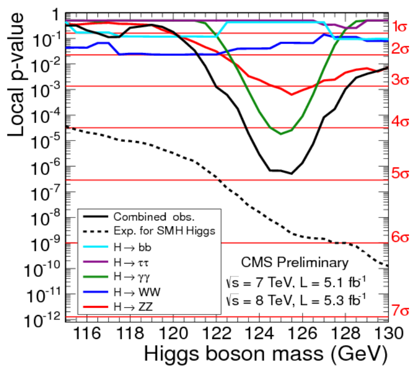
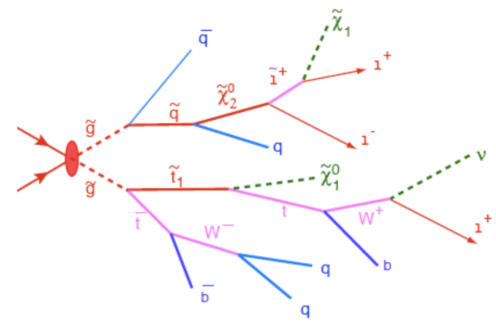
Supersymmetry; post discovery of a new (Higgs?) boson.



Oliver Buchmüller
(Imperial College London
& Senior LPC Fellow 2012)



- *Introduction Higgs, SUSY and the LHC*
- *Recent results from the SM Higgs search*
- *Landscape of SUSY searches Today*

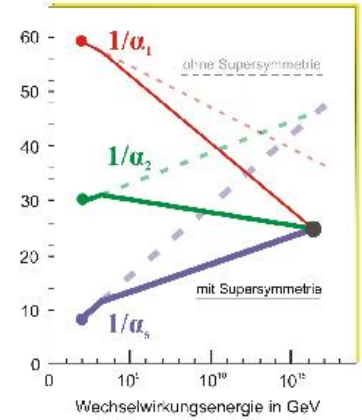
1 August 2012

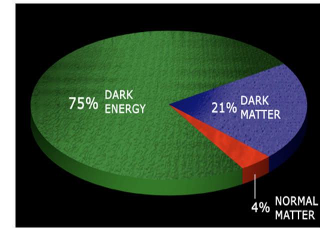
Imperial College London

Fundamental Open Question in Particle Physics

I. Is there a new symmetry - Supersymmetry ?

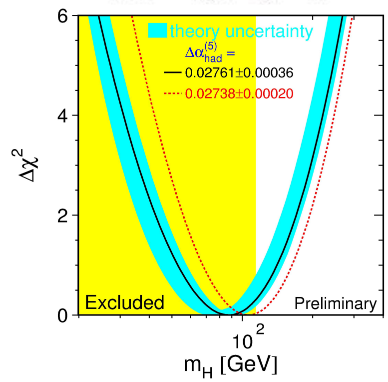
- Can we get experimental evidence to support the Grand Unification of all fundamental forces?
- What is the origin of Dark Matter in the Universe?
  → Is a fundamental particle responsible for it?

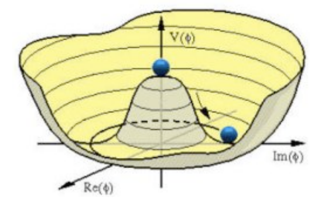




II. What is the origin of mass?

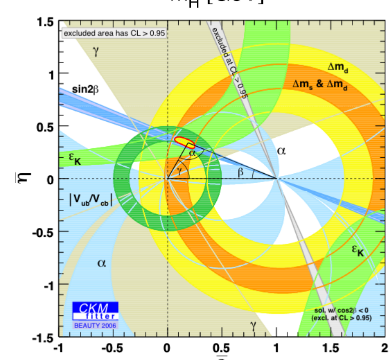
- Why are the vector bosons Z and W are massive whereas the photon is massless?
- Is there a Higgs boson - or even more of them ?

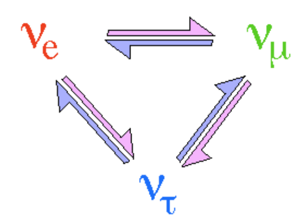




III. What is the origin of the matter-anti-matter asymmetry in our Universe?

- Does the answer lie in in CP violation?
- Neutrino masses and mixing - how do they fit in the picture?

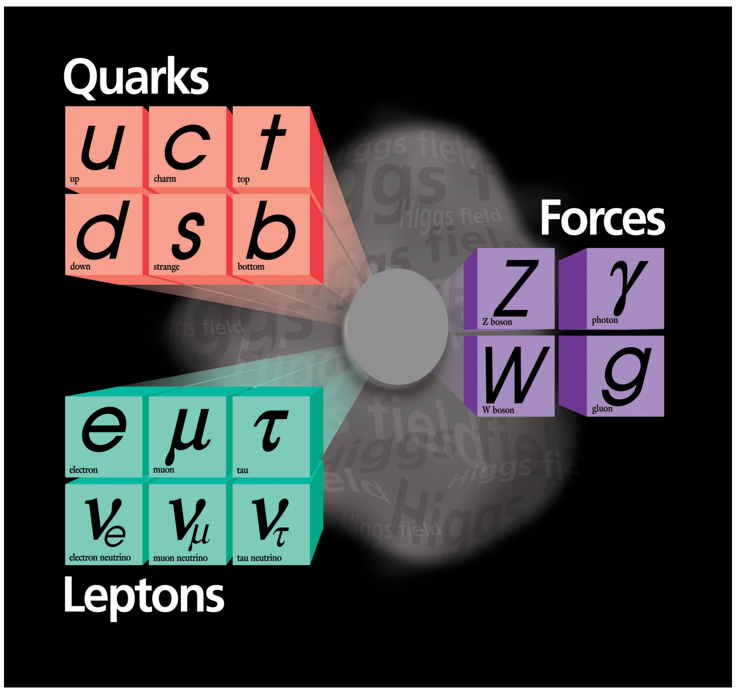




The Standard Model of Particle Physics

Over the last 100 years: combination of
Quantum Mechanics and Special Theory of relativity
along with all new particles discovered has led to the
Standard Model of Particle Physics (SM).
The new (final?) “Periodic Table” of fundamental elements

Matter particles



Force particles

- ***Matter is composed of spin-1/2 fermions***
  Three families of quarks and three families of lepton - of increasing masses, ‘normal’ matter is made of the first family
- ***Interactions (strong nuclear, electromagnetic, weak nuclear) are carried by exchange of spin-1 bosons (gluons, photons, weak bosons)***
- ***Very successful description of physics at the scale of ~ 100GeV***

The Standard Model of Particle Physics

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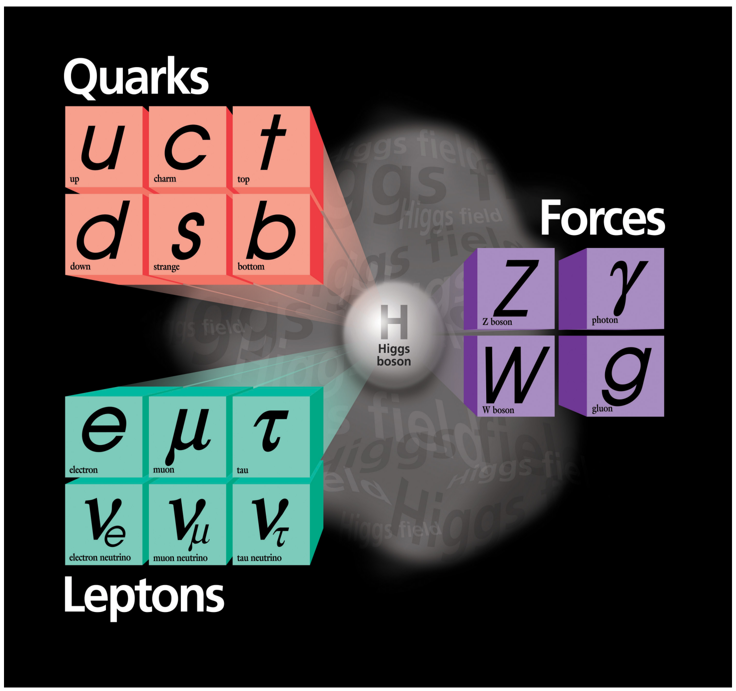
Matter particles



Force particles

A crowning achievement of 20th Century Science

Yet, its most basic mechanism, that of granting mass to particles, is (was?) missing. Quantum of this field is the Spin Zero Higgs boson.

Supersymmetry

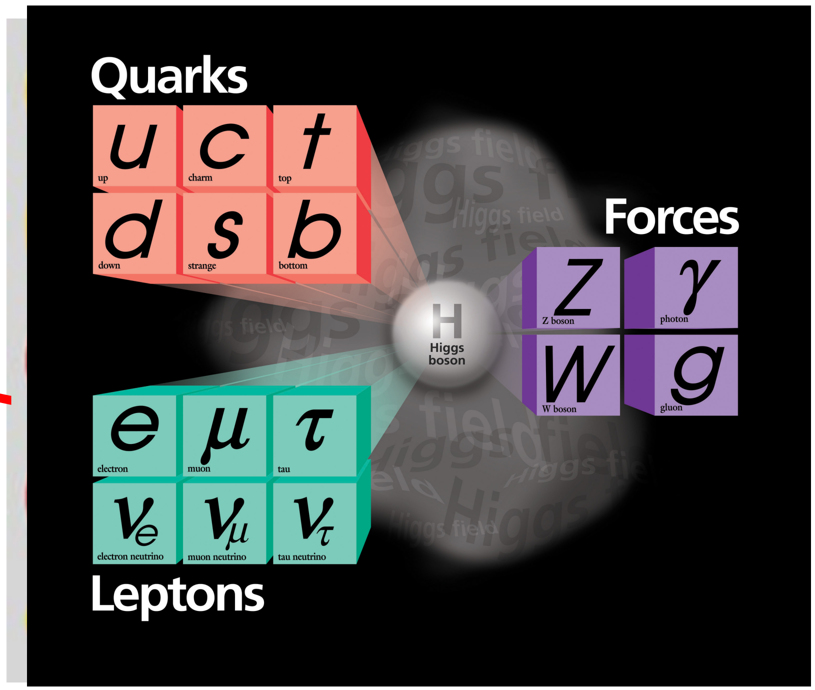
Extension of the Standard Model: Introduce a new symmetry

Spin ½ matter particles (fermions) ⇔ Spin 1 force carriers (bosons)

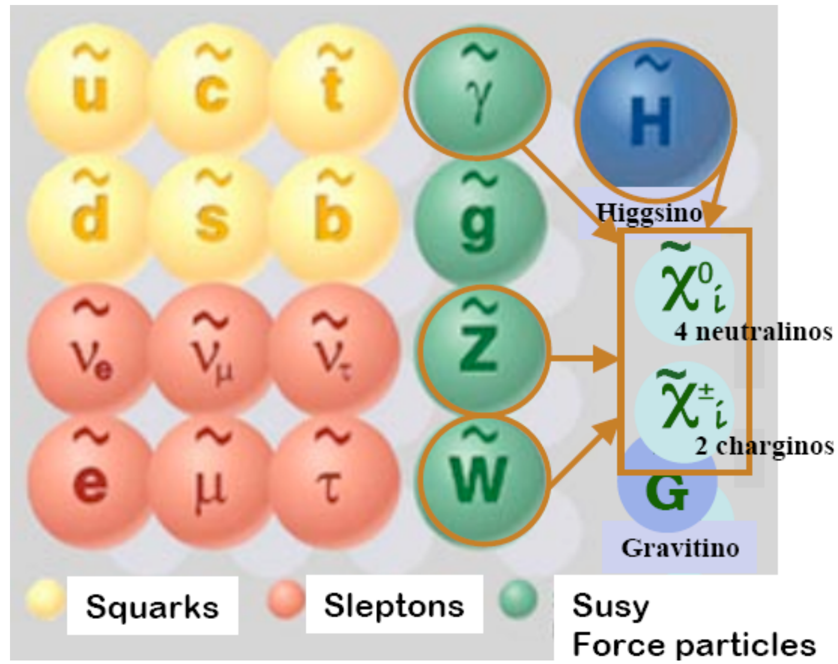
Standard Model particles

SUSY particles

Matter particles



Force particles



New Quantum number: R-parity: $R_p = (-1)^{B+L+2s}$ = *+1 SM particles*

- 1 SUSY particles

<u>R-parity conservation:</u>

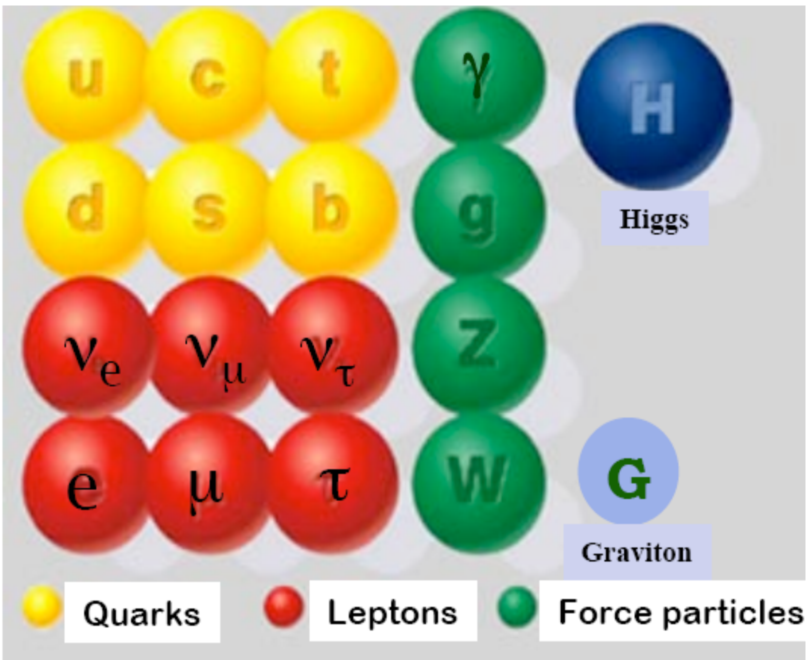
- *SUSY particles are produced in pairs*
- *The lightest SUSY particle (LSP) is stable*

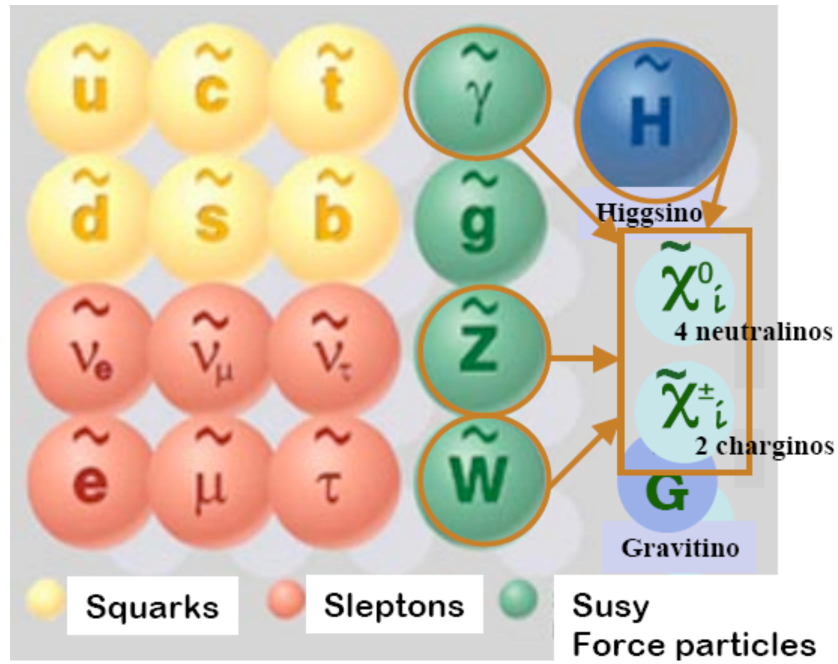
Supersymmetry

Extension of the Standard Model: Introduce a new symmetry

Spin ½ matter particles (fermions) ⇔ Spin 1 force carriers (bosons)

Standard Model particles | *SUSY particles*





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- *SUSY particles are produced in pairs*
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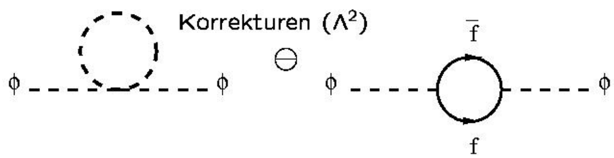
Why is SUSY so Attractive?

$m_{SUSY} \sim 1$ TeV

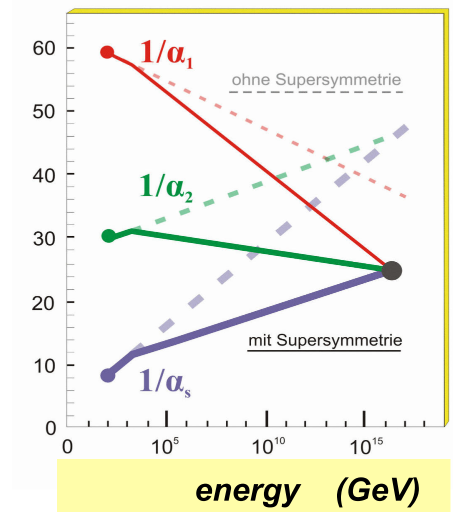
1. Quadratically divergent quantum corrections to the Higgs boson mass are avoided

$$\Delta m_H = f(m_B^2 - m_f^2)$$



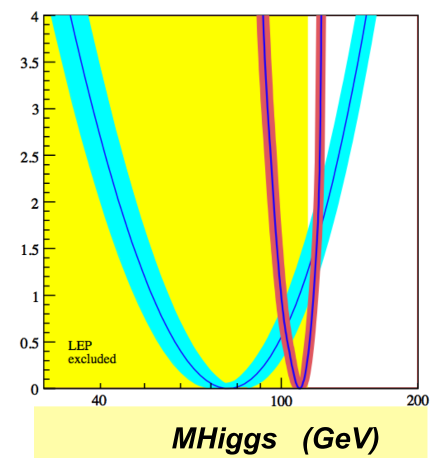
(Hierarchy or naturalness problem)

2. Unification of coupling constants of the three interactions seems possible



3. SUSY provides a candidate for dark matter,

The lightest SUSY particle (LSP)



4. A SUSY extension is a small perturbation, consistent with the electroweak precision data

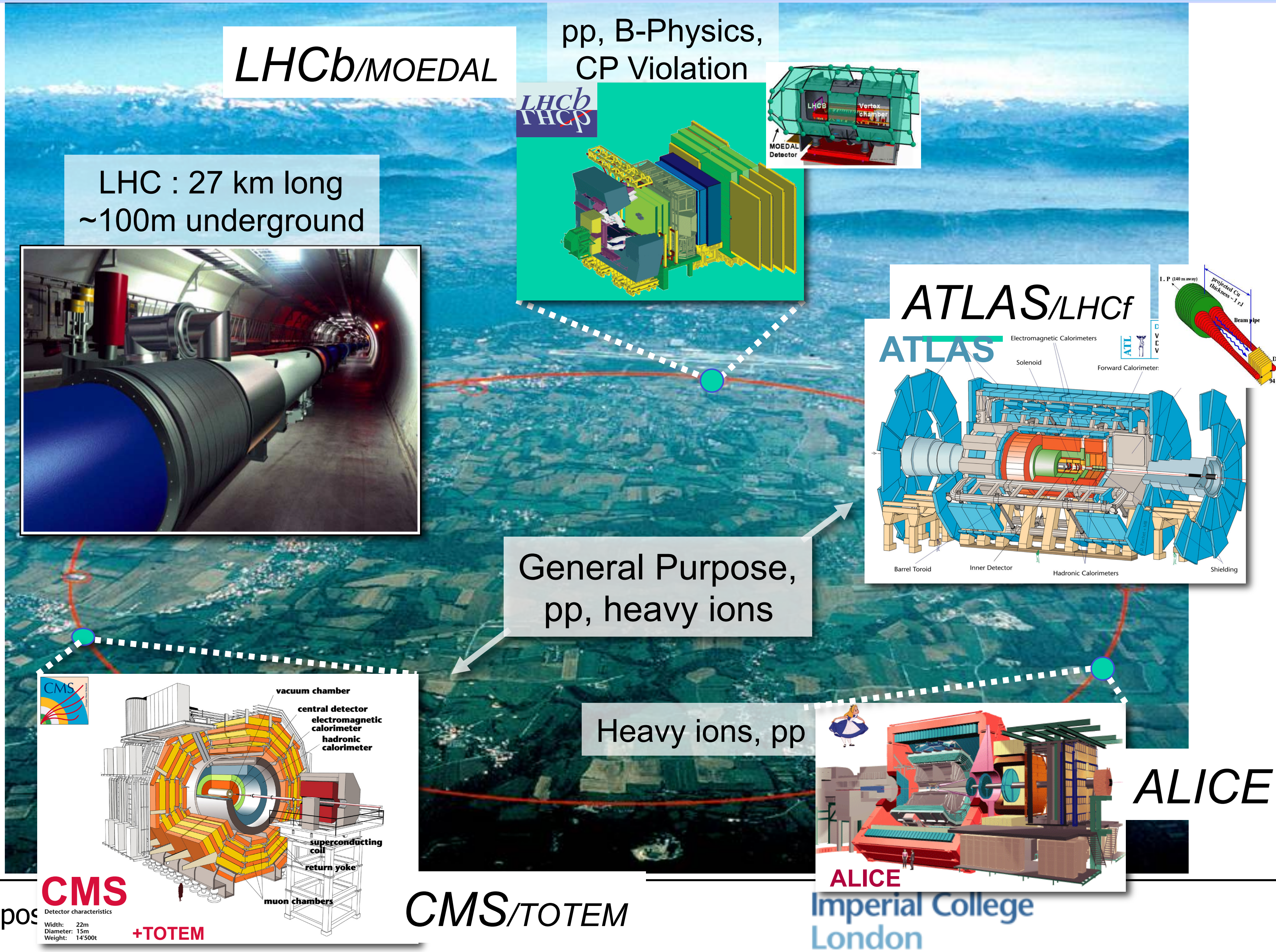
Groundbreaking Work in 1964 !

"Electroweak Symmetry Breaking Mechanism"

2010 Sakurai Prize of American Physical Society

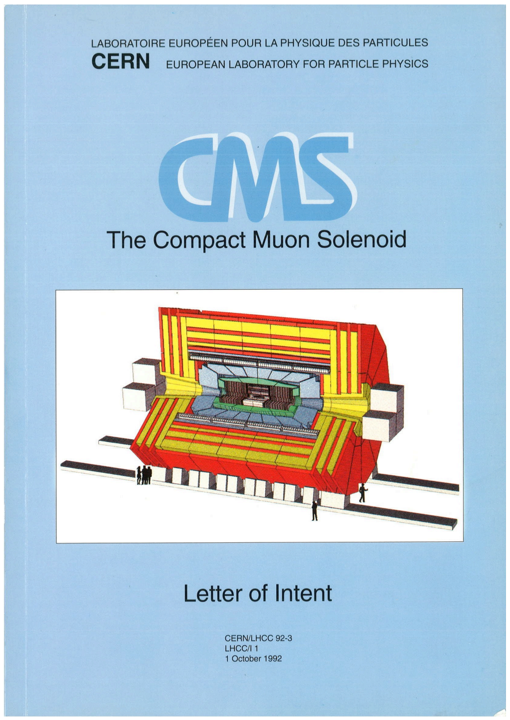
R. Brout, F. Englert, P. Higgs,
G. Guralnik, C. Hagen, T. Kibble

The Large Hadron Collider at CERN



First Official CMS Document submitted 1st Oct. 1992

Letter of Intent: Submitted to the CERN's Peer Review Committee (LHCC)



CERN/LHCC 92-3
LHCC/I 1
1 October 1992

20 years ago

Letter of Intent
by the

CMS Collaboration

for a General Purpose Detector at the LHC

We propose to build a general purpose detector designed to run at the highest luminosity at the LHC. The CMS (Compact Muon Solenoid) detector has been optimized for the search of the SM Higgs boson over a mass range from 90 GeV to 1TeV, but it also allows detection of a wide range of possible signatures from

LHC and CMS Timeline

1984 Workshop on a Large Hadron Collider in the LEP tunnel, Lausanne

1987 Rubbia "Long-Range Planning Committee" recommends Large Hadron Collider as the right choice for CERN's future

1990 ECFA LHC Workshop, Aachen (CMS design first presented)

1992 General Meeting on LHC Physics and Detectors, Evian les Bains

1993 Letters of Intent (ATLAS and CMS selected by LHCC)

1994 Technical Proposals Approved

1996 Approval to move to Construction (ceiling of 475 MCHF)

1998 Memorandum of Understanding for Construction Signed

1998 Construction Begins (after approval of Technical Design Reports)

2000 CMS assembly begins above ground. LEP closes

2004 CMS Underground Caverns completed

2008 CMS ready for LHC beams. The LHC incident 19th Sept

2009 CMS records first collisions

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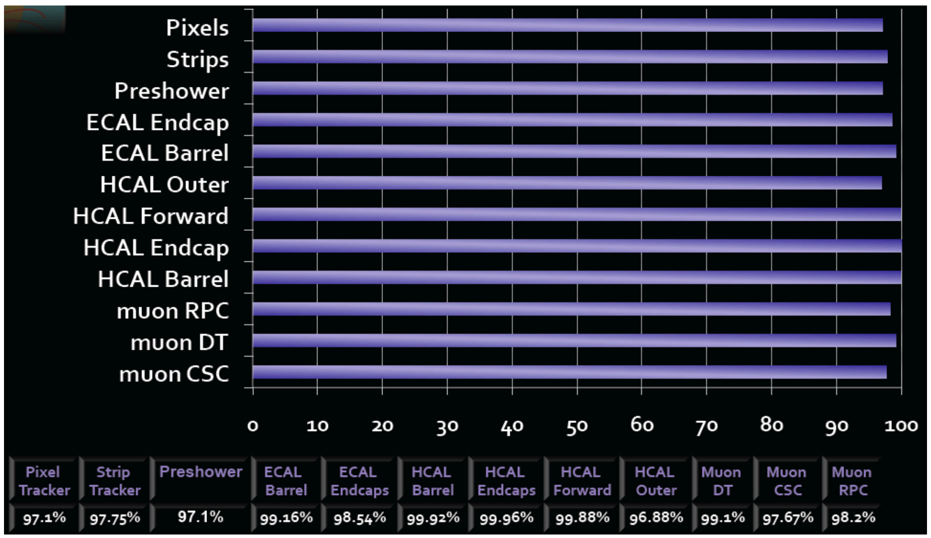
2009	**CMS records first collisions**

25 years from first ideas to first collisions!

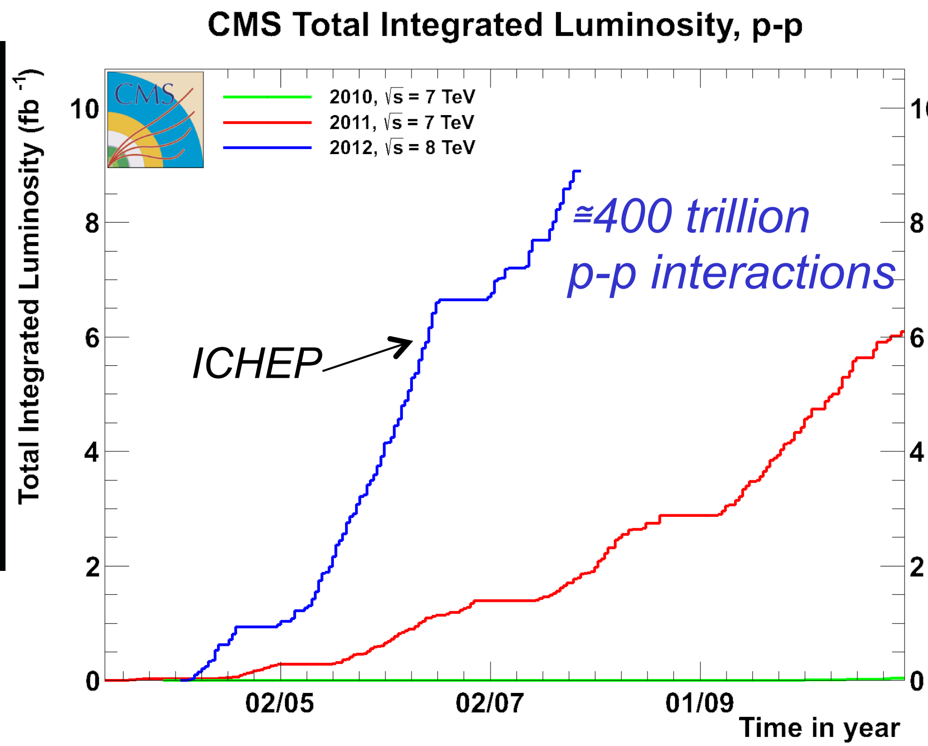
Performance: CMS and LHC

The CMS detector is performing according to (beyond) design!

99% of the channels operational



High Data recording efficiency
2012 certified for ICHEP2012
'Golden': 5.19 fb^{-1} (85%)
Muon: 5.62 fb^{-1} (92%)



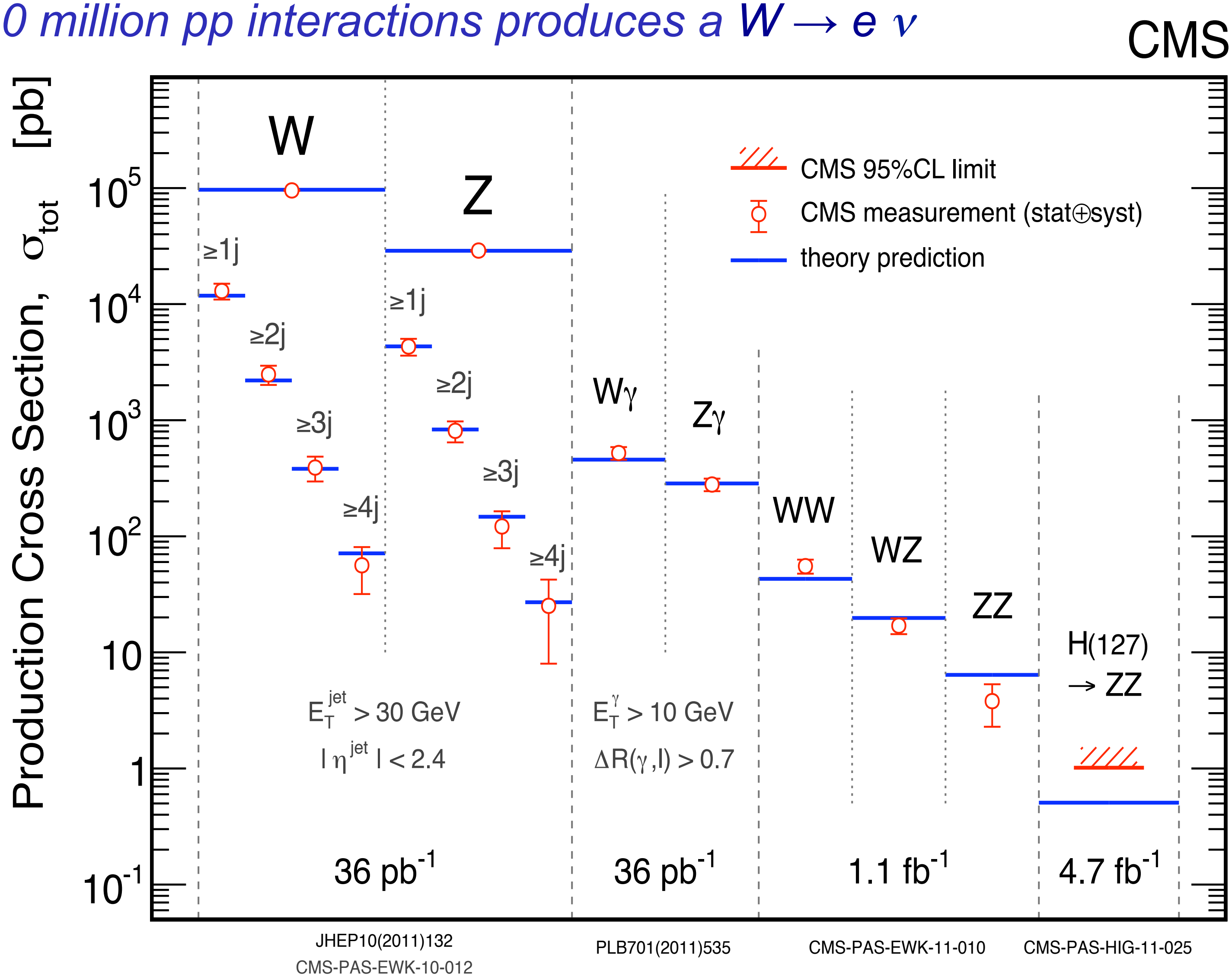
Computing:

Tens of petbytes/year
400M jobs/month

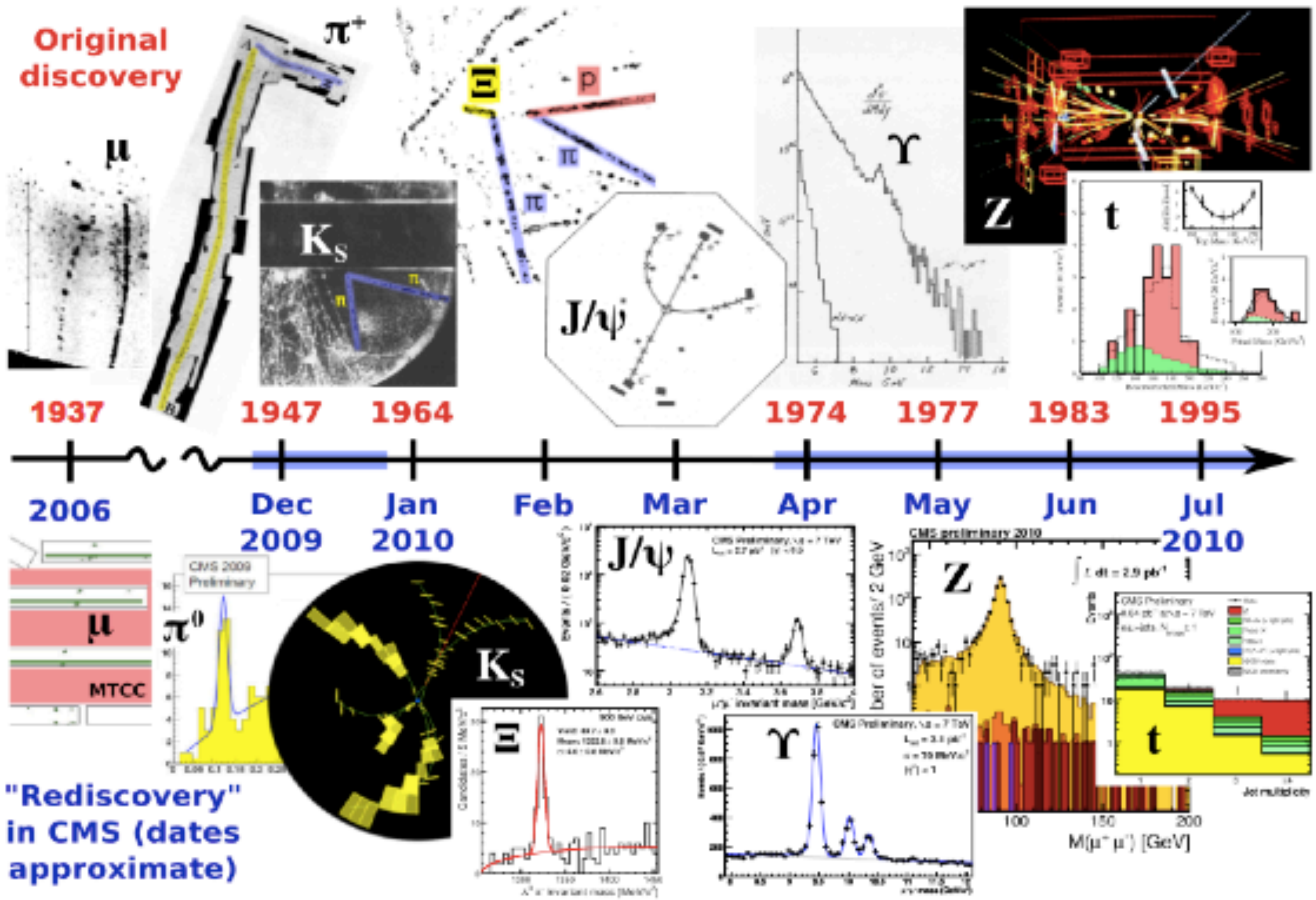
LHC currently running at 600 million proton-proton interactions/s!)

Standard Model (Electroweak) Measurements

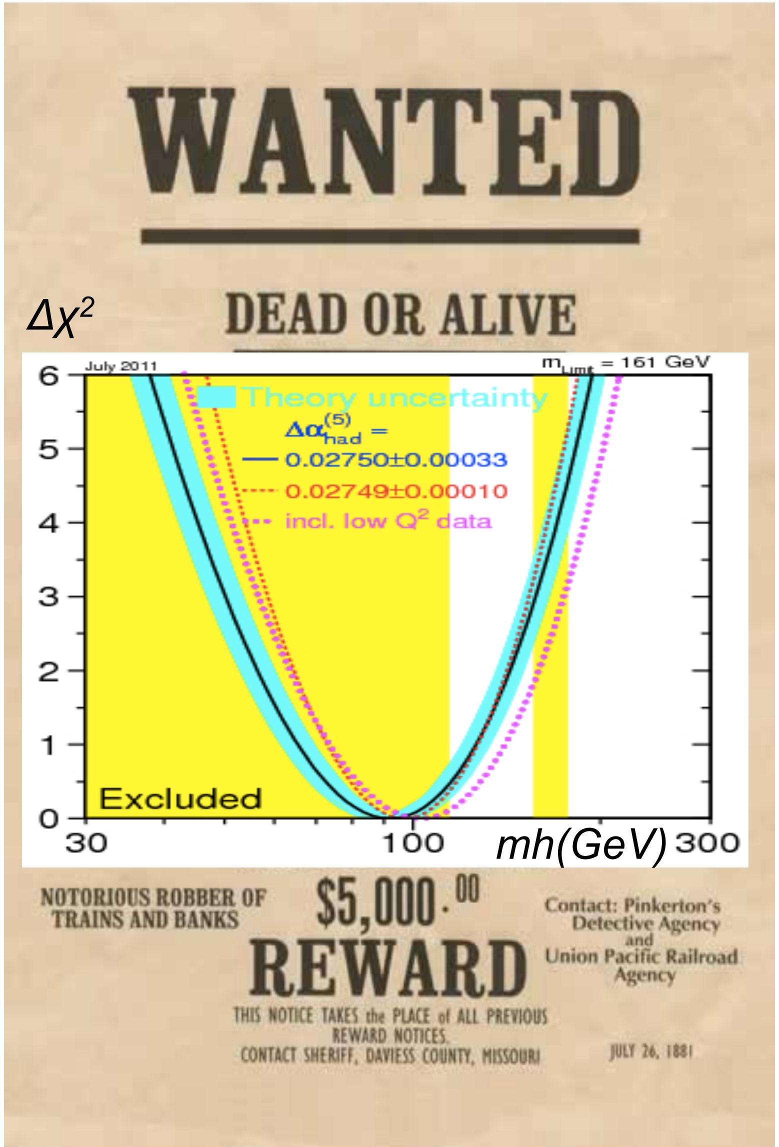
1 in 10 million pp interactions produces a $W \rightarrow e\,\nu$



Re-Discovery of the Standard Model



Standard Model Higgs Boson



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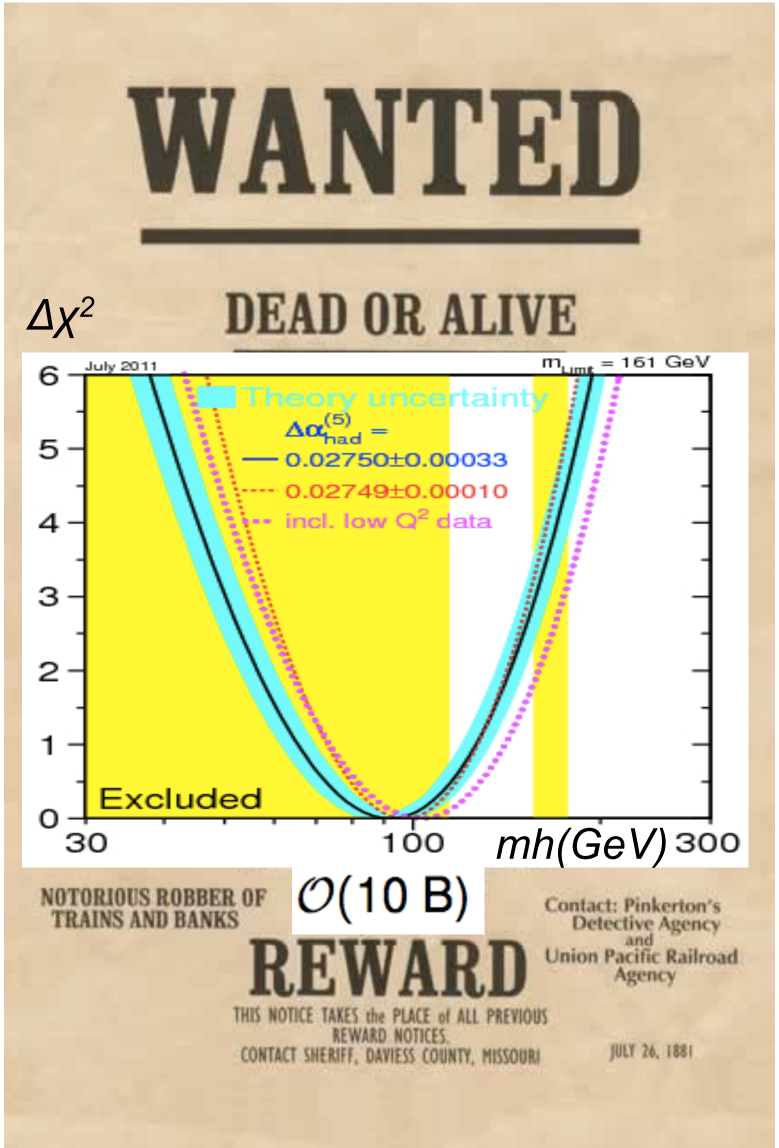
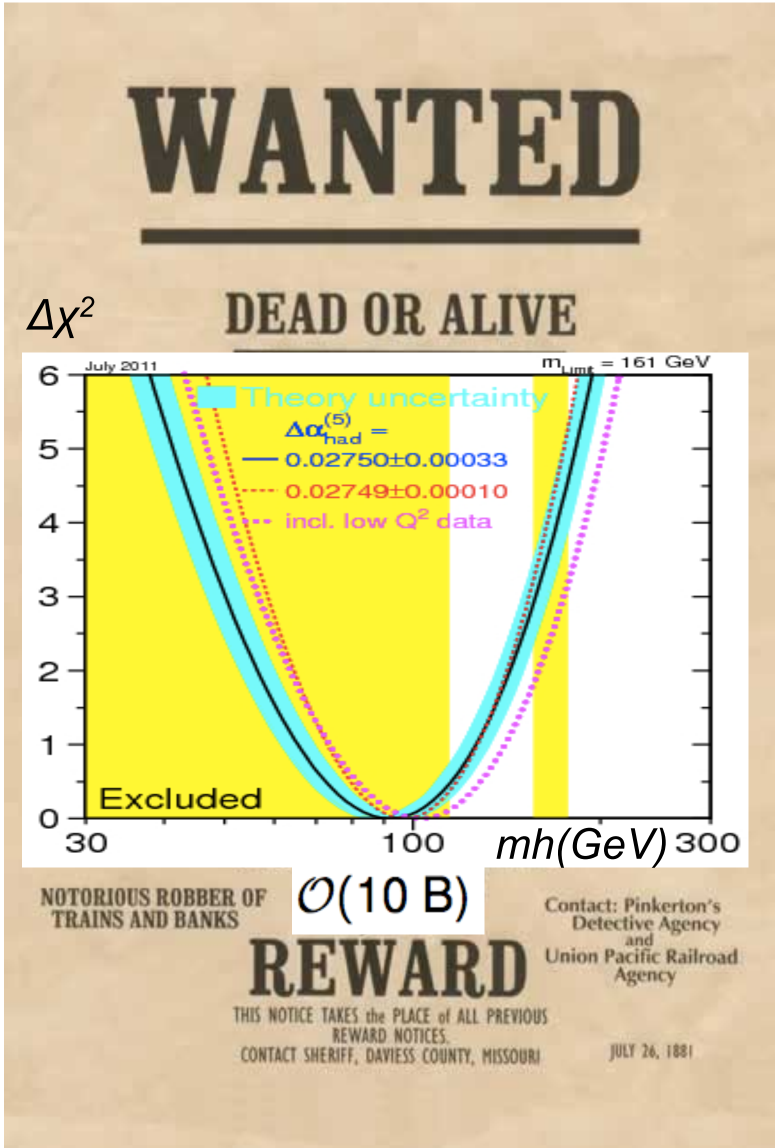


Standard Model Higgs Boson

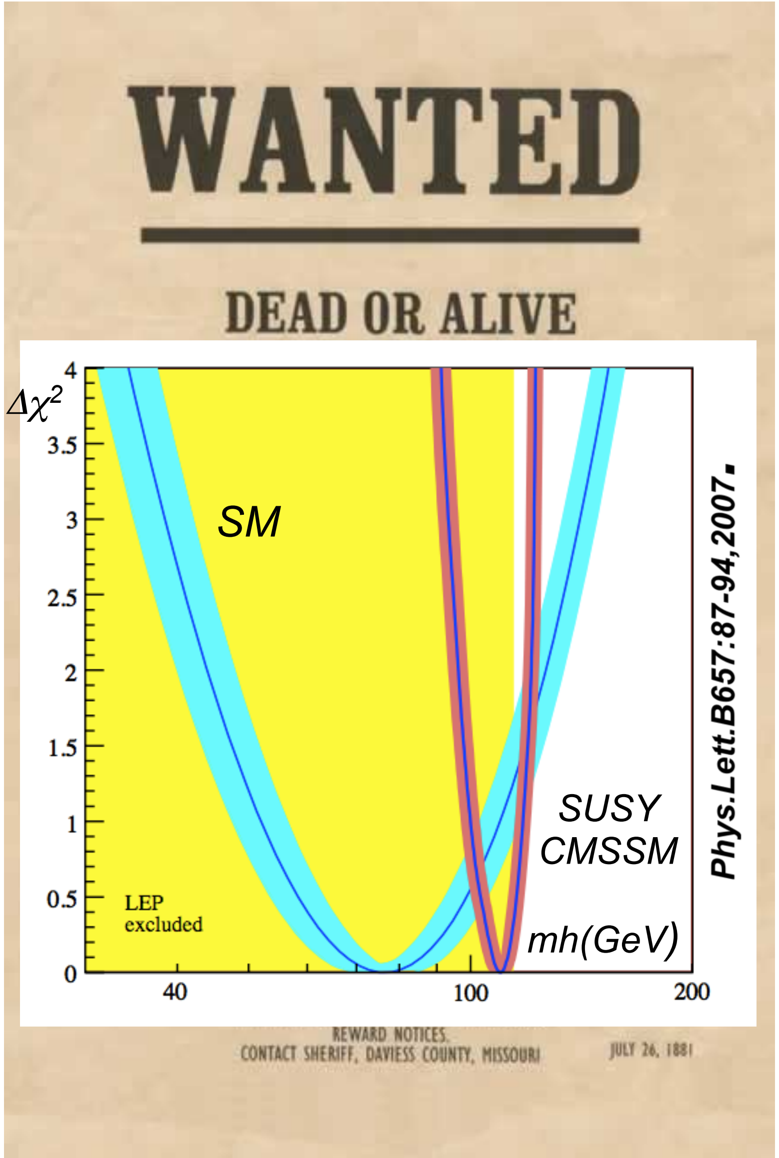


Pre-LHC:

- mh(SM)<161 GeV preferred @ 95% CL from EWK Fit
- mh(SM)< 114 GeV excluded @ 95% CL from direct searches at the LEP
- mh(SM) [156, 177] GeV excluded @ 95% CL from direct searches at the Tevatron

The preferred mass region of a SM-like Higgs was below 200 GeV (and above 114 GeV).

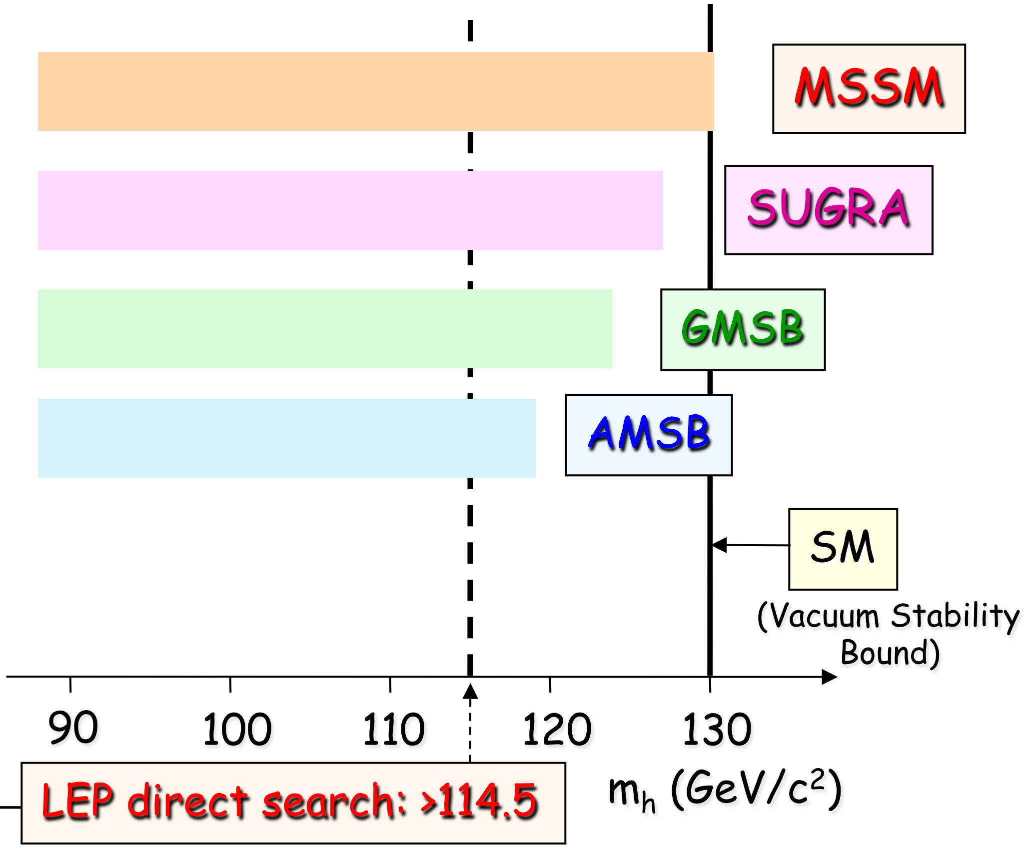
SM-like Higgs Boson



SM: Constrained Phase Space

mh(SM)<161 GeV @ 95% CL

SUSY: Accessible Phase Space



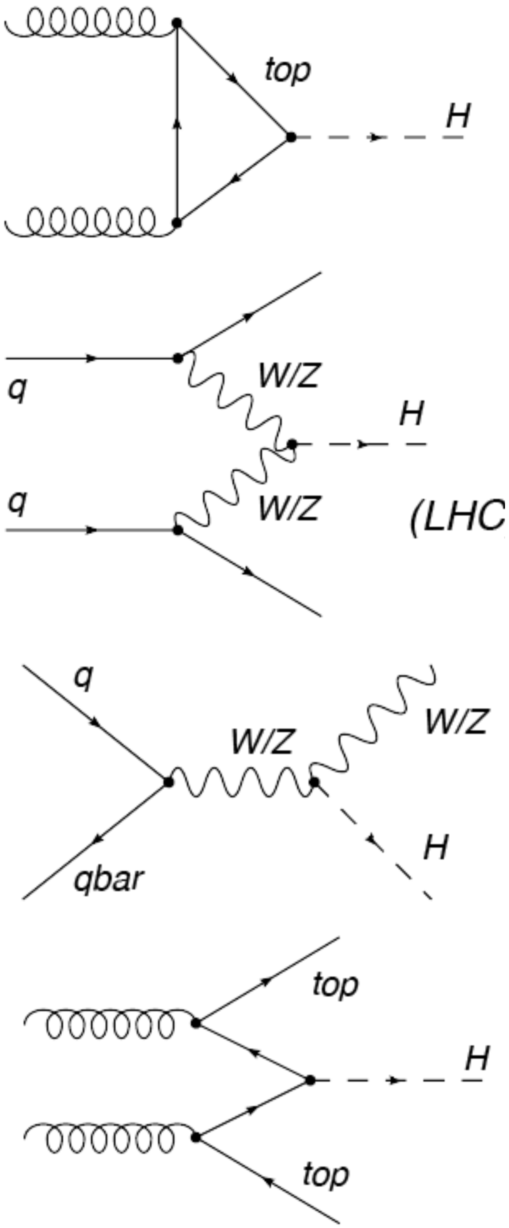
„SUSY post-Higgs discovery" O. Buchmüller

London

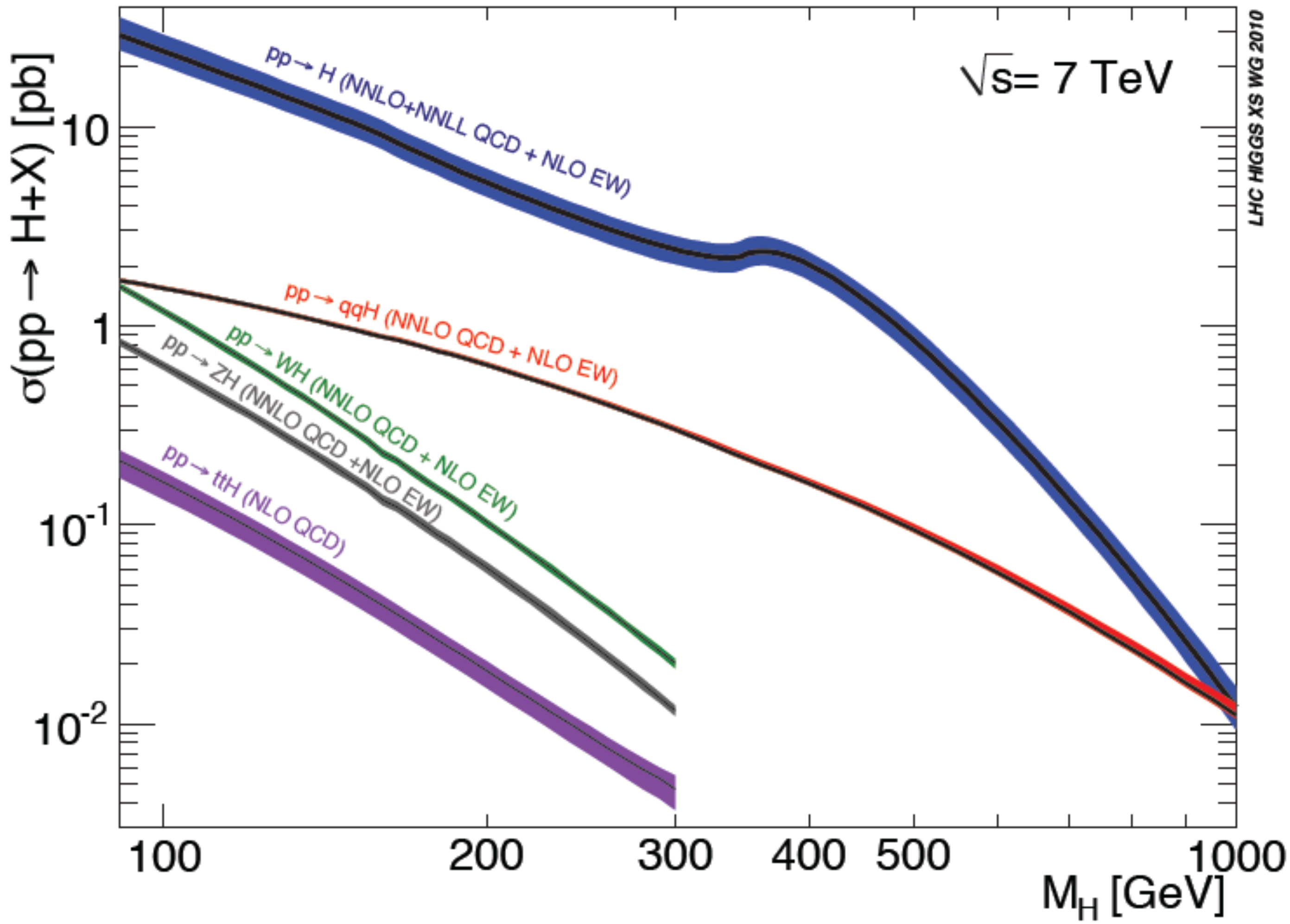
SM Higgs Boson Production

Gluon-gluon production (ttbar loop) dominates.

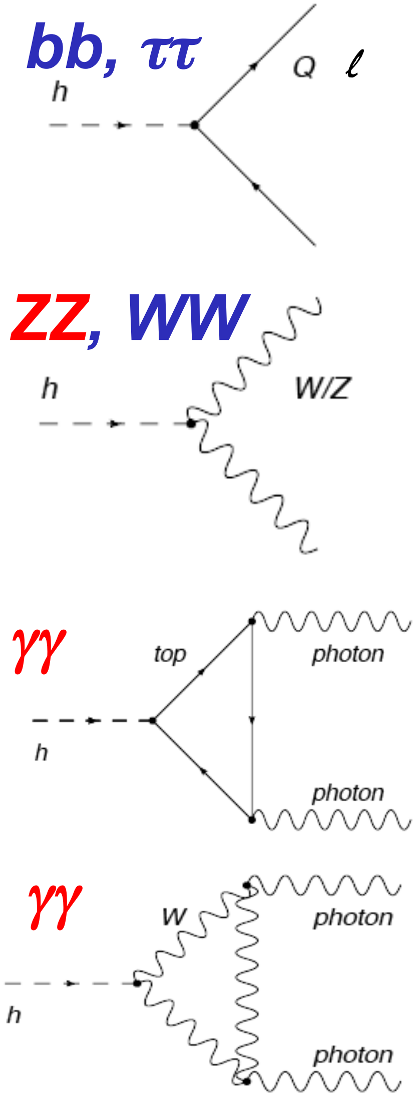
e.g. No. of "H_{125}" produced = 25pb × $10fb^{-1}$ = *250,000*

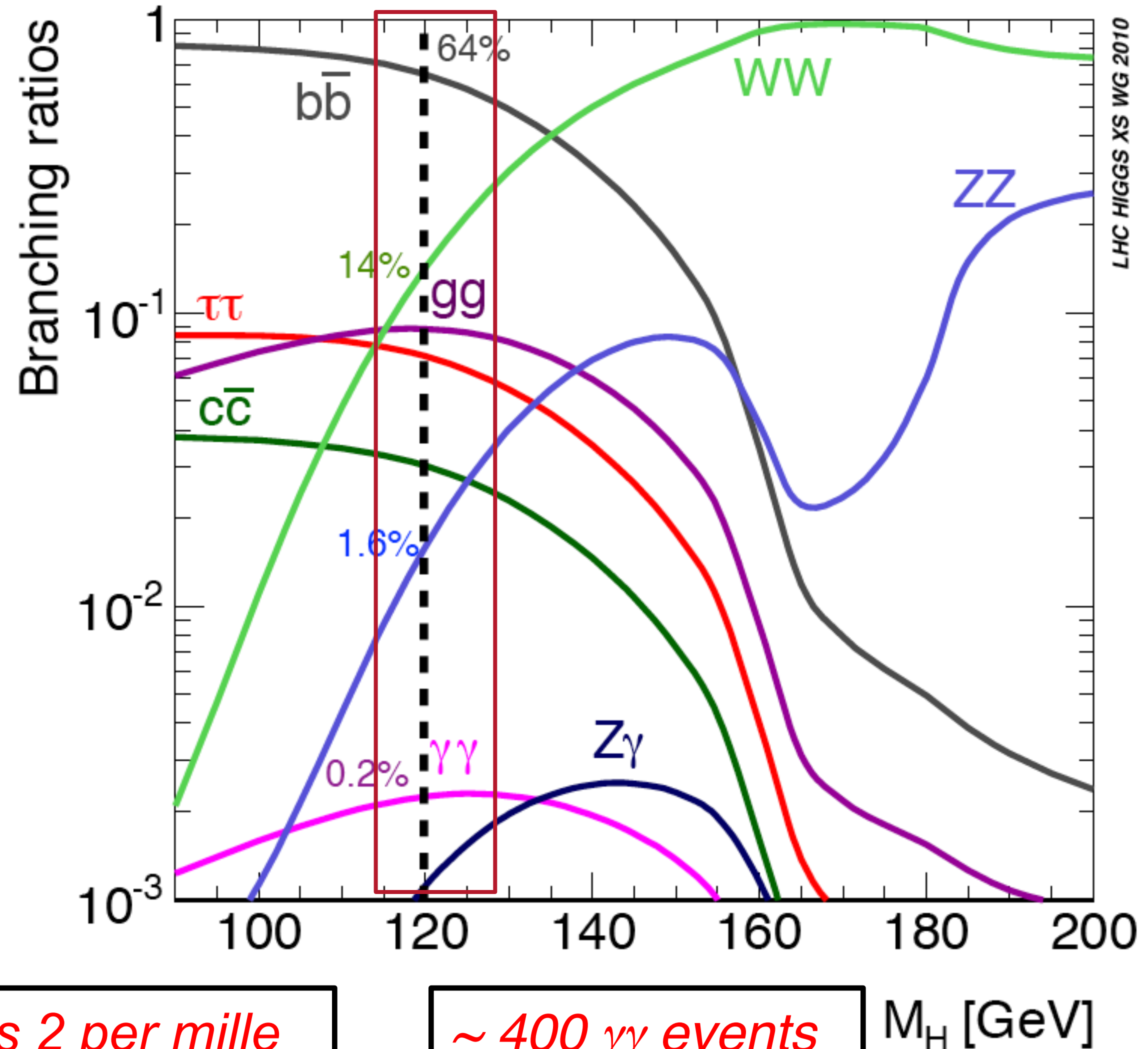


(LHC



SM Higgs Boson Decay



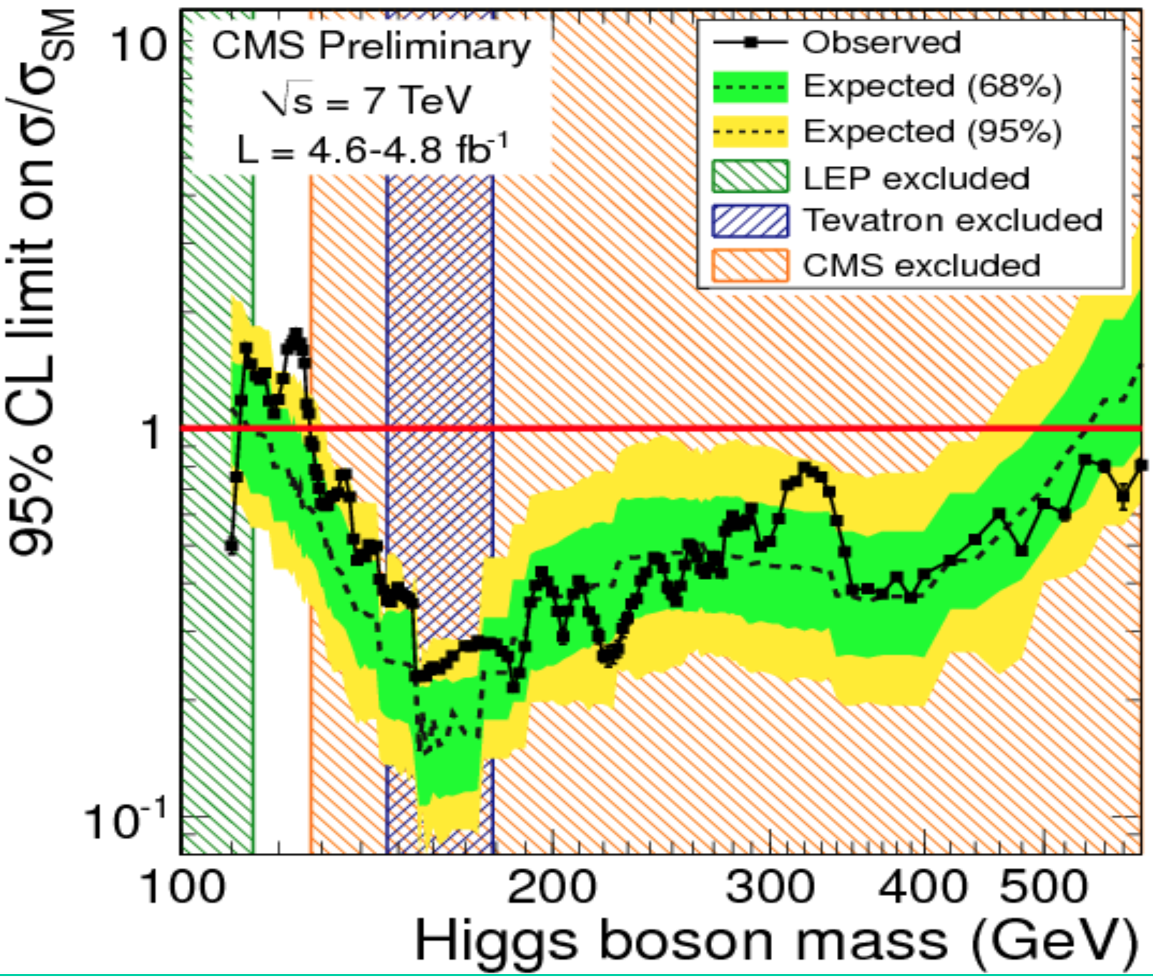


γγ is 2 per mille
ZZ → 4l is ~10^{-4}

→

~ 400 γγ events
~ 10 4l events

2011 Data: Status of Search for the SM Higgs Boson



From 2011 Data

Disfavoured at 99% CL

CMS: 129-525 GeV

ATLAS: 130-486

Dec'11 we said: ***an excess of events is observed around 126(125) GeV with a global significance of 2.2σ (2.1σ) in ATLAS (CMS)***

More data are needed to ascertain the origin of the observed excess

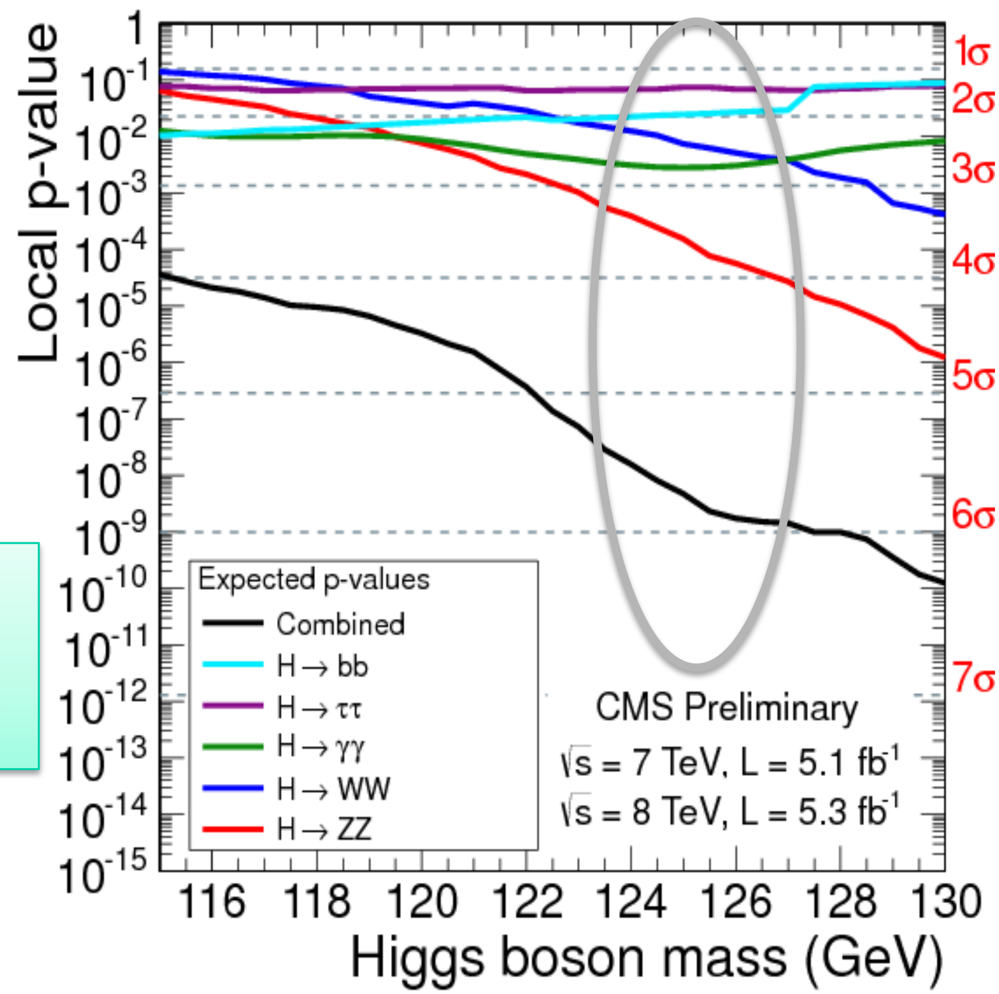
London

2011+2012: CMS Discovery Potential

- **p-values -** probability that **background** fluctuates to give an excess as large as the (average) signal size expected for a SM Higgs.

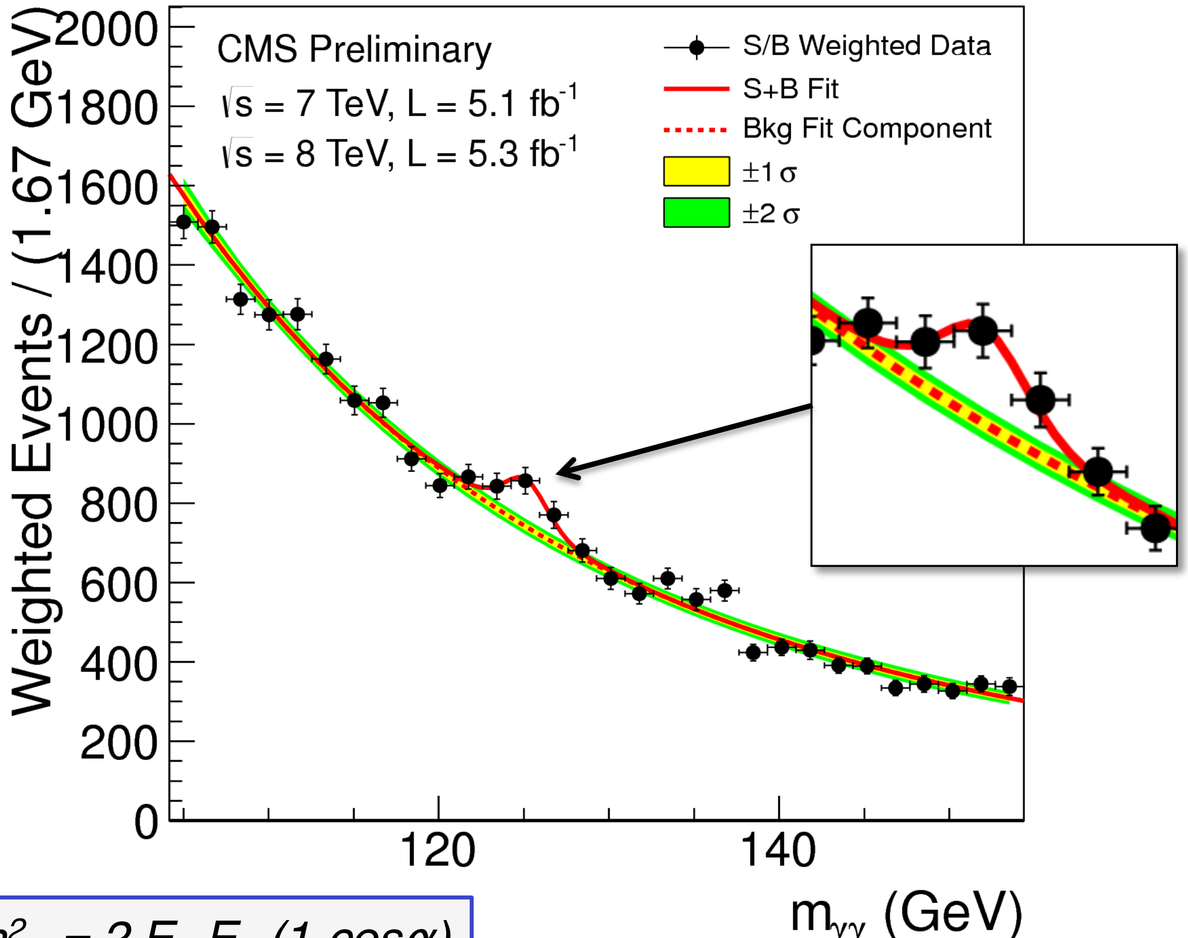
For m_H~125 GeV
CMS Expectation: 5.9σ
ATLAS Expectation: 4.6σ*

** ATLAS 2012: analysis includes only the $\gamma\gamma$ and 4l data*



$\gamma\gamma$ Mass Distribution from CMS

- Sum of mass distributions for each event class, weighted by S/B



$m^2_{\gamma\gamma} = 2\, E_1\, E_2\, (1-\cos\alpha)$

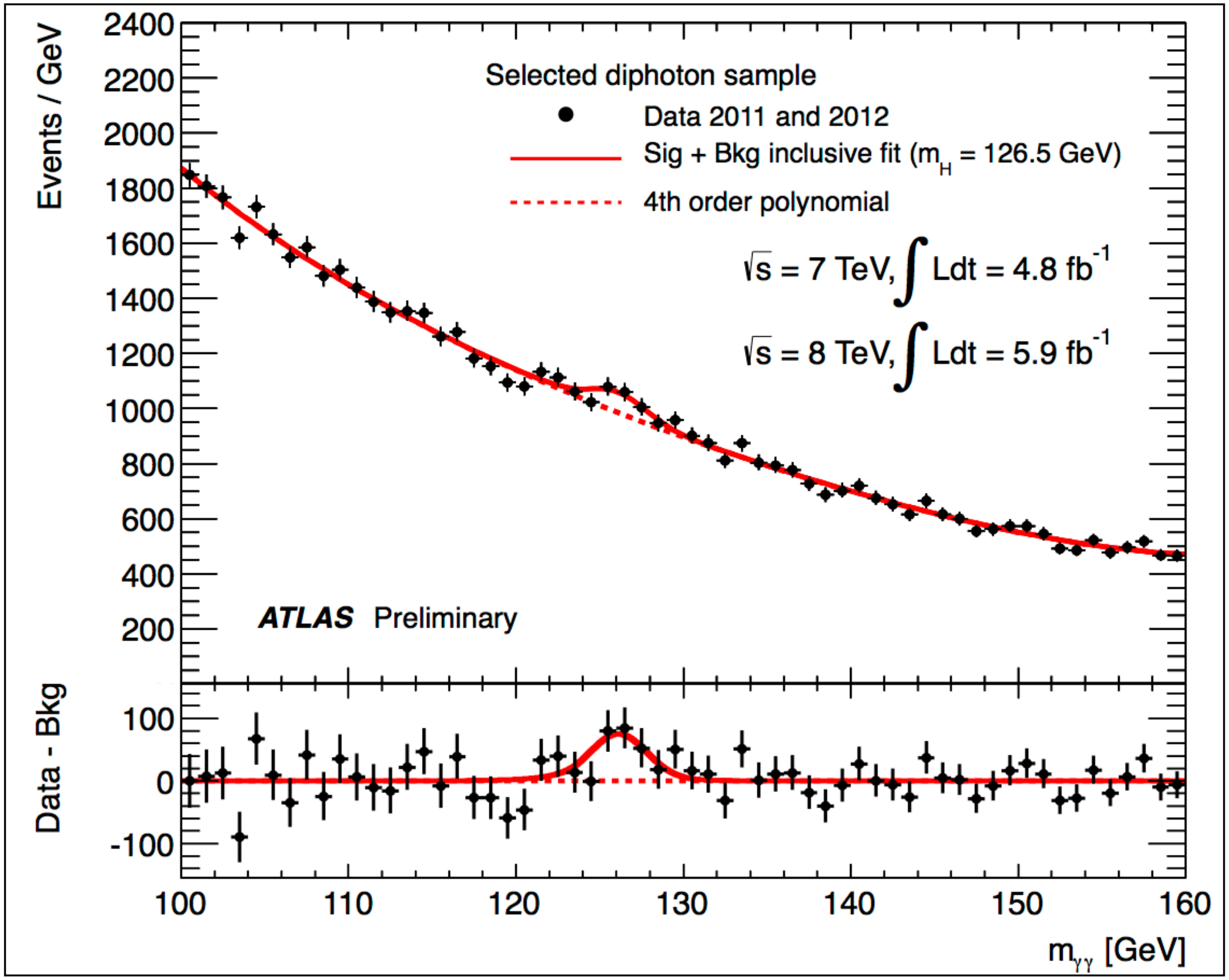
Observe a peak at 125.3 GeV

Local significance
Expected: 2.8σ
Observed: 4.1σ

Fitted signal strength 1.6±0.4 × SM

As particle seen in di-photon mode it must have spin 0 or 2

$\gamma\gamma$ Mass Distribution from ATLAS

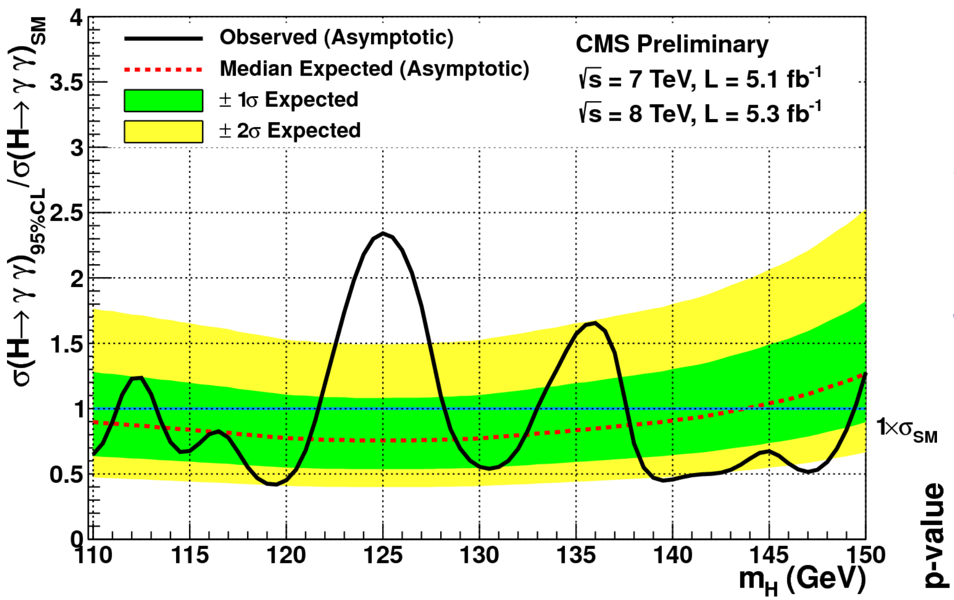


Observe a peak at 126.5 GeV

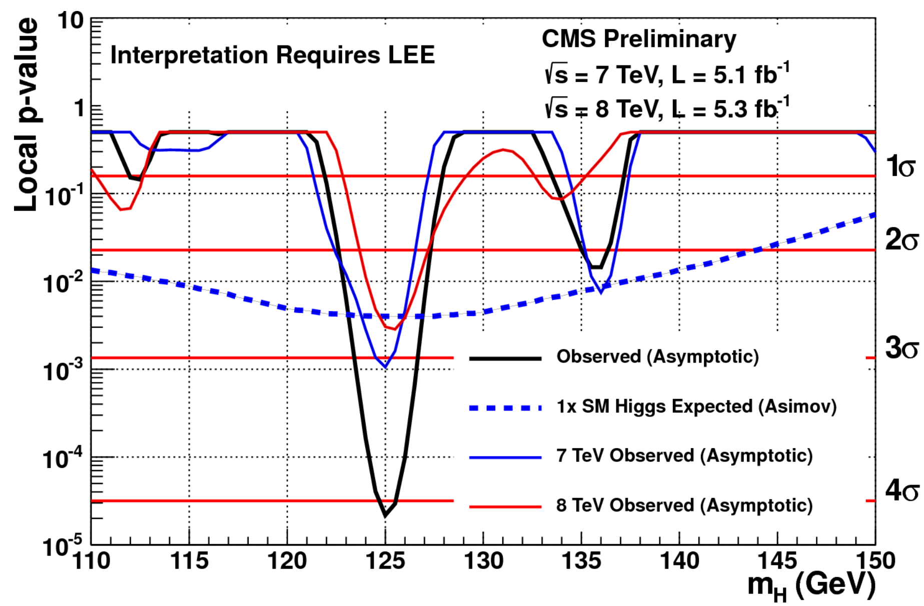
Local significance
Expected: 2.4σ
Observed: 4.5σ

Fitted signal strength
1.9±0.5 × SM

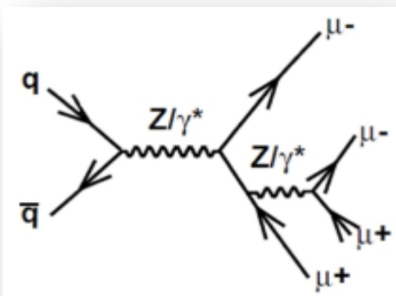
Results for the Search H → γγ

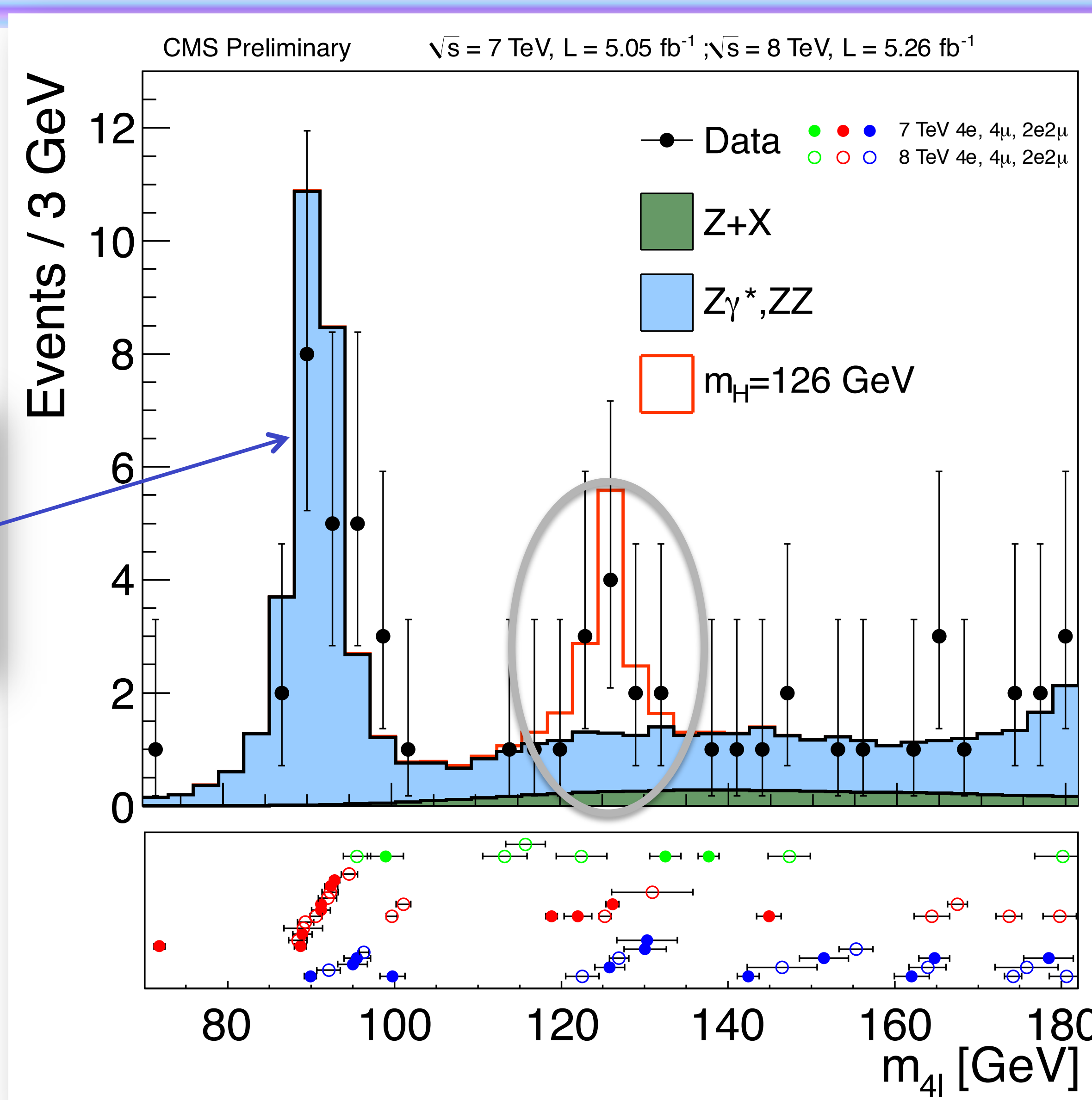


Minimum local p-value at 125 GeV with a local significance of 4.1 σ

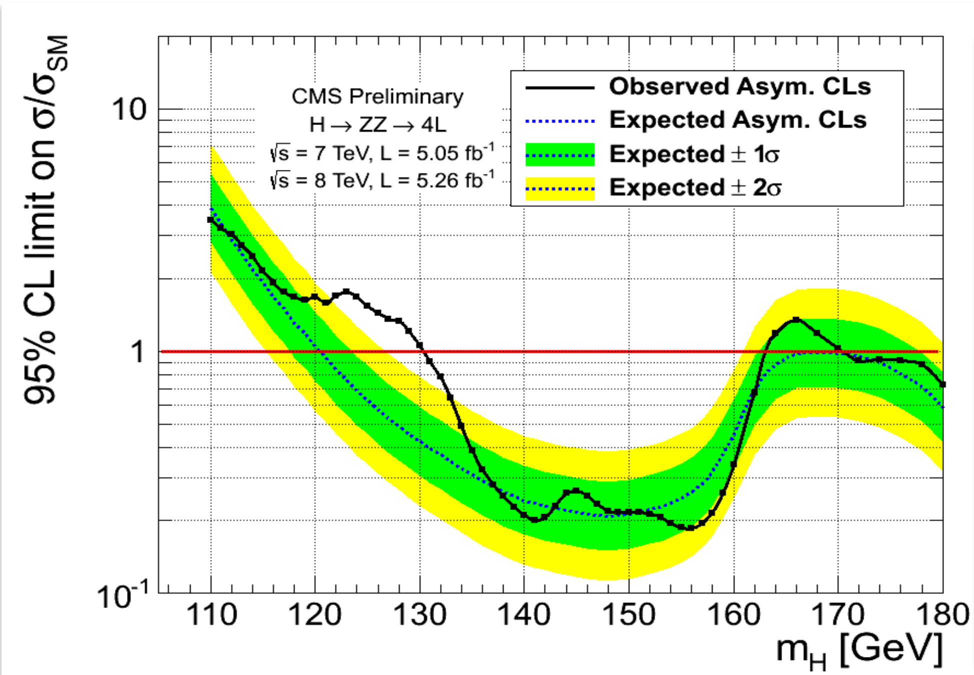


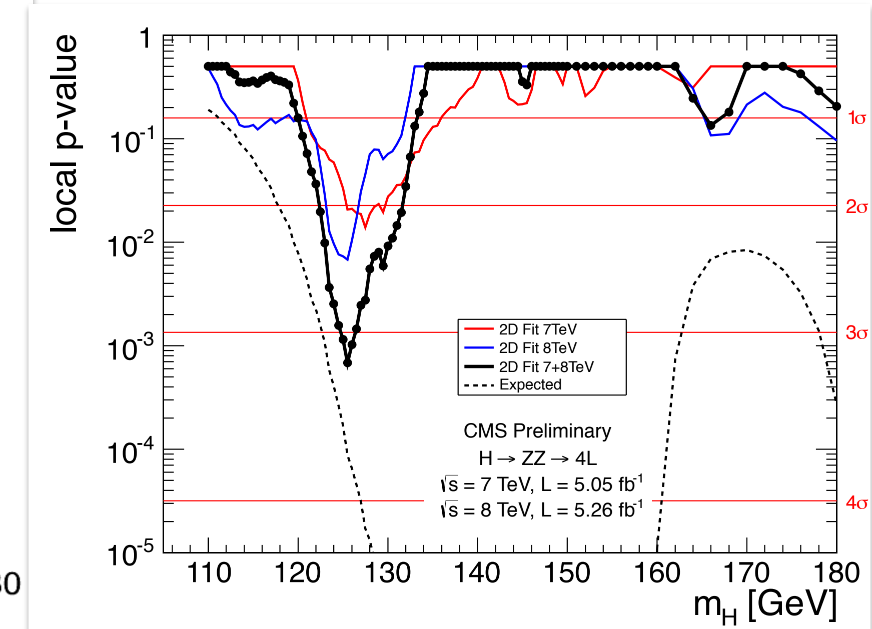
Results: M(4l) spectrum





Search in the ZZ → 4l channel:

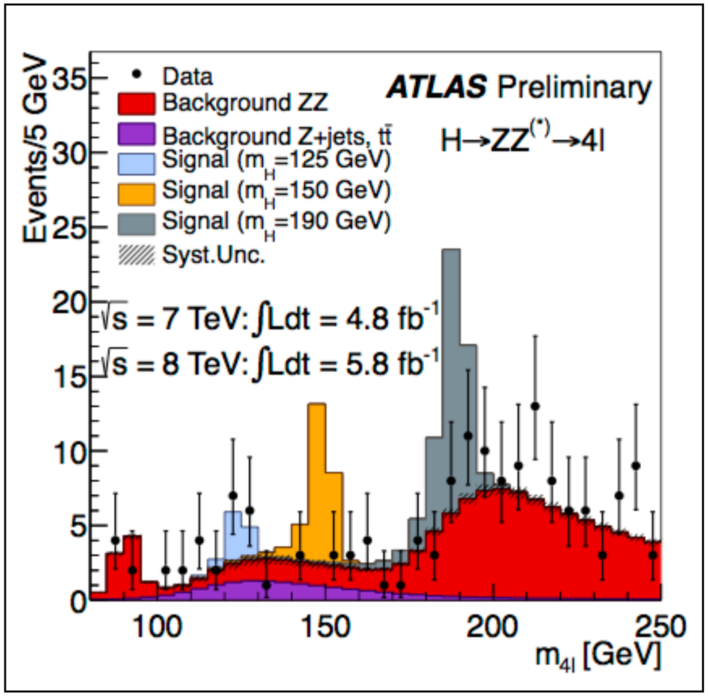


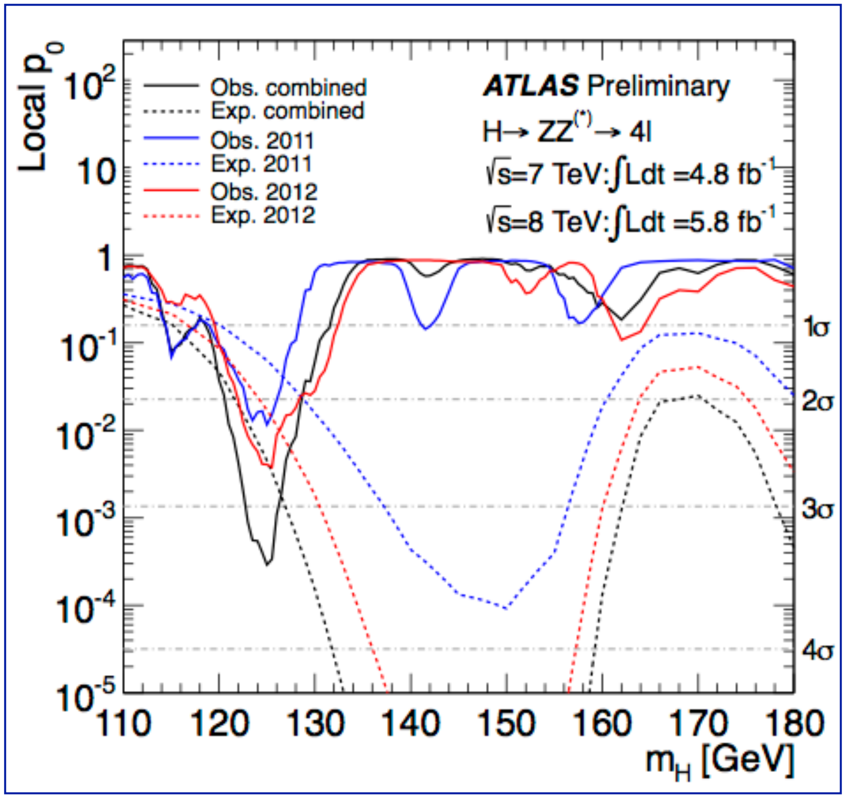


Expected exclusion at 95% CL :
121-550 GeV
Observed exclusion at 95% CL :
131-162 GeV and 172-530 GeV

Expected local significance
at 125.5 GeV : 3.8 σ
Observed local significance
at 125.5 GeV: ***3.2 σ***

Search in the ZZ → 4l channel: ATLAS

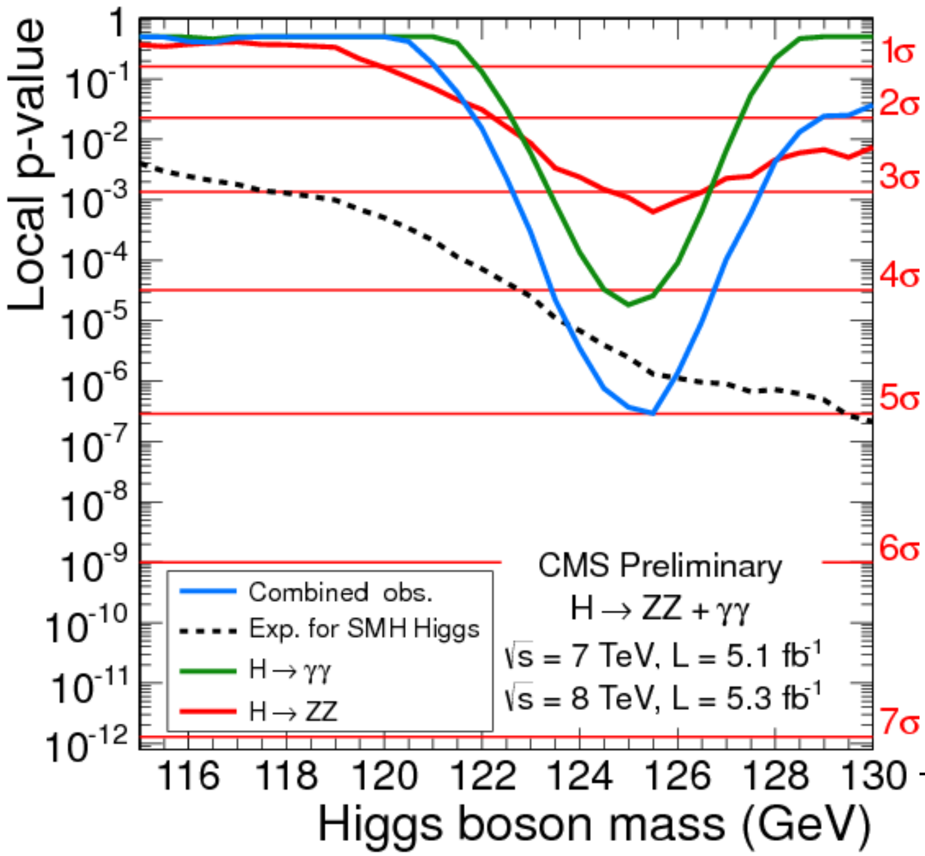


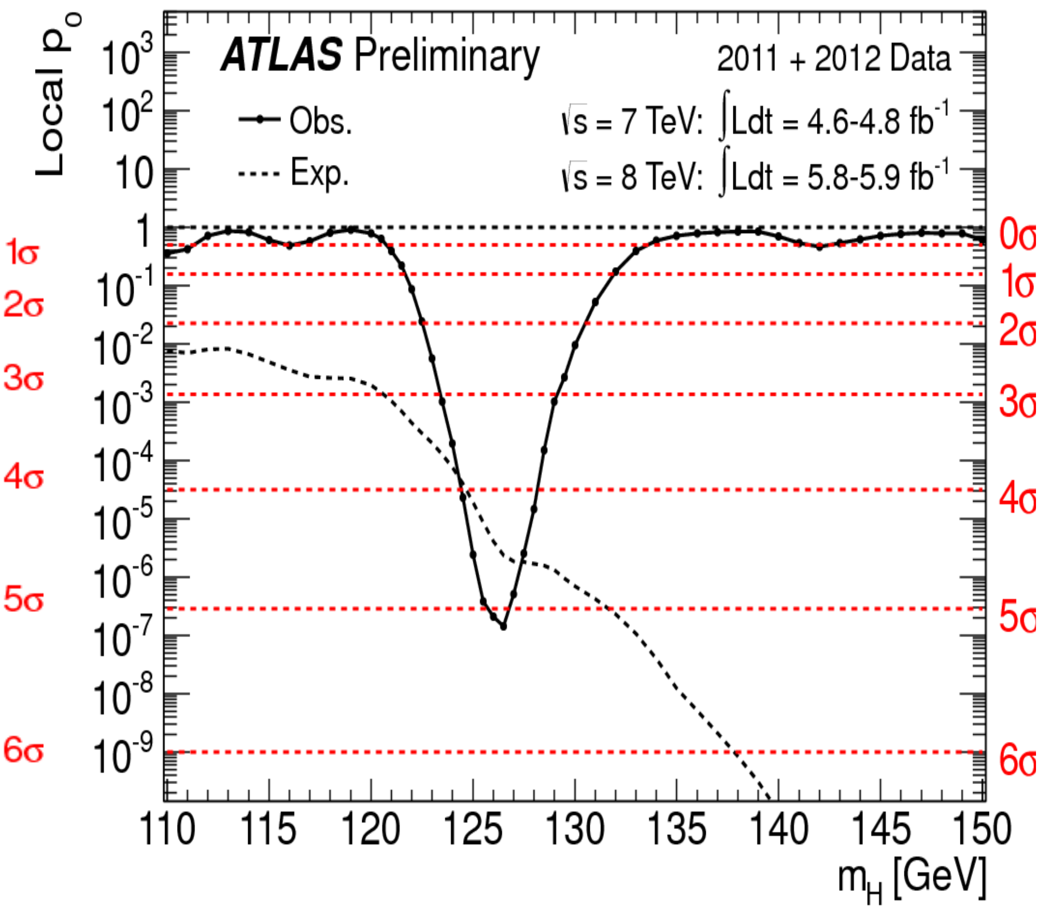


Expected local significance at 125.5 GeV : 2.6 σ
Observed local significance at 125.5 GeV: ***3.4 σ***

Characterization of the Excess

Combination of high sensitivity, high mass resolution channels: γγ + 4l





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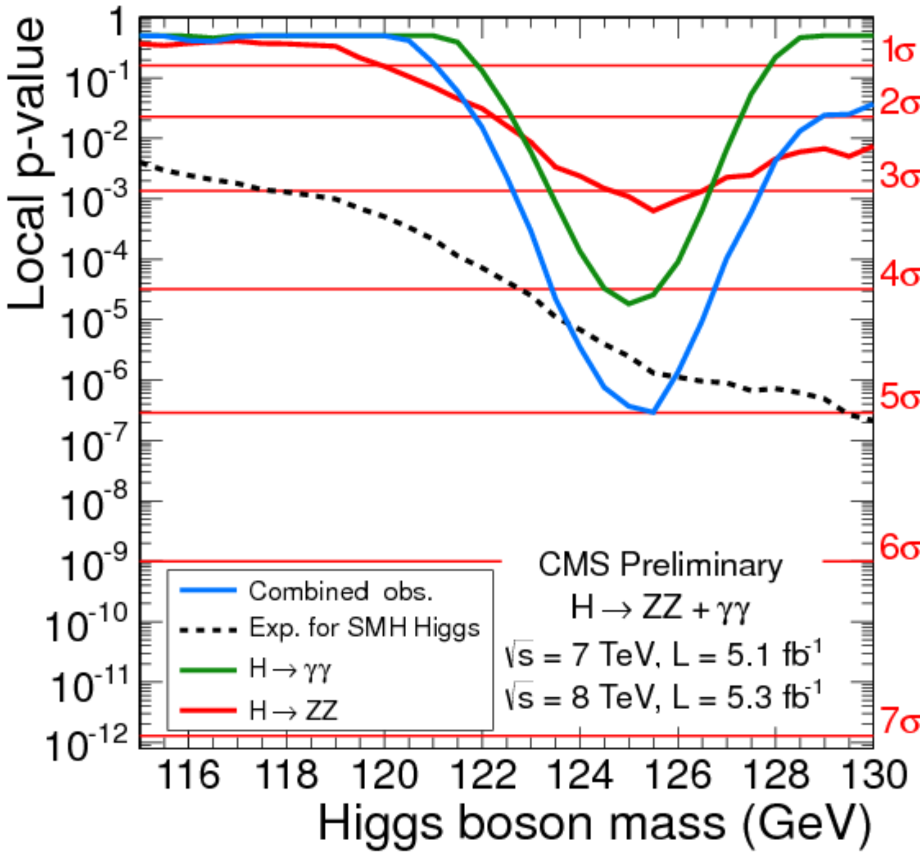


CMS Local significance

Observed:

$\gamma\gamma$: 4.1σ

4 leptons : 3.2σ

CMS combined local significance

Expected: 4.7σ

Observed: 5.0σ

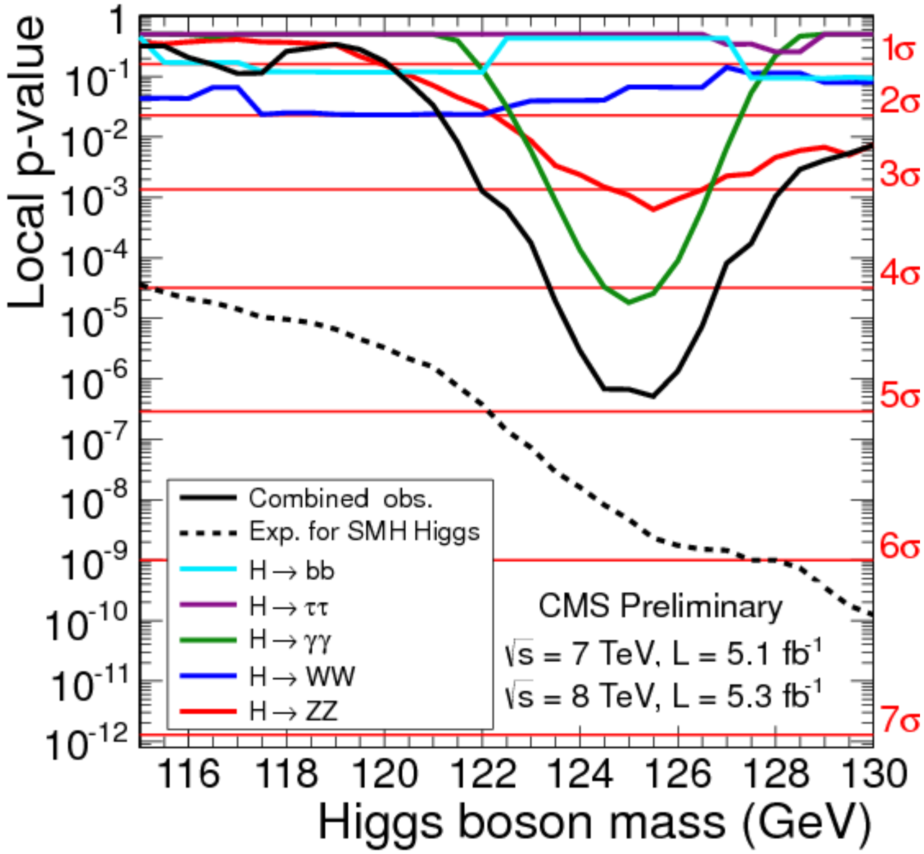
ATLAS combined local significance

Expected: 4.6σ

Observed: 5.0σ

CMS Characterization of the Excess

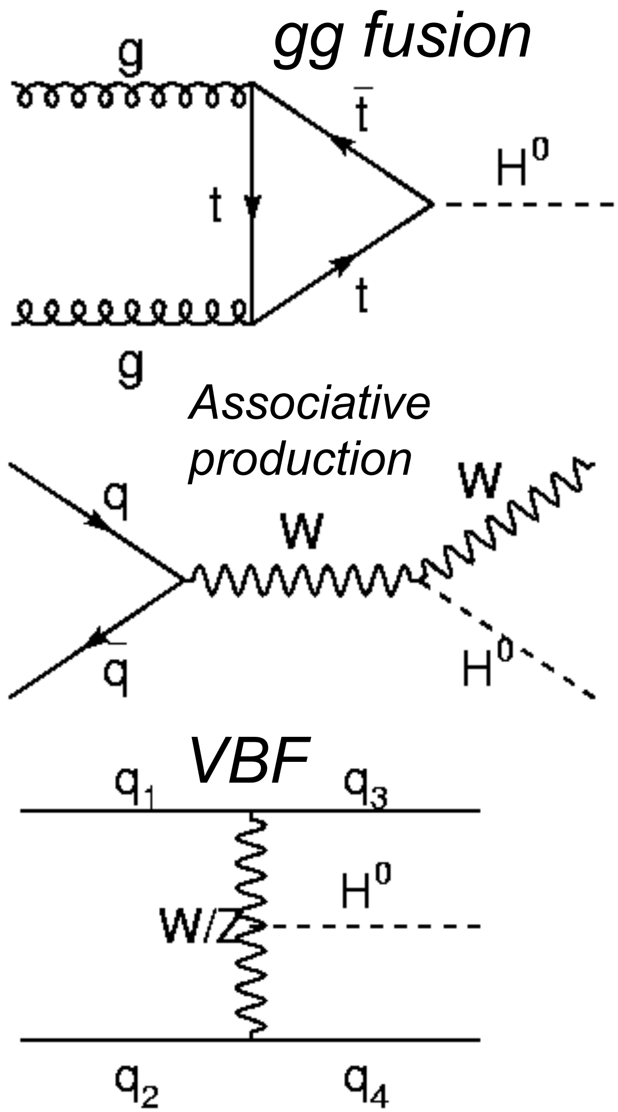
Combining all channels together

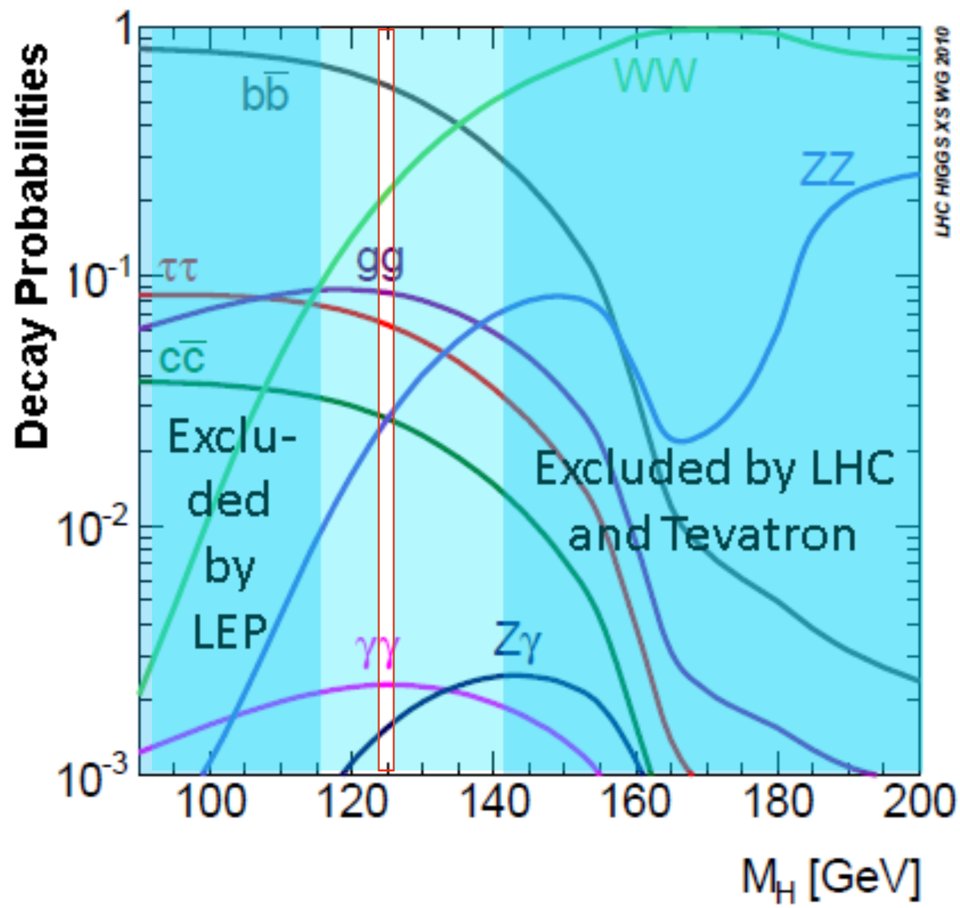


CMS combined local significance
Expected: 5.9σ
Observed: 4.9σ

***ATLAS combined local significance** (only : γγ + 4l 2012 so far)*
Expected: 4.6σ
Observed: 5.0σ

What a 125 GeV Higgs would have to offer...





… a lot! Different production mechanisms and a large variety of decay modes. All will tell us a lot about the nature of such a particle!

A New Boson but is a/THE Higgs?

A New Boson but is a/THE Higgs?

"It is very much a smoking duck that walks and quacks like the Higgs. But we now have to open it up and look inside before we can say that it is indeed the Higgs." [OB to Reuters]

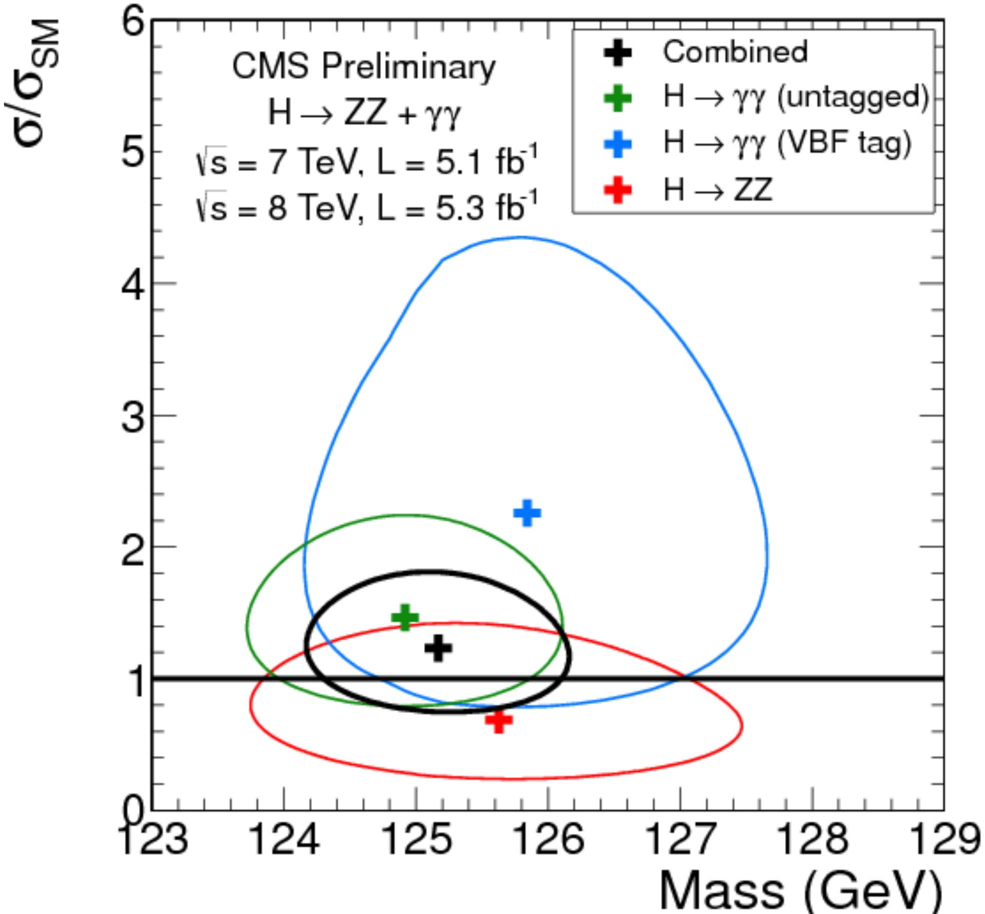
A New Boson but is a/THE Higgs?

"It is very much a smoking duck that walks and quacks like the Higgs. But we now have to open it up and look inside before we can say that it is indeed the Higgs." [OB to Reuters]

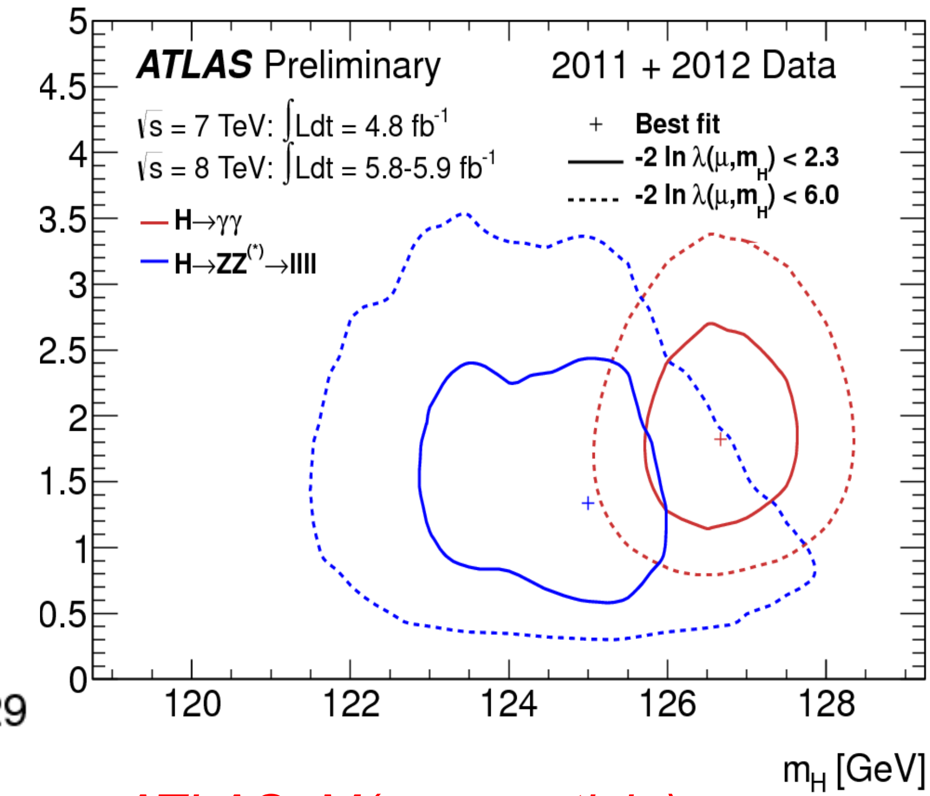
Need to measure the underlying properties of the new boson.

Work on this has just started and it will take some time … .

First Mass Measurement



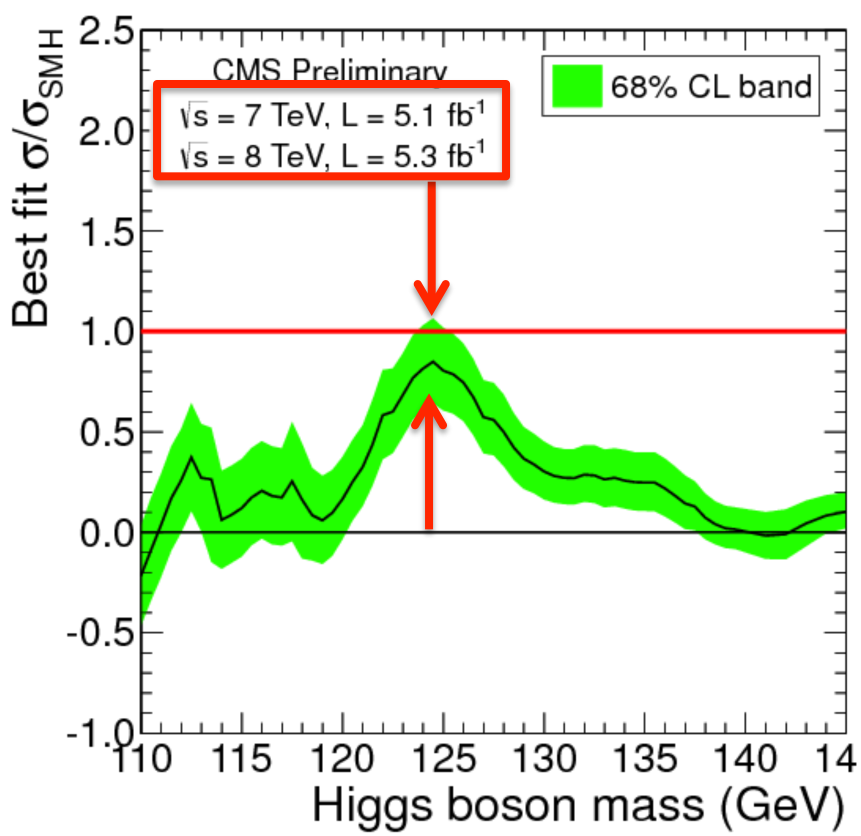
To reduce model dependence, allow for free cross sections in three channels and fit the common mass.

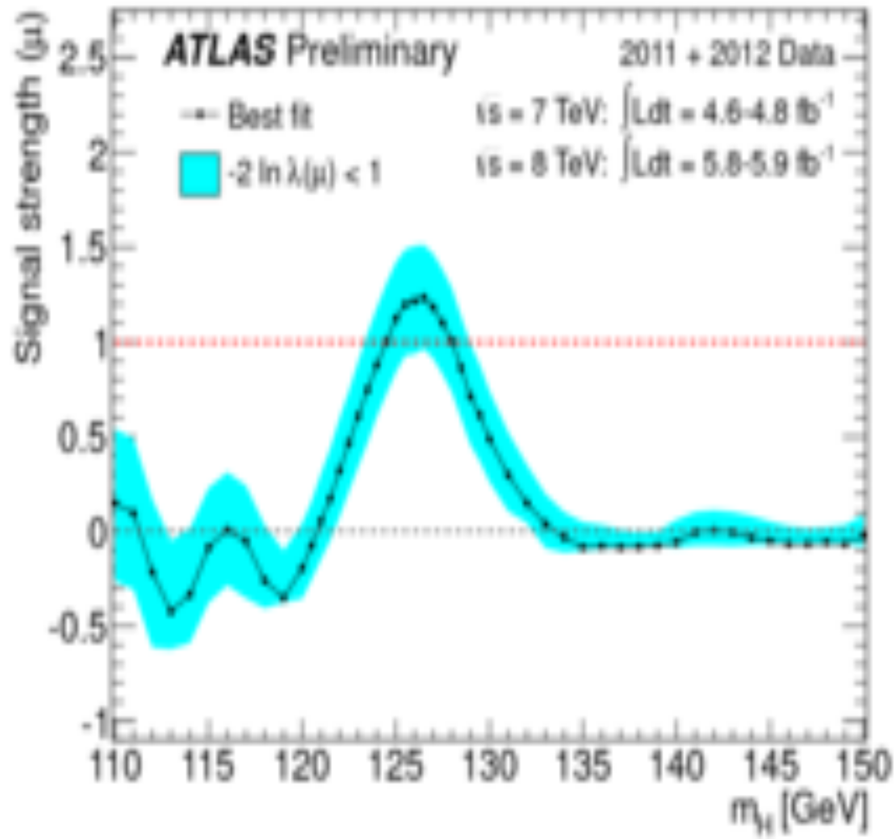


CMS: M(new particle) = 125 ±0.4(stat) ± 0.5(sys)

ATLAS: M(new particle) = 126.5 ±??(stat) ± ??(sys)

Compatibility with the SM Higgs Boson

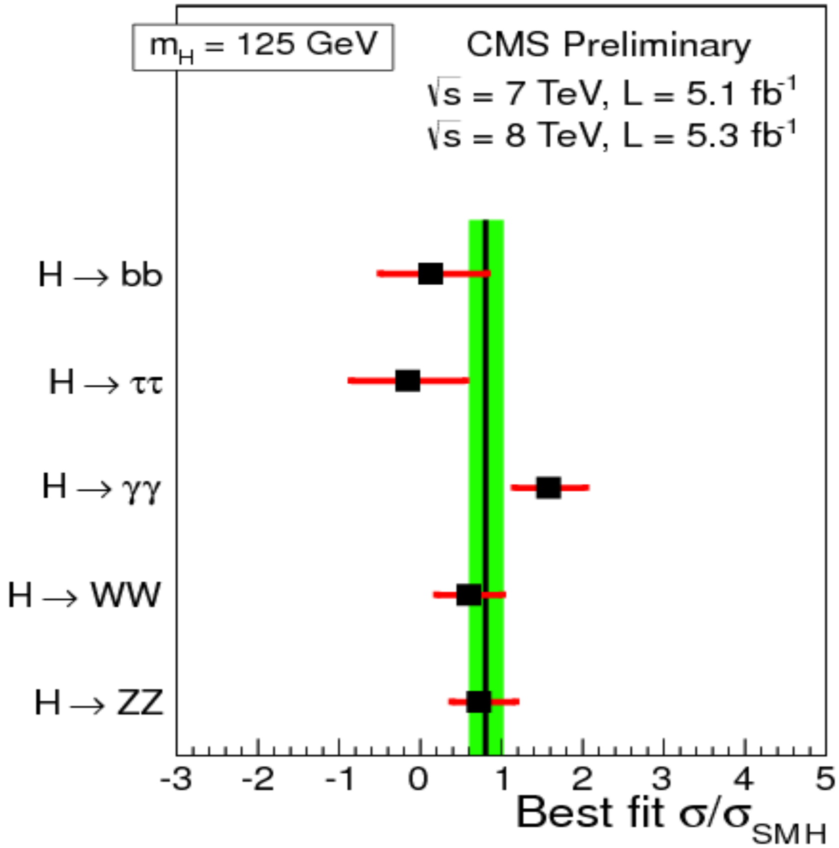


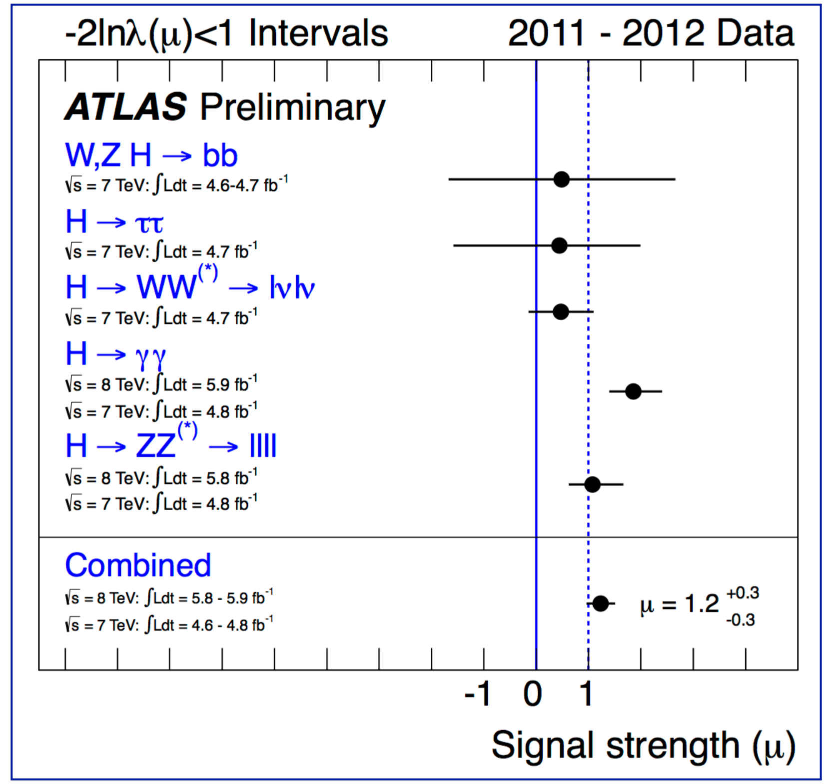


Overall best-fit signal strength in the combination:
σ/σ_{SM} = 0.80±0.22

Overall best-fit signal strength in the combination:
σ/σ_{SM} = 1.2±0.3

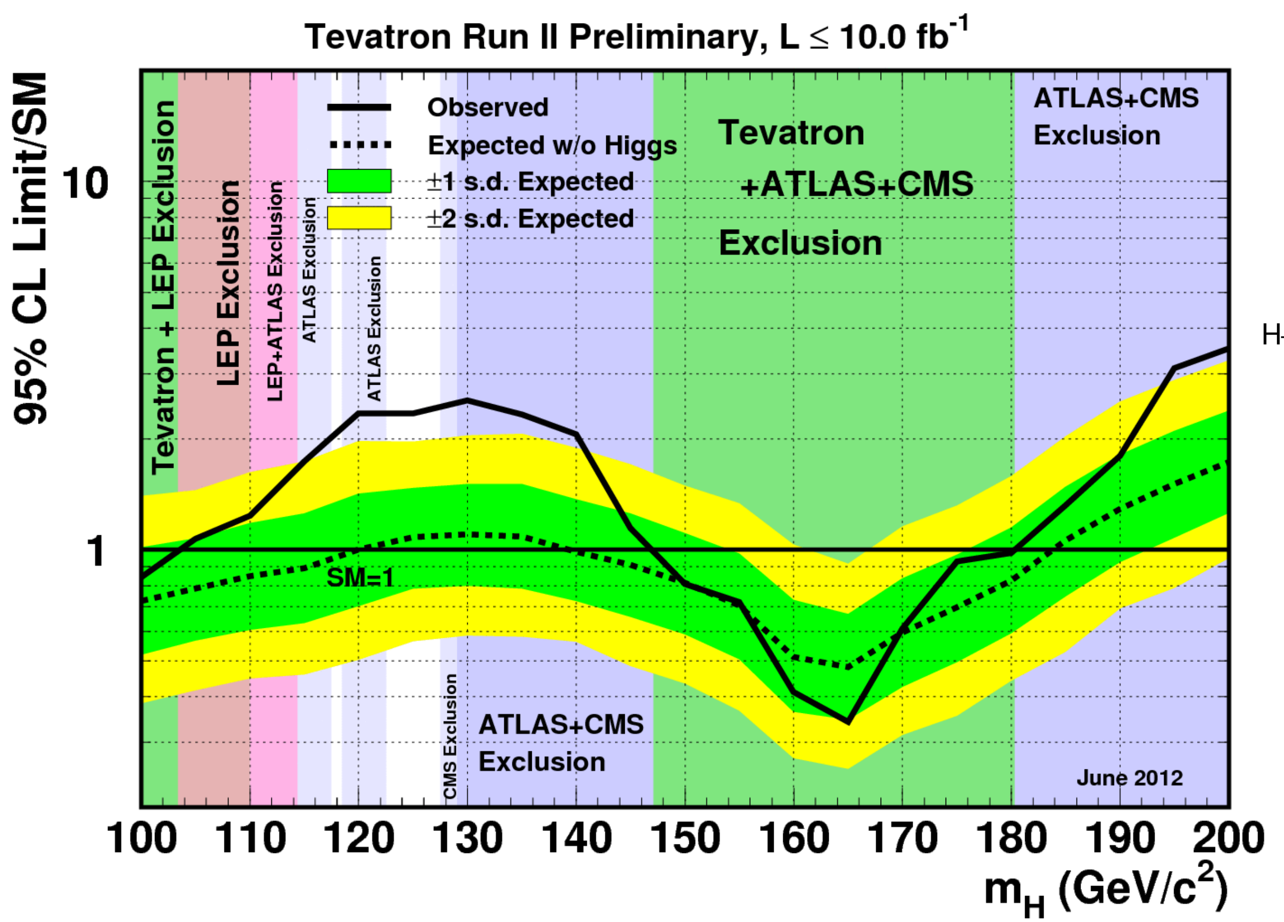
Compatibility with the SM Higgs Boson

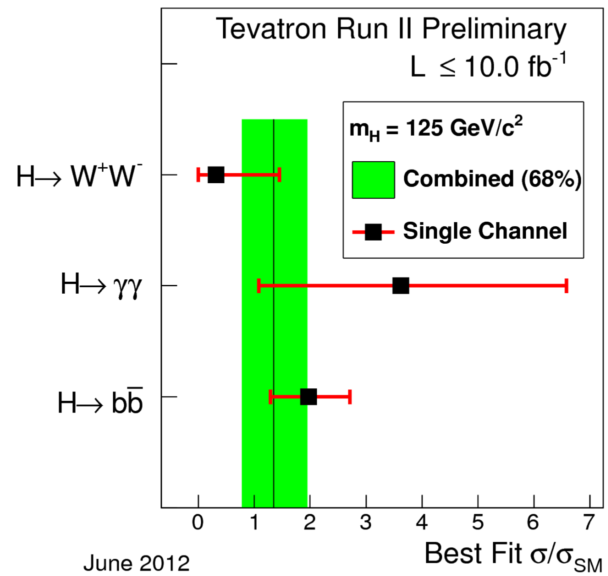




Event yields in different decay modes are self-consistent within the errors

The Tevatron search for the SM Higgs Boson





The discovery of a new boson

CMS has observed a new boson with
*a mass of **125.3 ± 0.6 GeV***
at a significance of 5 standard deviations,
strongest in $\gamma\gamma$ and 4-charged lepton modes

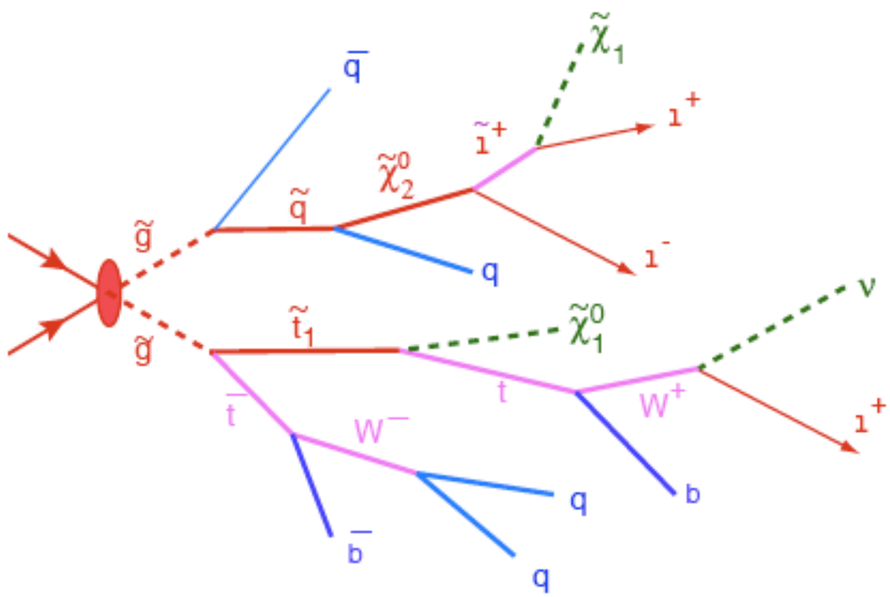
Independently, ATLAS has observed a new
*boson at a similar mass (**126.5 GeV)***
at a significance of 5 standard deviations,
strongest in $\gamma\gamma$ and 4-charged lepton modes

Search for SUSY

What do we call a “SUSY search”?

The definition is purely derived from the experimental signature.
Therefore, a “SUSY search signature” is characterized by

Lots of missing energy, many jets, and possibly leptons in the final state



Missing Energy:
- *from LSP*

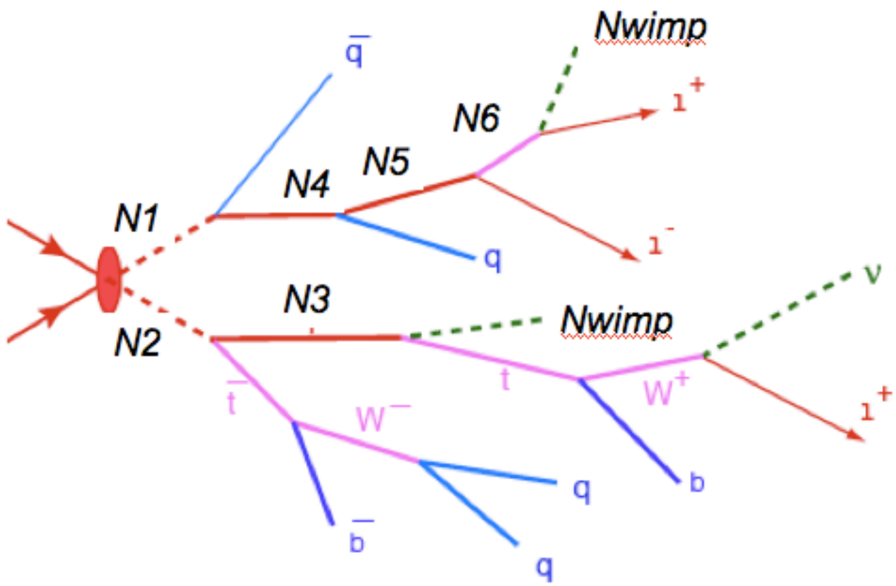
Multi-Jet:
- *from cascade decay (gaugino)*

Multi-Leptons:
- *from decay of charginos/neutralios*

RP-Conserving SUSY is a very prominent example predicting this famous signature but …

What is its experimental signature?

… by no means is it the only New Physics model predicting this experimental pattern. Many other NP models predict this genuine signature



Missing Energy:
- *Nwimp - end of the cascade*

Multi-Jet:
- *from decay of the Ns (possibly via heavy SM particles like top, W/Z)*

Multi-Leptons:
- *from decay of the N's*

Model examples are Extra dimensions, Little Higgs, Technicolour, etc but a more generic definition for this signature is as follows.

Early Search Strategy (2010+2011)

0-leptons	1-lepton	OSDL	SSDL	≥3 leptons	2-photons	γ+lepton
Jets + MET	Single lepton + Jets + MET	Opposite-sign di-lepton + jets + MET	Same-sign di-lepton + jets + MET	Multi-lepton	Di-photon + jet + MET	Photon + lepton + MET

- Generic missing energy signatures
- Categorised by numbers of leptons and photons
- Many include jet requirement ➔ strong production

Early Search Strategy (2010+2011)

0-leptons	1-lepton	OSDL	SSDL	≥3 leptons	2-photons	γ+lepton
Jets + MET	Single lepton + Jets + MET	Opposite-sign di-lepton + jets + MET	Same-sign di-lepton + jets + MET	Multi-lepton	Di-photon + jet + MET	Photon + lepton + MET

- Very challenging due to large amount and wide range of backgrounds
- However most sensitive search for strongly produced SUSY
- CMS pursues several complementary strategies based on kinematics and detector understanding
- Extend to b, τ and top-tagged final states

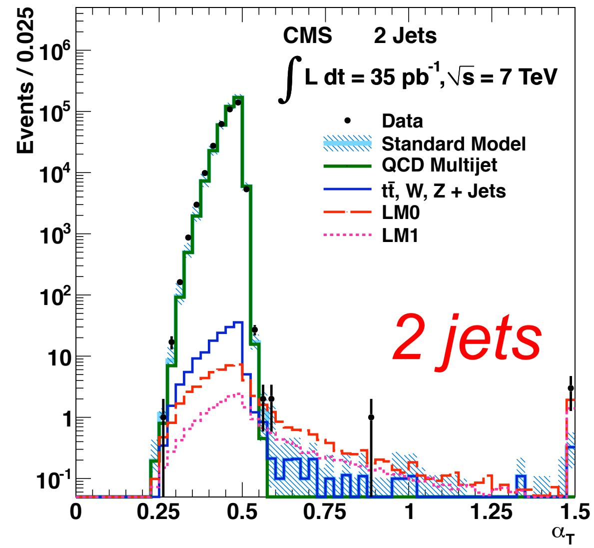
First SUSY Search of the LHC

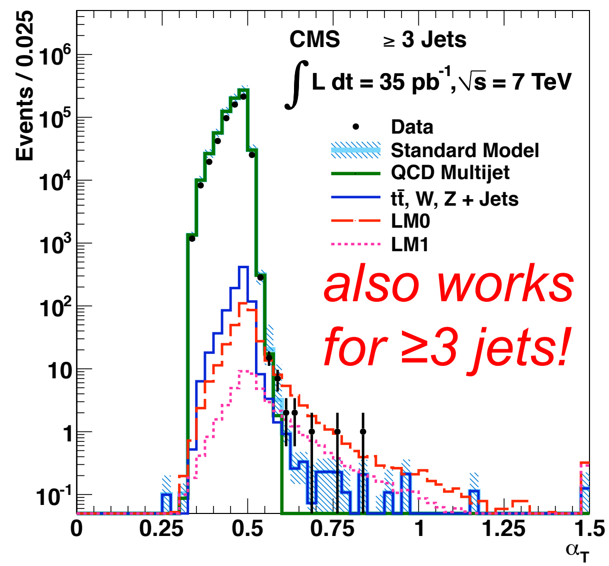
The "QCD killer" $a_T = \frac{E_{T\,j2}}{M_{T\,j1j2}} = \frac{\sqrt{E_{T\,j2}/E_{T\,j1}}}{\sqrt{2(1-\cos\Delta\varphi)}} \leq 0.5$

- Event selection:
  - Require >=2 jets with p_T>50 GeV
  - *leading 2 jets with p_T > 100 GeV*
  - Scalar sum of jet p_T, H_T > 350 GeV
  - Explicit veto on
    - isolated el/mu with p_T>10 GeV
    - photons with p_T > 25 GeV
  - α_T > 0.55
- QCD multijet events eliminated

Slide from 2010

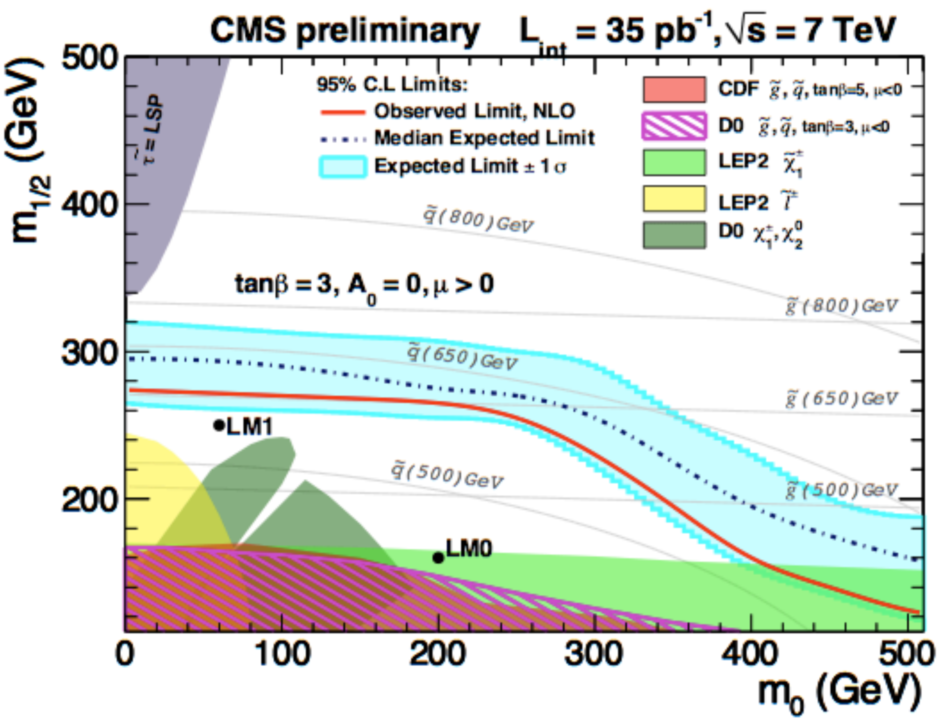
Selection	Data	SM	QCD multijet	$Z \to \nu\bar{\nu}$	W + jets	$t\bar{t}$
$H_T > 250$ GeV	4.68M	5.81M	5.81M	290	2.0k	2.5k
$E_T^{j2} > 100$ GeV	2.89M	3.40M	3.40M	160	610	830
$H_T > 350$ GeV	908k	1.11M	1.11M	80	280	650
$\alpha_T > 0.55$	37	30.5±4.7	19.5±4.6	4.2±0.6	3.9±0.7	2.8±0.1
$\Delta R_{ECAL} > 0.3 \vee \Delta\phi^* > 0.5$	32	24.5±4.2	14.3±4.1	4.2±0.6	3.6±0.6	2.4±0.1
$R_{miss} < 1.25$	13	9.3±0.9	0.03±0.02	4.1±0.6	3.3±0.6	1.8±0.1

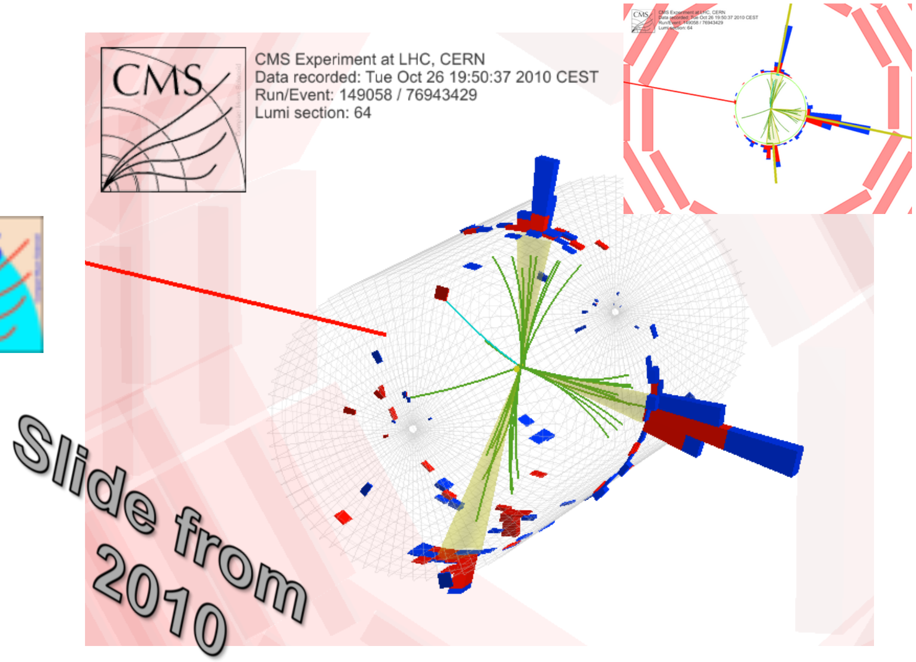




Exclusion in the CMSSM

- CMSSM: 4 parameter model assuming common gaugino and scalar masses at GUT scale ($m_{1/2}$, m_0)
- *In absence of signal, calculate* 95% CL exclusion limit using Feldman-Cousins
- *tanβ independent exclusion*
- *Exclude squark and gluino masses of ~550-650 GeV in CMSSM*



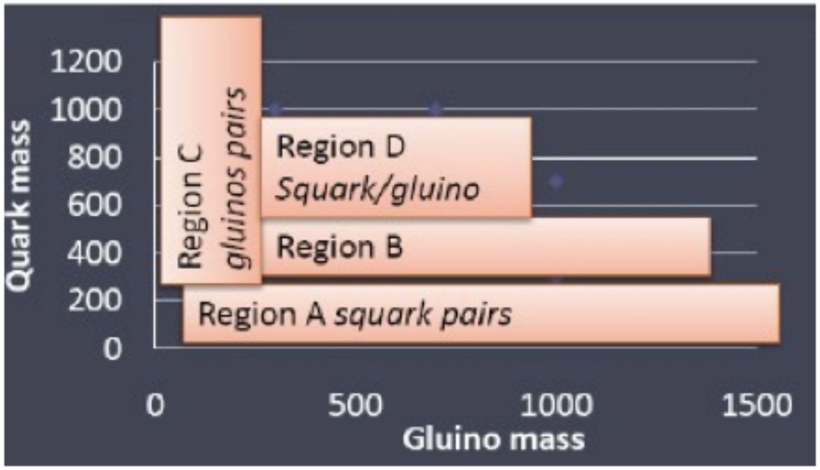


- Selection efficiency approximately production-process independent

Production mechanism	Yields for 35 pb^{-1}	ϵ_{total}(%)	$\epsilon_{signature}$(%)
$\tilde{q}\,\tilde{q}$	9.7±0.1	16.0±0.1	22.2±0.4
$\tilde{q}\,\tilde{g}$	8.8±0.1	14.4±0.1	23.0±0.5
$\tilde{g}\,\tilde{g}$	0.71±0.02	12.0±0.4	22.5±2.0

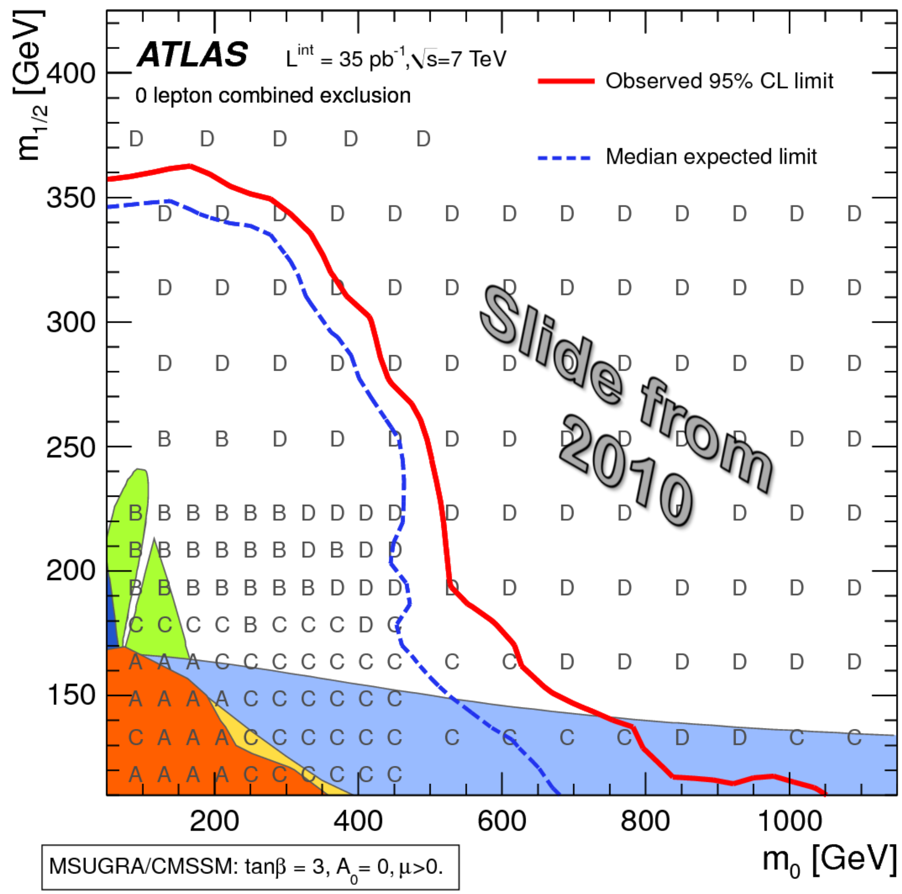
- *12% uncertainty on signal efficiency, dominated by 11% luminosity uncertaint*

ATLAS: Jets+E_t^{miss}

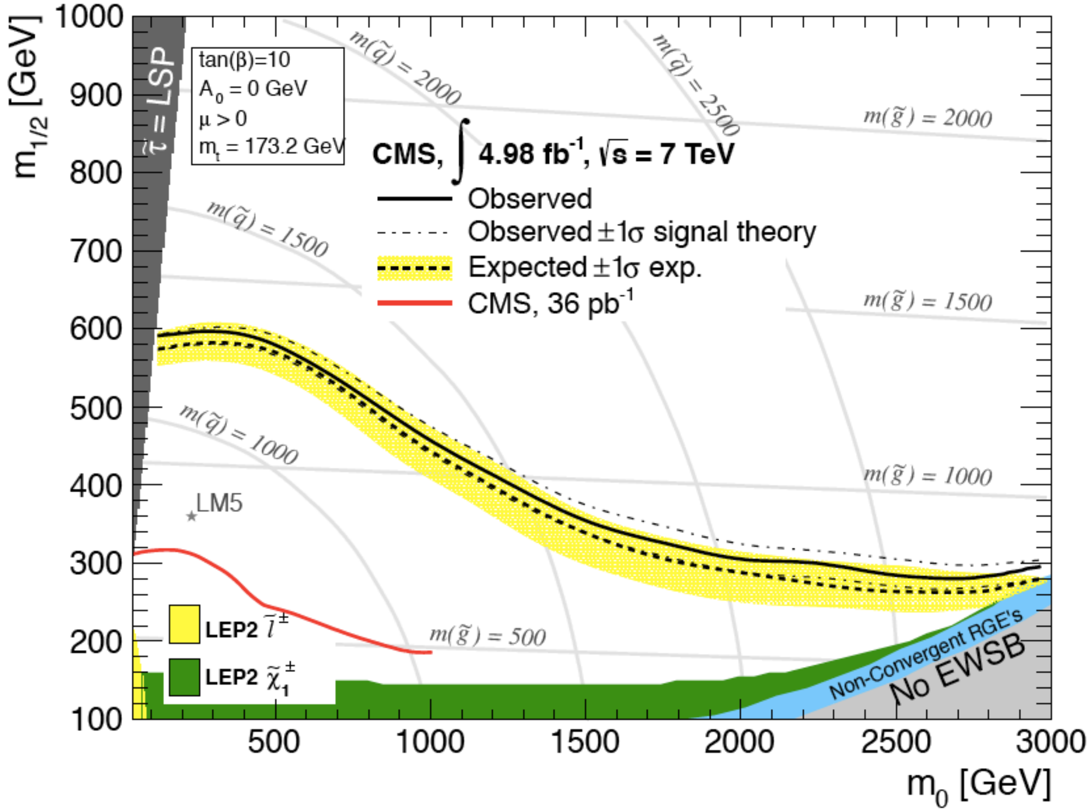


		A	B	C	D
Pre-selection	Number of required jets	≥ 2	≥ 2	≥ 3	≥ 3
	Leading jet p_T [GeV]	> 120	> 120	> 120	> 120
	Other jet(s) p_T [GeV]	> 40	> 40	> 40	> 40
	E_T^{miss} [GeV]	> 100	> 100	> 100	> 100
Final selection	$\Delta\phi(\text{jet}, \vec{P}_T^{miss})_{min}$	> 0.4	> 0.4	> 0.4	> 0.4
	E_T^{miss}/m_{eff}	> 0.3	–	> 0.25	> 0.25
	m_{eff} [GeV]	> 500	–	> 500	> 1000
	m_{T2} [GeV]	–	> 300	–	–

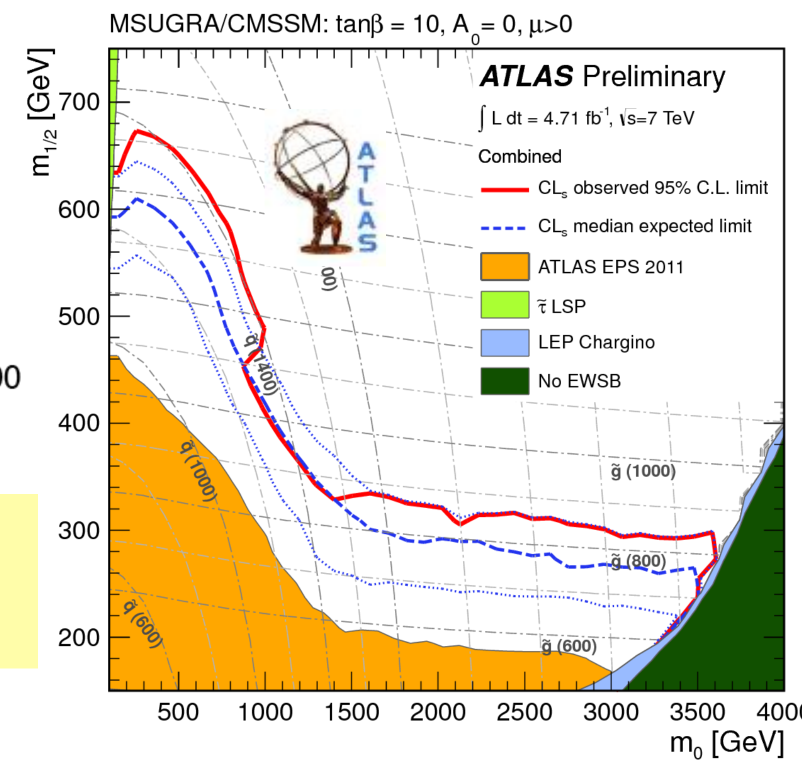
Define search in categories to cover different signatures and to improve sensitivity (e.g. in CMSSM).



Jets+E_T^{miss}: (Today)



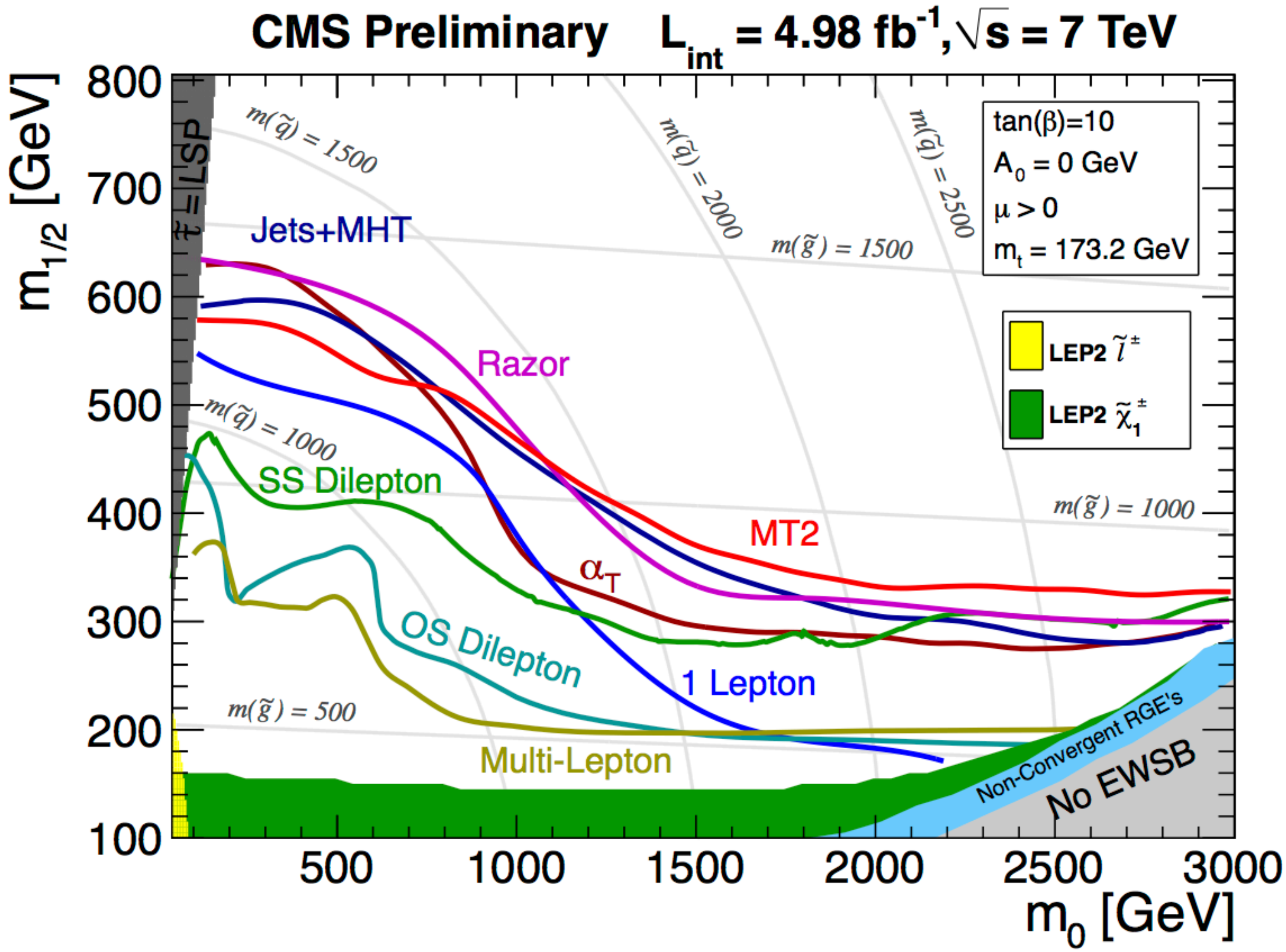
ATLAS & CMS are very similar in sensitivity.



Probing already 1 TeV mass scale and beyond for squarks and gluinos.

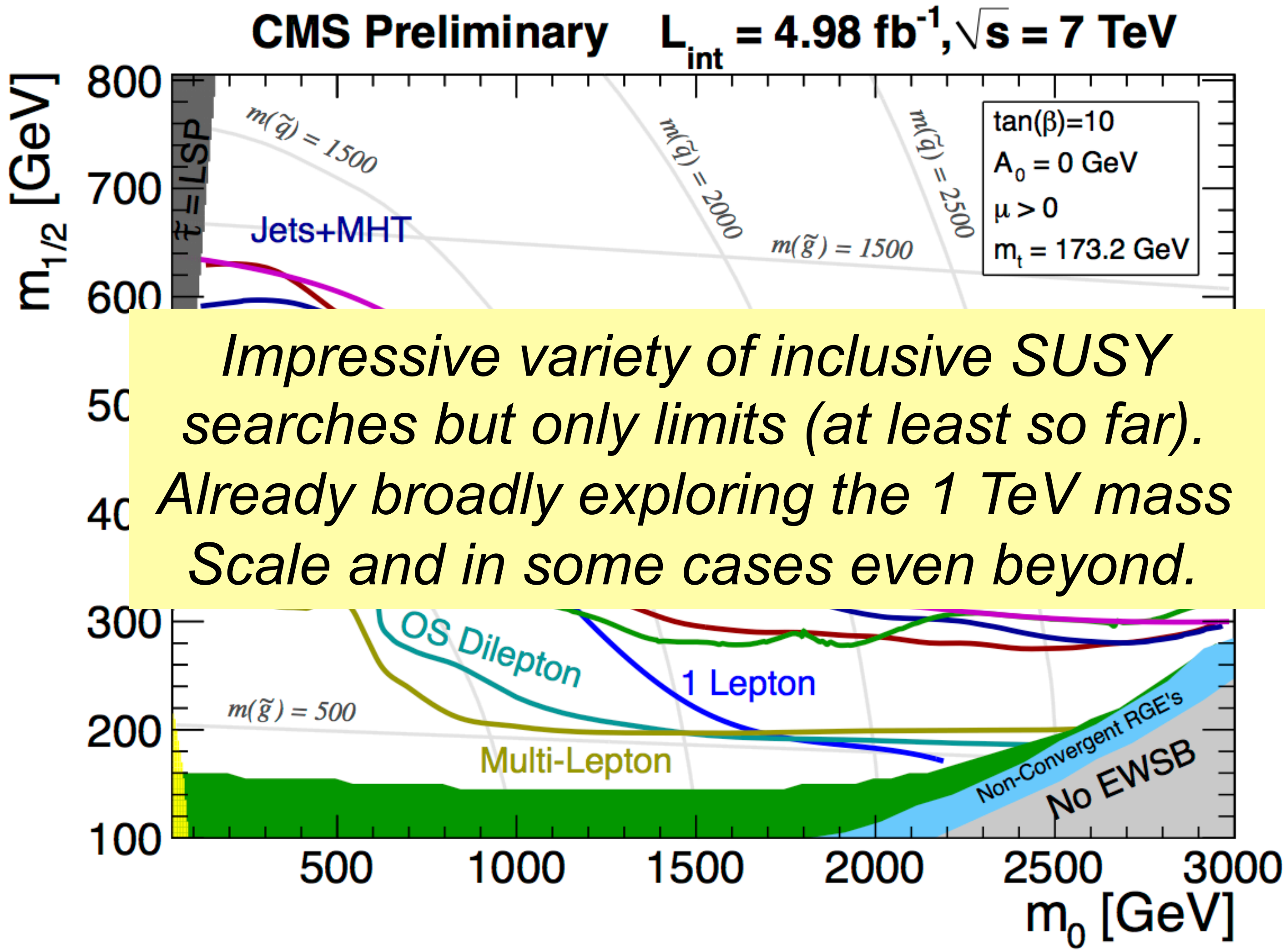
Inclusive SUSY Searches

Landscape Today: Example CMS



Inclusive SUSY Searches

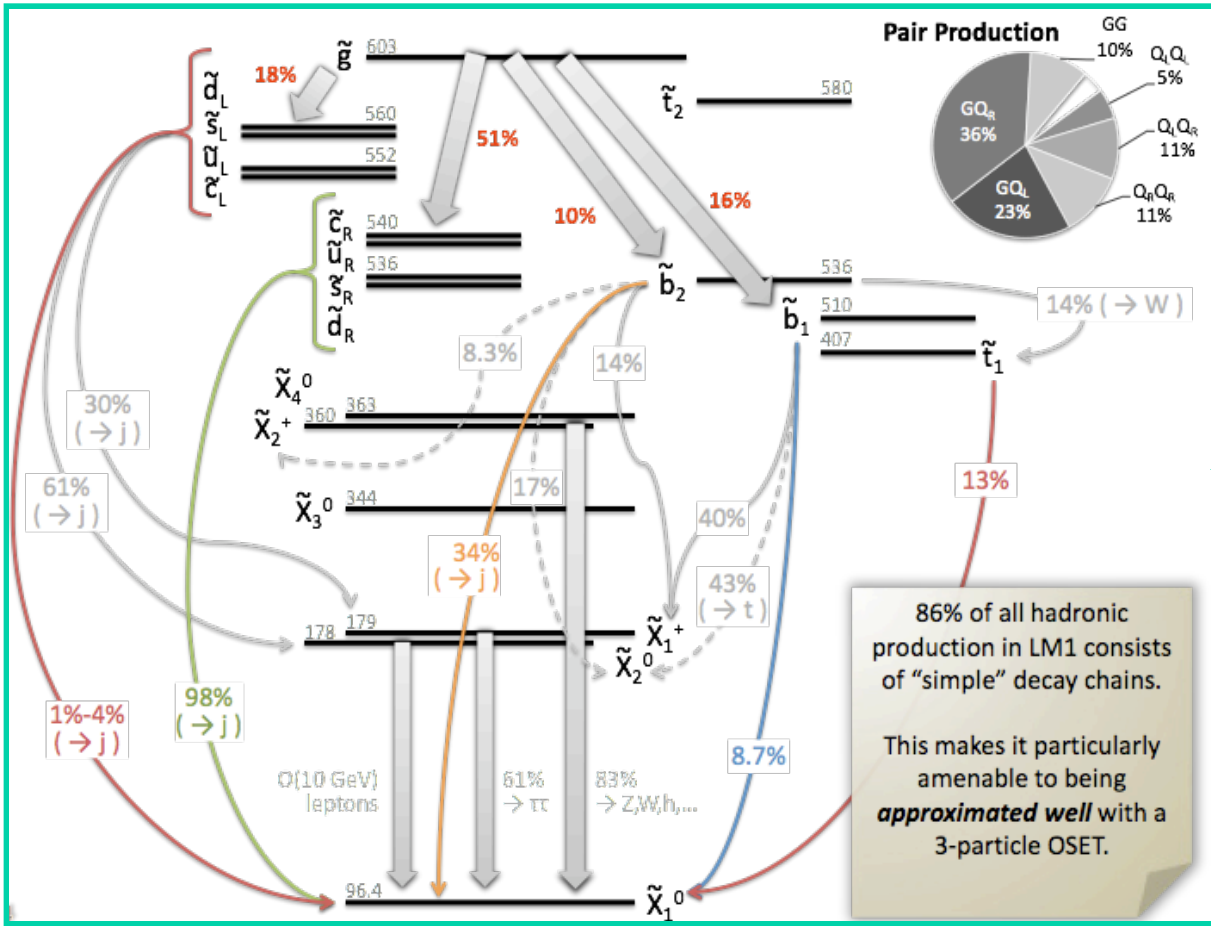
Landscape Today: Example CMS



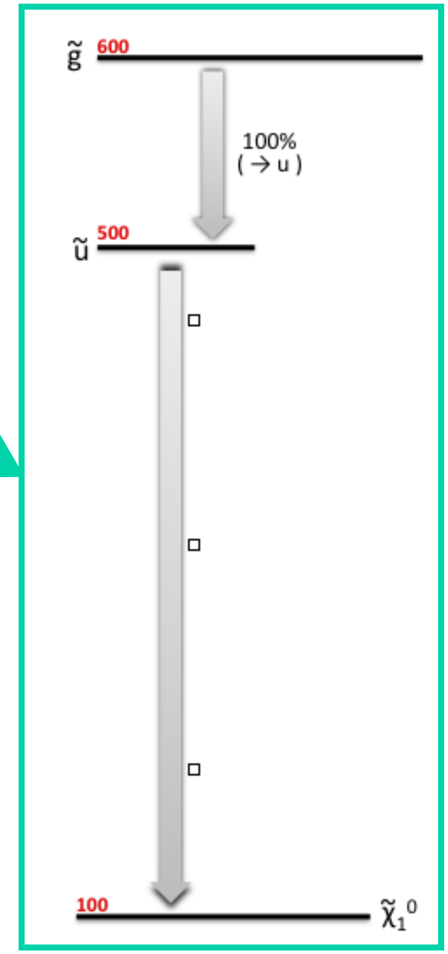
Impressive variety of inclusive SUSY searches but only limits (at least so far). Already broadly exploring the 1 TeV mass Scale and in some cases even beyond.

Additional Interpretation

CMSSM

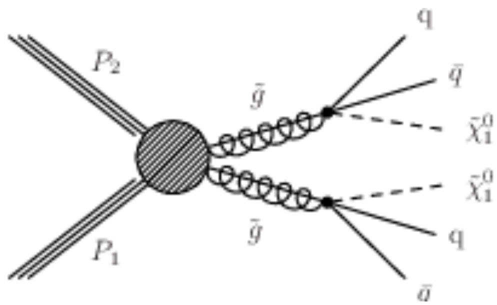


What we see is much more simple…

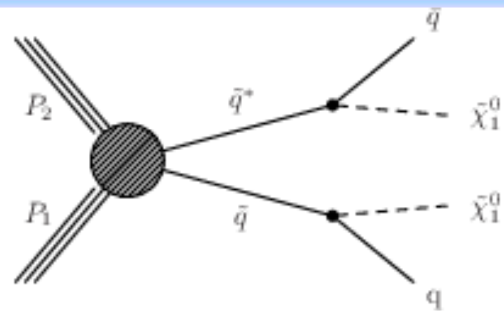


Simplified model spectrum or sms
with 3 particles, 2 decay modes

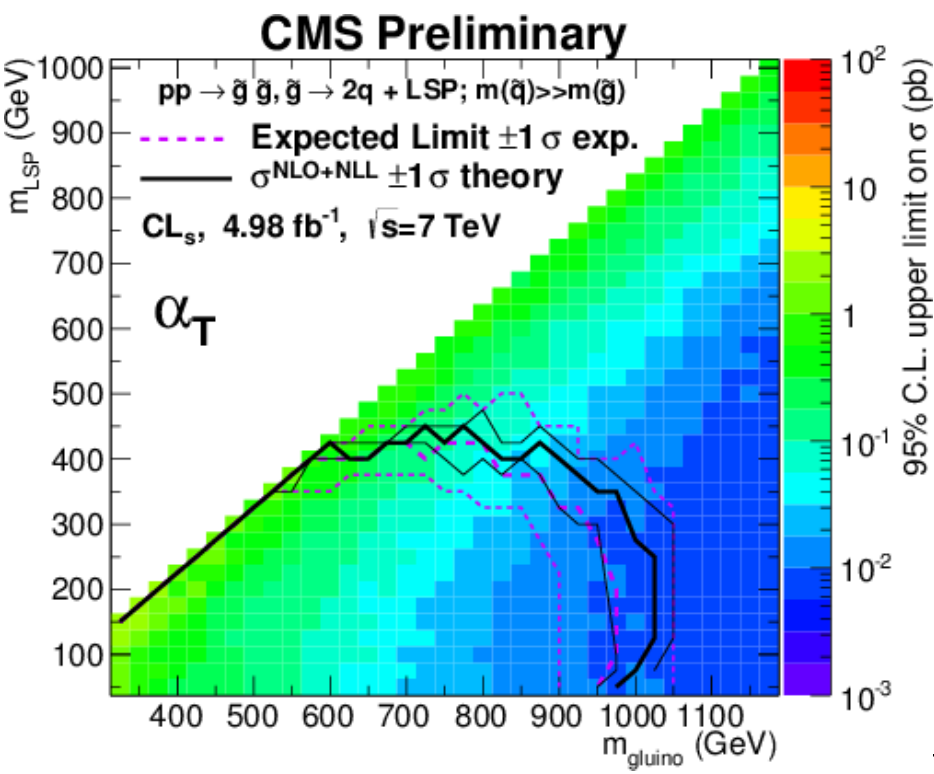
Simplified Model Spectra

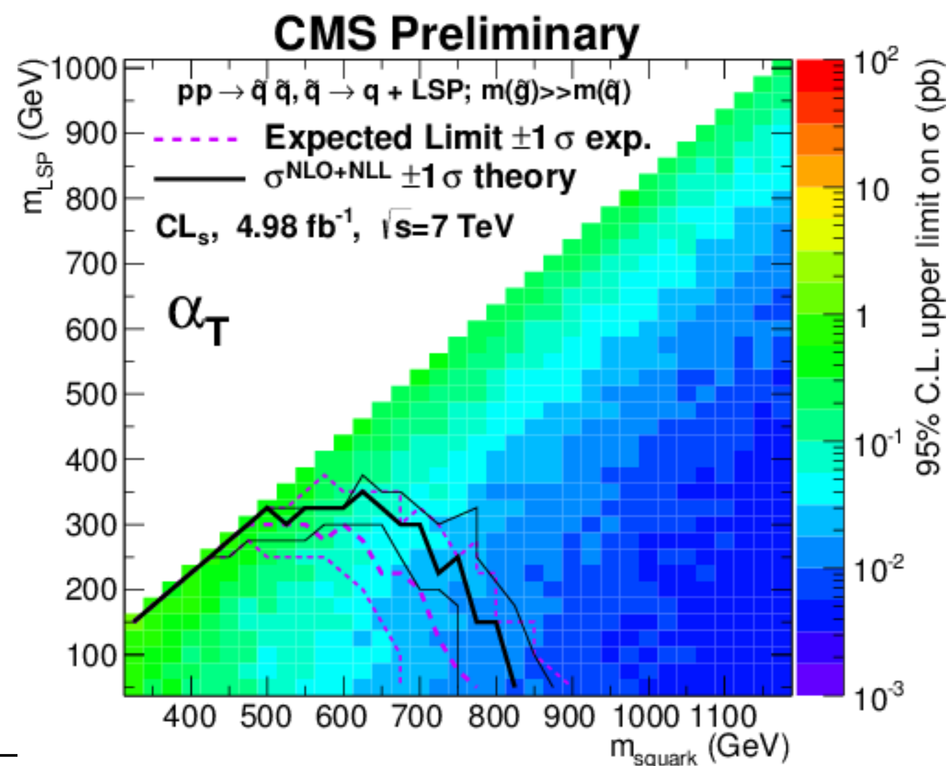


$$\tilde{g}\tilde{g} \rightarrow q\bar{q}\tilde{\chi}^0 q\bar{q}\tilde{\chi}^0$$



$$\tilde{q}\tilde{q} \rightarrow q\tilde{\chi}^0\bar{q}\tilde{\chi}^0$$





Refining SUSY Search Strategy

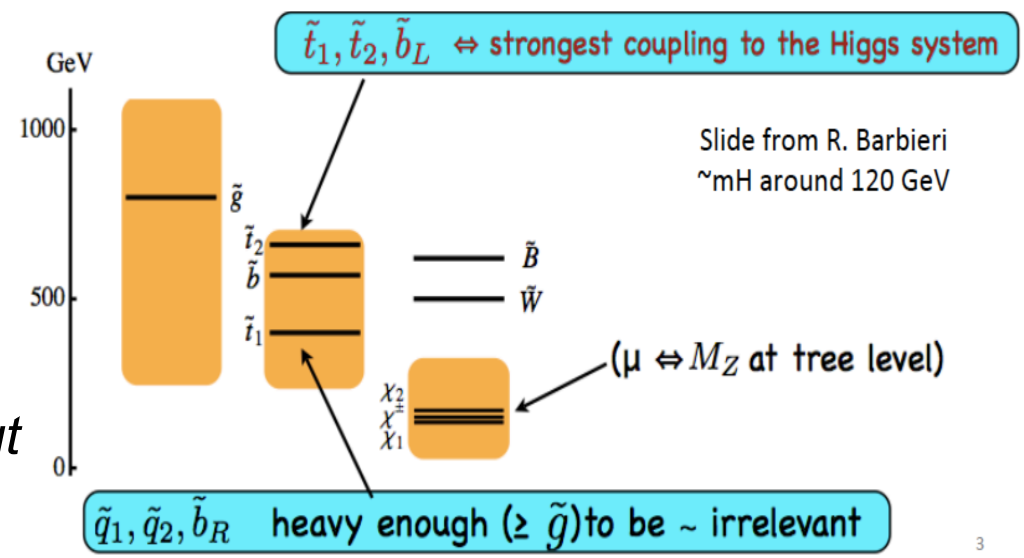
0-leptons	1-lepton	OSDL	SSDL	≥3 leptons	2-photons	γ+lepton
Jets + MET	Single lepton + Jets + MET	Opposite-sign di-lepton + jets + MET	Same-sign di-lepton + jets + MET	Multi-lepton	Di-photon + jet + MET	Photon + lepton + MET

- Focus more on 3rd Generation squark searches
  - Both interpretation of inclusive searches as well as dedicated searches

Example: "Natural SUSY"

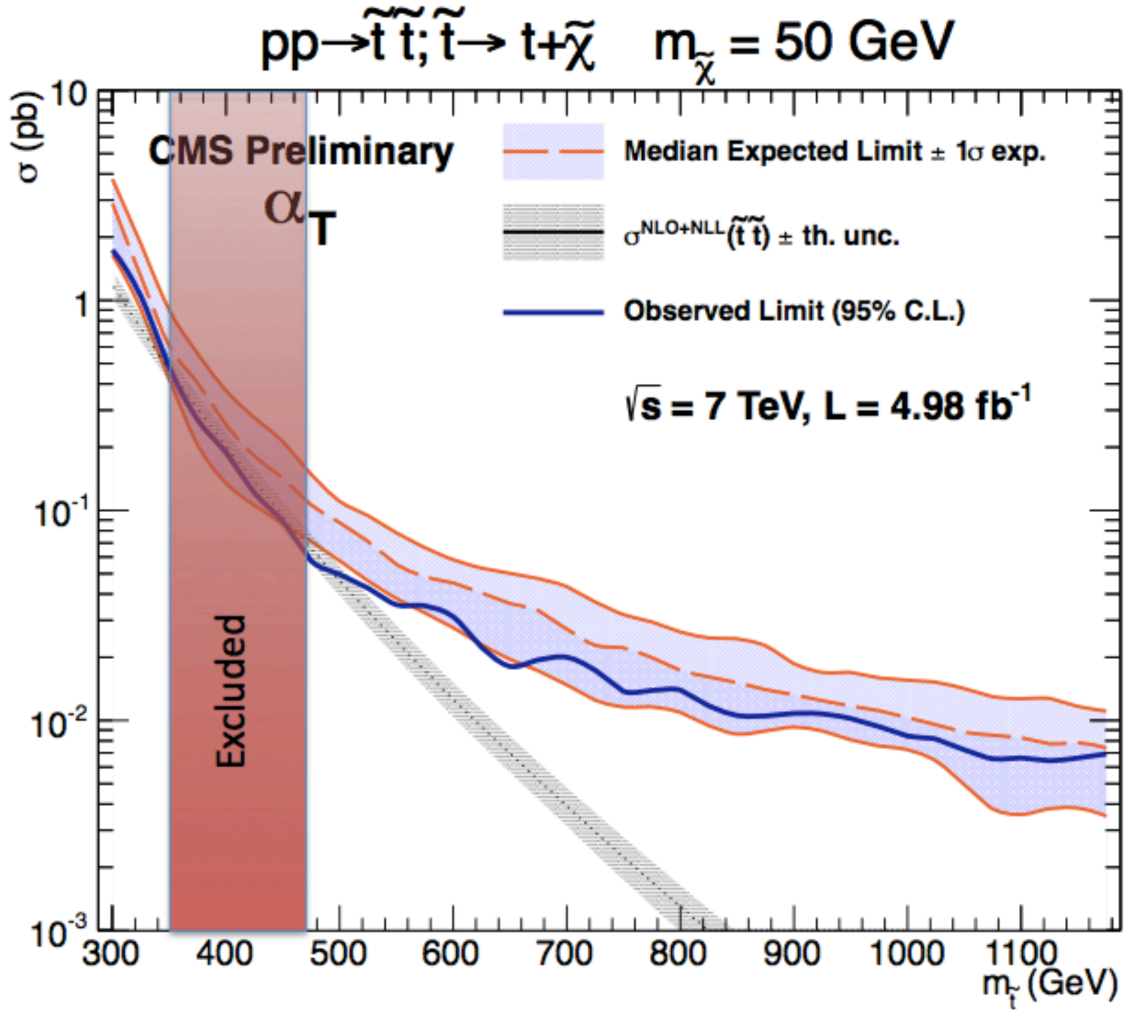
Use argument that light Higgs needs new physics to stabalise mass, which in turn motivates existences of a stop like particle.

Spectrum is model dependent but overall a good guideline for 3rd generation squark searches



Stop searches

- Mixture of dedicated signature searches as well as inclusive searches with b-tagging
  - Example CMS: add 0,1,2,>2 b-tag categories to inclusive α_T search

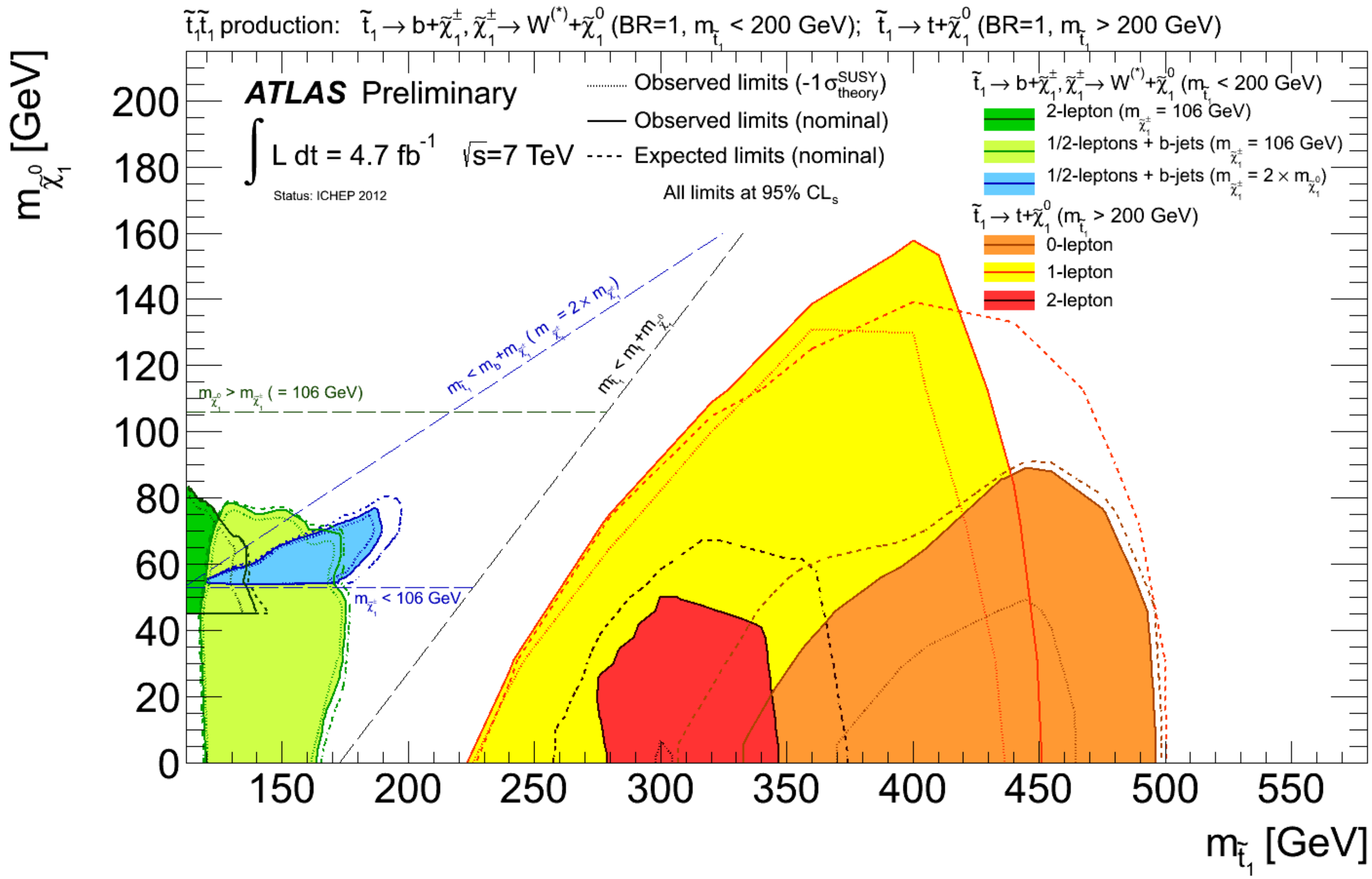


Just about to be sensitive to direct stop pair production.

Limits will improve rapidly with more data!

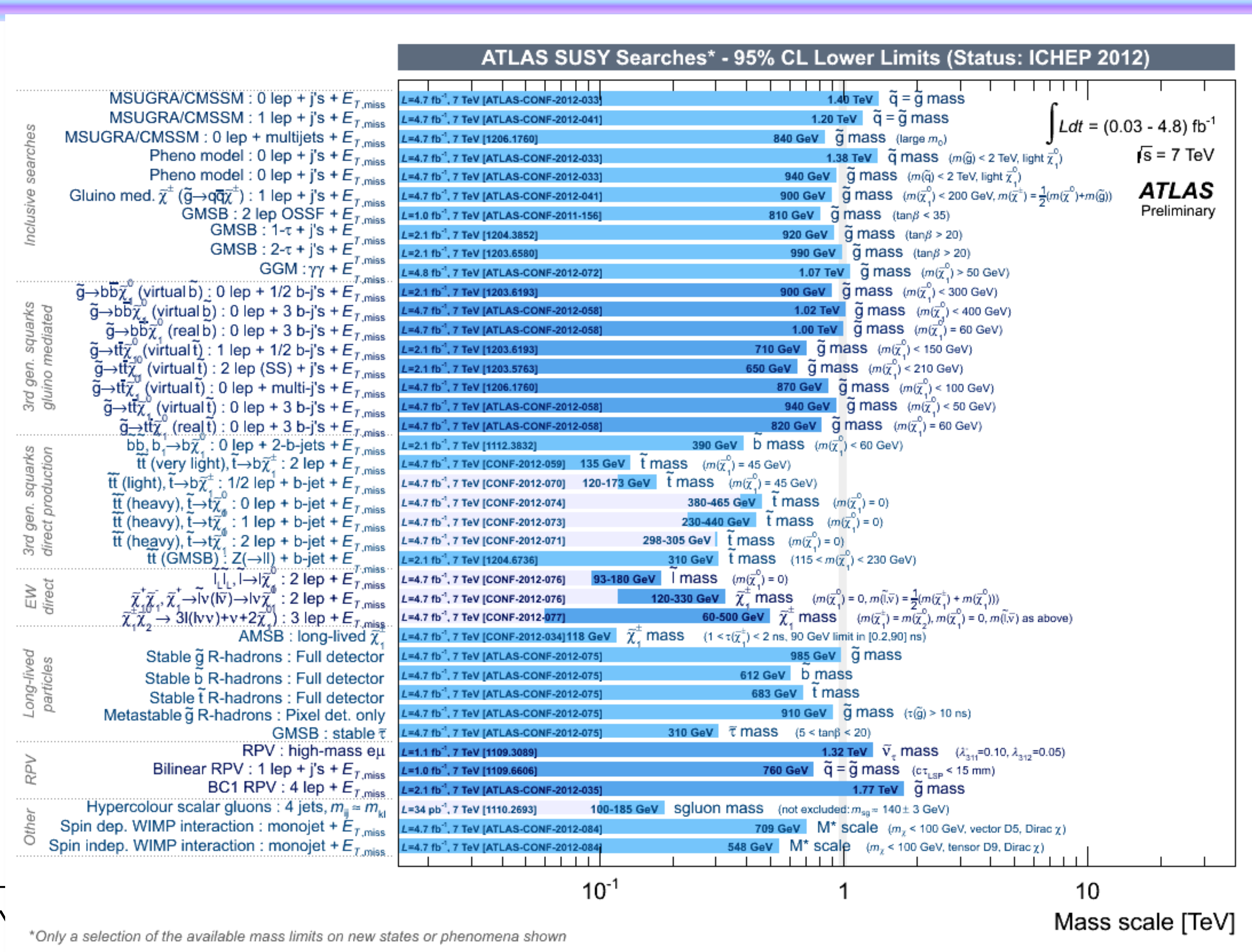
Stop Searches Today

Nice summary plot from ATLAS …



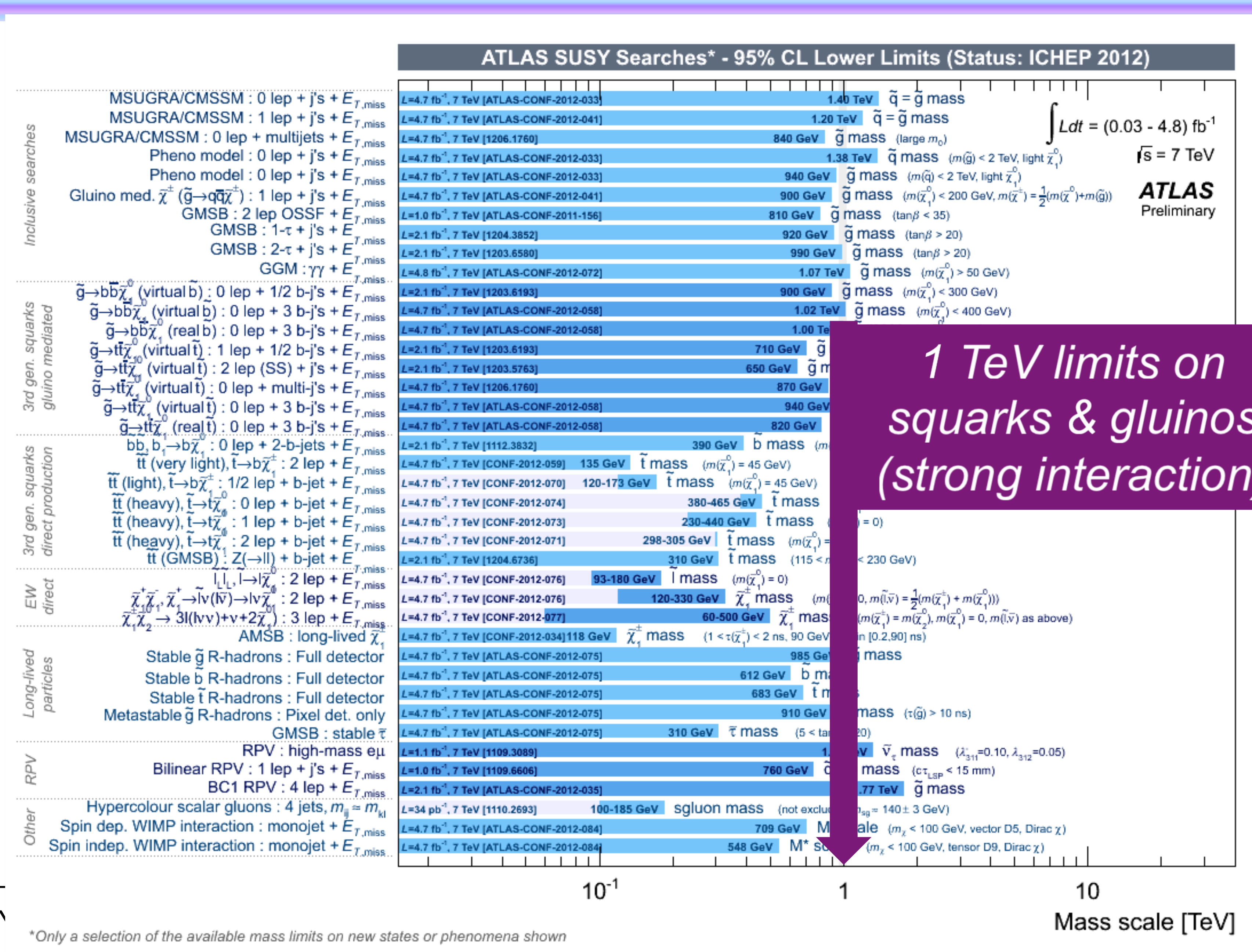
… but keep in mind; no limits for m_{LSP} > 150 GeV (so far)

SUSY Today – Only Limits!



„SUS

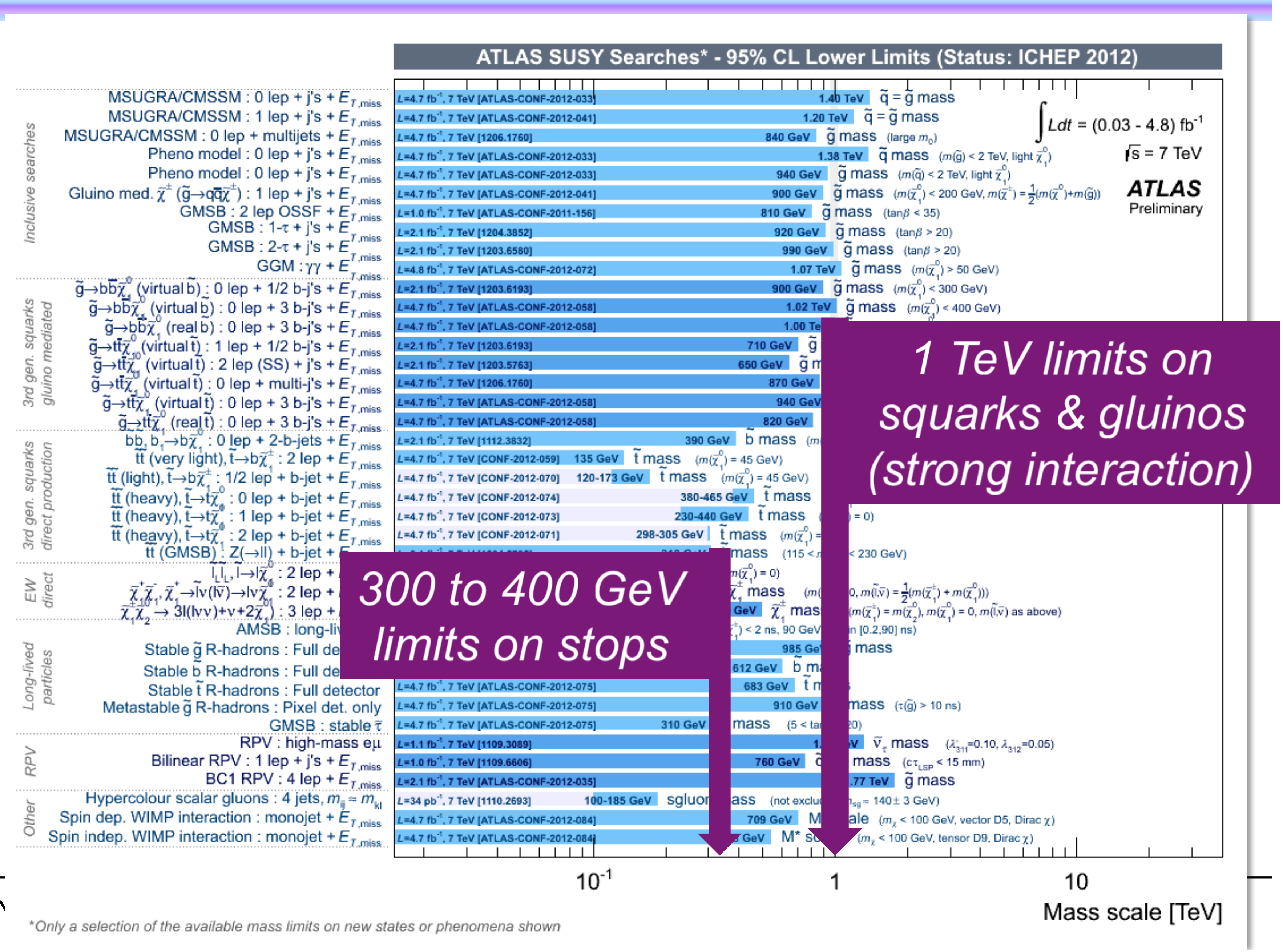
SUSY Today – Only Limits!



1 TeV limits on squarks & gluinos (strong interaction)

„SUS

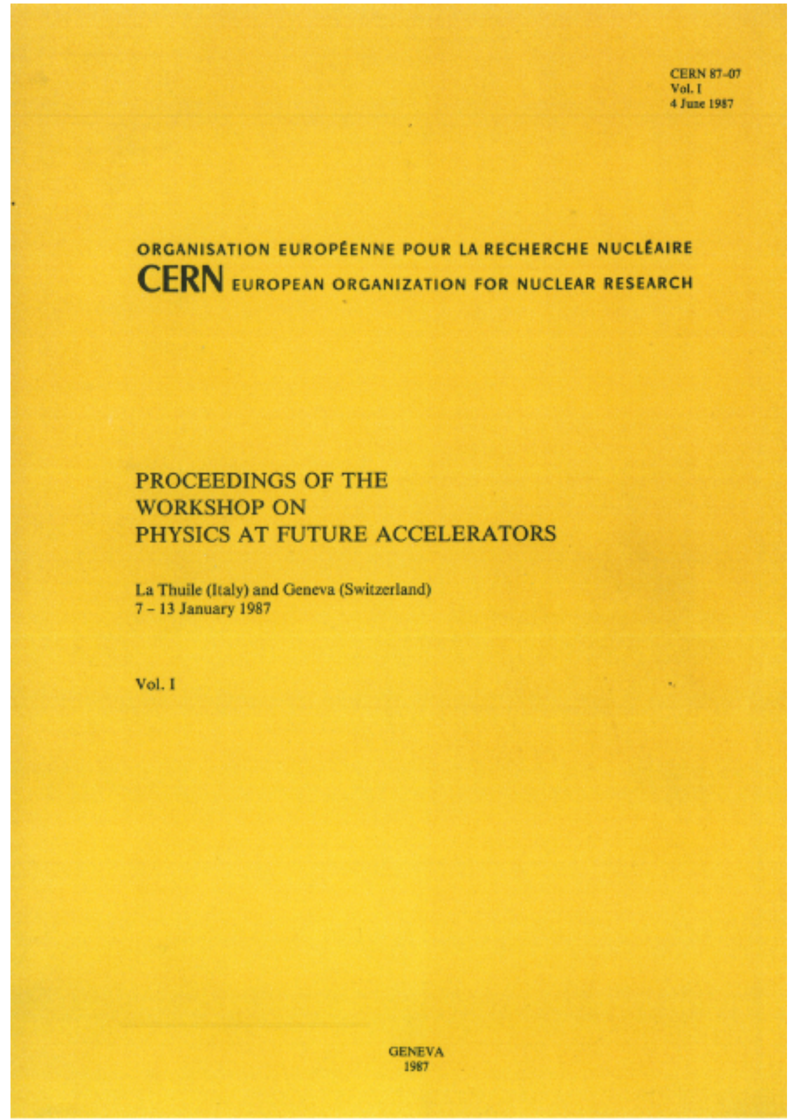
SUSY Today – Only Limits!



Search for Physics Beyond the SM

PROCEEDINGS OF THE WORKSHOP ON PHYSICS AT FUTURE ACCELERATORS

La Thuile 7-13 January 1987:
Still assumed $\sqrt{s}$ = 17 TeV !


CERN 87-07
Vol. I
4 June 1987

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

PROCEEDINGS OF THE
WORKSHOP ON
PHYSICS AT FUTURE ACCELERATORS

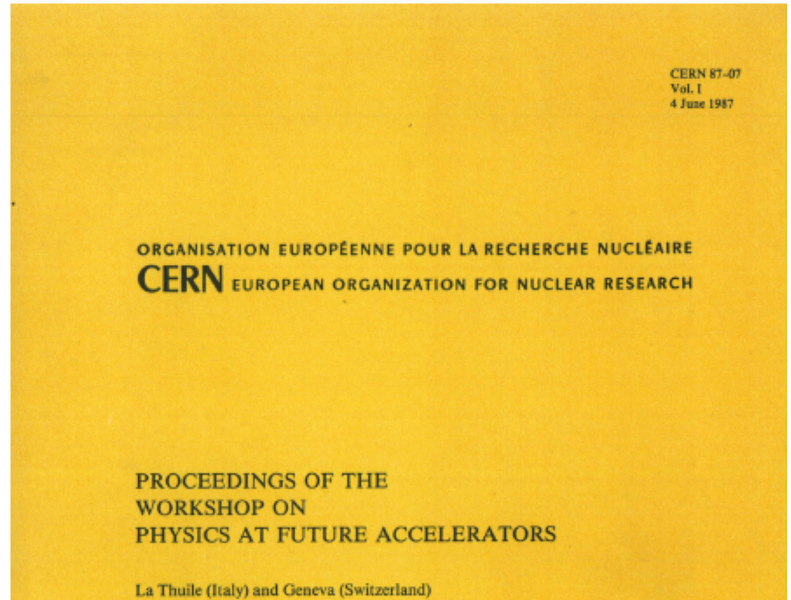
La Thuile (Italy) and Geneva (Switzerland)
7 – 13 January 1987

Vol. I

GENEVA
1987

Search for Physics Beyond the SM

La Thuile 7-13 January 1987:
Still assumed $\sqrt{s}$ *= 17 TeV*
PROCEEDINGS OF THE WORKSHOP ON PHYSICS AT FUTURE ACCELERATORS



Supersymmetry

The main conclusions of this analysis are as follows:

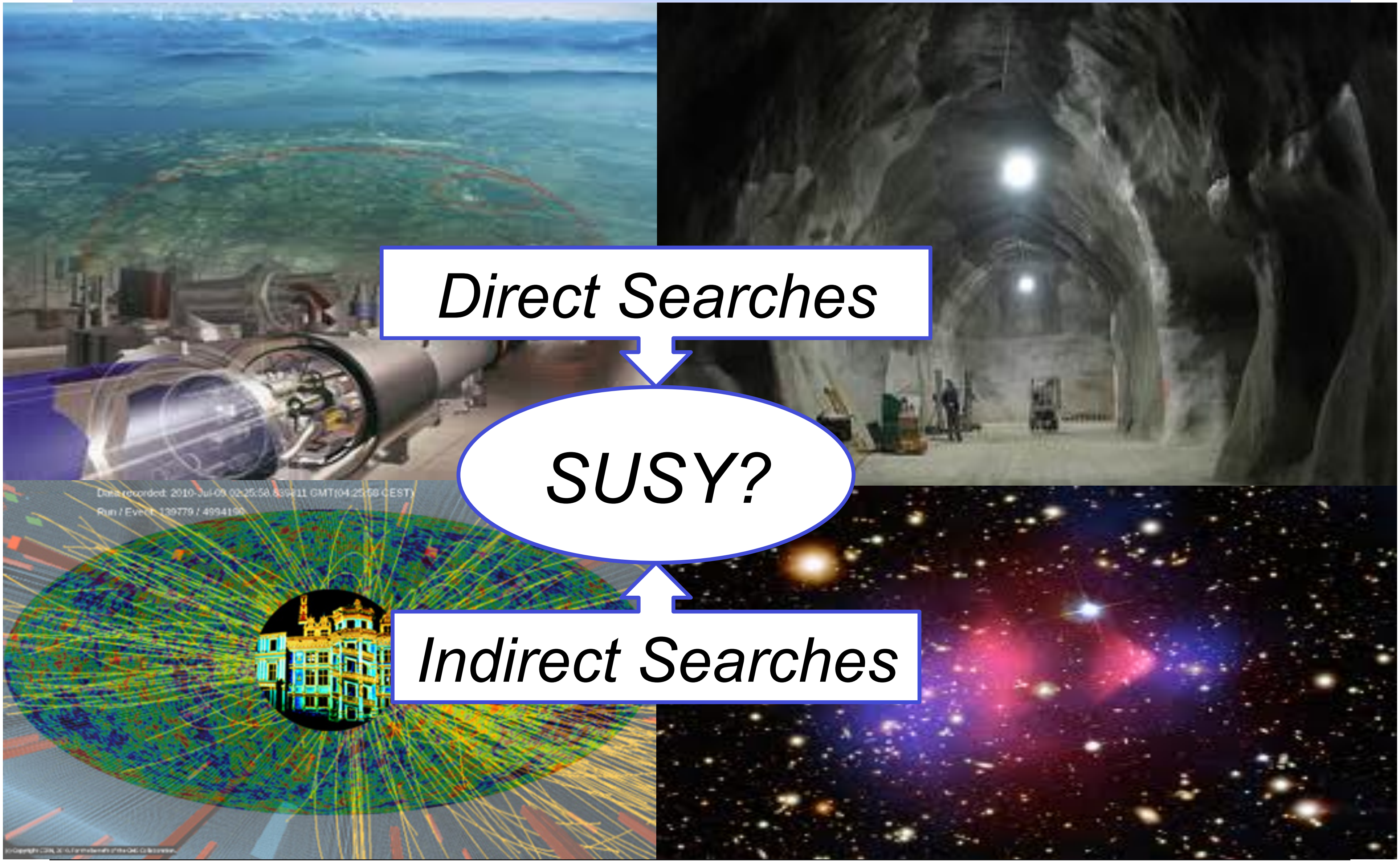
1) The Tevatron will be able to reach $m_{\tilde{q}}, m_{\tilde{g}} \approx 100$ GeV when it achieves $\int L dt = 10^{36}$ cm^{-2} s^{-1}, and $m_{\tilde{q}} \approx$ 350 GeV, $m_{\tilde{g}} = 200$ GeV if it achieves $\int L dt = 10^{39}$ cm^{-2} s^{-1}.

2) The LHC overlaps with the Tevatron for squarks and gluinos with masses between 200 and 400 GeV.

3) The rate at the LHC with 10 fb^{-1} varies from about 2×10^7 events for $m_{\tilde{q}} \approx m_{\tilde{g}} = 300$ GeV, compared with about 3×10^8 QCD background events, to about 2×10^4 events for $m_{\tilde{q}} \approx m_{\tilde{g}} \approx 1$ TeV, compared with about 2×10^7 QCD background events. After applying the proposed cuts, the signal-to-background ratio falls from 50 to 90 in the low-mass case, through about 10 to 20 when $m_{\tilde{q}} \approx m_{\tilde{g}} \approx 500$ GeV, to about 1 when $m_{\tilde{q}} \approx m_{\tilde{g}} \approx$ 1 TeV. A bound of about 1 TeV seems to be attainable at the LHC with effort.

4) The SSC could reach out to sparticle masses ≈ 1.5 TeV.

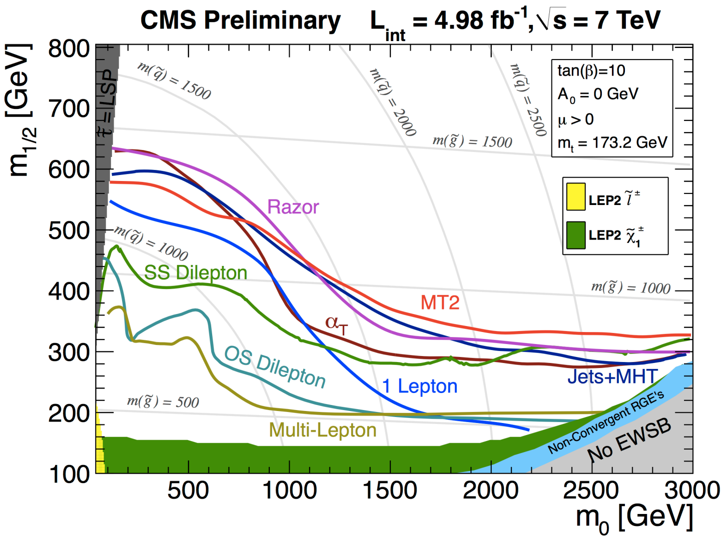
Searches for SUSY



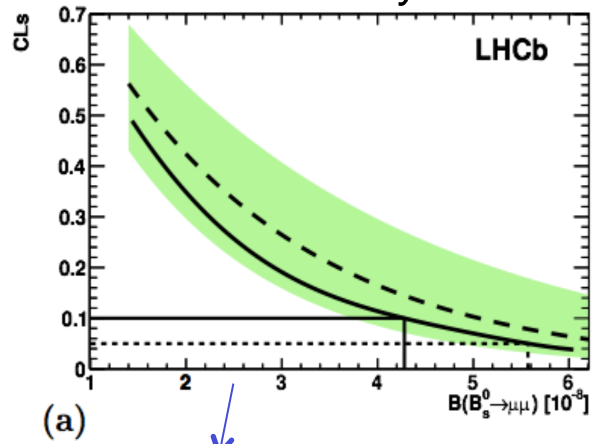
Searches for SUSY

Putting it all Together – Where are Toady?

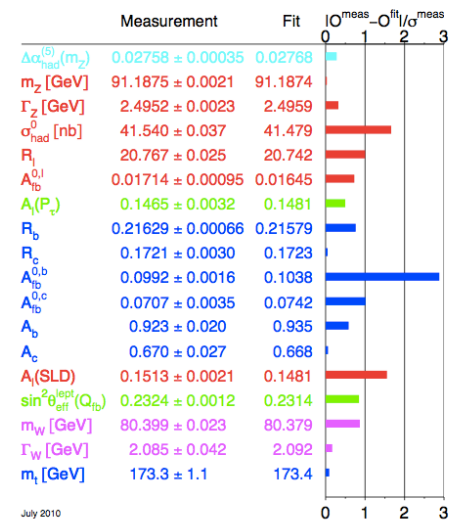
Direct Searches



Flavour Physics



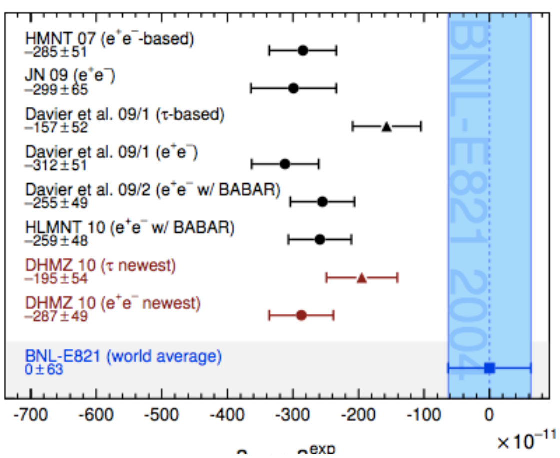
EWK results

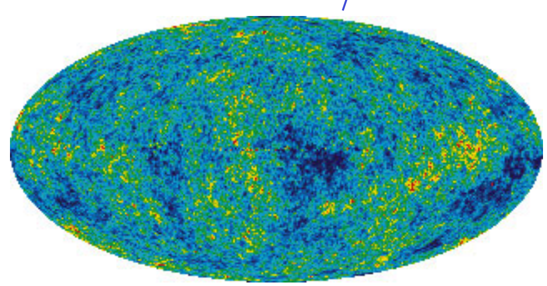


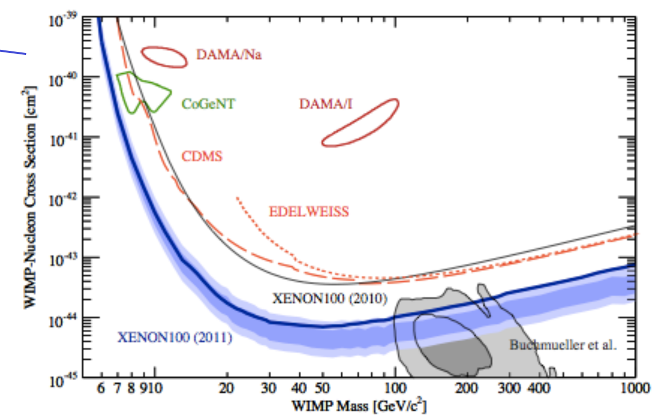
	Measurement	Fit	$\lvert O^{meas}-O^{fit}\rvert/\sigma^{meas}$
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02768	
m_Z [GeV]	91.1875 ± 0.0021	91.1874	
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959	
σ_{had}^0 [nb]	41.540 ± 0.037	41.479	
R_l	20.767 ± 0.025	20.742	
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645	
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481	
R_b	0.21629 ± 0.00066	0.21579	
R_c	0.1721 ± 0.0030	0.1723	
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038	
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742	
A_b	0.923 ± 0.020	0.935	
A_c	0.670 ± 0.027	0.668	
A_l(SLD)	0.1513 ± 0.0021	0.1481	
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314	
m_W [GeV]	80.399 ± 0.023	80.379	
Γ_W [GeV]	2.085 ± 0.042	2.092	
m_t [GeV]	173.3 ± 1.1	173.4	

July 2010

SUSY







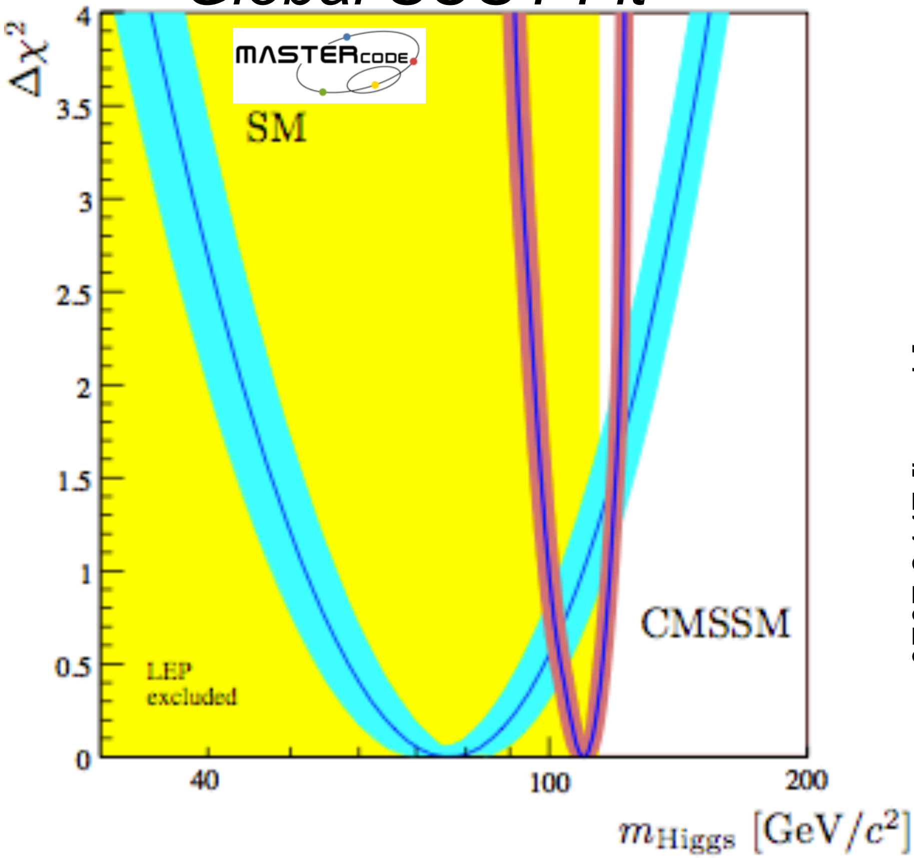
Low Energy Data e.g. g-2 *Dark Matter Searches*

Cosmology

Higgs: SUSY vs. SM

Slide from 2007

Global SUSY Fit



Example: “redo” SM fit in SUSY predicting the lightest higgs boson mass in the Constraint Minimal Supersymmeteric Standard Model (CMSSM)

MasterCode Collaboration

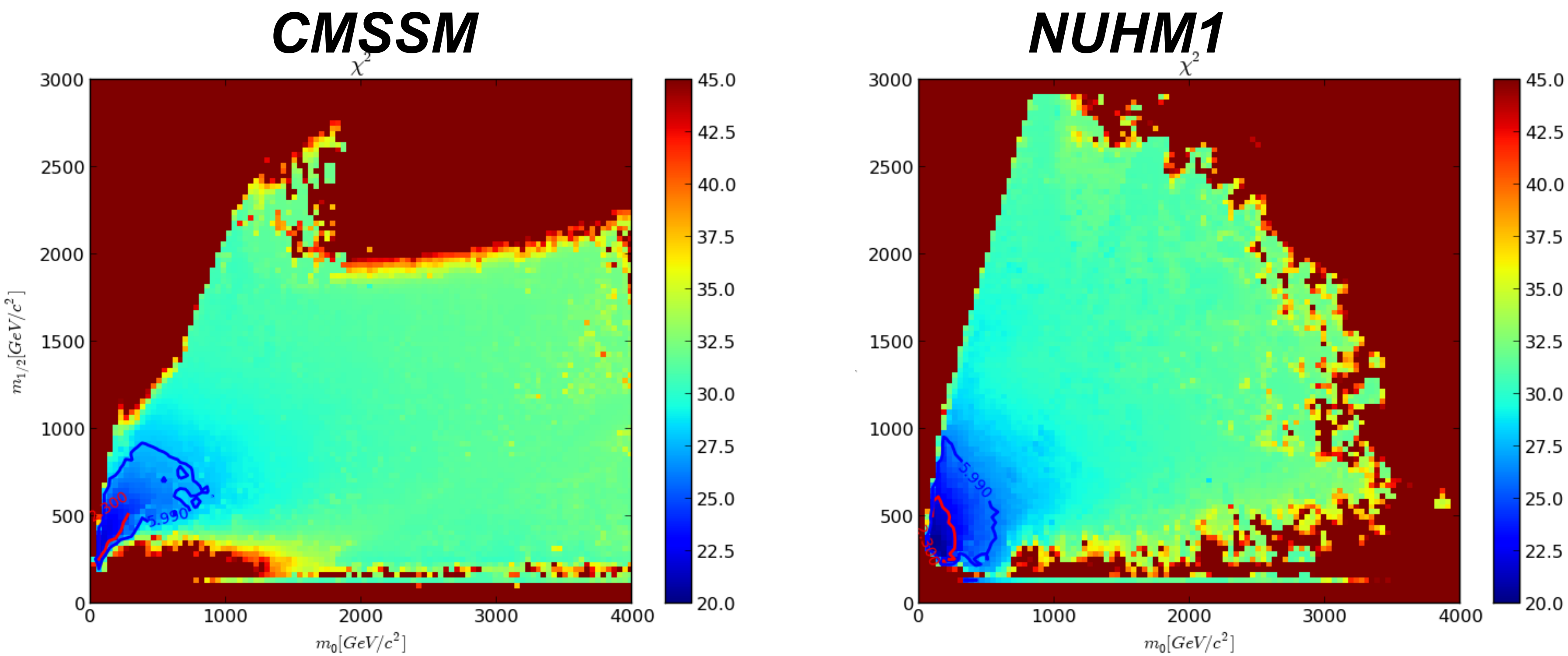
OB (Exp), R. Cavanaugh (Exp), A. De Roeck (Exp), J. Ellis (Theo), H. Flaecher (Exp), S. Heinemeyer (Theo), G. Isidori (Theo), K. Olive (Theo), P. Paradisi, (Theo), F. Ronga (Exp), G. Weiglein (Theo)

0707.3447 [hep-ph]

Pull for CMSSM fit

Variable	Measurement	Fit	$\lvert O^{meas}-O^{fit}\rvert/\sigma^{meas}$
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02774	
m_Z [GeV]	91.1875 ± 0.0021	91.1873	
Γ_Z [GeV]	2.4952 ± 0.0023	2.4952	
σ^0_{had} [nb]	41.540 ± 0.037	41.486	
R_l	20.767 ± 0.025	20.744	
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01641	
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1479	
R_b	0.21629 ± 0.00066	0.21613	
R_c	0.1721 ± 0.0030	0.1722	
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1037	
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0741	
A_b	0.923 ± 0.020	0.935	
A_c	0.670 ± 0.027	0.668	
A_l(SLD)	0.1513 ± 0.0021	0.1479	
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314	
m_W [GeV]	80.398 ± 0.025	80.382	
m_t [GeV]	170.9 ± 1.8	170.8	
$R(b\to s\gamma)$	1.13 ± 0.12	1.12	
$B_s\to\mu\mu$ [$\times10^{-8}$]	< 8.00	0.33	N/A (upper limit)
Δa_μ [$\times10^{-9}$]	2.95 ± 0.87	2.95	
Ωh^2	0.113 ± 0.009	0.113	

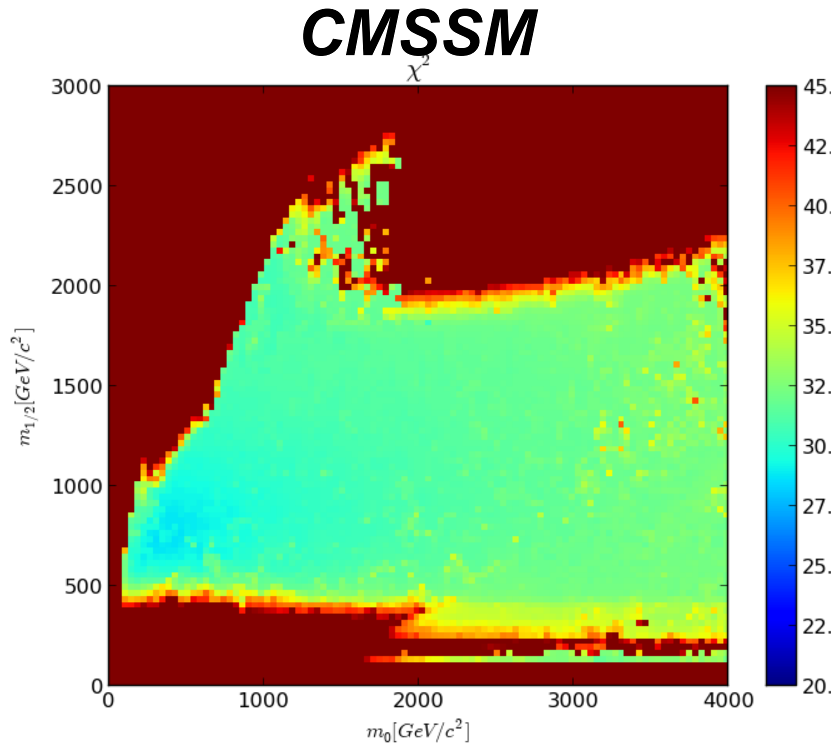
The pre-LHC era

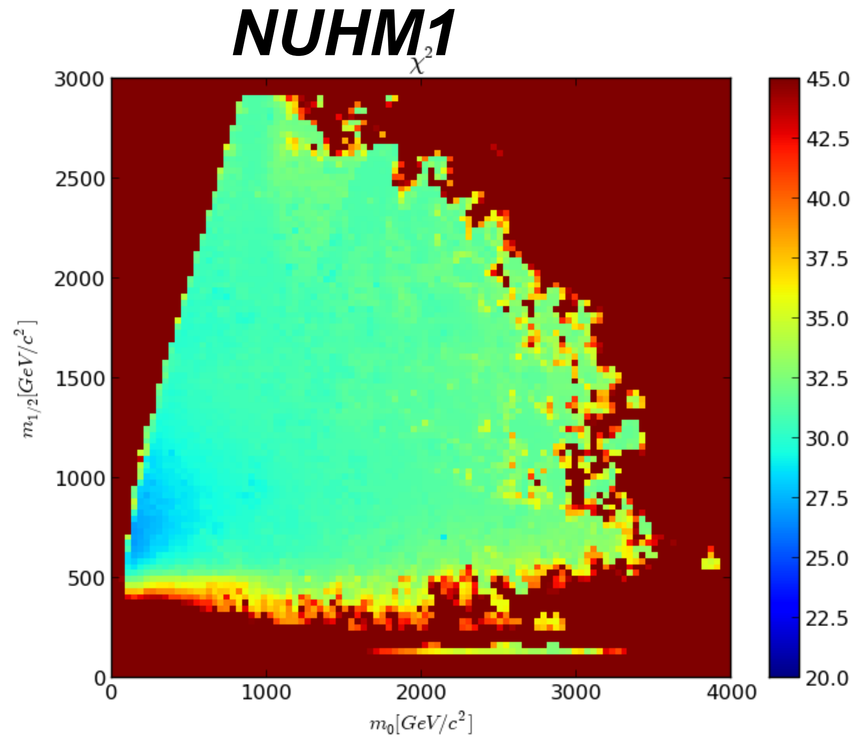


Model	Min χ^2	Prob	$m_{1/2}$	m_0	A_0	$\tan\beta$
CMSSM	21.5	37%	360	90	400	15
NUHM1	20.8	29%	340	110	-520	13

For references NDF ~ 22

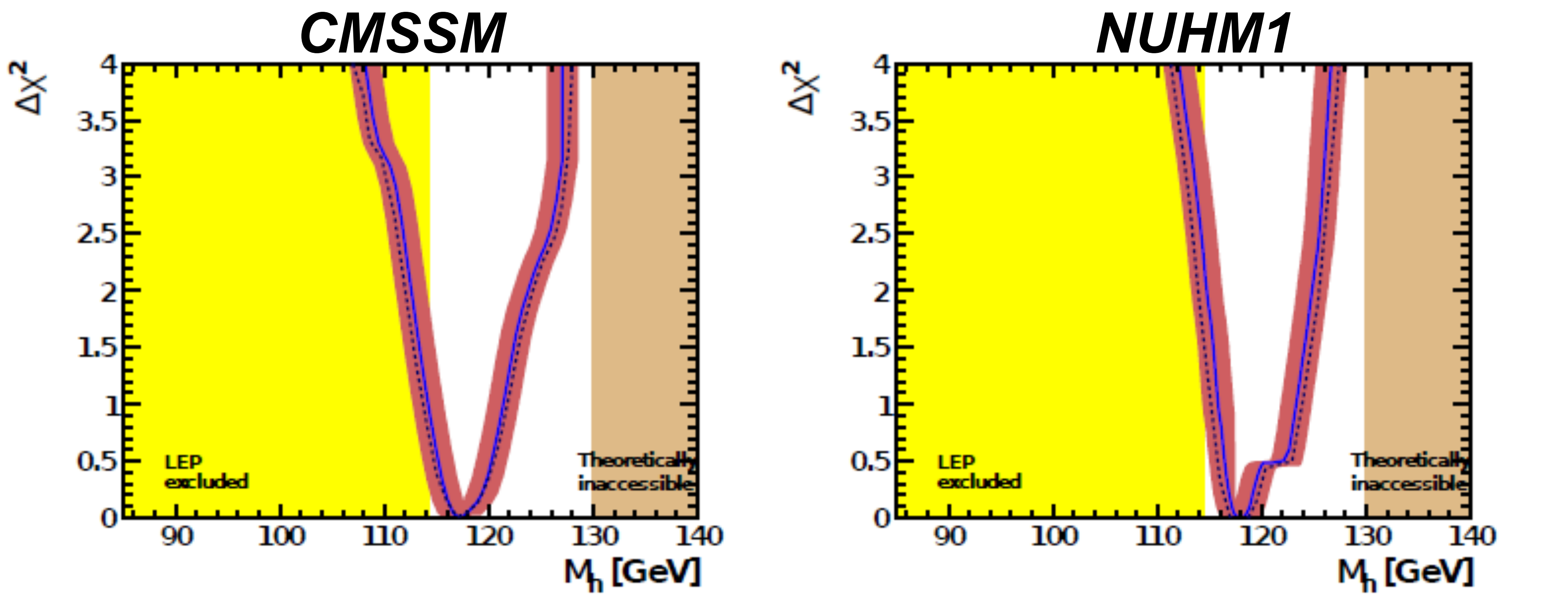
The "post-LHC" era in 2011





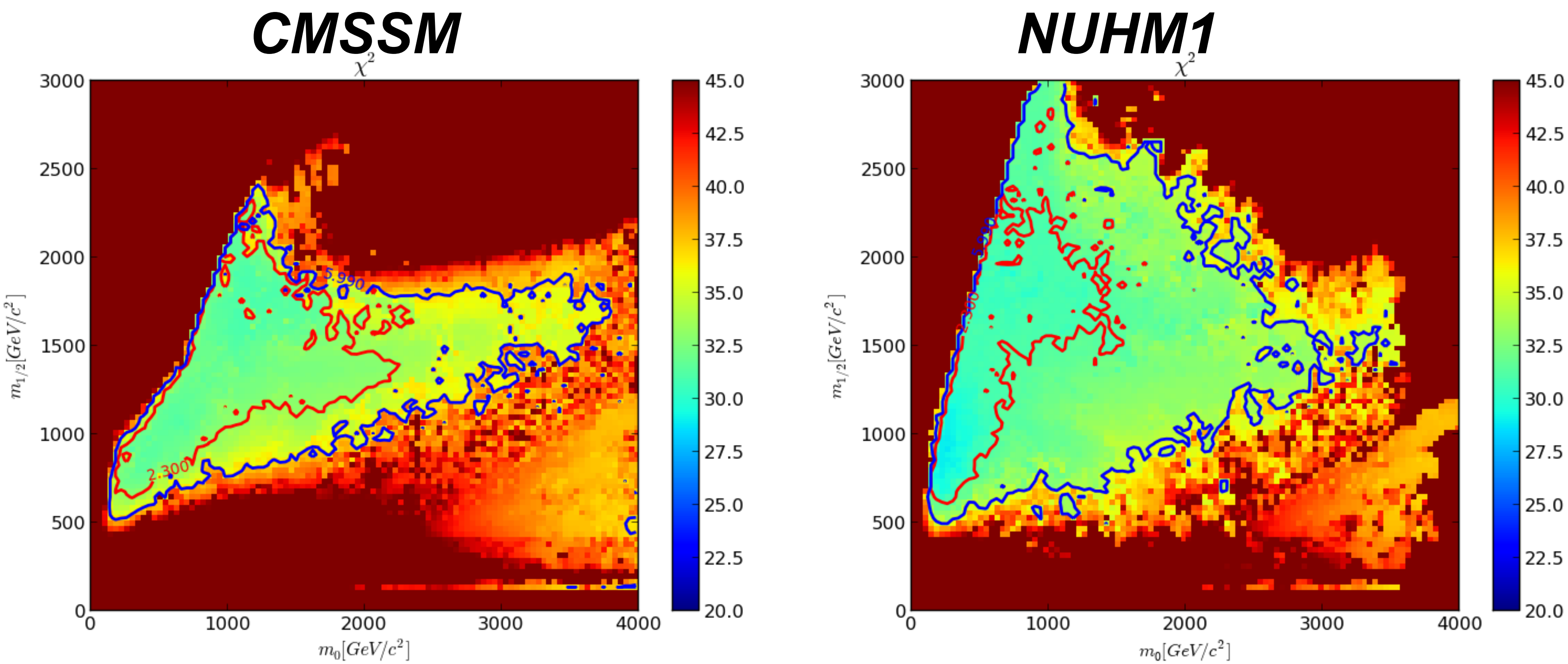
- Chi^2 increases
  - Shifting to higher masses, larger tan β
  - Plane relatively flat – no real preferred minima anymore

SUSY: Light Higgs Predictions



- Higgs important probe of SUSY
  - Predictions above produced based on analogous method to SM best-fit plots
    - → *No Higgs constraints imposed to make these plots!!*

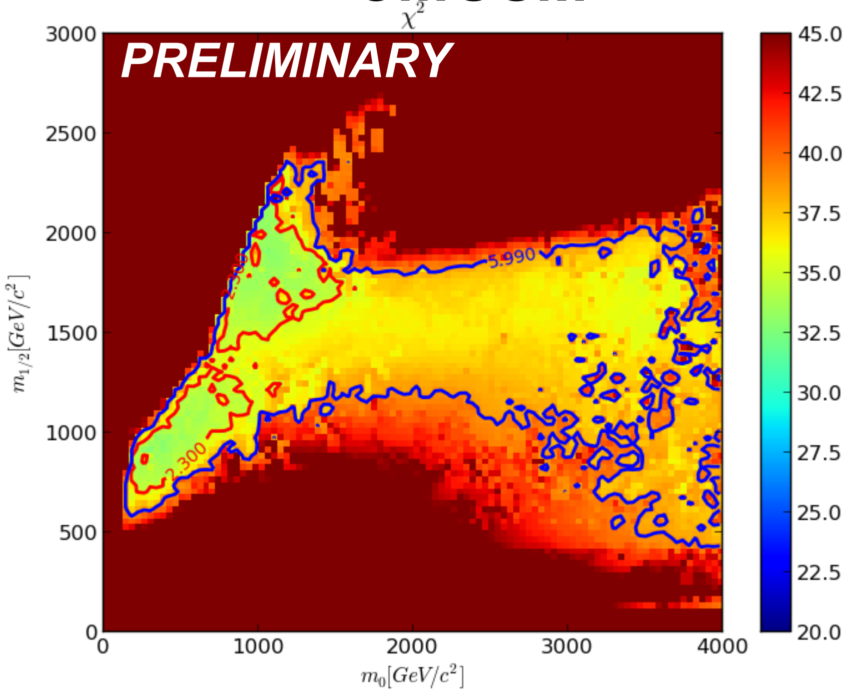
The "post-Higgs" era



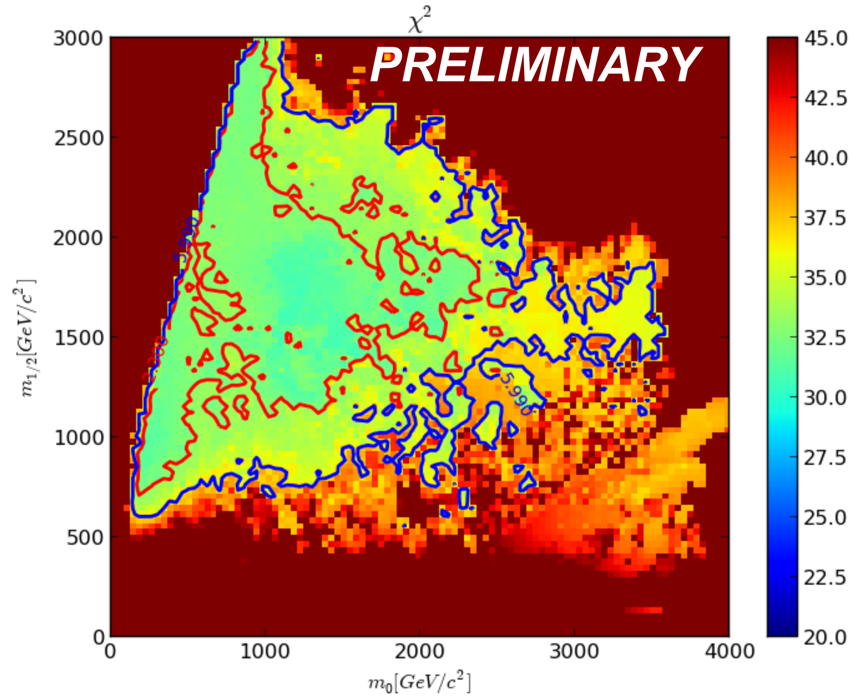
- Assume a putative measurement of m_H=125 +/- 1.5(theo) +/- 1.0 GeV
  - ➢ Further reduction in potential phase-space!

Post "LHC&Higgs" era in 2012

CMSSM

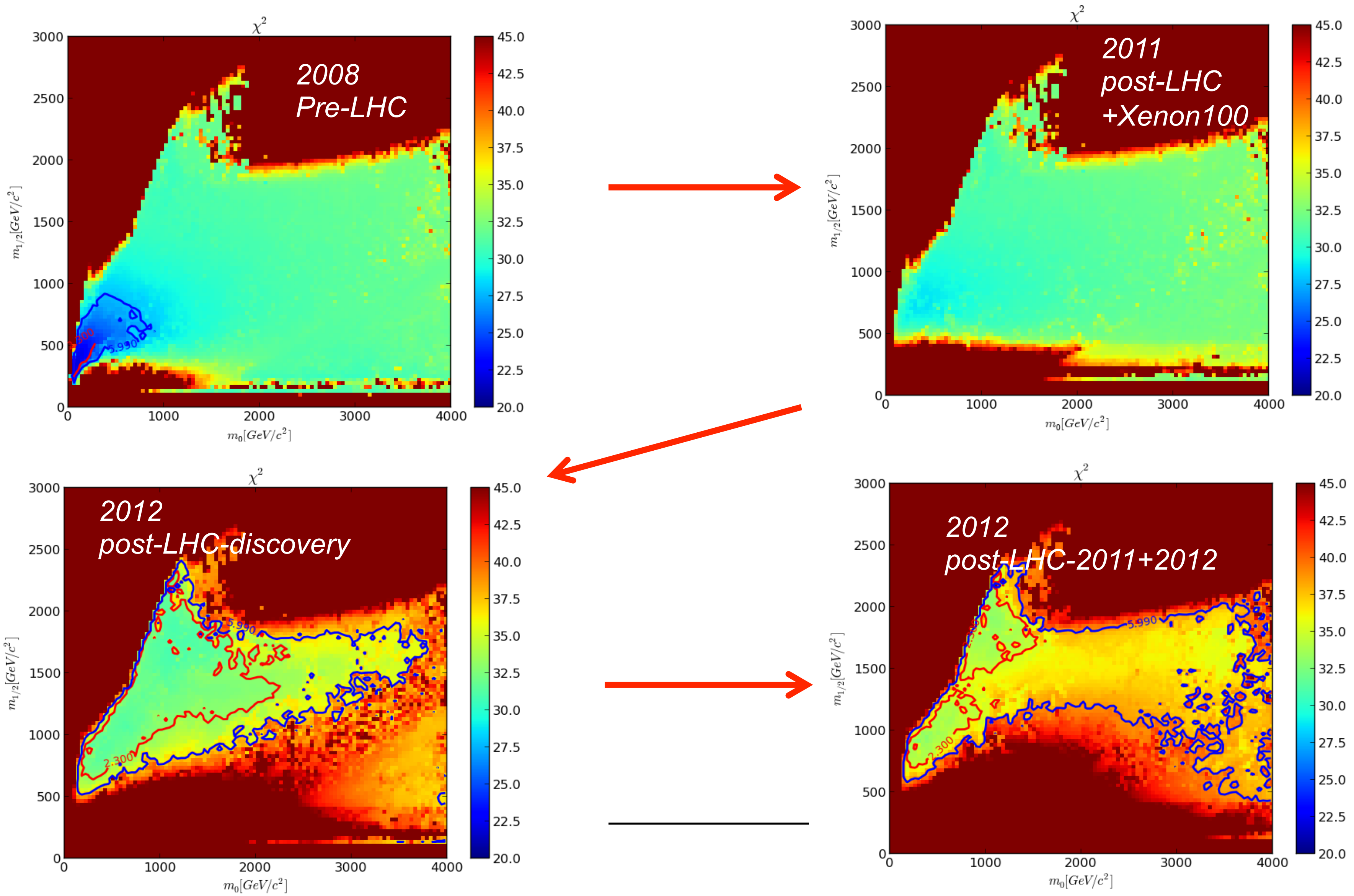


NUHM1



- Updated with
  - 5/fb direct search results
  - Updated BR(Bs-> $\mu\ \mu$) combination from the LHC (May 2012
- Prospects look bleak for constrained models
  - p-value ~10% (max)

CMSSM: Evolution with time

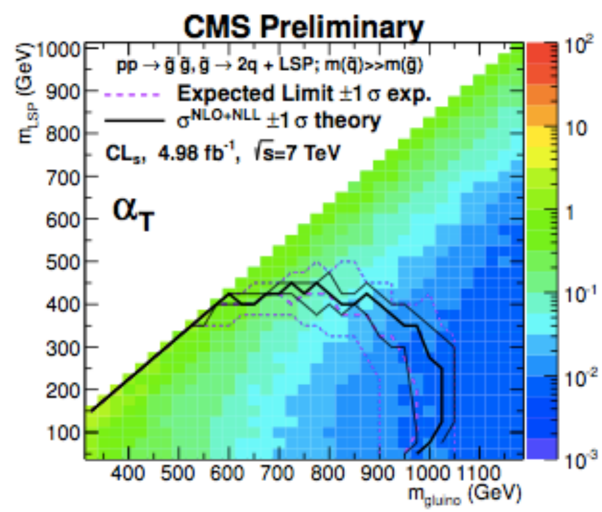


SUSY on life support?

The answer to this question is NO!

See 2012 Experimental SUSY PDG review [OB & Paul De Jong]:
http://pdg.lbl.gov/2012/reviews/rpp2012-rev-susy-2-experiment.pdf

Model	Assumption	$m_{\tilde q}$	$m_{\tilde g}$
CMSSM	$m_{\tilde q} \approx m_{\tilde g}$	1400	1400
	all $m_{\tilde q}$	-	800
	all $m_{\tilde g}$	1300	-
Simplified model $\tilde g \tilde g$	$m_{\tilde\chi_1^0} = 0$	-	900
	$m_{\tilde\chi_1^0} > 300$	-	no limit
Simplified model $\tilde q \tilde q$	$m_{\tilde\chi_1^0} = 0$	750	-
	$m_{\tilde\chi_1^0} > 250$	no limit	-
Simplified model $\tilde g \tilde q, \tilde g \bar{\tilde q}$	$m_{\tilde\chi_1^0} = 0$, $m_{\tilde q} \approx m_{\tilde g}$	1500	1500
	$m_{\tilde\chi_1^0} = 0$, all $m_{\tilde g}$	1400	-
	$m_{\tilde\chi_1^0} = 0$, all $m_{\tilde q}$	-	900



(a) $\tilde g\tilde g \rightarrow q\bar q\tilde\chi^0 q\bar q\tilde\chi^0$ (Model *A*)

SUSY on life support?

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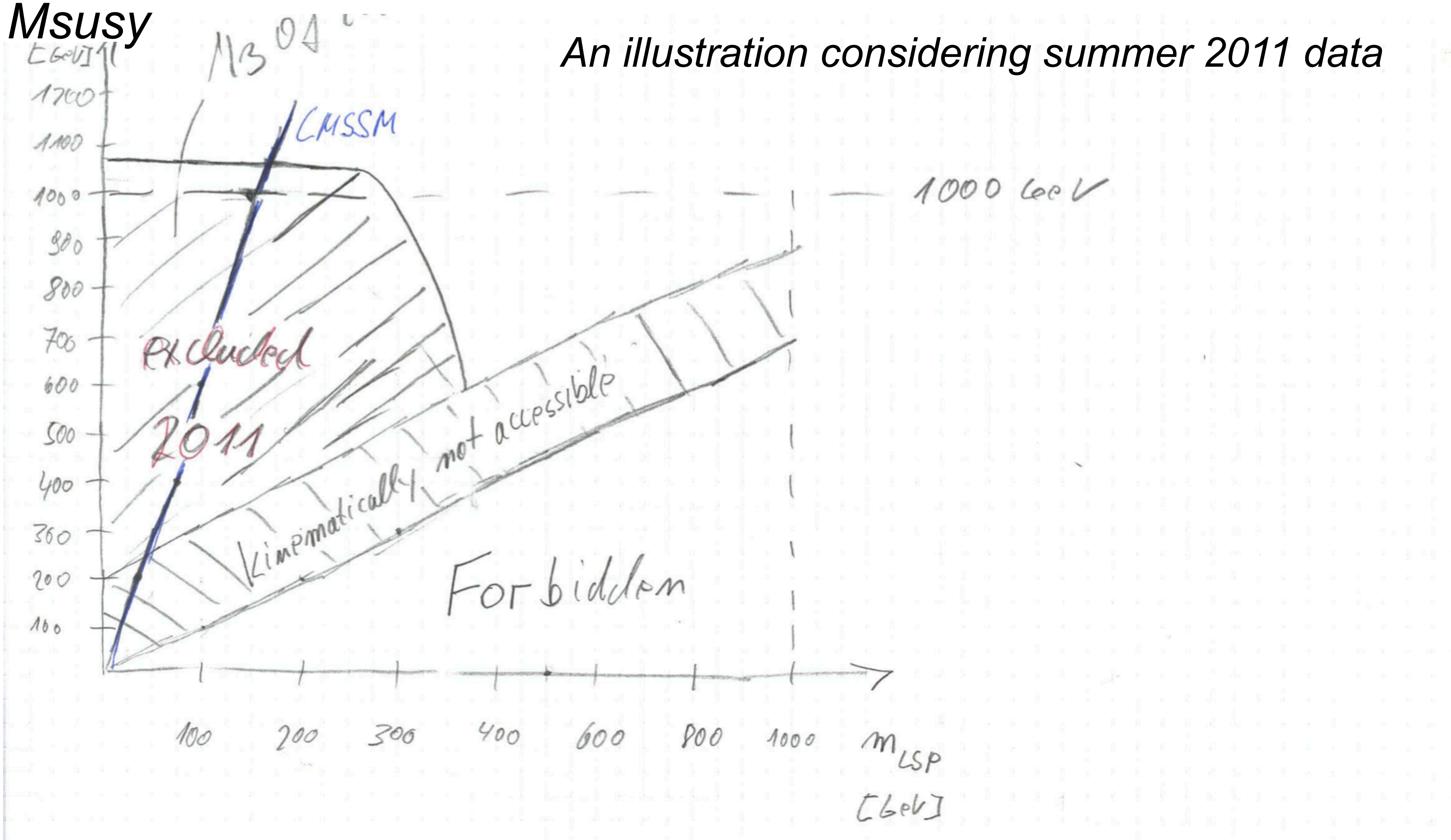
Simplified model $\tilde{g}\tilde{q}, \tilde{g}\bar{\tilde{q}}$	$m_{\tilde{\chi}_1^0} = 0$, $m_{\tilde{q}} \approx m_{\tilde{g}}$	1500	1500
	$m_{\tilde{\chi}_1^0} = 0$, all $m_{\tilde{g}}$	1400	-
	$m_{\tilde{\chi}_1^0} = 0$, all $m_{\tilde{q}}$	-	900

In general, the LHC does not (yet) place limits on parameter space with M_{LSP} >~400 GeV Leaving a very large Region of the MSSM, even at the mass scale below 1 TeV, unexplored!

SUSY Coverage

Msusy

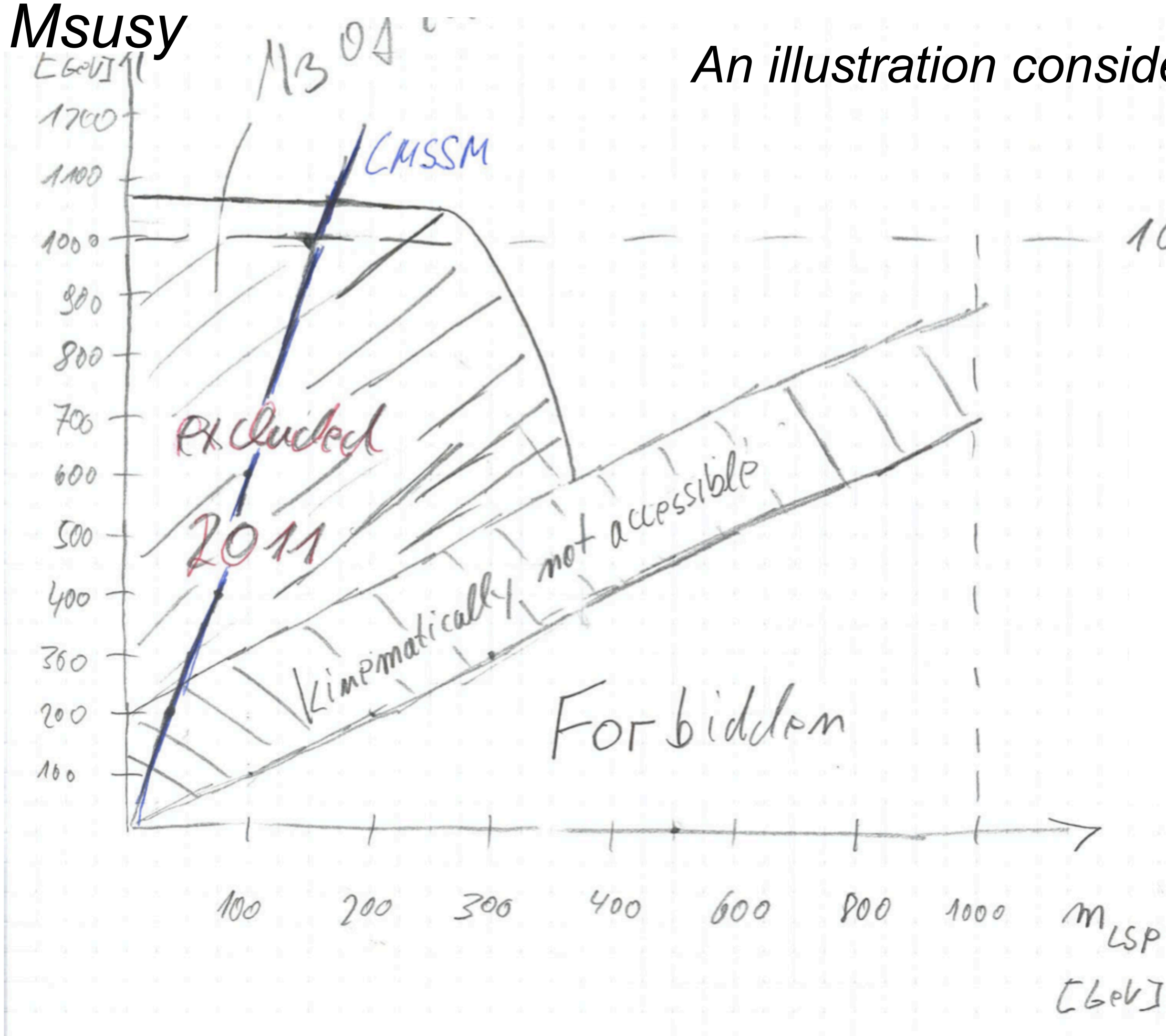
An illustration considering summer 2011 data

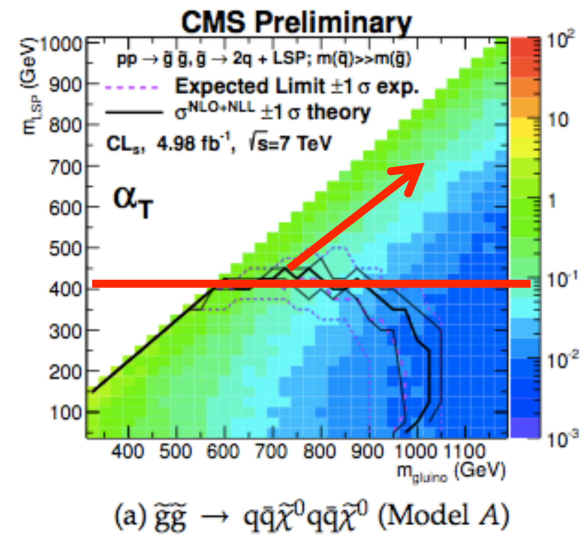


SUSY Coverage

Msusy

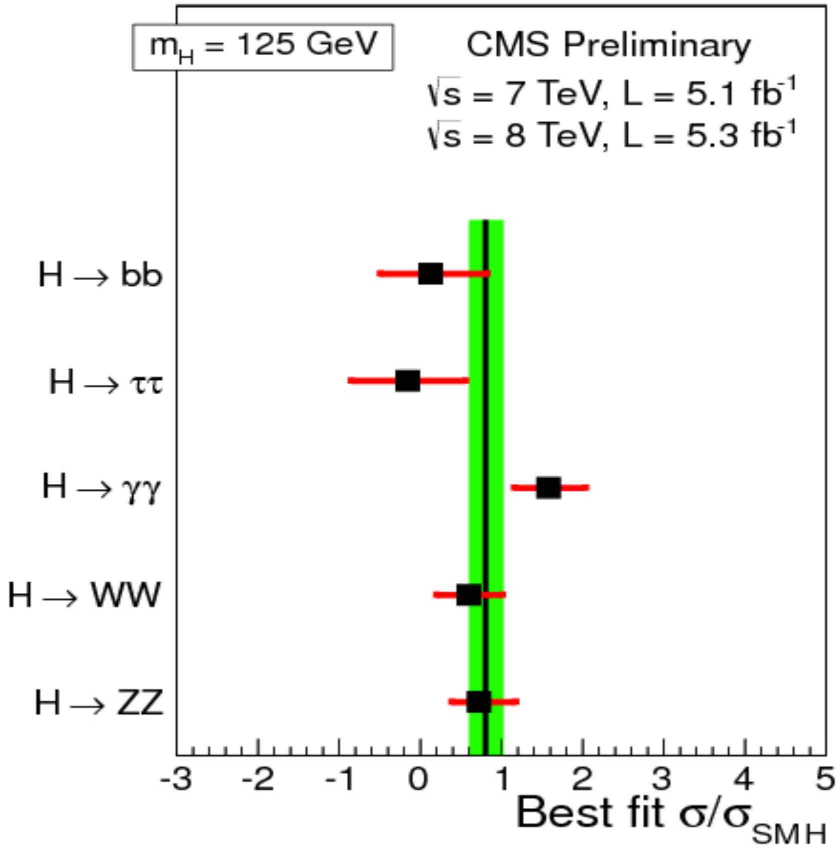
An illustration considering summer 2011 data

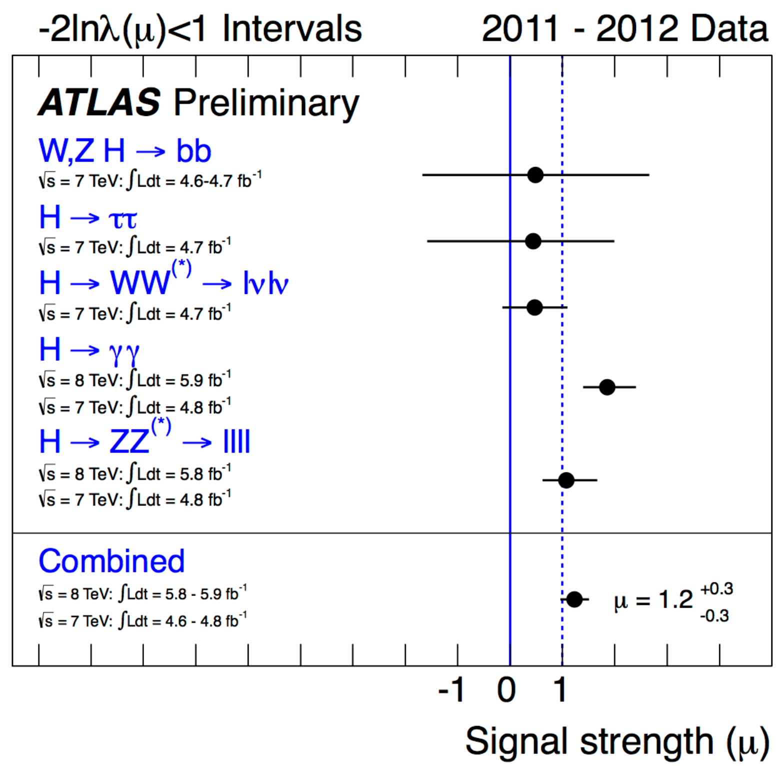




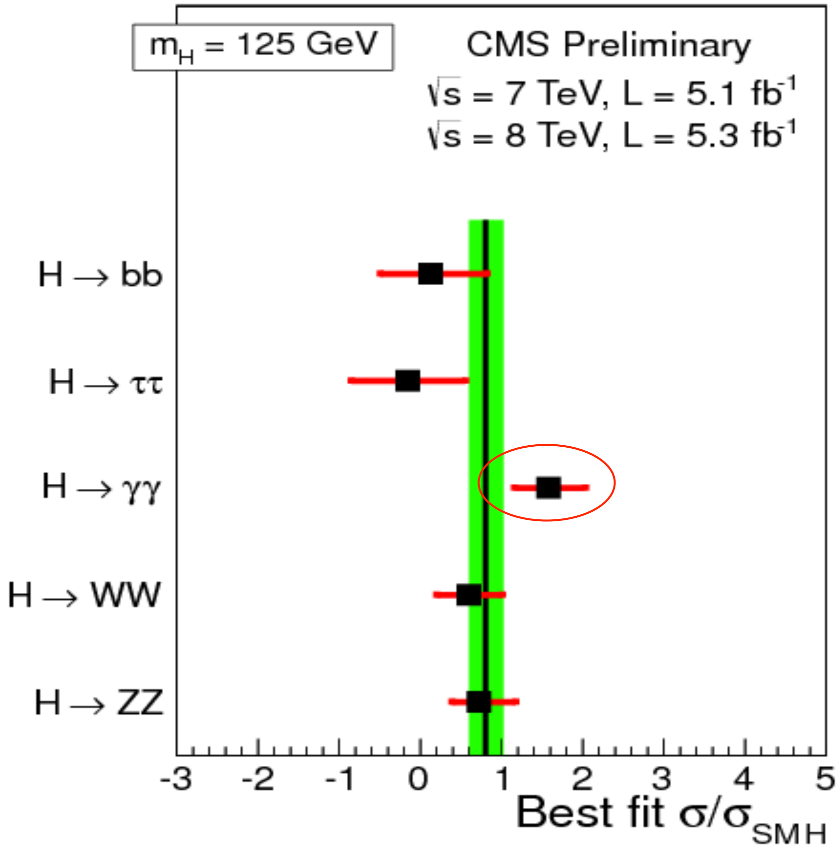
Note: axes are flipped

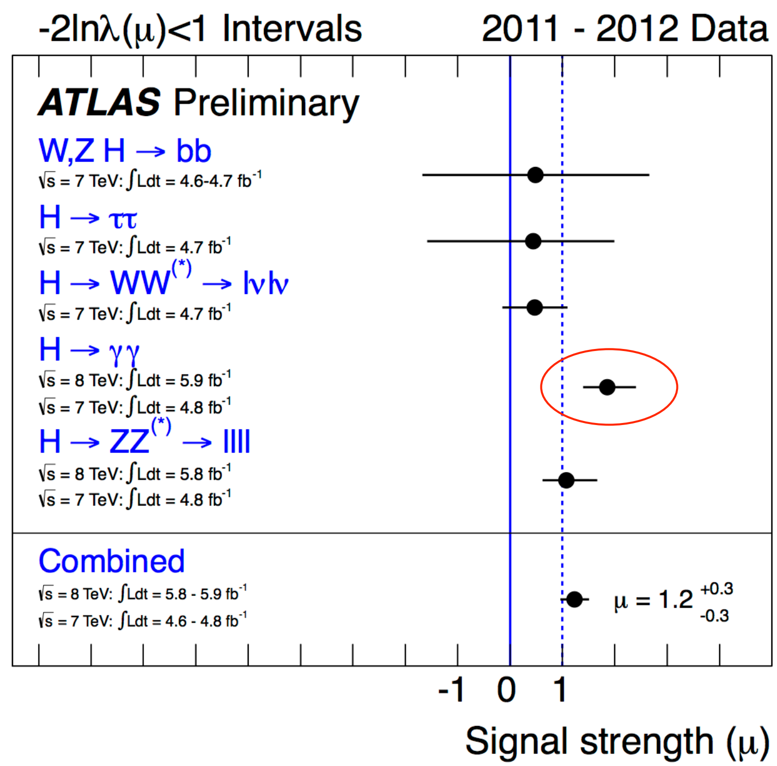
Compatibility with the SM Higgs Boson





Compatibility with the SM Higgs Boson

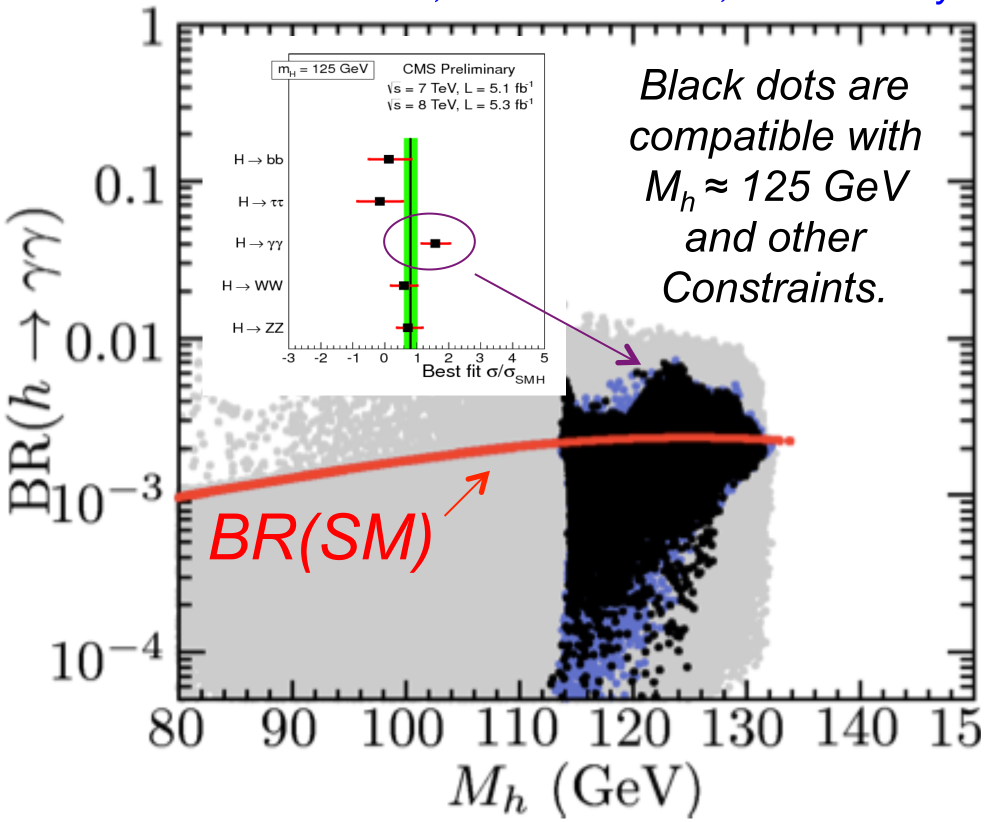


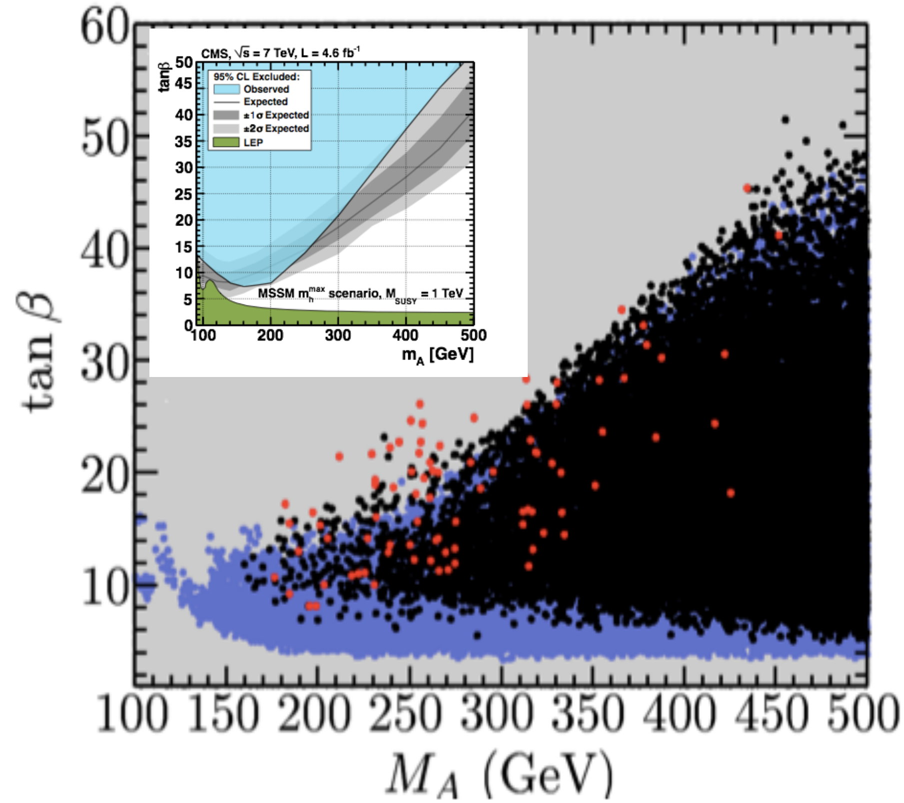


Evidences for a higher h to γγ branching fraction then expected in the SM?

(light) Higgs in MSSM

arXiv:1207.1096v1
R. Benbrik, M. Gomez Bock, S. Heinemeyer

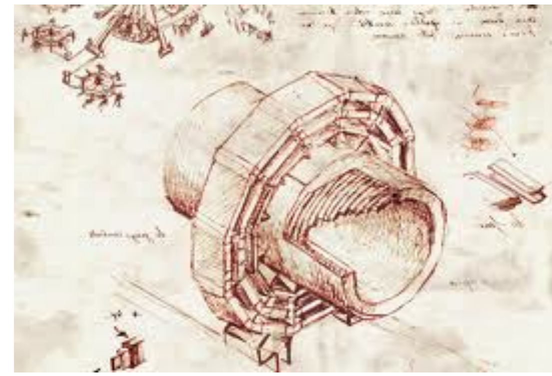


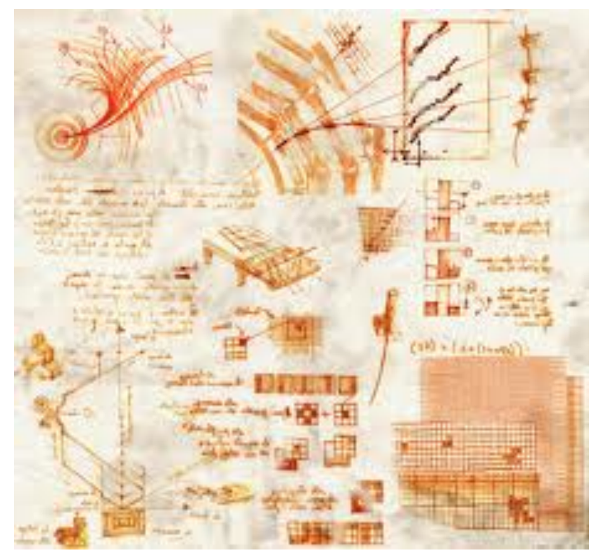


Plenty of MSSM parameter space could accommodate BR(h->γγ)>BR(SM) leaving still a lot of options for a SUSY and a heavy Higgs sector to exist.

We have finally opened the window!

Sergio Cittolin





We have finally opened the window!

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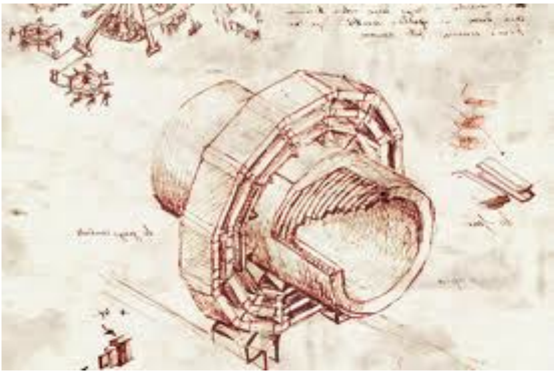
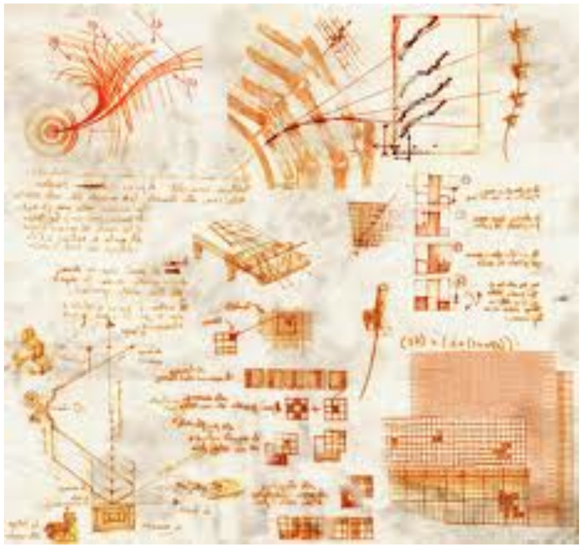




Backup Material

Another Way to Look at It …

Many people now ask:

Will the LHC discover the Higgs boson?

My answer is …

Another Way to Look at It …

Many people now ask:

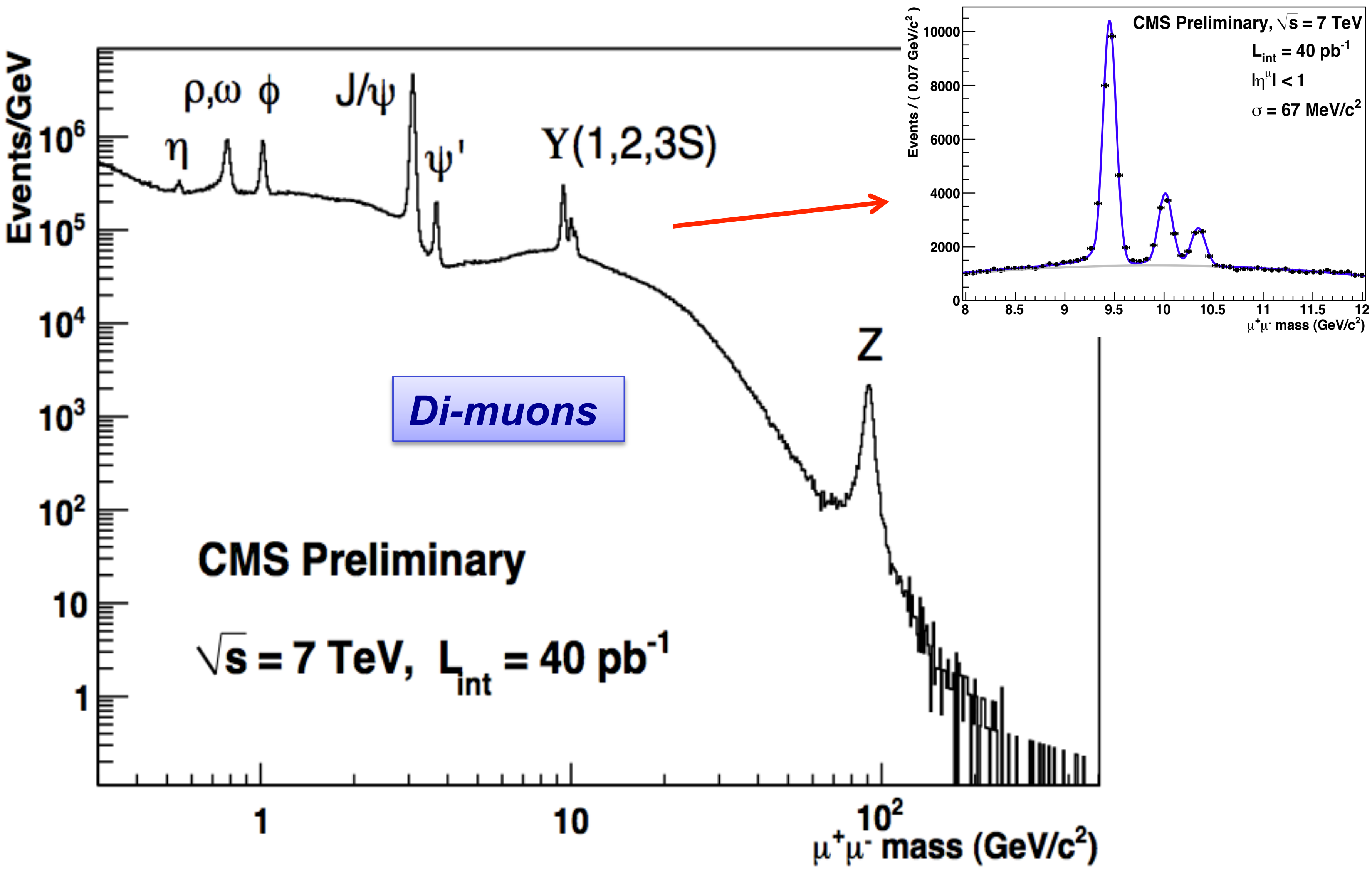
Will the LHC discover the Higgs boson?

My answer is …

By the time the LHC discovers the Higgs boson, that discovery will no longer be considered interesting.

M.E. Peskin - Tools 2008

CMS Performance: Tracking and Muons



Higgs

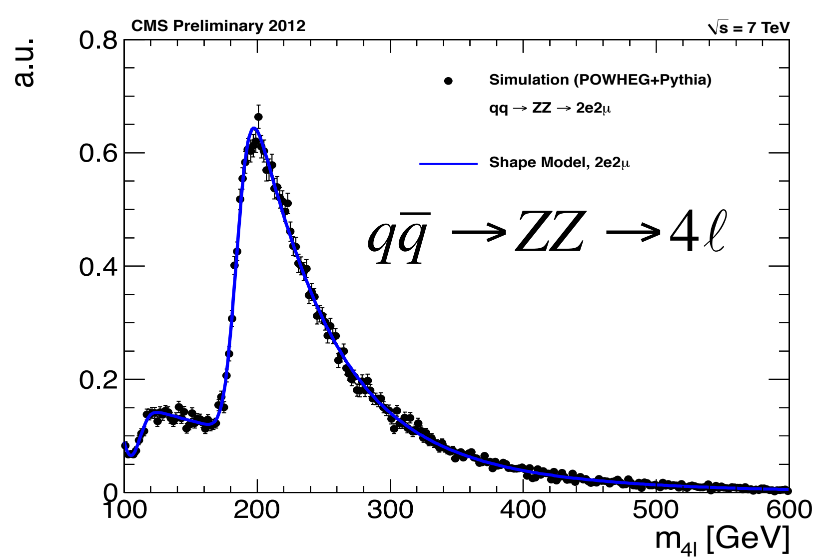
Search in the ZZ → 4l channel

Search for a narrow peak in the 4l mass spectrum over a low background, clean signature but expect few events

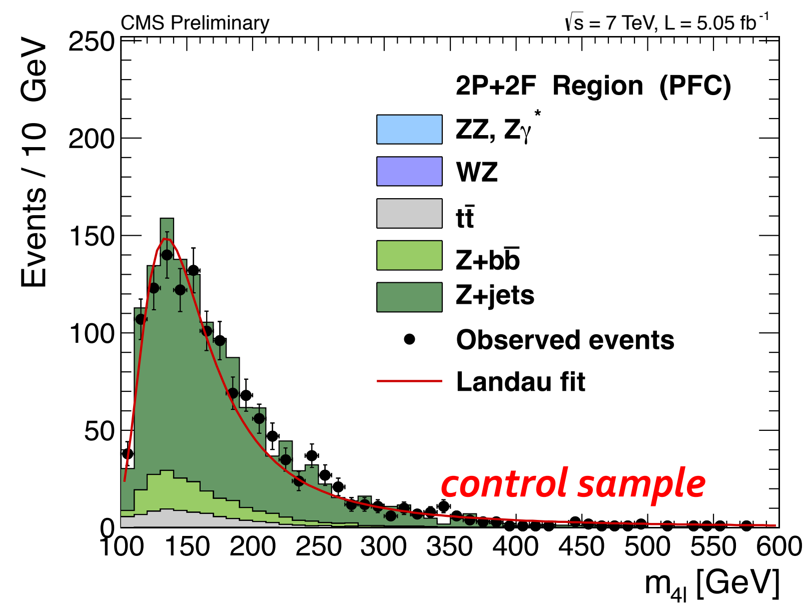
***Background**: irreducible $ZZ^{(*)}$; reducible Z+jets, ttbar, WZ*

Irreducible background ZZ → 4l

Estimated using simulation



Reducible backgrounds estimated from data



Search for the SM Higgs Boson

The relevant decay modes depend strongly on m_H
analysed 5 decay modes $\gamma\gamma$, ZZ, WW, bb, $\tau\tau$

Production modes

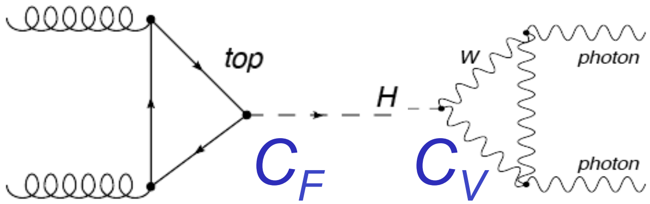
Decay modes

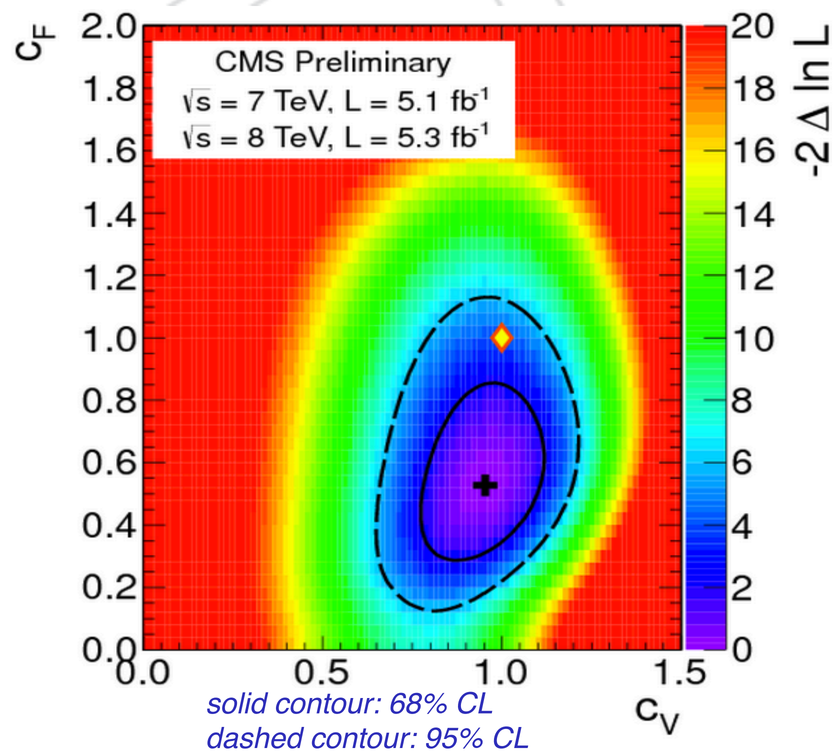
	untagged	VBF-tag	VH-tag	$t\bar{t}$H-tag
$H \to \gamma\gamma$	✓	✓		
$H \to b\bar{b}$			✓	✓
$H \to \tau\tau$	✓	✓	✓	
$H \to WW$	✓	✓	✓	
$H \to ZZ$	✓			

In the low mass range the $\gamma\gamma$, ZZ →4l modes play a special role due excellent two-photon and 4l mass resolution
(~1% compared with >10% for the others)

Properties of the New Boson: Couplings

	$gg \to H$	VBF	VH	ttH
$H \to \gamma\gamma$	$c_F^2 \cdot \lvert\alpha\, c_V + \beta\, c_F\rvert^2$	$c_V^2 \cdot \lvert\alpha\, c_V + \beta\, c_F\rvert^2$	($c_V^2 \cdot \lvert\alpha\, c_V + \beta\, c_F\rvert^2$)	($c_F^2 \cdot \lvert\alpha\, c_V + \beta\, c_F\rvert^2$)
$H \to bb$	($c_F^2\, c_F^2$)	($c_V^2 \cdot c_F^2$)	$c_V^2 \cdot c_F^2$	$c_F^2 \cdot c_F^2$
$H \to \tau\tau$	$c_F^2 \cdot c_F^2$	$c_V^2 \cdot c_F^2$	$c_V^2 \cdot c_F^2$	($c_F^2 \cdot c_F^2$)
$H \to WW$	$c_F^2 \cdot c_V^2$	$c_V^2 \cdot c_V^2$	$c_V^2 \cdot c_V^2$	($c_F^2 \cdot c_V^2$)
$H \to ZZ$	$c_F^2 \cdot c_V^2$	($c_V^2 \cdot c_V^2$)	($c_V^2 \cdot c_V^2$)	($c_F^2 \cdot c_V^2$)





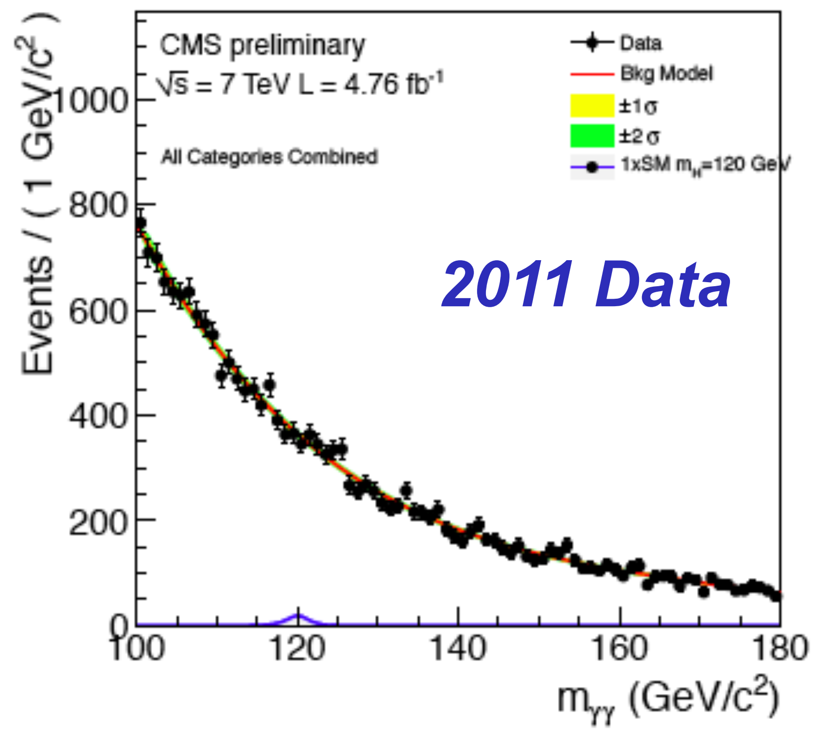
Group the Higgs couplings into "Vectorial" and "Fermionic" sets. Attach a modifier to the SM prediction to each of those (C_V and C_F).

In agreement with the SM within the 95% confidence range

→ Need more data!

The Analysis Method for H → γγ

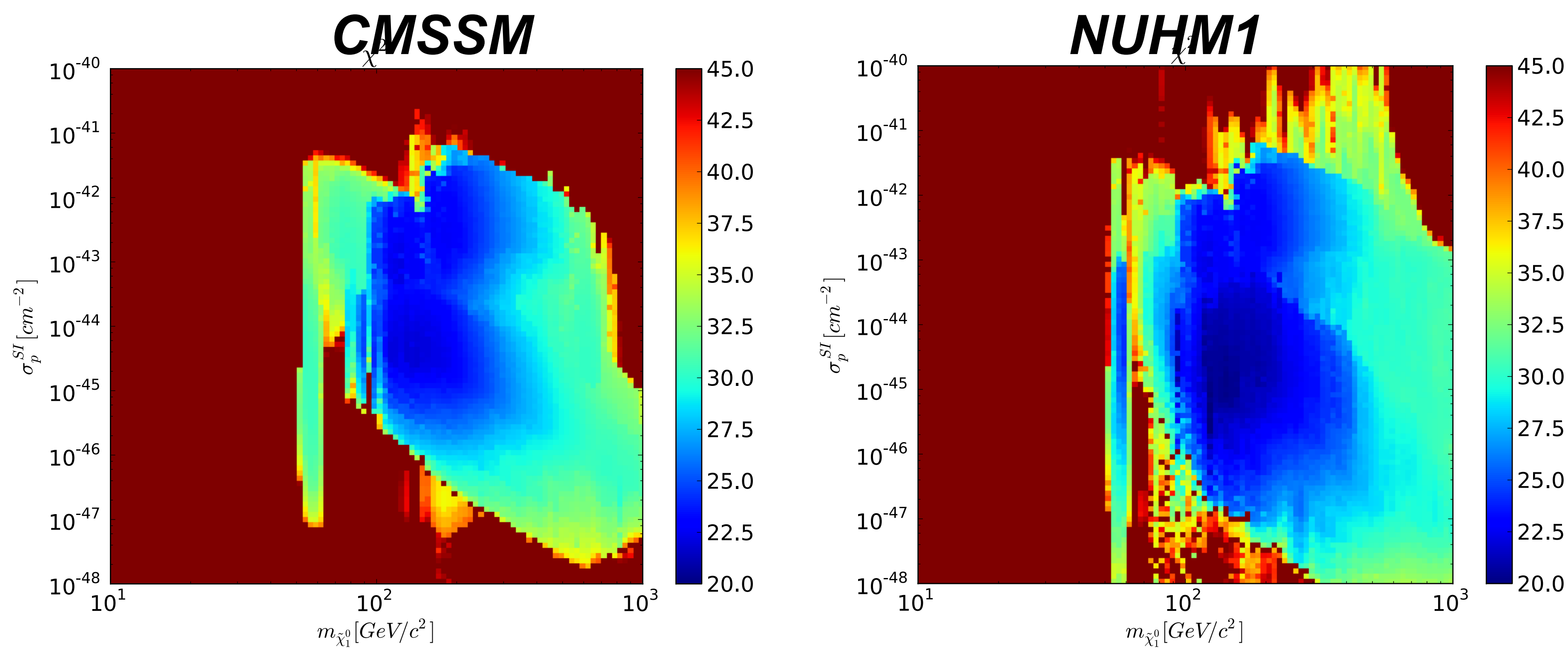
- **Main analysis is a Multi-Variate-Analysis (MVA)**
  - MVAs for photon identification and event classification
  - **1. Fit mass distribution in 4 event classes based on a diphoton MVA output + 2 di-jet categories**
  - **2. Cross-checked with an alternative background model extraction using** mass sidebands to construct the background model
- **3. Also cross-checked with a cut based analysis**
  - Simple and robust
    Fit data mass distribution in 2 angular x 2 shower shape i.e. 4 categories with different signal over background + 2 di-jet categories



SUSY

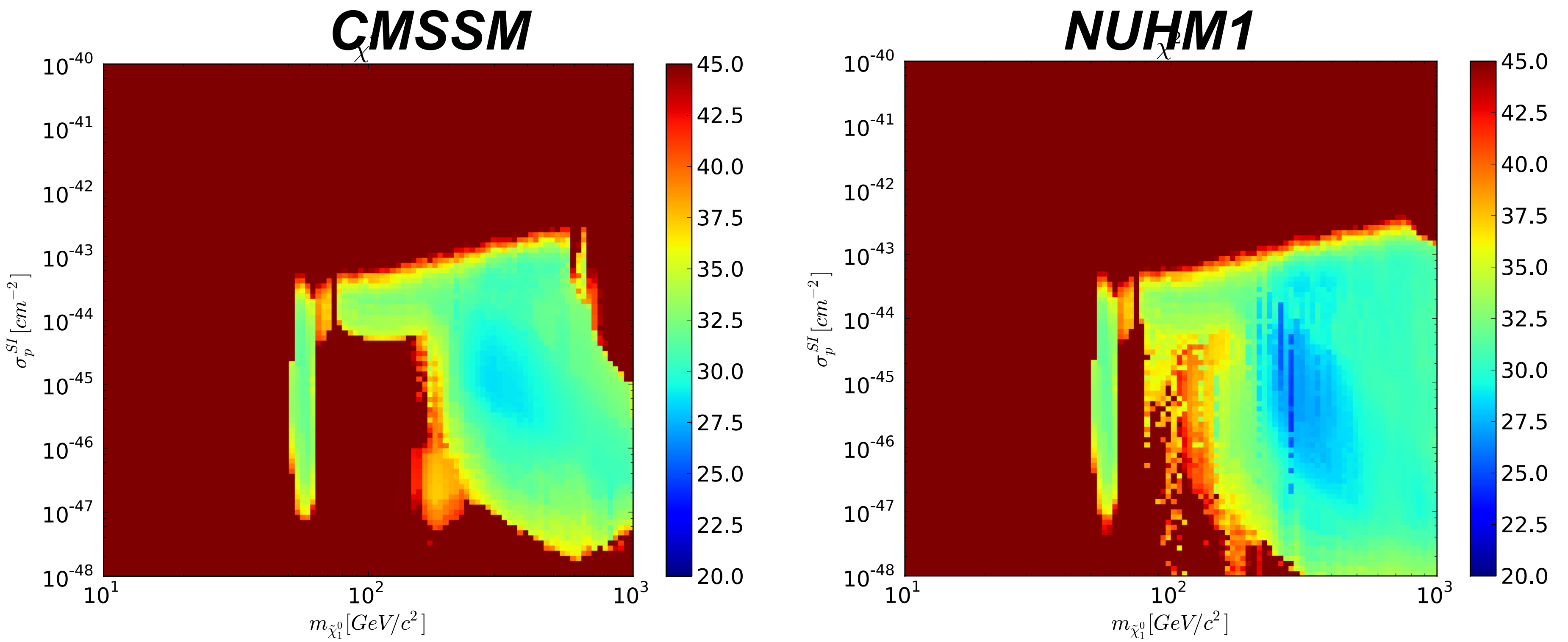
Spin Independent XS vs. M_{LSP}

Pre-LHC 2008



Spin Independent XS vs. M_{LSP}

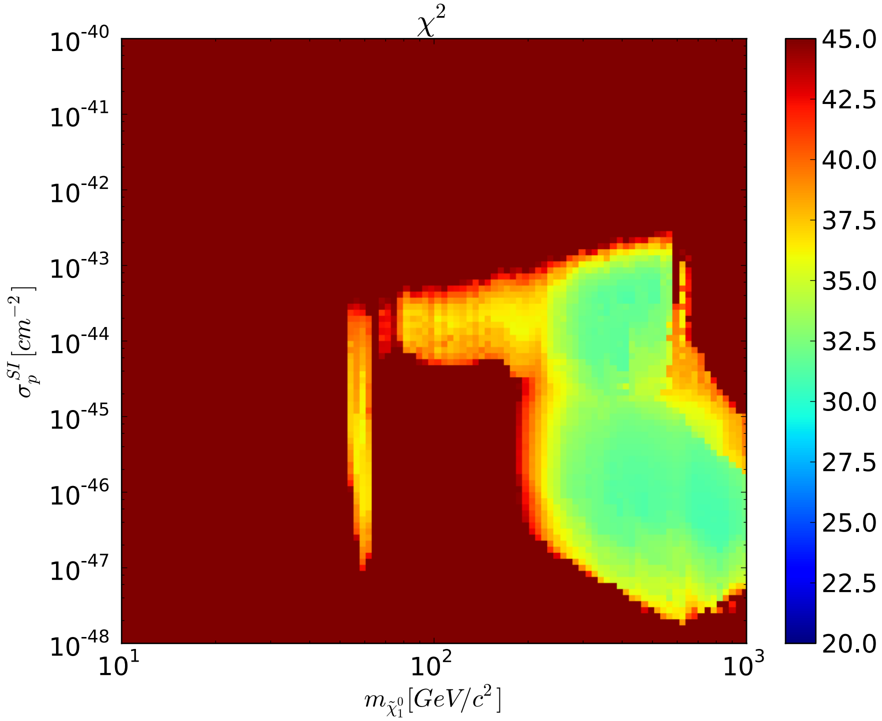
Post-LHC (1/fb), Post-Xenon100 - 2011



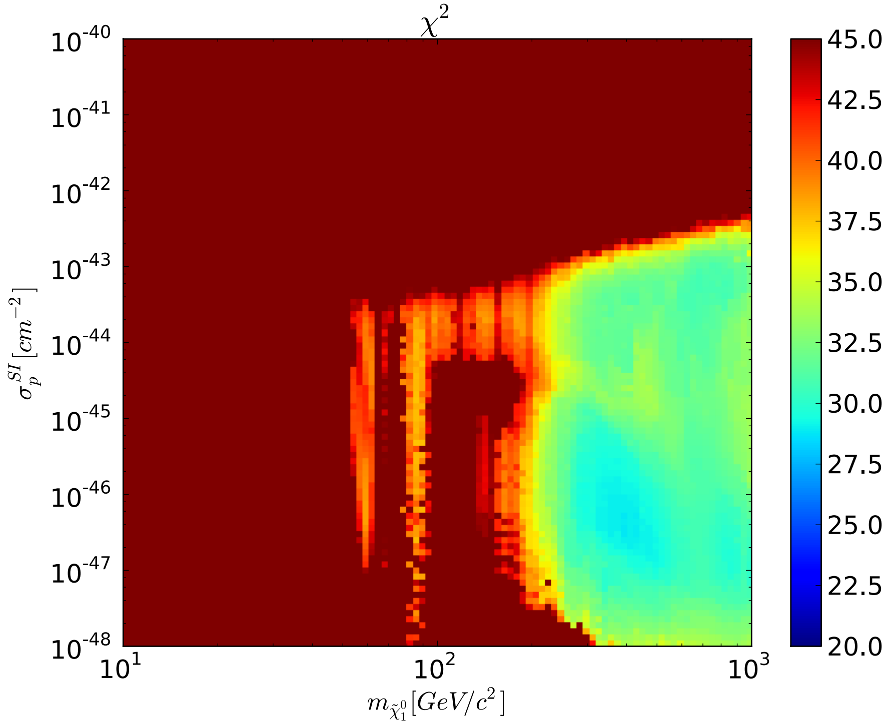
Spin Independent XS vs. M_{LSP}

Post Discovery!

assume m_H=125 +/- 1.5(theo) +/- 1.0 GeV



CMSSM

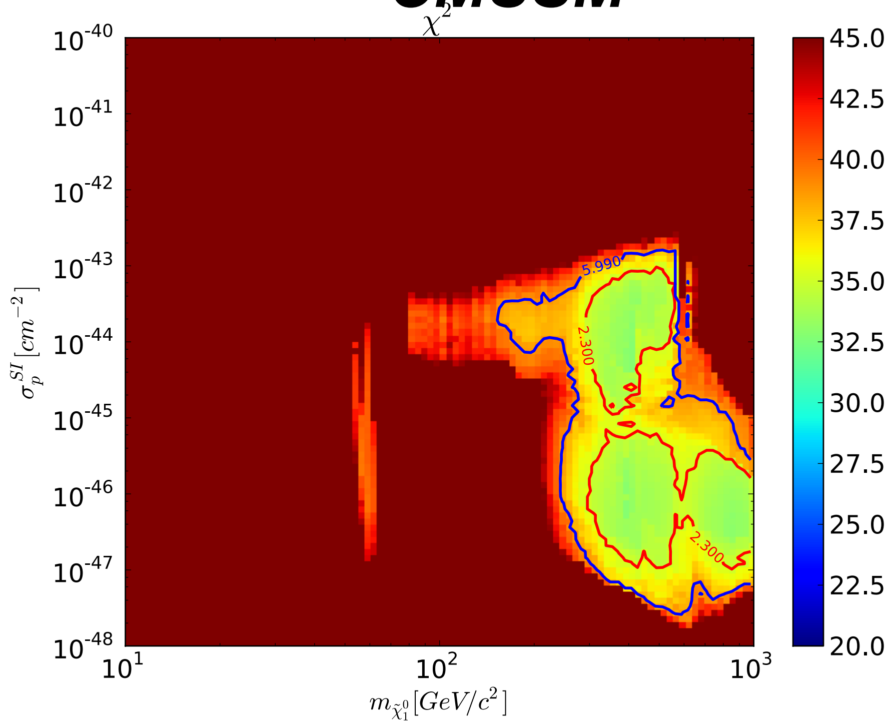


NUHM1

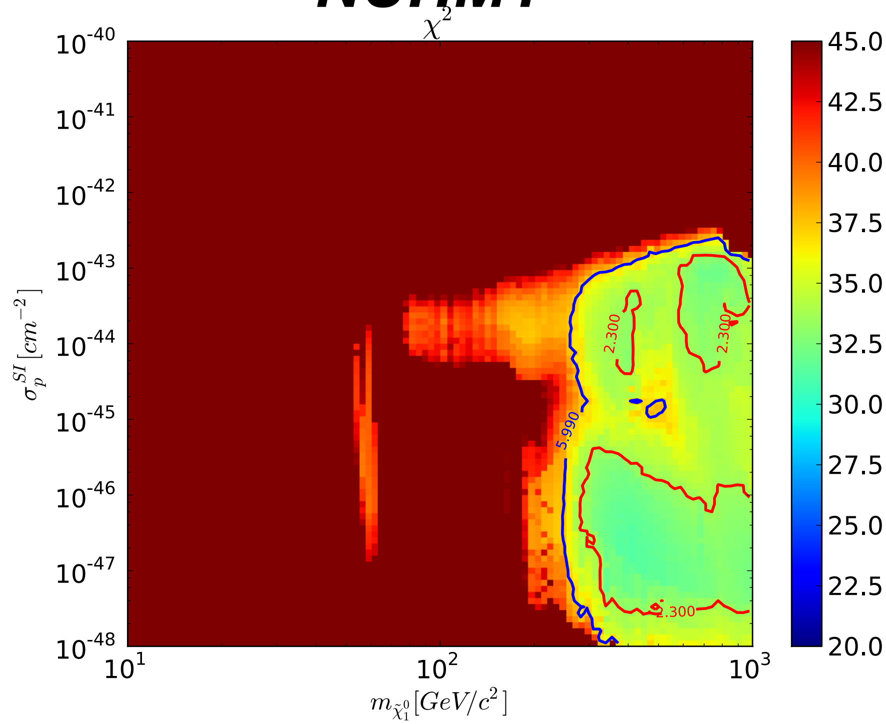
Spin Independent XS vs. M_{LSP}

Today

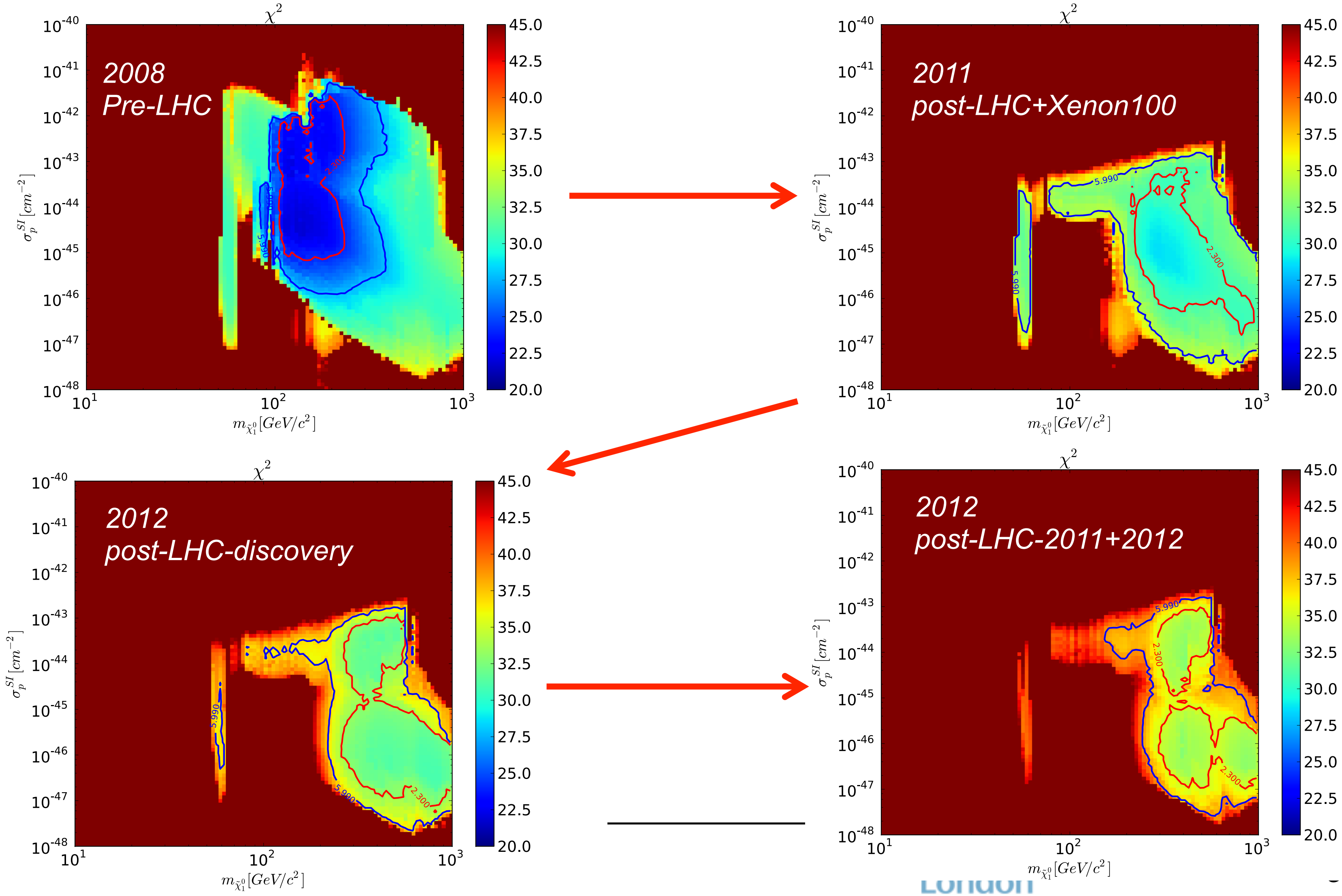
CMSSM



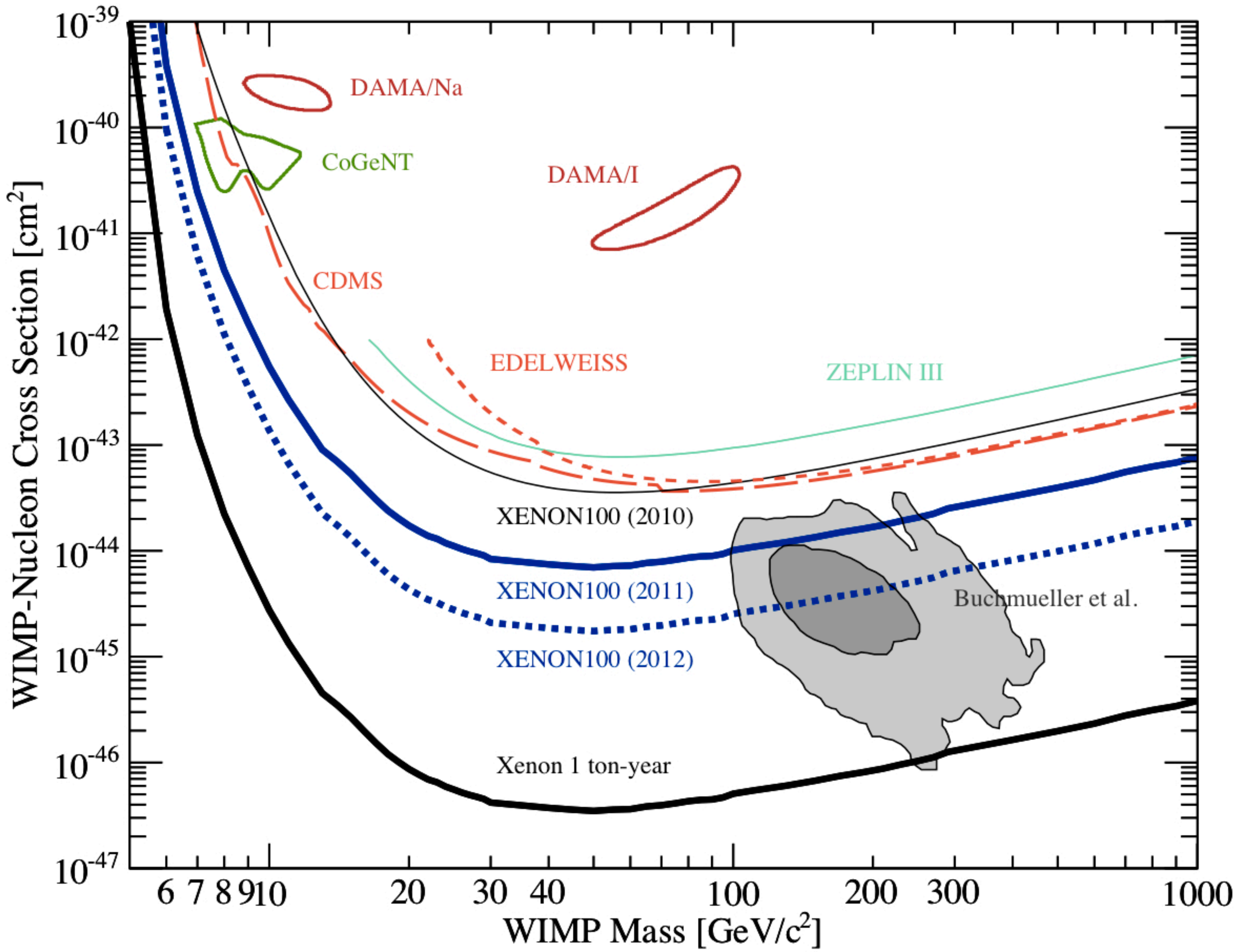
NUHM1



CMSSM: Evolution with time



SUSY & Dark Matter - Synergies in the Future!



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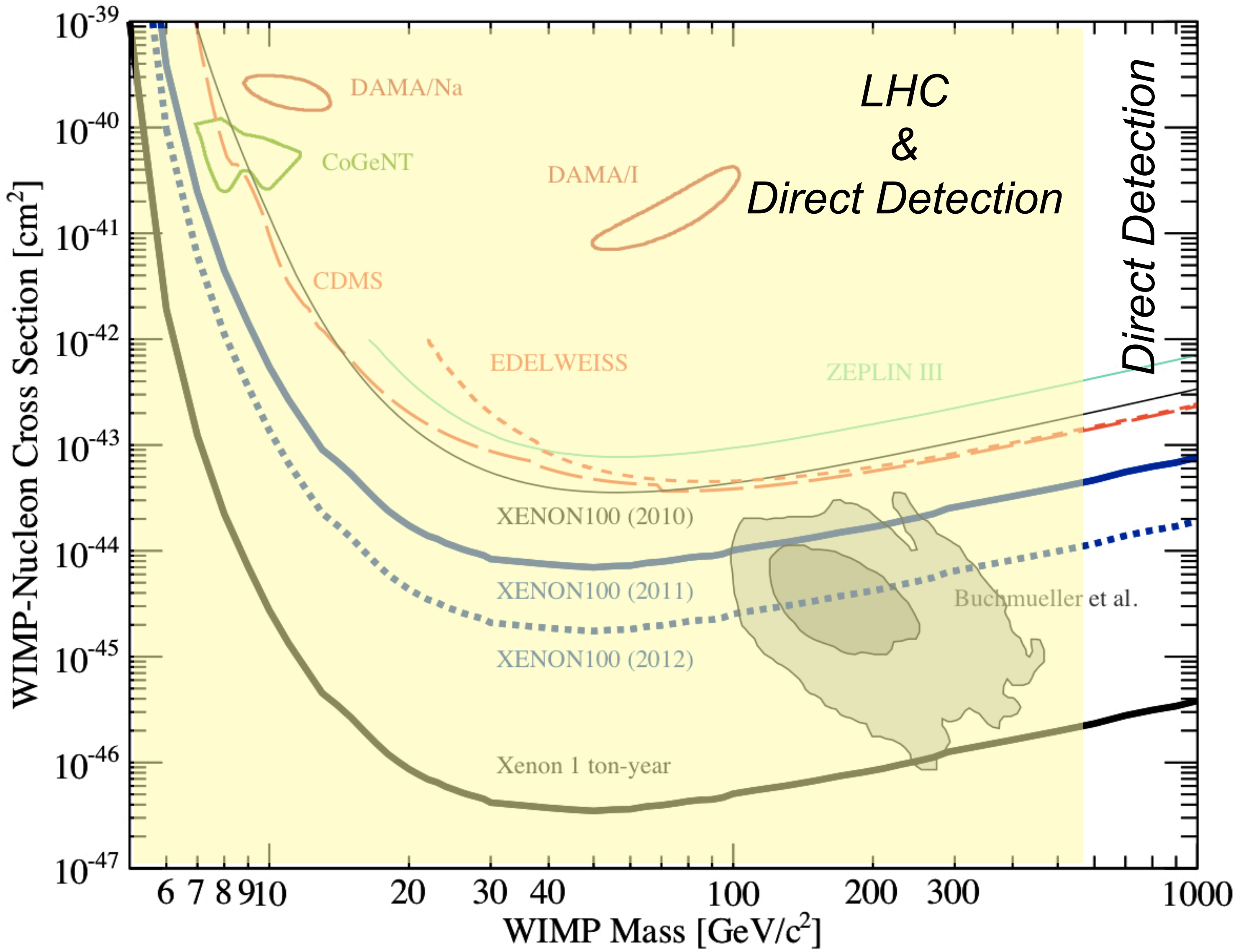
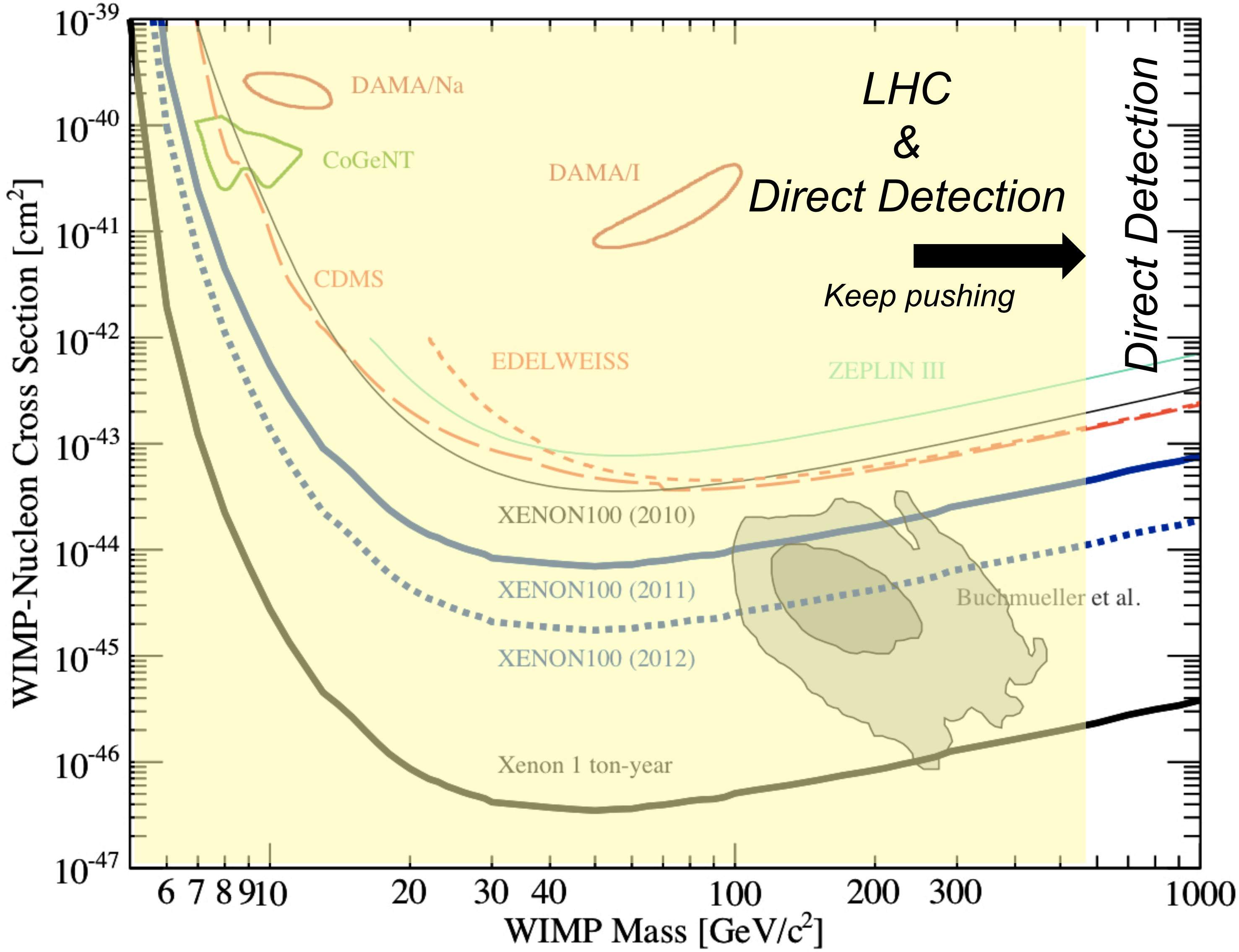


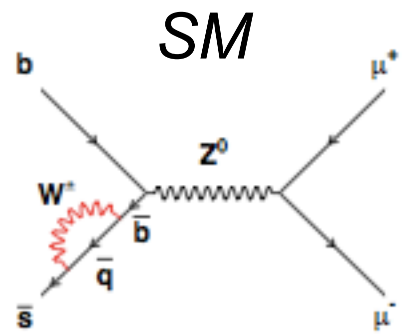
SUSY & Dark Matter - Synergies in the Future!

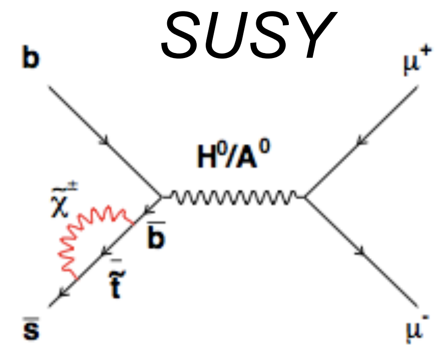


B_s -> μμ

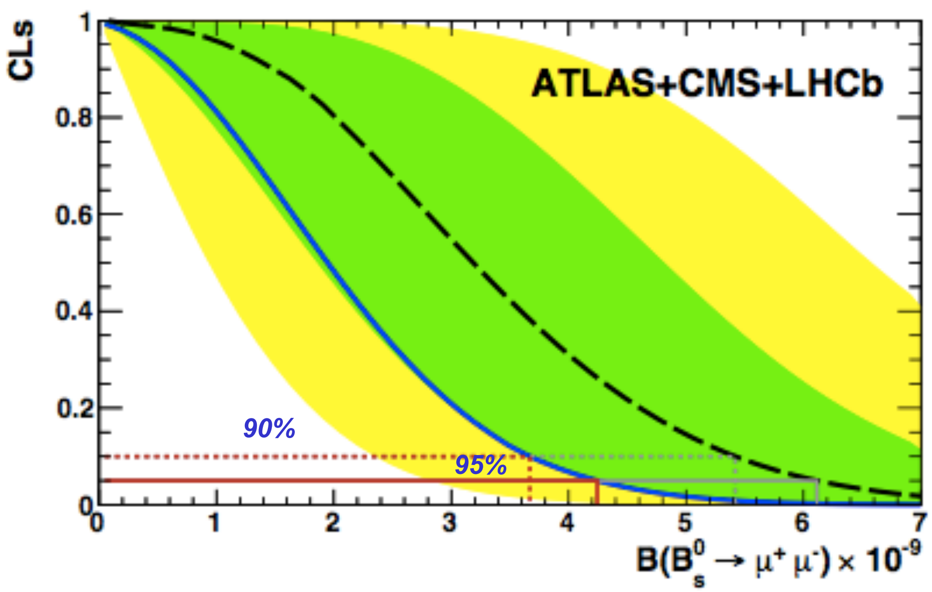
Also B-Physics provides powerful constraints on SUSY.

Example: B_s -> μμ





Signal + Background



For comparison:
SM: ~3x10^{-9}

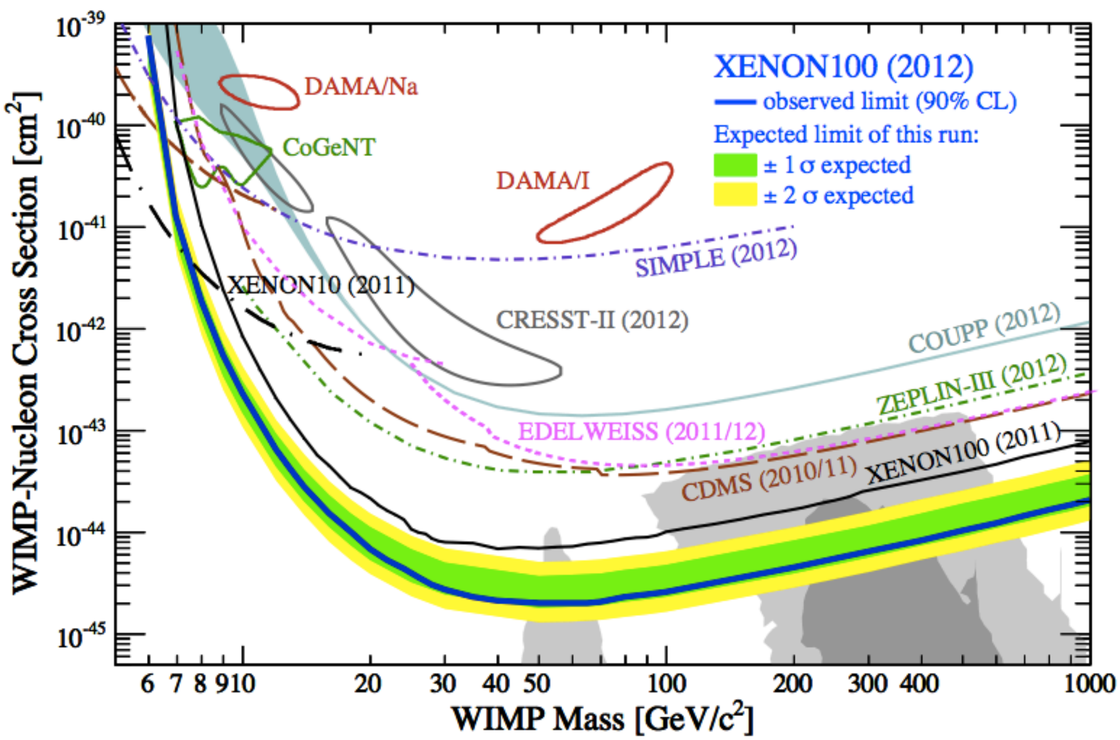
BR(B_s -> μμ) [10^{-9}]	90% CL	95% CL
ATLAS	xx	22
CMS	xx	7.7
LHCb	xx	4.5
CDF	xx	xx
D0		
Combined*	xx	xx

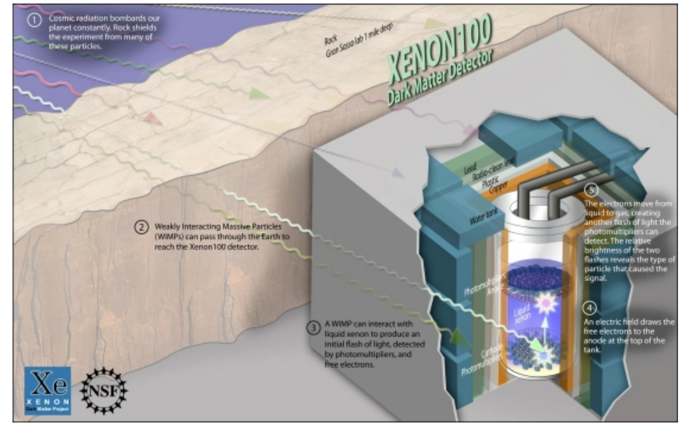
**) Private average performed for MasterCode studies*

Direct Dark Matter Searches

Example: Xenon100

New result: arXiv:1207.5988v1





The XENON100 experiment is located deep underground at the Gran Sasso National Laboratory in Italy.

34 kg liquid Xenon target
225 days of data taking
1.0±0.2 events expected
2 events observed
⇒Exclude 2.0×10^{-45} cm^2
for a M_{WIMP} = 55 GeV at 90% CL.

Why Global Fits?!

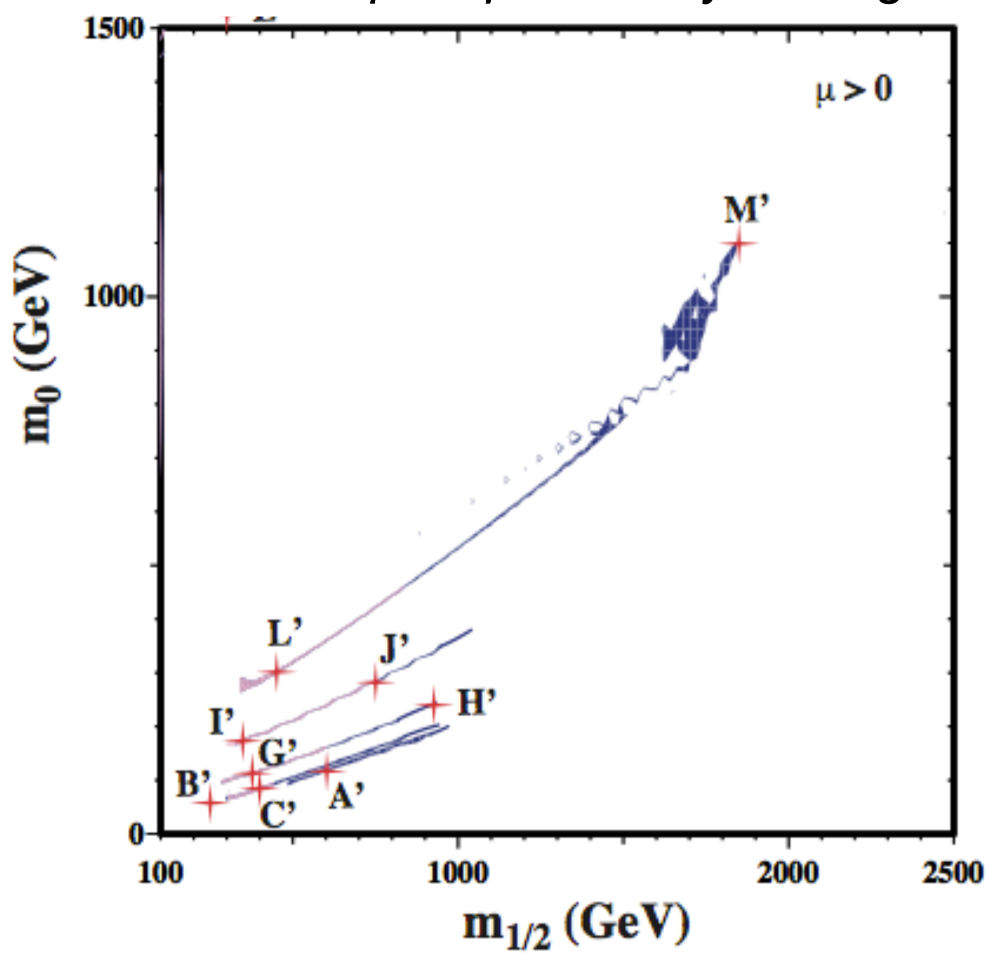
Example:
Wmap strips in the CMSSM

“Wmap strips” are the result of a 2D scan of m_0 and $m_{1/2}$ where the other two parameters in the CMSSM, i.e. A_0 and $\tan\beta$ are fixed.

Therefore, a 4D parameter space is collapsed to a 2D Model, WITHOUT taking into account the other parameters.

0306219 [hep-ph]

Wmap strips some years ago



Why Global Fits?!

Example:
Wmap strips in the CMSSM

Global Fit instead of 2D scan:

Carry out a simultaneous fit of all relevant NP and SM parameter to the experimental data/constraints.

The result of such a global fit will not suffer from the "ambiguity symptoms" of the scans and in addition will provide a well-defined statistical interpretation of the results

Its proper execution is by far a non-trivial problem, though!

Wmap strips today