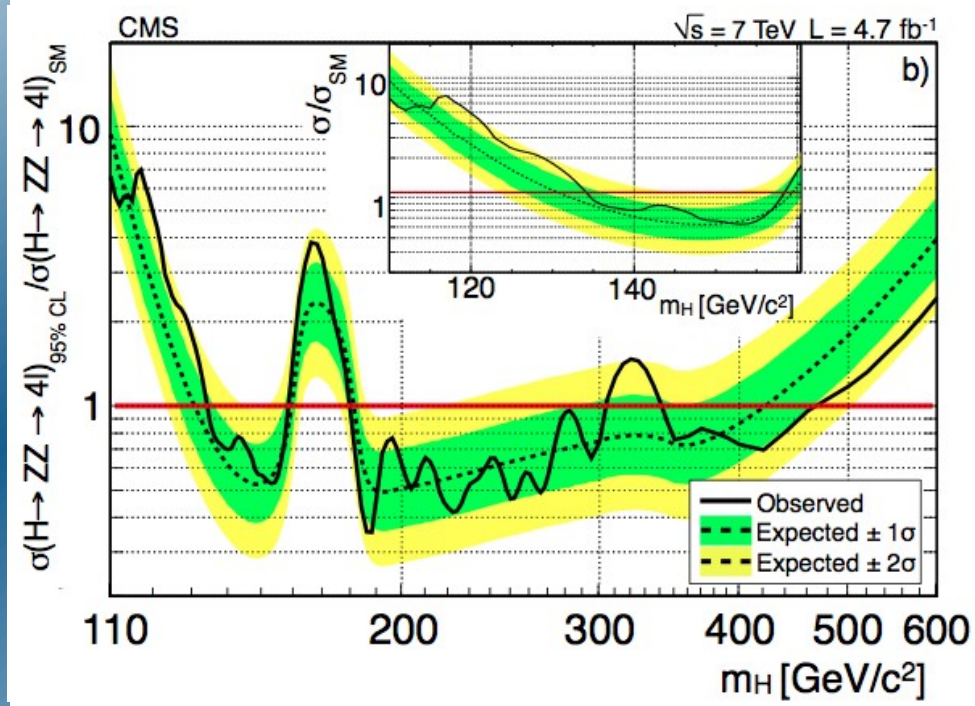
Channel	$4e$	4μ	$2e2\mu$
ZZ continuum	12.27 ± 1.16	19.11 ± 1.75	30.25 ± 2.78
Z+X	1.67 ± 0.55	1.13 ± 0.55	2.71 ± 0.96
All background	13.94 ± 1.28	20.24 ± 1.83	32.96 ± 2.94
$m_H = 120\,\mathrm{GeV}/c^2$	0.25	0.62	0.68
$m_H = 140\,\mathrm{GeV}/c^2$	1.32	2.48	3.37
$m_H = 350\,\mathrm{GeV}/c^2$	1.95	2.61	4.64
Observed	12	23	37

CMS arXiv:1202.1997

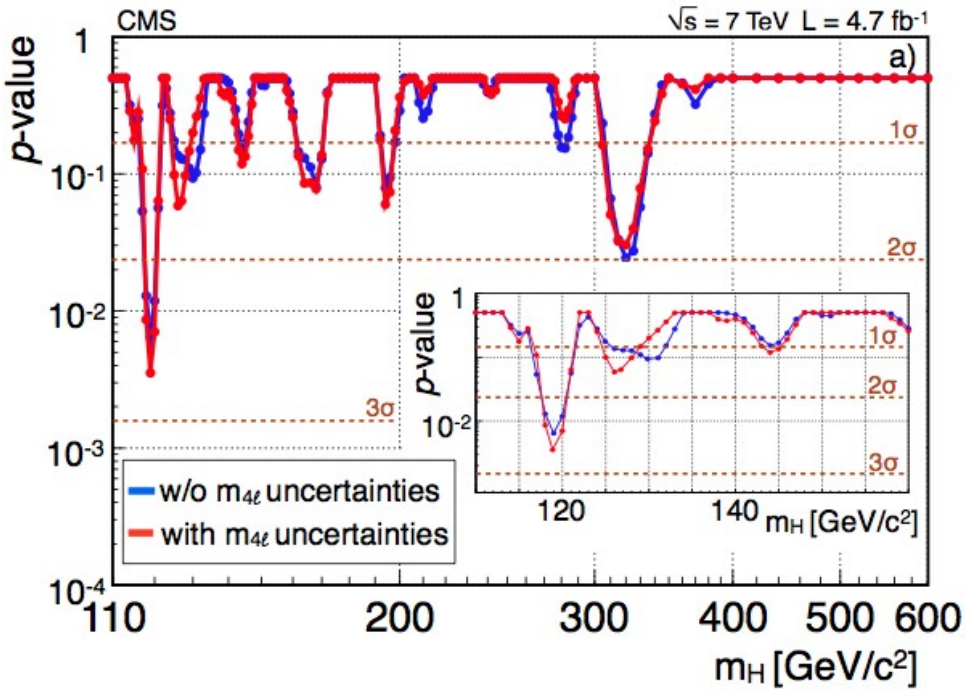
H->ZZ->4l : results

arXiv:1202.1997
Accepted by PRL

Exclusion



P-values



SM scalar boson excluded at 95% CL for M_H in [134-158], [180-305] and [340-465] GeV

Largest excess observed at 119.5 GeV

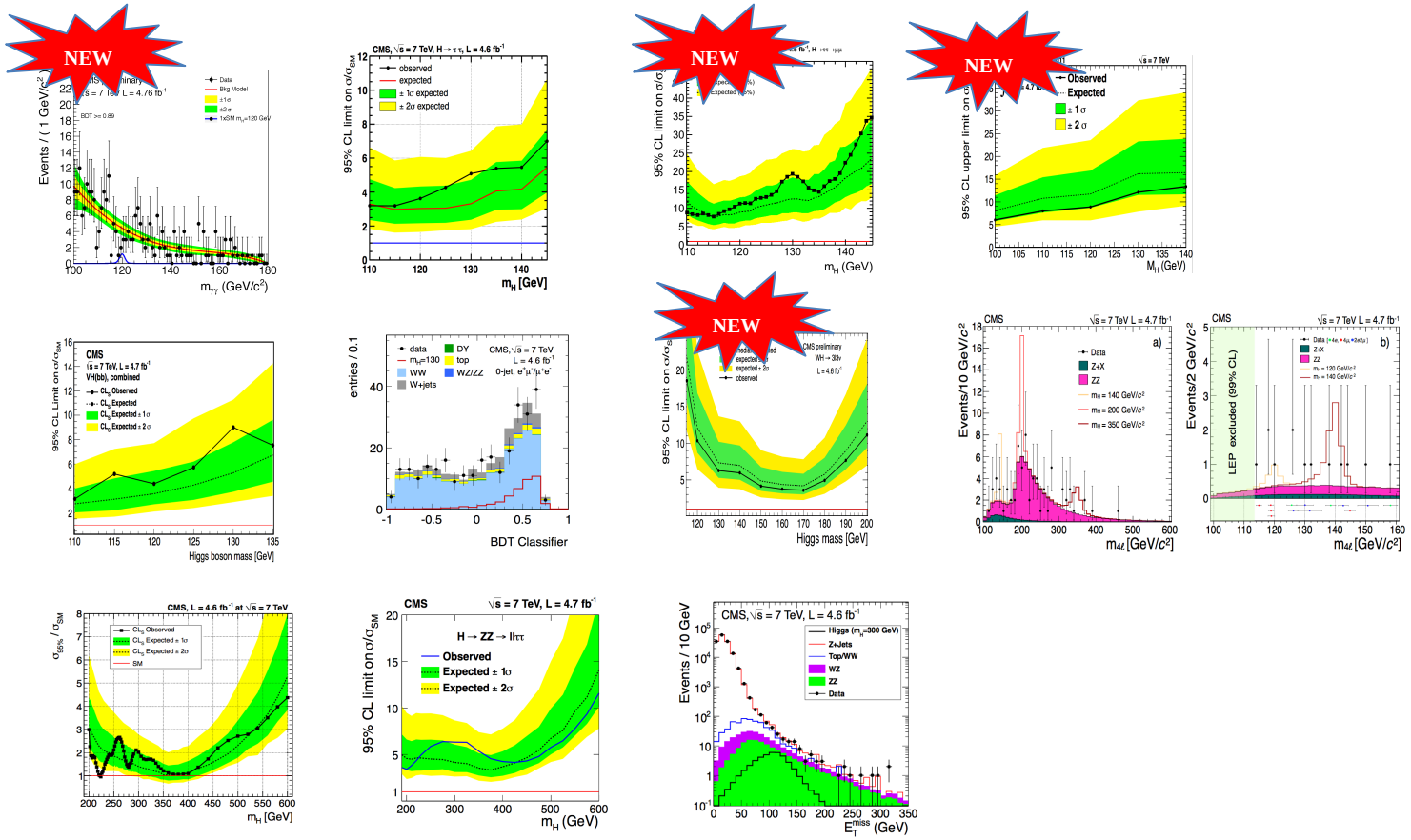
- local significance 2.5 σ
- global significance 1.0 σ in the full mass range, 1.6 in the mass range 100-160 GeV

Combination of 11 channels

arXiv:1202.1488, accepted by PLB

- Method for CL calculation is LHC-type Cls : Frequentist CLs with profiled likelihood test statistics and log-normal treatment of nuisance parameters

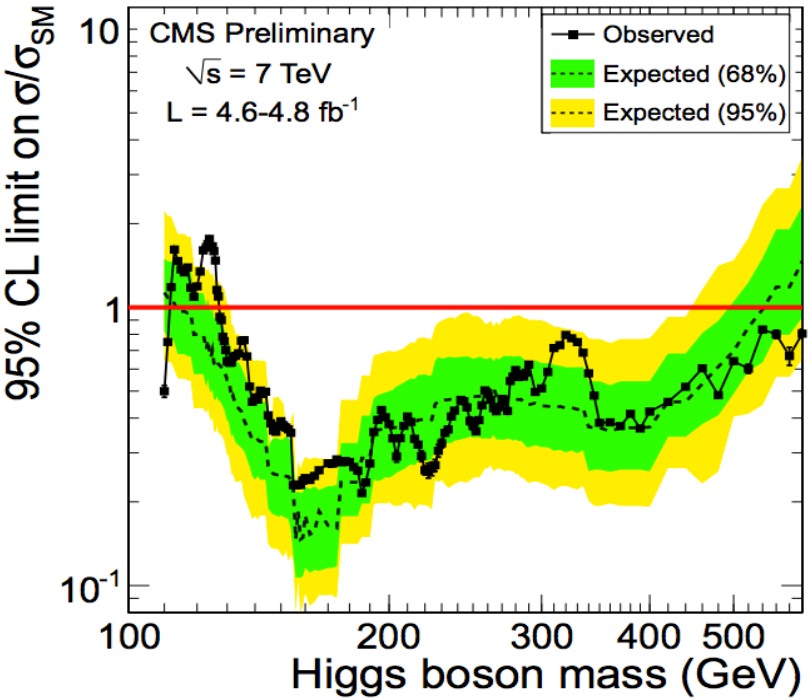
-SM cross sections and BR are assumed with their theoretical uncertainties



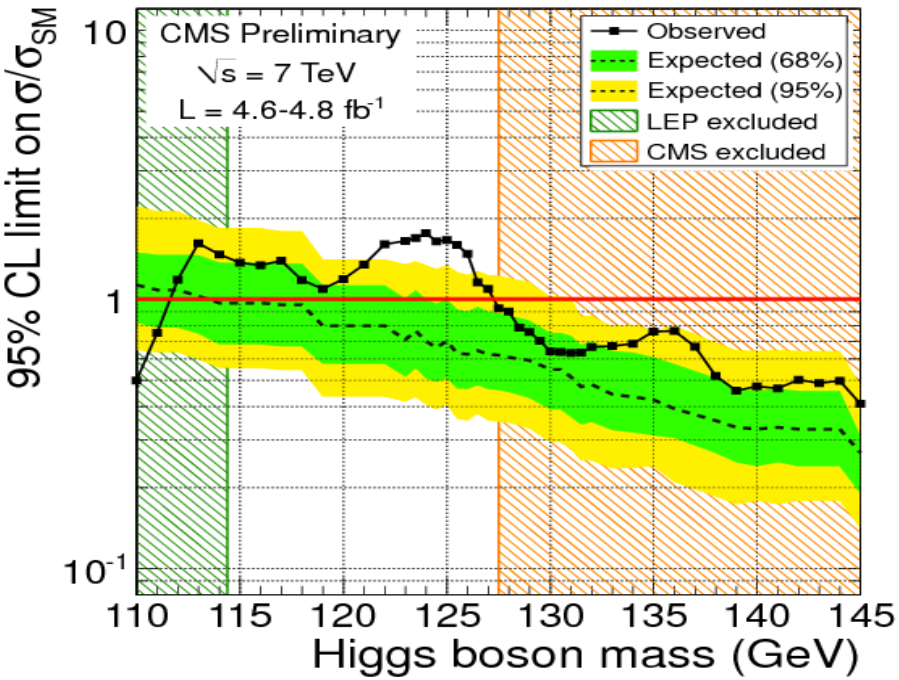
CMS Combination : exclusion CL

CMS HIG-12-008

Full mass range



Low mass region



Expected: 95% exclusion MH in [114.5-543] GeV

Observed: 95% exclusion MH in [127.5-600] GeV

99% exclusion MH in [129-525] GeV

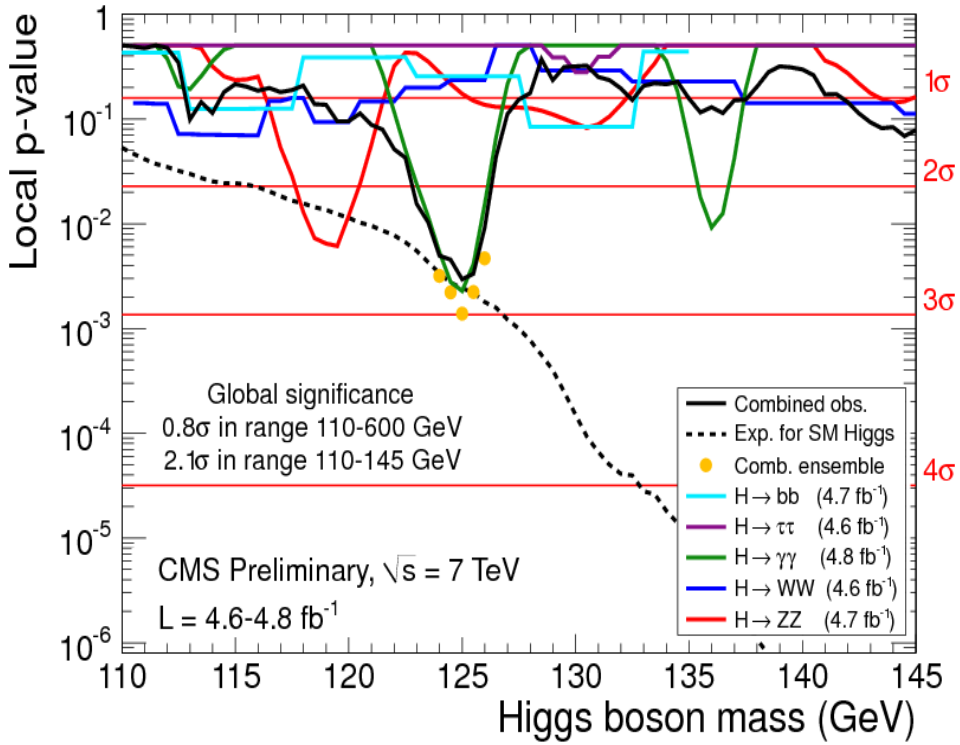
95% allowed Mass range: 114.4-127.5 GeV

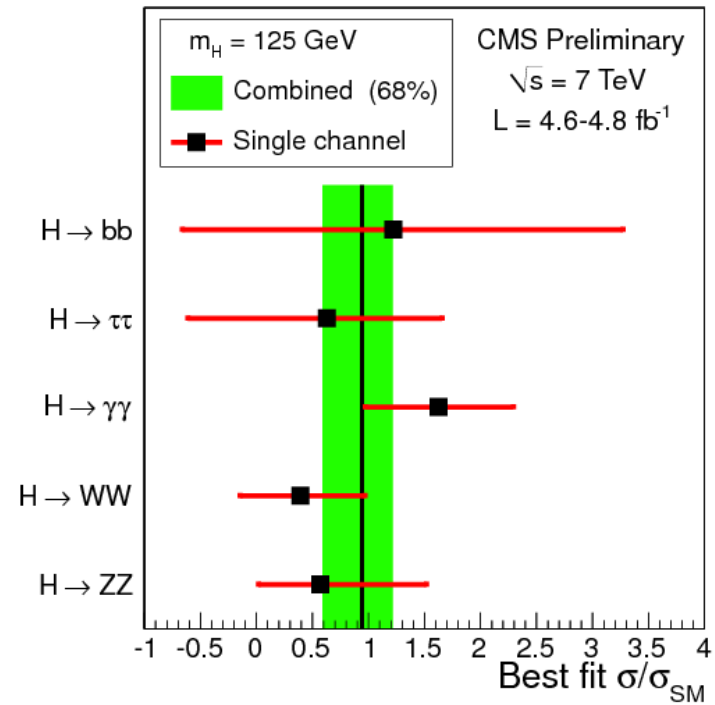
Observed lower limit higher than expected : because of excess in data at low mass

Combination : p-value

CMS HIG-12-008

Low mass region :



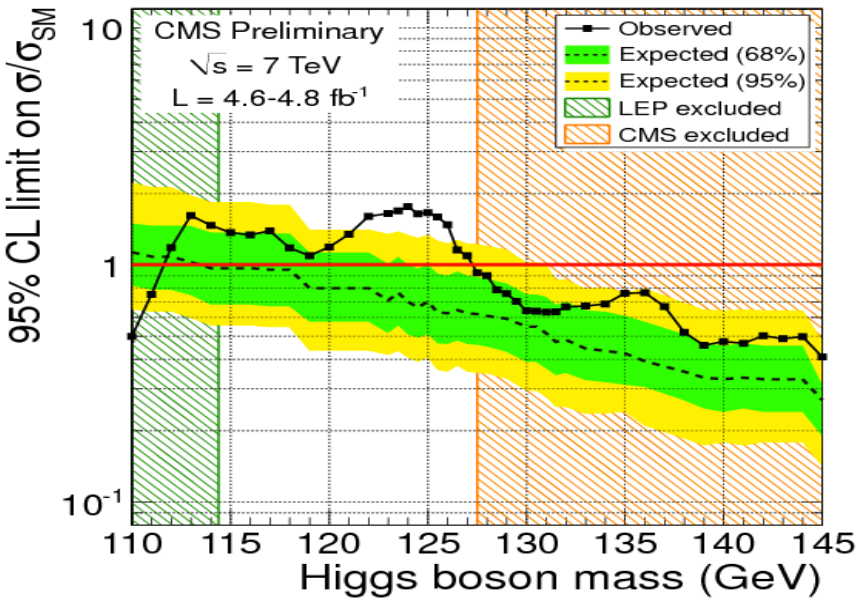


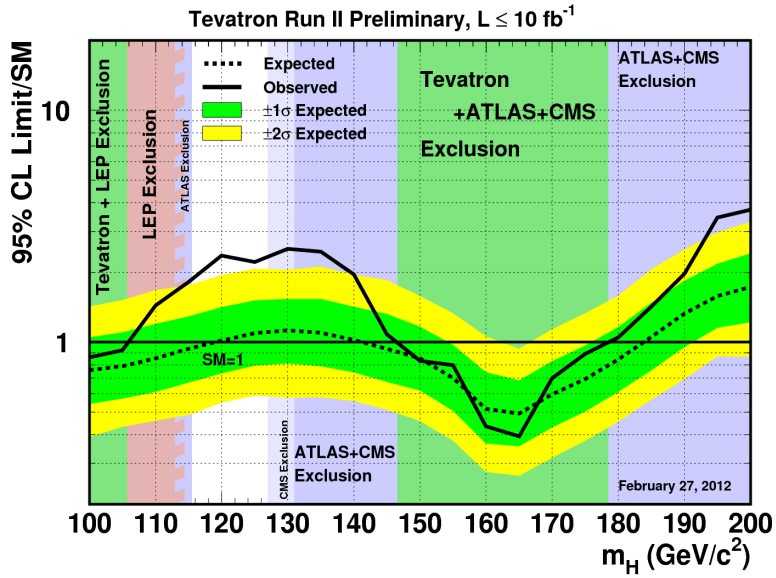
Minimum p-value observed at 125 GeV
local significance: 2.8 σ
global significance in [110-145] : 2.1 σ

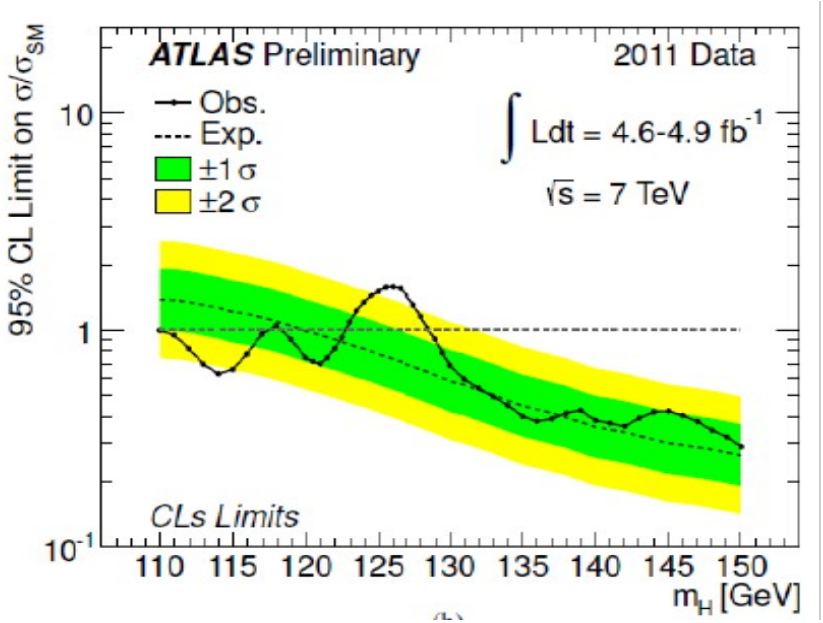
all channels are compatible
with a 125 GeV scalar boson

-> More data are needed to investigate the excess.

SM scalar boson : summary







Tevatron results combined:
excess in range 110-135 GeV :

- global pvalue of 2.2 s.d.
  (2.7 local)

PART II :

New physics searches at the LHC

Non - SM scalar boson

In the SM, the EWSB mechanism requires at minimum one doublet of a complex scalar field. Is this minimal version realised in nature ?

There are many extensions of the SM that change the predictions of this minimal version some particular examples :

- Fourth (heavy) generation of fermions modify scalar couplings :
Enhanced SM4 scalar cross section compared to SM

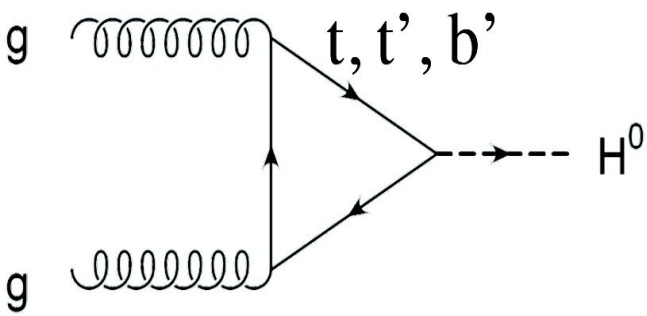
- Fermiophobic boson :
different mechanism to provide mass to gauge bosons and to fermions
Changes low mass scalar production & decays dramatically

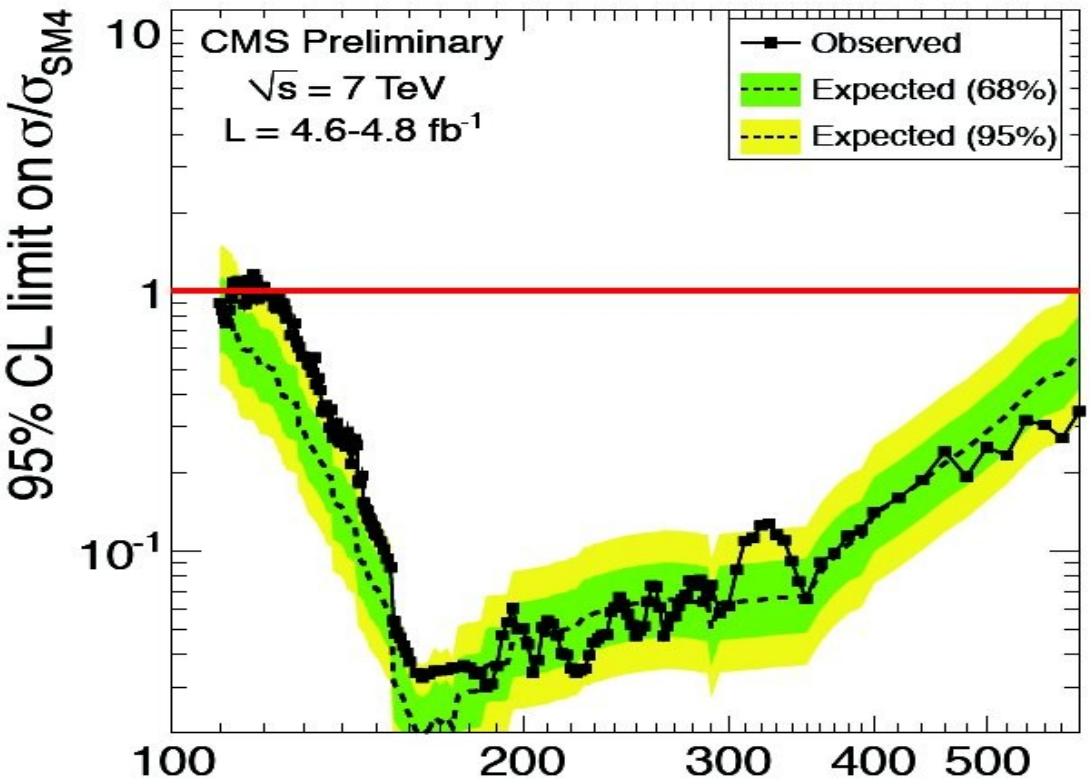
- Two or more scalar doublet fields :
- 2HDM : Multiple scalar bosons: 3 neutral and 2 charged
  Example : Minimal Supersymmetric Model
- NMSSM, triplets … more complex:
  very light pseudoscalar boson, doubly charged scalars …

Fourth generation

CMS PAS HIG-12-008

Additional heavy quarks enhance significantly the gg→H production
BR is also affected (virtual heavy quarks)





SM4 Higgs boson mass (GeV)

Benchmark fourth generation quark masses of ~600 GeV

σ(SM4) = 10–4 x σ(SM) for M_H 110–600 GeV

M_H > 120 GeV excluded

Should have excluded M_H > 110 GeV

Exclusion of most of the parameter space for models with a fourth generation fermion

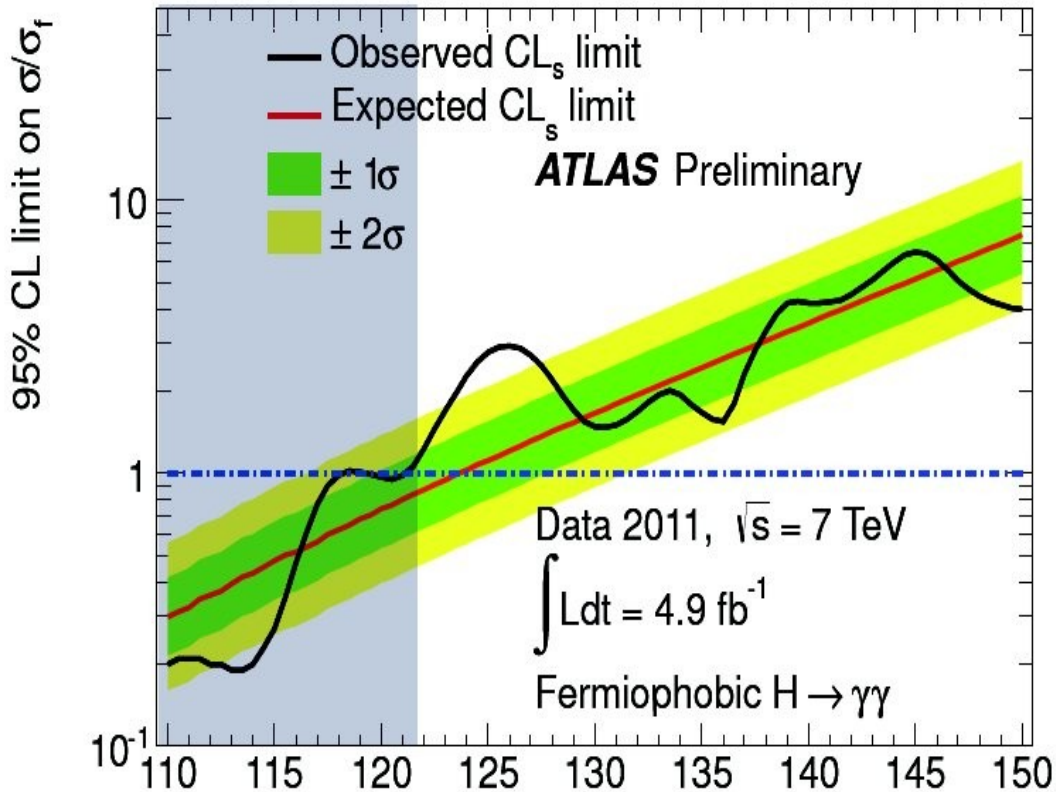
Fermiophobic scalar boson

Fermiophobic scalar appears in a variety of extensions to the SM

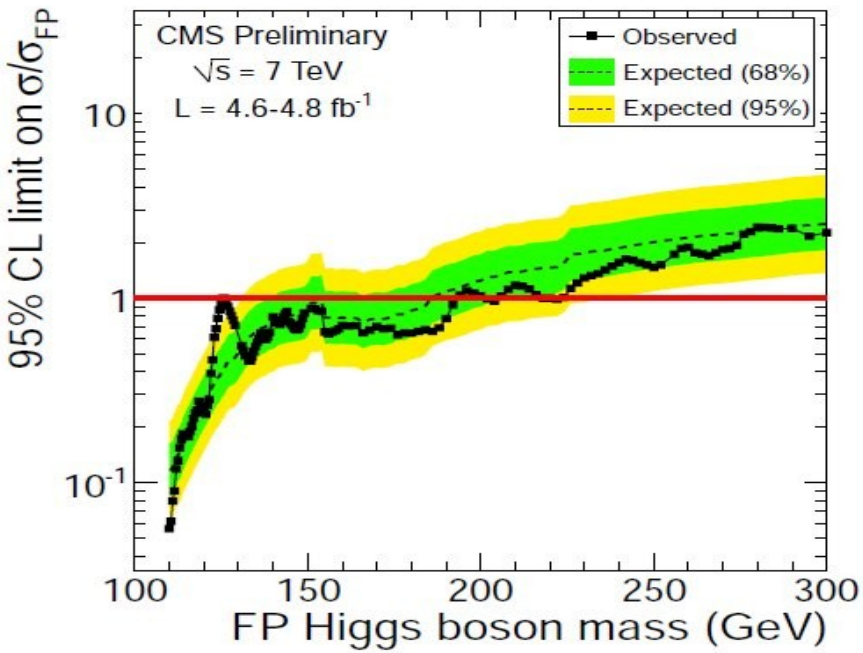
Scalar does not couple to fermions :

- gg→H and ttH production disappear while VBF, VH are unchanged
- direct decay H→ττ, bb impossible H→γγ, WW, ZZ enhanced

ATLAS CONF 2012-13



CMS PAS HIG-12-008



CMS : H→γγ, WW, ZZ combined :
M(FB) > 192 GeV at 95% CL

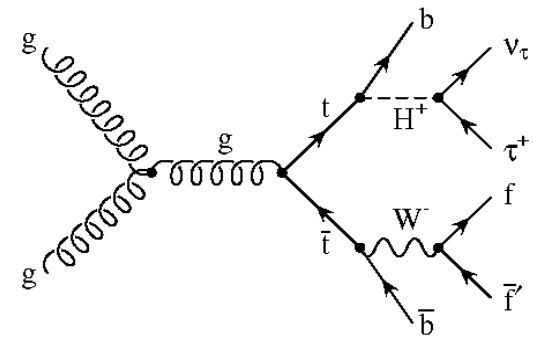
ATLAS : H→γγ
M(FB) > 121 GeV at 95% CL

MSSM scalar boson(s)

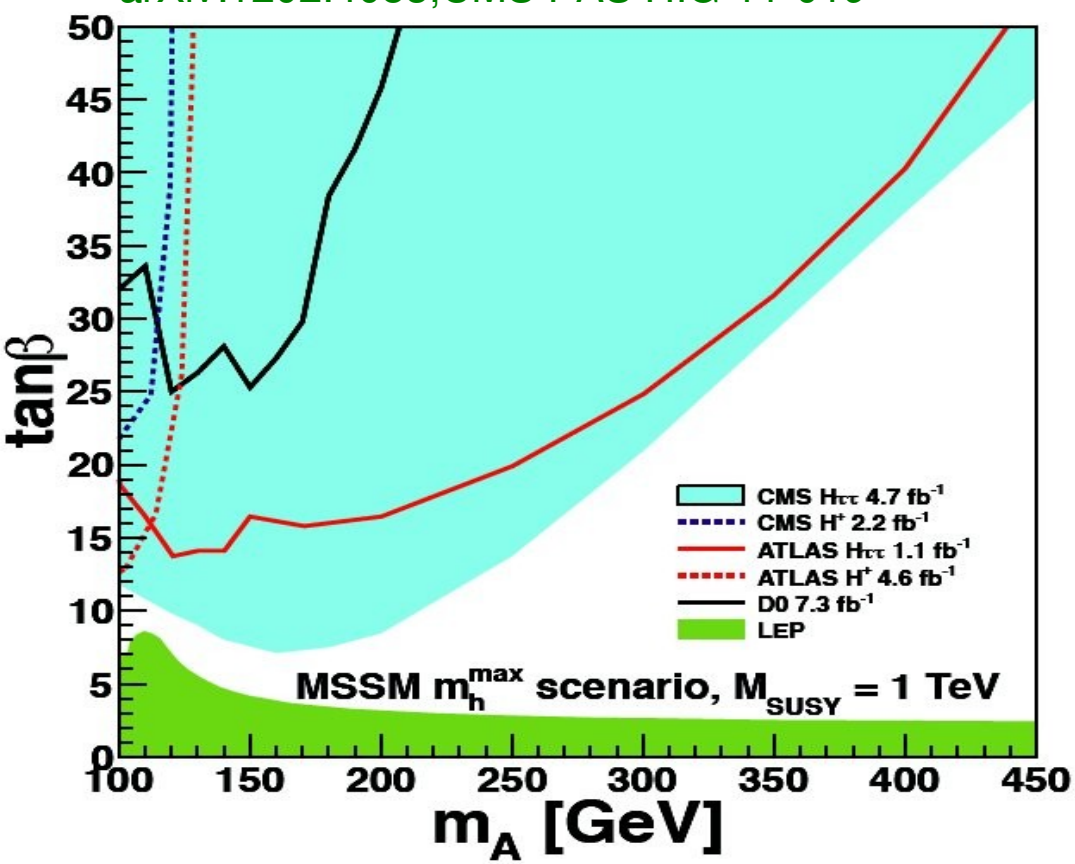
Five BEH bosons

- Three neutral: h, H, A, two charged: $H^{\pm}$
- m_A : mass of pseudoscalar, tan(β) : ratio of the vacuum expectation values of the two Higgs doublets
- Look for ϕ = (h, A,H) in decay to τ-leptons
- Look for H^+ in top decay

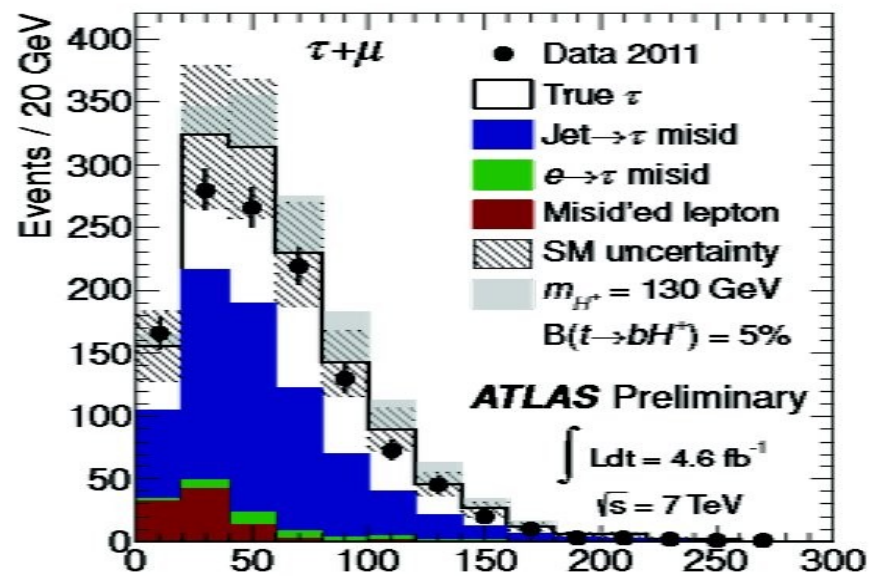
Search for H^+ in top decay :



ATLAS CONF 2012-011
arXiv:1202.4083,CMS PAS HIG-11-019



Event with (τ + MET) from $H^{\pm}$, 2 b-jets
2 jets or (e/μ + MET) from W



MET (GeV) →

Searches at LHC : latest results

Searches in lepton production
- Z' ->ee,mm (CMS, Atlas)
- W' ->ev, W'->mu v, W'->WZ (CMS)
- Multileptons in RPV (CMS)
- Excited leptons (Atlas)

Searches for TeV scale gravity
- black holes (CMS)
- Large ED in mm+ee (CMS)
- DM + LED in g+MET (CMS)
- DM + LED in monojet events (CMS)
- RS graviton in jets+MET (CMS)

Searches for rare decay process
- Bs->μμ (LHCb, CMS)

Searches in lepton + jet production
- 2nd generation LeptoQuarks (Atlas)
- Heavy bottom like quark (CMS)
- Search for t' ->bW(CMS)
- searches for Z'-> ttbar (CMS)
- Search for heavy V- like quark (CMS, Atlas)
- Fourth gen up-type quark (CMS)
- new particle decaying in ZZ (Atlas)
- Fourth gen Down type quark (Atlas)
- Same sign top pair (Atlas)
- Heavy quark in Wq, Wb (Atlas)

Searches for SUSY :
- lepton + MET (CMS)
- opposite sign leptons + jet + MET (CMS)
- Razor variable (CMS)
- photon + MET (CMS)
- SS dileptons with b-jets + MET (CMS)
- SS dileptons + MET (CMS)
- multileptons (CMS)
- Z+jet + MET (CMS)
- 0 lepton + (6-8) jets + MET (Atlas)
- 0 lepton + (2-4) jets + MET (Atlas)
- 1 lepton + jets + MET (Atlas)
- 2, 3, >4 leptons + MET (Atlas)
- search for disappearing tracks (Atlas)
- Long lived particles (Atlas)

Searches in jet production
- Search quark compositeness in dijet angular distribution (CMS)
- resonance in dijet, delta eta ratio (CMS, Atlas)

Searches for long lived charged particles
- Heavy Stable Charged Particle (CMS)
- Light Higgs -> long lived pp(Atlas)

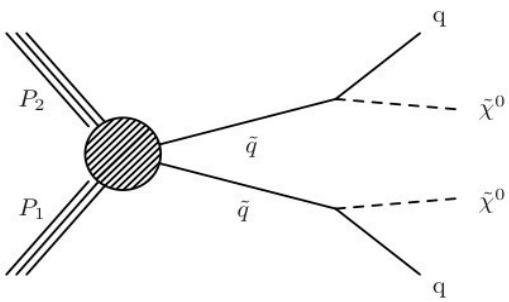
many new results available, all data compatible with Expected backgrounds

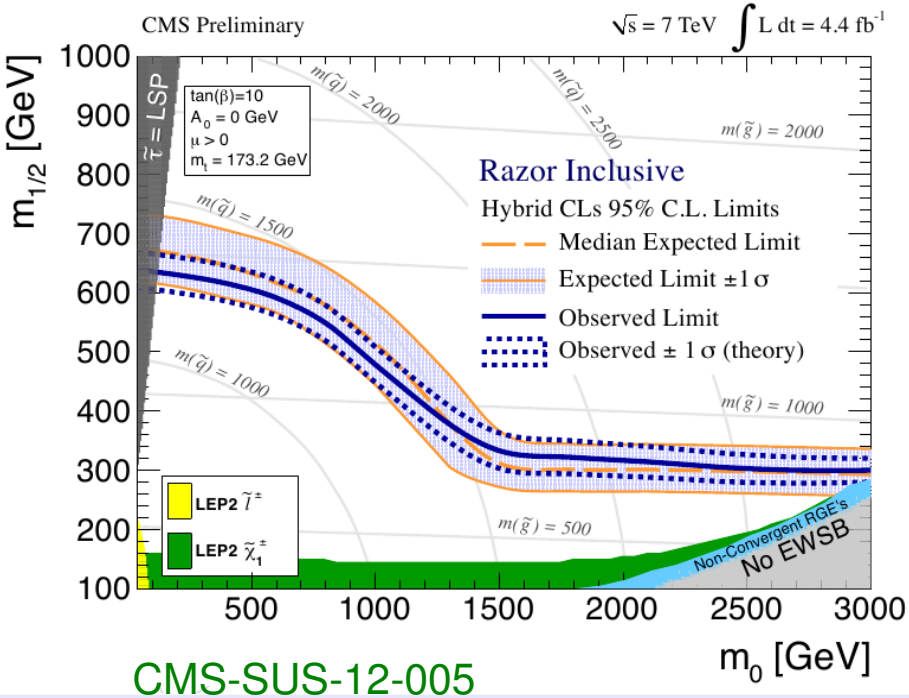
See "Electroweak and Searches" parallel session

SUSY searches

Squark-gluino mediated SUSY production was the first line of attack
Large production cross section - rich phenomenology of final states to explore

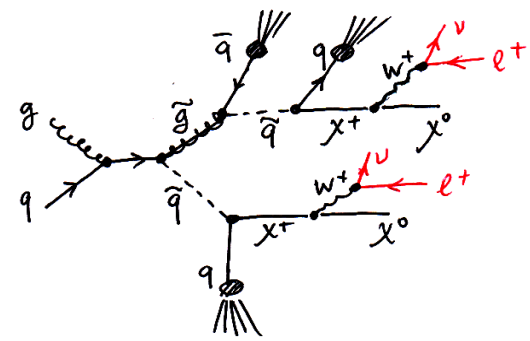
Multi jet + MET searches

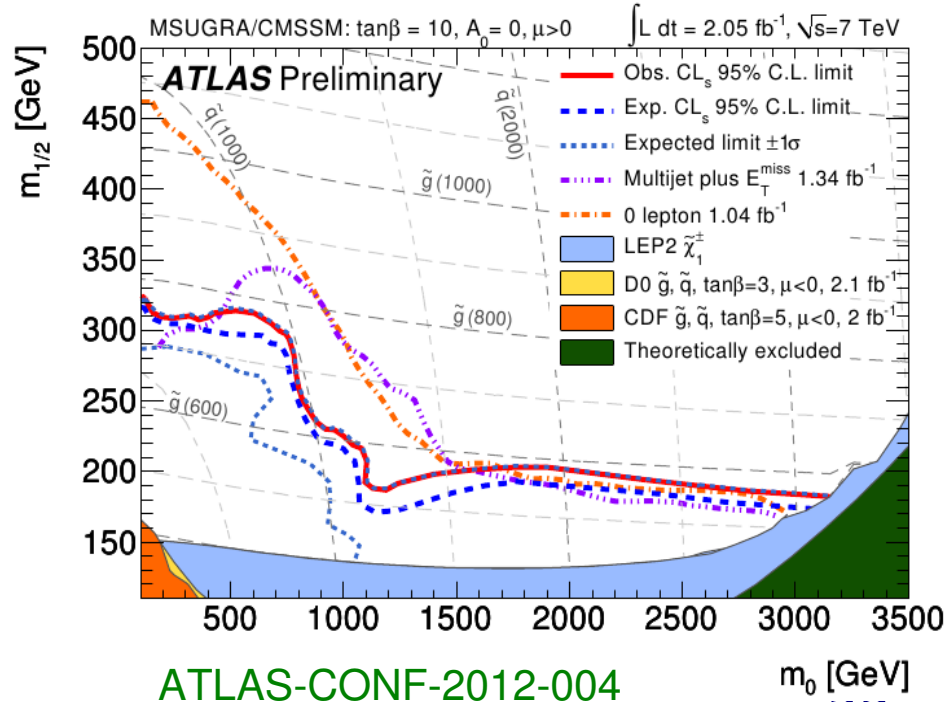




CMS-SUS-12-005

Same sign lepton + jet + MET searches





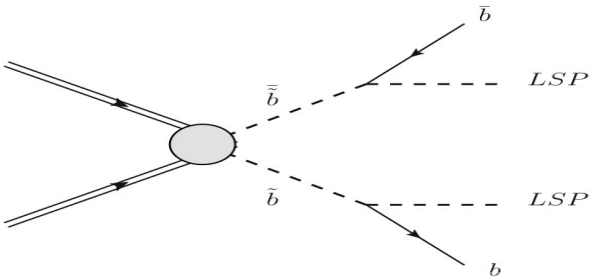
ATLAS-CONF-2012-004

SUSY searches

With the large luminosity we now also become sensitive to more exclusive production modes

(1) Direct sbottom and stop production :

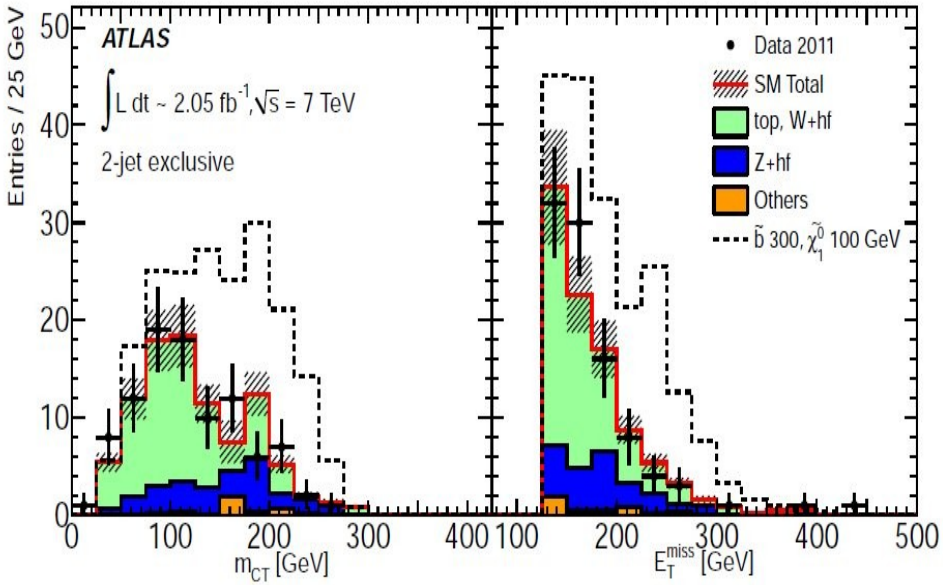
in general the third generation is special
- desired light for SUSY naturalness
- mixing can push the stop, sbottom and stau masses below other generations

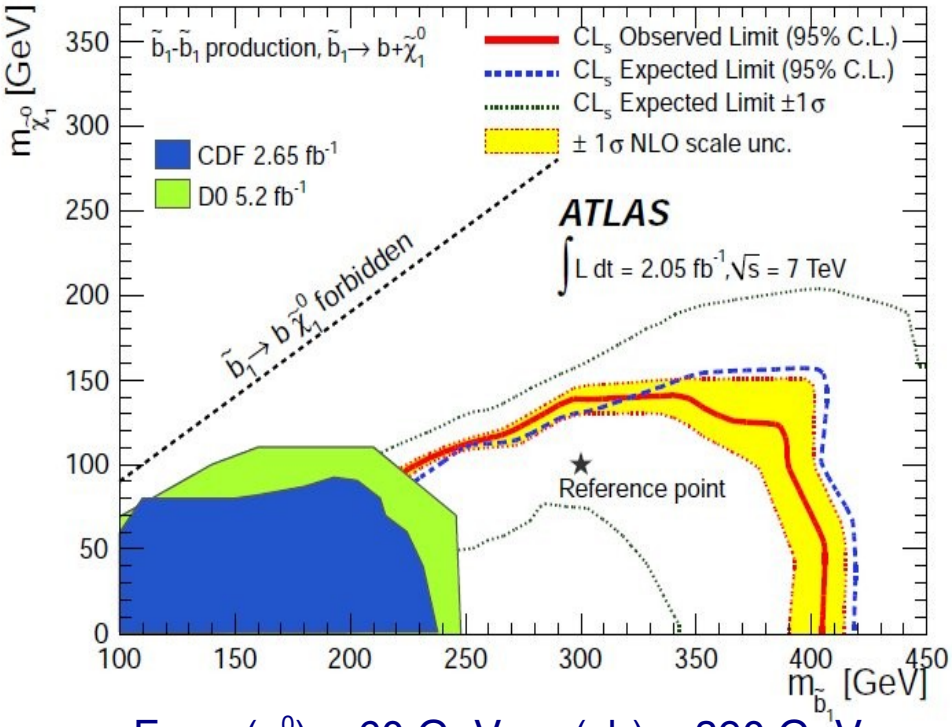


arXiv :1112.3832

Search for direct sbottom pair production with sb → b + χ^0 : Exactly 2 b-jets + ME**T**

MSSM BR(sb → b + χ^0) = 100 %





MSSM Reference point ★ :
m(sb) = 300 GeV, m(χ^0) = 100 GeV

→ For m(χ^0) < 60 GeV, m(sb) > 390 GeV

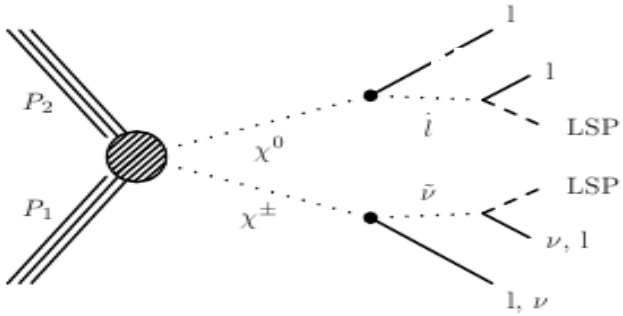
SUSY searches

ATLAS-CONF-2012-023

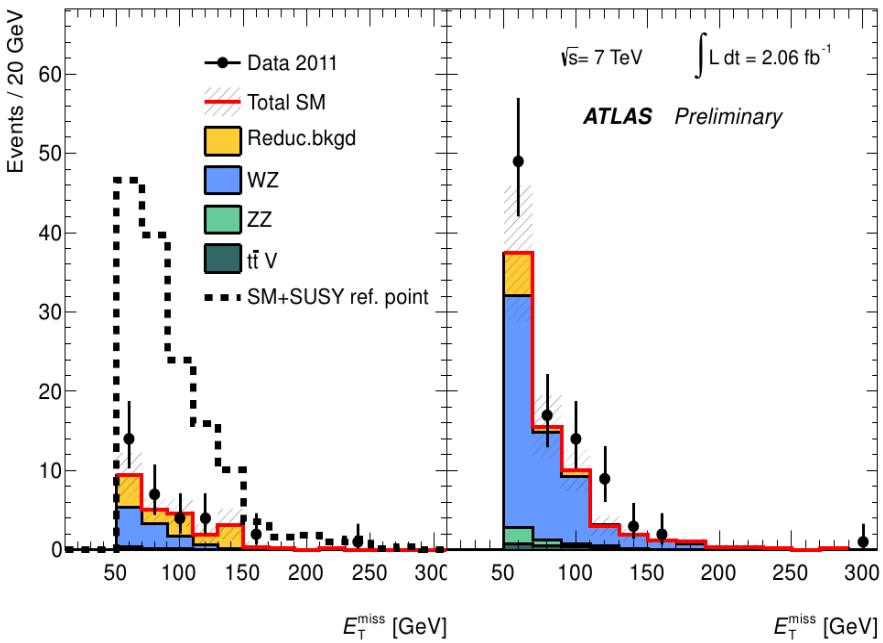
With the large luminosity we now also become sensitive to more exclusive production modes

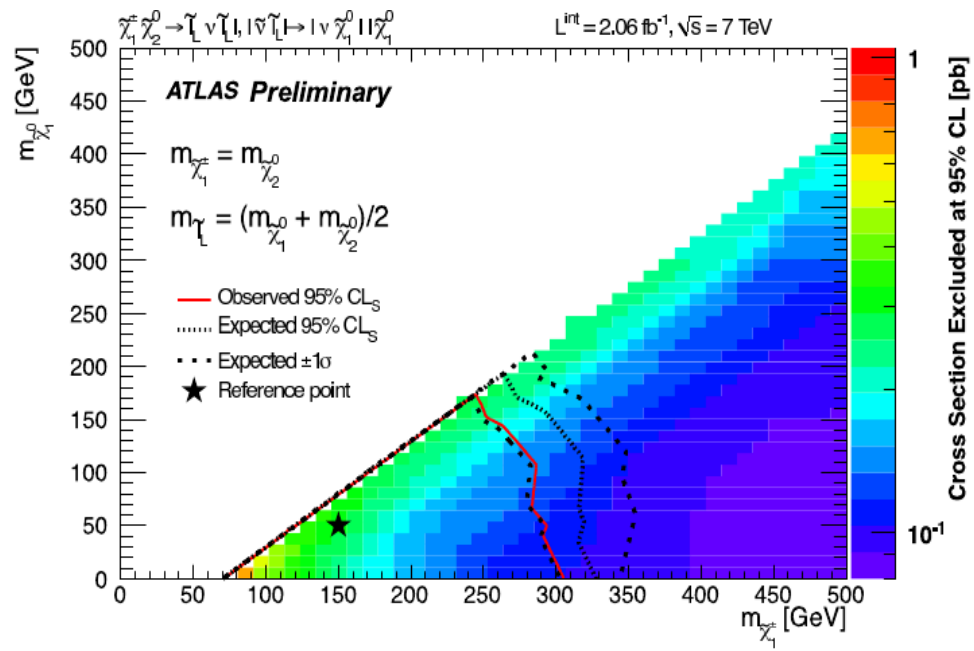
(2) Electroweak chargino/neutralino production

3 isolated leptons (e and μ)
MET > 50 GeV
➔ 2 regions in/out Z-mass window



out Z-mass in Z-mass





MSSM, simplified model scenario

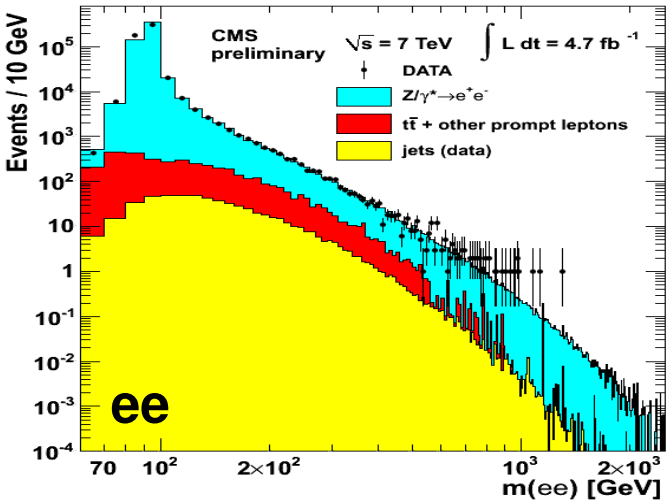
Reference point ★ : mχ+, mχ02, mslL, mχ01 = 150, 150, 100, 50 GeV

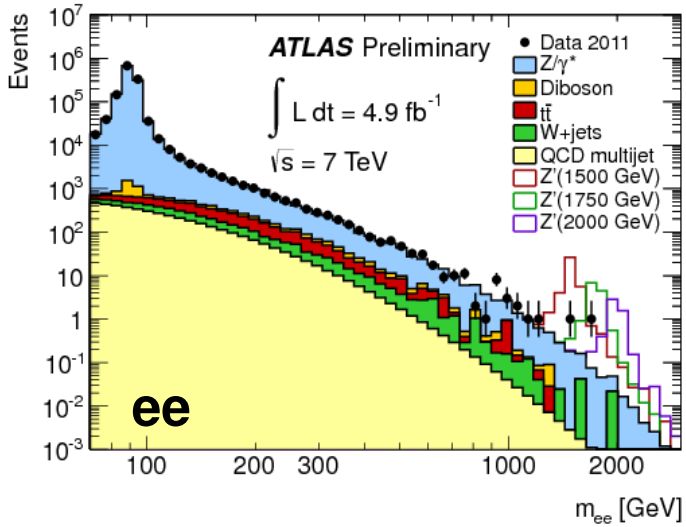
→ Degenerate χ+ and χ02 excluded up to 300 GeV

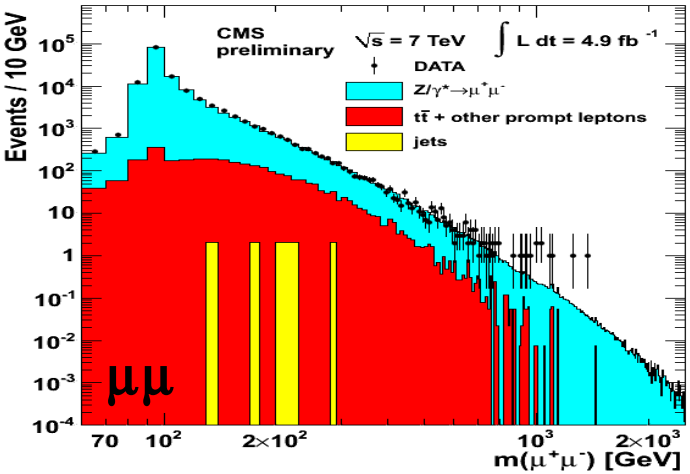
BSM : heavy resonance searches

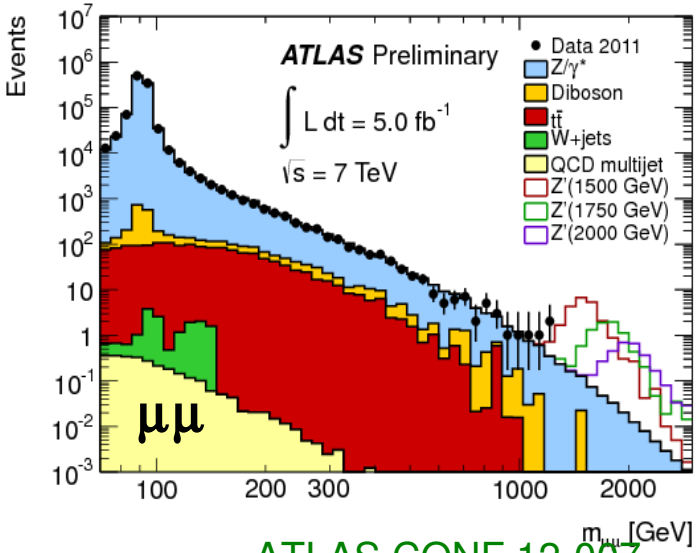
Search for narrow high mass resonances decaying into ee or μμ pairs

Predicted by many BSM models : spin 1 (GUT, LED, techni-mesons, ...) and spin 2 (RS gravitons, ...)









Very clean signature :
Two isolated high pt electrons or muons

CMS (ATLAS) :

electrons :
Et>35 barrel/40 endcap (25)
|eta|< 2.5(2.47)

-muons :
pt>35((25) GeV

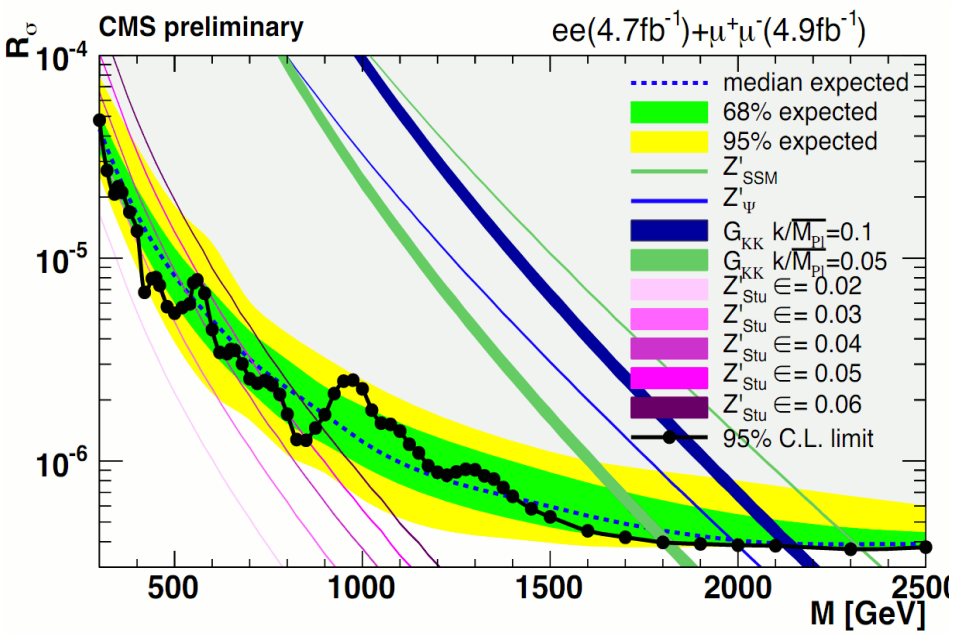
Z' SSM : benchmark model
Same couplings as SM Z boson

CMS EXO-11-019

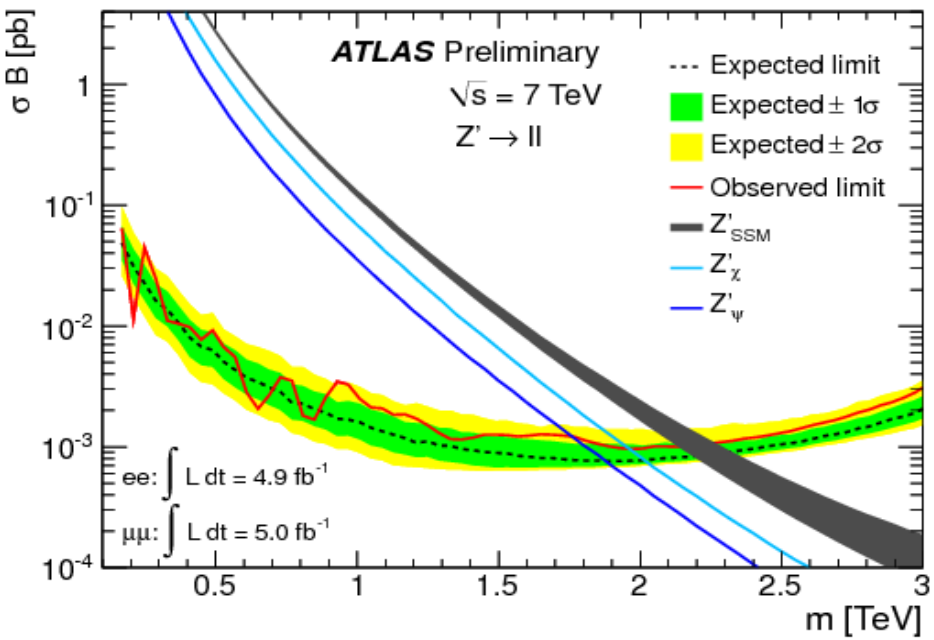
ATLAS CONF 12-007

BSM : heavy resonance searches

CMS EXO-11-019



ATLAS CONF 12-007



95% CL lower limits on heavy resonance mass :

	mass Z' SSM	mass RS Graviton c=0.05	mass RS Graviton c=0.1
CMS	2.32 TeV	1.81 TeV	2.14 TeV
ATLAS	2.21 TeV	1.71 TeV	2.16 TeV

DM searches : monojet and monophoton

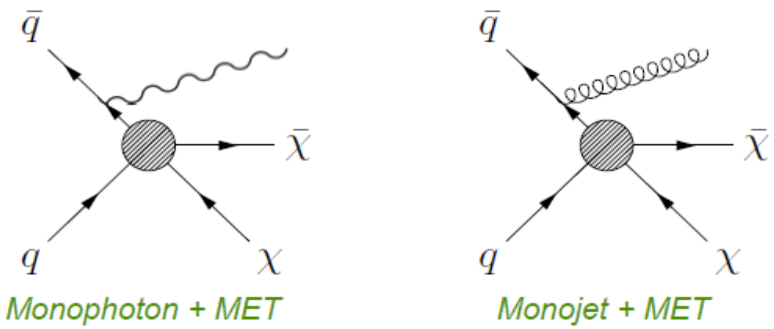
Search for high pt γ+MET and high pt jet+MET - Look for evidence of :

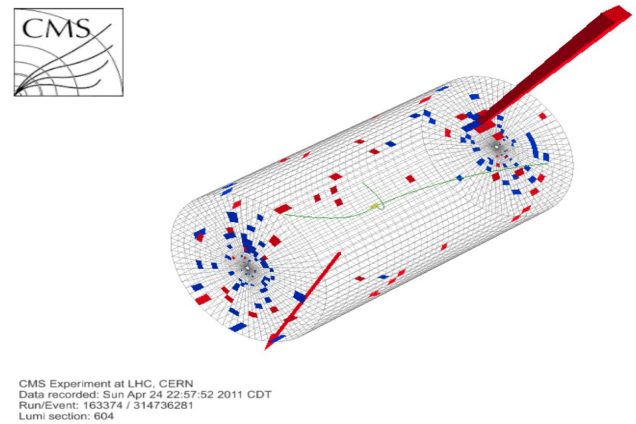
(i) Extra-dimension ADD model

(ii) Dark Matter production

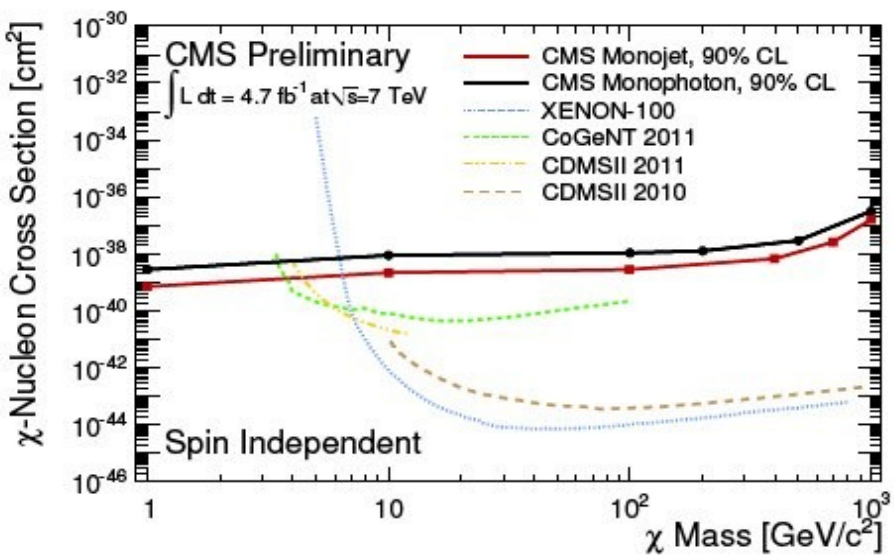
Monojet: ADD limits set M_D >3.7 TeV for n=2

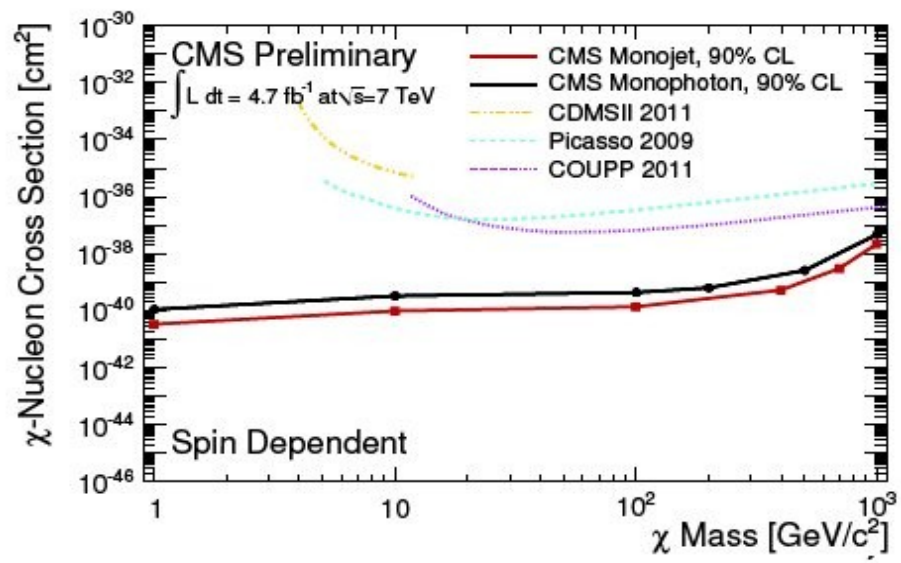
Monophoton: M_D>1.65(1.71) TeV for n = 3 (6)





Effective operator : [Bai,Fox and Harnik,JHEP 1012:048(2010)]
massive mediator vector or axial vector



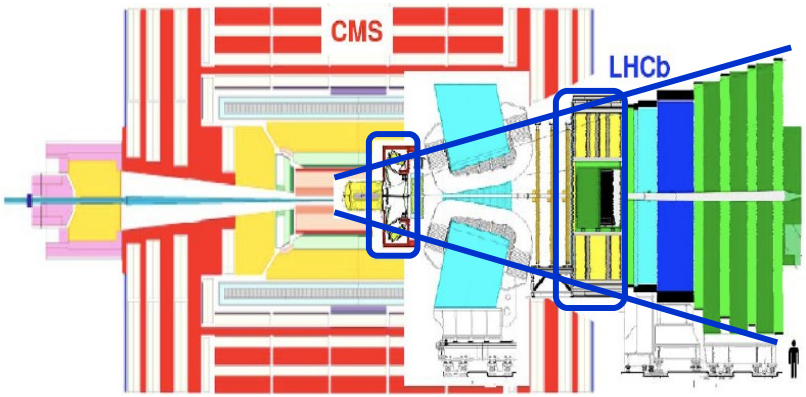


Best limits for low Mass DM, below 3.5 GeV,
A region yet unexplored by direct detection experiments

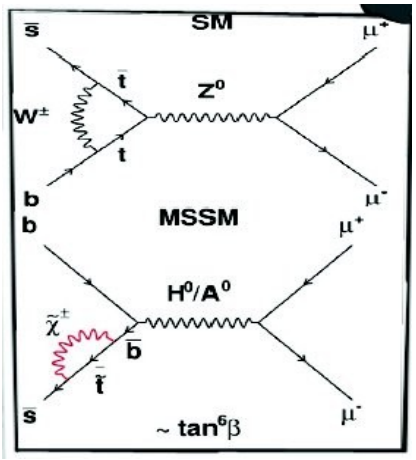
CMS EXO-11-096, CMS EXO-11-059

BSM searches : $B_s \to \mu\mu$

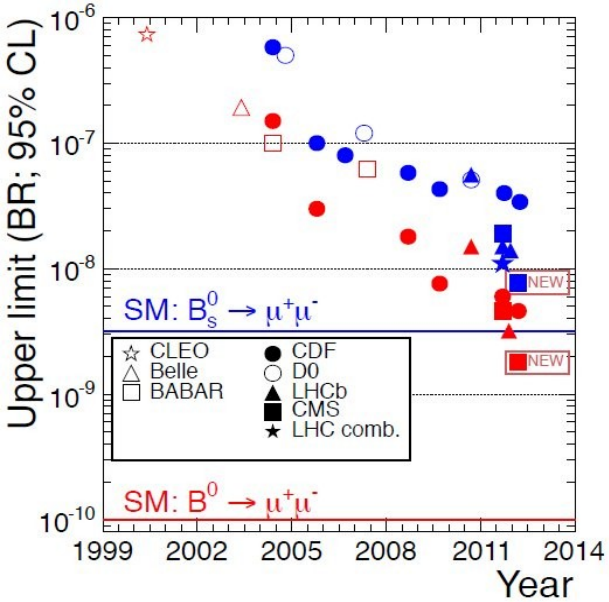
Search for NP in rare decay: $B_s \to \mu\mu$



THIS IS A MONTAGE...



CMS arXiv:1203.3976



SM prediction (FCNC, helicity suppressed):

SM $B(B_s \to \mu\mu) = (3.2 \pm 0.2)\ 10^{-9}$

arXiv:1005.5310
arXiv:1012.1447

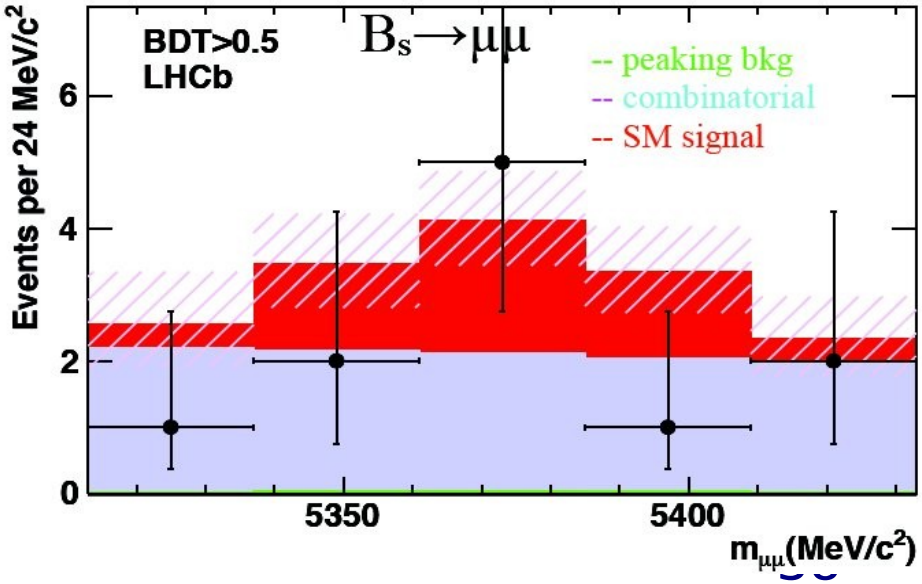
CMS limit ($5\ fb^{-1}$)

$B(B_s \to \mu\mu) < 7.7\ 10^{-9}$ 95 % C.L (CMS)

LHCb : Results with $1\ fb^{-1}$

$B(B_s \to \mu\mu) < 4.5\ 10^{-9}$ at 95% CL

LHCb-PAPER-2012-007



Conclusions

- CMS SM scalar boson search in 11 independent channels

Expected 95% CL exclusion : M_H in (114.5-543) GeV

Observed 95% CL exclusion : M_H in (127.5-600) GeV

Thanks to : (i) great LHC performance in 2011, (ii) precise measurement from CMS detector, (iii) very hard working people

- Observe an small excess around 125 GeV in the unexcluded region

Local significance 2.8 σ, and 2.1 σ (in 110-145 GeV), global significance 0.8 σ

Compatible with both minimal SM scalar signal and bg fluctuation

Some small excess for at 125 GeV also observed in Atlas

Some small broad excess also observed in D0 and CDF

- Search for new physics in many different possible topologies

More exotic final states – more exclusive final states

No evidence of new physics so far

- Need more data :

- 2012 run at 8 TeV :

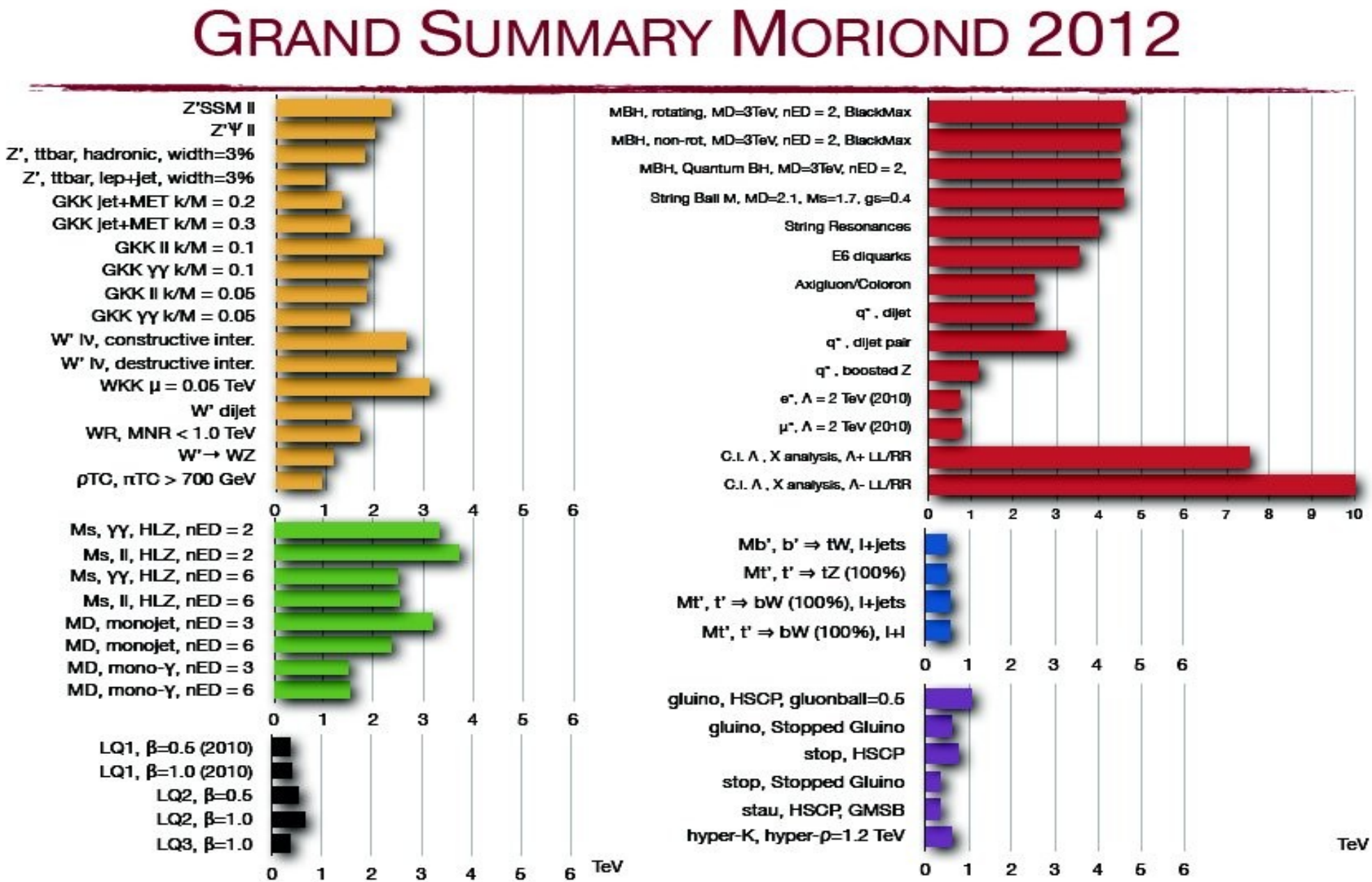
will give a final answer for the minimal SM scalar boson

Continue searching for new physics - more phase space

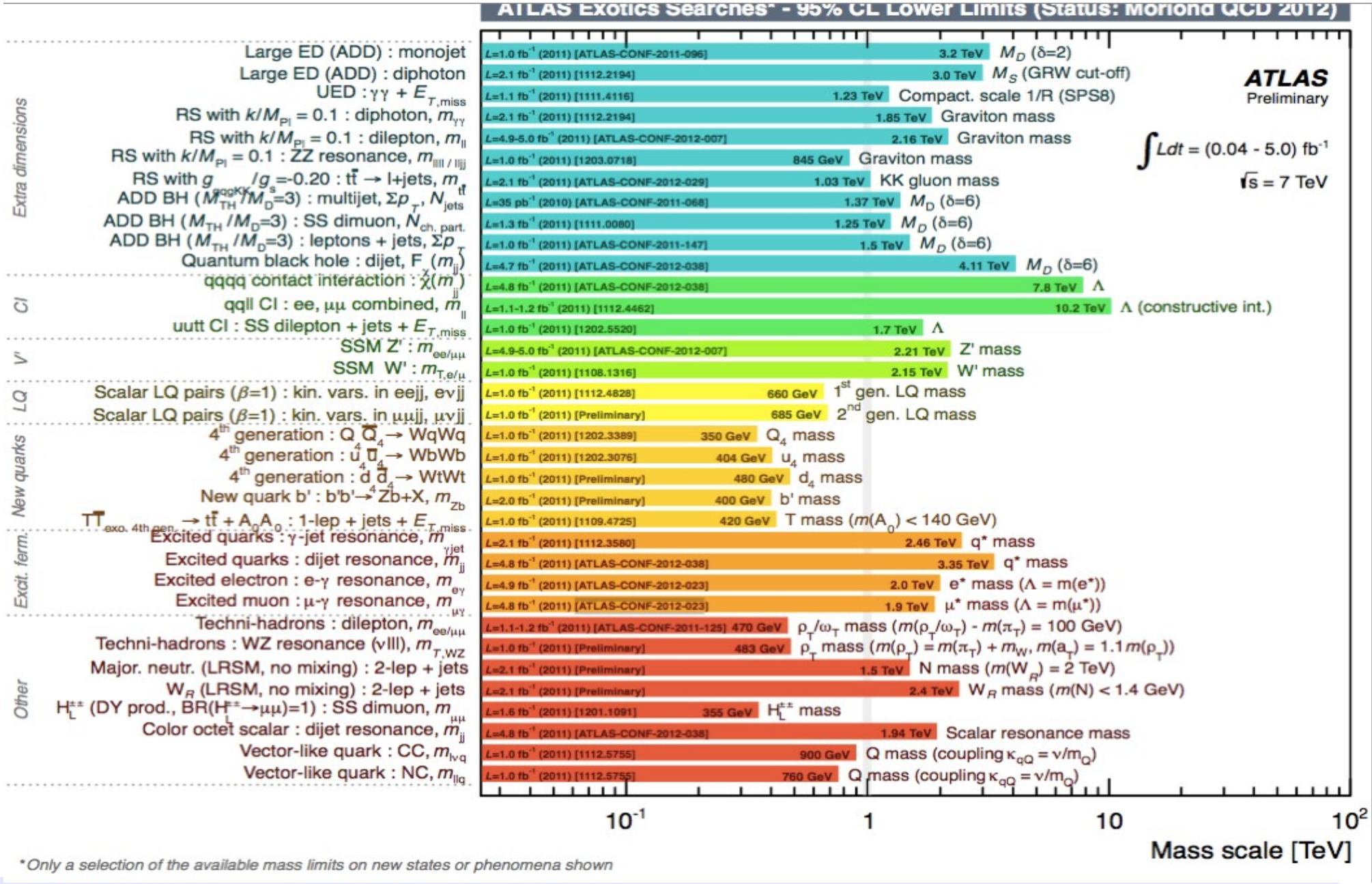
- **LHC Data > 2014 at 14 TeV :** identify/study the properties of any signal hopefully

Back up

CMS exotics searches

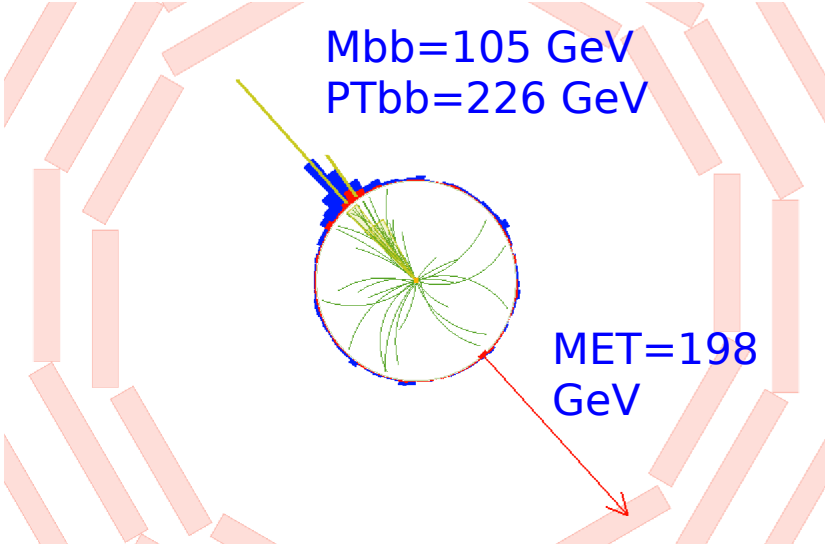


ATLAS exotics searches



Low Mass H→bb channel

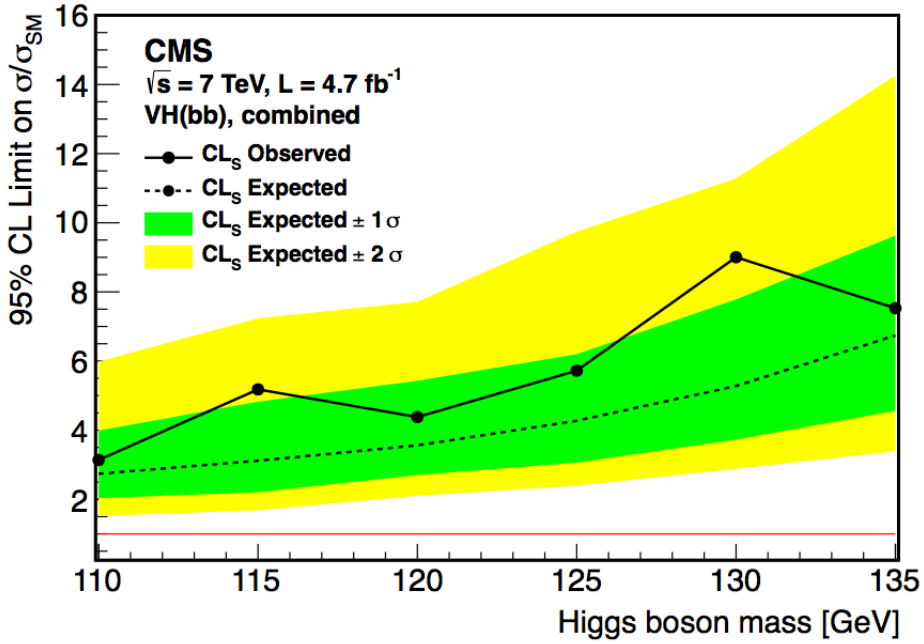
ZH->ννbb candidate



bg too large, needs additional tag
Exploit VH associated production with W and Z decaying leptonically

W->e,μ
Z->ee,μμ, νν

Require boosted bb system
Mass resolution ~10%



Excluded at
95% CL
3-9xSM

arXiv:1202.4083
Submitted to JHEP

High mass : H→ZZ→llνν

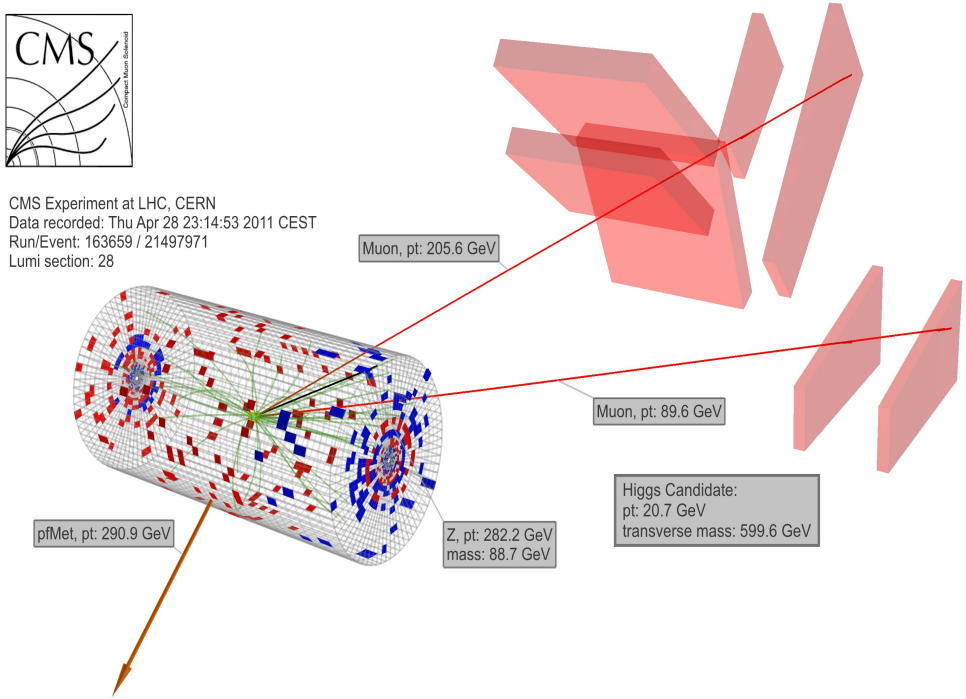
Most sensitive channel for high mass search
- BR 6 times larger than ZZ → 4l

Missing neutrinos implies mass resolution 7%

Only accessible for high mass (MH >~ 250 GeV):
- the two Z bosons are boosted
- large MET due to invisible decay

Main backgrounds
- ZZ (irreducible)
- Z+jets, tt, WZ

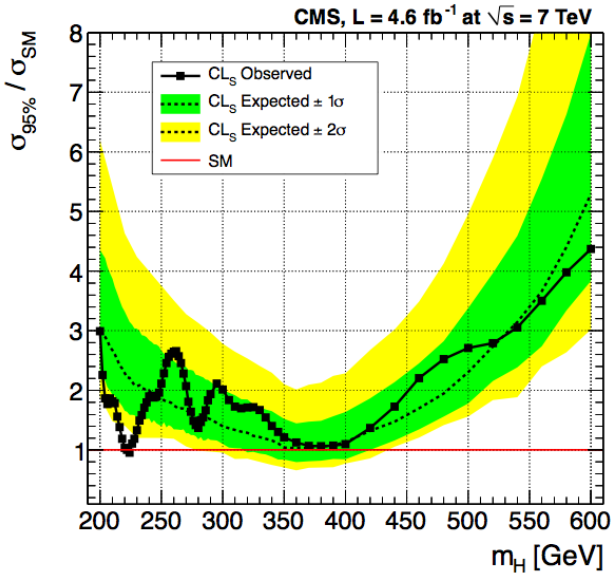
H->ZZ->llνν candidate



High mass : others

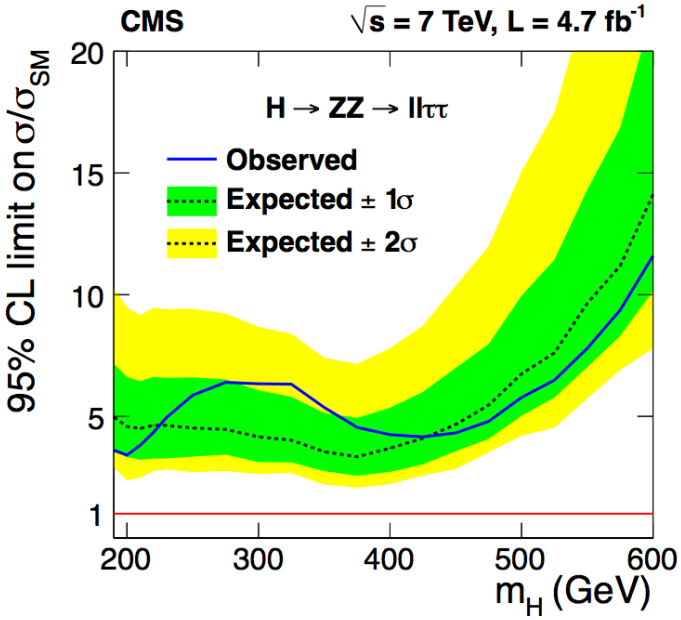
H →ZZ → llqq (high mass)
Sensitivity similar to other ZZ decays

arXiv:1202.1416
Submitted to JHEP



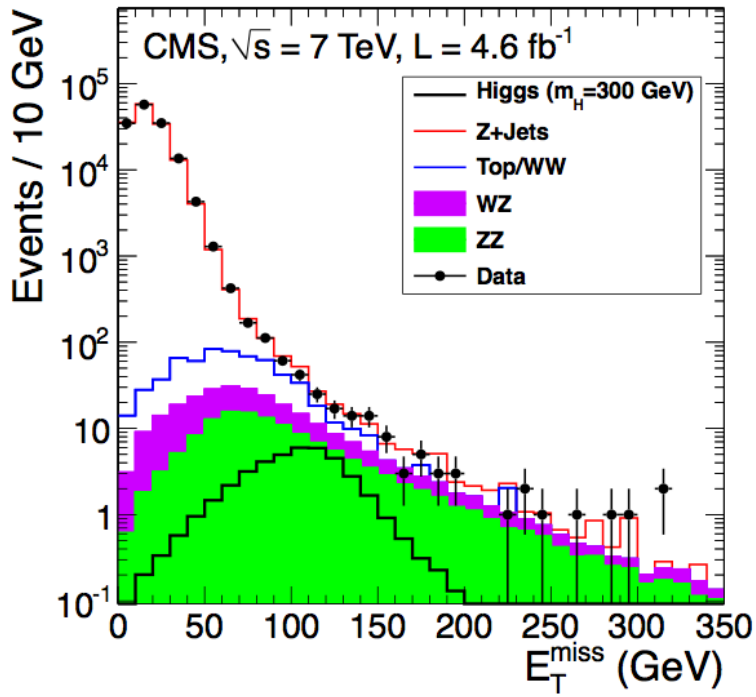
H →ZZ → llττ (high mass)
All τ decay channels searched for
Lower sensitivity (~4xSM)

arXiv:1202.3617
Accepted by JHEP



High mass : H→ZZ→llνν

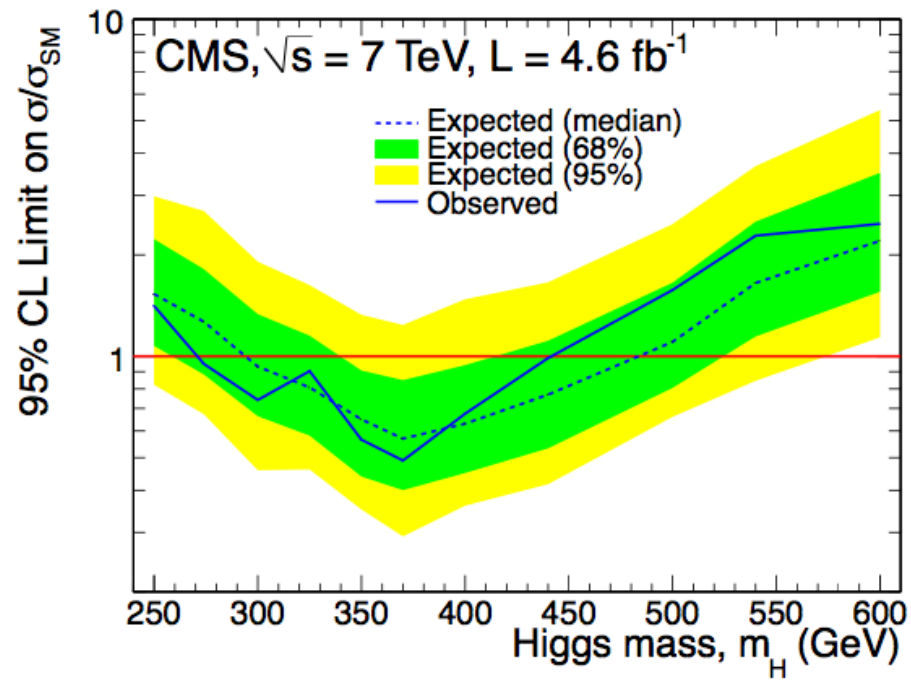
MET after preselection



arXiv:1202.3478
Accepted by JHEP

Two analyses: cut and count and mass shape
Discriminating variable for shape analysis transverse mass:

$$M_T^2 = \left(\sqrt{p_T(\ell\ell)^2 + M(\ell\ell)^2} + \sqrt{E_T^{miss\,2} + M(\ell\ell)^2}\right)^2 - (\vec{p}_T(\ell\ell) + \vec{E}_T^{miss})^2$$



BG estimation :

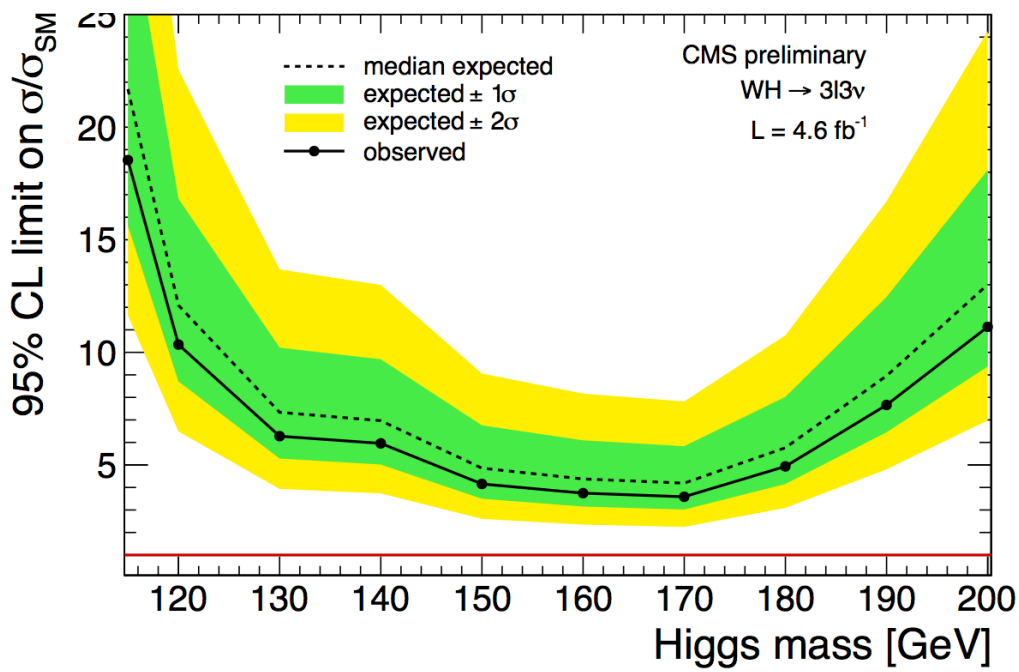
- **Z+jets estimated using γ+jet to model the MET distribution**
- **Non resonant BG normalization from eμ events**
- **ZZ and WZ from MC**

No excess observed in data
Expected 95% exclusion for MH in [290-480] GeV
Observed 95% CL exclusion for MH [270-440] GeV

WH→WWW→3l3ν

Similar to WW analysis
Cut and count analysis with mass independent selection
Main backgrounds estimated from data

stage	WH (120) $H \to \tau\tau$	WH (120) $H \to WW$	data	all bkg.	WZ $\to 3\ell\nu$	ZZ $\to 4\ell$	top + Z/γ^*
3-lepton preselection	2.1 ± 0.0	3.5 ± 0.1	950	968.3 ± 11.9	482.9 ± 1.8	78.4 ± 0.9	348.0 ± 9.7
min-MET > 40 GeV	1.0 ± 0.0	1.8 ± 0.1	244	270.5 ± 4.4	208.2 ± 1.1	7.9 ± 0.3	54.5 ± 4.3
Z removal	0.4 ± 0.0	1.0 ± 0.1	40	47.9 ± 3.1	15.9 ± 0.4	0.7 ± 0.1	31.3 ± 3.1
top veto	0.1 ± 0.0	0.6 ± 0.1	12	14.2 ± 1.3	8.8 ± 0.4	0.4 ± 0.1	4.9 ± 1.3
$\Delta R_{\ell^+\ell^-}$ & $m_{\ell\ell}$	0.1 ± 0.0	0.5 ± 0.1	7	8.4 ± 0.9	5.7 ± 0.2	0.3 ± 0.1	2.6 ± 0.9



NEW

CMS document
HIG-11-034

CMS Detector