What have we learnt so far from the LHC?

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DESY

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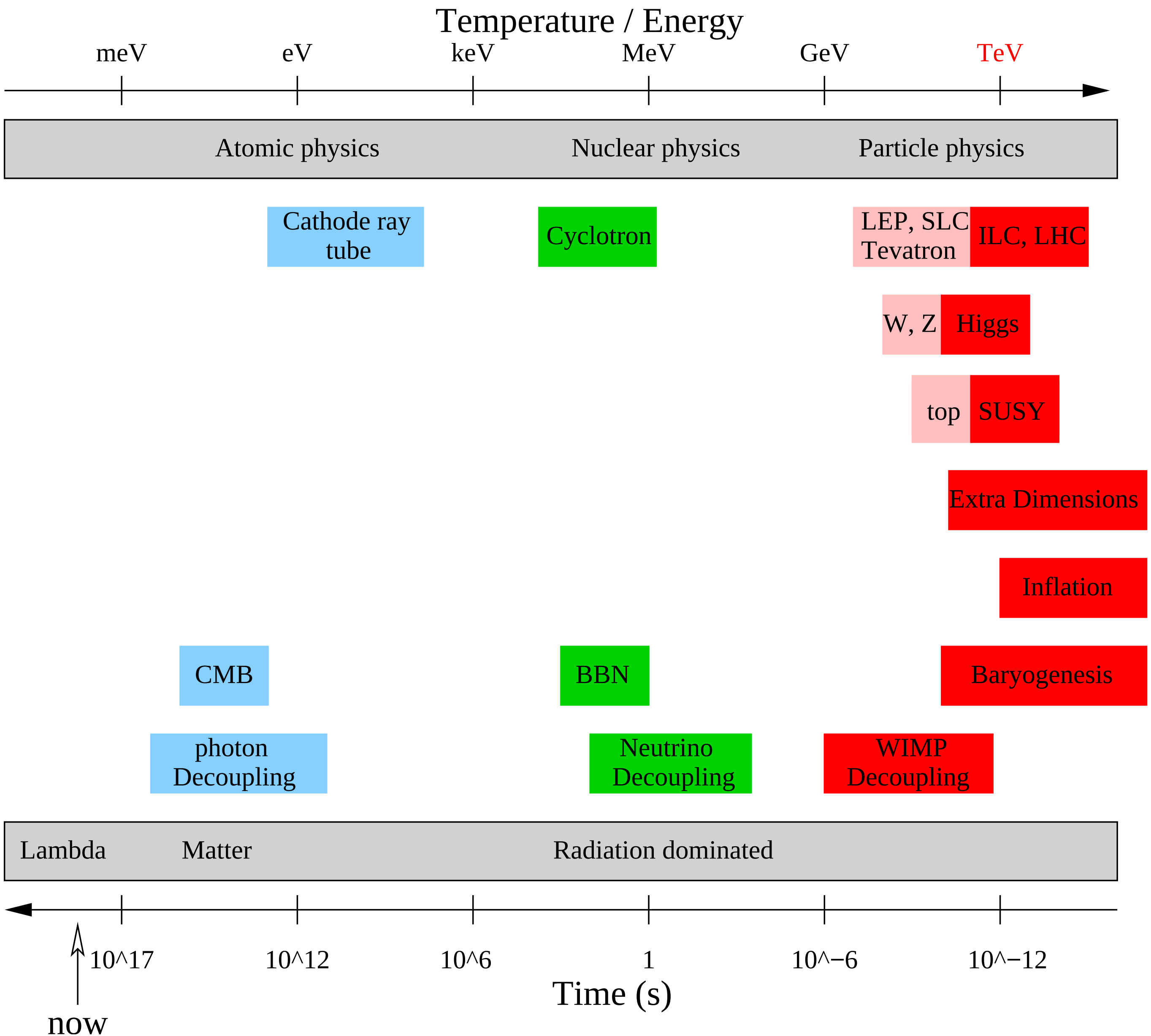
- Introduction: exploring the Terascale
- What to expect?
- Results up to now
- Conclusions

Introduction: exploring the Terascale

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



Particle accelerators: viewing the early Universe

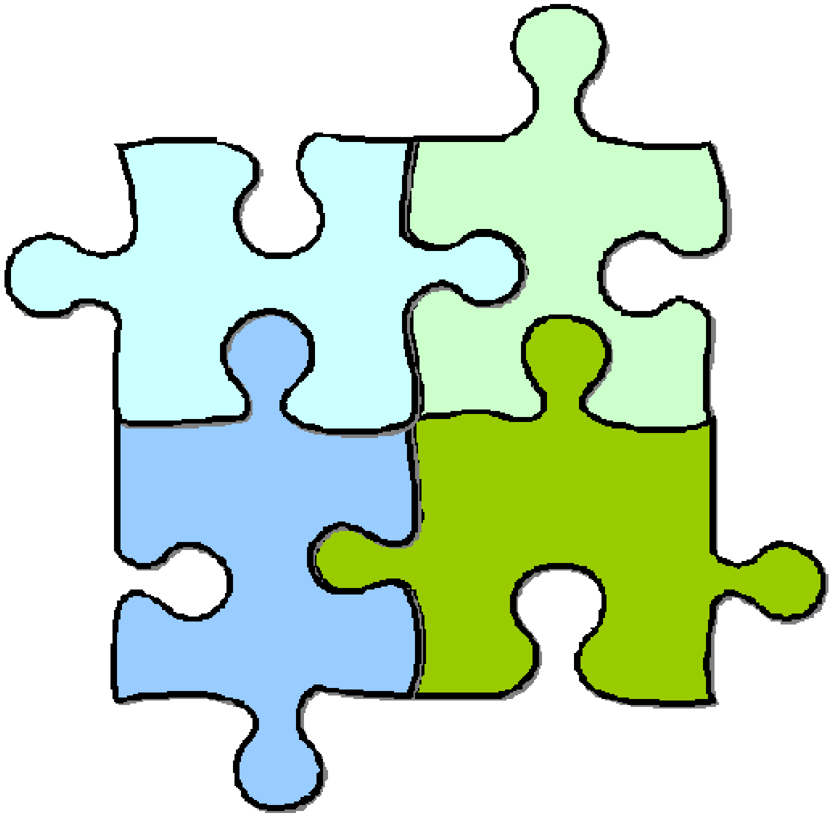
Today’s universe is cold and empty: only the stable relics and leftovers of the big bang remain

The unstable particles have decayed away with time, and the symmetries that shaped the early Universe have been broken as it has cooled

⇒ Use particle accelerators to pump sufficient energy into a point in space to re-create the short-lived particles and uncover the forces and symmetries that existed in the earliest Universe

⇒ Accelerators probe not only the structure of matter but also the structure of space-time, i.e. the fabric of the Universe itself

The Quantum Universe



Particle
Physics
Experiments
Accelerators
Underground

Quantum
Field
Theory
(Standard
Model)

Astronomy
Experiments
Telescopes
Satellites

Standard
Cosmology
Model

10^{-18} m

10^{26} m

What can we learn from exploring the new territory of TeV-scale physics?

- 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?
- . . .

What's so special about the Higgs?

- The fundamental interactions of elementary particles are described very successfully by quantum field theories that follow an underlying symmetry principle:
  "gauge invariance"

- This fundamental symmetry principle requires that all the elementary particles and force carriers should be massless

- However: W, Z, top, bottom, . . . , electron are massive, have widely differing masses

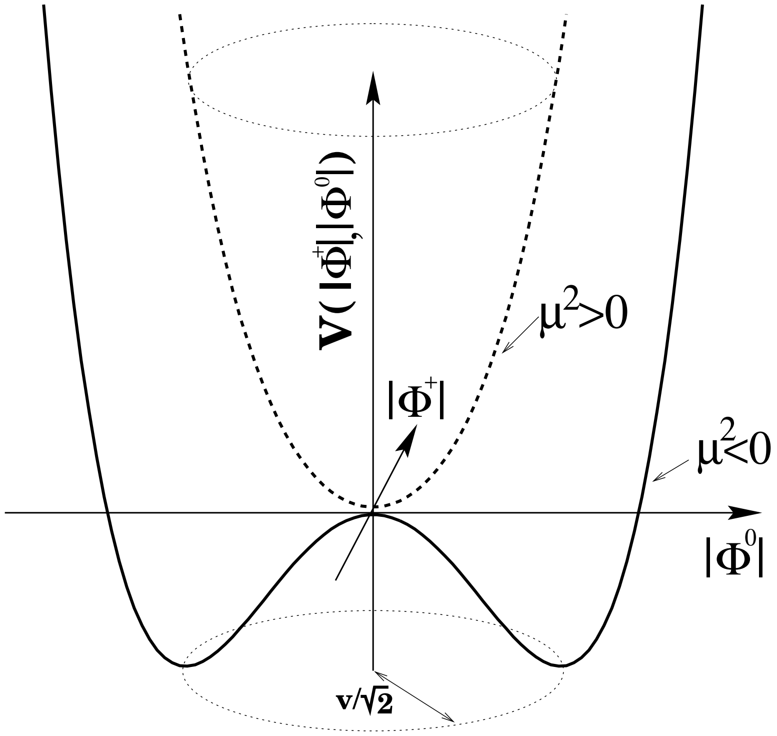
How can elementary particles acquire mass without spoiling the fundamental symmetries of nature?

The Higgs mechanism

Spontaneous symmetry breaking: the interaction obeys the symmetry principle, but not the state of lowest energy

New field postulated that fills all of the space: the Higgs field

The state of the lowest energy of the Higgs field (vacuum state) does not obey the underlying symmetry principle (gauge invariance)



⇒ Spontaneous breaking of the gauge symmetry

The Higgs field and the Higgs boson

Higgs mechanism: fundamental particles obtain their masses from interacting with the Higgs field

Higgs boson(s): field quantum of the Higgs field

(like the photon is the quantum of the electromagnetic field)

The postulated Higgs boson is a scalar particle (spin 0)

Up to now no fundamental scalar particle has been observed in nature

The Higgs mechanism sounds like a rather bold assumption to cure a theoretical / aesthetical problem

But: Our current description of the fundamental interactions breaks down at the TeV scale

We know that there has to be new physics that is responsible for electroweak symmetry breaking

This new physics must manifest itself at the TeV scale

⇒ LHC, future Linear Collider (LC)

Possible alternatives to the Higgs mechanism:

- A new fundamental strong interaction (“strong electroweak symmetry breaking”)
- New dimensions of space (electroweak symmetry breaking happens via boundary conditions for SM gauge bosons and fermions on “branes” in a higher-dimensional space)

How to find the Higgs (or more than one)?

- Heavy particle

  ⇒ need high-energy collider, $E = mc^2$

- Unstable:

  ⇒ need to look for decay products

- Comprehensive set of precision measurements and accurate theory predictions will be needed to establish the Higgs mechanism and to determine the Higgs properties

⇒ One of the main goals for physics at the LHC and a future Linear Collider

Higgs: last missing ingredient of the "Standard Model"

But: the Standard Model cannot be the ultimate theory

- The Standard Model does not include gravity

  ⇒ breaks down at the latest at $M_{\rm Planck} \approx 10^{19}$ GeV

- "Hierarchy problem": $M_{\rm Planck}/M_{\rm weak} \approx 10^{17}$

  How can two so different scales coexist in nature?

  Via quantum effects: physics at $M_{\rm weak}$ is affected by physics at $M_{\rm Planck}$

  ⇒ Instability of $M_{\rm weak}$

  ⇒ Would expect that all physics is driven up to the Planck scale

- Nature has found a way to prevent this
  The Standard Model provides no explanation

Hierarchy problem: how can the Planck scale be so much larger than the weak scale?

$\Rightarrow$ Expect new physics to stabilise the hierarchy

Supersymmetry:

Large corrections cancel out because of symmetry
fermions $\Leftrightarrow$ bosons

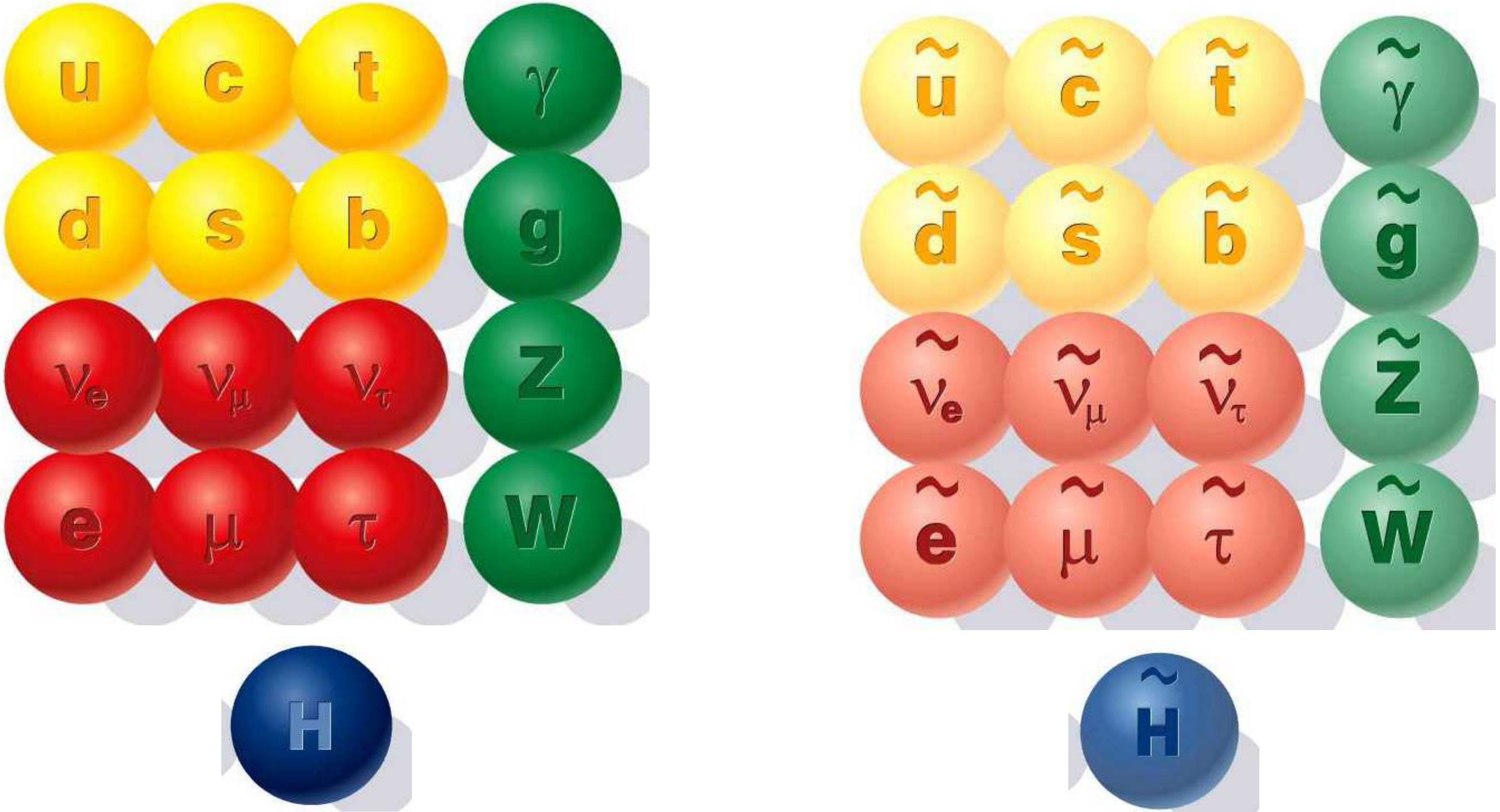
Extra dimensions of space:

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 ⟷ boson symmetry,
leads to compensation of large quantum corrections



The Minimal Supersymmetric Standard Model (MSSM)

Superpartners for Standard Model particles:

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

$$\left[\tilde{u}, \tilde{d}, \tilde{c}, \tilde{s}, \tilde{t}, \tilde{b}\right]_{L,R} \quad \left[\tilde{e}, \tilde{\mu}, \tilde{\tau}\right]_{L,R} \quad \left[\tilde{\nu}_{e,\mu,\tau}\right]_L \qquad \text{Spin } 0$$

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

$$\tilde{g} \qquad \tilde{\chi}_{1,2}^\pm \qquad \tilde{\chi}_{1,2,3,4}^0 \qquad \text{Spin } \frac{1}{2}$$

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

Supersymmetry (SUSY)

SUSY: unique possibility to connect space–time symmetry (Lorentz invariance) with internal symmetries (gauge invariance):

Unique extension of the Poincaré group of symmetries of relativistic quantum field theories in $3+1$ dimensions

Local SUSY includes gravity, called “supergravity”

Lightest superpartner (LSP) is stable if “R parity” is conserved

$\Rightarrow$ Candidate for cold dark matter in the Universe

Gauge coupling unification, $M_{\mathrm{GUT}} \sim 10^{16}\ \mathrm{GeV}$

neutrino masses: see-saw scale $\sim .01$–$.1\, M_{\mathrm{GUT}}$

How does SUSY breaking work?

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

$\Rightarrow$ SUSY can only be realised as a broken symmetry

MSSM: no particular SUSY breaking mechanism assumed, parameterisation of possible soft SUSY-breaking terms

$\Rightarrow$ relations between dimensionless couplings unchanged

$\Rightarrow$ cancellation of large quantum corrections preserved

Most general case: 105 new parameters

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_{GUT}, M_{Pl}, $\ldots$)

renormalisation group running down to weak scale

require correct value of M_{Z}

$\Rightarrow$ CMSSM characterised by

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

CMSSM has been the most widely studied SUSY scenario up to now

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

CMSSM phenomenology

m_0, $m_{1/2}$, A_0: GUT scale parameters

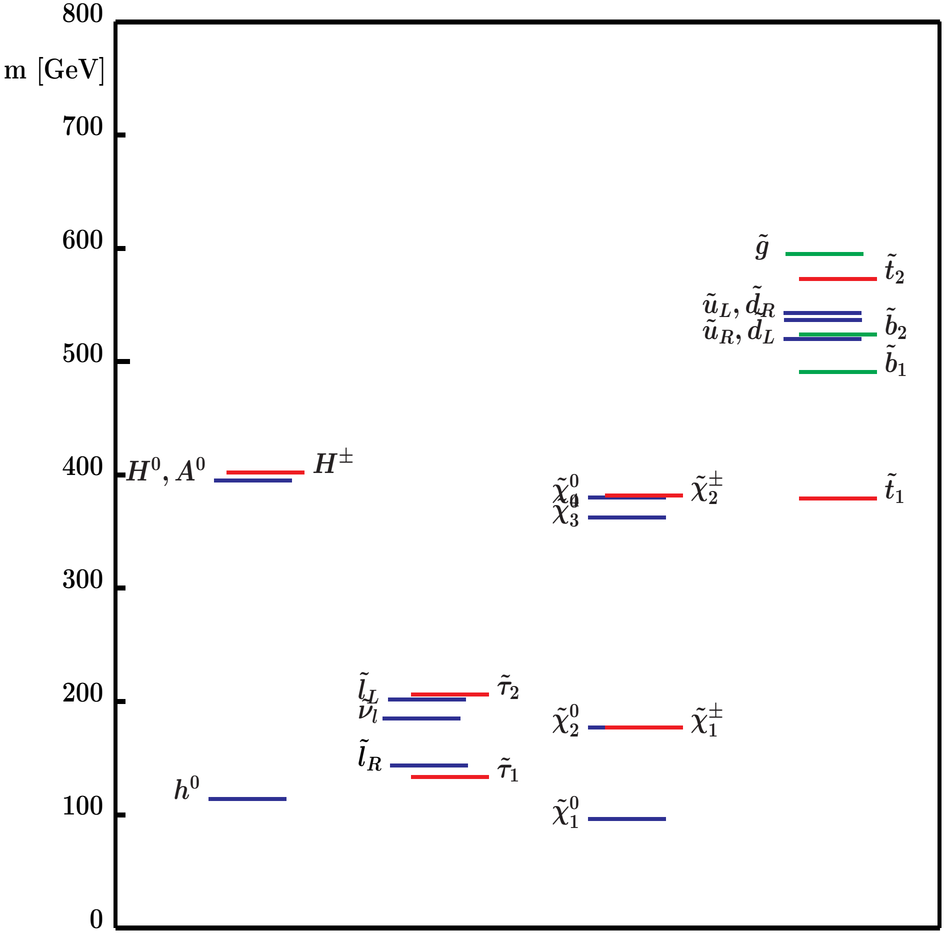
$\Rightarrow$ Spectra from renormalisation group running to weak scale

Lightest SUSY particle (LSP) is usually lightest neutralino

Gaugino masses run in same way as gauge couplings

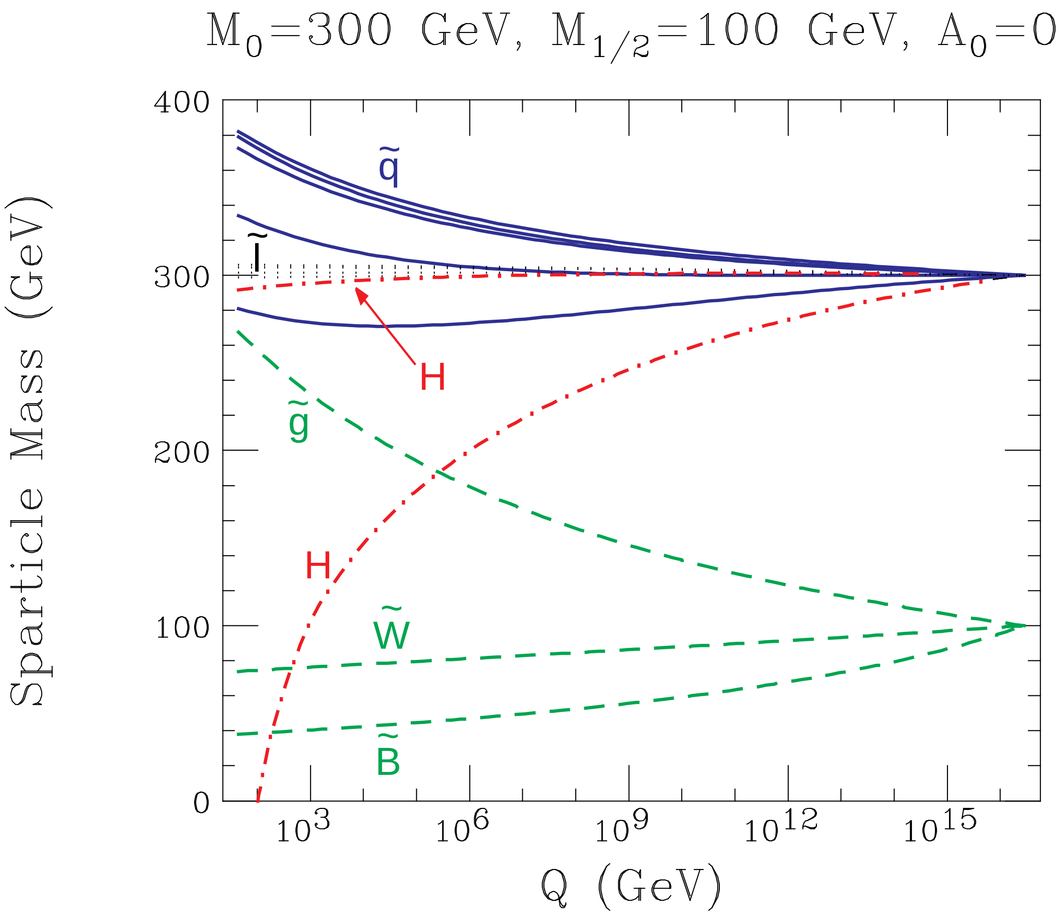
$\Rightarrow$ gluino heavier than charginos, neutralinos

“Typical” CMSSM scenario (SPS 1a benchmark scen.):



Radiative electroweak symmetry breaking

Universal boundary conditions at GUT scale,
renormalisation group running down to weak scale



large corrections from top-quark Yukawa coupling

$\Rightarrow$ $m^2_{H_u}$ driven to negative values

$\Rightarrow$ ew symmetry breaking

emerges naturally at scale $\sim 10^2$ GeV for
$100 \text{ GeV} \lesssim m_t \lesssim 200 \text{ GeV}$

SUSY-breaking scenarios

“Hidden sector”: $\longrightarrow$ Visible sector:

SUSY breaking MSSM

“Gravity-mediated”: SUGRA
“Gauge-mediated”: GMSB
“Anomaly-mediated”: AMSB
“Gaugino-mediated”

. . .

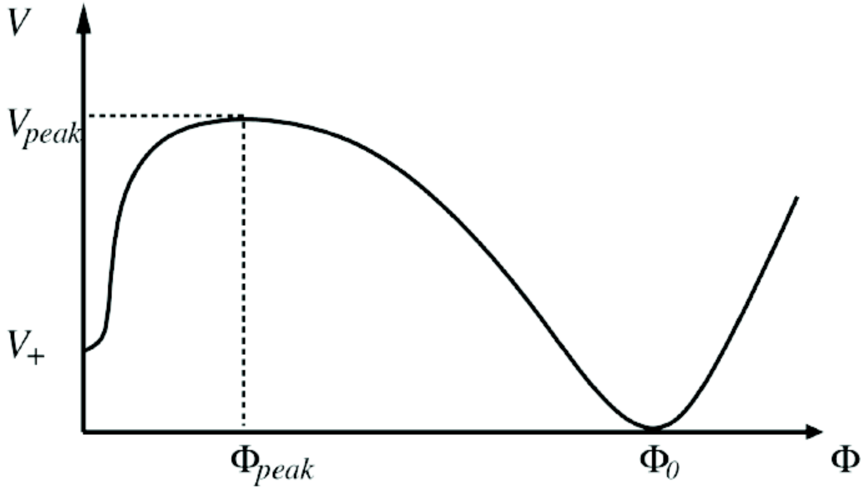
SUGRA: mediating interactions are gravitational

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

Do we live in a meta-stable vacuum?

Suppose we live in a SUSY-breaking meta-stable vacuum, while the global minimum has exact SUSY

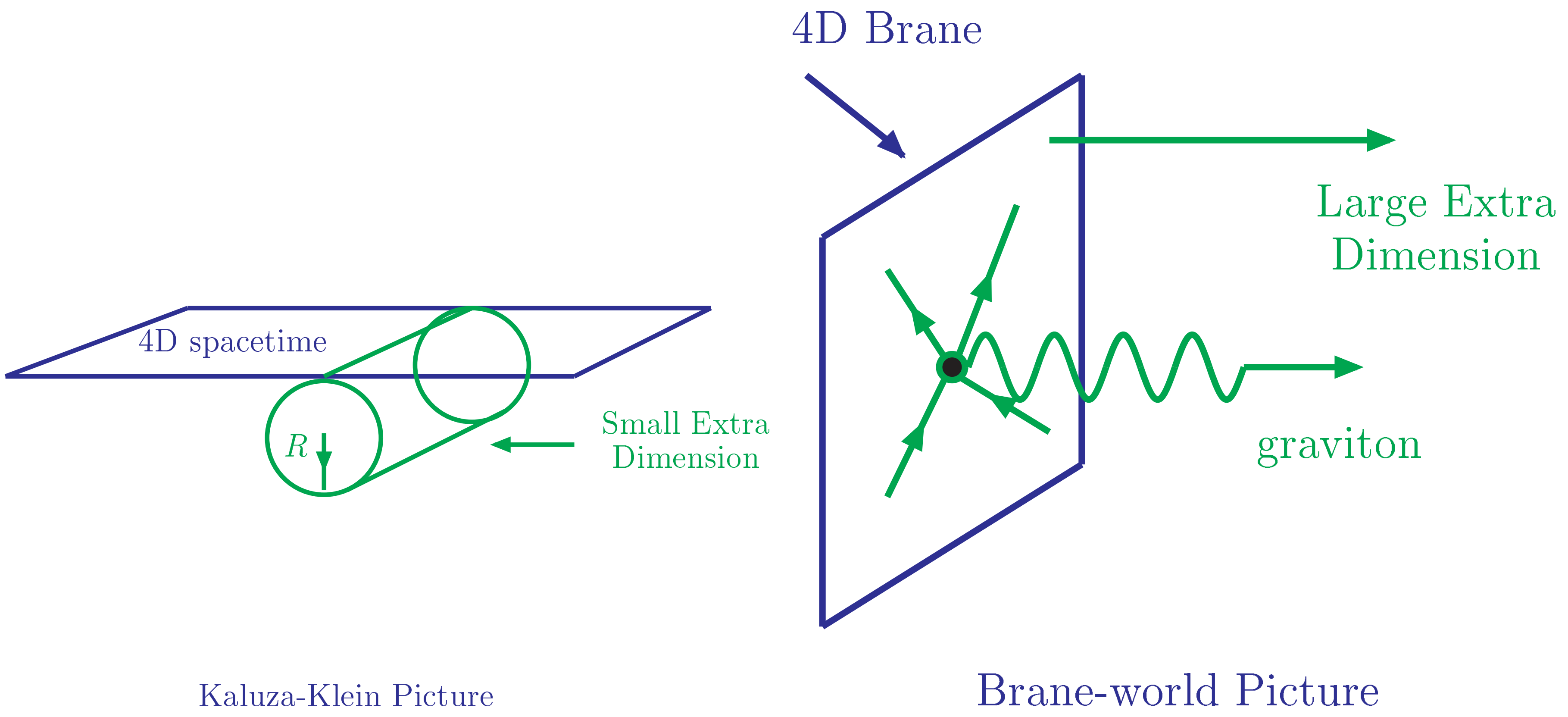


Recent developments: meta-stable vacua arise as generic feature of SUSY QCD with massive flavours

Meta-stable SUSY-breaking vacua are “generic” in local SUSY / string theory, can have cosmologically long life times [*K. Intriligator, N. Seiberg, D. Shih ’06*], . . .

⇒ Many new ideas — hope for experimental input!

Models with extra dimensions of space



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

$\Rightarrow$ observable effects at the TeV scale

Why extra dimensions?

String theories predict that there are actually 10 or 11 dimensions of space-time

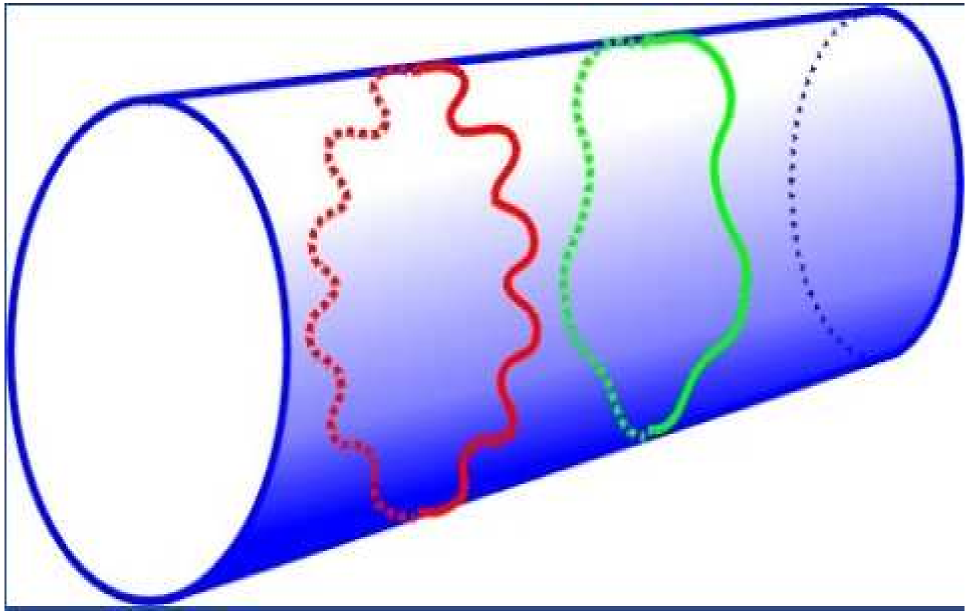
The “extra” dimensions may be “compactified”, too small to be detectable so far

To a tightrope walker, the tightrope is one-dimensional: he can only move forward or backward

But to an ant, the rope has an extra dimension: the ant can travel around the rope as well

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

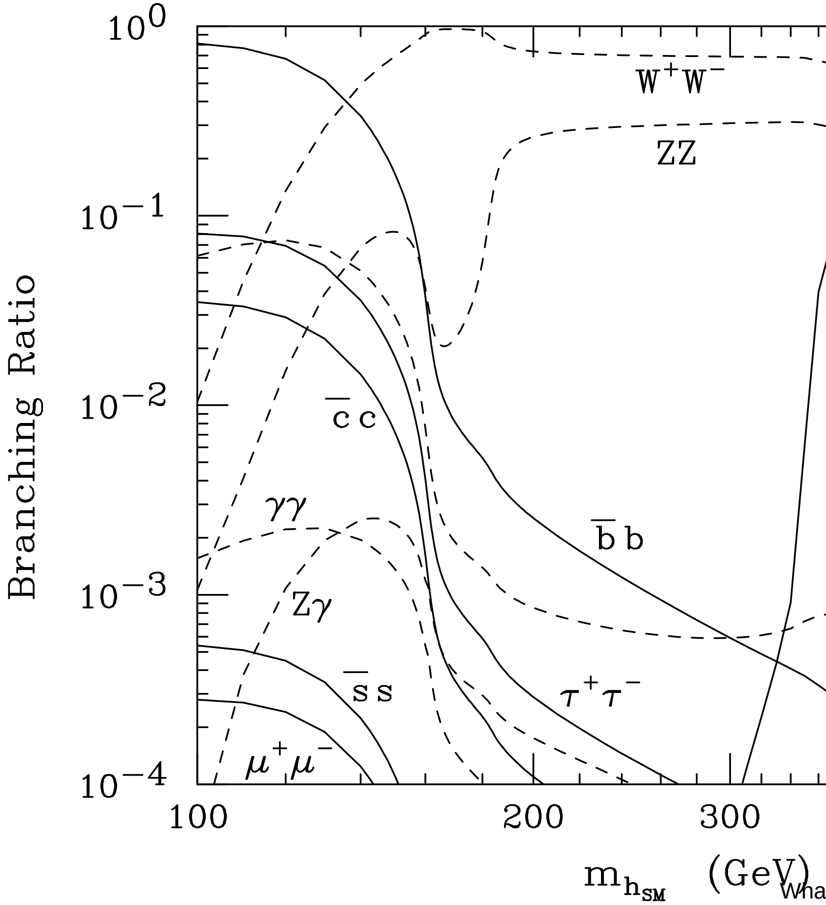
If gravity is strong at the TeV scale, particle collisions at the LHC could form “mini black holes”

What to expect?

Physics of electroweak symmetry breaking

Standard Model: a single parameter determines the whole Higgs phenomenology: M_H

Branching ratios of the SM Higgs:



⇒ dominant BRs:

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

$H \to b\bar{b}$

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

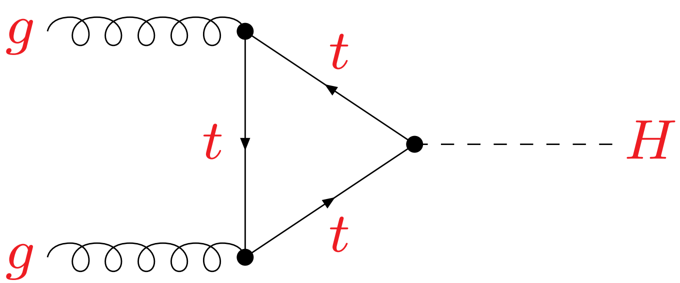
$H \to W^+W^-, ZZ$

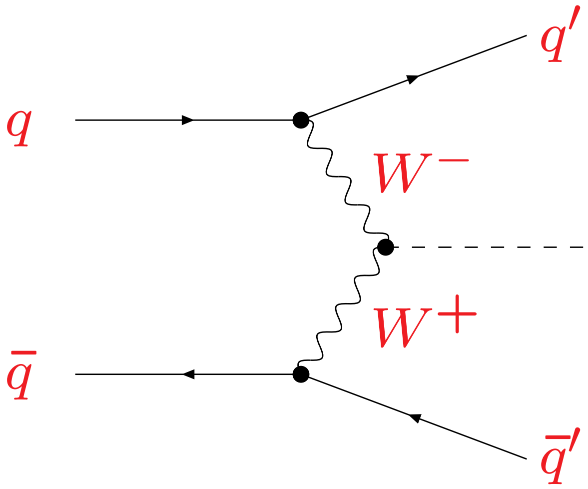
Production of a SM-like Higgs at the LHC

SM Higgs production at the LHC:

Dominant production processes:

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





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”

$\Rightarrow$ Would result in several Higgs states

Many extended Higgs theories have over large part of their parameter space a lightest Higgs scalar with properties very similar to those of the SM Higgs boson

Example: SUSY in the “decoupling limit”

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

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

⇒ Upper bound on lightest Higgs mass, M_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

MSSM with complex parameters: a very light SUSY Higgs?

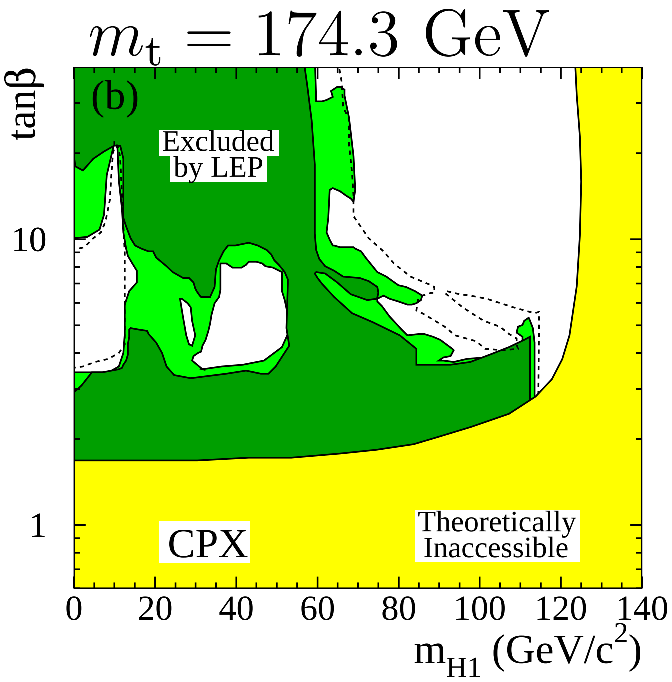
MSSM with $\mathcal{CP}$-violating phases (CPX scenario):

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

[*LEP Higgs WG '06*]



⇒ Light SUSY Higgs not ruled out!

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, . . .)?
- . . .

⇒ Intense effort will be needed to identify the nature of electroweak symmetry breaking

What to expect?

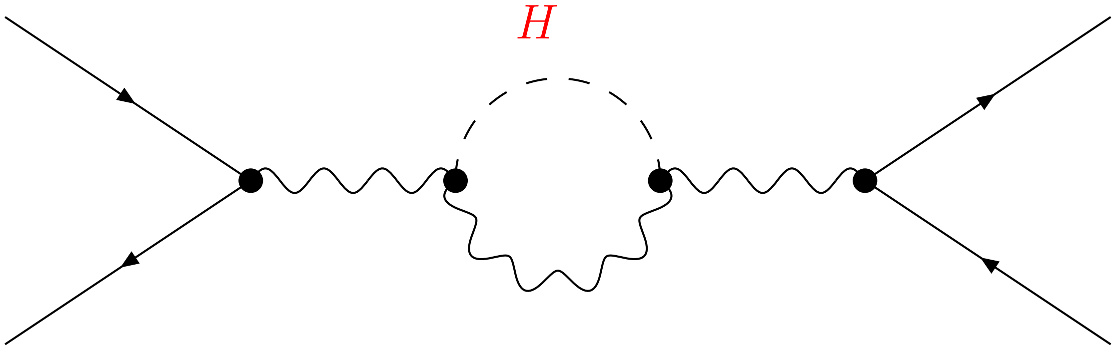
What is the scale of new physics?

EW precision data:
$M_Z, M_W, \sin^2\theta_{\rm eff}^{\rm lept}, \ldots$

Theory:
SM, MSSM, . . .

$\Downarrow$

Test of theory at quantum level: loop corrections



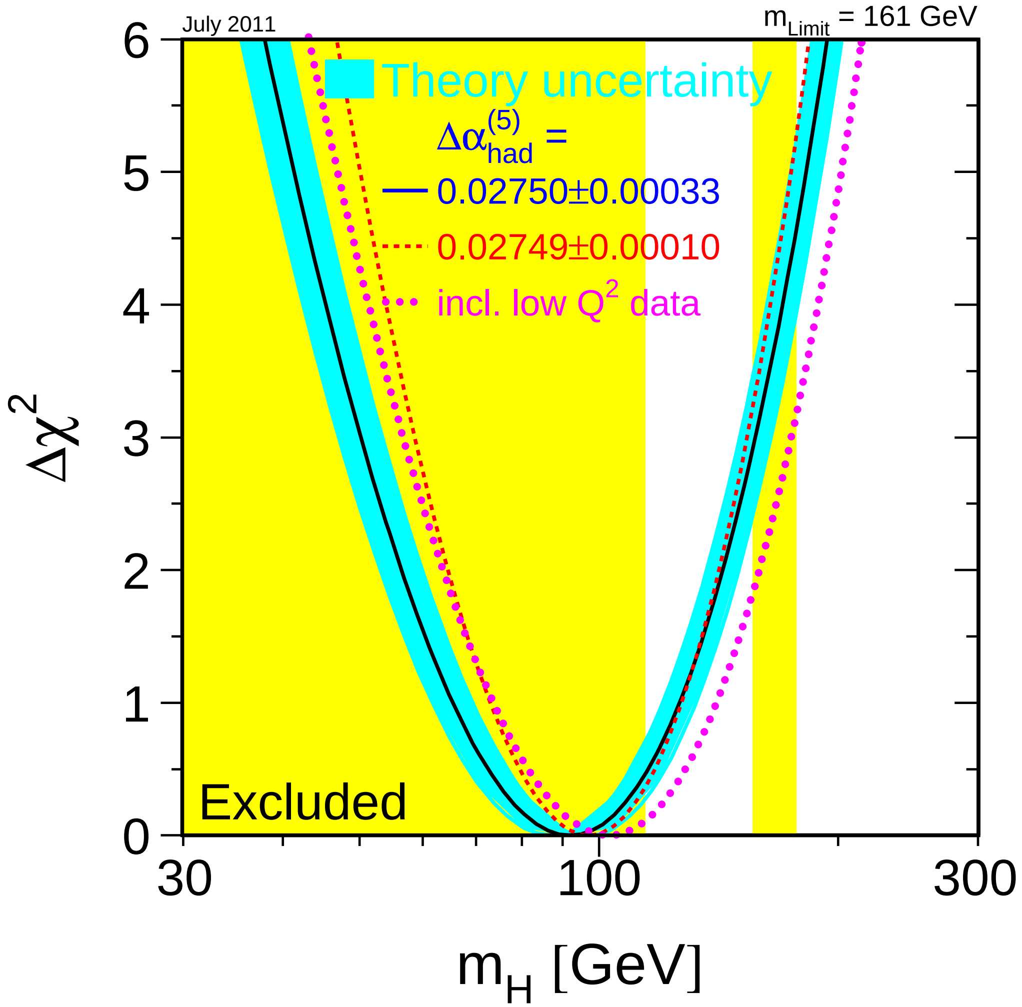
$\Downarrow$

Sensitivity to effects from unknown parameters: M_H, $M_{\tilde{t}}$, . . .

Window to “new physics”

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, $M_{\mathrm{H_{SM}}} < 161\ \mathrm{GeV}$, 95% C.L.

Global fit in constrained SUSY model: indirect experimental and cosmological constraints

SUSY search prospects:

Global χ^2 fit in the CMSSM ($m_{1/2}$, m_0, A_0 (GUT scale), $\tan\beta$, $\mathrm{sign}(\mu)$ (weak scale))

Fit includes (*MasterCode*, Markov-chain Monte Carlo sampling): [*O. Buchmueller, R. Cavanaugh, A. De Roeck, J. Ellis, H. Flächer, S. Heinemeyer, G. Isidori, K. Olive, P. Paradisi, F. Ronga, G. W. '08*]

- Electroweak precision observables: M_W, $\sin^2\theta_{\mathrm{eff}}$, Γ_Z, ...
- $+$ Cold dark matter (CDM) density (WMAP, ...), $\Omega_{\mathrm{CDM}}\,h^2 = 0.1099 \pm 0.0062$
- $+\ (g-2)_\mu$
- $+$ BPO: $\mathrm{BR}(b \to s\gamma)$, $\mathrm{BR}(B_s \to \mu^+\mu^-)$, $\mathrm{BR}(B \to \tau\nu)$, ...
- $+$ Kaon decay data: $\mathrm{BR}(K \to \mu\nu)$, ...

The anomalous magnetic moment of the muon:

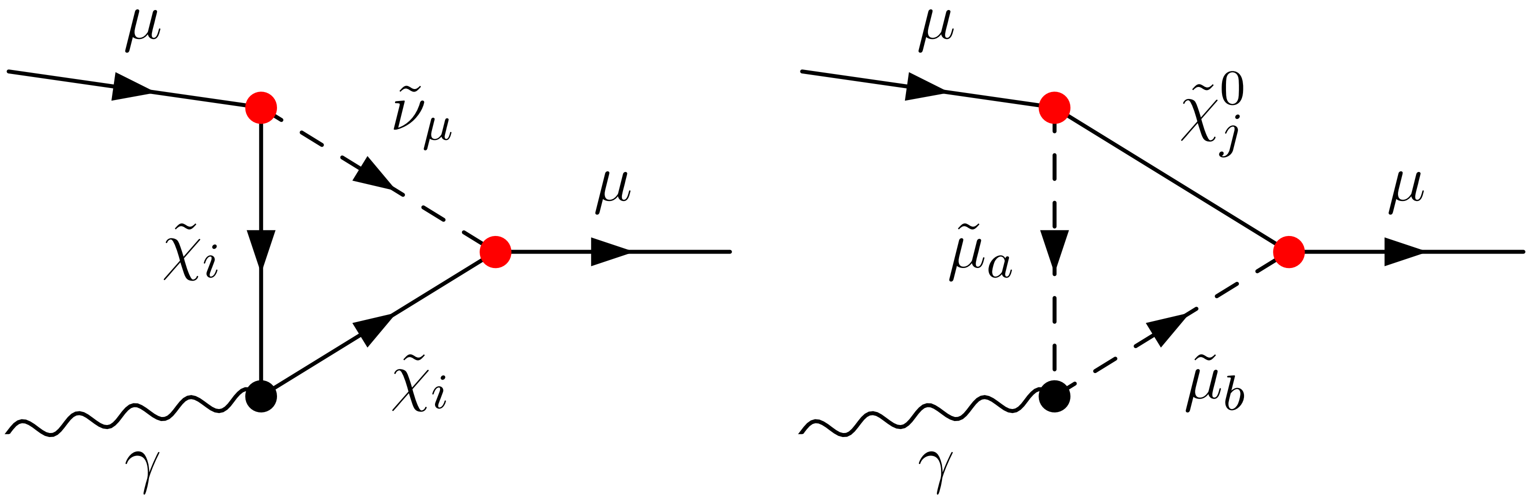
$$(g-2)_\mu \equiv 2a_\mu$$

Experimental result for a_μ vs. SM prediction (using e^+e^- data for hadronic vacuum polarisation):

$$a_\mu^{\text{exp}} - a_\mu^{\text{theo}} = (30.2 \pm 8.8) \times 10^{-10} \;:\; 3.4\,\sigma\ .$$

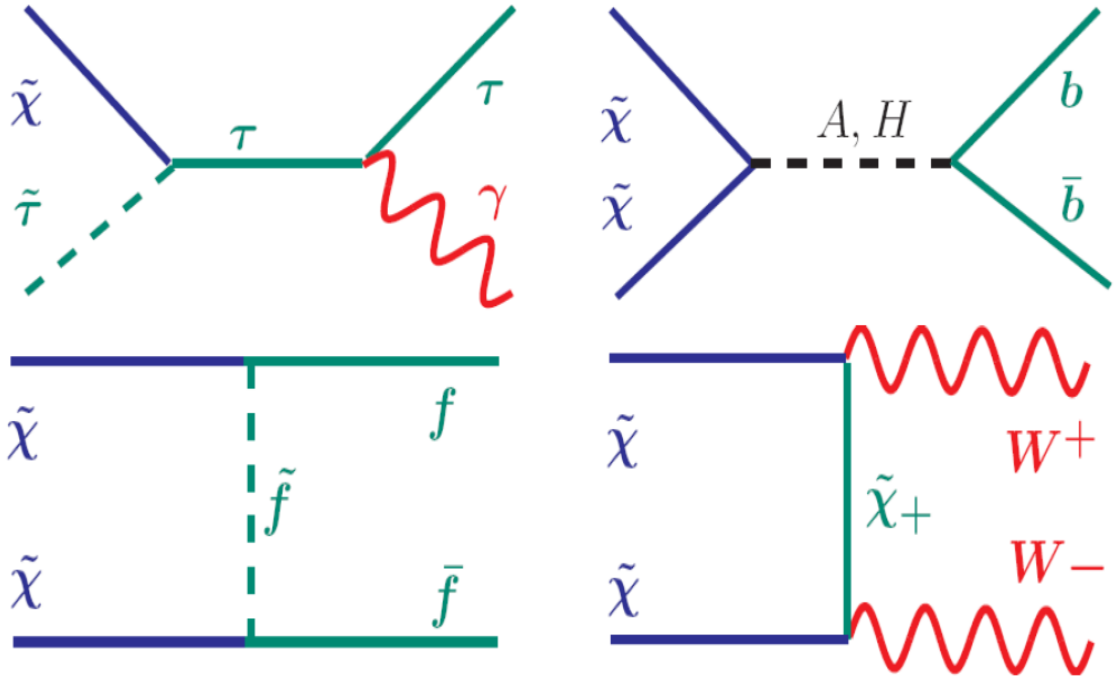
Better agreement between theory and experiment possible in models of physics beyond the SM

Example: one-loop contributions of superpartners of fermions and gauge bosons



Prediction for the density of cold dark matter (CDM) in the Universe

Cross sections for annihilation and co-annihilation processes



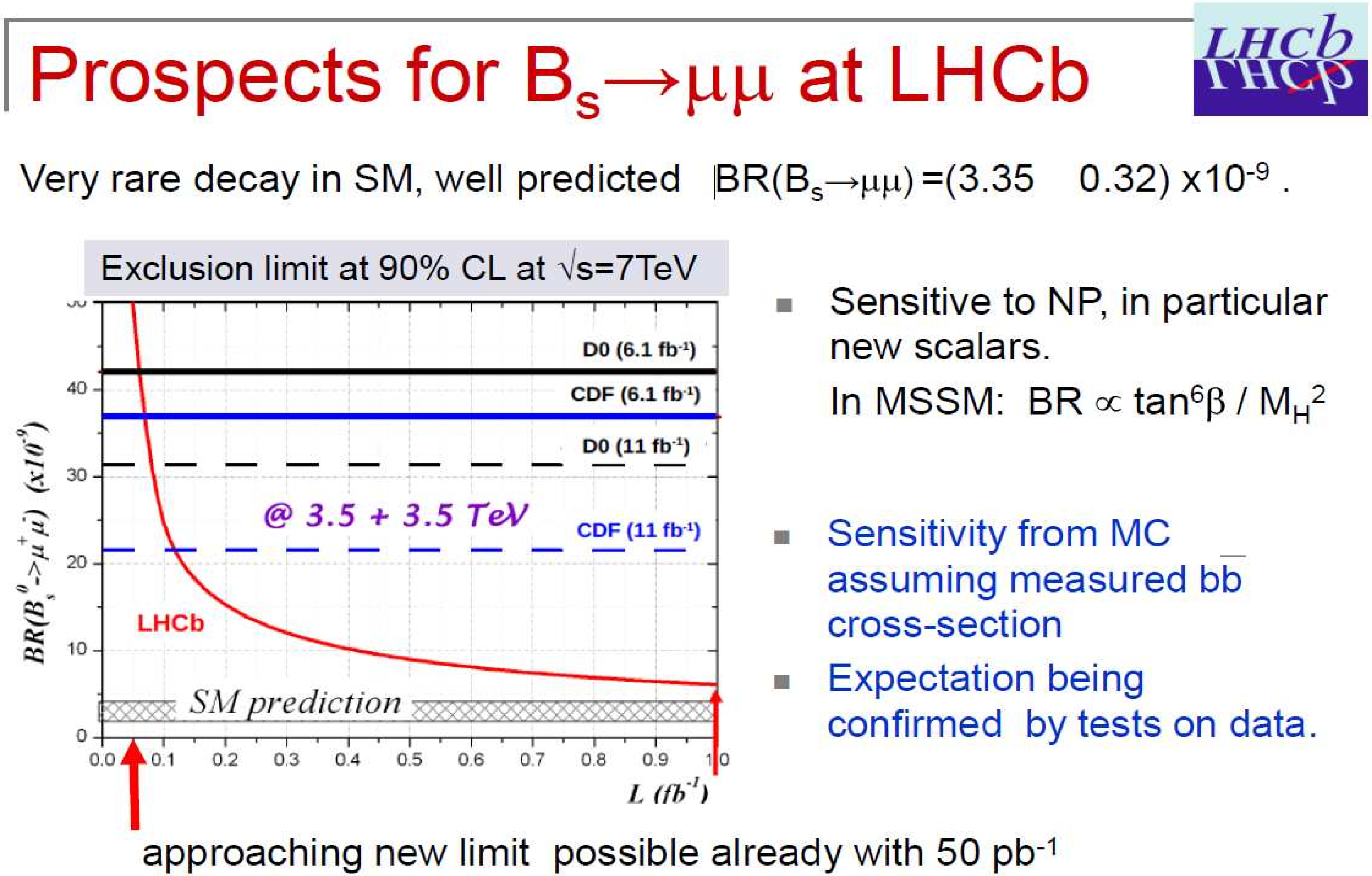
Cold Dark Matter density (WMAP, . . .):

$$\Omega_{\rm CDM}\, h^2 = 0.1099 \pm 0.0062$$

⇒ Comparison yields constraints on new physics

Rare decay: $B_s \to \mu^+\mu^-$

[LHCb Collaboration ’10]



Prospects for $B_s \to \mu\mu$ at LHCb

Very rare decay in SM, well predicted BR($B_s \to \mu\mu$) =(3.35 0.32) x10^{-9} .

Exclusion limit at 90% CL at √s=7TeV

- Sensitive to NP, in particular new scalars.
  In MSSM: BR ∝ $\tan^6\beta / M_H^2$
- Sensitivity from MC assuming measured $b\bar{b}$ cross-section
- Expectation being confirmed by tests on data.

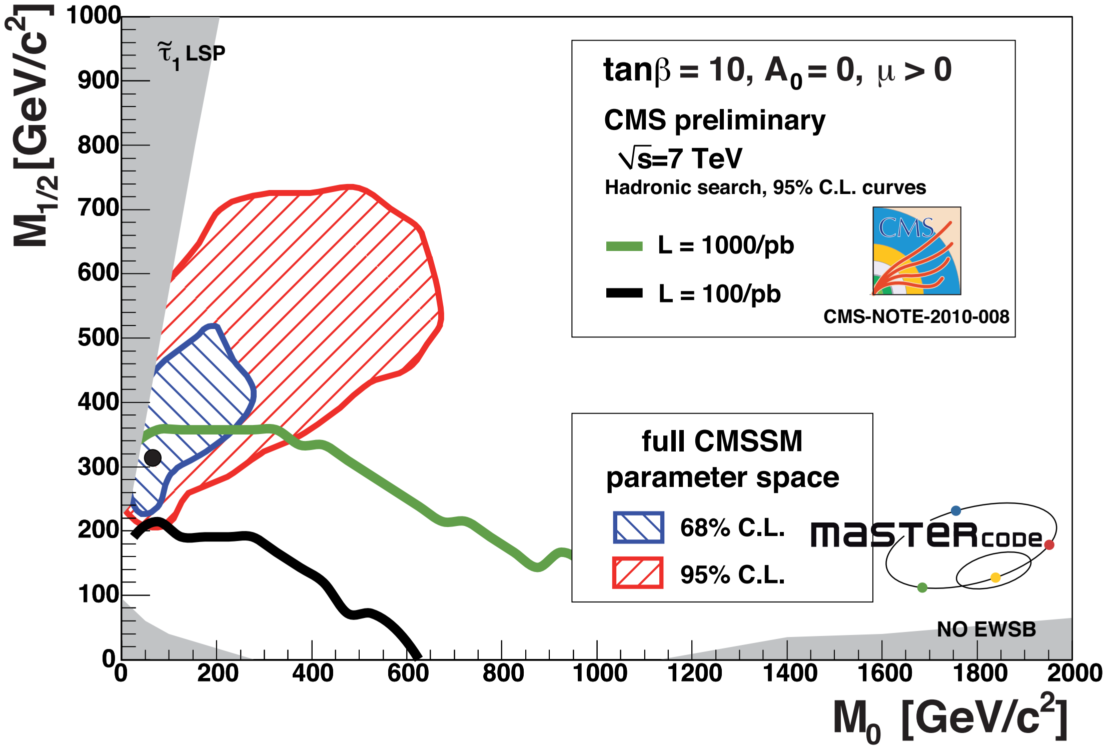
approaching new limit possible already with 50 pb^{-1}

⇒ High sensitivity to effects of new physics

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

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

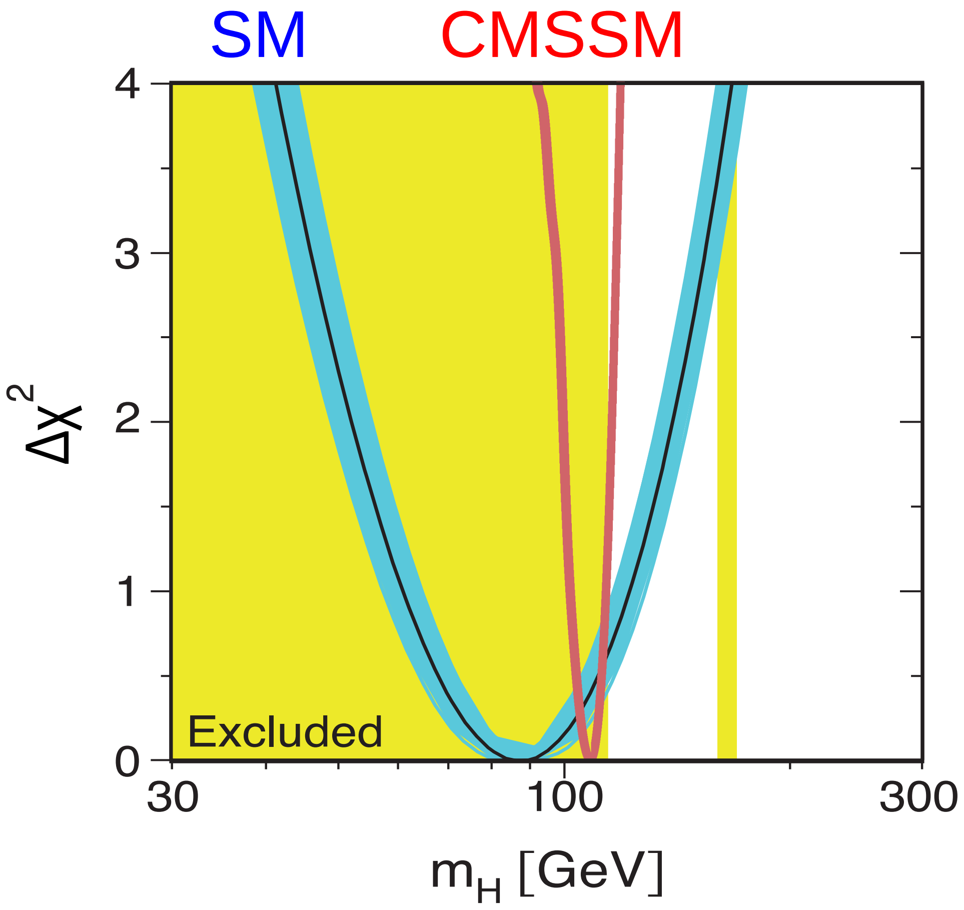
[*O. Buchmueller, R. Cavanaugh, A. De Roeck, J. Ellis, H. Flächer, S. Heinemeyer, G. Isidori, K. Olive, P. Paradisi, F. Ronga, G. W. '10*]



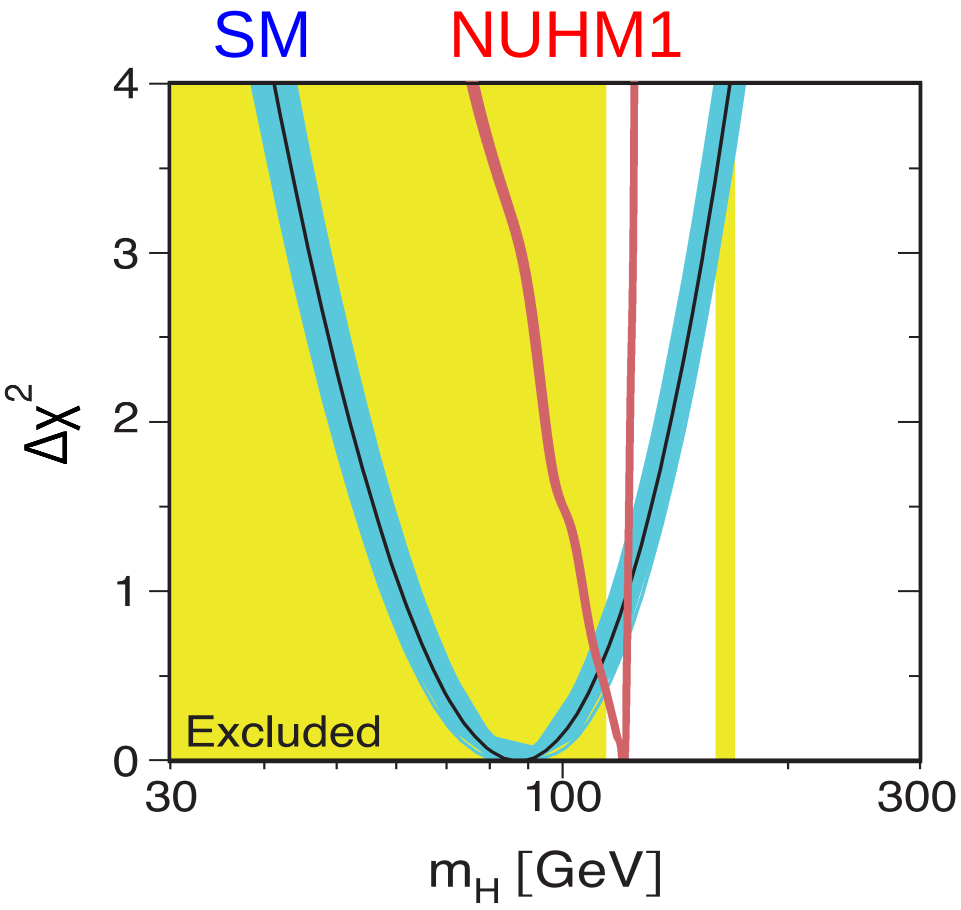
⇒ Best fit point was within the 95% C.L. reach with $1\ \mathrm{fb}^{-1}$

Indirect prediction for the Higgs mass in the SM and the CMSSM / NUHM1 from precision data

χ^2 fit for M_h, without imposing direct search limit



$$M_\mathrm{h}^\mathrm{CMSSM} = 108 \pm 6\ \mathrm{GeV}$$

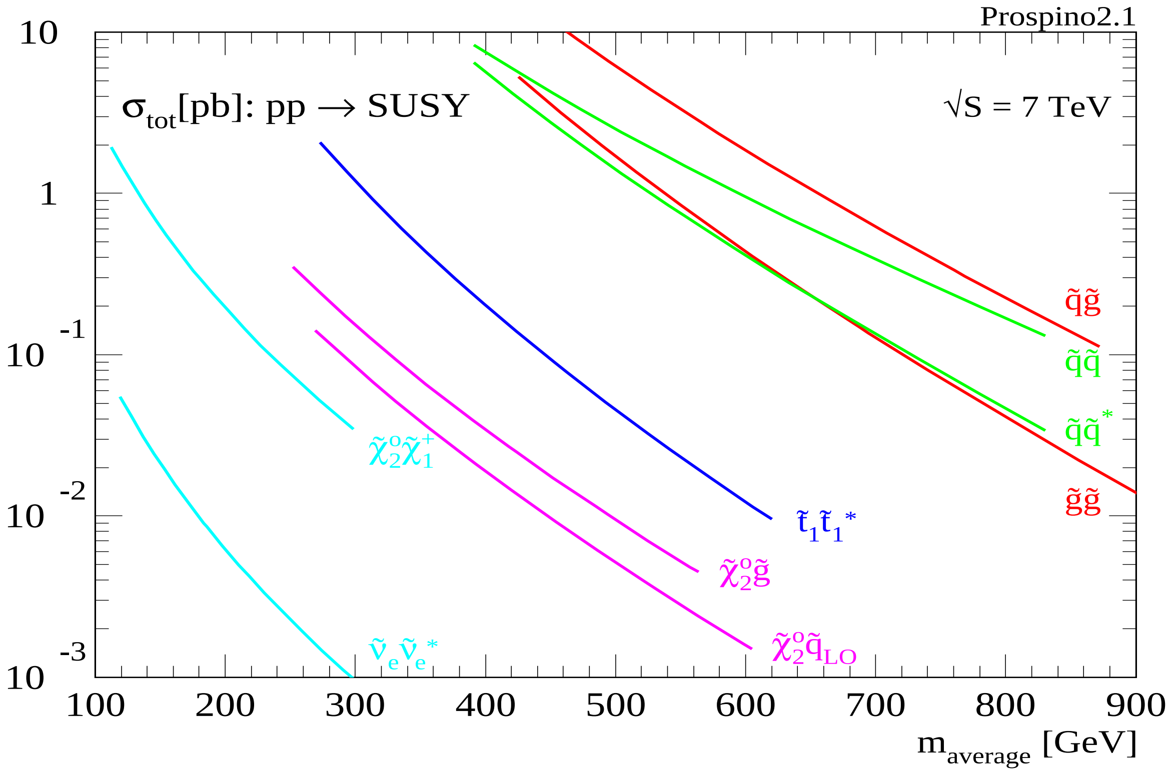


$$M_\mathrm{h}^\mathrm{NUHM1} = 121^{+2}_{-14}\ \mathrm{GeV}$$

⇒ Accurate indirect prediction; Higgs “just around the corner”?

Production of SUSY particles at the LHC

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

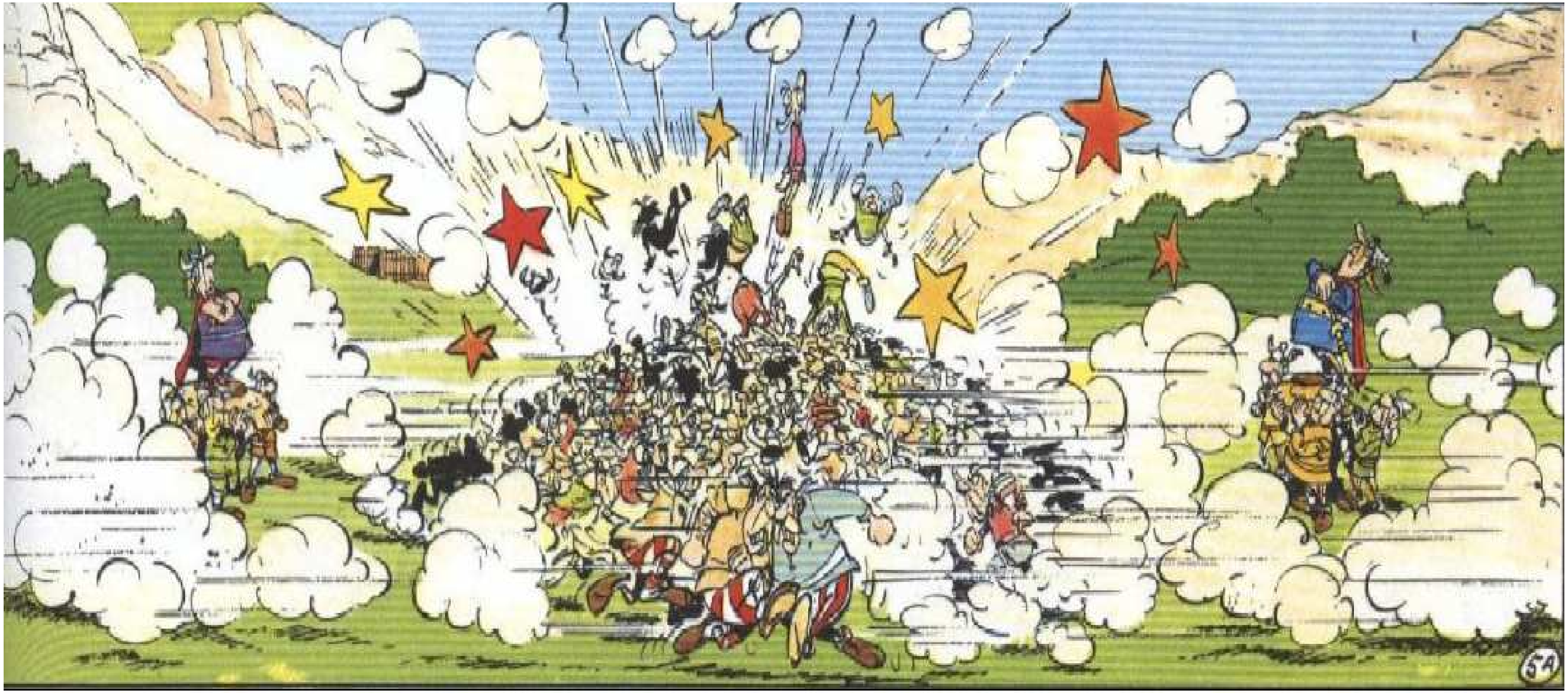
$\Rightarrow$ long decay chains possible; complicated final states

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

Many states produced at once, difficult to disentangle

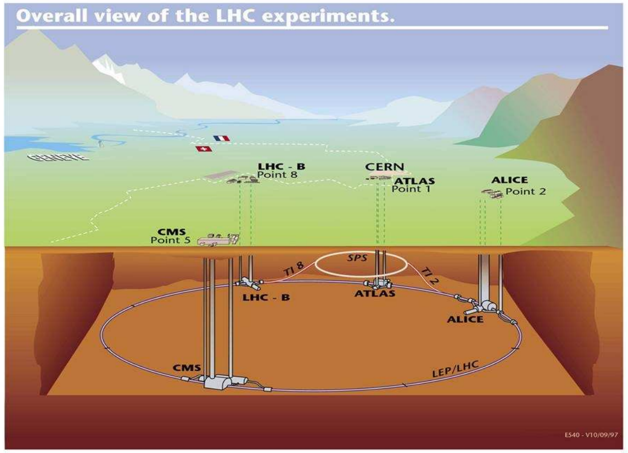
Results up to now

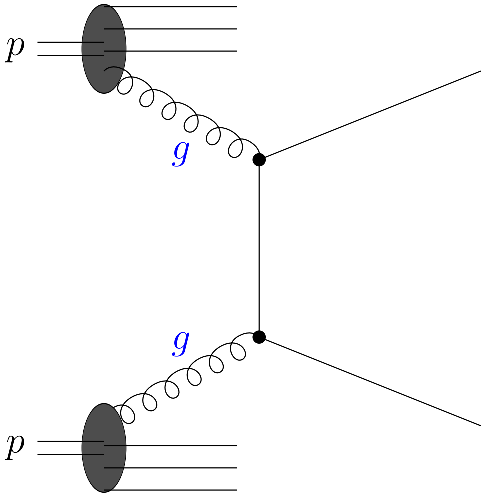
The LHC:
proton–proton collisions at 7 TeV (now) and 14 TeV ($\gtrsim 2014$)



The Large Hadron Collider (LHC)

Proton–proton scattering at 7–14 TeV: composite objects of quarks and gluons, bound together by strong interaction





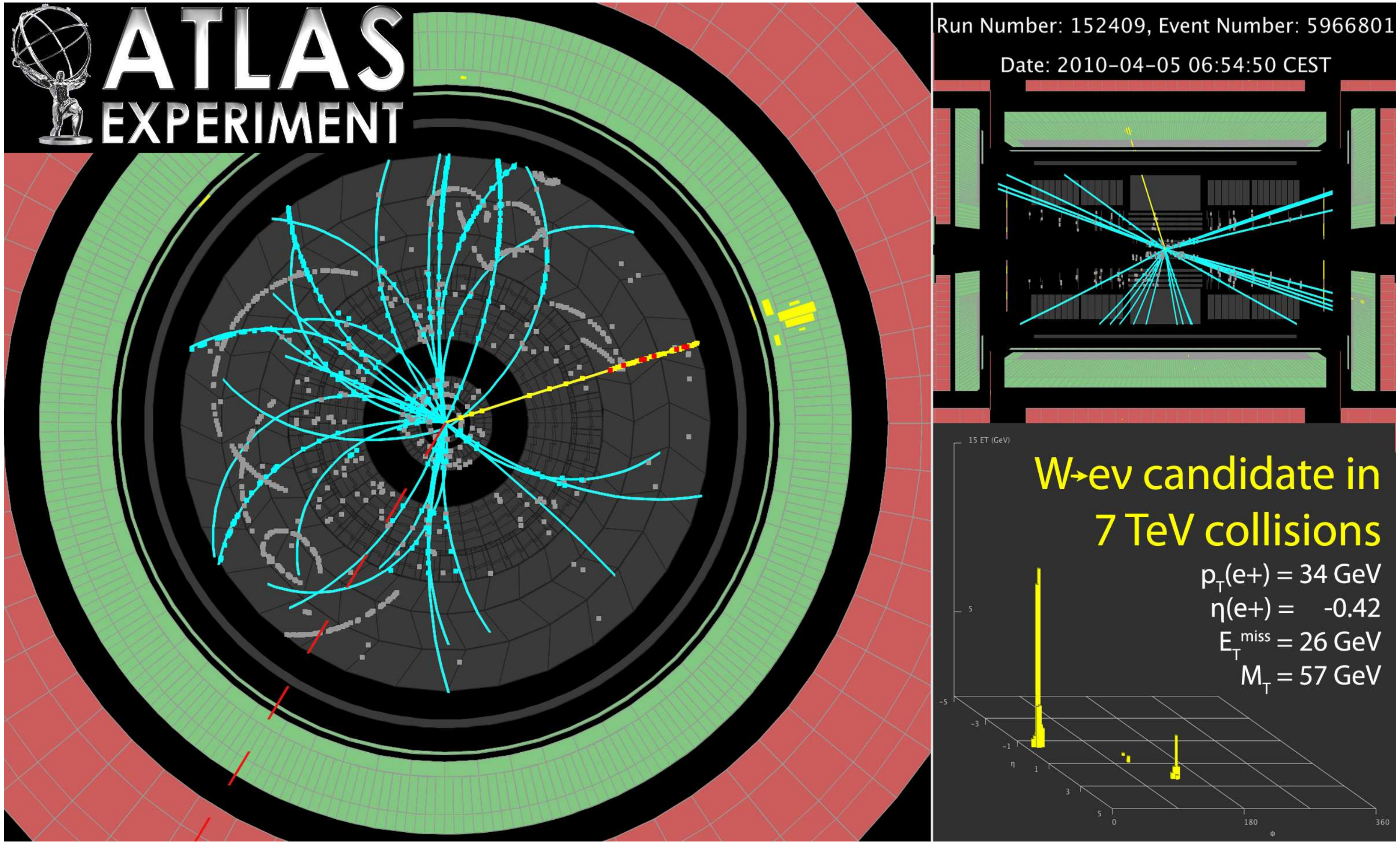
$\Rightarrow$ Has opened up new a energy domain

complicated scattering processes

10^9 scattering events$/s$ at LHC design luminosity

The LHC physics programme at 7 TeV started on March 30, 2010

Candidate for a W^+ boson decaying into $e^+\nu_e$:

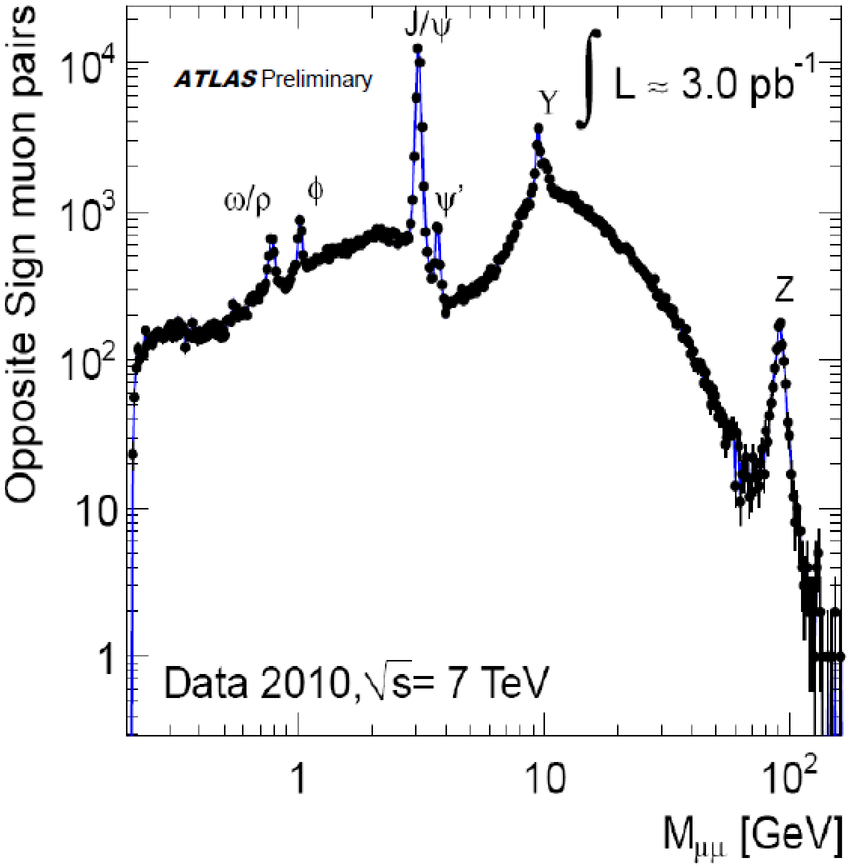


⇒ First steps: “rediscovery” of the Standard Model

Example: di–muon invariant mass distribution

[*ATLAS Collaboration ’10*]

Dimuon Resonances (+ the Z)

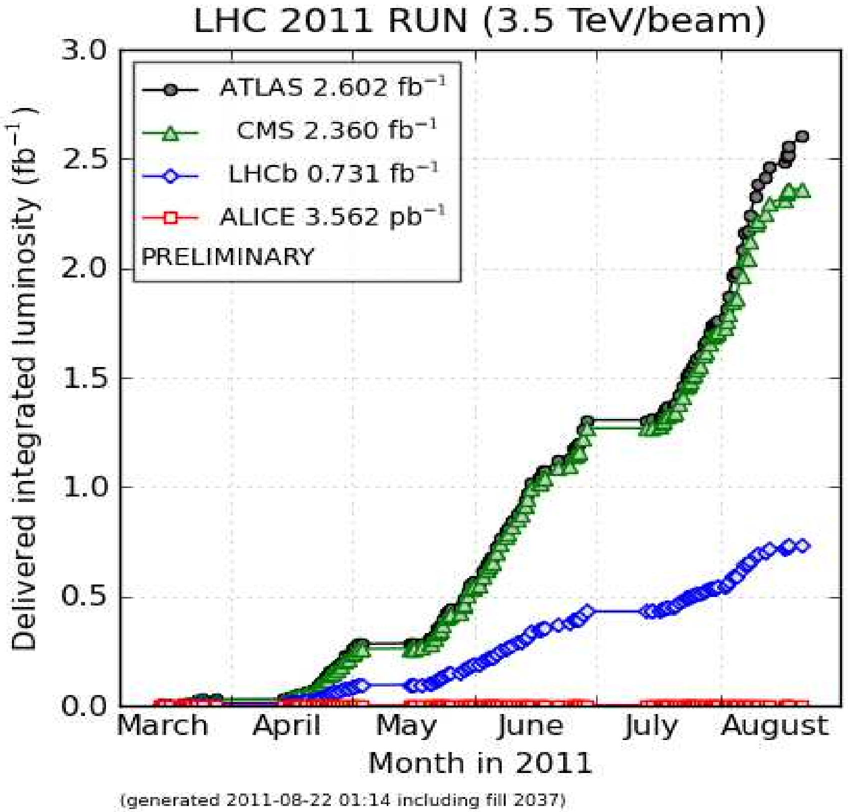


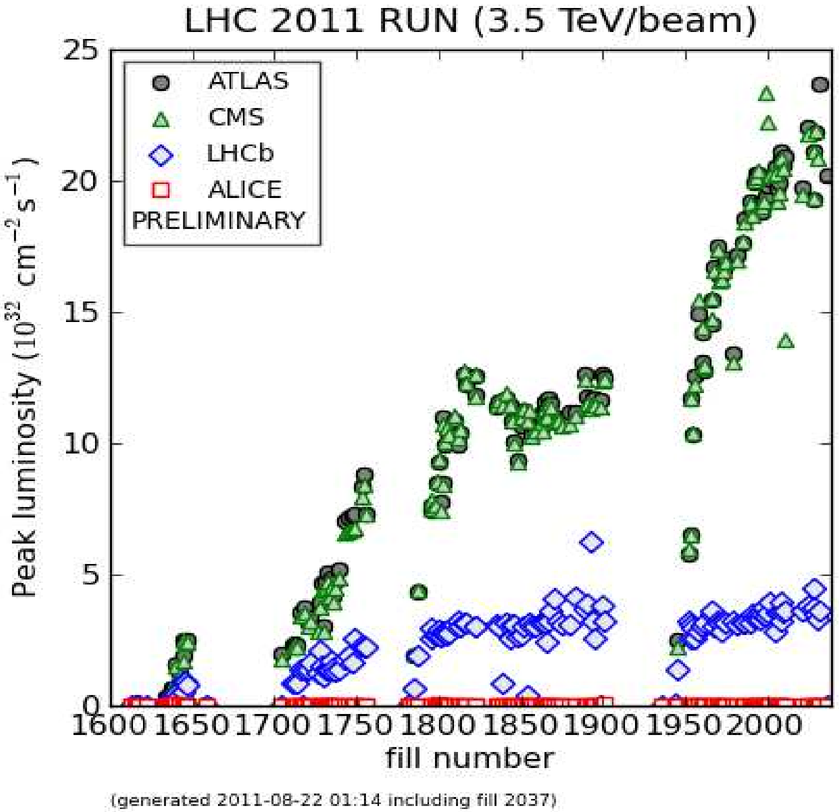
Simple analysis:

- ☐ LVL1 muon trigger with p_T ~ 6 GeV threshold
- ☐ 2 opposite-sign primary muons reconstructed by combining tracker and muon spectrometer

LHC production of W, Z, top, . . . has been observed

LHC luminosity: where do we stand?

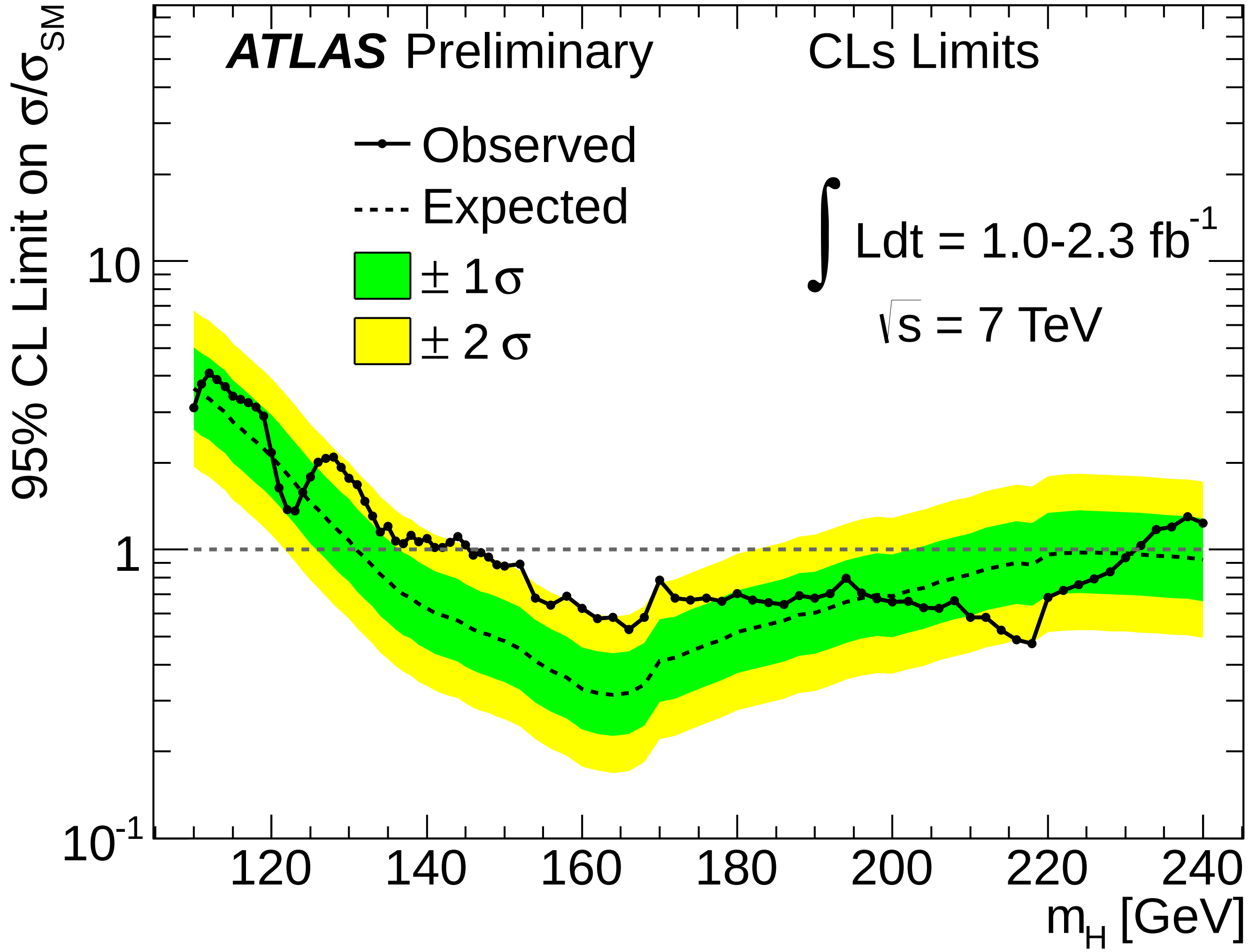




SM Higgs search: latest results from ATLAS

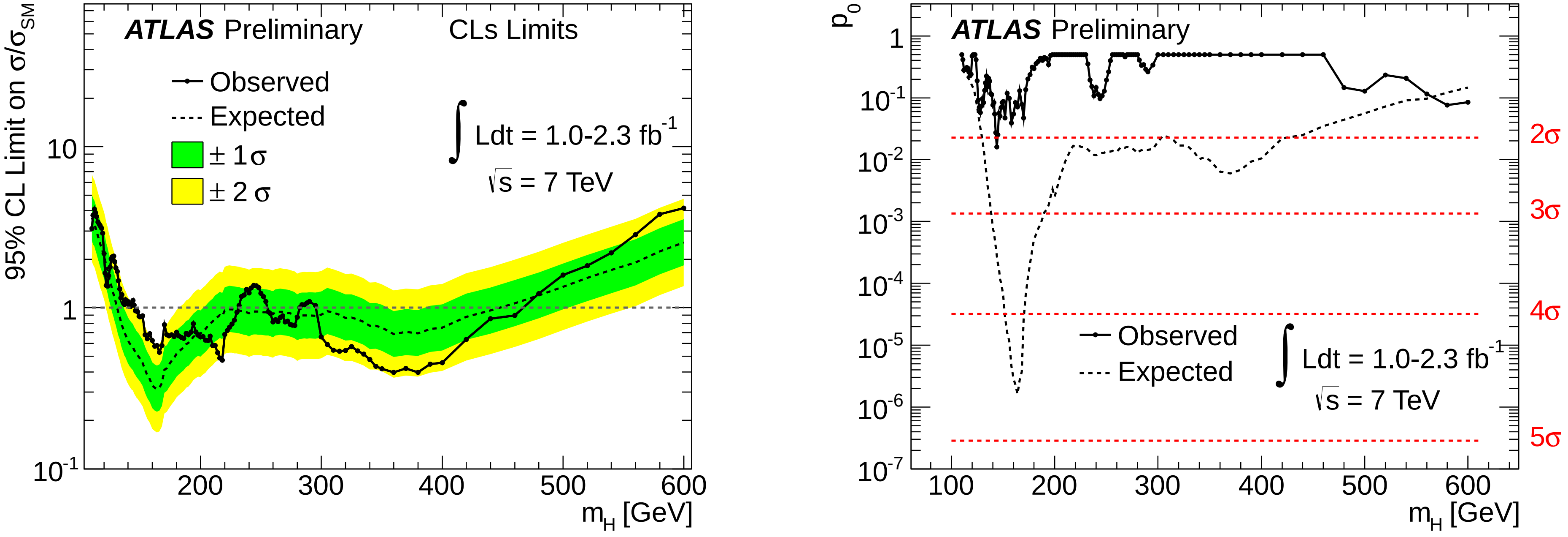
Combined upper limit normalised to the SM expectation

[*ATLAS Collaboration '11*]



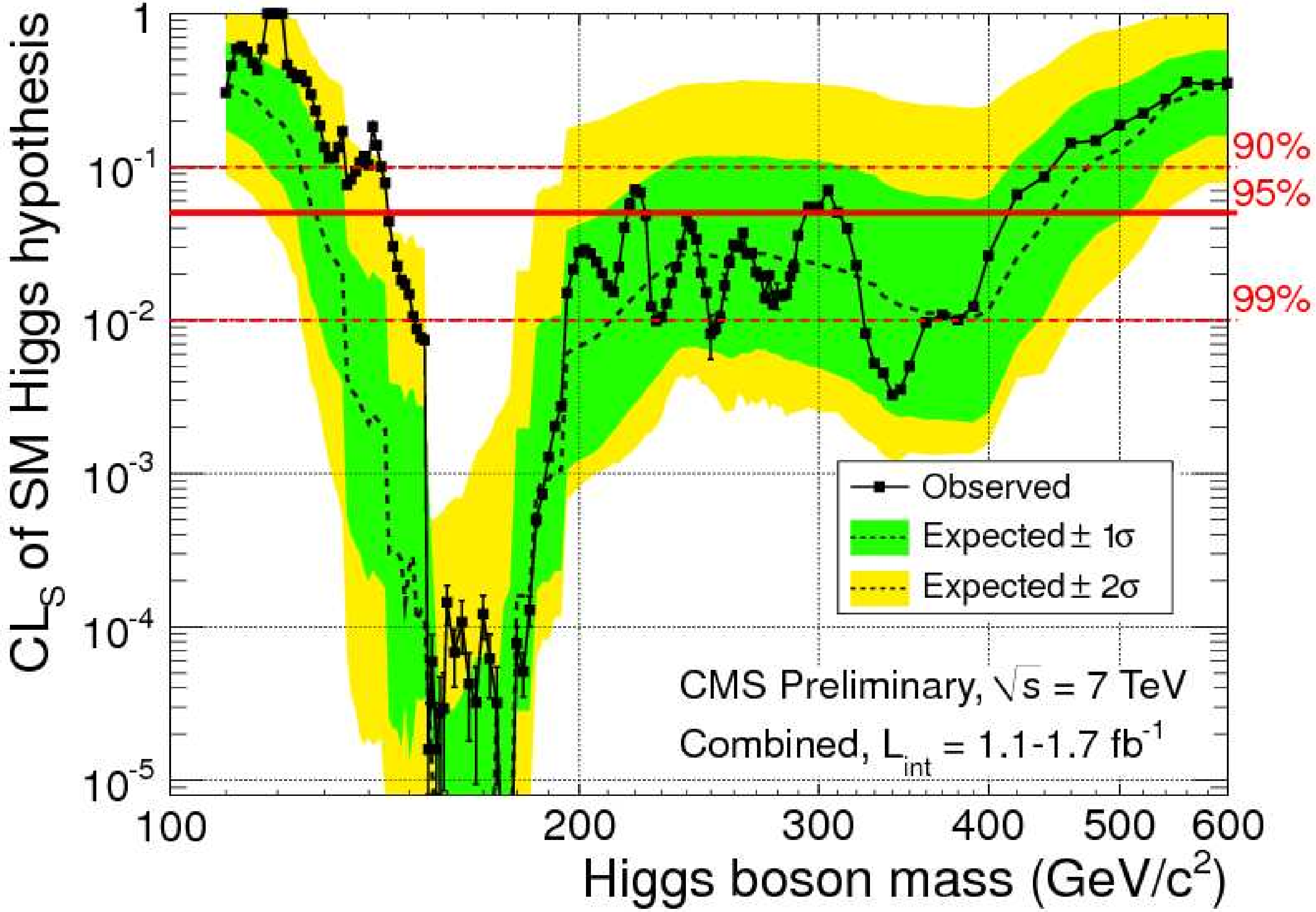
SM Higgs search: latest results from ATLAS

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



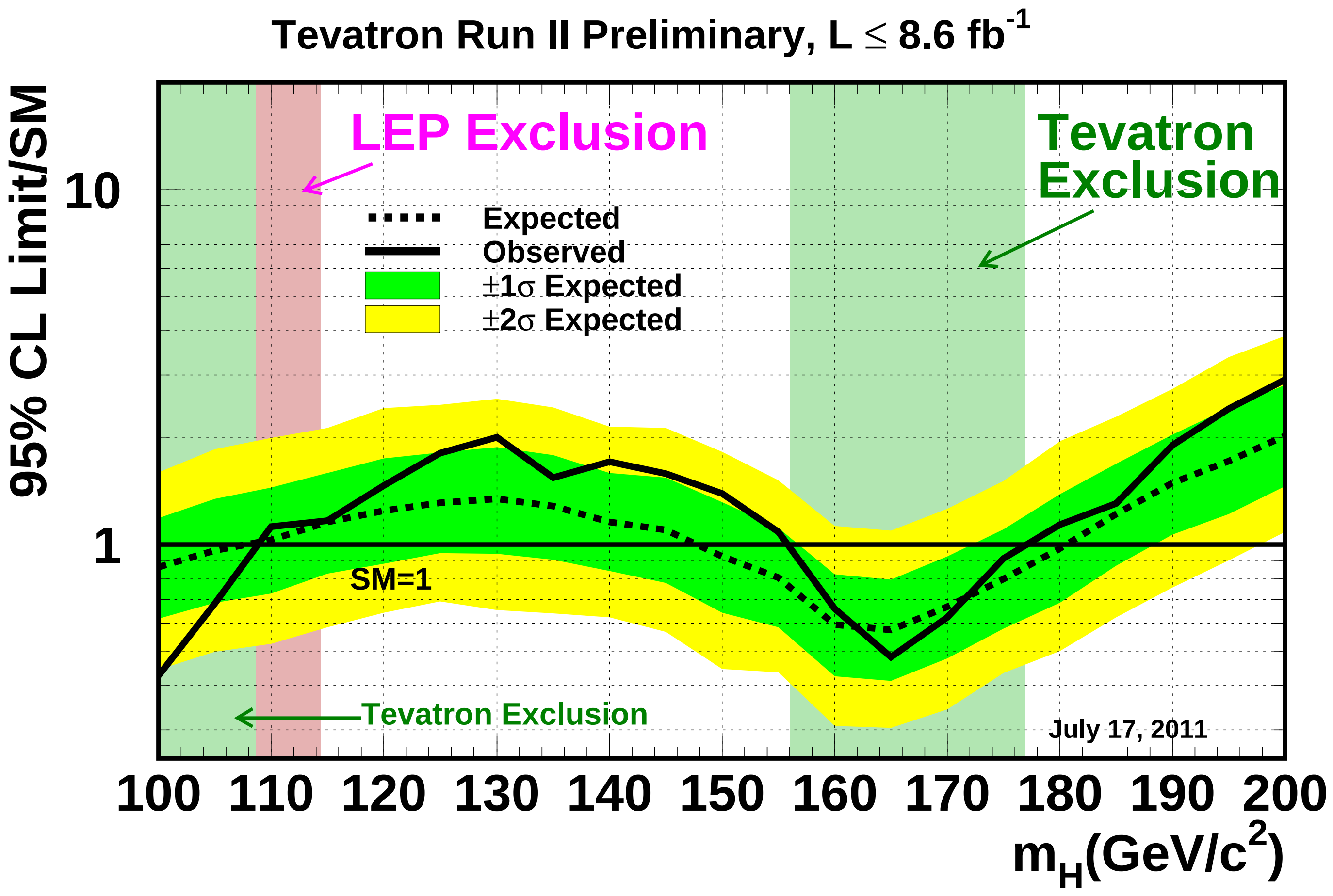
SM Higgs search: latest results from CMS

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



SM Higgs search: Tevatron results, CDF + D0

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



Status of SM Higgs searches

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

  $\Rightarrow$ Results from direct searches are in agreement with indirect constraints from electroweak precision data

- LEP exclusion: $M_{\mathrm{H}_{\mathrm{SM}}} > 114.4\ \mathrm{GeV}$, 95% C.L.

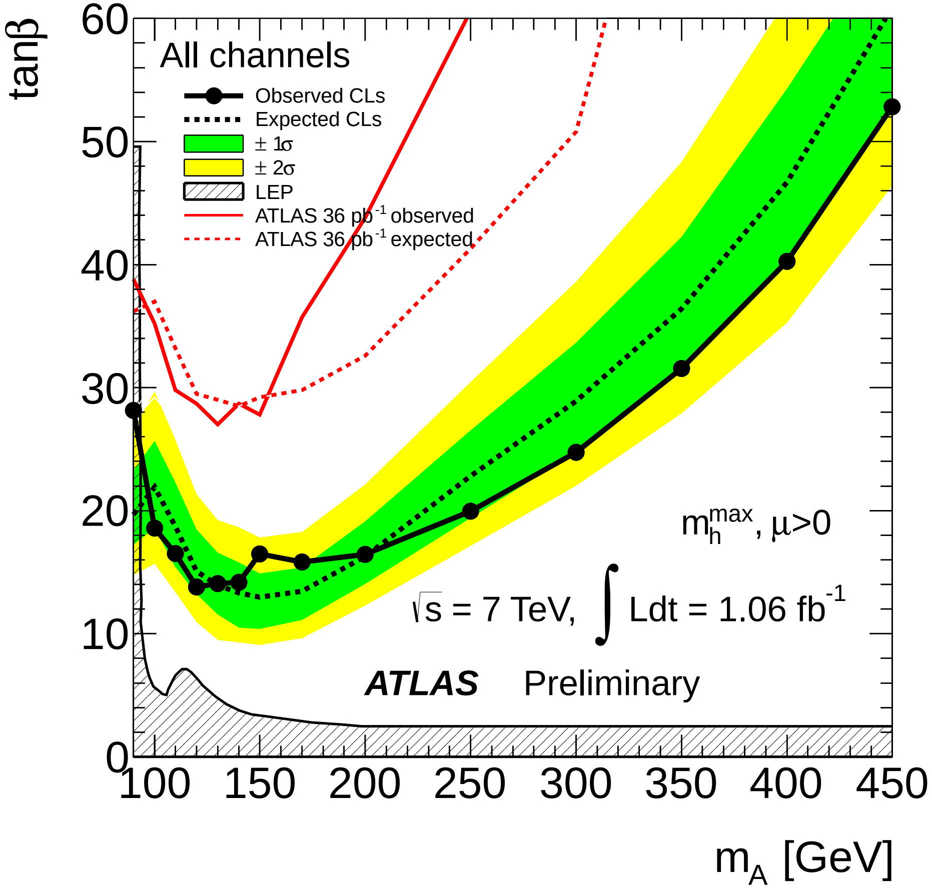
- Slight excess in the low-mass region, $M_{\mathrm{H}_{\mathrm{SM}}} \approx 130\ \mathrm{GeV}$, observed by ATLAS, CMS and in Tevatron combination

  Compatible with SUSY prediction

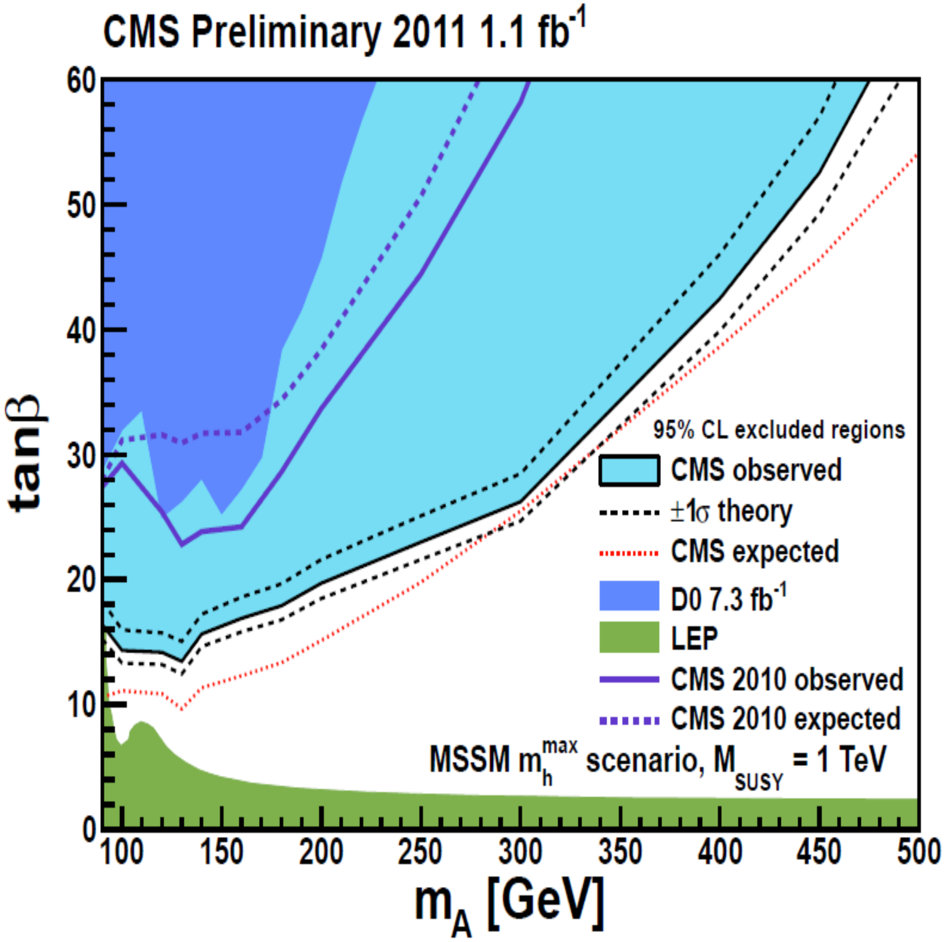
  $\Rightarrow$ More data needed to clarify the situation

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

[*ATLAS Collaboration '11*]



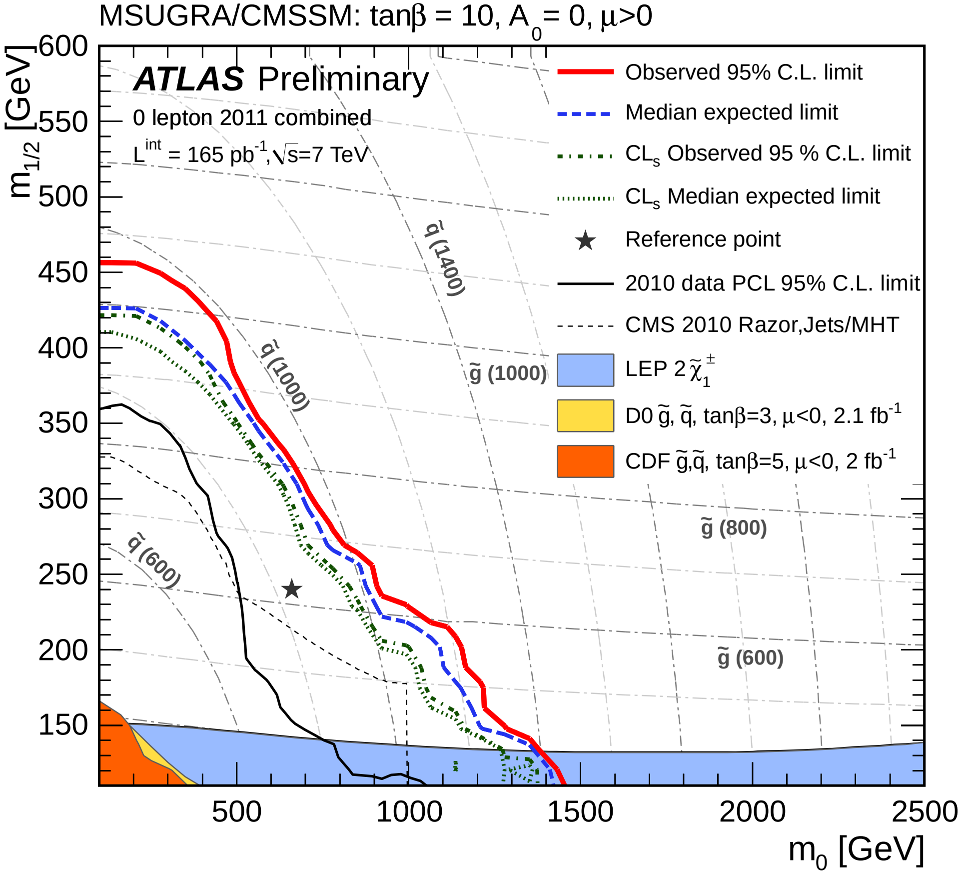
[*CMS Collaboration '11*]



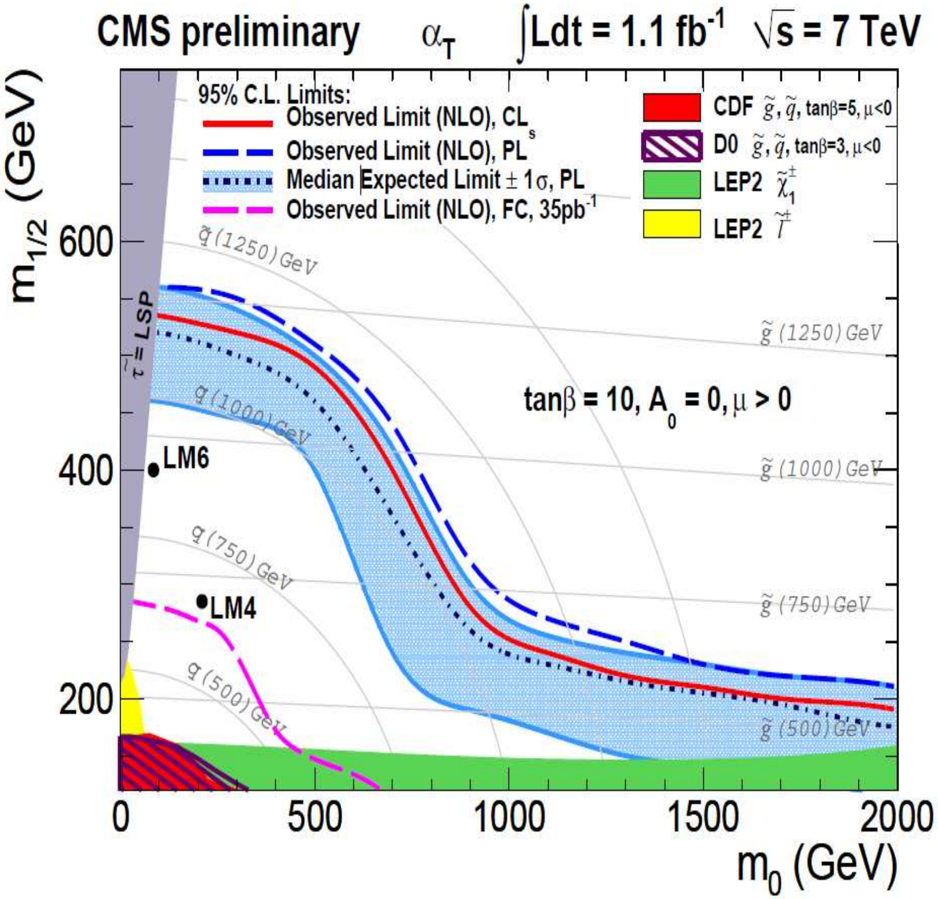
⇒ High sensitivity for large $\tan\beta$ and relatively low M_A

SUSY search results for the CMSSM

[ATLAS Collaboration ’11]



[CMS Collaboration ’11]



⇒ High sensitivity from search for jets + missing energy

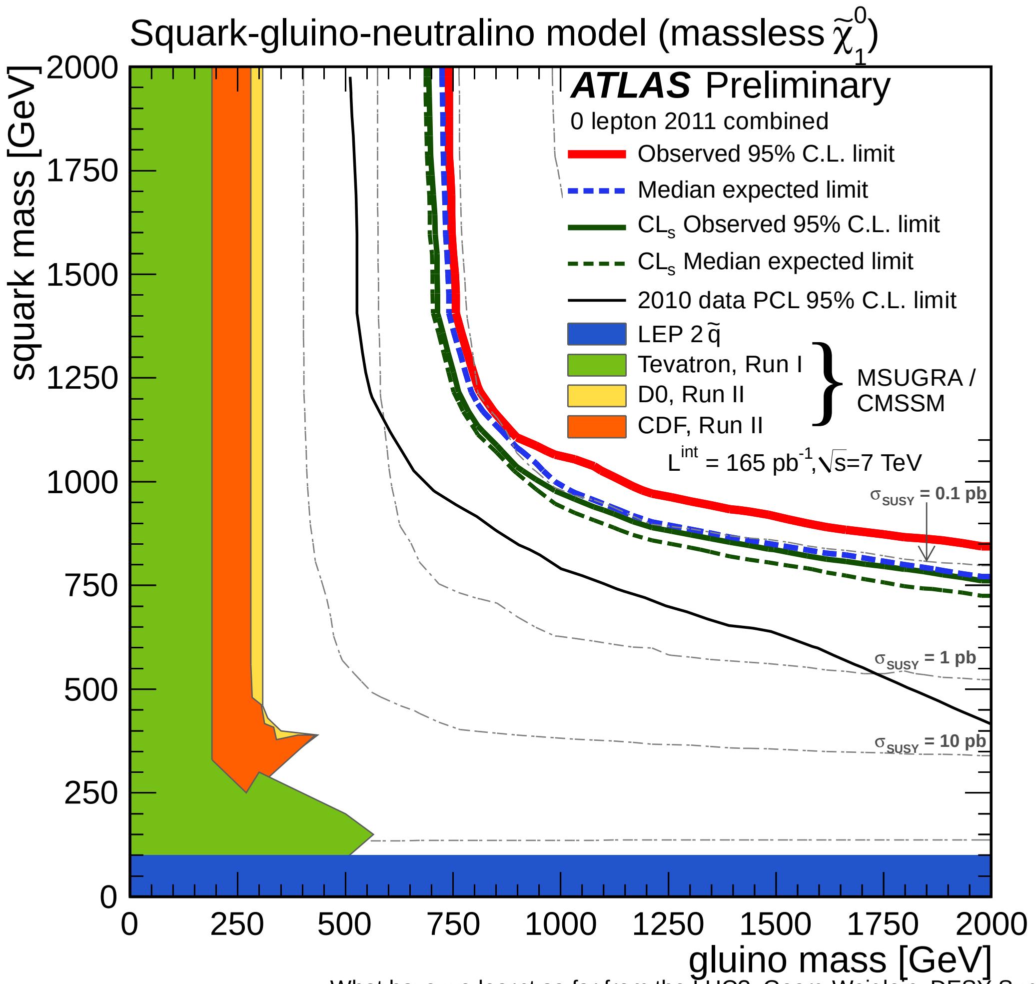
Previous best-fit point is excluded

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*]



Status of SUSY searches

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

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

  $\Rightarrow$ The constrained scenario CMSSM starts to get under some tension: direct search limits vs. $(g-2)_\mu$

- Limited sensitivity to 3rd generation squarks

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

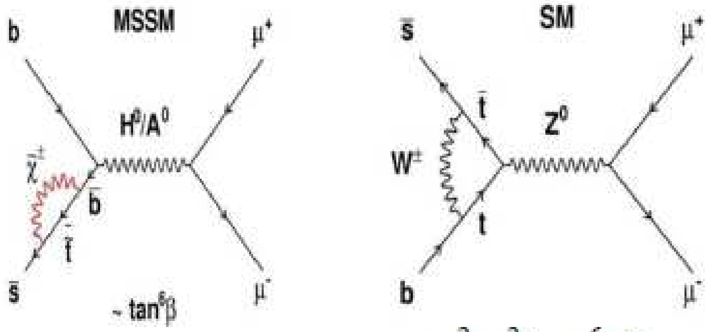
Search for the rare decay $B_s \to \mu^+\mu^-$

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) !

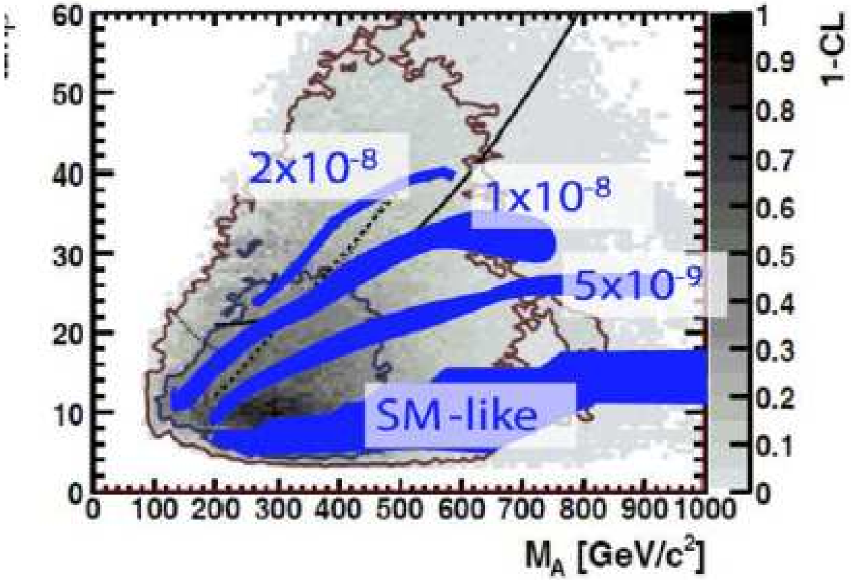


Very high sensitivity to NP, eg. MSSM:

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

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}): $< 5.6 \times 10^{-8}$

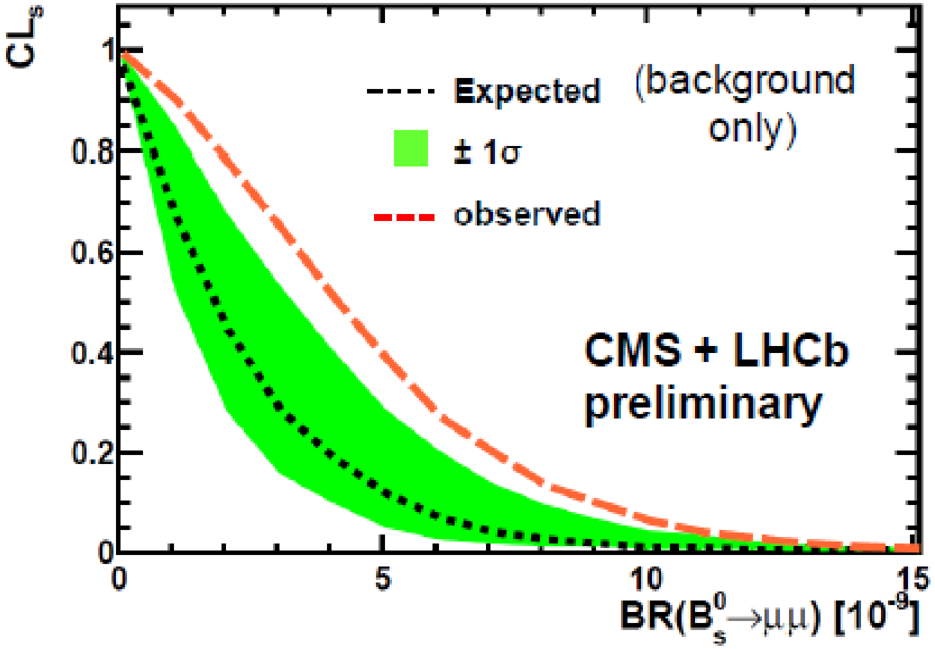
Recent exciting hint from CDF (7 fb^{-1}):

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

[arXiv:1107.2304]

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

A preliminary CMS-LHCb combination on $\mathrm{BR}(B_s \to \mu^+\mu^-)$ has been performed, again using the CLs approach, & taking LHCb value of f_s/f_d as common input



Observed limit at 95% (90%): 1.1 (0.9) x 10^{-8}

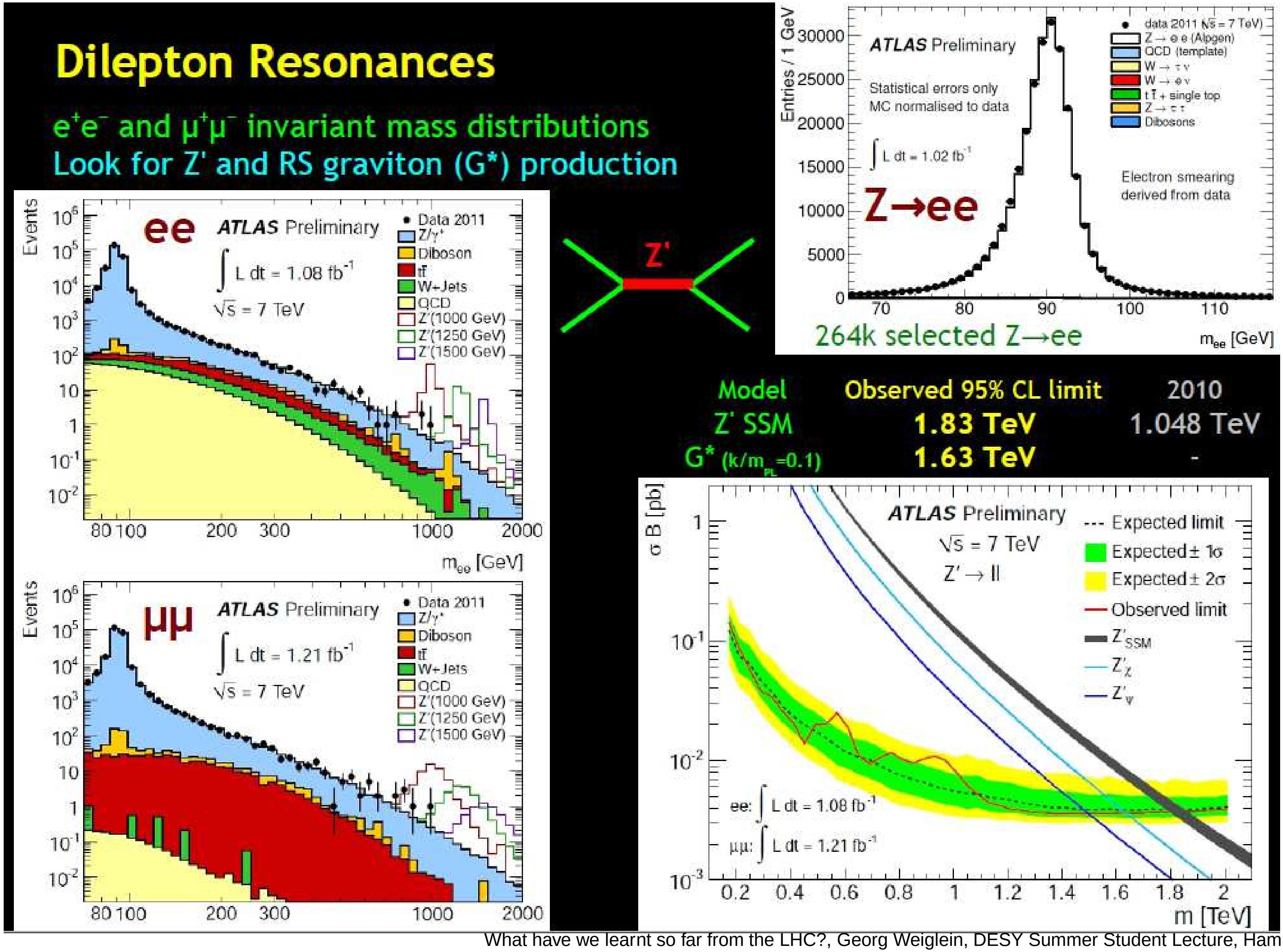
This is 3.4 times the expected SM value

A BR of 1.8 x 10^{-8} has a CLs value of ~0.3%

⇒ Compatible with SM prediction (so far)

Search for dilepton resonances: ATLAS

[*ATLAS Collaboration ’11*]



Dilepton Resonances

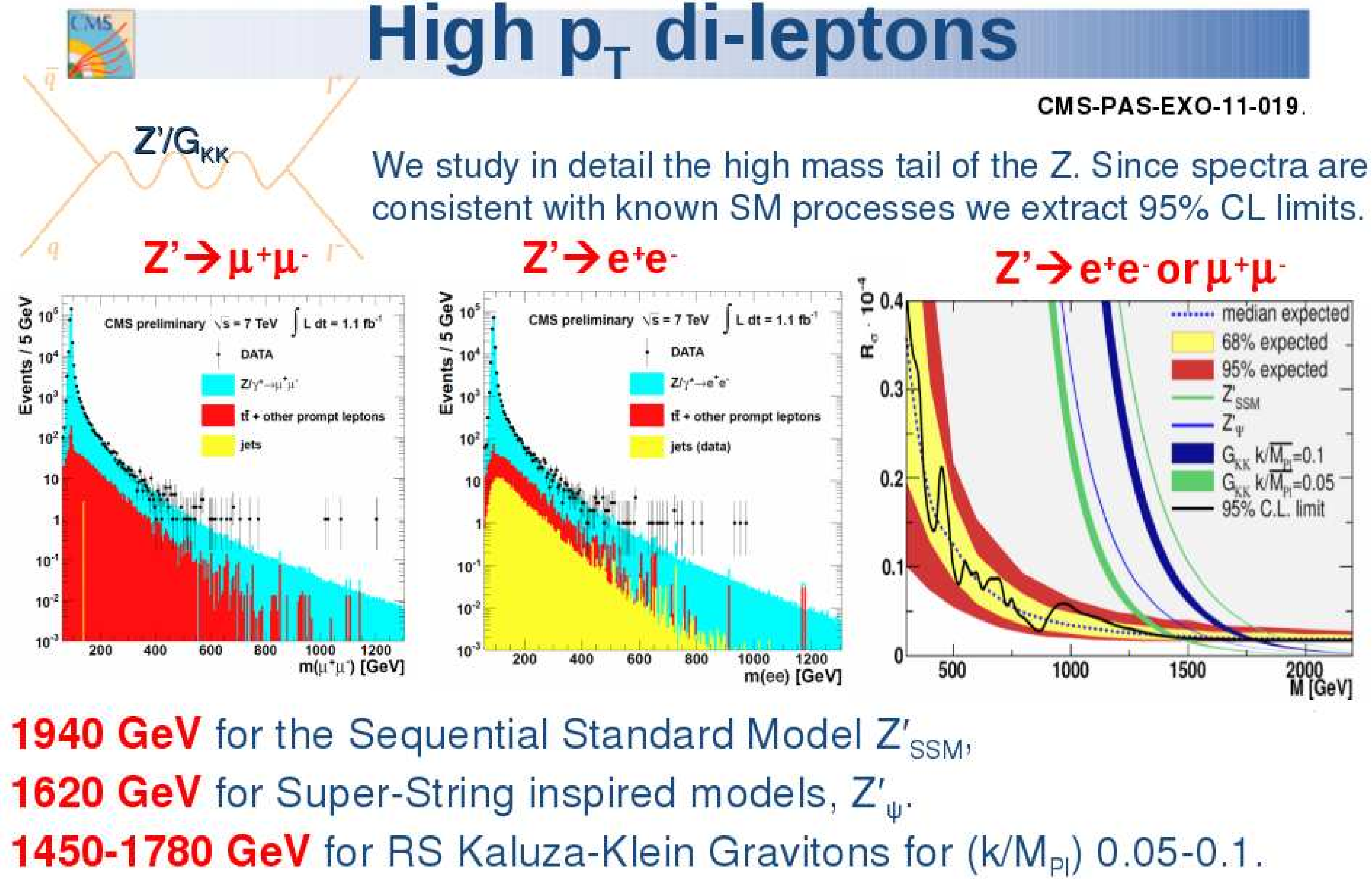
e^+e^- and $\mu^+\mu^-$ invariant mass distributions
Look for Z' and RS graviton (G*) production

Model	Observed 95% CL limit	2010
Z' SSM	1.83 TeV	1.048 TeV
G* ($k/m_{PL}=0.1$)	1.63 TeV	-

264k selected Z→ee

Search for dilepton resonances: CMS

[*CMS Collaboration '11*]



High p_T di-leptons

CMS-PAS-EXO-11-019.

We study in detail the high mass tail of the Z. Since spectra are consistent with known SM processes we extract 95% CL limits.

1940 GeV for the Sequential Standard Model Z'_{SSM},

1620 GeV for Super-String inspired models, Z'_ψ.

1450-1780 GeV for RS Kaluza-Klein Gravitons for (k/M_{Pl}) 0.05-0.1.

⇒ Limits up to 1.9 TeV

Conclusions

- LHC has started the exploration of the new territory of TeV-scale physics
- No discoveries yet
- Heavy SM Higgs is disfavoured, in agreement with constraints from electroweak precision physics
  Slight excess in the low-mass region
  ⇒ Closing in on the SM Higgs
- BSM searches: limits on coloured states of new physics, heavy resonances, . . .
  SUSY: limits on gluino and 1st and 2nd gen. squarks
  ⇒ Tension building up for CMSSM-like scenarios
  Little sensitivity so far to other parts of a possible SUSY spectrum (similarly for other kinds of new physics)

Stay tuned — the party has just begun!