# *Physics prospects for the LHC*

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DESY

Abingdon, 09 / 2011

- Introduction
- Physics of electroweak symmetry breaking
- New physics addressing the hierarchy problem
- Conclusions

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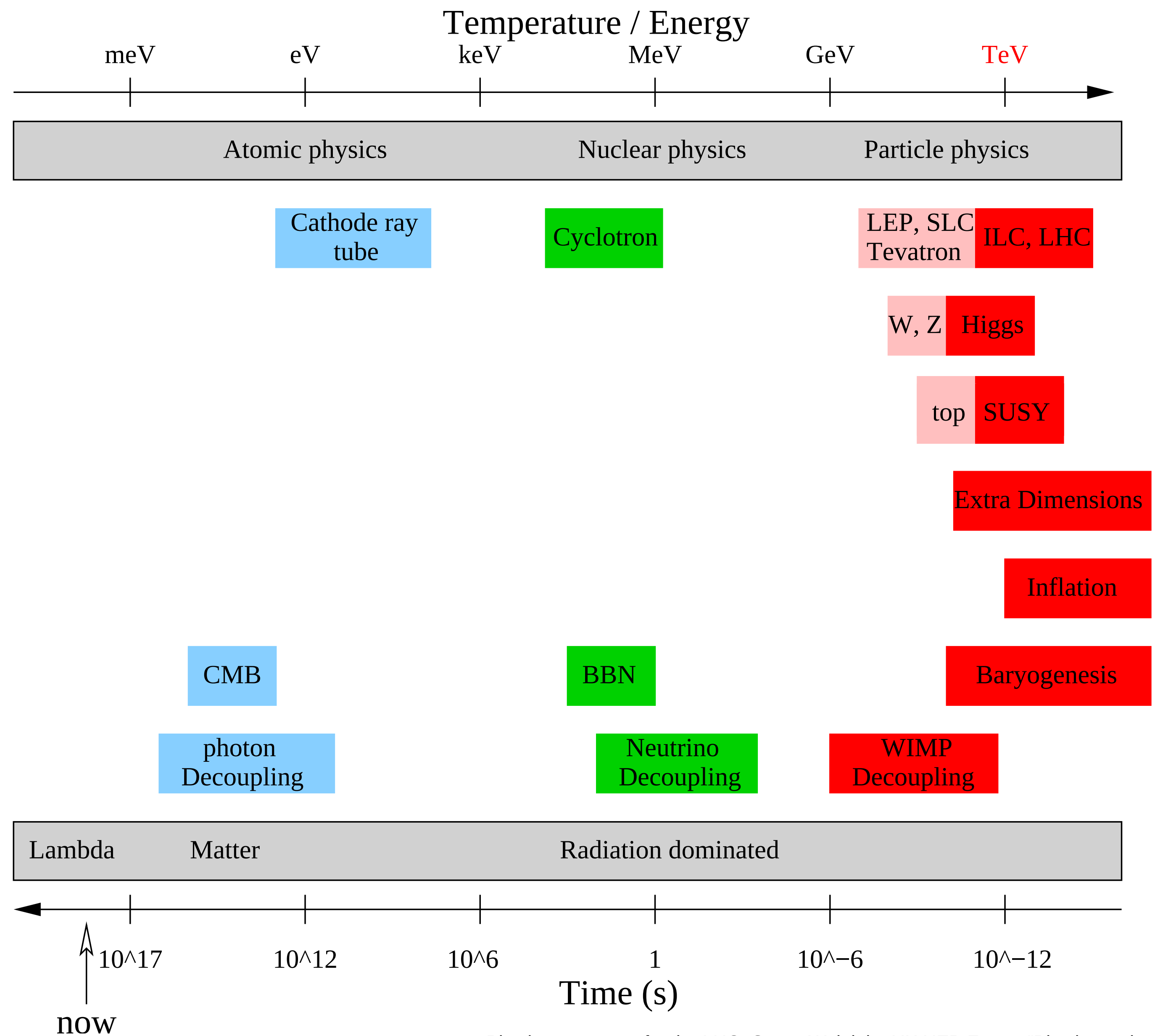
Impressive rediscovery of the known ingredients of the Standard Model

No evidence for new physics yet

# *LHC physics: exploring the Terascale*

$$1 \text{ TeV} \approx 1000 \times m_{\text{proton}} \Leftrightarrow 2 \times 10^{-19} \text{ m}$$



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- How do elementary particles obtain the property of mass: what is the mechanism of electroweak symmetry breaking? Is there a Higgs boson (or more than one)?
- Do all the forces of nature arise from a single fundamental interaction?
- Are there more than three dimensions of space?
- Are space and time embedded into a "superspace"?
- What is dark matter? Can it be produced in the laboratory?
- Are there new sources of $\mathcal{CP}$-violation?
  Can they explain the asymmetry between matter and anti-matter in the Universe?
- . . .

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- Nature has found a way to prevent this

  The Standard Model provides no explanation

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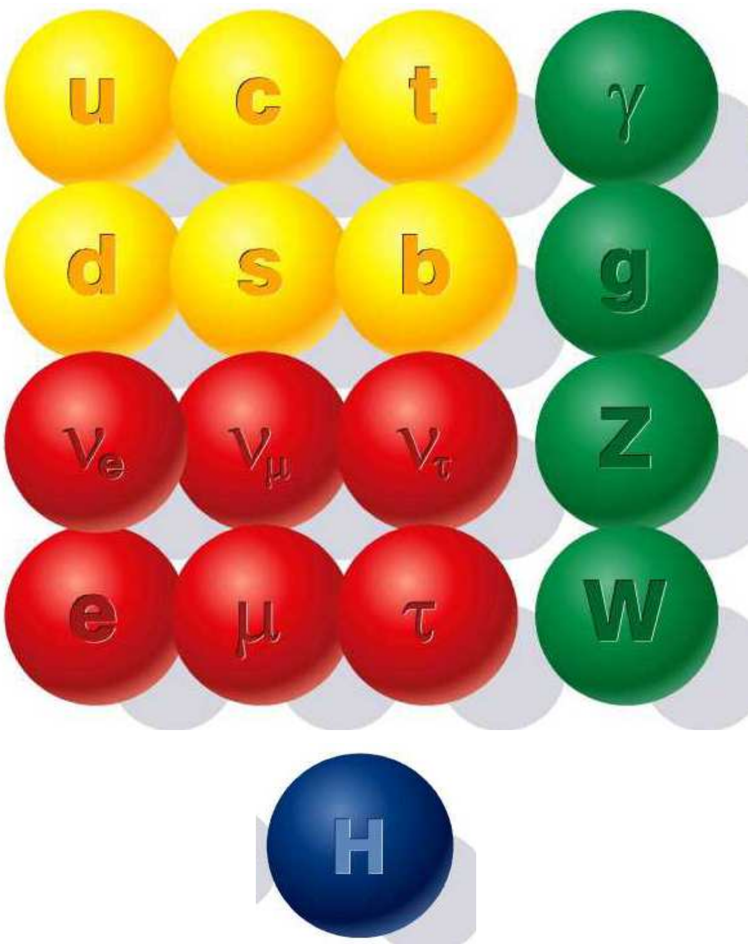
Extra dimensions of space:

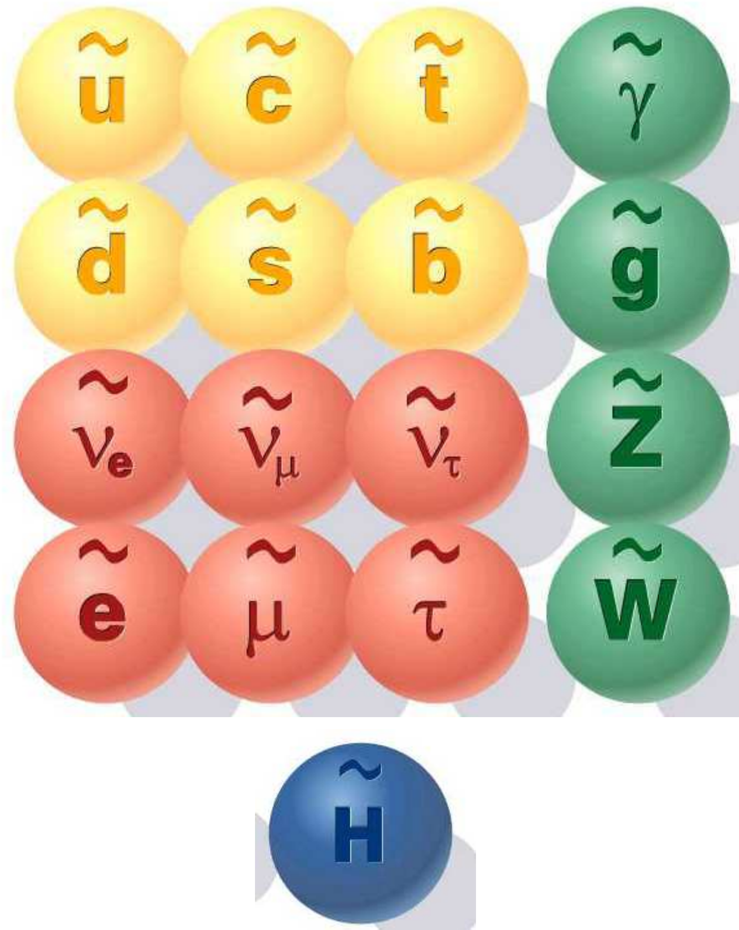
Fundamental Planck scale is $\sim \mathrm{TeV}$ (large extra dimensions),

hierarchy of scales is related to a “warp factor”
(“Randall–Sundrum” scenarios)

# *Supersymmetry (SUSY)*

Supersymmetry: fermion $\longleftrightarrow$ boson symmetry,
leads to compensation of large quantum corrections



# The Minimal Supersymmetric Standard Model (MSSM)

Superpartners for Standard Model particles:

$$\left[u, d, c, s, t, b\right]_{L,R} \quad \left[e, \mu, \tau\right]_{L,R} \quad \left[\nu_{e,\mu,\tau}\right]_L \qquad \text{Spin } \tfrac{1}{2}$$

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$$g \quad \underbrace{W^{\pm}, H^{\pm}} \quad \underbrace{\gamma, Z, H_1^0, H_2^0} \qquad \text{Spin } 1 \text{ / Spin } 0$$

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Two Higgs doublets, physical states: $h^0, H^0, A^0, H^{\pm}$

General parametrisation of possible SUSY-breaking terms
$\Rightarrow$ free parameters, no prediction for SUSY mass scale

Hierarchy problem $\Rightarrow$ expect observable effects at TeV scale

# ***How does SUSY breaking work?***

Exact SUSY $\Leftrightarrow m_{\mathrm{e}} = m_{\tilde{\mathrm{e}}}, \ldots$

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Strong phenomenological constraints on flavour off-diagonal and $\mathcal{CP}$-violating SUSY-breaking terms

$\Rightarrow$ Good phenomenological description for universal SUSY-breaking terms ($\approx$ diagonal in flavour space)

# Simplest ansatz: the Constrained MSSM (CMSSM)

Assume universality at high energy scale ($M_{\rm GUT}$, $M_{\rm Pl}$, $\ldots$)
renormalisation group running down to weak scale
require correct value of $M_{\rm Z}$

$\Rightarrow$ CMSSM characterised by

$$m_0^2,\ m_{1/2},\ A_0,\ \tan\beta,\ \mathrm{sign}\,\mu$$

CMSSM has been the "favourite toy" for both theorists and experimentalists so far

CMSSM is in agreement with the experimental constraints from electroweak precision observables (EWPO) $+$ flavour physics $+$ cold dark matter density $+$ $\ldots$

# *SUSY-breaking scenarios*

"Hidden sector": $\longrightarrow$ Visible sector:

SUSY breaking MSSM

"Gravity-mediated": SUGRA
"Gauge-mediated": GMSB
"Anomaly-mediated": AMSB
"Gaugino-mediated"

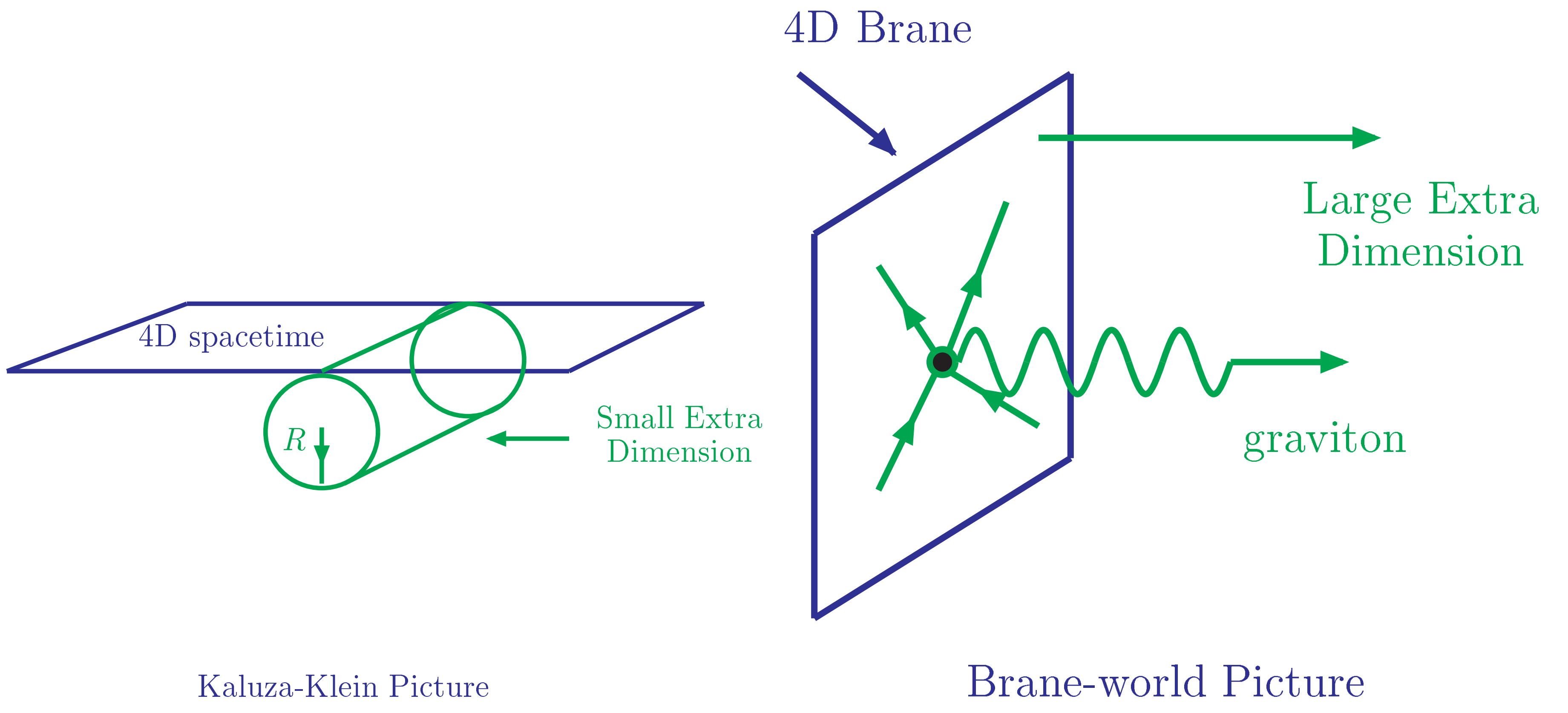
...

SUGRA: mediating interactions are gravitational

GMSB: mediating interactions are ordinary electroweak and QCD gauge interactions

AMSB, Gaugino-mediation: SUSY breaking happens on a different brane in a higher-dimensional theory

# *Models with extra dimensions of space*



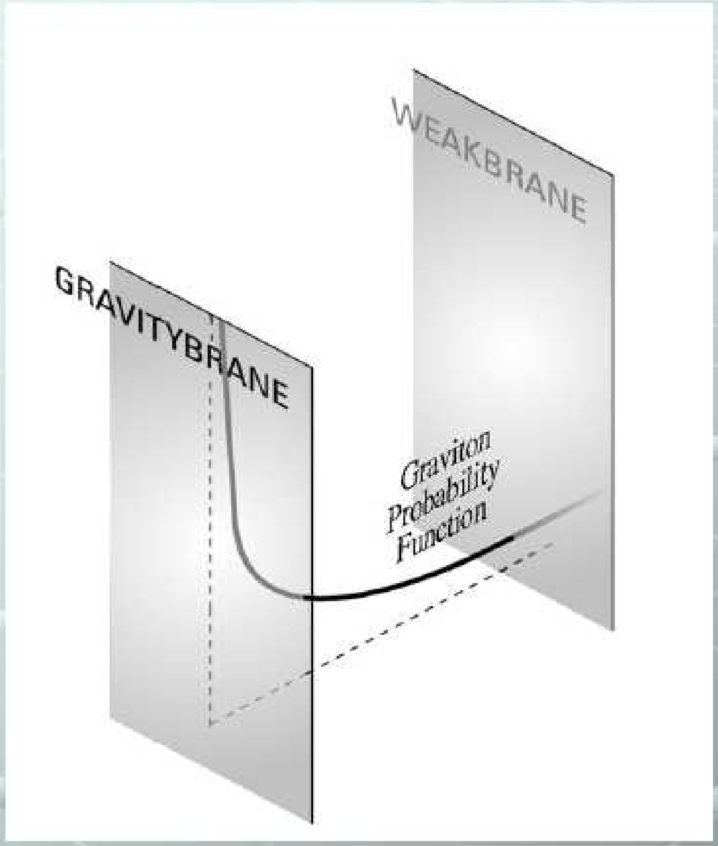

Hierarchy between $M_{\text{Planck}}$ and $M_{\text{weak}}$ is related to the volume or the geometrical structure of additional dimensions of space

$\Rightarrow$ observable effects at the TeV scale

# *Gravity in a warped spacetime geometry*

[*L. Randall, LHC2TSP Workshop '11*]

## Natural for gravity to be weak!

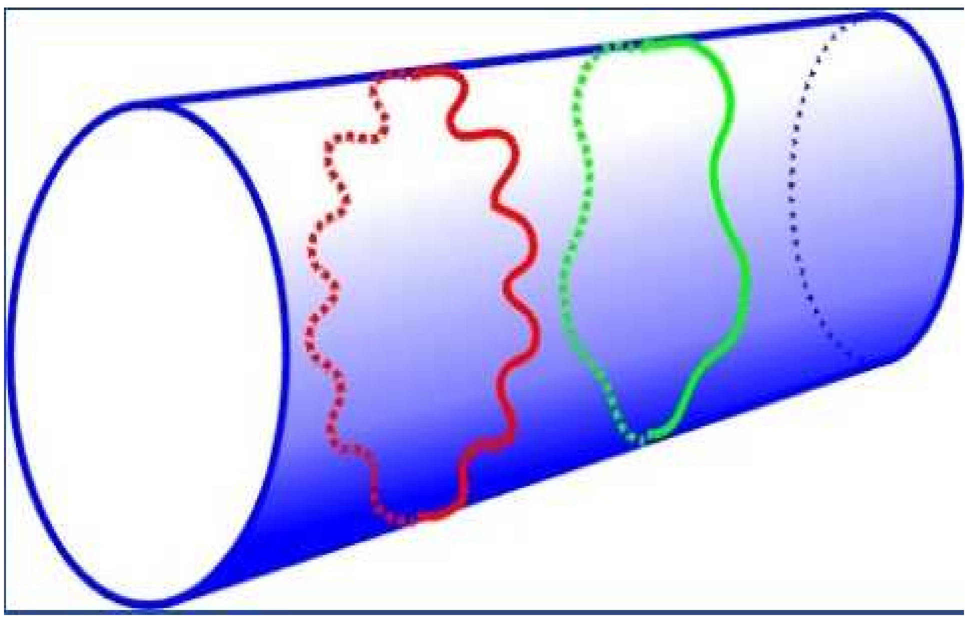



- Small probability for graviton to be near the Weakbrane
- If we live anywhere but the Gravitybrane, gravity will seem weak
- Natural consequence of warped geometry

$$ds^2 = g_{MN}\,dx^M dx^N = e^{-2\sigma}\eta_{\mu\nu}\,dx^\mu dx^\nu - dy^2 \,,$$

# *Phenomenological consequences of extra dimensions*

The wave function of a free particle must be $2\pi R$ periodic



$$e^{ip.x_5} = e^{ip.(x_5+2\pi R)}$$

$$p = \frac{n}{R}$$

$\Rightarrow$ momentum is quantised

$\Rightarrow$ Looks in 4-dim like a series of new, more massive partners associated with each known particle: “Kaluza–Klein tower”

# *Phenomenological consequences of extra dimensions*

We may be trapped on a $(3+1)$-dimensional brane in a higher-dimensional space-time, while gravity can enter the extra dimensions

Extra dimensions could be large, even infinite

$\Rightarrow$ Could explain the apparent weakness of gravity in our 4-dimensional world

$\Rightarrow$ At the LHC, gravitons could be emitted into the extra dimensions

$\Rightarrow$ "missing energy" signals

If gravity is strong at the TeV scale, particle collisions at the LHC could form "mini black holes"

# *Physics of electroweak symmetry breaking*

What is the mechanism of electroweak symmetry breaking?

- Standard Model (SM), SUSY, . . . :
  Higgs mechanism, elementary scalar particle(s)

- Strong electroweak symmetry breaking:
  a new kind of strong interaction

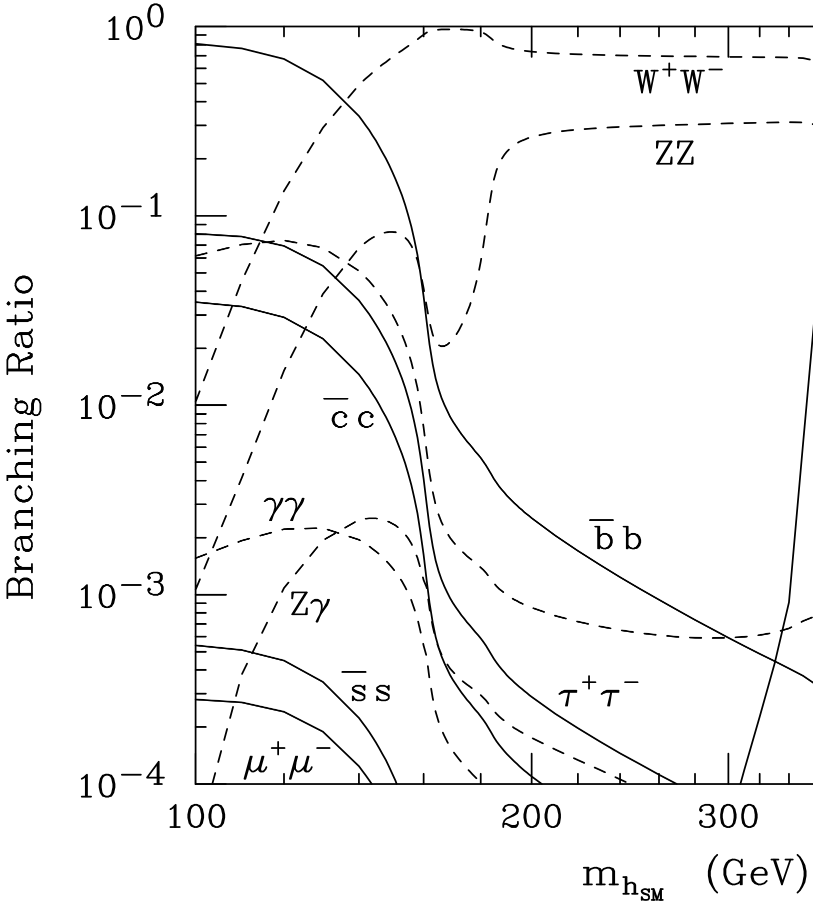
- Higgsless models in extra dimensions: boundary conditions for SM gauge bosons and fermions on Planck and TeV branes in higher-dimensional space

$\Rightarrow$ New phenomena required at the TeV scale

# Higgs phenomenology: SM and beyond

Standard Model: a single parameter determines the whole Higgs phenomenology: $M_{\rm H}$

Branching ratios of the SM Higgs:




$\Rightarrow$ dominant BRs:

$M_{\rm H} \lesssim 140$ GeV:

$H \to b\bar{b}$

$M_{\rm H} \gtrsim 140$ GeV:

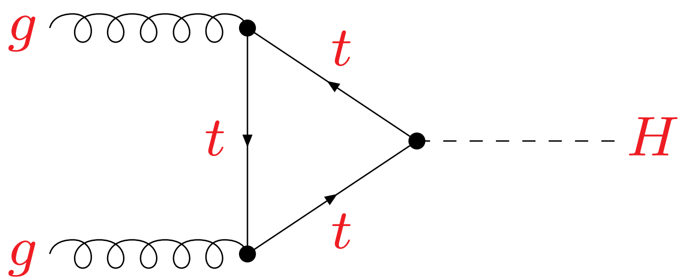
$H \to W^+W^-, ZZ$

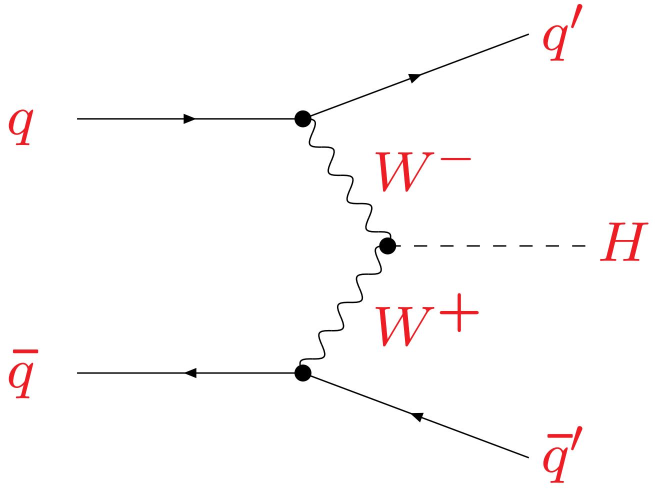
# Production of a SM-like Higgs at the LHC

SM Higgs production at the LHC:

Dominant production processes:

gluon fusion: $gg \to H$, weak boson fusion (WBF): $q\bar{q} \to q'\bar{q}'H$

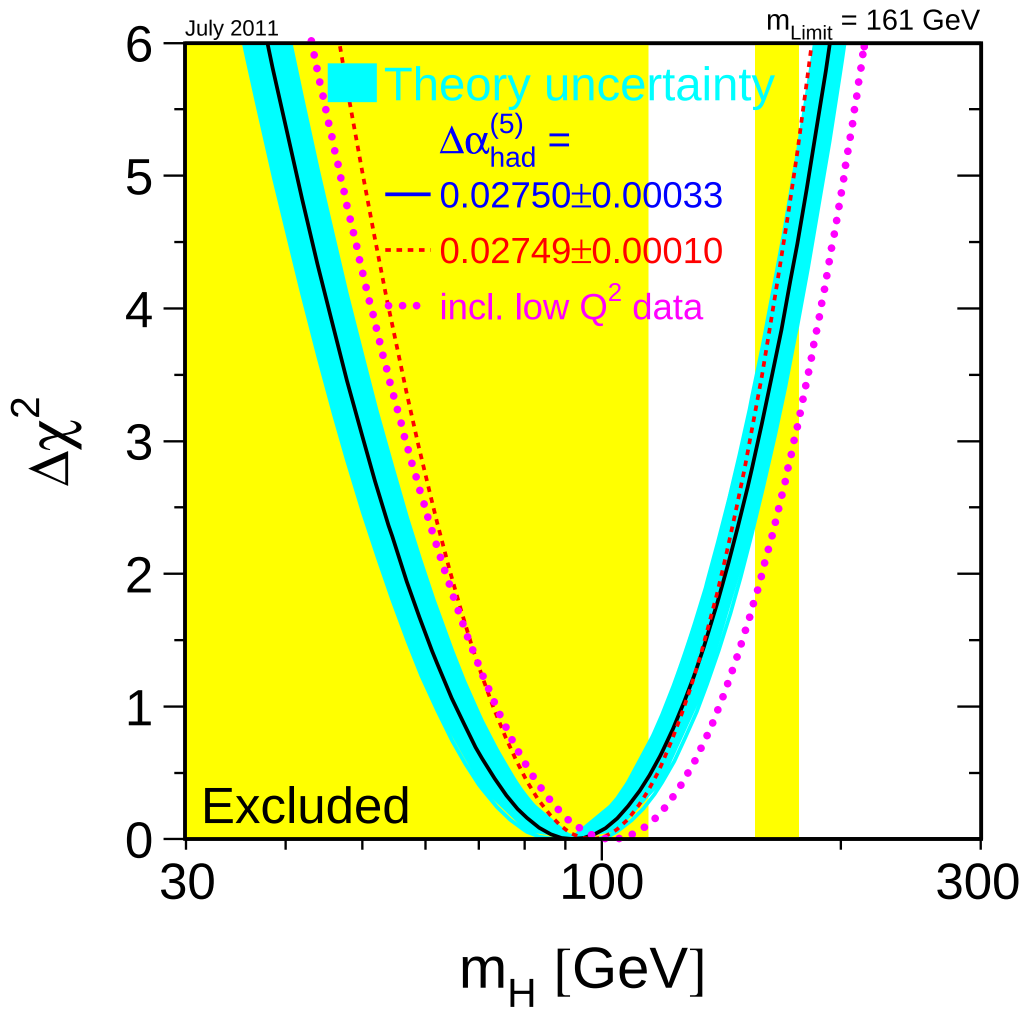


# *Constraints on the SM Higgs from electroweak precision data*

Indirect constraint on $M_{\mathrm{H_{SM}}}$, no direct search limits included in the fit

[*LEPEWWG '11*]




⇒ Preference for a light Higgs, $M_{\mathrm{H_{SM}}} < 161$ GeV, 95% C.L.

## *Higgs physics beyond the SM*

In the SM the same Higgs doublet is used “twice” to give masses both to up-type and down-type fermions

$\Rightarrow$ extensions of the Higgs sector having (at least) two doublets are quite “natural”

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But there is also the possibility that none of the Higgs bosons is SM-like

# *Higgs physics in Supersymmetry*

“Simplest” extension of the minimal Higgs sector:

Minimal Supersymmetric Standard Model (MSSM)

- Two doublets to give masses to up-type and down-type fermions (extra symmetry forbids to use same doublet)
- SUSY imposes relations between the parameters

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- SUSY imposes relations between the parameters

$\Rightarrow$ Two parameters instead of one: $\tan\beta \equiv \frac{v_u}{v_d}, \quad M_\mathrm{A}$ (or $M_{\mathrm{H}^\pm}$)

$\Rightarrow$ Upper bound on lightest Higgs mass, $M_\mathrm{h}$ (*FeynHiggs*):
[*S. Heinemeyer, W. Hollik, G. W. '99*], [*G. Degrassi, S. Heinemeyer, W. Hollik, P. Slavich, G. W. '02*]

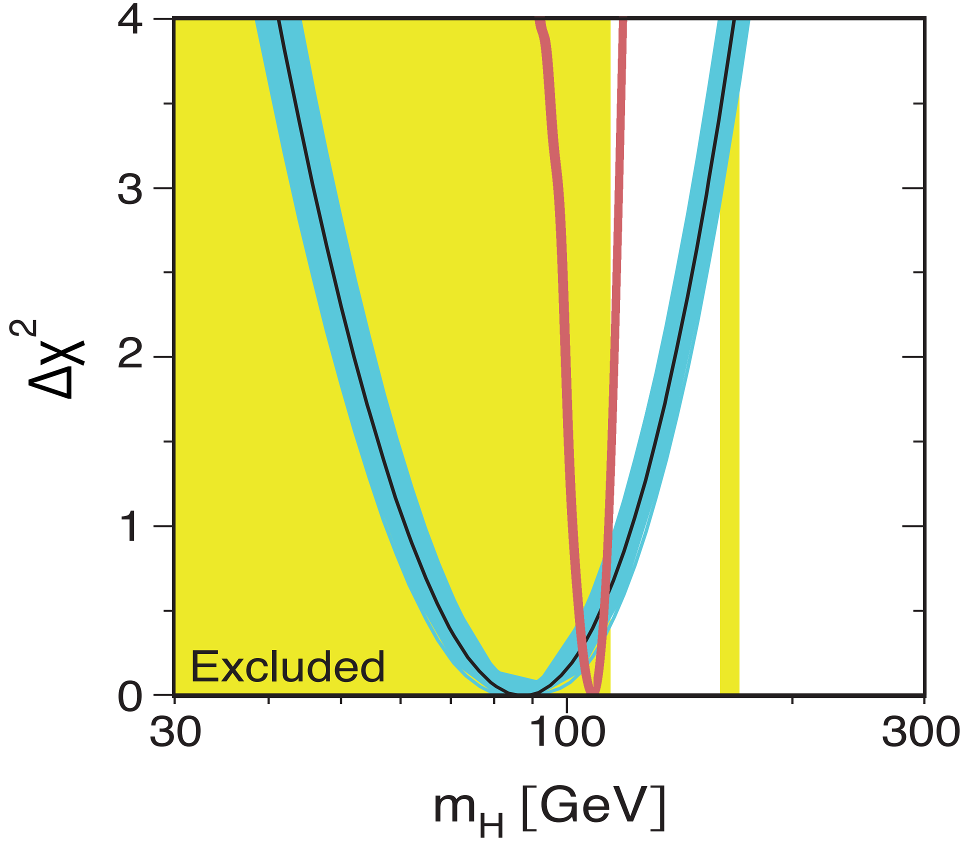
$$M_\mathrm{h} \lesssim 130\,\mathrm{GeV}$$

Very rich phenomenology

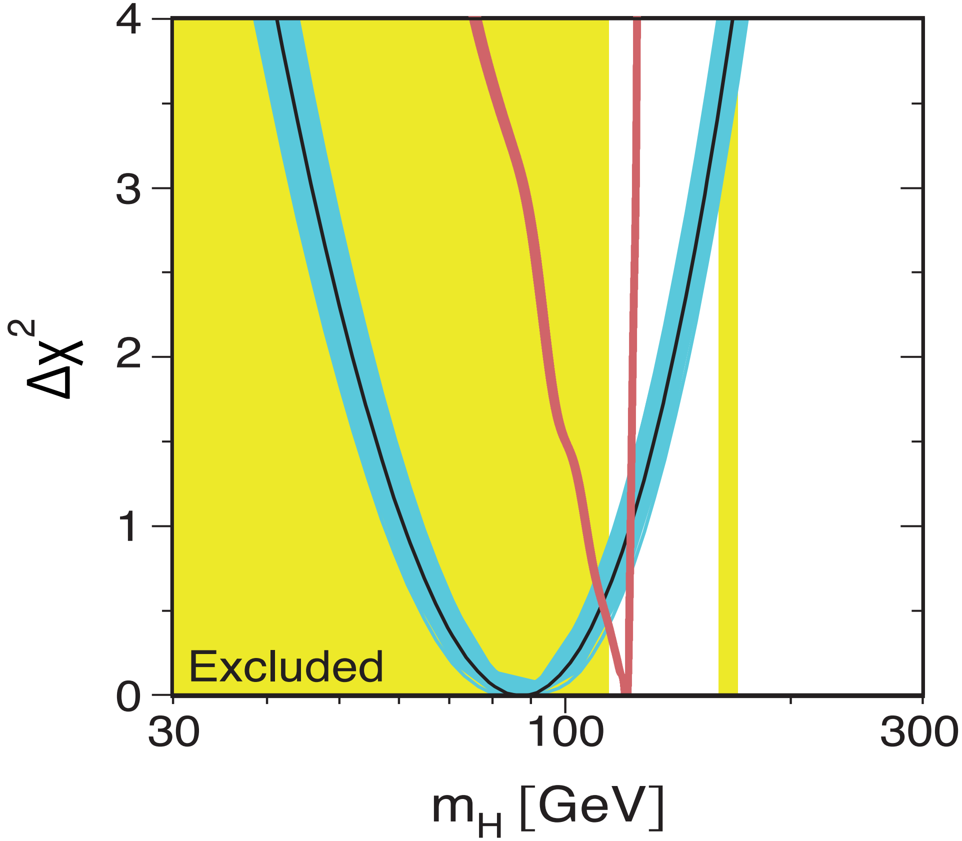
## *Indirect prediction for Higgs mass in SM and constrained SUSY models (CMSSM / NUHM1) from precision data*

$\chi^2$ fit for $M_\mathrm{h}$, without imposing direct search limits

SM CMSSM




SM NUHM1




$$M_\mathrm{h}^\mathrm{CMSSM} = 108 \pm 6\ \mathrm{GeV} \qquad M_\mathrm{h}^\mathrm{NUHM1} = 121^{+2}_{-14}\ \mathrm{GeV}$$

$\Rightarrow$ Accurate indirect prediction; Higgs “just around the corner”?

# *BSM $\oplus$ Higgs phenomenology*

- Large enhancement / suppression of standard search channels possible
  Example: large enhancement of $H\bar{b}b$ coupling
  $\Rightarrow$ large suppression of BR($h \to \gamma\gamma$), BR($h \to WW^*$), ...

- New channels, different phenomenology:
  - Experimental evidence for dark matter
    $\Rightarrow$ if dark matter particle is lighter than $M_{\mathrm{H}}/2$
    $\Rightarrow$ large branching fraction into invisible particles
    $\Rightarrow$ large suppression of all other BRs
  - Higgs production in decays of BSM particles
  - $h_i \to h_j h_j$ decays
  - Higgs–radion mixing, ...
  - Higgses with nearly degenerate masses: large interference effects, resonance-type behaviour possible

# *MSSM with complex parameters: a very light SUSY Higgs?*

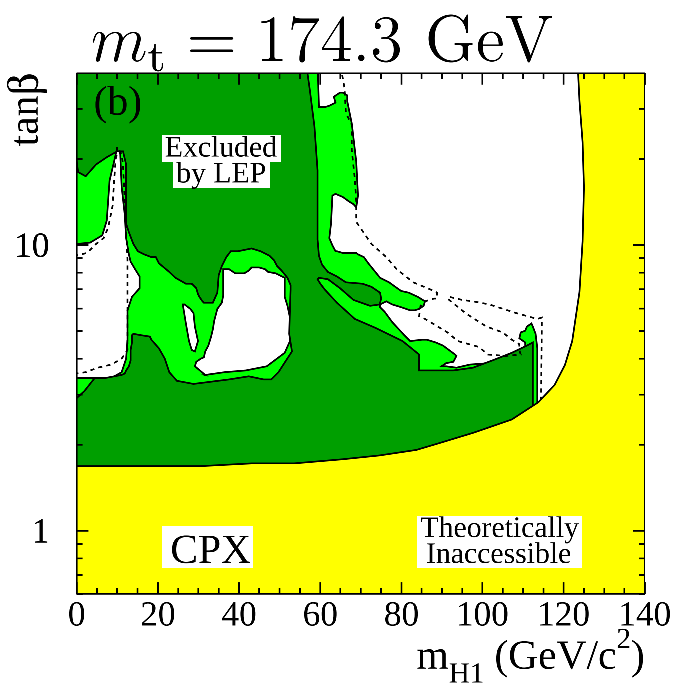
MSSM with $\mathcal{CP}$-violating phases (CPX scenario):

Light Higgs, $h_1$: strongly suppressed $h_1VV$ couplings

Second-lightest Higgs, $h_2$, possibly within LEP reach (with reduced $VVh_2$ coupling), $h_3$ beyond LEP reach

Large $\mathrm{BR}(h_2 \to h_1 h_1) \Rightarrow$ difficult final state

[*LEP Higgs WG '06*]




$\Rightarrow$ Light SUSY Higgs not ruled out!

# *A light Higgs in SUSY cascades*

Example: NMSSM scenario, light $\mathcal{CP}$-even Higgs, $20\ \mathrm{GeV} < M_{\mathrm{h}_1} < 110\ \mathrm{GeV}$, in agreement with all search limits (large singlet component)

$\mu_{\mathrm{eff}} = -200\ \mathrm{GeV}$, $M_1 = 300\ \mathrm{GeV}$, $M_2 = 600\ \mathrm{GeV}$

$M_{\mathrm{SUSY}} = 750\ \mathrm{GeV}$, $m_{\tilde{\mathrm{g}}} = 1\ \mathrm{TeV}$

⇒ Higgs production in chargino and neutralino decays in SUSY cascades

$$\tilde{q} \to q\tilde{\chi}_i^0 \to q\tilde{\chi}_1^0 h_k \to q\tilde{\chi}_1^0 b\bar{b}$$

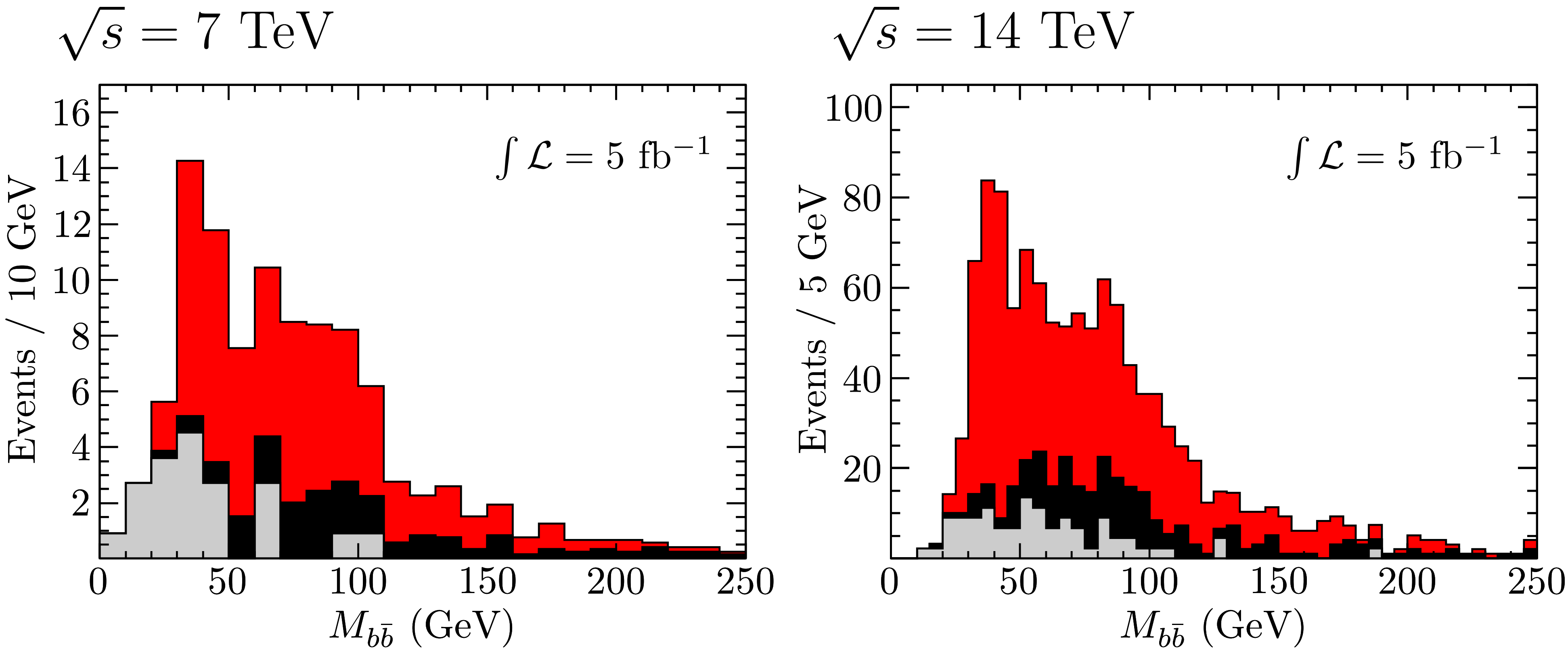
$$\tilde{g} \to g\tilde{q} \to gq\tilde{\chi}_i^0 \to gq\tilde{\chi}_1^0 h_k \to gq\tilde{\chi}_1^0 b\bar{b}$$

$\ldots$

# *Results for $b\bar{b}$ jet invariant mass distribution:*

## *SUSY signal, SUSY background, SM $t\bar{t}$ background (grey)*

$\int \mathcal{L} = 5\ \text{fb}^{-1}$, $M_{\text{h}_1} \approx 40\ \text{GeV}$ [*O. Stål, G. W. '11*]




$\Rightarrow$ Signal over background ratio looks encouraging
$h_1$ peak and $Z$ peak visible

$\Rightarrow$ We could get a signal for SUSY + Higgs at once

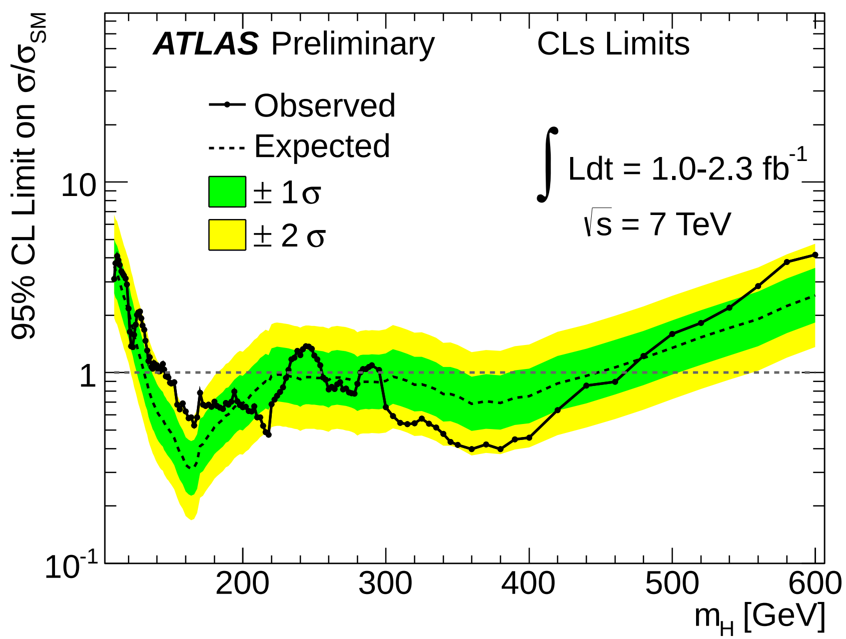
# *How to infer the underlying physics from the experimental signatures?*

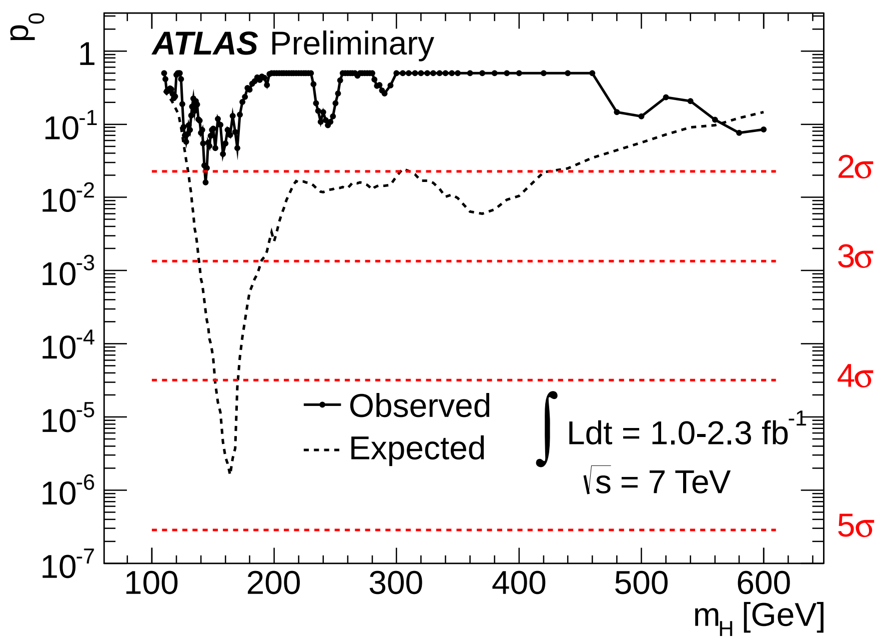
- A Higgs or not a Higgs?
- Fundamental or composite?
- SM, MSSM or beyond?
- Is there other new physics; what is it?
- How does the observed new physics fit into the global picture (ew precision observables, flavour physics, . . . )?
- . . .

$\Rightarrow$ Intense effort will be needed to identify the nature of electroweak symmetry breaking

# *Higgs searches: what did we learn so far?*

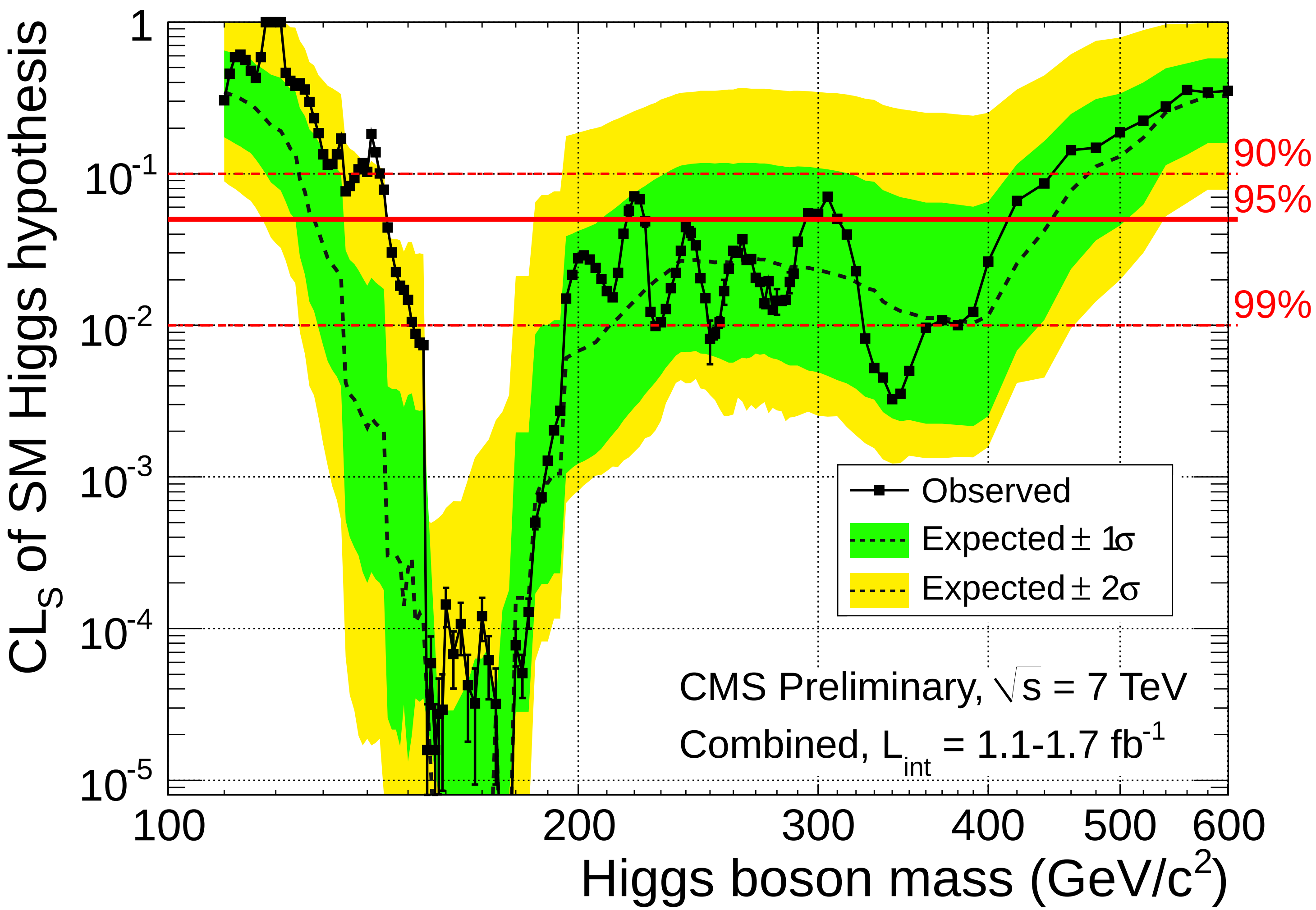
ATLAS SM Higgs search: combined upper limit normalised to the SM expectation (left) and observed result vs. expectation for a SM Higgs signal (right) [*ATLAS Collaboration '11*]



# *SM Higgs search: combined CMS results*

Combined confidence limit vs. expectation for a SM Higgs signal [*CMS Collaboration '11*]



# *SM Higgs searches, high-mass region*

- LHC excludes (at least at 90% C.L.) the range of $145 \text{ GeV} \lesssim M_{\text{H}_{\text{SM}}} \lesssim 460 \text{ GeV}$

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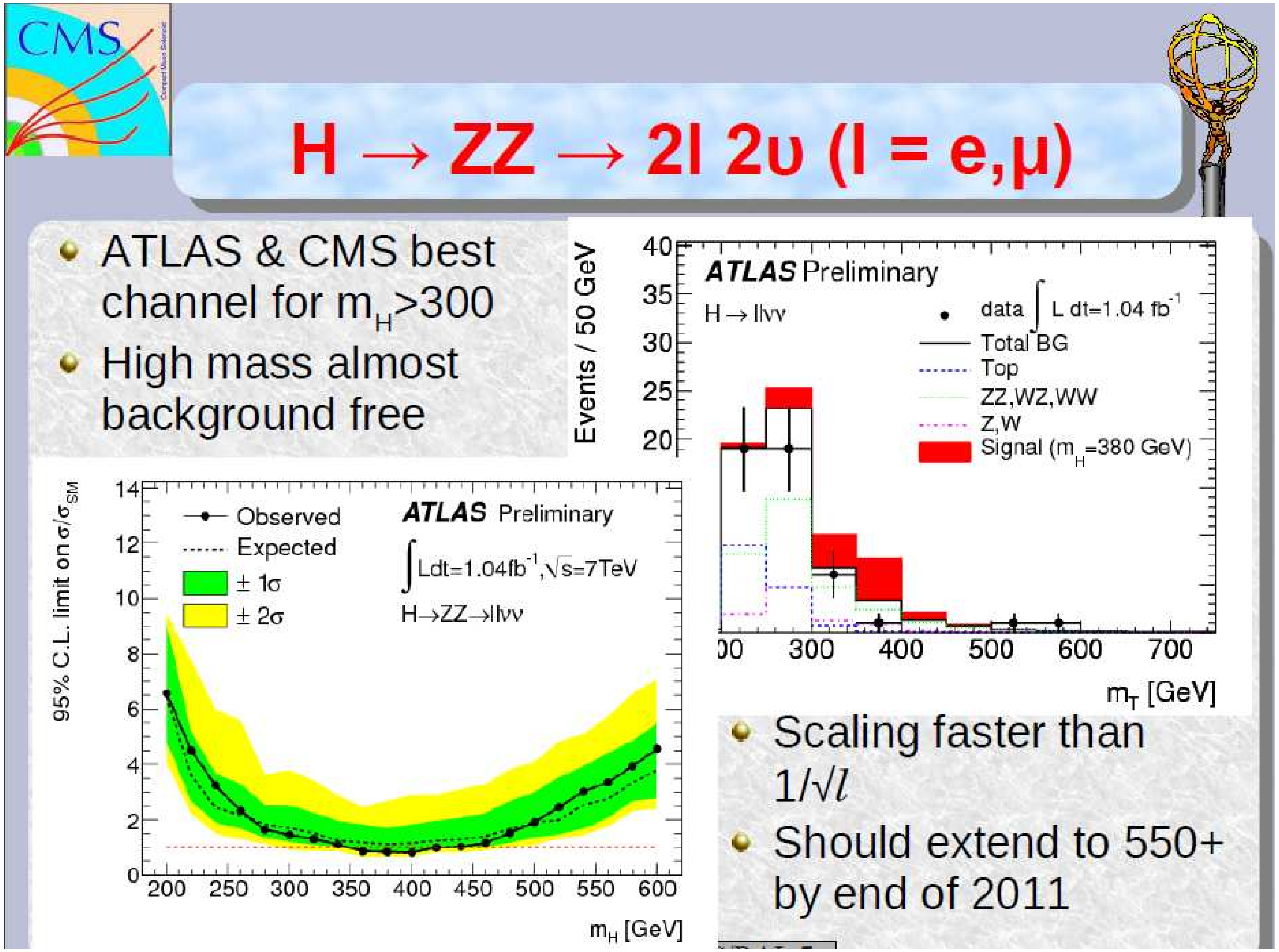
- A high mass Higgs?

  ATLAS sees an excess beyond $M_{\mathrm{H_{SM}}} = 460 \text{ GeV} \ldots$

  However: a heavy SM-like Higgs appears to be theoretically questionable

# Prospects for SM Higgs searches in the high mass region

[*W. Murray, LHC2TSP Workshop '11*]

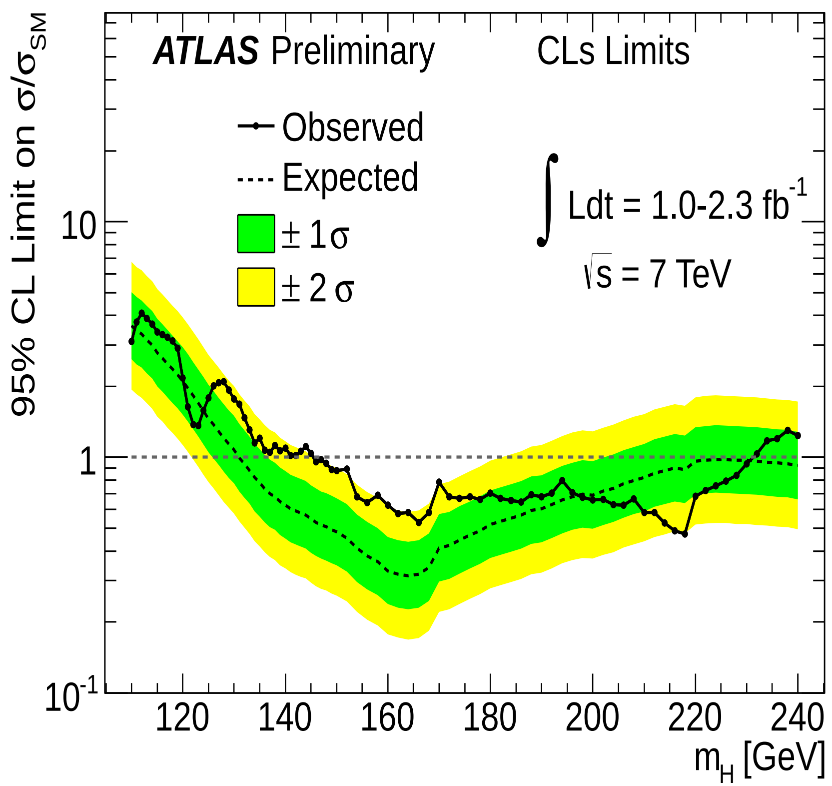


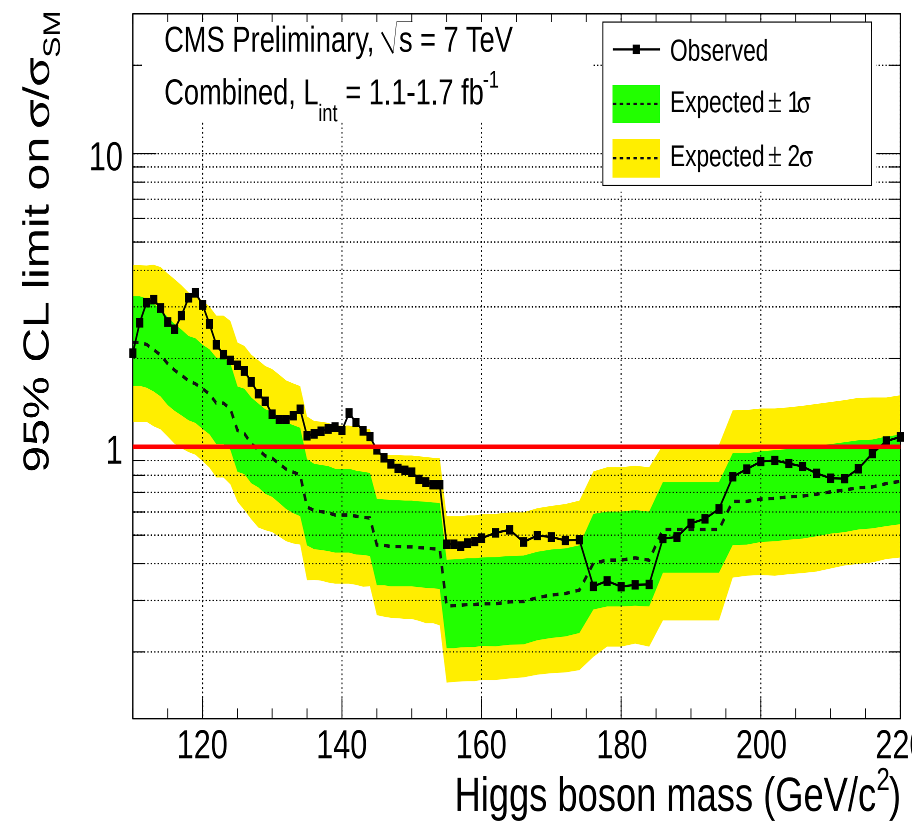

⇒ Large increase in coverage expected

# *SM Higgs search: ATLAS and CMS results in the low mass region*

Combined upper limit normalised to the SM expectation, low mass region

*[ATLAS Collaboration '11]* *[CMS Collaboration '11]*

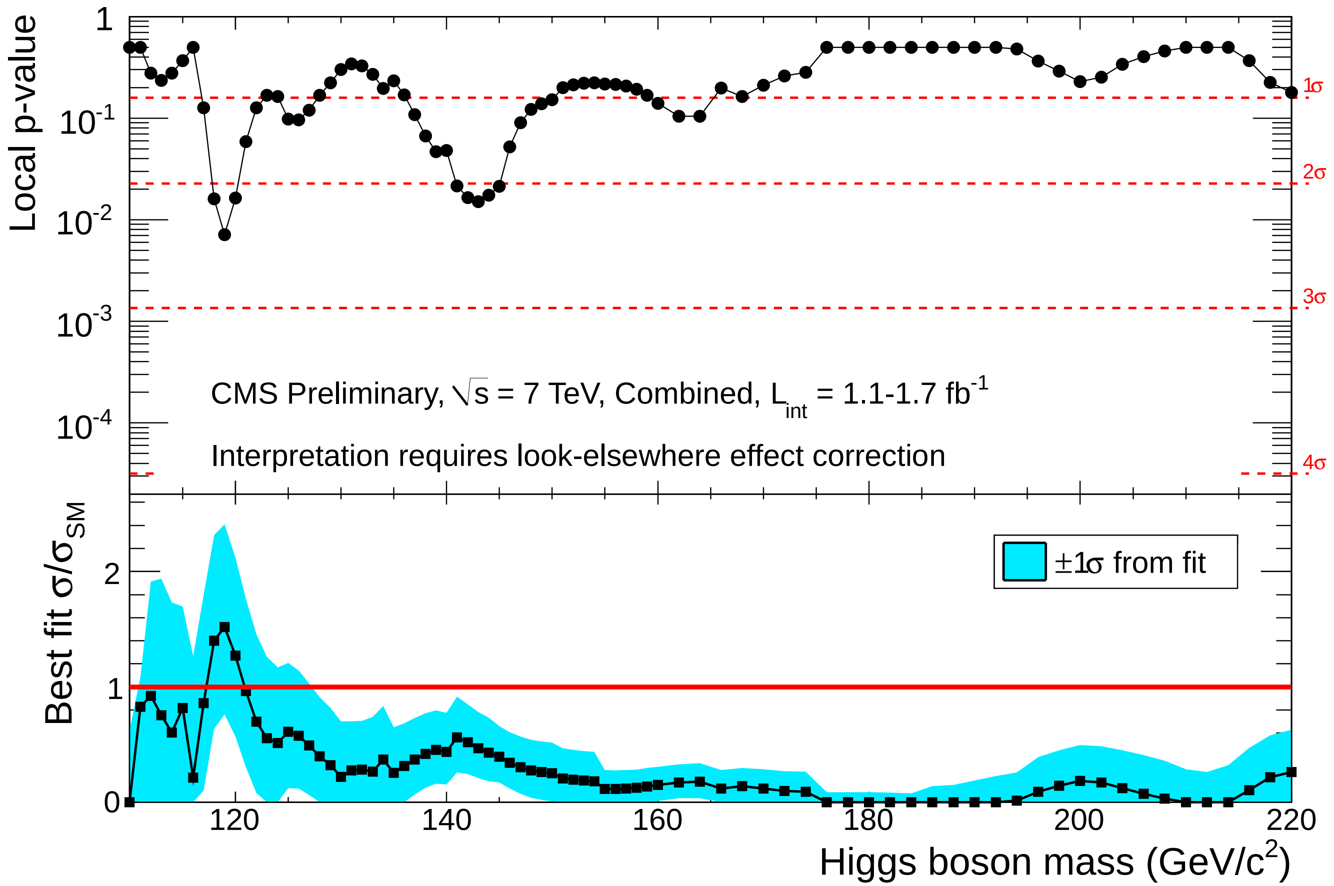



⇒ Broad excess in low mass region

# *CMS results for SM Higgs searches: local p value and observed best-fit signal strength*

[*CMS Collaboration '11*]

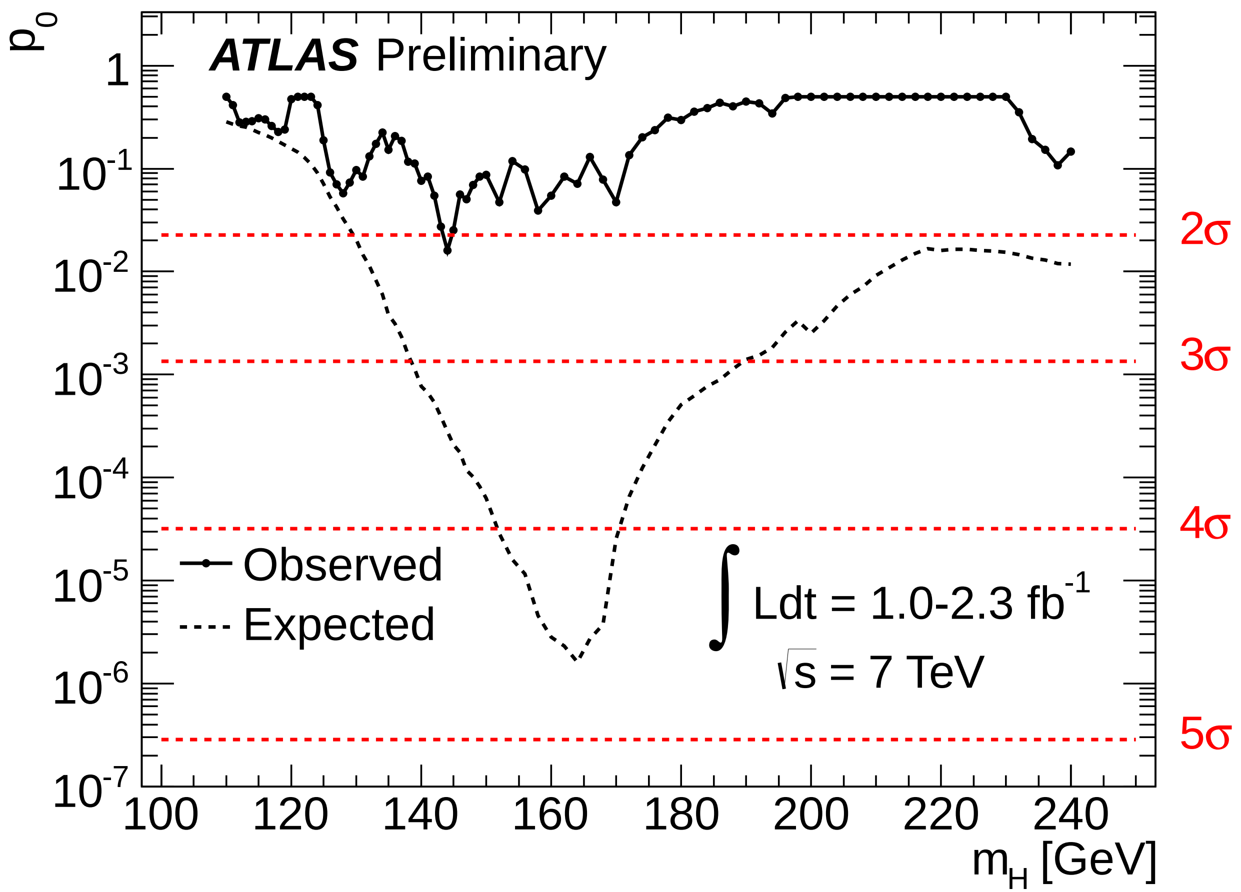



⇒ With LEE: probability to see an excess at least as large as the one observed in the data is $\approx 0.4$

Best compatibility with a SM Higgs for $M_{H_{SM}} \lesssim 125$ GeV

# ATLAS results for SM Higgs searches: local p value vs. expectation for a SM Higgs signal

[*ATLAS Collaboration '11*]

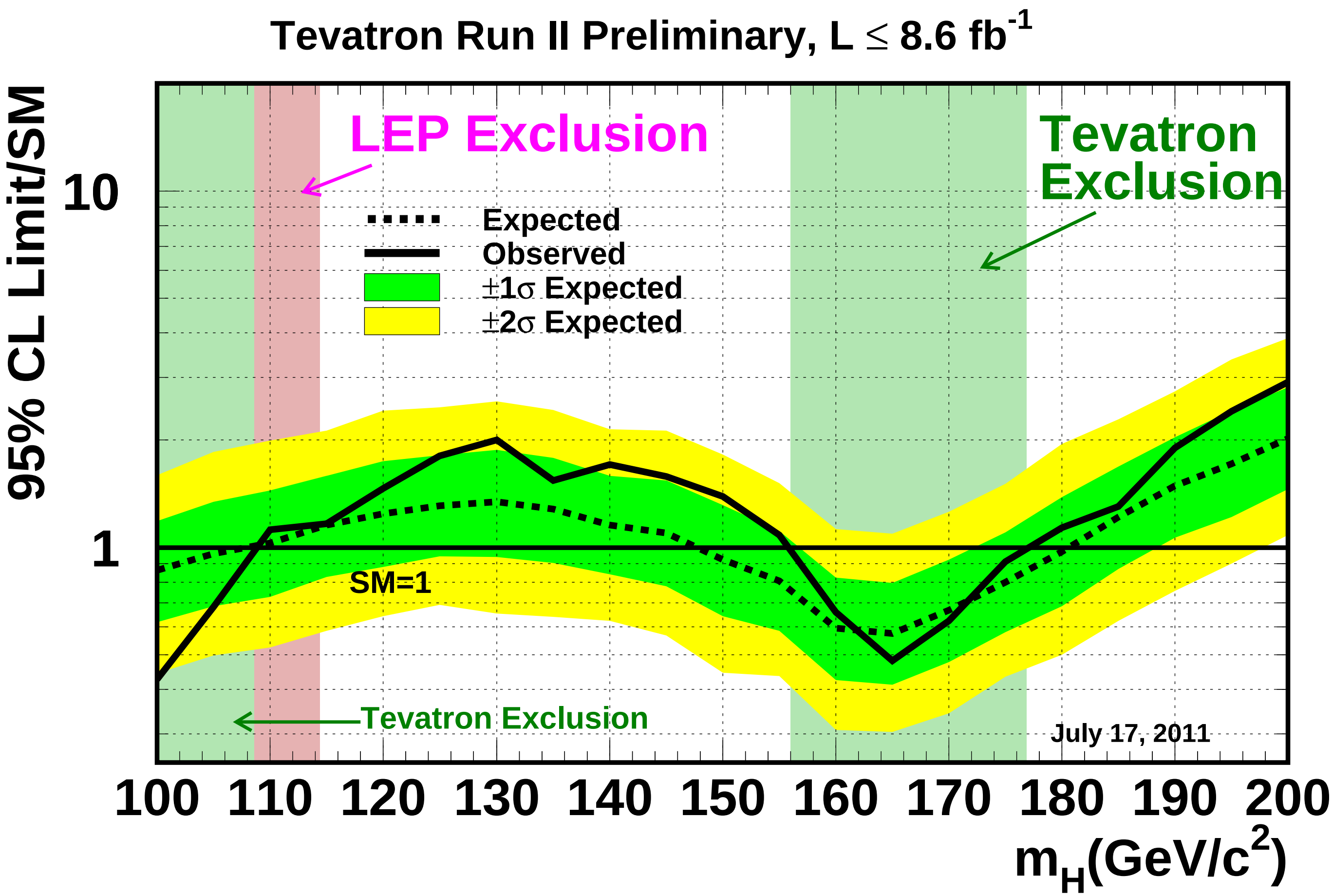



⇒ Best compatibility with a SM Higgs for $M_{H_{SM}} \lesssim 130$ GeV

Slight deficit w.r.t. SM expectation

# *SM Higgs search: Tevatron results, CDF + D0*

CDF + D0 combined upper limit normalised to the SM expectation [*CDF and D0 Collaborations '11*]




⇒ Broad excess in low mass region

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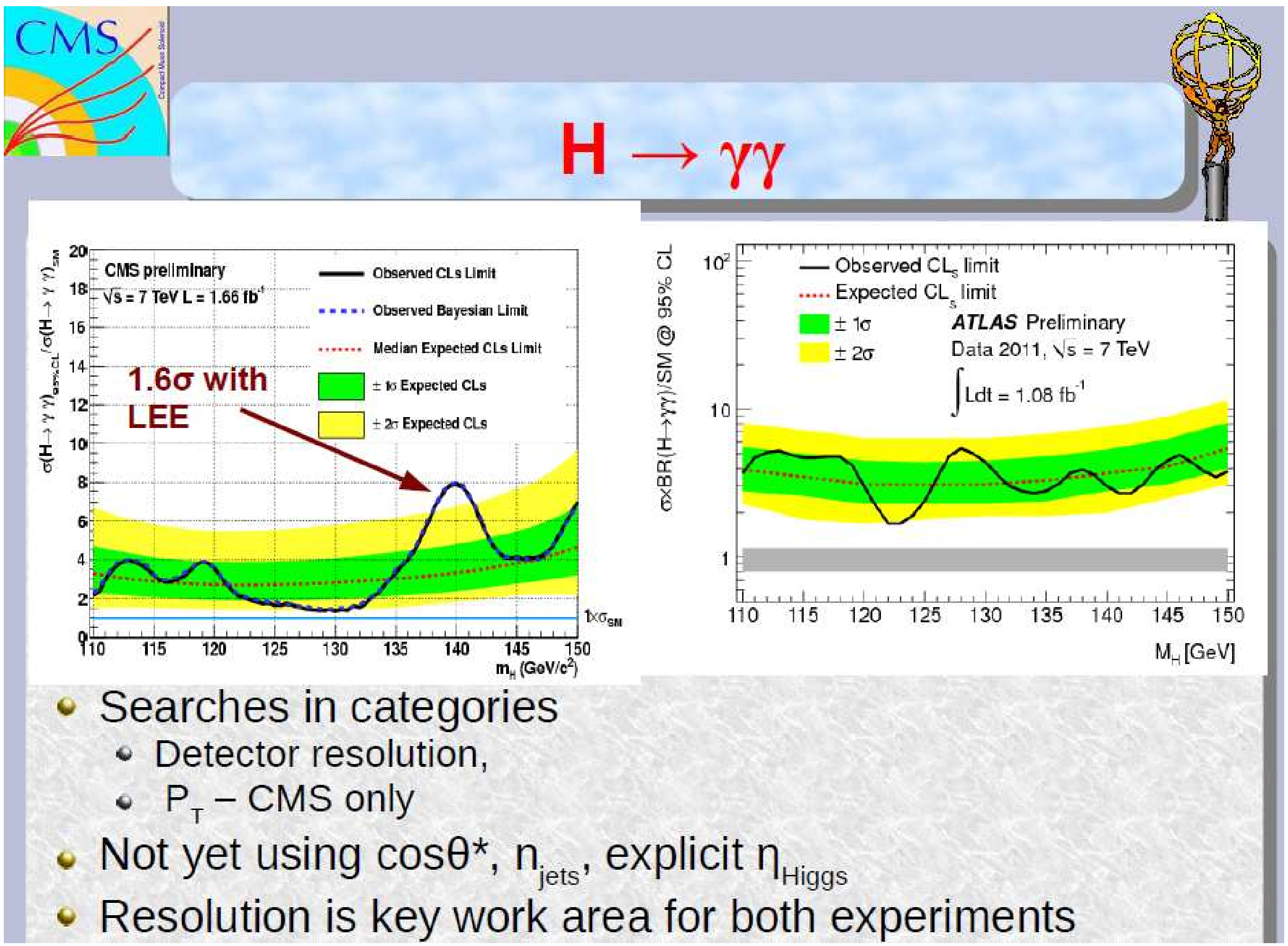
- What about a Higgs with $M_{\text{H}} \approx 145 \text{ GeV}$ with somewhat reduced $\sigma \times \text{BR}(H \to WW^*)$ compared to SM case?

  Difficult to get sufficiently large $\text{BR}(H \to WW^*)$ in the MSSM, can better be accomodated in the NMSSM

# *CMS excess in* $H \to \gamma\gamma$ *search*

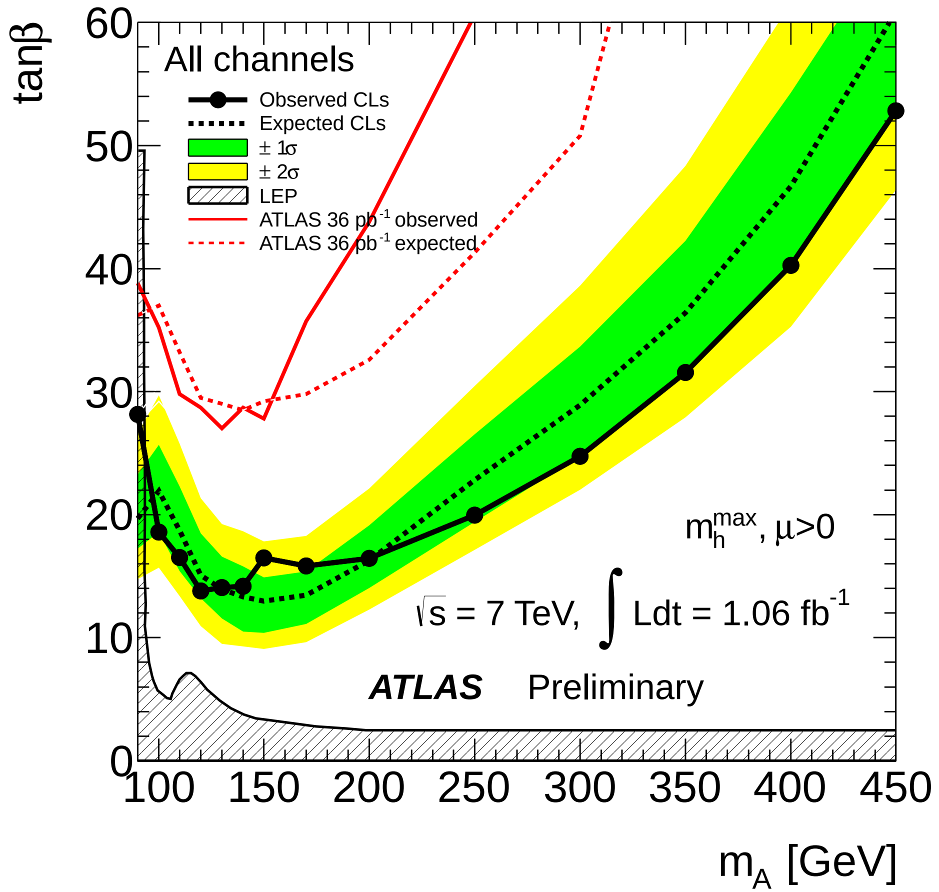
*[W. Murray, LHC2TSP Workshop '11]*



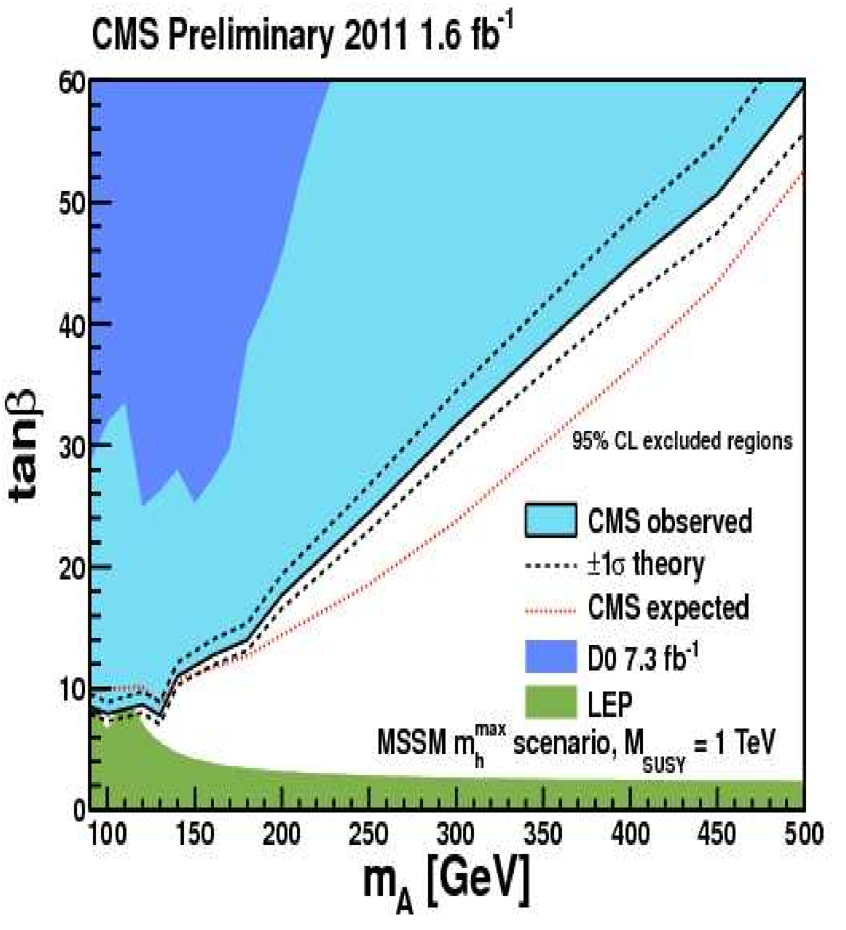

$\Rightarrow 1.6\sigma$ excess at $M_{\rm H} \approx 140~\mathrm{GeV}$ after taking into account LEE

# Search for the heavy SUSY Higgs bosons $H$, $A$: limits in the $M_A$–$\tan\beta$ plane

[*ATLAS Collaboration '11*]




[*CMS Collaboration '11*]

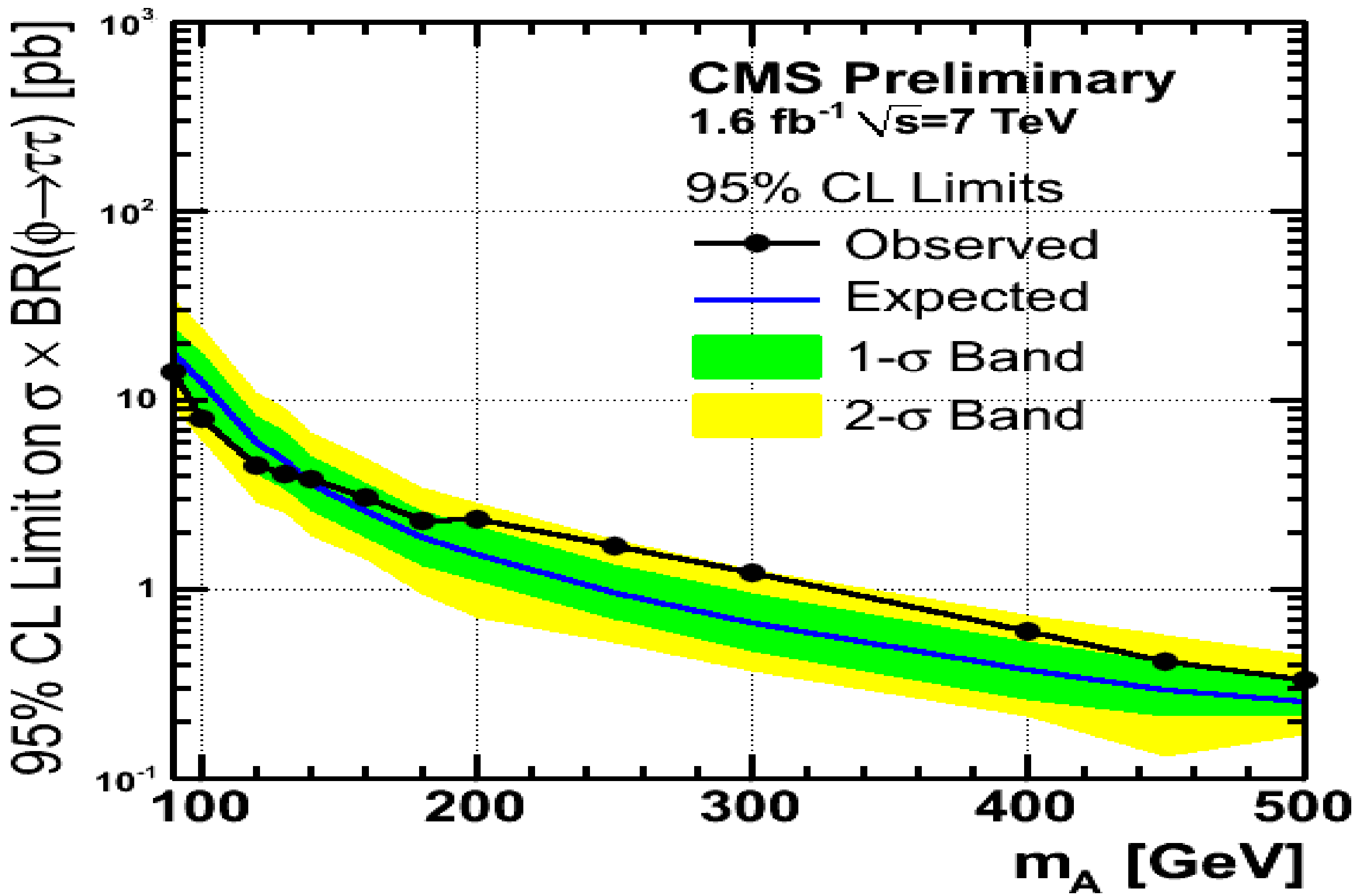



⇒ Large coverage in $M_A$–$\tan\beta$ plane

LHC + LEP start to close the region of very low $M_A$

# *Search for the heavy SUSY Higgs bosons $H$, $A$: cross section limit from CMS*

[*CMS Collaboration '11*]



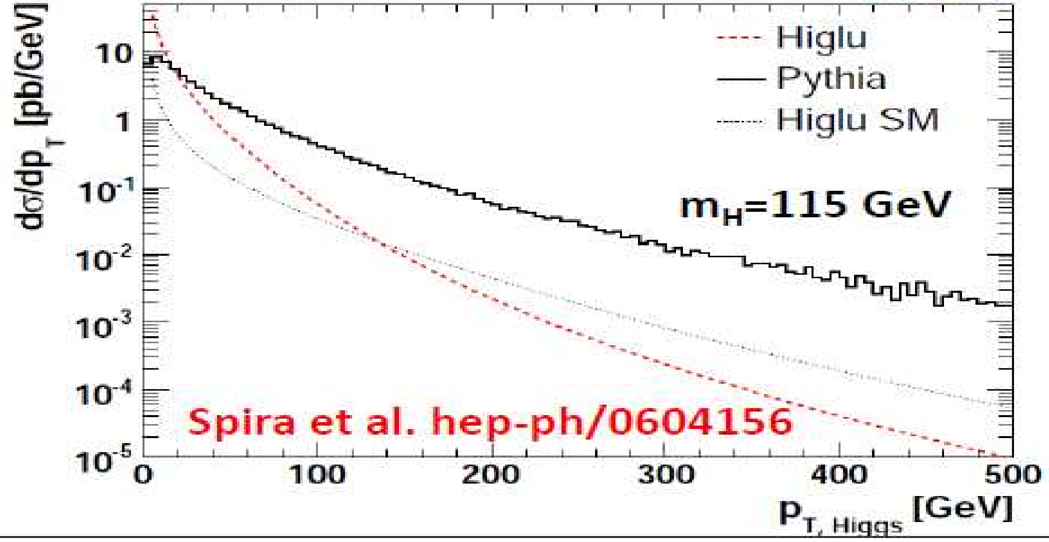

$\Rightarrow$ Excess for $M_{\rm A} \gtrsim 200$ GeV

# However: has the acceptance for $gg \to H, A$ be overestimated?

[*A. Nikitenko, LHC2TSP Workshop '11*]

- **Remark on gg->ϕ generation**
  - **CMS used PYTHIA, ATLAS used POWHEG**
  - **both generators do not include b-quark in the loop:**
    - **acceptance for gg->ϕ is overestimated; how much ?**

**top-loop vs b-loop in gg->h : different Higgs $p_T$ !**



# *Fundamental or composite Higgs?*

Renewed interest in composite Higgs models, mostly from extra dimensions

[*N. Arkani-Hamed, A. Cohen, H. Georgi '01*]

[*K. Agashe, R. Contino, A. Pomarol '05*], . . .

Composite Higgs: light remnant of a strong force

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Relation extra dimensions $\Leftrightarrow$ new strong forces?

Correspondence (AdS/CFT):

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Signatures at LHC: new resonances, $W'$, $Z'$, $t'$, KK excitations

Under pressure from electroweak precision tests

# Effective field-theory description of a composite Higgs

Agreement with electroweak precision data can be improved if there is a strongly interacting light Higgs, e.g.

Little Higgs [*N. Arkani-Hamed, A. Cohen, E. Katz, A. Nelson '02*]

Holographic Higgs [*R. Contino, Y. Nomura, A. Pomarol '03*], [*K. Agashe, R. Contino, A. Pomarol '05*], . . .

Effective Lagrangian formalism for model-independent analysis of effects of a Strongly-Interacting Light Higgs (SILH) [*G. Giudice, C. Grojean, A. Pomarol, R. Ratazzi '07*]

$\Rightarrow$ Specific pattern of modified Higgs couplings

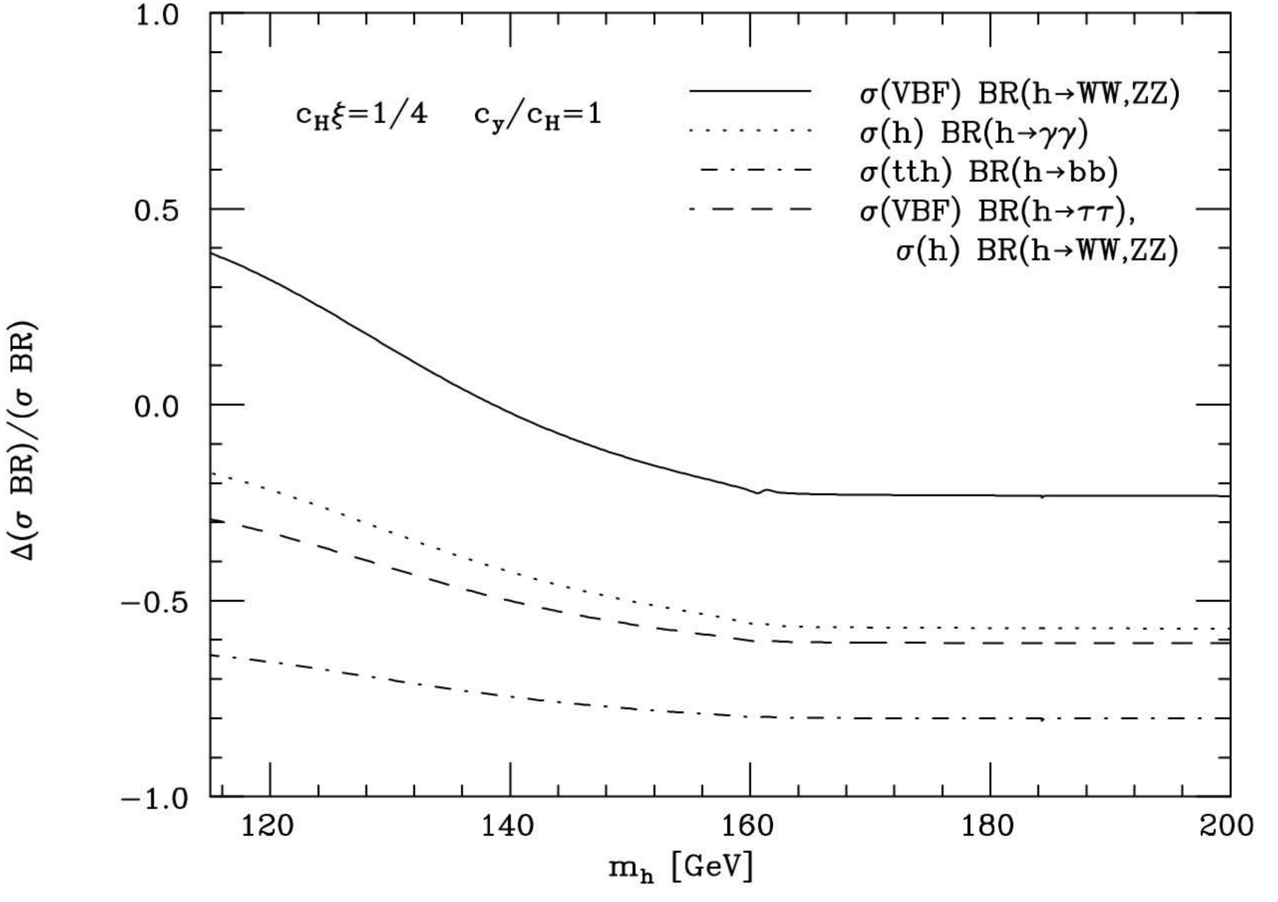
Strong $WW$ scattering at high energies despite light Higgs

$\Rightarrow$ Need precision measurement of Higgs couplings

$+$ test of longitudinal gauge-boson scattering

# *Strongly-Interacting Light Higgs: deviation of* $\sigma \times \mathrm{BR}$ *from the case of a SM Higgs*

*[G. Giudice, C. Grojean, A. Pomarol, R. Ratazzi '07]*



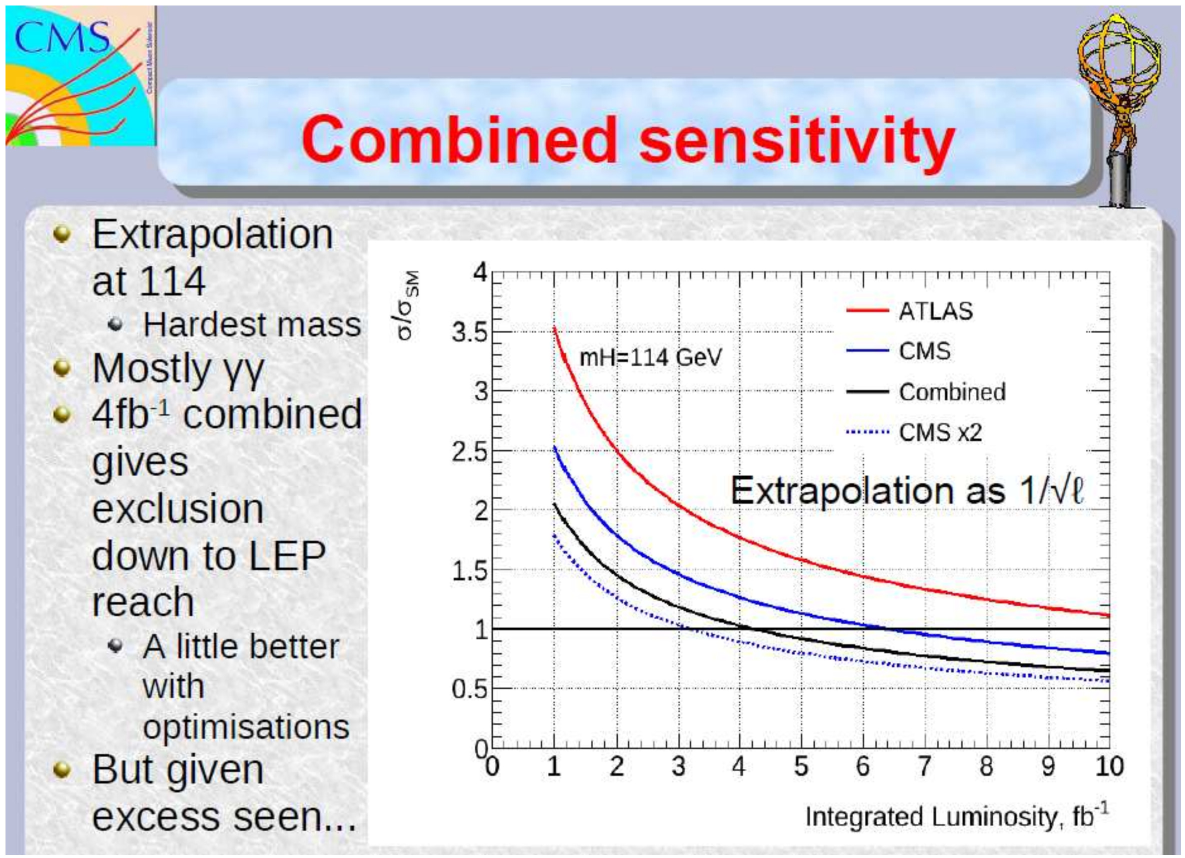

Sensitivity at LHC: 20–40%, ILC: 1%

⇒ ILC can test scales up to $\sim 30$ TeV

# *Further prospects*

Prospects for searches for a $114$ GeV SM-like Higgs:

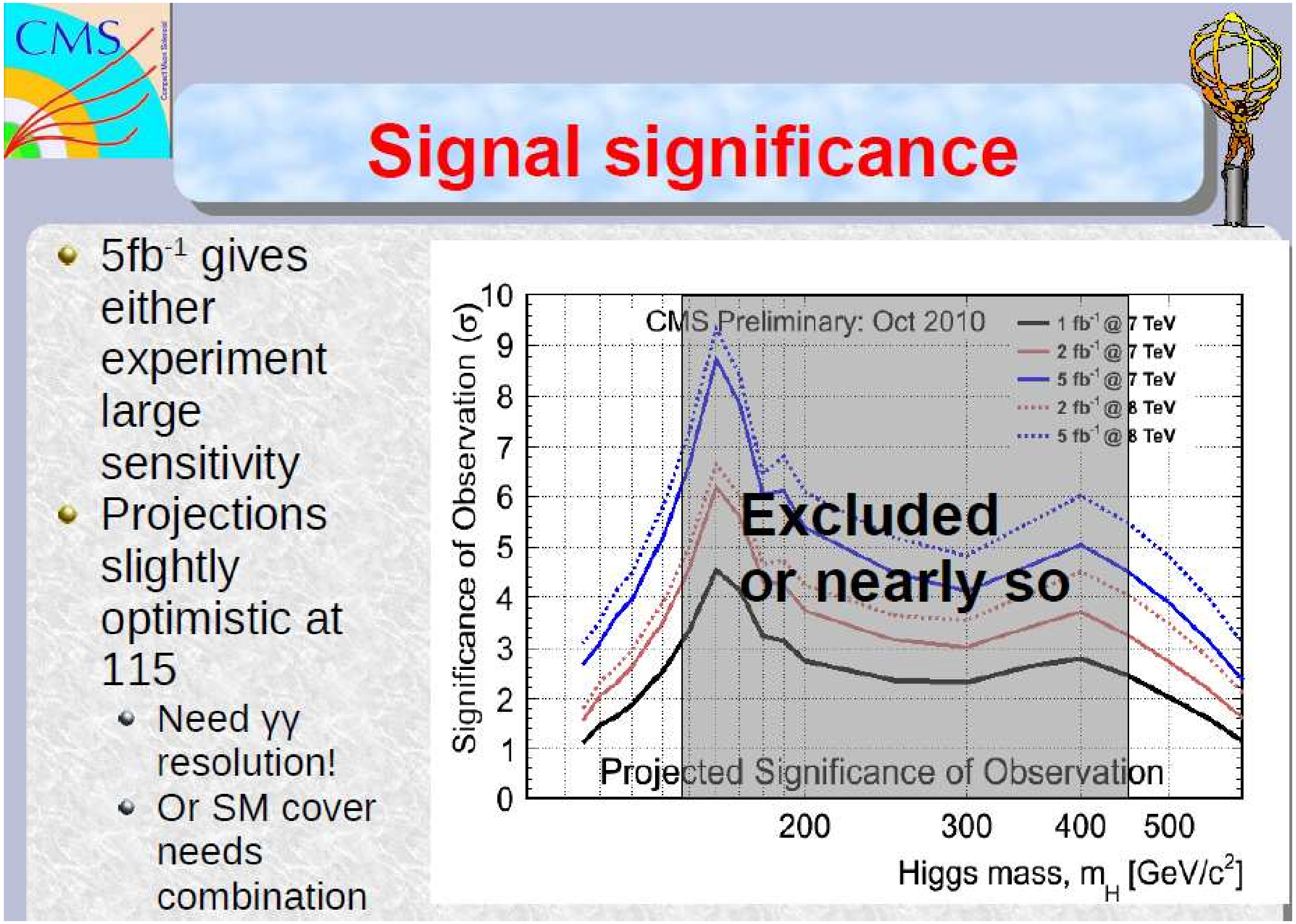
[*W. Murray, LHC2TSP Workshop '11*]




$\Rightarrow$ 2011 data, when combined between ATLAS + CMS, should provide $2\sigma$ sensitivity down to $M_{\mathrm{H}} = 114$ GeV

# Prospects for the signal significance

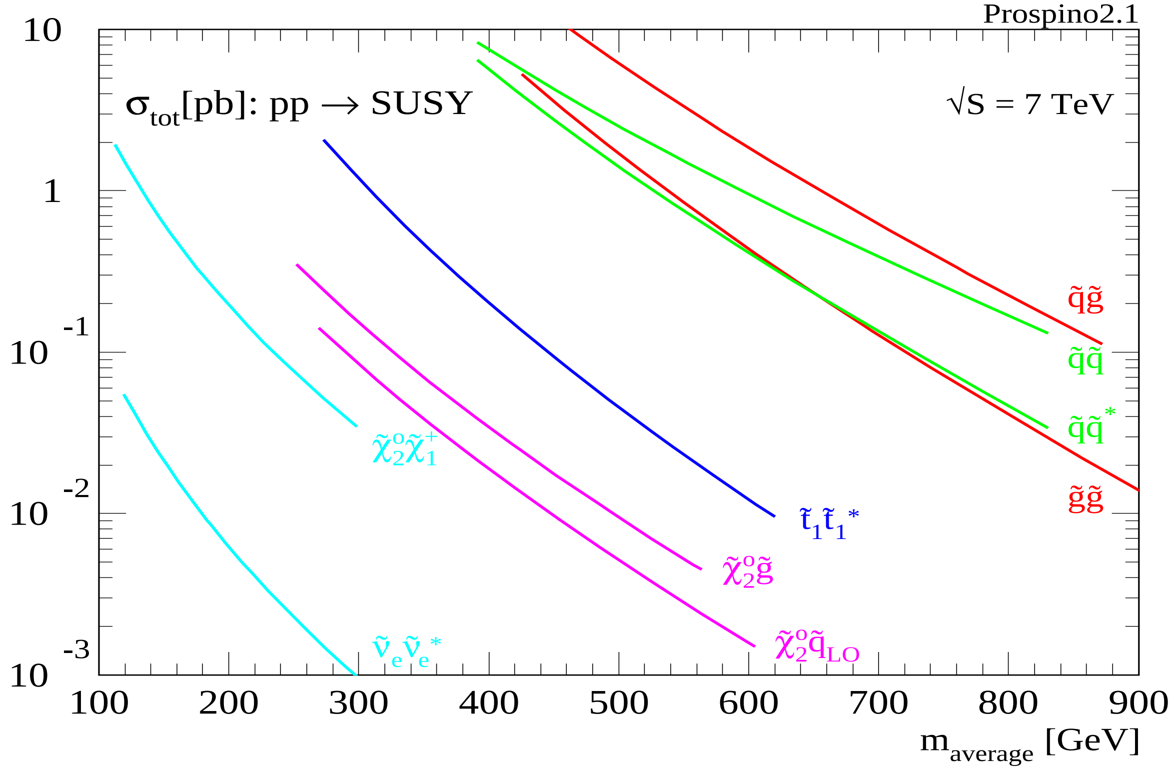
[*W. Murray, LHC2TSP Workshop '11*]




⇒ With 2012 data, ATLAS + CMS combined: expect sensitivity of at least $3.5\sigma$

# *New physics addressing the hierarchy problem*

SUSY production cross sections at the LHC with $7\ \mathrm{TeV}$:




⇒ Highest cross section for gluino and squarks of the first two generations

Squark and gluino couplings $\sim \alpha_s$; cross sections mainly determined by $m_{\tilde{q},\tilde{g}}$, small residual model dependence

# *SUSY searches at the LHC*

Dominated by production of coloured particles:

gluino, squarks (mainly first two generations)

Very large mass reach in the searches for
jets $+$ missing energy

$\Rightarrow$ gluino, squarks accessible up to 2–3 TeV at LHC ($14\ \mathrm{TeV}$)

Coloured particles are usually heavier than the colour-neutral ones

$\Rightarrow$ long decay chains possible; complicated final states

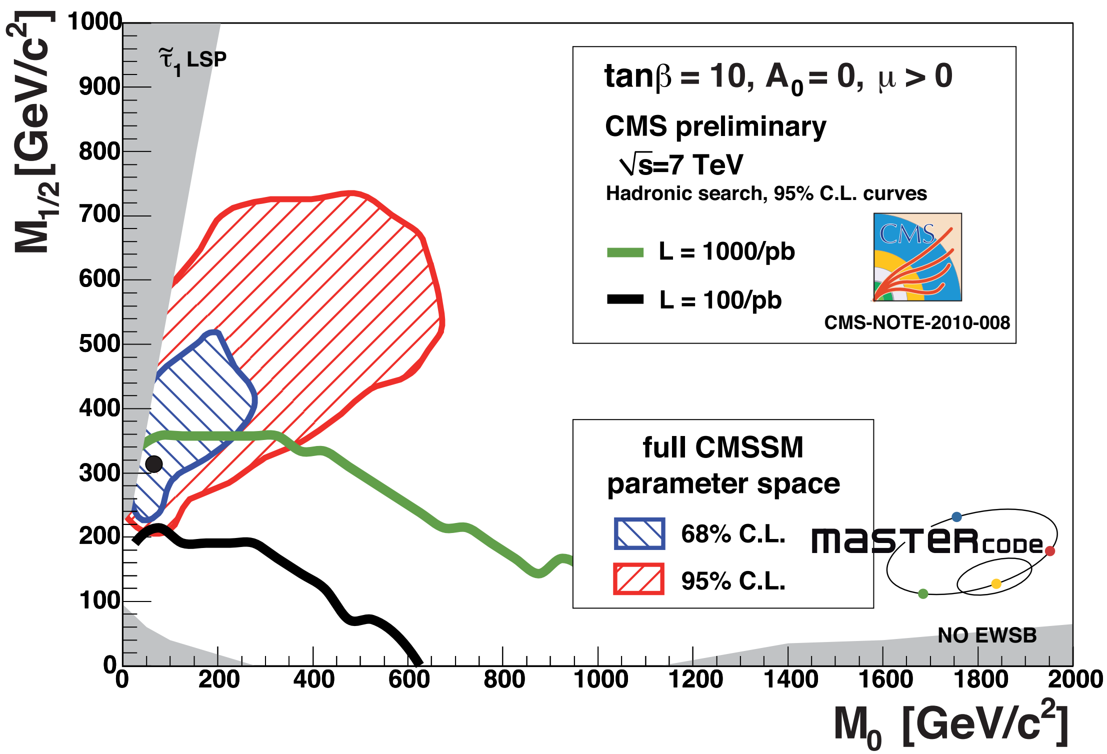
e.g.: $\tilde{g} \rightarrow \bar{q}\tilde{q} \rightarrow \bar{q}q\tilde{\chi}_2^0 \rightarrow \bar{q}q\tilde{\tau}\tau \rightarrow \bar{q}q\tau\tau\tilde{\chi}_1^0$

Many states produced at once, difficult to disentangle

# Pre–LHC: Fit results for the CMSSM from precision data

Comparison: preferred region in the $m_0$–$m_{1/2}$ plane vs. prospective CMS 95% C.L. reach for $0.1, 1 \text{ fb}^{-1}$ at $7 \text{ TeV}$

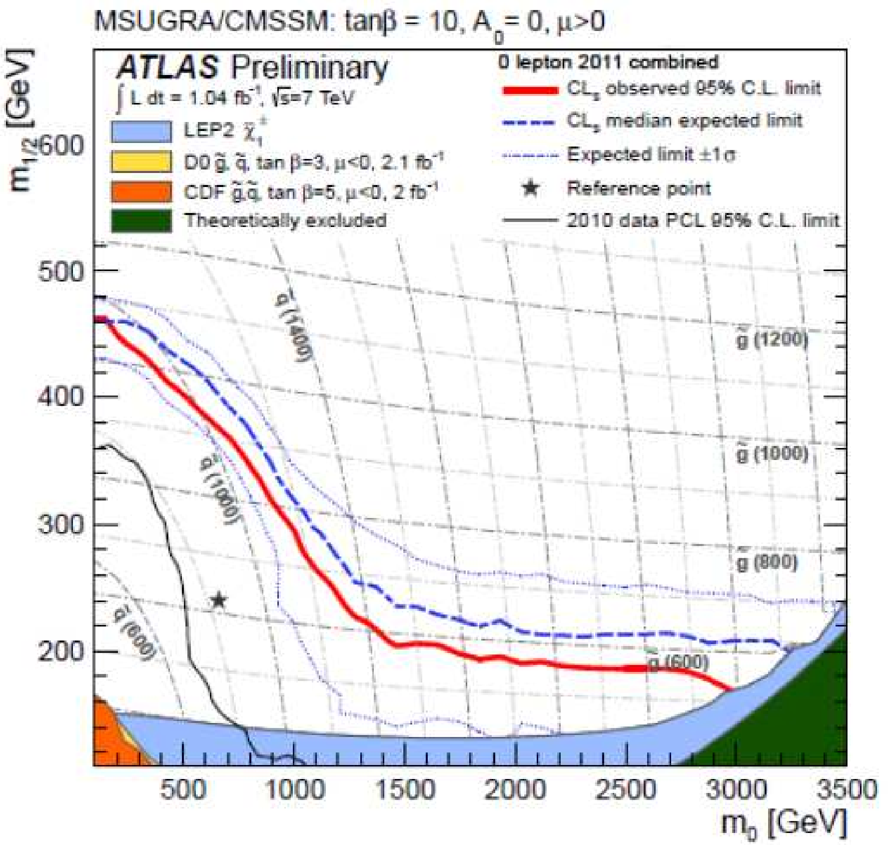
[*O. Buchmueller, R. Cavanaugh, A. De Roeck, J. Ellis, H. Flächer, S. Heinemeyer, G. Isidori, K. Olive, P. Paradisi, F. Ronga, G. W. '10*]



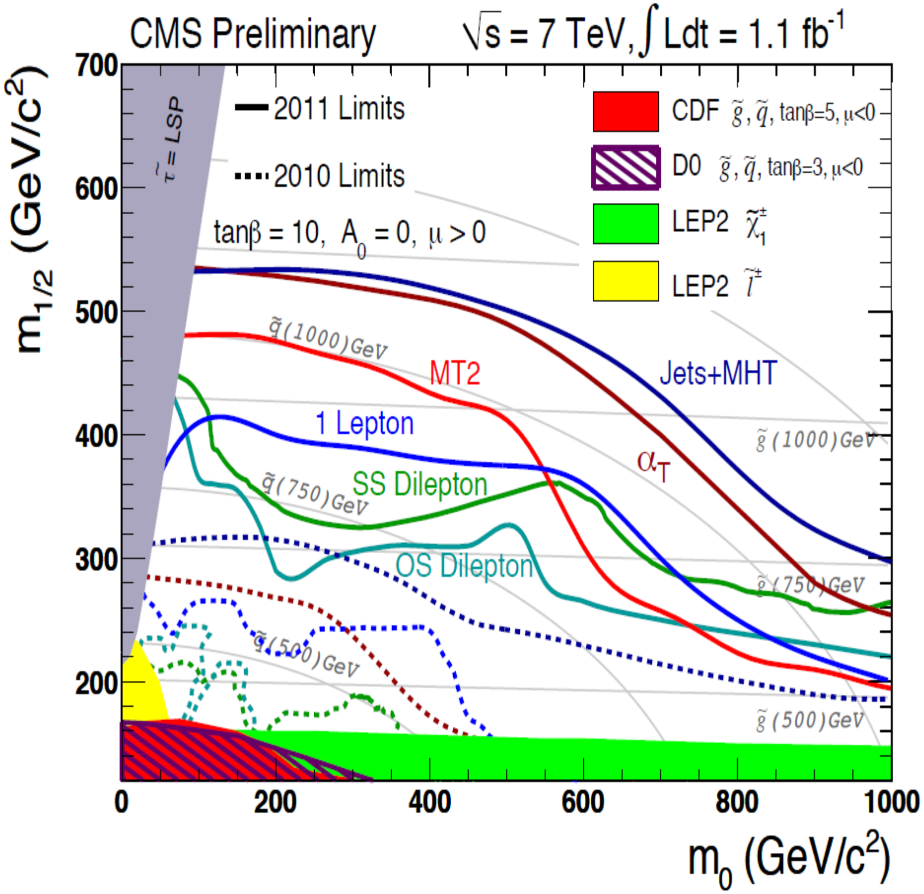

⇒ Best fit point was within the 95% C.L. reach with $1 \text{ fb}^{-1}$

# SUSY search results for the CMSSM

[ATLAS Collaboration '11]




[CMS Collaboration '11]




$\Rightarrow$ High sensitivity from search for jets $+$ missing energy

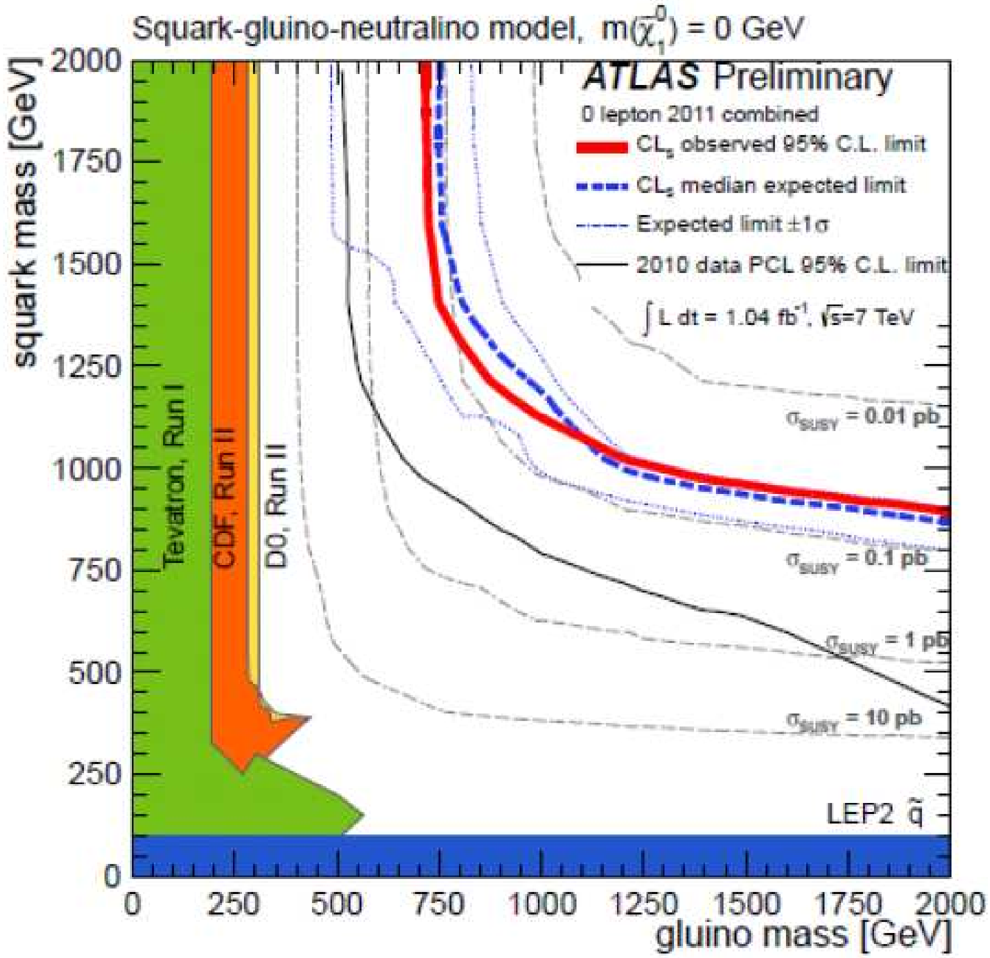
Previous best-fit point is excluded

CMSSM starts to get under pressure

# *Interpretation of SUSY search result in "simplified model"*

"Simplified model": squarks of first two generations, gluino + massless neutralino (LSP), all other SUSY particles heavy

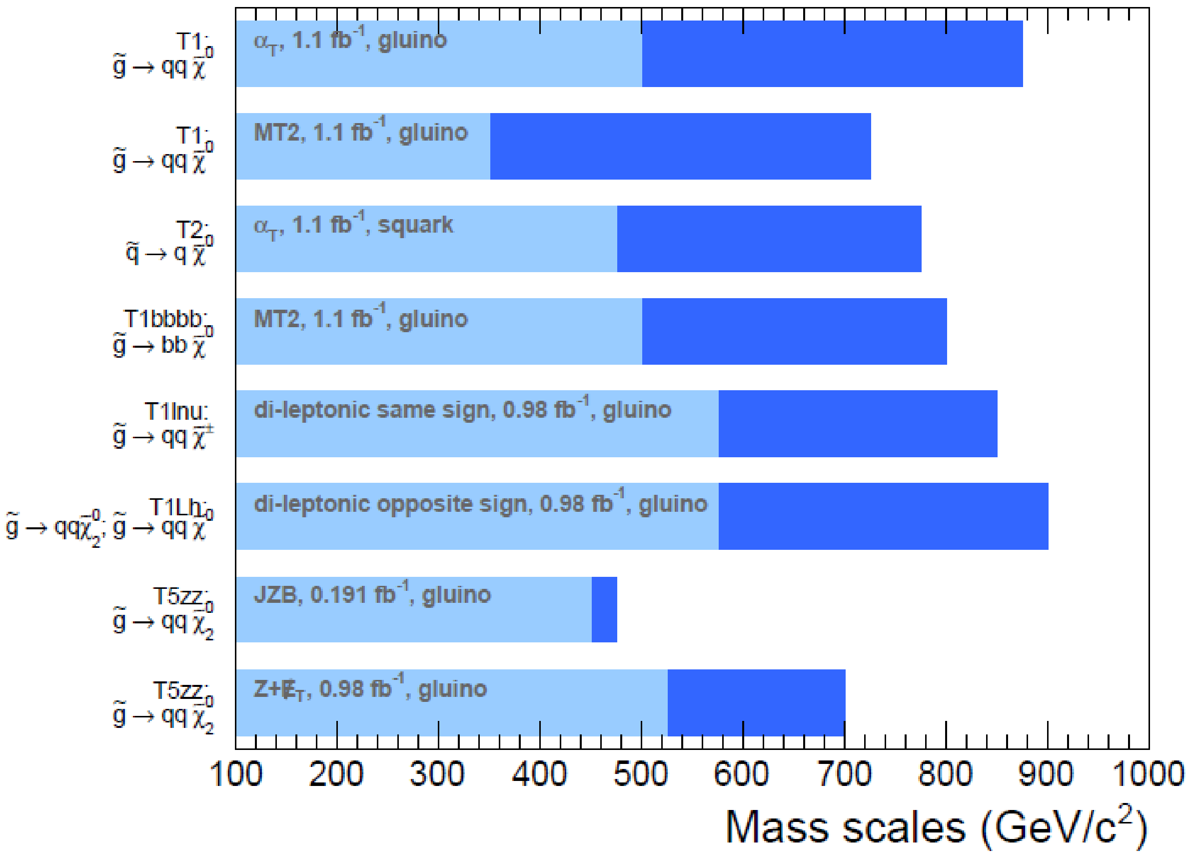
[*ATLAS Collaboration '11*]



# *Limits for gluinos and squarks in simplified models, LSP mass varied between* $0$ *and* $200\ \mathrm{GeV}$

**Ranges of exclusion limits for gluinos and squarks, varying $m(\tilde{\chi}^0)$**
**CMS preliminary**

[*CMS Collaboration '11*]




**For limits on $m(\tilde{g})$, $m(\tilde{q}) >> m(\tilde{g})$ (and vice versa). $\sigma^{prod} = \sigma^{NLO\text{-}QCD}$.**

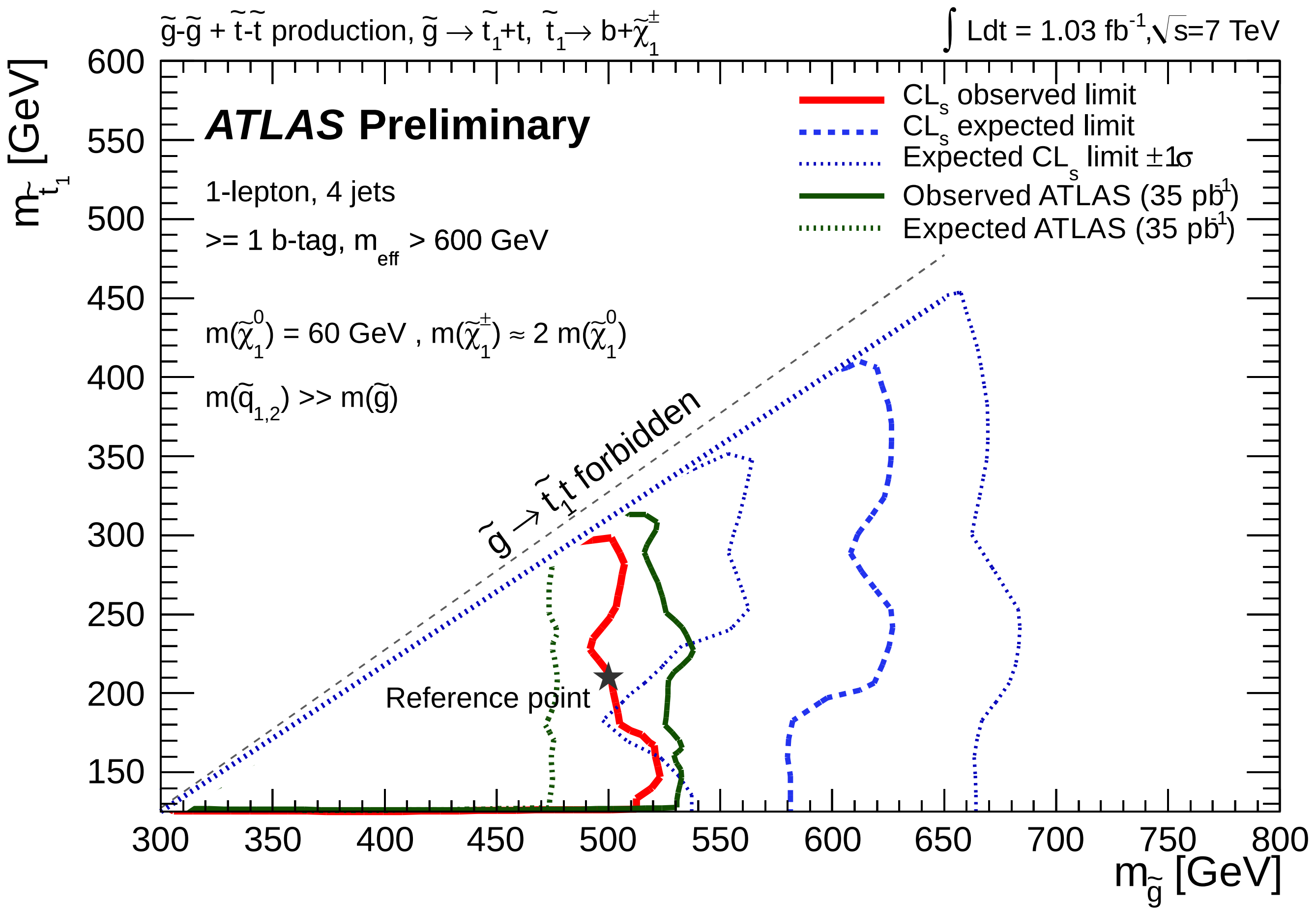
**$m(\tilde{\chi}^\pm), m(\tilde{\chi}_2^0) \equiv \frac{m(\tilde{g}) + m(\tilde{\chi}^0)}{2}$.**

**$m(\tilde{\chi}^0)$ is varied from 0 GeV/c$^2$ (dark blue) to $m(\tilde{g})$-200 GeV/c$^2$ (light blue).**

$\Rightarrow$ Large dependence on LSP mass

# Excitement at SUSY ’11

Stop production in gluino decays *[ATLAS Collaboration ’11]*



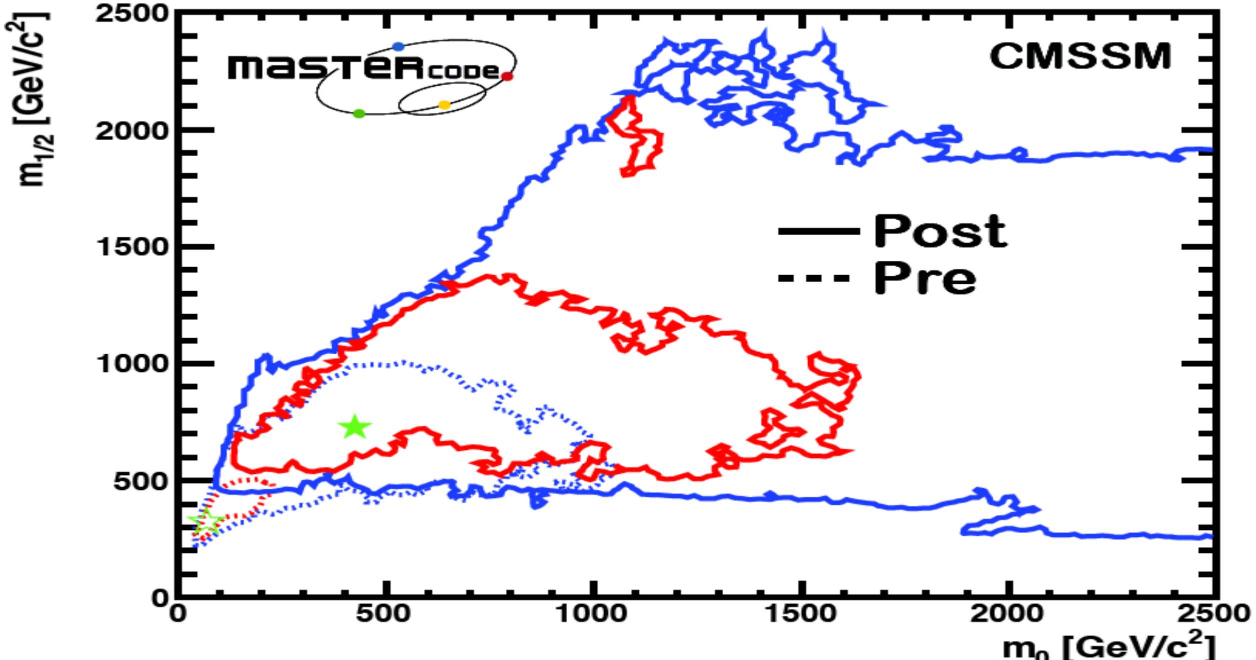

$\Rightarrow$ Observed limit decreased with 30 $\times$ more luminosity

1.2 $\sigma$ excess in both electron and muon channels

# Global fit in the CMSSM including 2011 LHC data ($1\ \mathrm{fb}^{-1}$) and XENON100 results

68% and 95% CL contours, pre- and post-LHC

[*O. Buchmueller, R. Cavanaugh, A. De Roeck, M. Dolan, J. Ellis, H. Flächer, S. Heinemeyer, G. Isidori, D. Martínez Santos, K. Olive, S. Rogerson, F. Ronga, G. W. '11*]




$\Rightarrow$ Preferred region "opens up", overall $\chi^2$ worsened
Shift towards higher mass scales, higher values of $\tan\beta$

Comparison: GMSB yields much larger splitting between coloured and colour-neutral part of the spectrum

# *Status of SUSY searches*

- Search for jets ($+$ leptons) $+$ missing energy

  $\Rightarrow$ Bounds on gluino and squarks of first two generations of $\mathcal{O}(\text{ TeV})$

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- Reduced sensitivity to compressed spectra

- Limited sensitivity to 3rd generation squarks

  Hardly any direct constraints from the LHC on colour neutral SUSY particles up to now

# *SUSY searches: what next?*

*[S. Padhi, LHC2TSP Workshop '11]*

Assuming colored particles ($1^{st}$ and $2^{nd}$ generation squarks and gluinos) are beyond the LHC range:

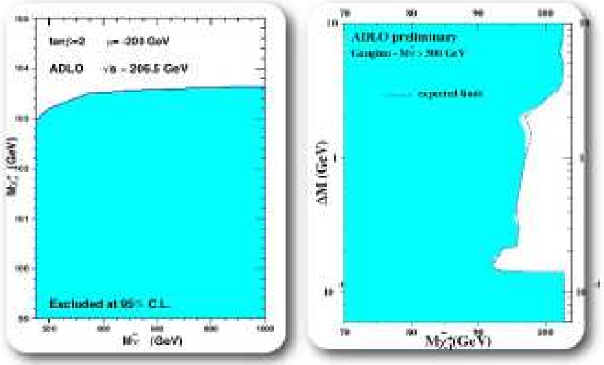
**a) Need dedicated exclusive studies to constrain stops and sbottoms**

- With and without the cross section help from the colored particles
- See also M. Papucci's EPS-2011 talk
- http://indico.in2p3.fr/contributionDisplay.py?contribId=904&sessionId=6&confId=5116

**b) Need dedicated activity on EWK inos**

- Current limits on Chargino/neutralinos are low
- Explore LHC reach for the electroweak sector (See also Shufang Su SUSY-11 talk)

canonical case | degenerate case




$m\chi_1^{\pm} > 103.5$ GeV for $m_{snue} > 300$ GeV

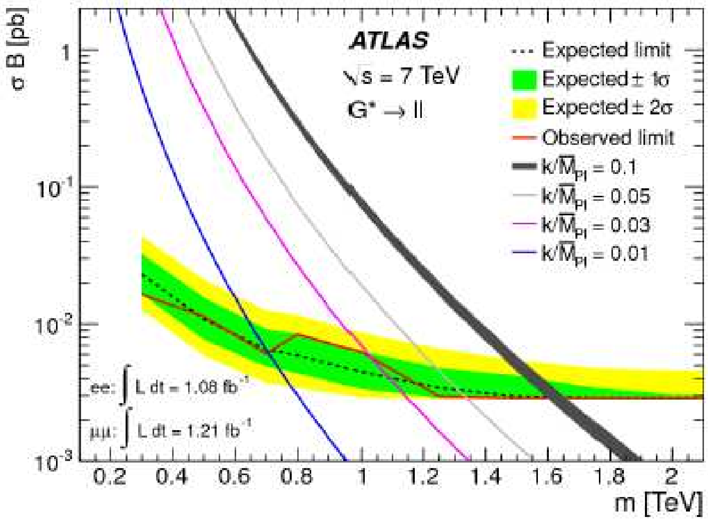
$m\chi_1^{\pm} > 91.9$ /92.4 GeV

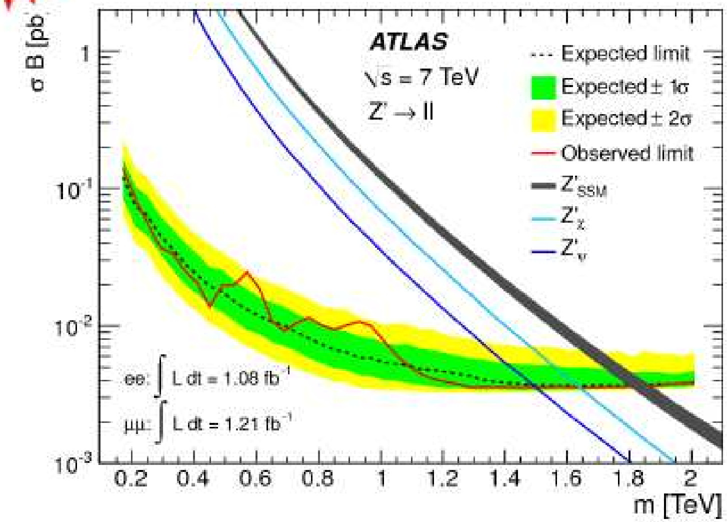
# *Search for dilepton resonances: ATLAS*

[*ATLAS Collaboration '11*]

## Search for Heavy Resonance: dileptons

arXiv:1108.1582




| | RS Graviton | | | |
|---|---|---|---|---|
| Model/Coupling | 0.01 | 0.03 | 0.05 | 0.1 |
| Mass limit [TeV] | 0.71 | 1.03 | 1.33 | 1.63 |

| $E_6$ $Z'$ Models | | | | | |
|---|---|---|---|---|---|
| $Z'_\psi$ | $Z'_N$ | $Z'_\eta$ | $Z'_I$ | $Z'_S$ | $Z'_\chi$ |
| 1.49 | 1.52 | 1.54 | 1.56 | 1.60 | 1.64 |

RS graviton ($k/M_{Pl} = 0.1$):
$m(G_{kk}) > 1.63$ TeV @ 95% C.L.

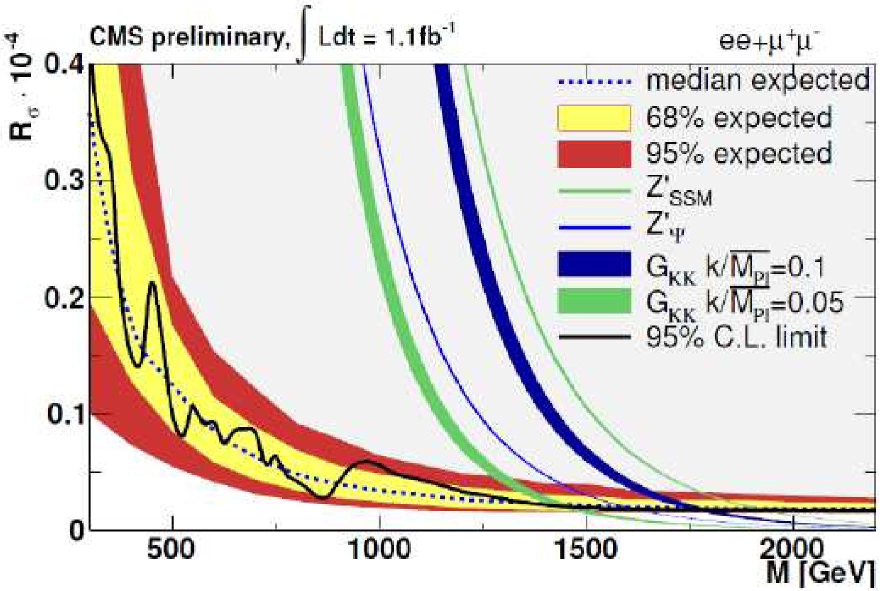
Sequential SM:
$m(Z'_{SSM}) > 1.83$ TeV @ 95% C.L.

As expected with current data

# Search for dilepton resonances: CMS

[*CMS Collaboration '11*]

## Limits with dimuons, dielectrons




**EXO-11-019**

$Z'_{SSM}$: 1940 GeV

$Z'_{\psi}$: 1620 GeV

$KK$: 1450 GeV ($\frac{k}{M}$ =0.05)

$KK$: 1780 GeV ($\frac{k}{M}$ =0.1)

Exclusion limits for SSM, superstring-inspired, RS KK (1.5-2 TeV, as well as ADD models for several parameters (2-3 TeV)

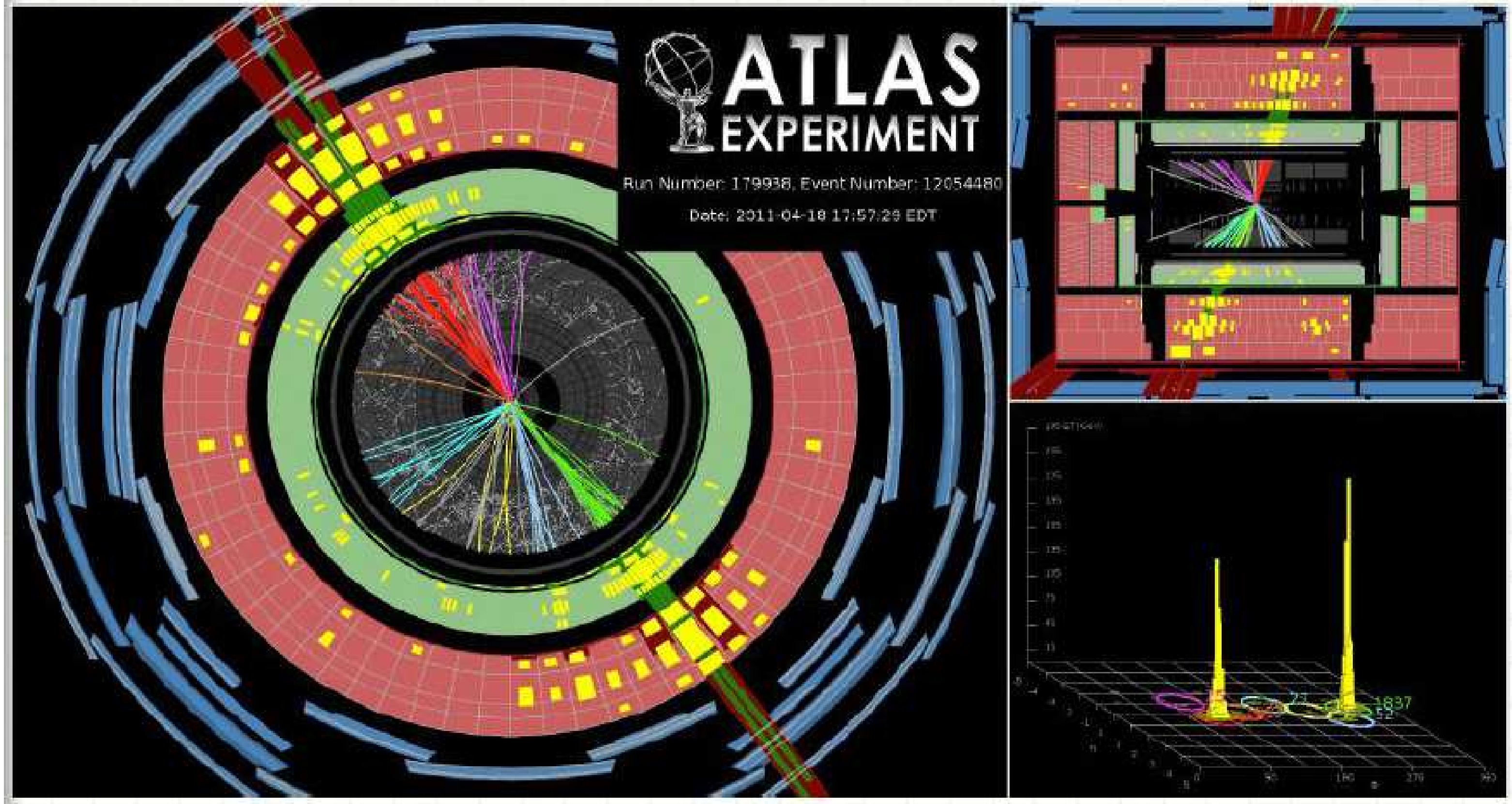
| $\Lambda_T$ [TeV] (GRW) | $M_s$ [TeV] (HLZ) | | | | | |
|---|---|---|---|---|---|---|
| | $n=2$ | $n=3$ | $n=4$ | $n=5$ | $n=6$ | $n=7$ |
| ADD k-factor: 1.0 | | | | | | |
| 2.62 | 2.58 | 3.12 | 2.62 | 2.36 | 2.20 | 2.08 |
| 2.56 | 2.58 | 3.10 | 2.56 | 2.27 | 2.09 | 1.95 |
| ADD k-factor: 1.3 | | | | | | |
| 2.70 | 2.72 | 3.22 | 2.70 | 2.44 | 2.28 | 2.16 |
| 2.66 | 2.72 | 3.20 | 2.66 | 2.37 | 2.17 | 2.02 |

**EXO-11-039**

# Search for dijet resonances: ATLAS

[ATLAS Collaboration '11]

## Search for Heavy Resonance: dijet

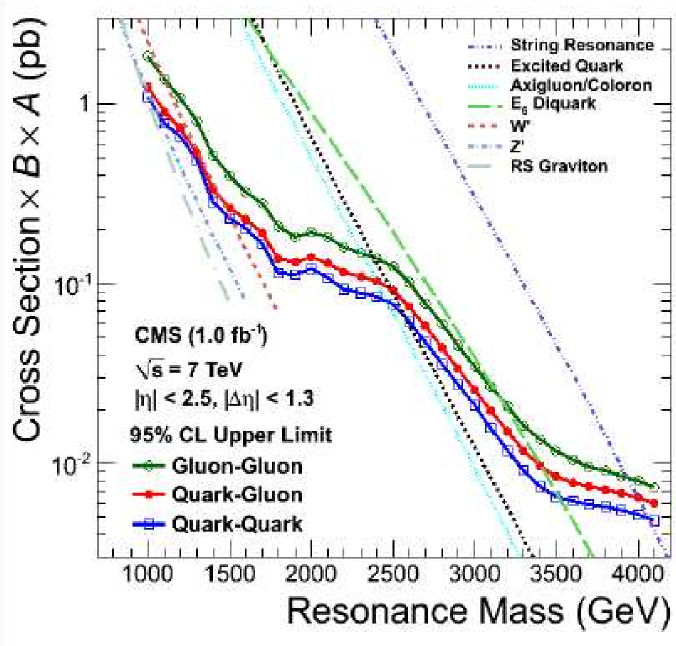



**m(jet-jet) = 4.0 TeV** **Missing $E_T$ = 100 GeV**

# Search for dijet resonances: CMS

[*CMS Collaboration '11*]

## Resonances: limits with dijets




Derived limits for several models, with excluded masses up to 4 TeV

| Model | Excluded Mass (TeV) | |
|---|---|---|
| | Observed | Expected |
| String Resonances | 4.00 | 3.90 |
| $E_6$ Diquarks | 3.52 | 3.28 |
| Excited Quarks | 2.49 | 2.68 |
| Axigluons/Colorons | 2.47 | 2.66 |
| $W'$ Bosons | 1.51 | 1.40 |

arXiv.1107.4771
(submitted to PLB)
EXO-11-015

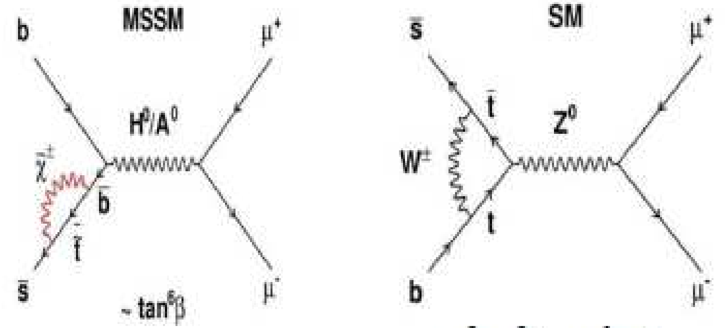
# Search for the rare decay $B_s \to \mu^+\mu^-$

B physics rare decay par excellence:

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

[A.J.Buras, arXiv:1012.1447]

Precise prediction (which will improve) !

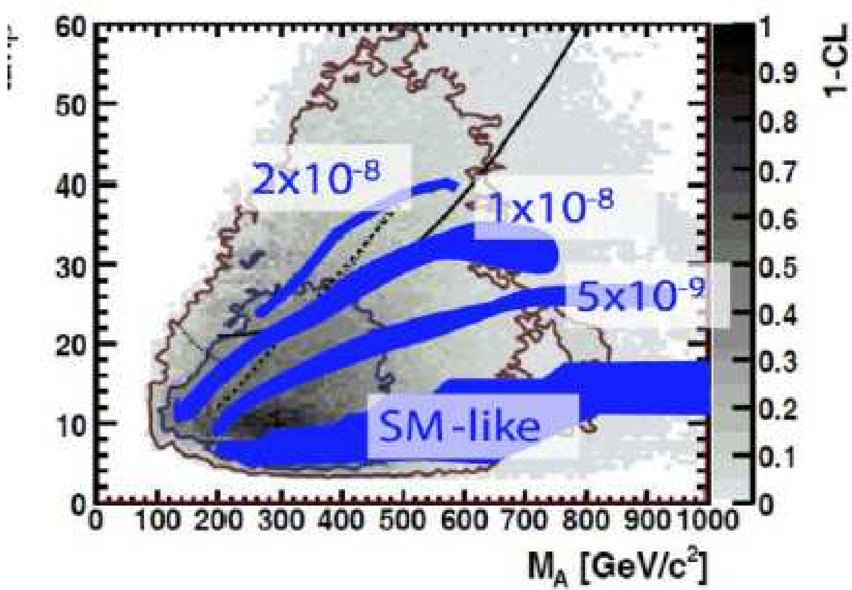



Very high sensitivity to NP, eg. MSSM:

$$Br^{MSSM}(Bq \to l^+l^-) \propto \frac{m_b^2 m_l^2 \tan^6\beta}{M_{A0}^4}$$

*One* example [O. Buchmuller et al, arXiv:0907.5568] : NUHM (= generalised version of CMSSM)

$BR(B_s \to \mu\mu)$ - highly discriminatory




BR UL 95% CL as of Spring 2011:

CDF (3.7 $fb^{-1}$): $< 4.3 \times 10^{-8}$

D0 (6.1 $fb^{-1}$): $< 5.1 \times 10^{-8}$

LHCb (37 $pb^{-1}$): $< 5.6 \times 10^{-8}$

Recent exciting hint from CDF (7 $fb^{-1}$):

$BR = 1.8^{+1.1}_{-0.9} \times 10^{-8}$ !?!

[arXiv:1107.2304]

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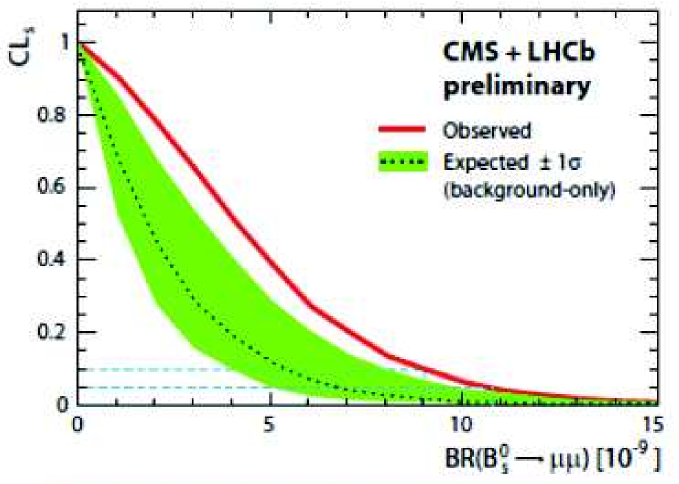
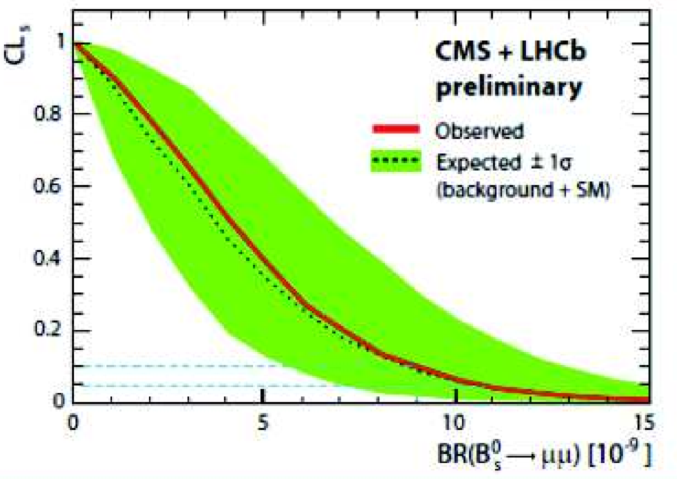
# $\mathrm{BR}(B_s \to \mu^+\mu^-)$: *combined result from LHCb and CMS*

$B_s \to \mu^+\mu^-$ : combination with CMS

- LHCb and CMS have performed a preliminary combined limit [LHCb-CONF-2011-043, CMS PAS BPH-11-019]
  - LHCb BR($B_s \to \mu^+\mu^-$) < 1.5 (1.2) x $10^{-8}$ at 95%(90%) c.l.
  - CMS: BR($B_s \to \mu^+\mu^-$) < 1.9 (1.6) x $10^{-8}$ at 95%(90%) c.l




LHCb+CMS limit: BR($B_s \to \mu^+\mu^-$) < 1.1 (0.9) x $10^{-8}$ at 95%(90%) c.l.

This is ~ 3 times the SM BR

40

$\Rightarrow$ Very good agreement with SM expectation (so far)

# Conclusions

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- No discoveries yet

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- LHC has started the exploration of the new territory of TeV-scale physics
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- Heavy SM Higgs is disfavoured, in agreement with constraints from electroweak precision physics
  Slight excess in the low-mass region
  $\Rightarrow$ Closing in on the SM Higgs

# *Conclusions*

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There is much more to come — the party has just begun!