Exotic Higgs Searches in CMS

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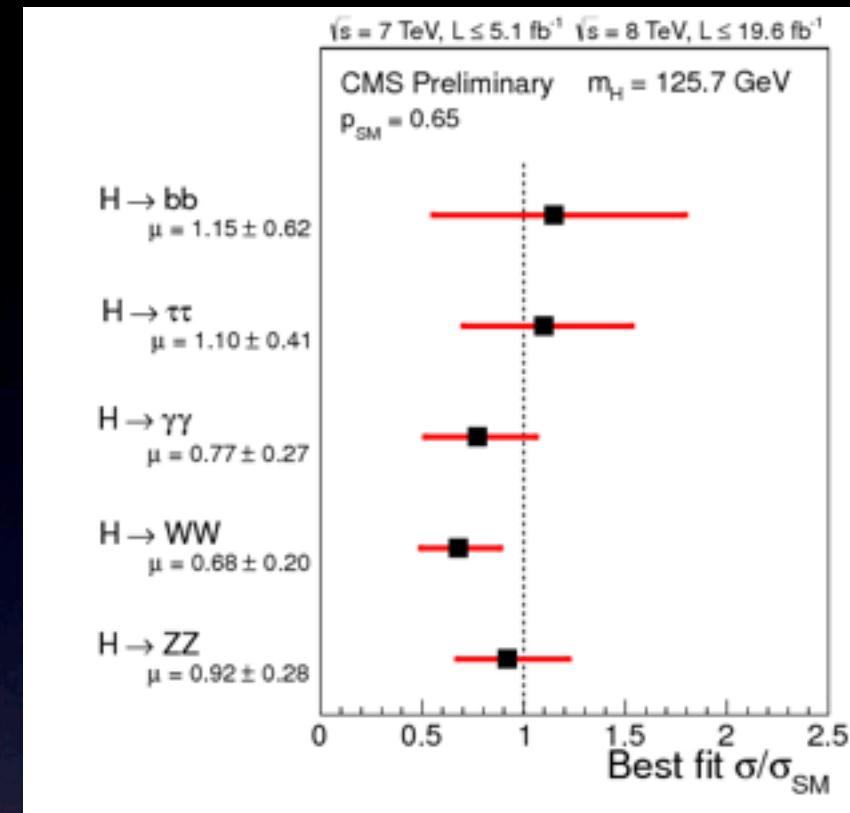
Outline

- Introduction:
  - ✓ Overview of the newly discovered boson
- BSM Higgs models:
  - ✓ Introduction to Minimal Supersymmetric Standard Model (MSSM)
  - ✓ MSSM searches in CMS
  - ✓ Introduction to Next-to-Minimal Supersymmetric Standard Model
  - ✓ NMSSM searches in CMS
  - ✓ Double Charged Higgs searches in CMS
- Summary and Perspectives

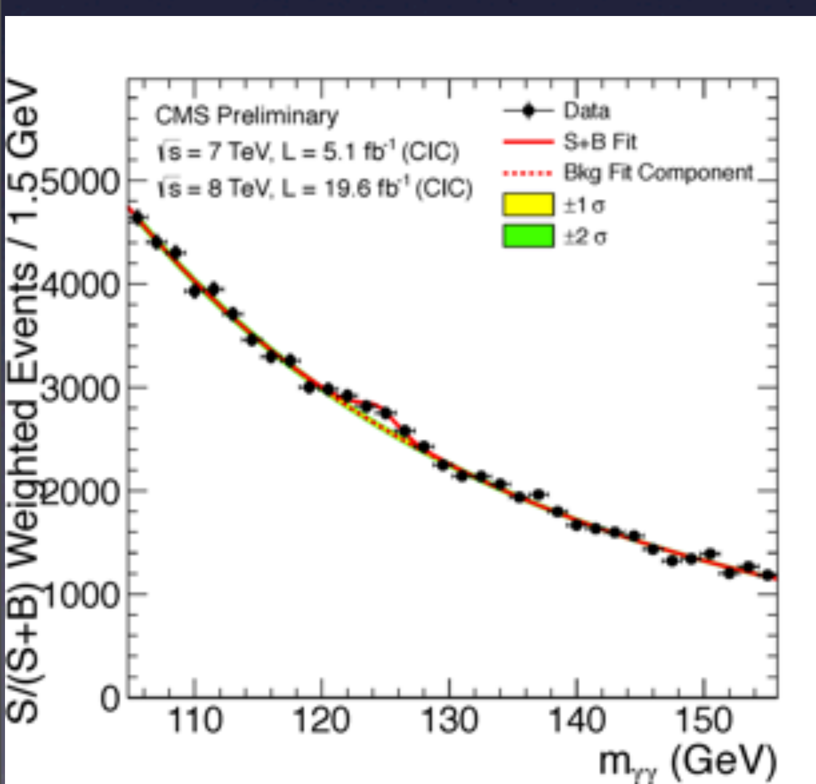
The discovery of a new boson

✓ In 2012 CMS and ATLAS experiments reported the discovery of a new boson with a mass of ~126 GeV

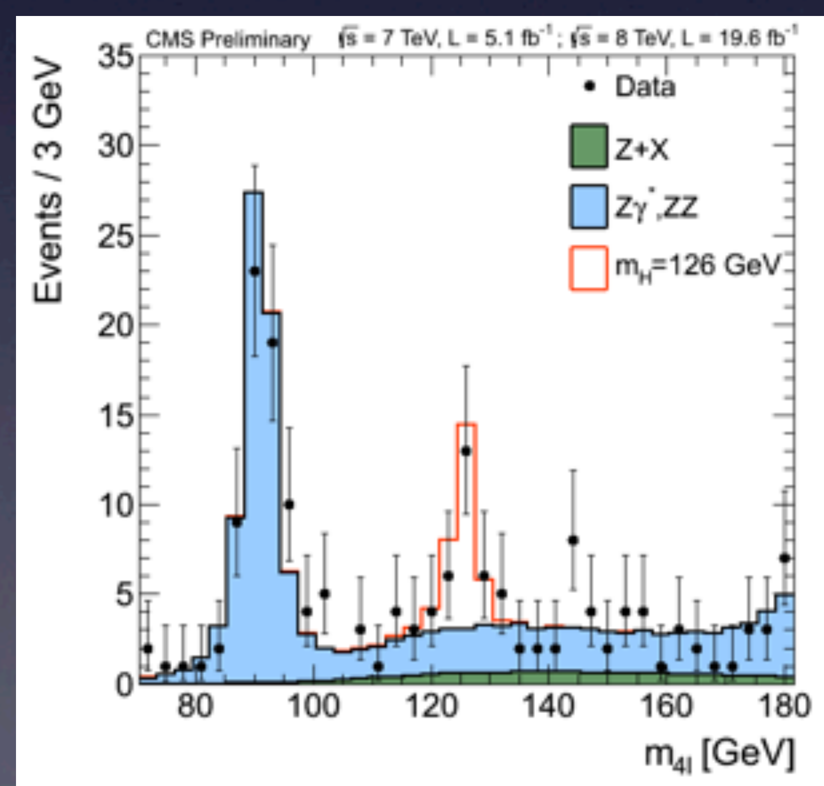
✓ The measured properties indicate a consistency with the predicted SM Higgs Boson



$H \rightarrow \gamma\gamma$



$H \rightarrow ZZ$

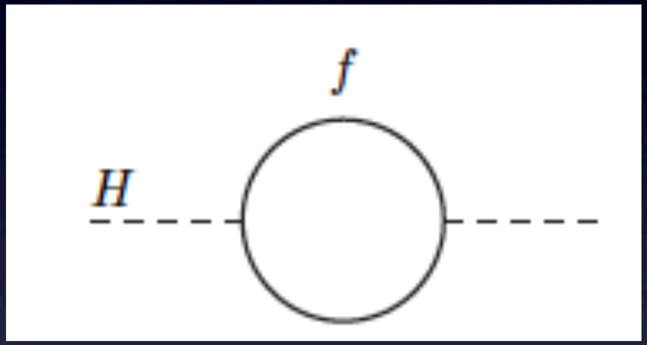


- What is next?
  - Precision particle measurements with more data (2015 and beyond)
  - Understand if this particle correspond to the SM prediction or an extended theory (MSSM,NMSSM,2HDM,etc.....)

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG

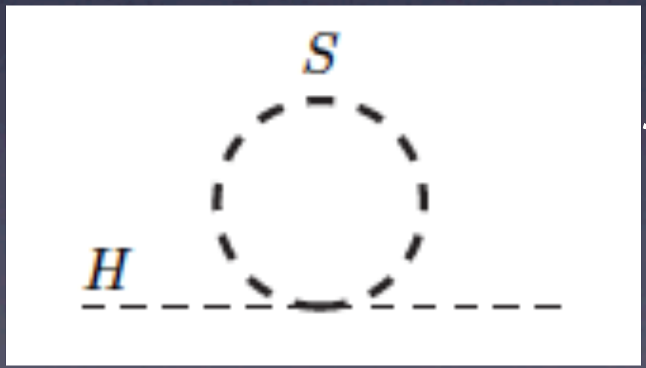
Minimal Supersymmetric Standard Model (MSSM)

- So far SM describing successfully known phenomena
- The experimental frontier has advance into the TeV scale
- SM has to be modified in order to describe phenomena between the Electroweak and the Planck Scale



Quantum correction due to Dirac Fermion

$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}\Lambda_{UV}^2 + \ldots \quad (1)$$



Quantum correction due to Scalar S

$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}\left[\Lambda_{UV}^2 - 2m_S^2 \ln(\Lambda_{UV}/m_S) + \ldots\right] \quad (2)$$

Unstable quantum corrections to Higgs mass

The electrically neutral part of the SM Higgs

$$V = m_H^2|H|^2 + \lambda|H|^4$$

Heavy particles may interact with the Higgs field, leading to corrections on the squared Higgs mass

$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}\Lambda_{UV}^2 + \ldots.$$

Λ_{UV} scale at which new physics alter the high energy behavior

Minimal Supersymmetric Standard Model (MSSM)

- If Λ_{UV} is of order M_P, quantum correction is 30 order magnitude larger than the required $m_H^2 \sim (100GeV)^2$

- By renormalization and fine tuning those large corrections are controlled but it would be desirable that the solution comes in a natural way

- Looking into (1) and (2) is clear that by introducing a new symmetry relating fermions and bosons the large quantum corrections are canceled, such symmetry is the so-called Supersymmetry (SUSY)

- A supersymmetry transformation turns a bosonic state into a fermionic state and viceversa

Minimal Supersymmetric Standard Model (MSSM)

Field Content of the MSSM					
Super-Multiplets	Boson Fields	Fermionic Partners	SU(3)	SU(2)	U(1)
gluon/gluino	g	$\widetilde{g}$	8	1	0
gauge/	$W^{\pm}, W^0$	$\widetilde{W}^{\pm}, \widetilde{W}^0$	1	3	0
gaugino	B	$\widetilde{B}$	1	1	0
slepton/	$(\widetilde{\nu}, \widetilde{e}^-)_L$	$(\nu, e^-)_L$	1	2	-1
lepton	$\widetilde{e}^-_R$	e^-_R	1	1	-2
squark/	$(\widetilde{u}_L, \widetilde{d}_L)$	$(u, d)_L$	3	2	$1/3$
quark	$\widetilde{u}_R$	u_R	3	1	$4/3$
	$\widetilde{d}_R$	d_R	3	1	$-2/3$
Higgs/	(H^0_d, H^-_d)	$(\widetilde{H}^0_d, \widetilde{H}^-_d)$	1	2	-1
higgsino	(H^+_u, H^0_u)	$(\widetilde{H}^+_u, \widetilde{H}^0_u)$	1	2	1

Phenomenology of the MSSM Higgs sector can be effectively described using only two parameters

m_A mass of the CP odd Higgs boson

$\tan_\beta$ ratio of the vacuum expectation values of the two Higgs doublets

Five physical states: h^0, H^0, A^0, $H^{+/-}$
Three neutral Higgs bosons ϕ

- For large tan(beta) the Higgs boson decays to tau and b-quarks play a more important role than in the SM

Experimental searches in CMS
MSSM (Neutral Higgs Boson ϕ)

- $\phi \to bb$ (Br=90%)
- $\phi \to \tau\tau$ (Br=10%)
- $\phi \to \mu^+\mu^-$ (Br=10%)

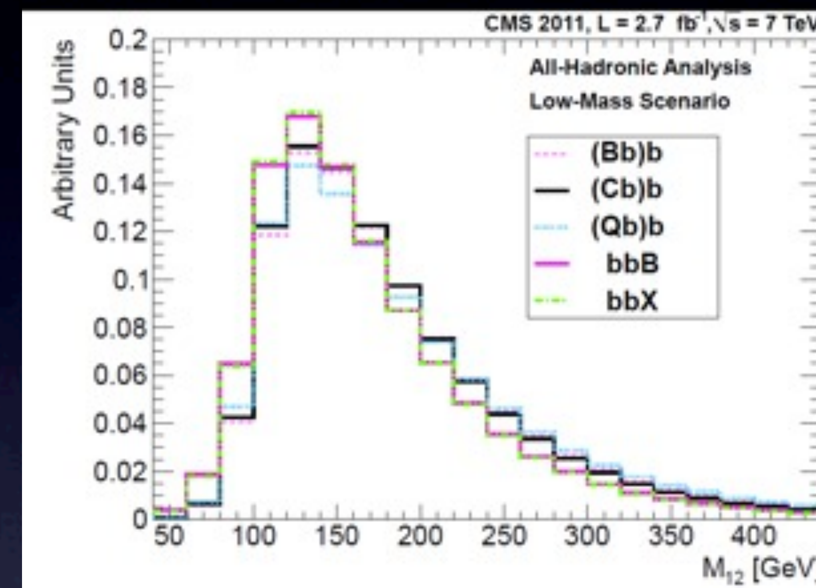
ϕ->bb

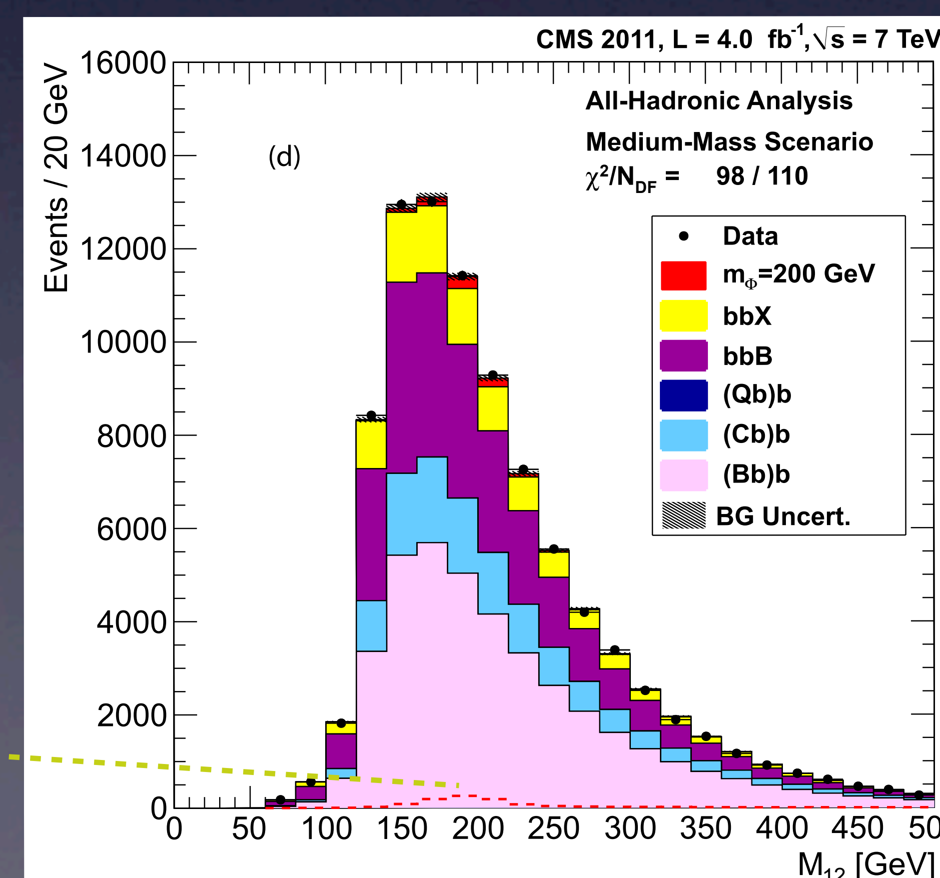
http://arxiv.org/pdf/1302.2892.pdf

- Search for a Higgs boson decaying into b-quark pair and produced in association with at least one b-quark
- All hadronic signature
  - 3 leading b-tagged jets
  - Dominant background comes from QCD multi-jet production
- Semi-leptonic signature
  - Events with 3 leading b-jets
  - One muon from semi-leptonic b-decay
  - Dominant background QCD multi-jet events
  - Other background such as tt+jets, Z->bb+jets are predicted by MC to be less than 1%

QCD estimation from data

A pure QCD sample selecting events with only 2 b-tag jets, 5 bkg templates

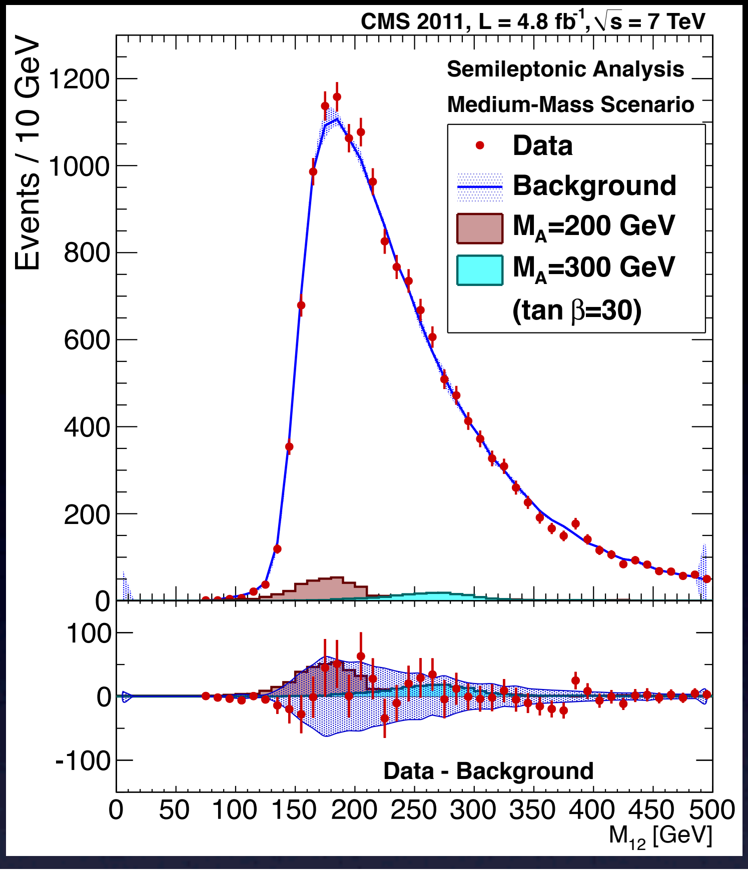




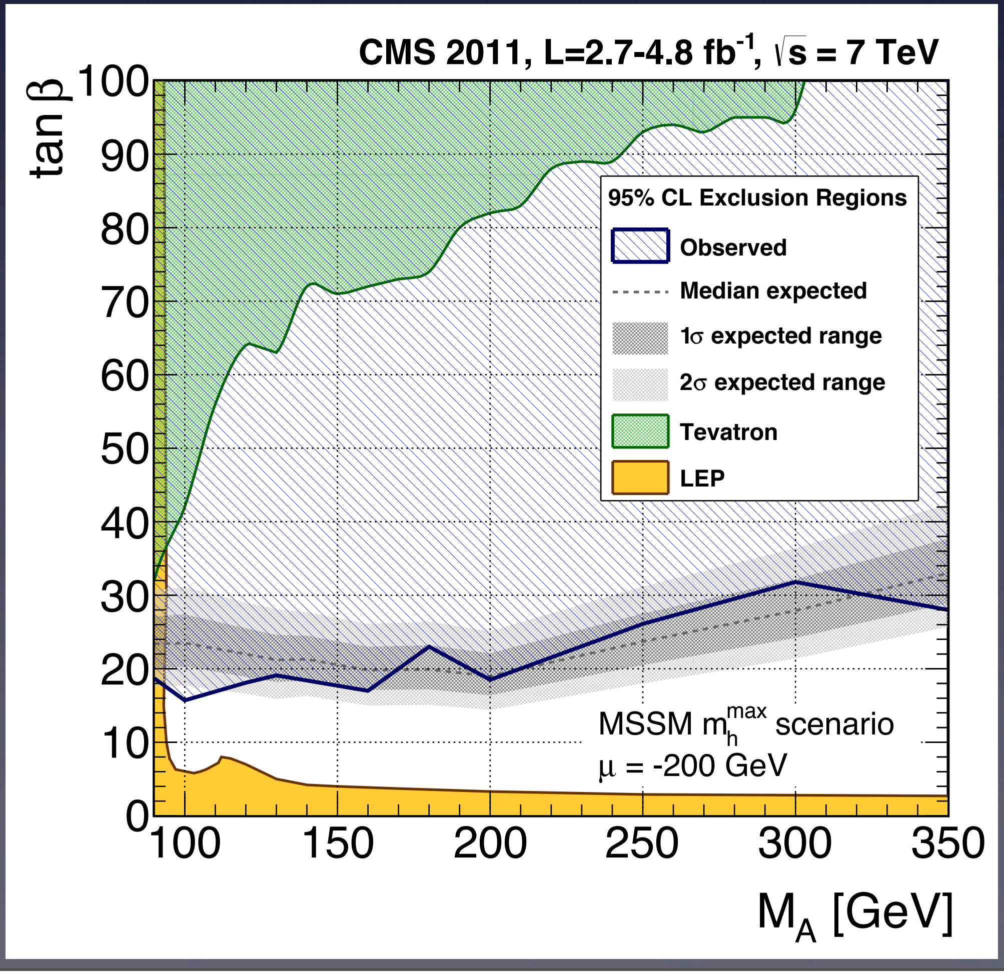
Both analysis search for an excess of events in the invariant mass of the two leading jets

ϕ->bb

http://arxiv.org/pdf/1302.2892.pdf



- Clean signature by requiring a muon from semi-leptonic b-decay
- Possibility of lowering thresholds at the cost of loosing some signal acceptance



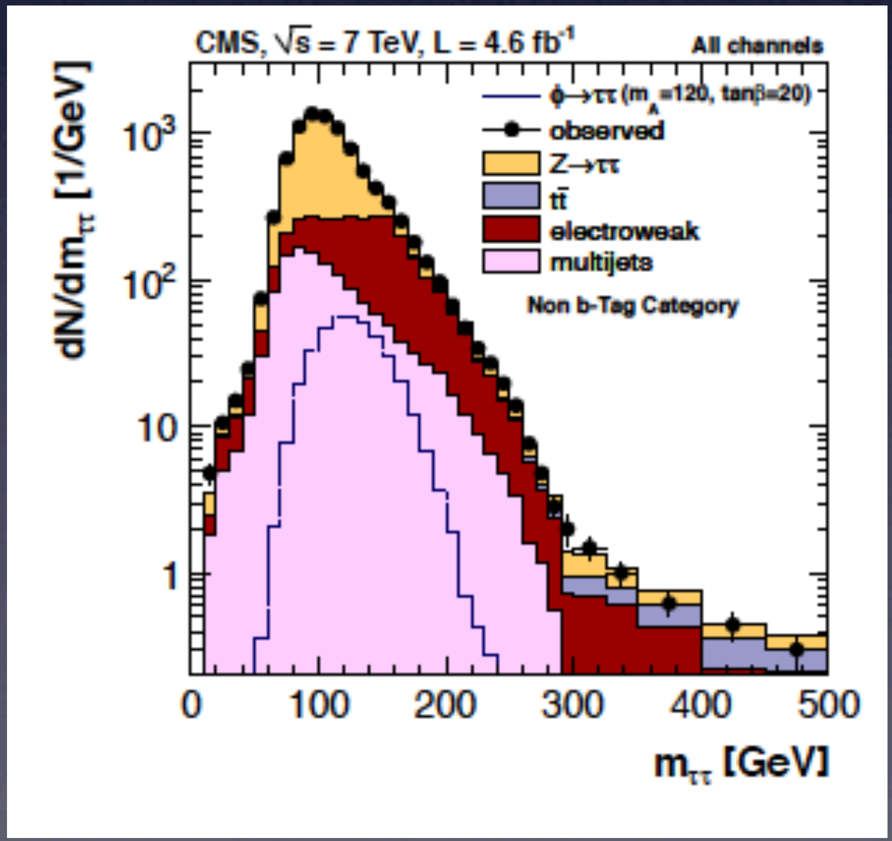
- No visible excess of events is observed neither in all-hadronic or semi-leptonic channels
- 95% CL limits are set on tan(β) as a function of M_A for the combined all-hadronic and semi-leptonic analysis
- Results are compared with previous limits from LEP and Tevatron experiments

ϕ->$\tau\tau$

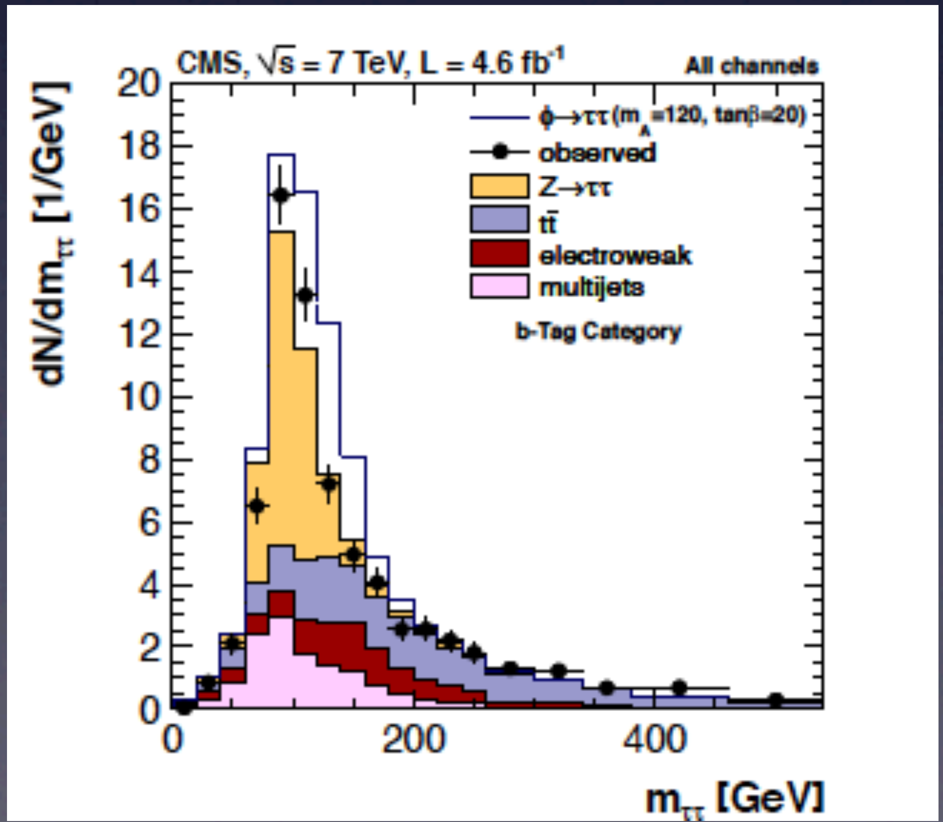
http://arxiv.org/pdf/1202.4083v1.pdf

- Three independent tau pair final states $e\tau_h, \mu\tau_h, e\mu$
- For each of the lepton candidates isolation is required
- To enhance sensitivity the events were divided into several categories based on jet multiplicity and b-jet content
- Analysis sensitive to both SM and MSSM searches

Non b-tagged



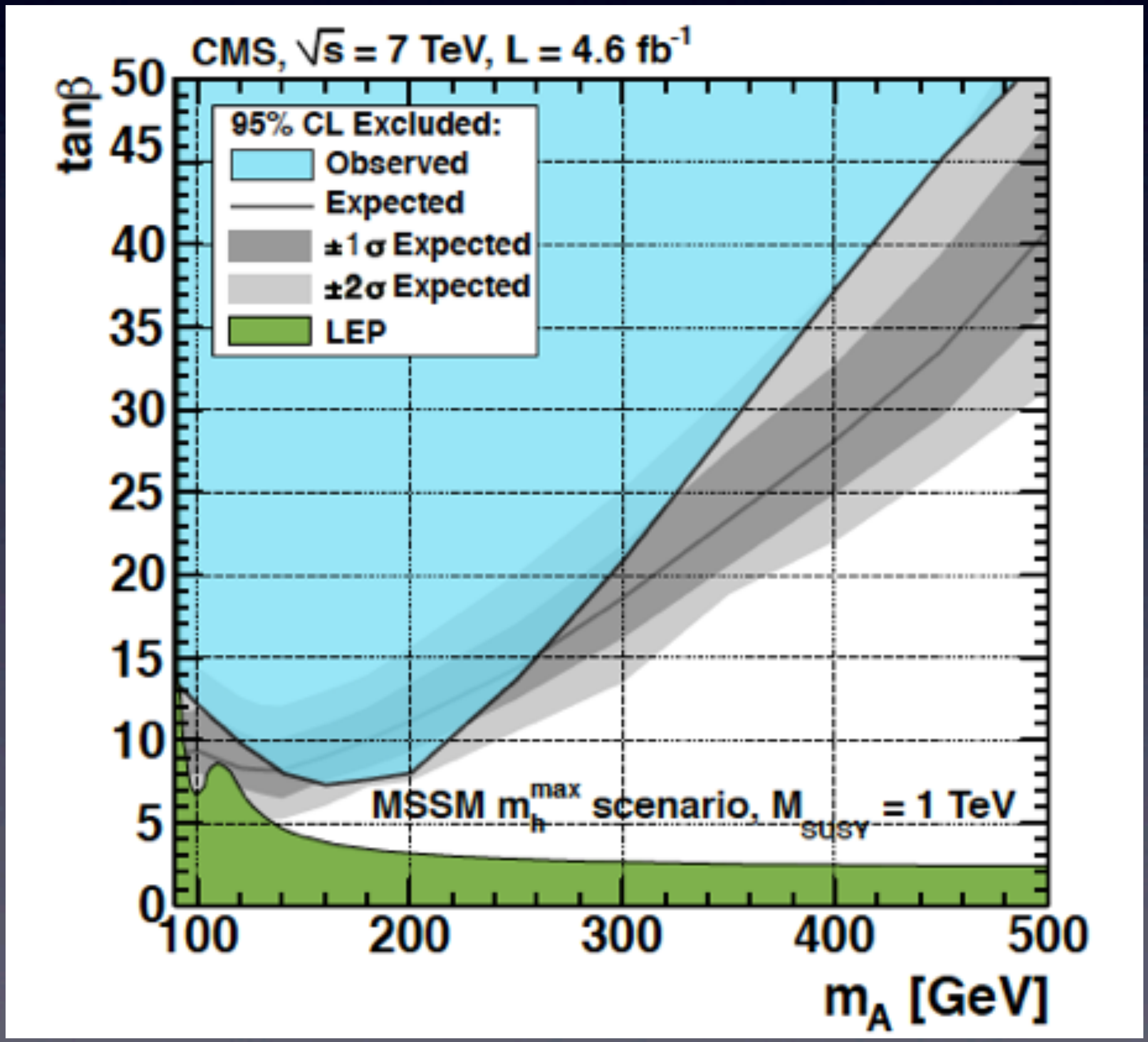
b-tagged



$\phi \to \tau\tau$

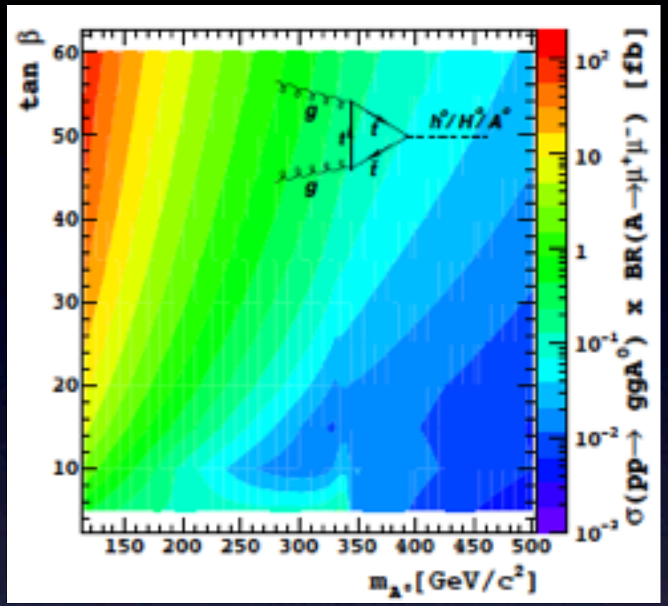
http://arxiv.org/pdf/1202.4083v1.pdf

- No visible excess of events, limits are set in the m_A,tan (β) plane
- Results are compared with previous limits from LEP

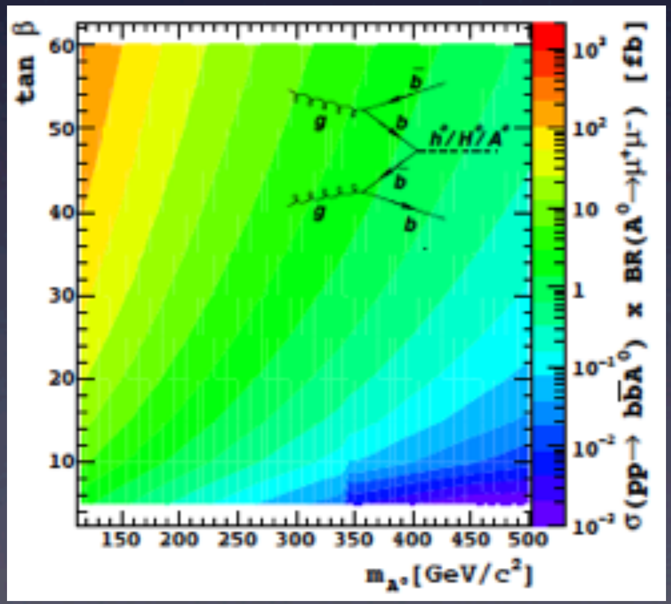


$\phi \to \mu^+\mu^-$

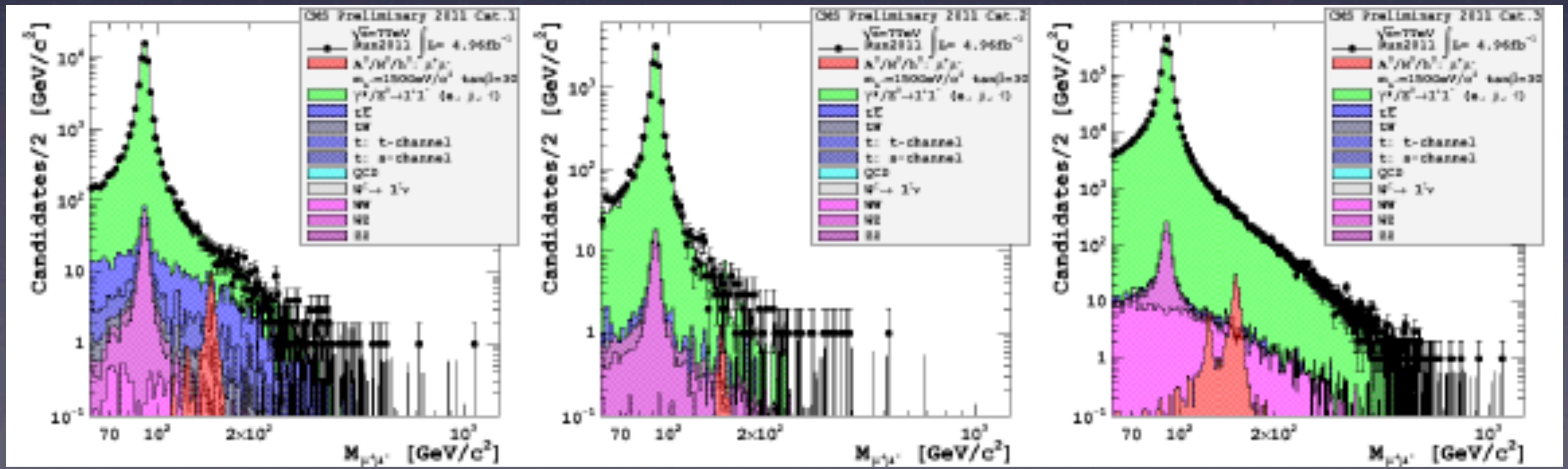
- Search for the Neutral MSSM Higgs Boson in the $\mu^+ \mu^-$ final state
- Sensitive search for SUSY higgs boson production in association with bbbar and via gluon-gluon fusion processes



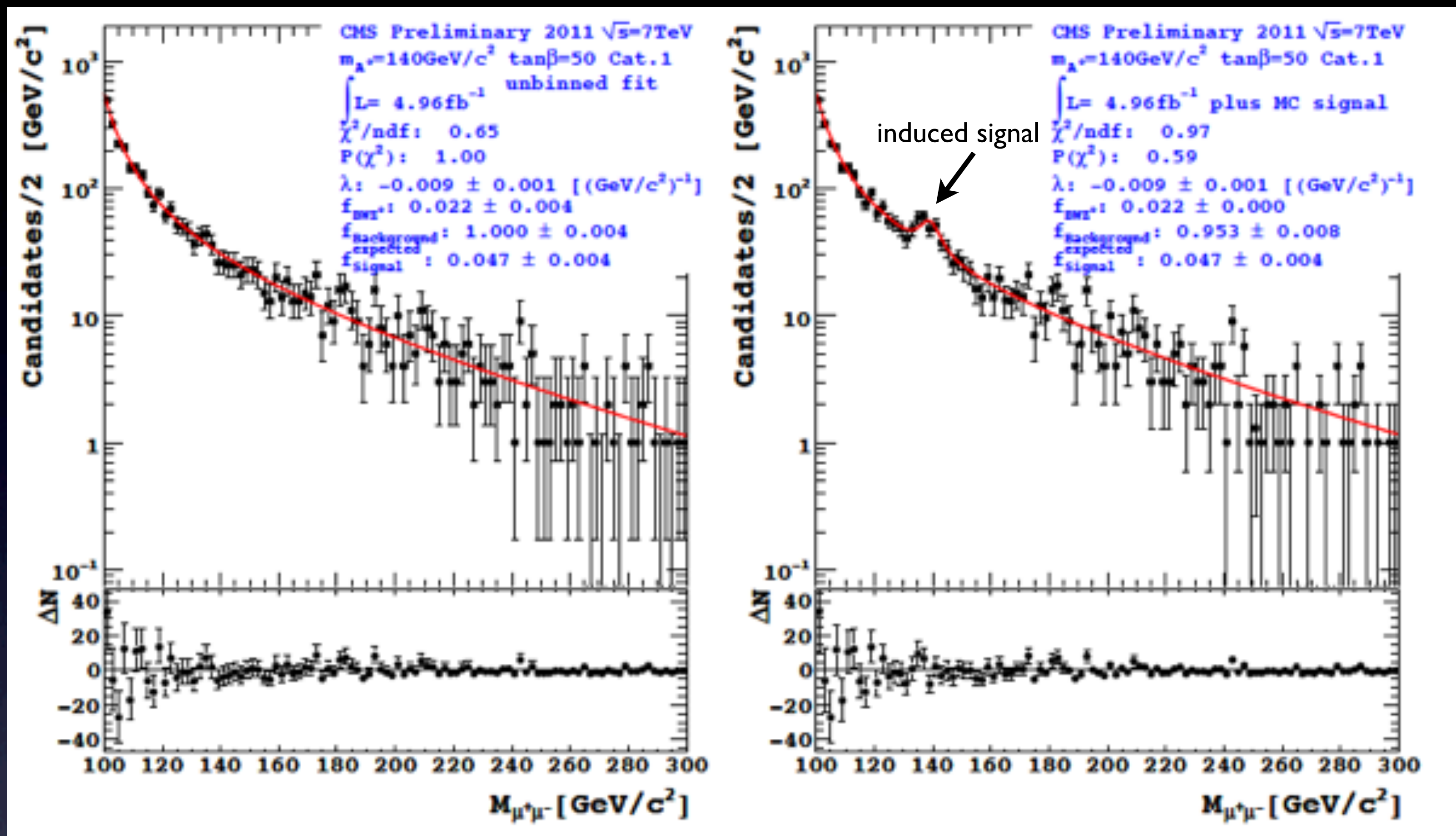
- Three non overlaping categories:
  - categ1: at least one b-tagged jet
  - categ2: No b-jet but additional third muon as a signature of semileptonic b-decay
  - categ3: Events that do not belong to first two categories



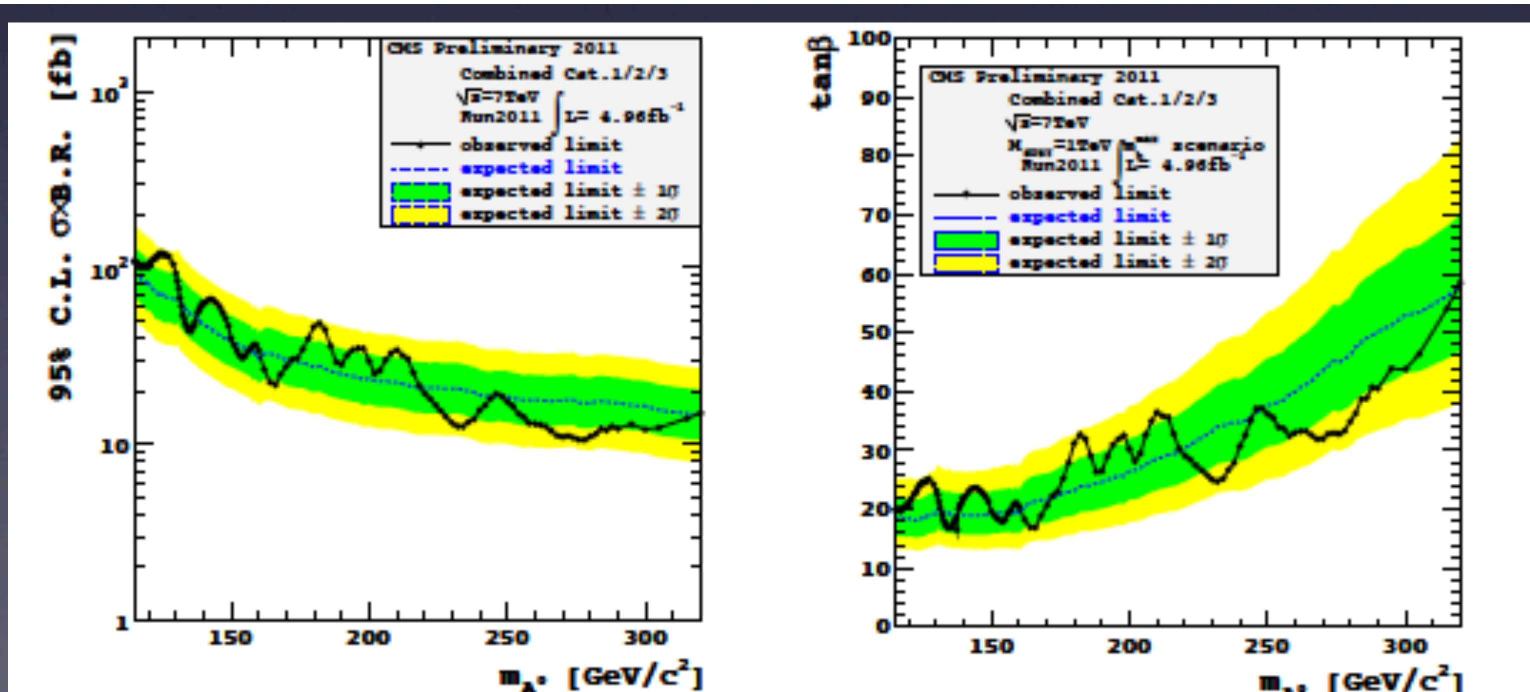
- Main background is due to Drell-Yan process
- Other less important source of backgrounds are: ttbar, $W^{+/-}W^{+/-}$



ϕ->$\mu^+\mu^-$



- Data driven approach for limit setting
- background contribution determined from a fit to data
- Signal shape for various m_A and tan(β) determined by a fit to the invariant mass distribution of the simulated signal events



- Excluded Regions Above the curves

Next-to-Minimal Supersymmetric Standard Model (NMSSM)

- Some reasons to take into account NMSSM
  - Naturally solves in an elegant way the so-called μ problem
  - Reduce the fine tuning in MSSM theory
  - Higgs sector is highly restricted in MSSM (lightest Higgs is always SM like). An extended Higgs sector may relax this restriction and lower experimental bounds (In NMSSM the lightest Higgs boson can be as light as 1 GeV)

3 CP even Higgs Bosons
2 CP odd Higgs Bosons
2 charged Higgs Bosons

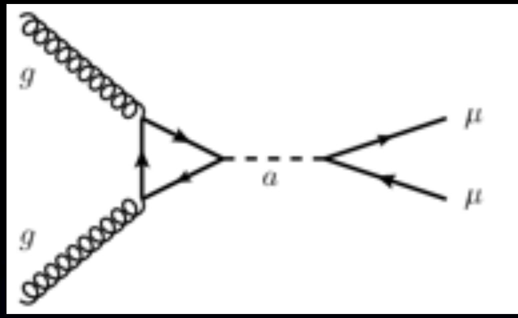
chiral supermultiplets		spin-0	spin-1/2	$SU_C(3)$	$SU_L(2)$	$U_Y(1)$
quark–squark	$\hat{Q}$	$\tilde{Q} = (\tilde{u}_L,\, \tilde{d}_L)^T$	$Q = (u_L,\, d_L)^T$	3	2	1/6
	$\hat{u}$	$\tilde{u}_R^*$	$u_R^\dagger$	3	1	−2/3
	$\hat{d}$	$\tilde{d}_R^*$	$d_R^\dagger$	3	1	1/3
lepton–slepton	$\hat{L}$	$\tilde{L} = (\tilde{\nu}_e,\, \tilde{e}_L)^T$	$L = (\nu_e,\, e_L)^T$	1	2	−1/2
	$\hat{e}$	$\tilde{e}_R^*$	$e_R^\dagger$	1	1	1
Higgs–Higgsino	$\hat{H}_u$	$H_u = (H_u^+,\, H_u^0)^T$	$\tilde{H}_u = (\tilde{H}_u^+,\, \tilde{H}_u^0)^T$	1	2	1/2
	$\hat{H}_d$	$H_d = (H_d^0,\, H_d^-)^T$	$\tilde{H}_d = (\tilde{H}_d^0,\, \tilde{H}_d^-)^T$	1	2	−1/2
	$\hat{S}$	S	$\tilde{S}$	1	1	0
gauge supermultiplets		**spin-1/2**	**spin-1**	**$SU_C(3)$**	**$SU_L(2)$**	**$U_Y(1)$**
gluon–gluino		$\tilde{g}$	g	8	1	0
W-boson–wino		$\tilde{W}^\pm, \tilde{W}^0$	$W^\pm, W^0$	1	3	0
B-boson–bino		$\tilde{B}^0$	B^0	1	1	0

Experimental searches in CMS

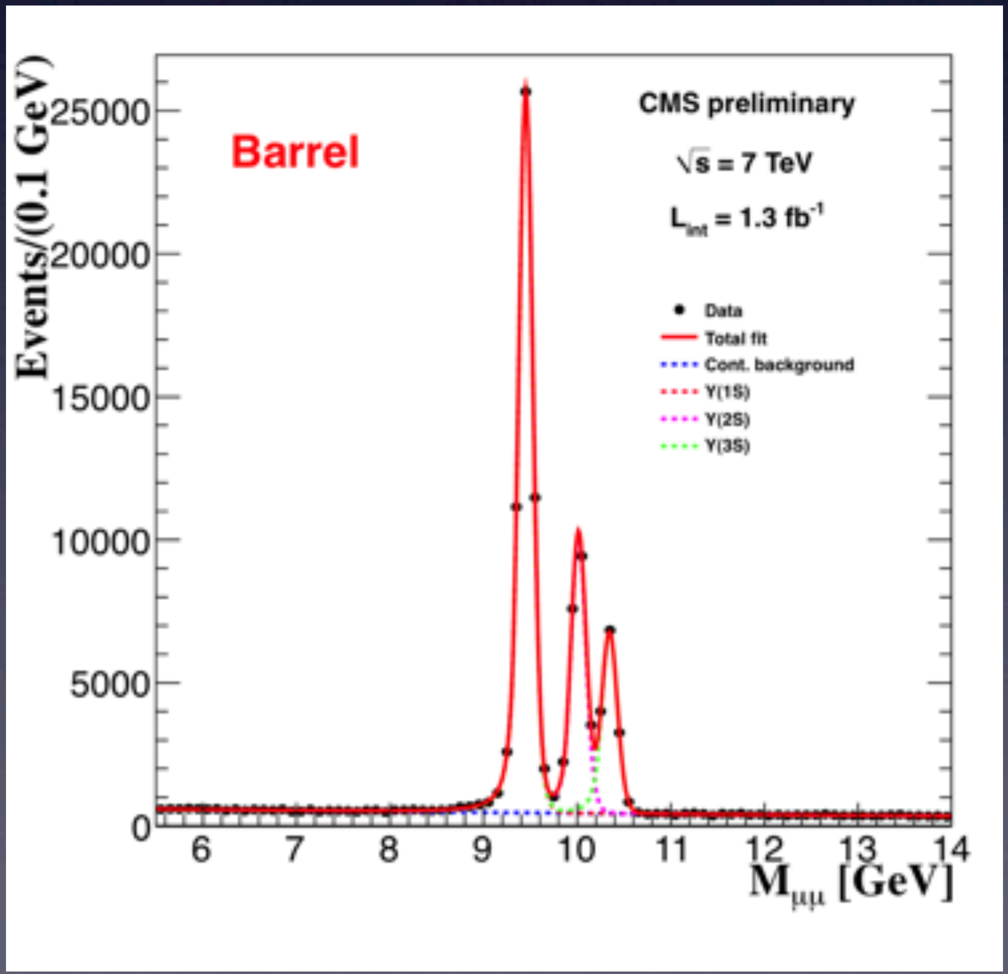
NMSSM
$$a \to \mu^+\mu^-$$
$$h \to 2a \to 4\mu$$

$a \to \mu^+\mu^-$

http://arxiv.org/pdf/1206.6326.pdf



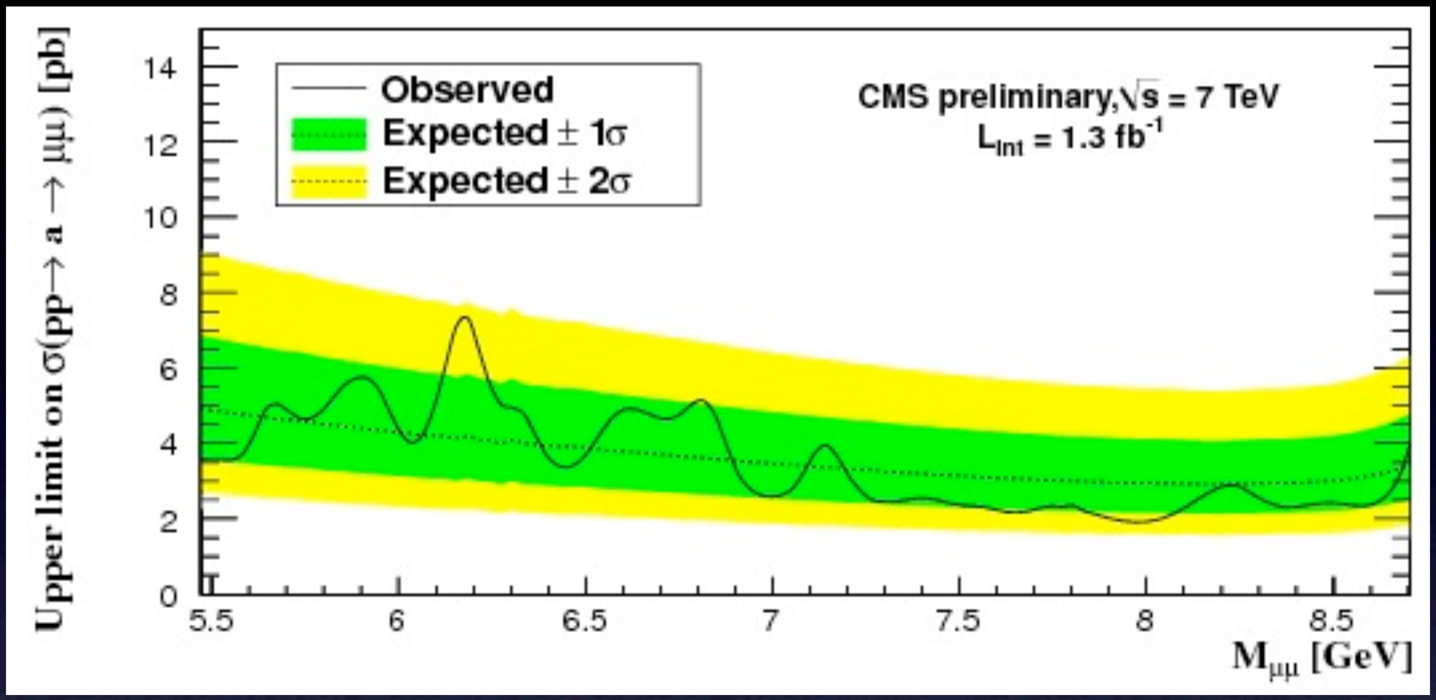
- Search for light pseudo-scalar Higgs boson a
- a is a superposition of the MSSM doublet pseudo-scalar and the additional single pseudo-scalar of the NMSSM
- Large cross section for gg->a->$\mu^+\mu^-$ event though B(a->$\mu^+\mu^-$) is small

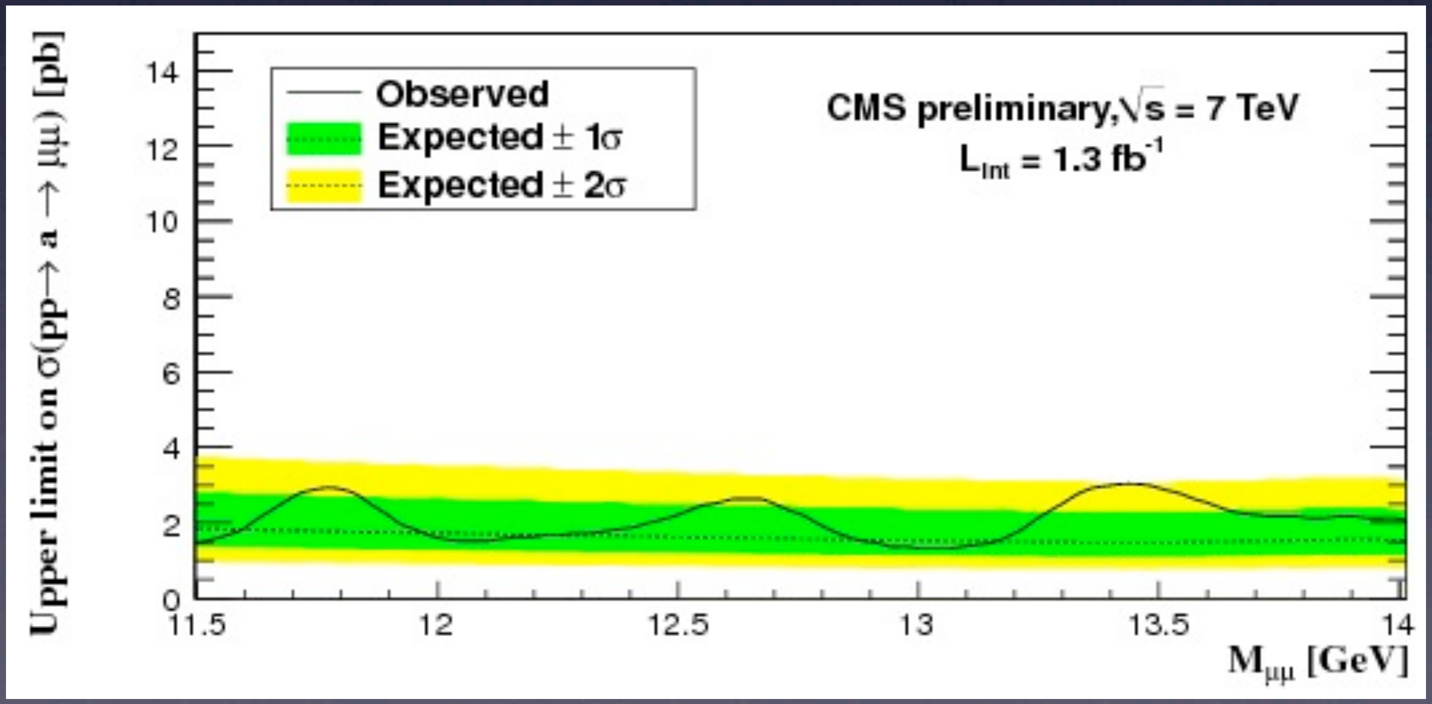


- Main background from QCD processes
- Background shape extracted from DATA and use of simulation as a cross check
- Search exclusively between 5.5 and 8.8 GeV and between 11.5 and 14 GeV, to avoid the range where the abundant contribution of bottonium resonances

$a \to \mu^+ \mu^-$

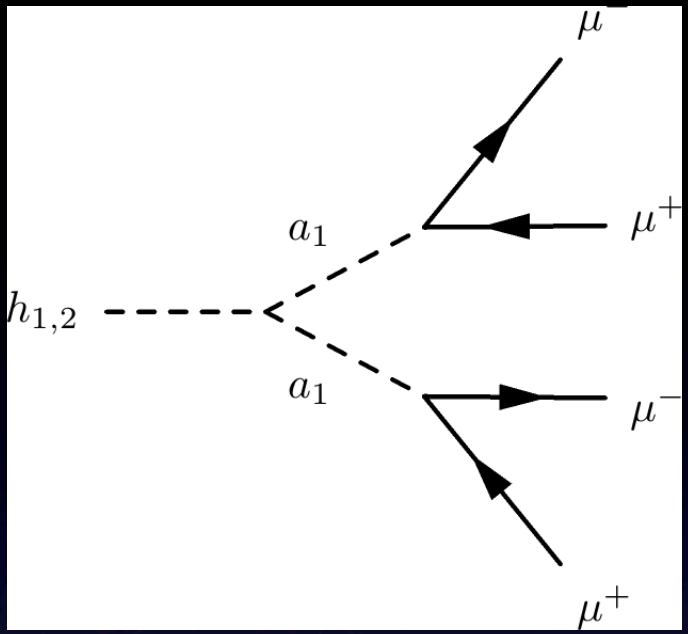
http://arxiv.org/pdf/1206.6326.pdf





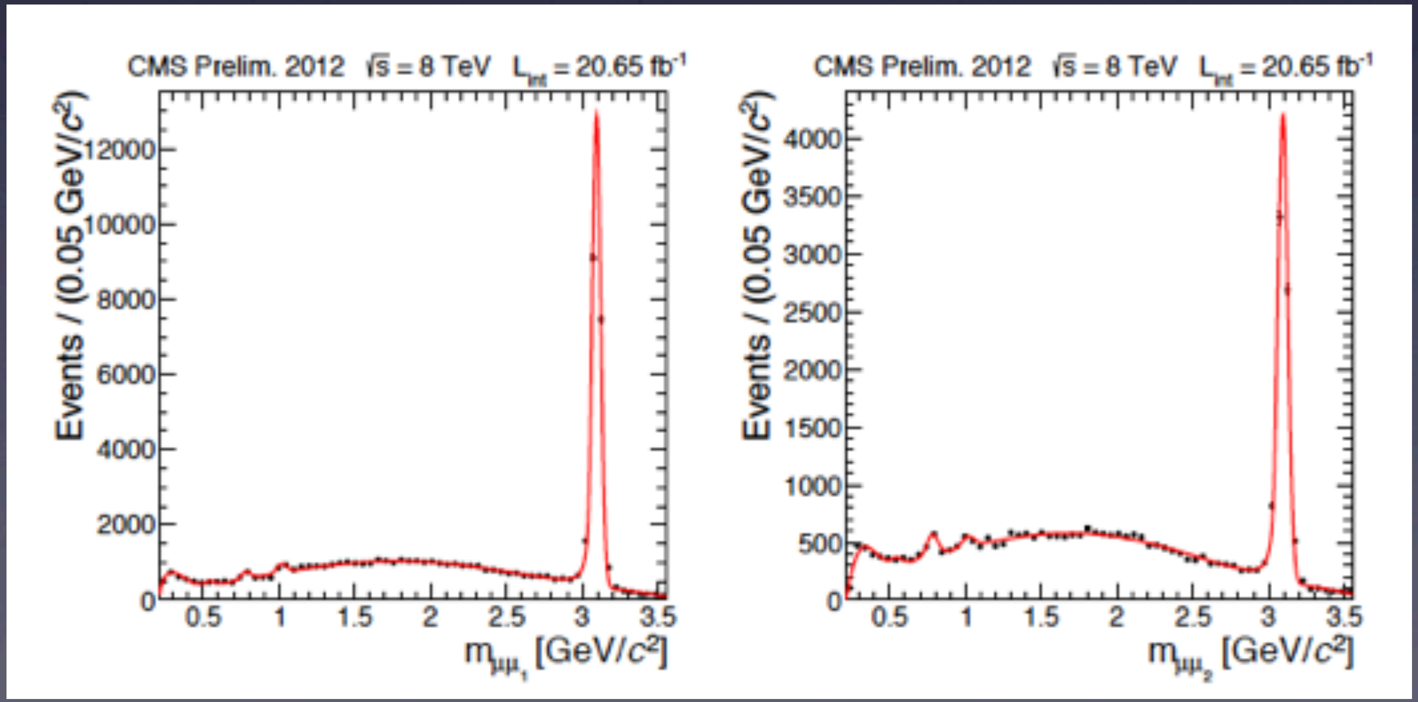
- No visible excess of events
- Limit on cross section times branching ratio as a function of $m_{\mu\mu}$
- The region between 11.5 and 14 GeV not included due to the overwhelming contribution of bottonium processes

$h \to 2a \to 4\mu$



- Non SM Higgs Boson decay to pairs of new light bosons predicted in the context of NMSSM
- Each light boson decays to a pair of muons
- Final topology: pair of di-muons with compatible mass
- Main backgrounds for this search are bbbar and double jpsi production

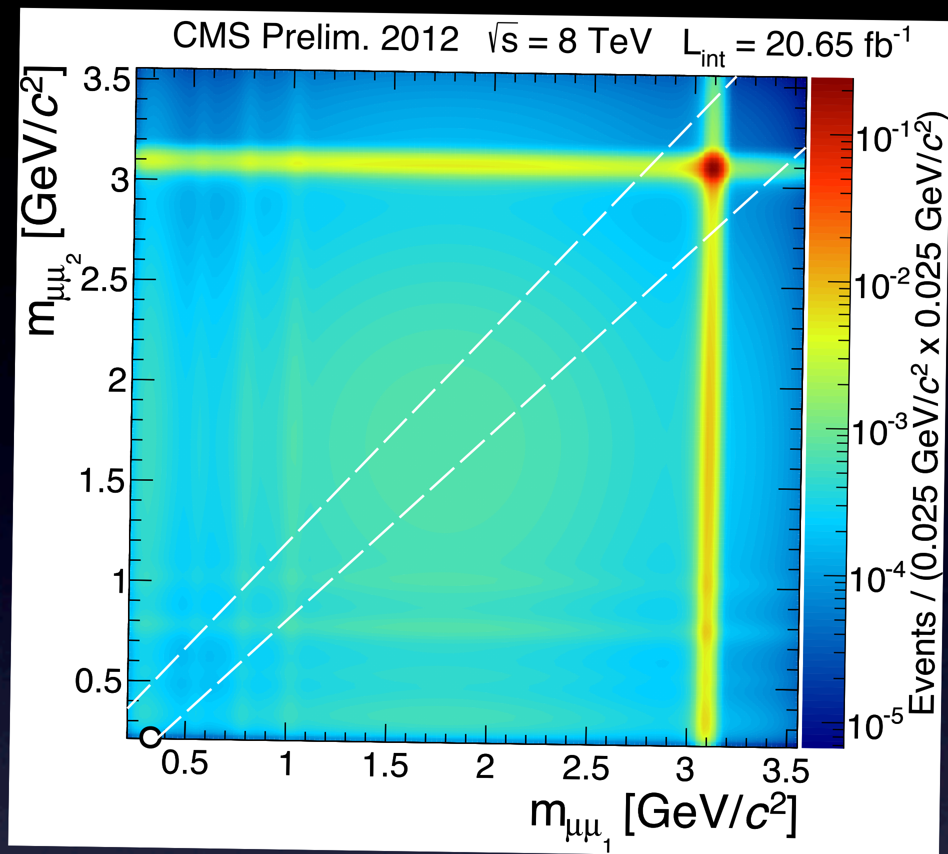
Bkg estimation from data

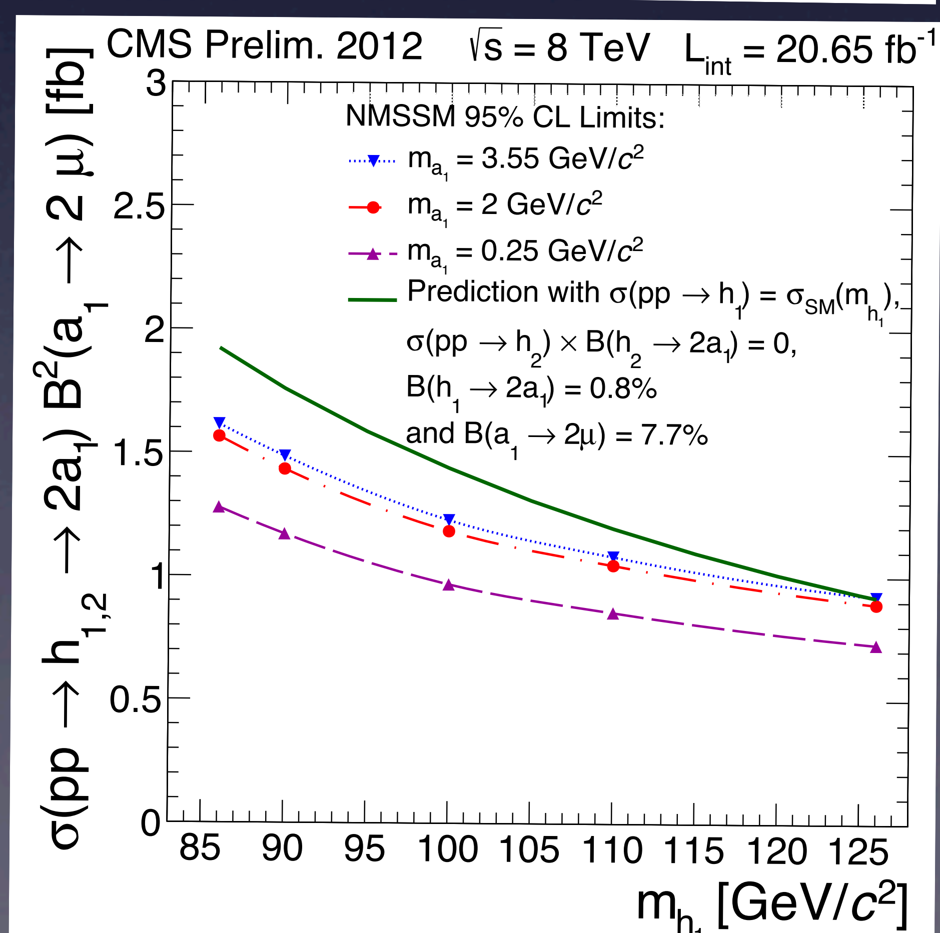


- bbbar estimation directly from data
- bbbar background enriched sample by selecting events with one di-muon + one "orphan" muon
- No isolation is required to the di-muon
- Background template is validated in events with two dimuons

https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig13010TWiki

$h \rightarrow 2a \rightarrow 4\mu$





- One event surviving all the selection and located inside the mass corridor (signal region)
- The intensity of the shading indicates the background expectation which is the sum of bbbar and double jpsi contribution
- Double jpsi estimated using MC expectation corrected with cross section measurements in data
  - No excess of events over SM expectation
  - 95% CL limit on the production cross section (of the two light bosons) x the BR (to muons) as a function of m_{h1}

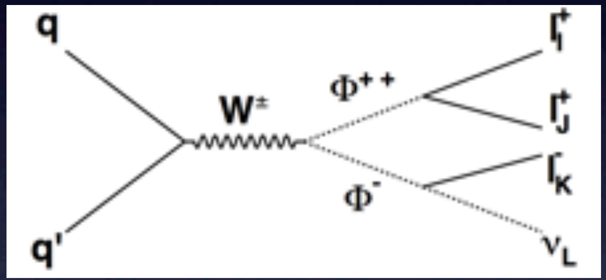
https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig13010TWiki

Double Charged Higgs

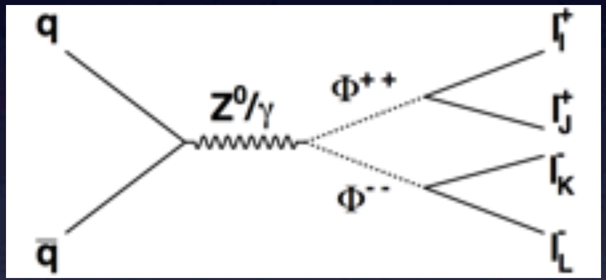
http://arxiv.org/pdf/1207.2666.pdf

- Search for the double charged Higgs boson
- Charge Higgs boson is a member of SU(2)L scalar triplet Φ in extension of the SM which include the seesaw mechanism of type II
- Inclusive search in events with three or more leptons originated from the decay of pair produced triplet components Φ++Φ-- and Φ++Φ-

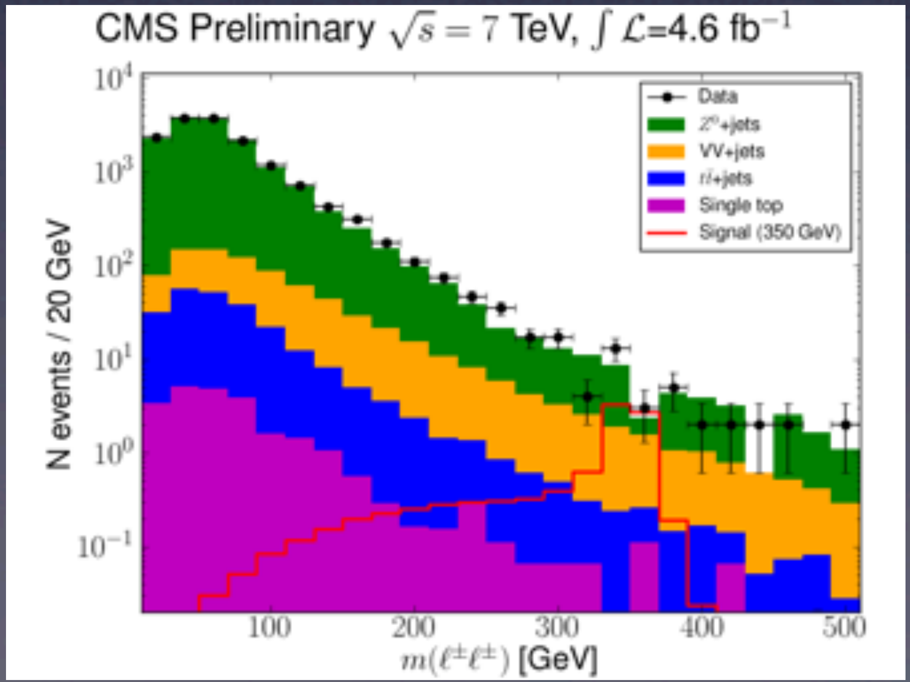
Associated production



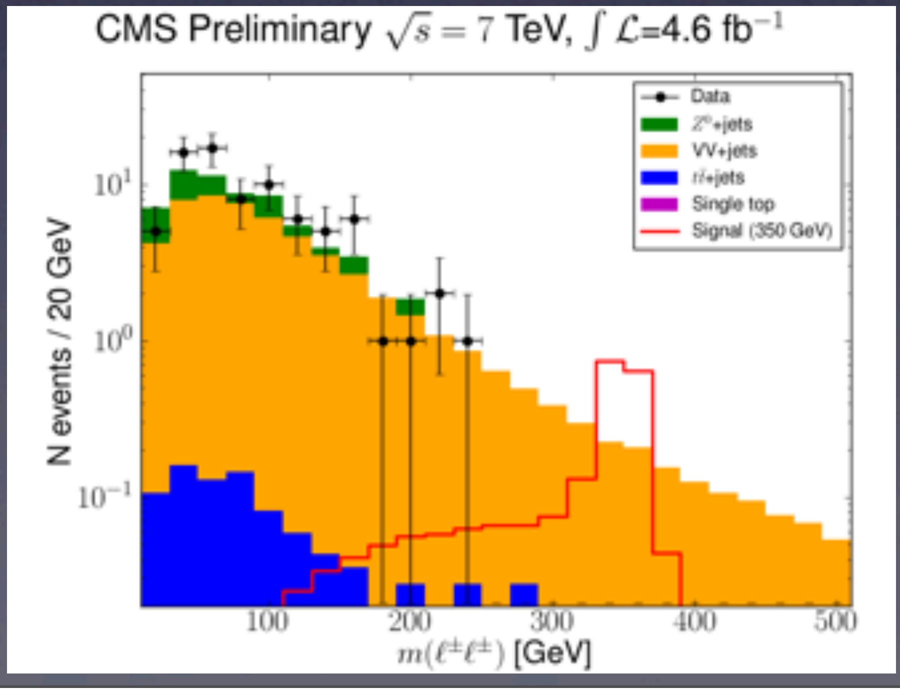
pair production



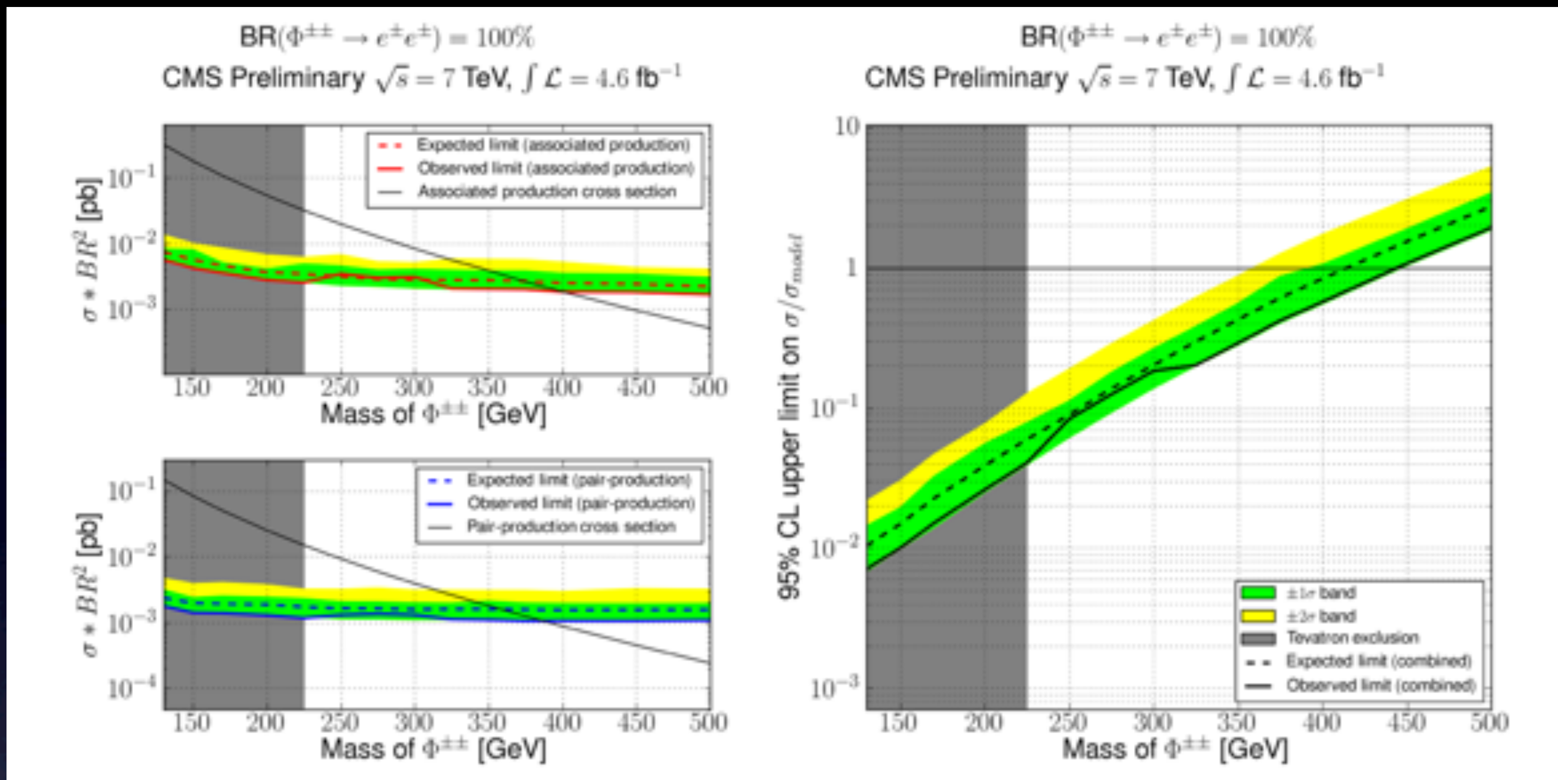
Invariant mass distribution from three lepton final state



Invariant mass distribution from four lepton final state

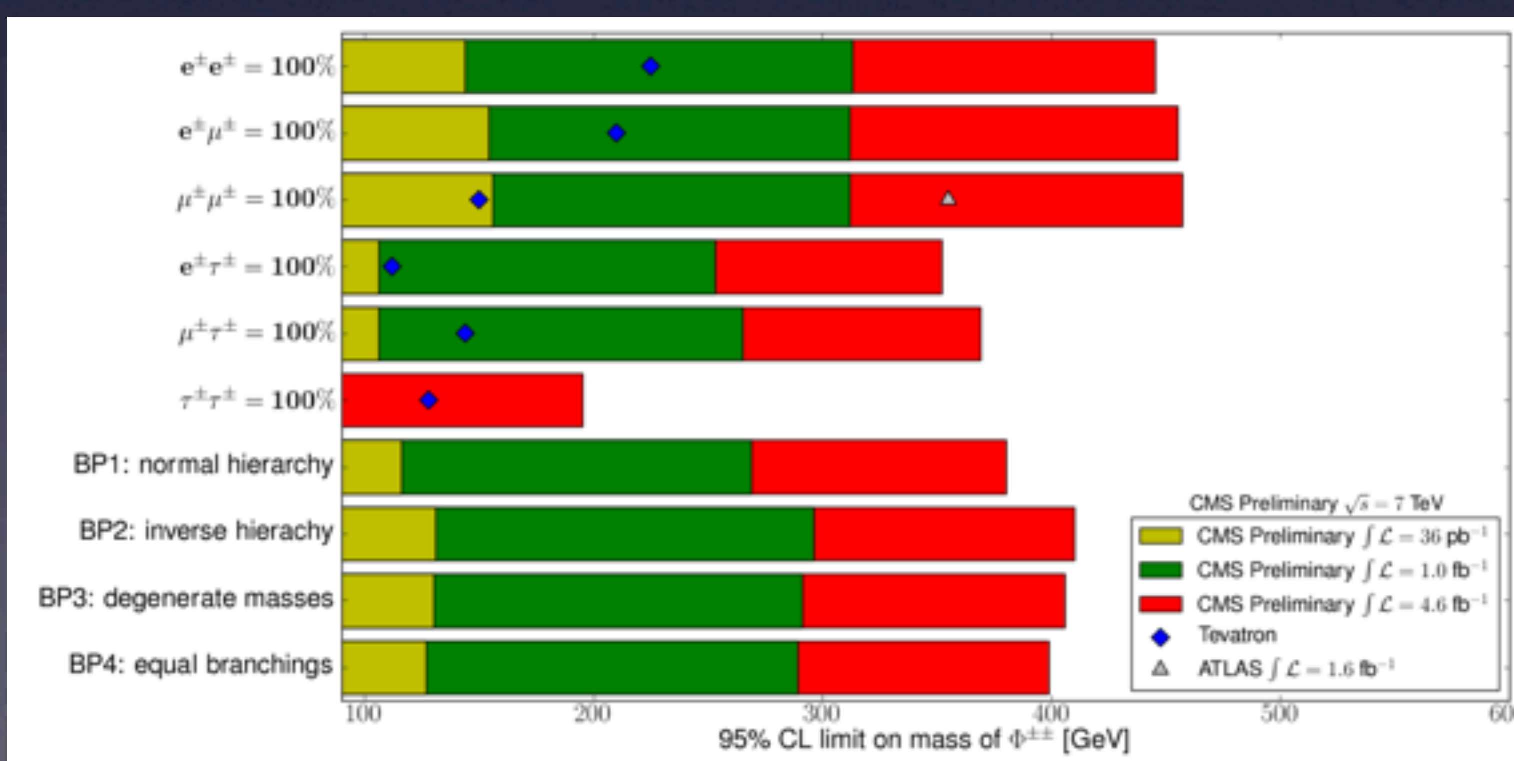


Double Charged Higgs



http://arxiv.org/pdf/1207.2666.pdf

- Observed Φ++ mass limits at 95% CL for 100% Branching fraction to ee channel



- Summary of results for all lepton combinations
- Results are compared for different CMS luminosities and ATLAS and Tevatron limits

SUMMARY

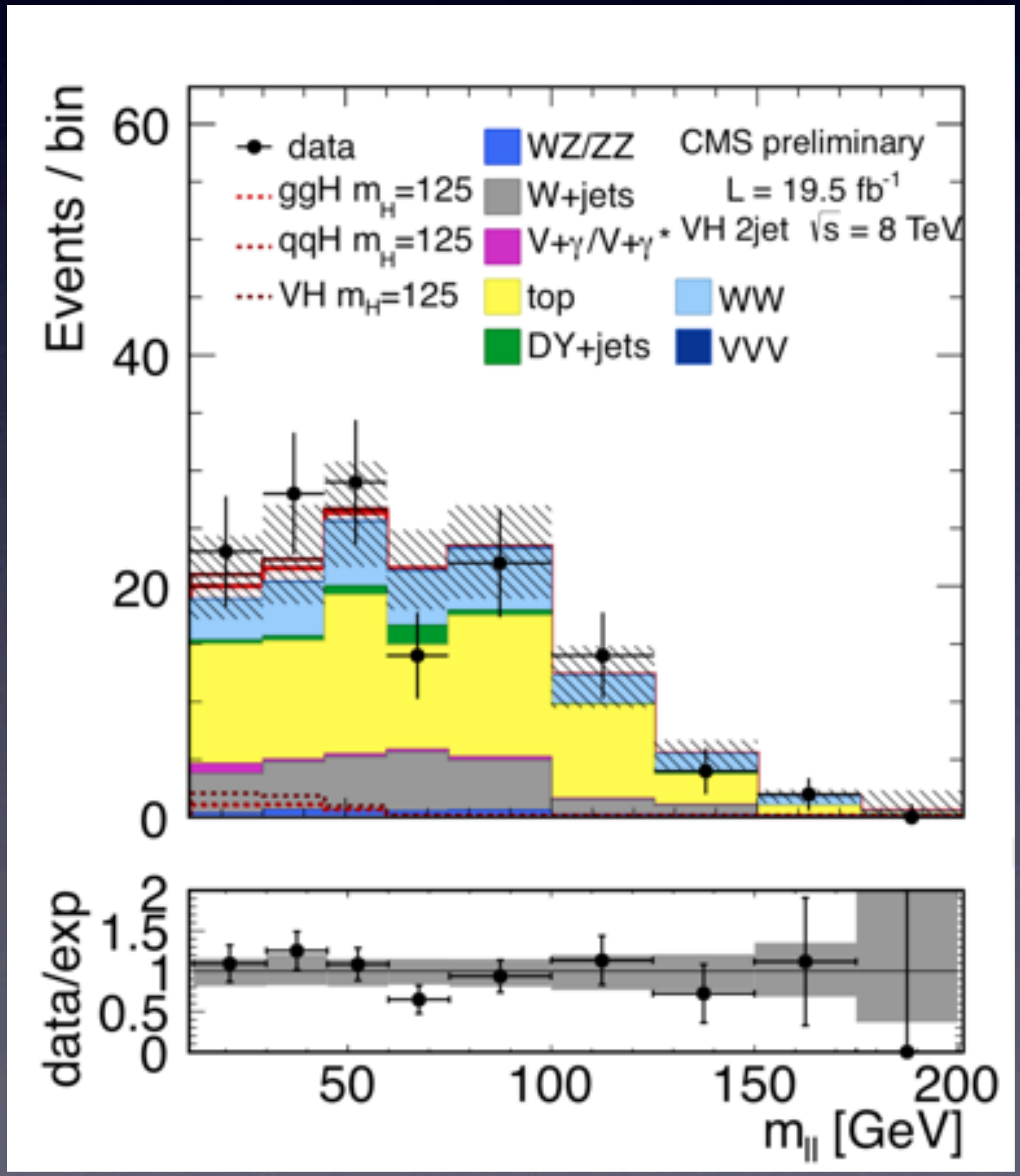
- The recent discovery of a new boson with mass of 126 GeV has fired the question whether it corresponds to the SM Higgs boson or a new particle from an extended theory
- There is an extensive number of BSM Higgs models, in this talk the latest experimental constrains for MSSM, NMSSM and the double charged Higgs results in CMS were reviewed
- There is no visible excess of events over SM expectations in all the channels explored, exclusion limits are set as a function of the parameters of each extended theory
- We are looking forward to analyze more data (2015 and beyond) and reveal “true” identity of the new

Backup

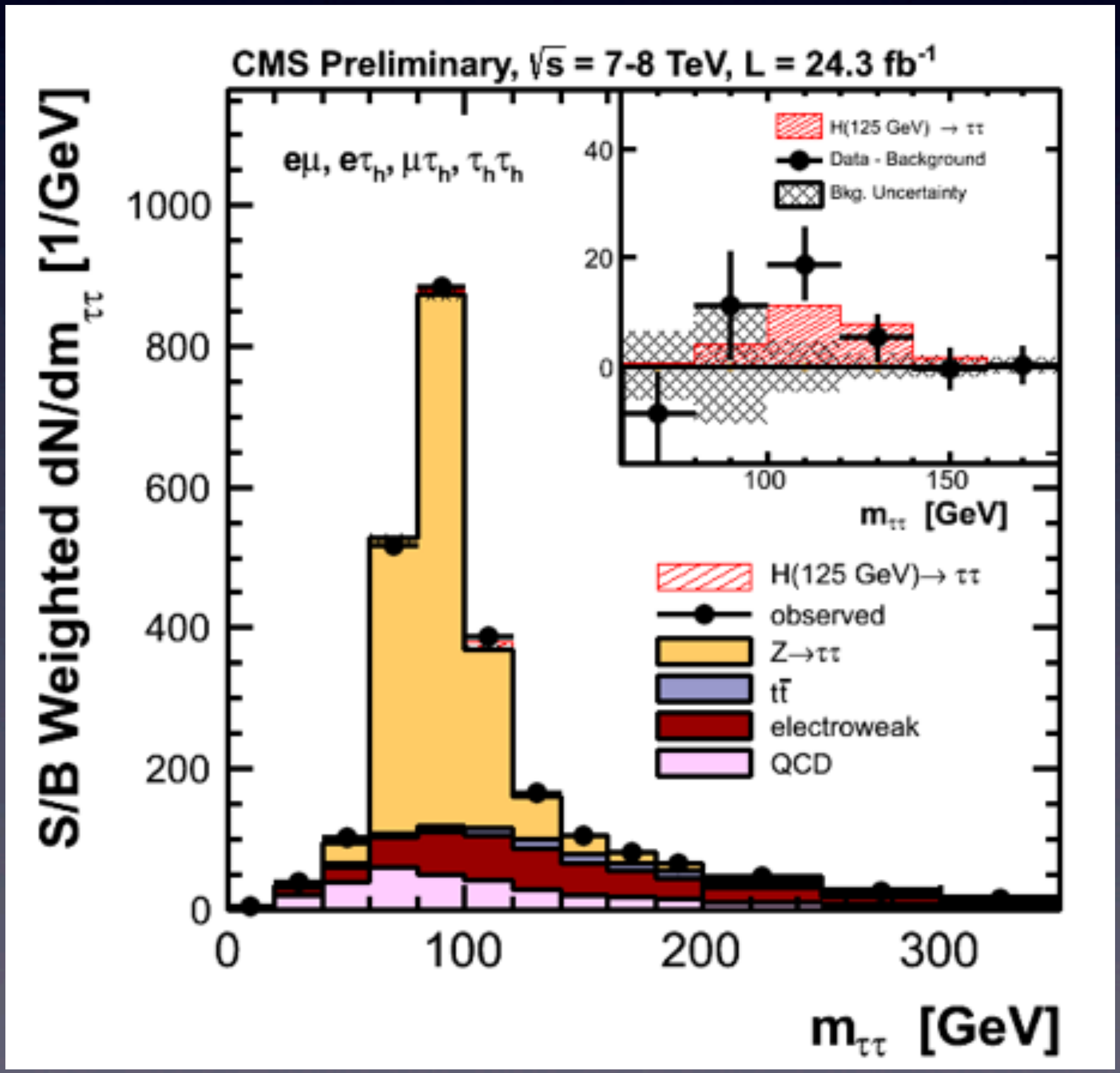
H->WW and H->tautau SM CMS searches

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG

m_{ll} distribution in the emu channel



tautau invariant mass



Triggers for H->bb

Higgs boson decaying to a pair of b-quarks in association with at least another b-quark

- Triggers adjusted according to the increasing luminosity

all hadronic channel	semi-leptonic channel
category 1: di-jet trigger (46,38) GeV	category 1: muon with pT>12 GeV, one or two jets ($\|\eta\|<2.6$) with pT>20 GeV
category II: di-jet trigger (60,53) GeV	category II: Same as 1 but jet threshold raised from 20 to 30 GeV
category 3: same as 1 but requiring a third jet with pT>20 GeV	

H->tautau

etau

Process	SM 0/1-Jet	SM Boosted	SM VBF	MSSM Non b-Tag	MSSM b-Tag
$Z \to \tau\tau$	13438 ± 977	190 ± 14	19 ± 1	14259 ± 1037	135 ± 9
Multijets	6365 ± 299	27 ± 3	15 ± 2	6404 ± 301	100 ± 7
W+jets	2983 ± 216	62 ± 4	4.2 ± 0.4	5432 ± 377	39 ± 3
$Z \to ll$	5170 ± 464	28 ± 4	5 ± 1	6146 ± 502	28 ± 4
$t\bar{t}$	63 ± 7	42 ± 6	2 ± 1	47 ± 7	75 ± 11
Dibosons	68 ± 21	5 ± 2	0.1 ± 0.1	105 ± 22	1 ± 1
Total Background	28087 ± 1142	354 ± 17	45 ± 2.9	32392 ± 1249	378 ± 17
$H \to \tau\tau$	53 ± 9	2.7 ± 0.6	2.0 ± 0.2	279 ± 29	26 ± 4
Data	27727	318	43	32051	391

mutau

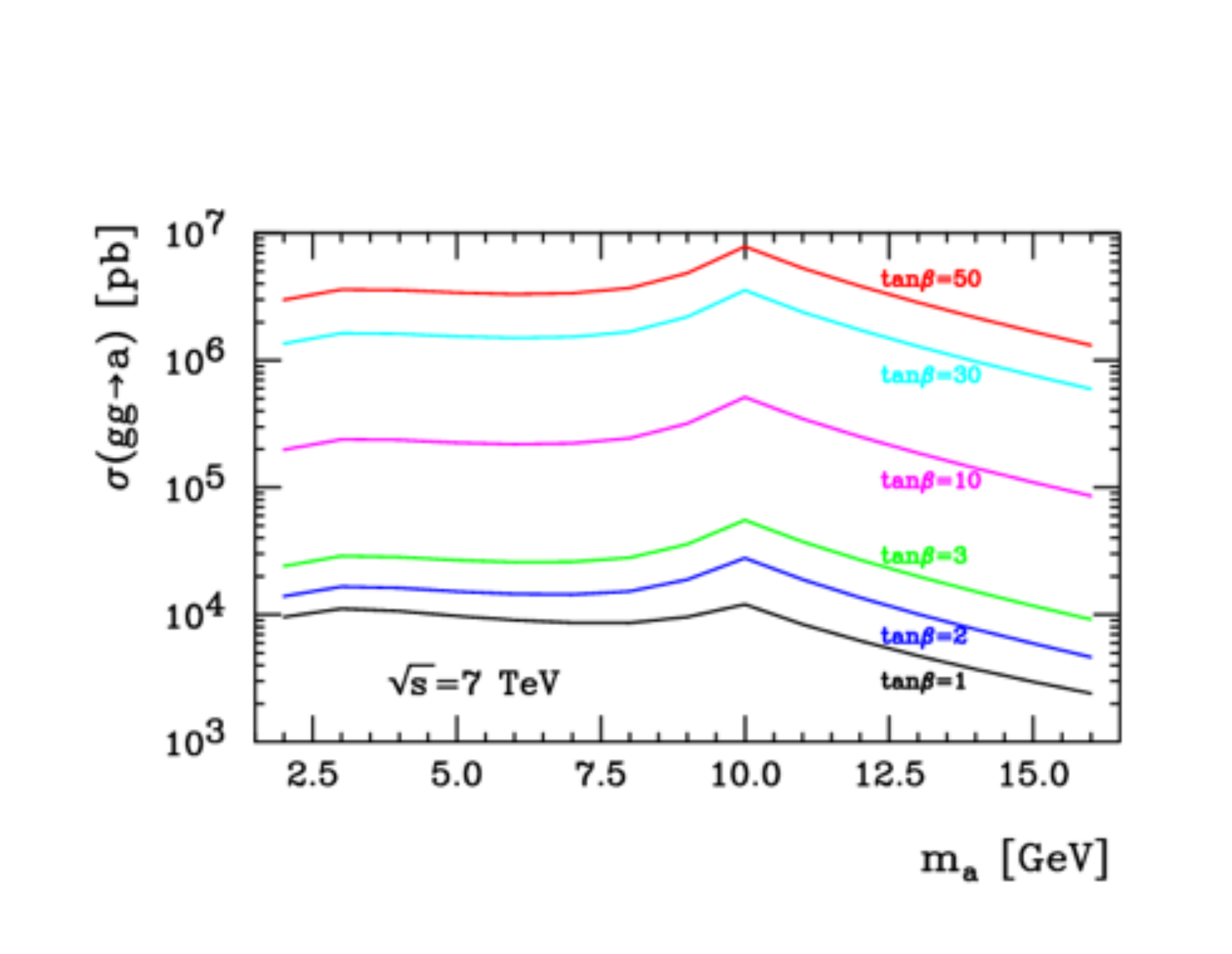
Process	SM 0/1-Jet	SM Boosted	SM VBF	MSSM Non b-Tag	MSSM b-Tag
$Z \to \tau\tau$	28955 ± 2054	295 ± 22	36 ± 2	29795 ± 2114	259 ± 18
Multijets	7841 ± 141	36 ± 2	23 ± 2	6387 ± 115	160 ± 9
W+jets	5827 ± 392	65 ± 4	9 ± 1	9563 ± 628	110 ± 9
$Z \to ll$	777 ± 70	5 ± 1	1.0 ± 0.2	924 ± 115	3 ± 1
$t\bar{t}$	147 ± 15	94 ± 12	4 ± 1	101 ± 15	145 ± 20
Dibosons	178 ± 55	9 ± 4	0.4 ± 0.4	217 ± 46	5 ± 2
Total Background	43725 ± 2097	504 ± 26	73 ± 3.9	46987 ± 2211	681 ± 30
$H \to \tau\tau$	96 ± 17	3.9 ± 0.8	3.0 ± 0.5	502 ± 52	45 ± 6
Data	43612	500	76	47178	680

emu

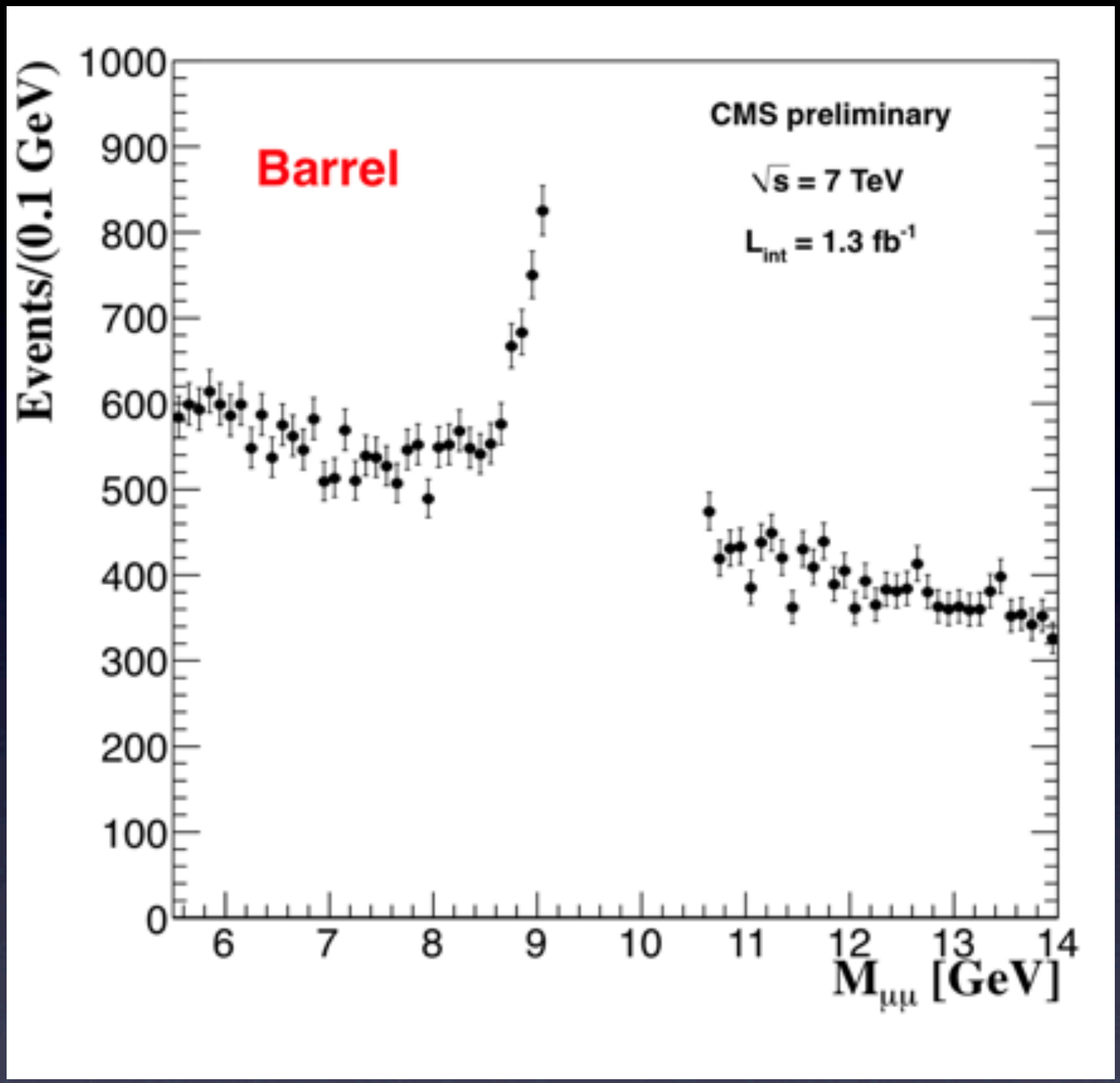
Process	SM 0/1-Jet	SM Boosted	SM VBF	MSSM Non b-Tag	MSSM b-Tag
$Z \to \tau\tau$	11787 ± 790	98 ± 11	16 ± 4	11718 ± 797	112 ± 11
Multijet and W+jets	483 ± 145	9 ± 3	2 ± 1	474 ± 147	15 ± 5
$t\bar{t}$	427 ± 41	70 ± 8	14 ± 3	161 ± 15	289 ± 35
Dibosons	570 ± 91	21 ± 4	2.0 ± 0.6	527 ± 84	55 ± 10
Total Background	13267 ± 809	197 ± 14	34 ± 5	12881 ± 815	471 ± 38
$H \to \tau\tau$	36 ± 6	1.0 ± 0.3	1.0 ± 0.2	161 ± 10	17 ± 1.6
Data	13152	189	26	12761	468

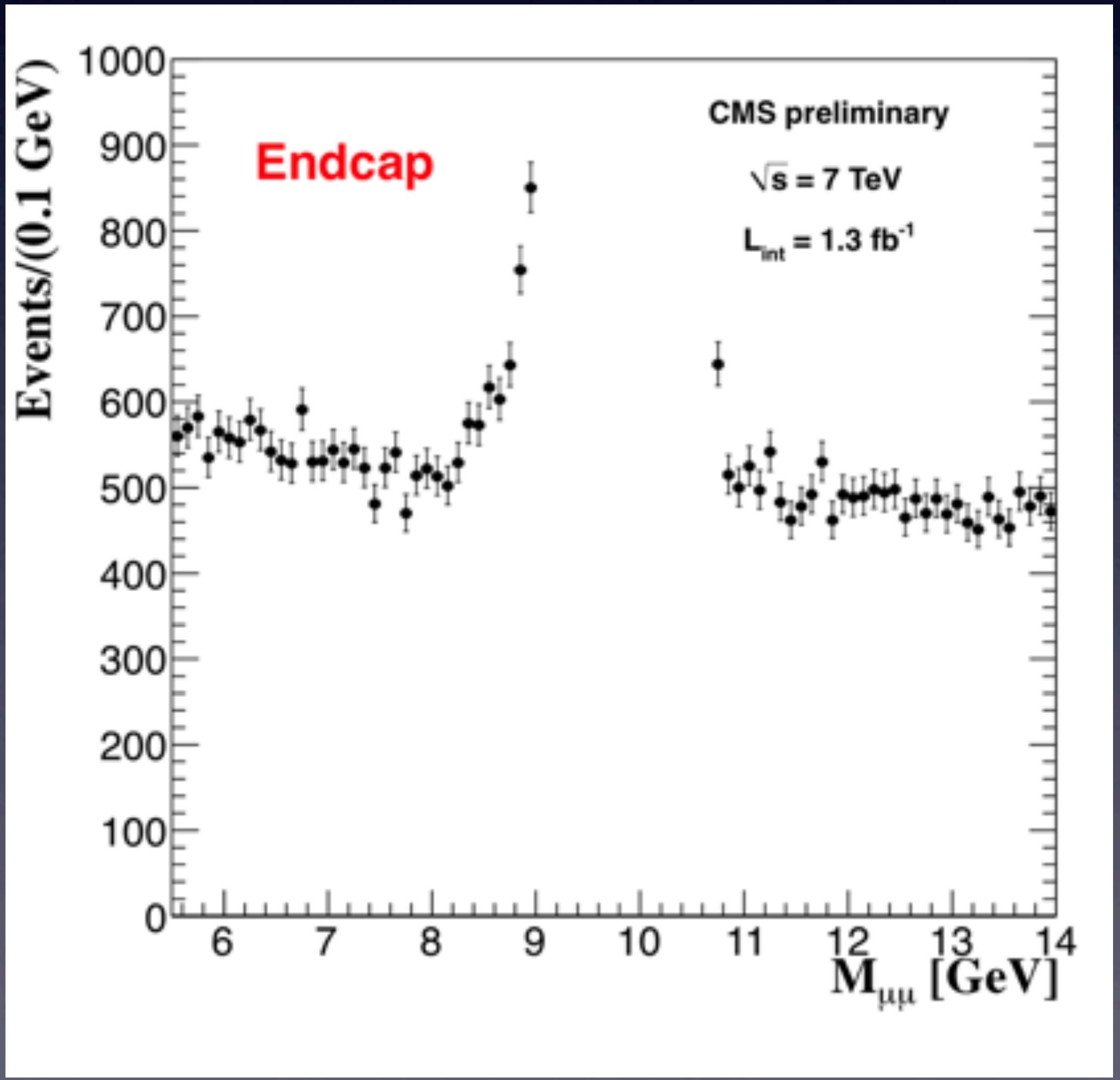
MSSM $a \to \mu^+\mu^-$

- Cross section for gg->a for tan(beta)=1,2,3,10,30,50
- Including all available higher order corrections (HIGLU)



MSSM $a \to \mu^+\mu^-$





NMSSM $h \to 2a \to 4\mu$

- Limit as a function of m_H for the dark-SUSY scenario
- The limit is compared with the predicted rate (solid line) using a simplified SM scenario