

Particle Physics at Year Two of the Large Hadron Collider

Andreas Hoecker (CERN)

Colloquium, 17 October 2011, Berkeley, CA

Outline

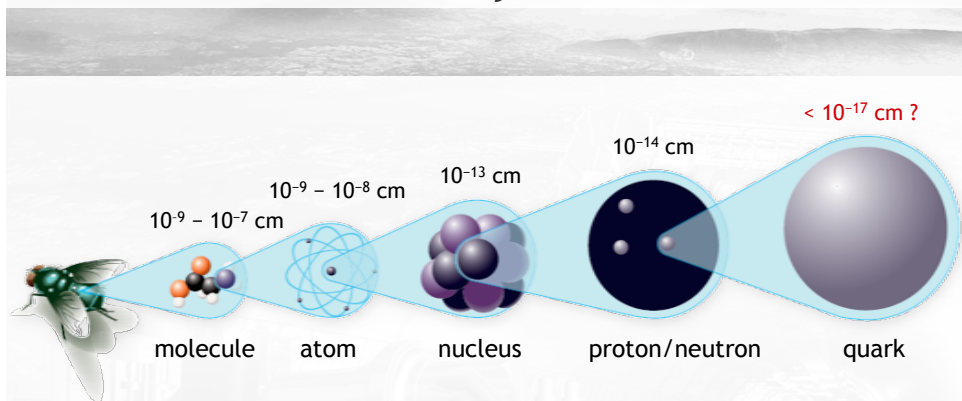
- Introduction of the Standard Model
- The Large Hadron Collider
- Physics measurements and searches
- Epilogue

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Particle Physics Scales



$$\text{Length scale (am)} \sim \frac{200 \text{ GeV am}}{\text{Energy (GeV)}}$$

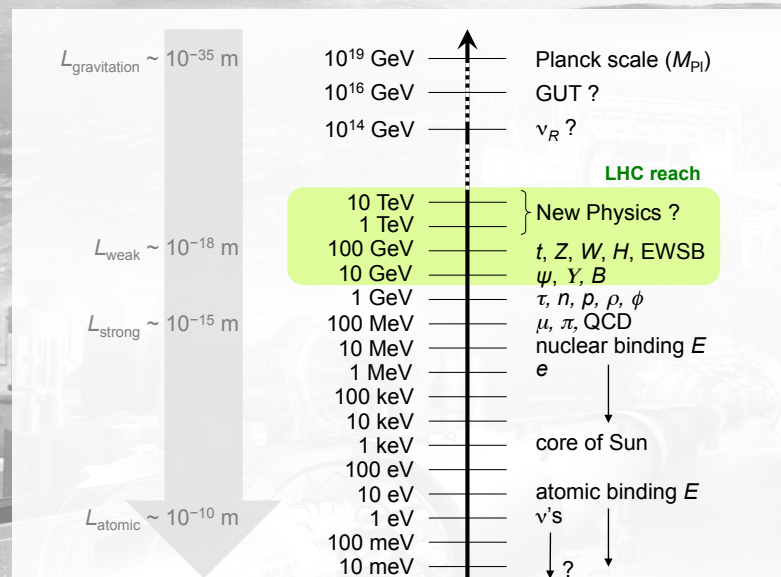
$a = \text{atto} = 10^{-18}$

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Particle Physics Scales



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The SM is the legacy of 20th century particle physics

It unifies quantum theory and special relativity

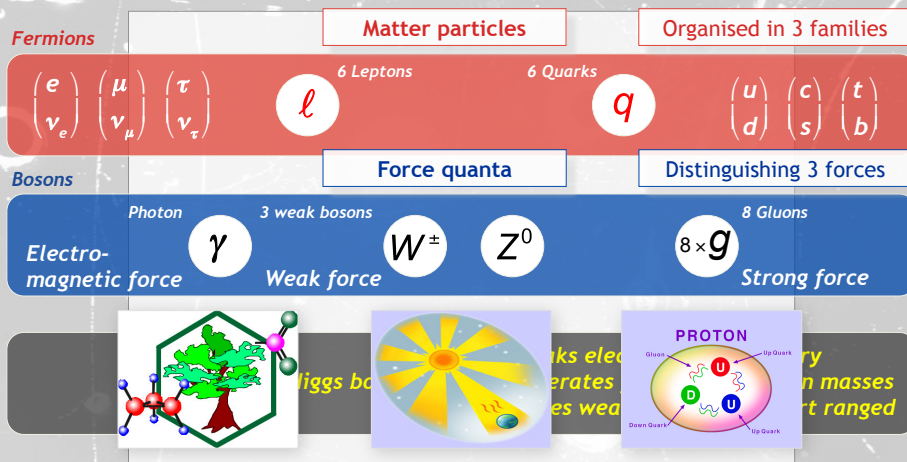
It describes ~ all laboratory data

But, the model has problems and even flaws,
and that's why we think it cannot be the final theory

Theorists have suggested many ways to improve the SM,
but we need the experiments to separate right from wrong

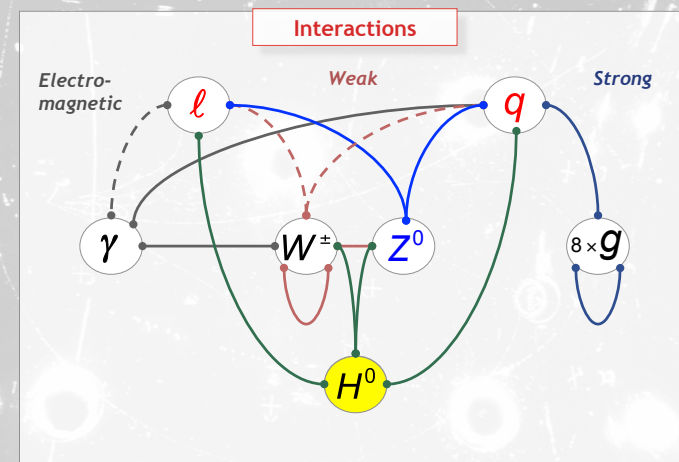
The Standard Model

The Standard Model consists of 24 elementary matter particles and 3 forces



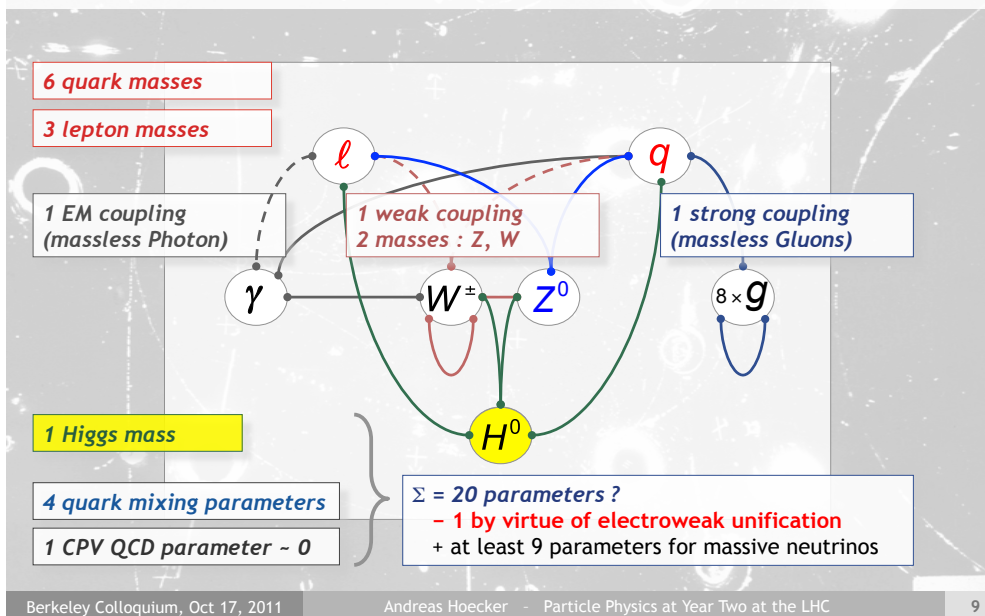
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The Standard Model

The SM describes all observed phenomena in particle physics by **19 parameters (?)**



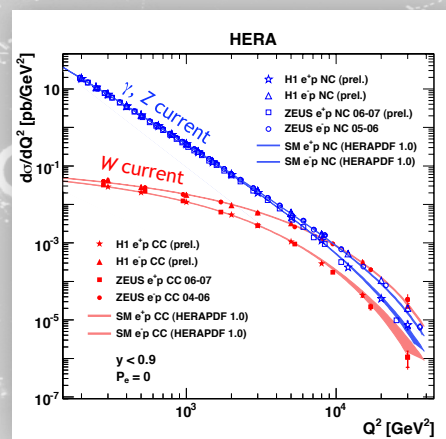
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The Standard Model

The SM describes all observed phenomena in particle physics by **19 parameters (?)**



- Above ~100 GeV, electromagnetic and weak interactions are unified
- Below 100 GeV, **weak interaction** is weaker than **electromagnetism**
- Electroweak interaction**

HERA data from electron-quark scattering into e⁺q (NC = γ, Z) or ν+q (CC = W[±])

Σ = 20 parameters ?
- 1 by virtue of electroweak unification
+ at least 9 parameters for massive neutrinos

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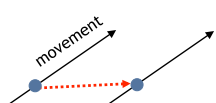
The Standard Model

Elementary particle physics is successfully described by **local gauge theories**

Gauge symmetry is the invariance of equations of motion with respect to a local transformation belonging to a symmetry group

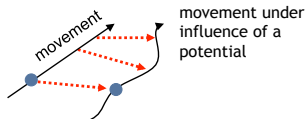
Example: translation group – uniform movement of particle

Global symmetry:



$$\vec{x} \mapsto \vec{x} + \vec{a}$$

Local symmetry:



$$\vec{x} \mapsto \vec{x} + \vec{a}(\vec{x}, t)$$

A new trajectory is possible, if **forces** act on the particle: a potential that restores the symmetry of the dynamic under this particular gauge transformation

The dynamic found is not just any dynamic, but one of the 4 forces of nature: **gravitation**

Requiring the same local gauge invariance for a wave function gives us: **QED**

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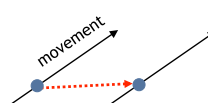
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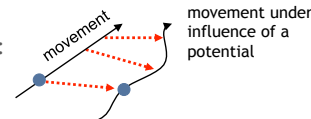
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We can do so for **all fundamental forces** of the Standard Model, which have thus a

Geometric origin !

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The Standard Model

Brout-Englert-Higgs mechanism

A problem: local gauge symmetry requires **massless spin-1 “gauge” (=force) boson**

This has been well verified for QED, with a massless photon (= infinite range)

However, the **W, Z bosons are massive** (= finite range $\sim 10^{-15}$ cm)

Only way to break gauge symmetry consistently is to **spontaneously break the symmetry of the vacuum**:

$$M_{Z,W} \neq 0 \Leftrightarrow \langle 0 | \phi | 0 \rangle = v \neq 0 \quad [\text{non-zero vacuum expectation value}]$$

ϕ is a complex doublet field: 3 d.o.fs become Z, $W^\pm$ masses, remaining d.o.f is **massive scalar Higgs boson**

This is called the **Brout-Englert-Higgs Mechanism**

The Standard Model

Brout-Englert-Higgs mechanism

Let's imagine all particles have zero mass $\rightarrow$ gauge symmetry is respected

A **Higgs field** displaces ground state breaking gauge symmetry

It fills all space time (but w/o orientation as spin=0)

The particles interact with the Higgs field thus reducing their velocity, **which is equivalent to acquiring a mass**

$\rightarrow$ Action of the Higgs field creates a **vacuum viscosity**

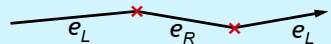
Higgs quantum liquid in broken phase

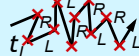
Gravity 

EM boson 

Weak boson 

Neutrinos 

Electrons 

Top quark 

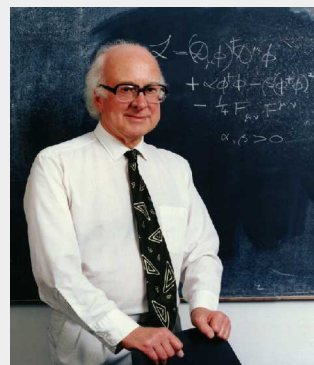
H. Murayama

The Higgs boson is the last elusive elementary particle of the SM

The Higgs boson -
last of the particles ?

What is known about the Higgs Boson ?

P.W. Higgs, Phys. Lett. 12 (1964) 132



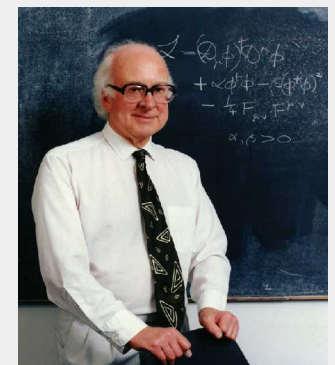
The Higgs boson is the last elusive elementary particle of the SM

Daniel Froidevaux (CERN):

The Higgs has been with us for >4 decades as

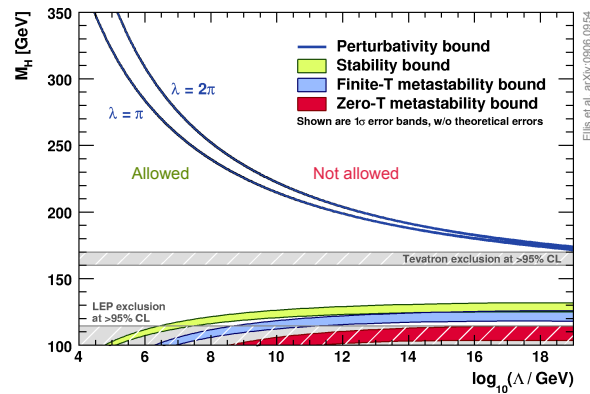
- a theoretical concept
- an incarnation of the “Communist Party since it controls the *Masses*”
[L. Alvarez-Gaumé at CERN summer school in Alushta]
- a painful part of the first chapter in our PhD thesis ...

P.W. Higgs, Phys. Lett. 12 (1964) 132



The Higgs boson should not be too light, and not too heavy...

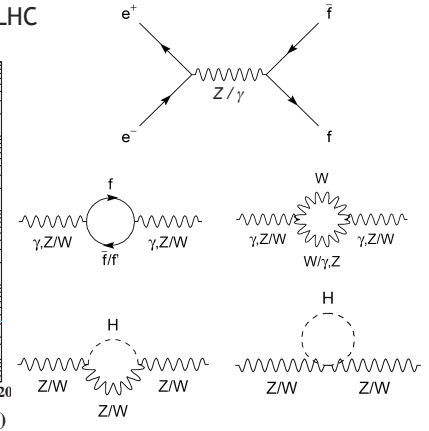
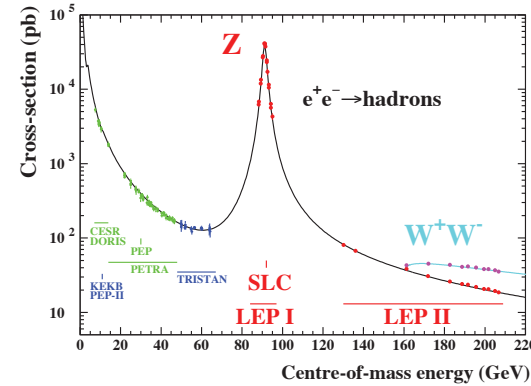
Perturbativity and (meta)stability bounds versus the SM cut-off scale Λ



The SM Higgs must steer a narrow course between two disastrous situations if the SM is to survive up to the Planck scale $M_P \sim 2 \times 10^{18}$ GeV

Constraints on Higgs mass from electroweak precision data

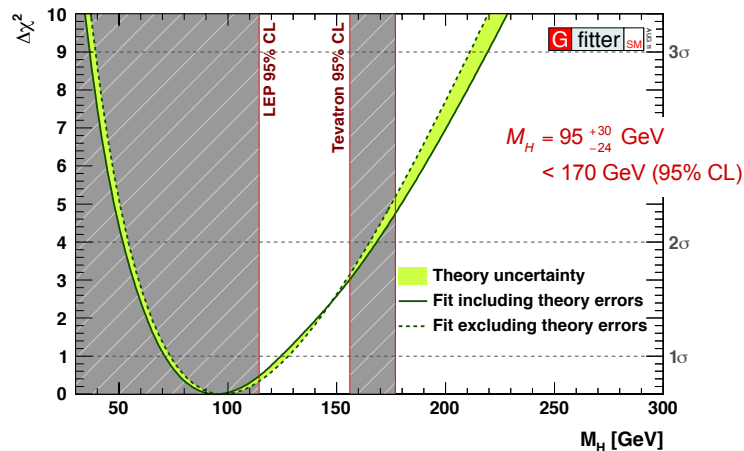
Precision results also from Tevatron and soon LHC



Precisely measured couplings around the Z peak (M_W also at Tevatron) via Z decay widths and asymmetry observables sensitive to parity violation $\rightarrow$ fit constrains $\log(M_H)$ and m_t ²

Constraints on Higgs mass from electroweak precision data

Global fit of all EW precision measurements to SM prediction constrains M_H

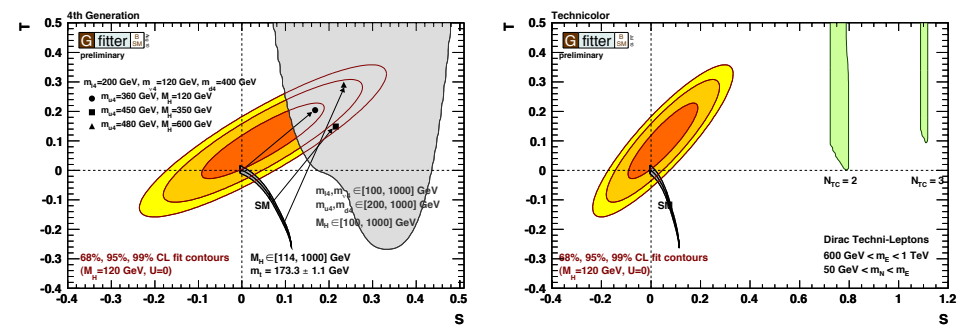


Constraints on Higgs mass from electroweak precision data

We can also use the precision data to look beyond the SM !

For example: Can we add a 4th generation?

Or: can the vacuum be broken by a new interaction?



Constraints on Higgs mass from electroweak precision data

In the Standard Model the Higgs must be light.

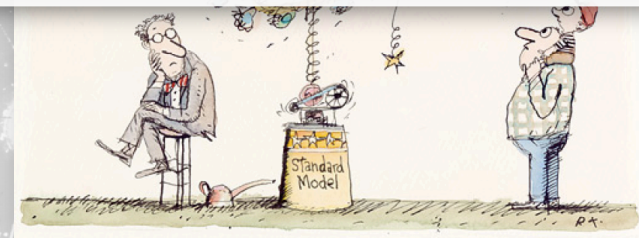
BUT: Beyond the Standard Model the Higgs can be heavy !

→ **MUST NOT stop searching for heavy Higgs boson !**

[Weak isospin violating new physics contributions may cancel heavy Higgs effects on electroweak precision data !]

Once the Higgs boson is discovered
The Standard Model is complete

But ... does it hold tight ?



The Standard Model

During the last 35 years the Standard Model has been tested to great precision

- **Excited fundamental bosons or fermions** have been excluded up to the TeV scale
- **Electroweak unification** has been verified at, below and above the Z-boson scale
- **Universality of weak interaction** has been verified at the per-mil level
- **Conservation of the charged lepton number** verified at 10^{-12} level
- **Asymptotic freedom of strong interaction** has been verified at the percent level
- All observations of **matter-antimatter symmetry violations** are described by single complex parameter in the quark mixing matrix
- The **tininess of electric dipole moments** has been verified at 10^{-27} ecm
- The **electron and muon magnetic moments** have been verified at ppm level...
- *Examples only, there are many more successful tests ...*

The Standard Model

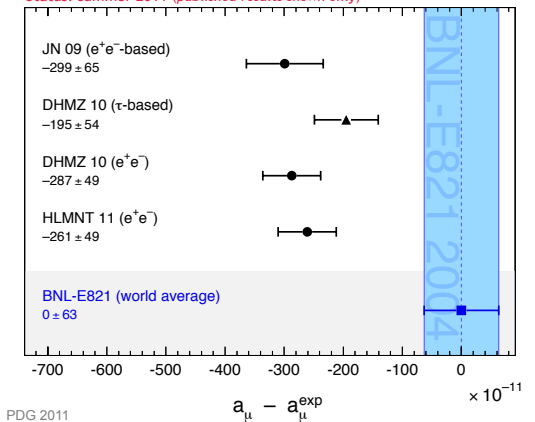
During the last 35 years the Standard Model has been tested to great precision

Not **everything** perfectly agrees with expectation:

- Top pairs produced in hadron collisions may have large angular asymmetry
- Di-muon events at Tevatron may exhibit unexpected charge asymmetry
- The muon anomalous magnetic moment may be stronger than expected

Muon magnetic moment: comparison between measurement (blue band) and predictions (dots)

Status: summer 2011 (published results shown only)



PDG 2011

Problems and Unexplained Observations

The success of the SM should not make us forget that it is an incomplete theory

- The Higgs is not yet discovered !
- The Higgs is the only fundamental scalar
- Huge mass hierarchy between matter particles
- Dark matter (particle) and accelerated expansion of universe
- Causally connected observable universe
- Matter-antimatter asymmetry in universe
- Grand unification of the forces (related to baryon decay)
- Gauge hierarchy (see later)
- Why no matter-antimatter symmetry violation in strong interaction?
- Neutrino masses
- Gravitation

Neutrino masses and inclusion of gravity in the SM require new physics at the scales $\sim 10^{14}$ GeV and $\sim 10^{19}$ GeV, respectively !

Producing the Higgs Boson and Searching for New Physics at the TeV Scale Requires a Huge Machine

Particles accelerators:

accelerate particles to the highest energies to

- Look deeper into matter (size $\sim 1/E$) ("powerful microscopes")
- Discover new heavier particles ($E = mc^2$)
- Probe conditions of the early universe ($E = kT$)

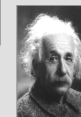
F. Gianotti



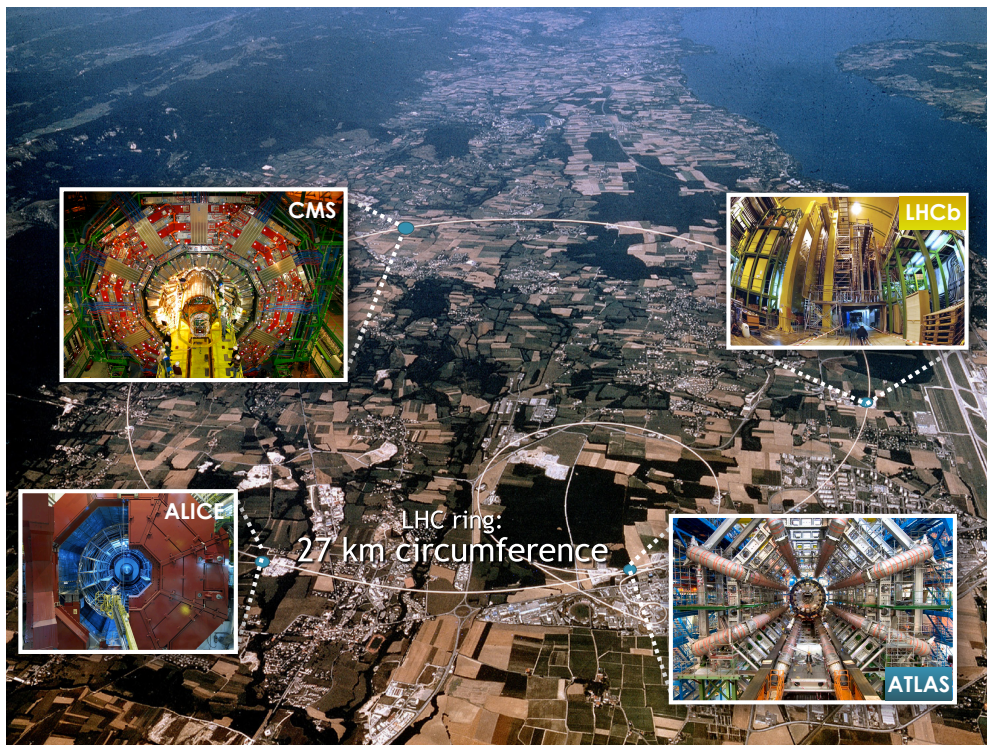
de Broglie



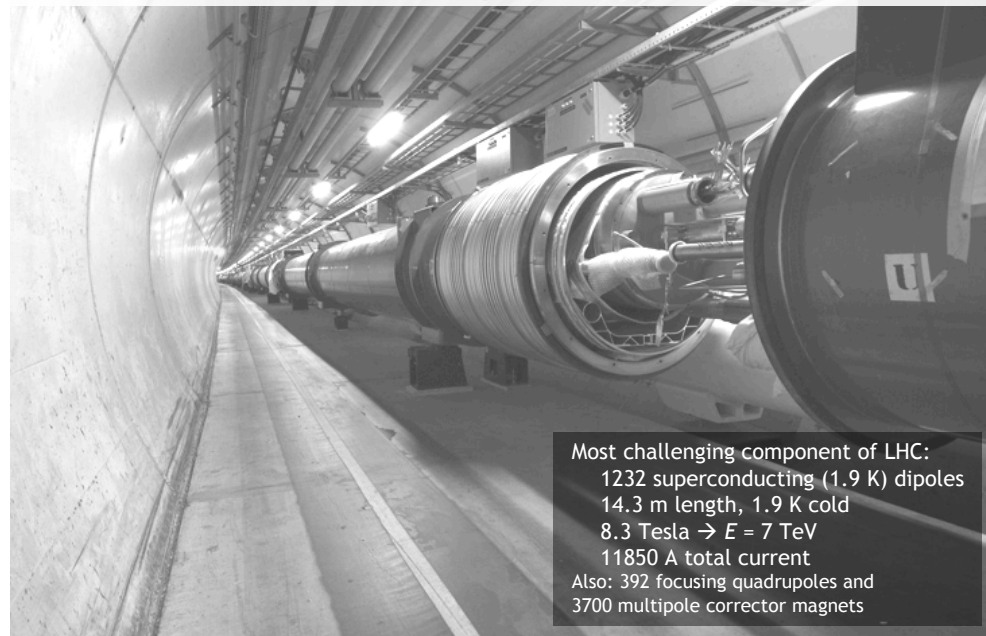
Einstein



Boltzmann



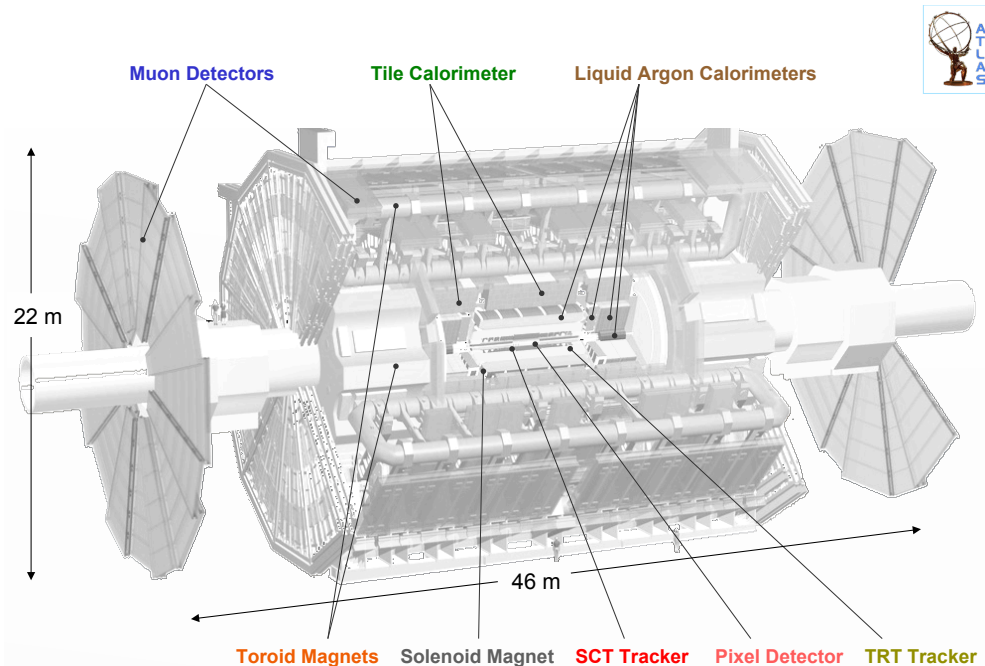
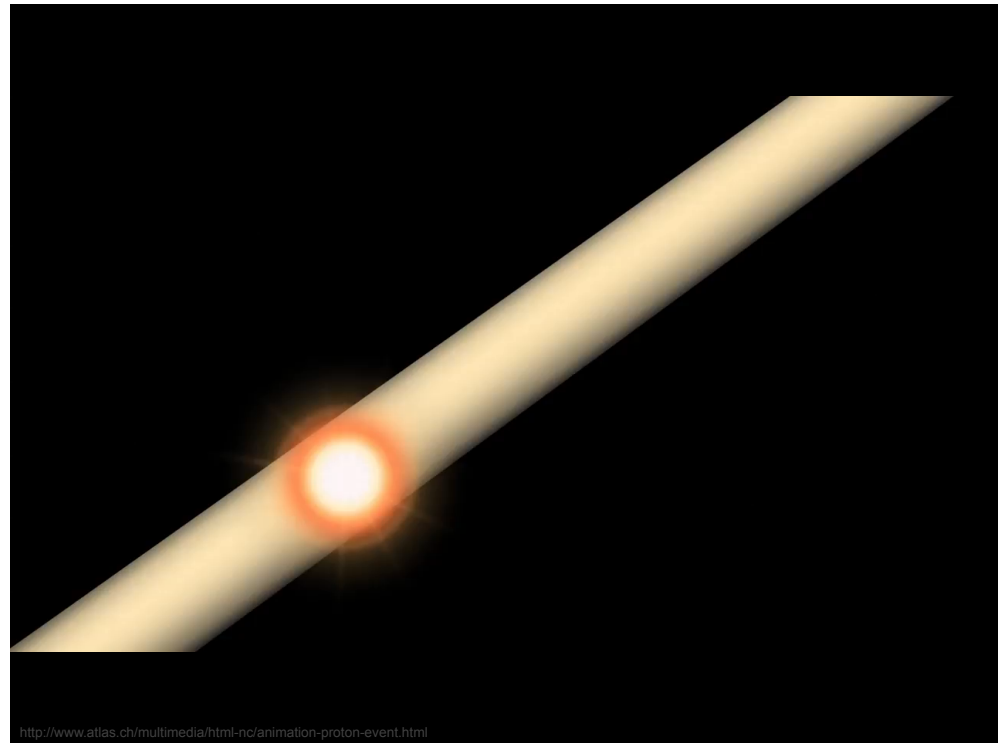
The LHC Dipole Sections



The LHC Dipole Sections

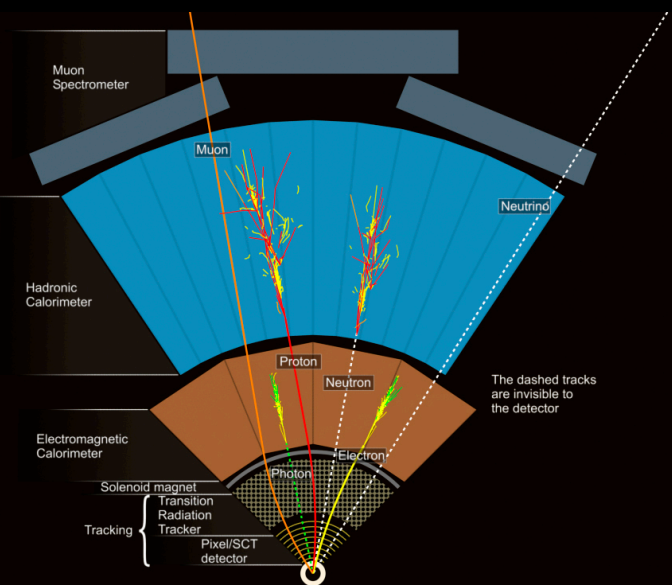


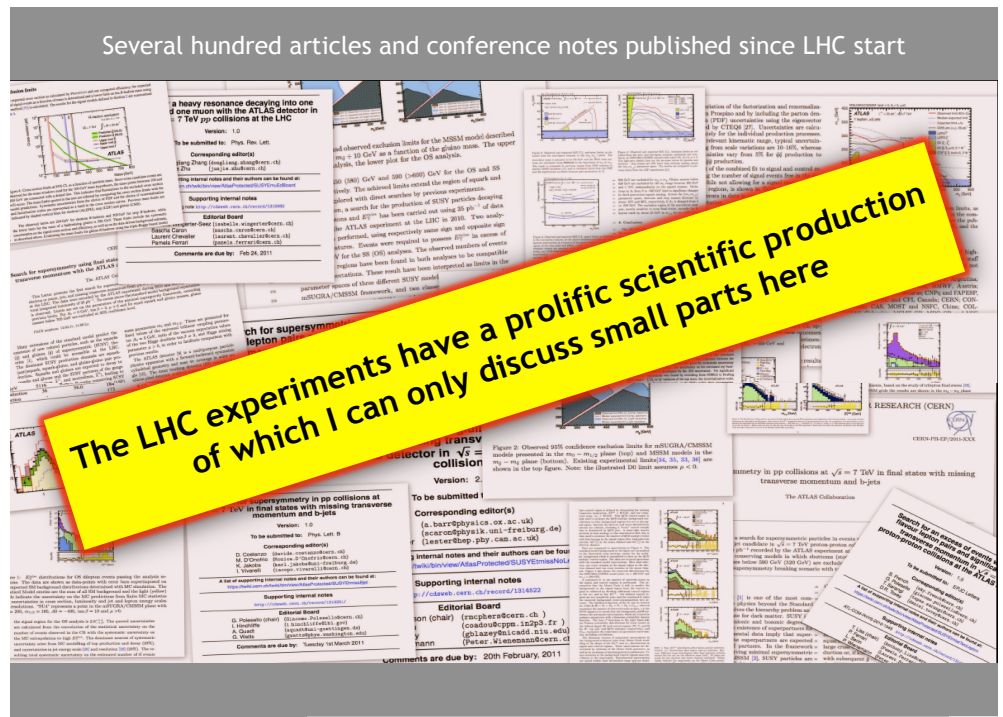
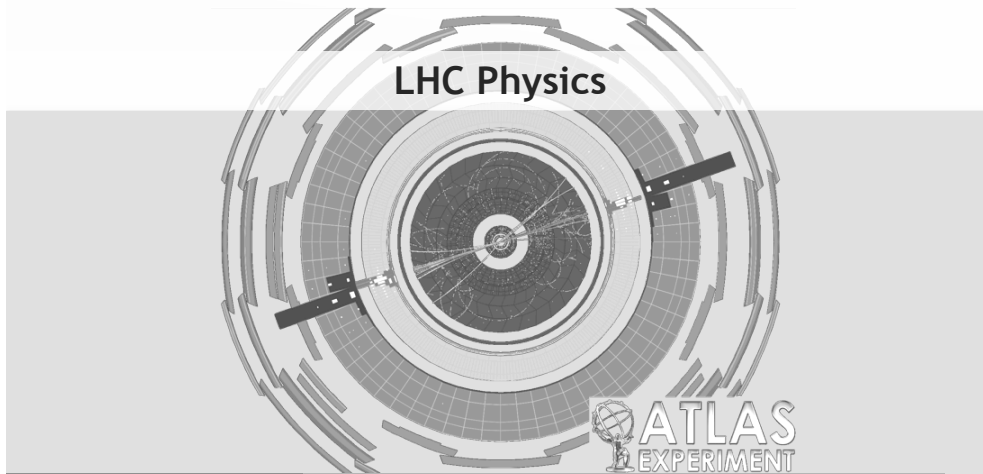
As a consequence of an accident on September 2008, the dipole currents cannot presently be raised to full power. The LHC is thus constrained to run at 7 TeV CM energy in 2010 and 2011, possibly being raised to 8 TeV in 2012. After a repair in 2013/14 14 TeV CM energy will be targeted.



Detector Layers

Particles are detected through their interaction with the active detector materials

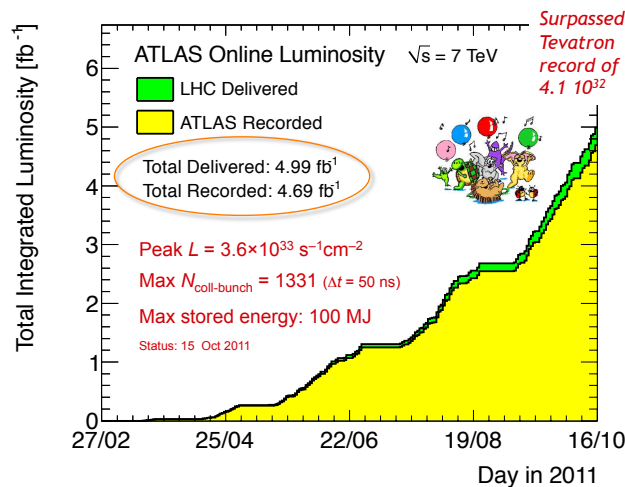




Recorded Luminosity in 2011

Luminosity is key quantity: $\text{rate} = \text{cross section} \times \text{efficiency} \times \text{luminosity}$

ATLAS integrated luminosity in 2011
(in 2010: 0.04 fb^{-1} collected)

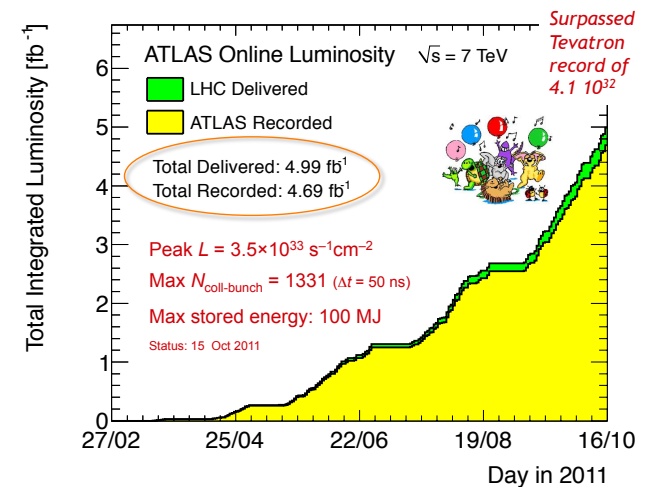


Recorded Luminosity in 2011

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**At $L = 3 \times 10^{33} \text{ s}^{-1}\text{cm}^{-2}$,
produce 225 (129) Higgs
bosons of 115 (150) GeV
mass in ATLAS and CMS
per hour**

Tevatron @ 115 GeV: 2/h at max luminosity



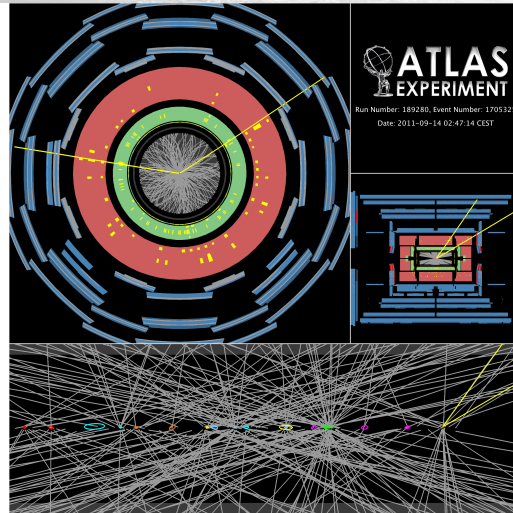
Recorded Luminosity in 2011

Measured with forward detectors, calibrated with beam separation scans

High luminosity comes at a price: probability of parasitic collisions in one bunch crossing (= *pileup*) increases

Peak of up to 22 collisions per crossing reached

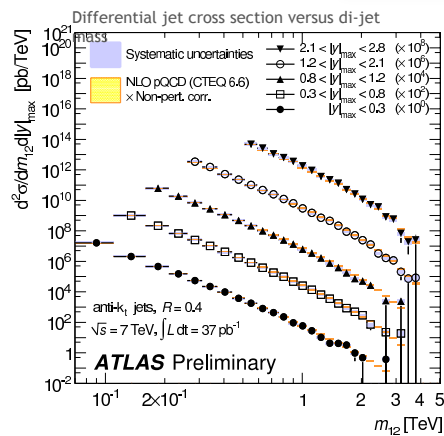
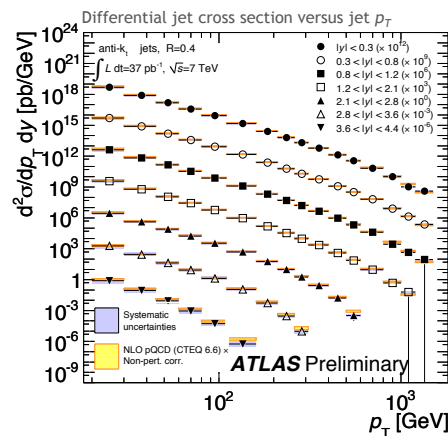
Another price to pay: higher trigger thresholds $\rightarrow$ low- p_T physics suffers



$Z \rightarrow \mu\mu$ event in ATLAS with 20 reconstructed vertices

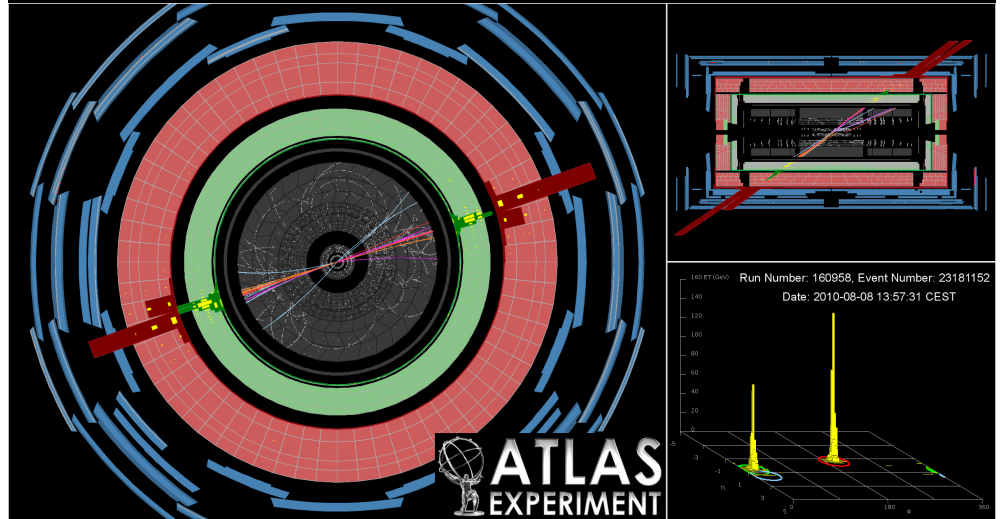
ATLAS and CMS have Measured Inclusive and Exclusive Jet Cross Sections at never Explored Energies

ATLAS-CONF-2011-047



Agreement over many orders of magnitude gives confidence for new physics searches

A beautiful dijet event from ATLAS: $m(\text{jet-jet}) = 1.9$ TeV, $p_T : 0.9$ TeV, 0.8 TeV



High-energy jets probe new particles and interactions

Measure di-jet invariant mass and angular distributions

$2 \rightarrow 2$ parton scattering to two jets described by QCD

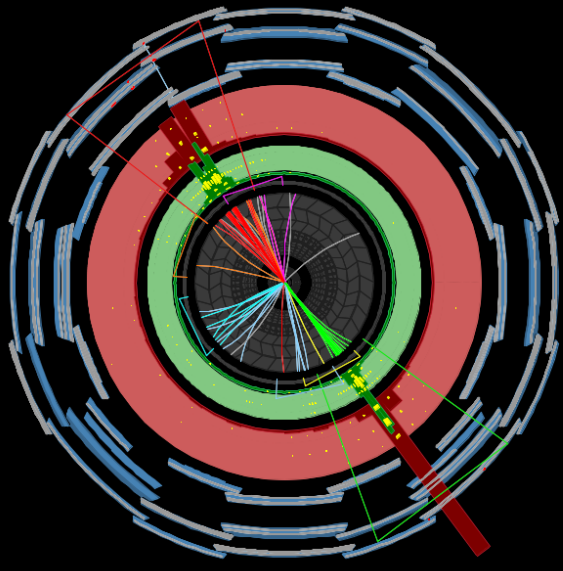
Tends to scatter at smaller angles than if there were new particles produced

Recall atomic substructure discovery in Rutherford scattering: deflection at large angles !



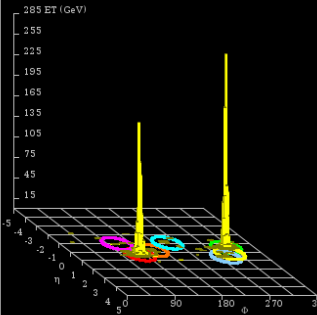
New, high-scale interaction ?
New bound state (particle) ?
Are quarks composites ?

Event with 4.04 TeV dijet invariant mass



**ATLAS
EXPERIMENT**

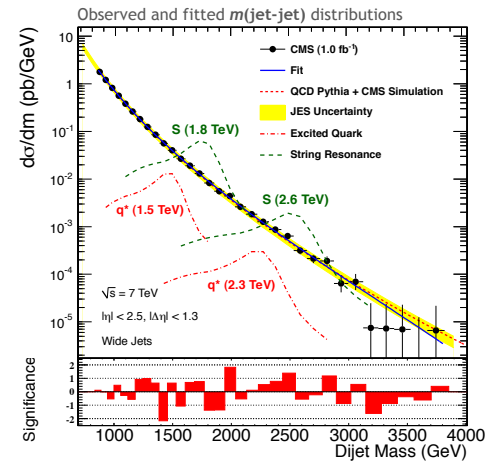
Run Number: 179938, Event Number: 1205448C
Date: 2011-04-18 17:57:29 EDT



High-energy jets probe new particles and interactions

Measure di-jet invariant mass and angular distributions

CMS arXiv: 1107.4771



No deviations from SM seen

→ set limits on new phenomena

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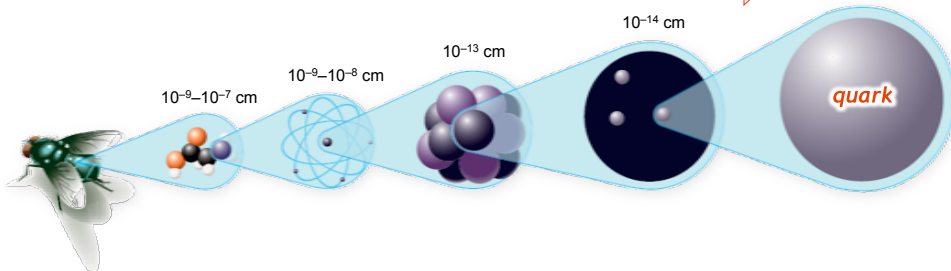
High-energy jets probe new particles and interactions

Measure di-jet invariant mass and angular distributions

ATLAS arXiv:1108.6311, arXiv:1103.3864

	Benchmark model	Observed limit at 95% CL
Resonant	Excited quarks	$m(q^*) > 3.0 \text{ TeV}$
Non-resonant	4-quark contact interactions	$\Lambda > 6.7 \text{ TeV}$

$< 2.1 \times 10^{-18} \text{ cm}$



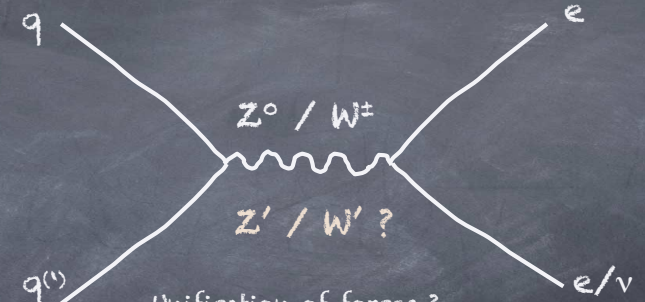
Leptons are pure SM and new physics probes with much reduced strong-interactions background

Z and W bosons have mass of O(100) GeV

Created from quark initial states and decay to charged leptons and (undetected) neutrinos

Z and W are heaviest known resonances producing lepton pairs.

Many theories predict new heavy Z / W bosons with similar properties



Unification of forces ?
Left-right symmetric models ?
Compact extra dimensions ?
Technicolour ?
Higgs extensions ?

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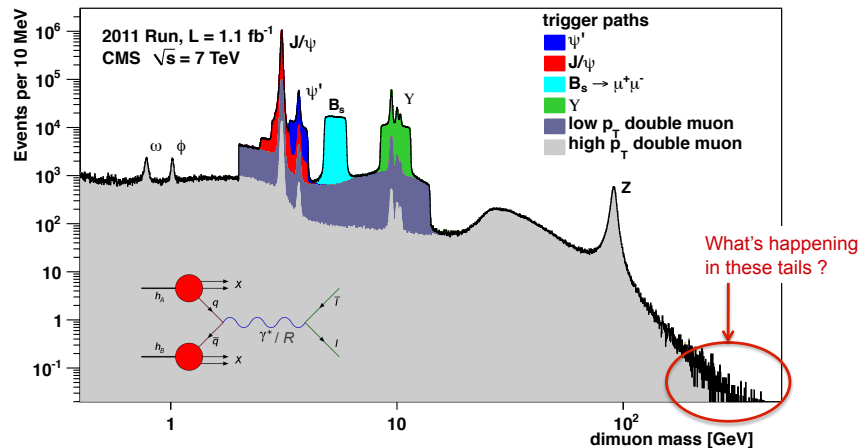
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Leptons are pure SM and new physics probes with much reduced strong-interactions background



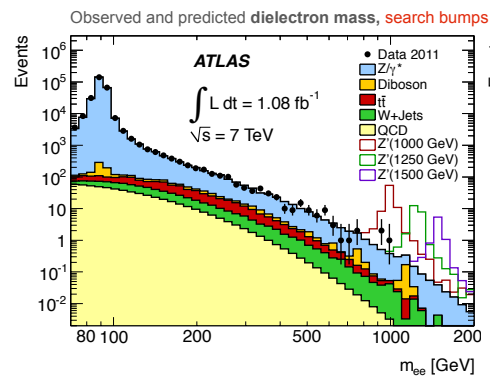
Search new physics in high-mass tails of di-lepton and lepton-neutrino mass

Searches for Z' and W' resonances in decays to e/μ

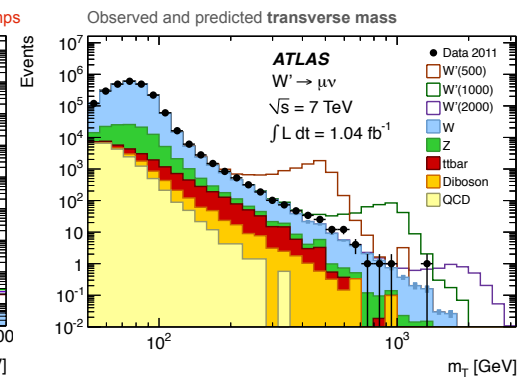
Use transverse / dilepton mass to search for excess over SM

ATLAS arXiv:1108.1582, CMS PAS-EXO-11-019

ATLAS arXiv:1108.1316, CMS PAS-EXO-11-024

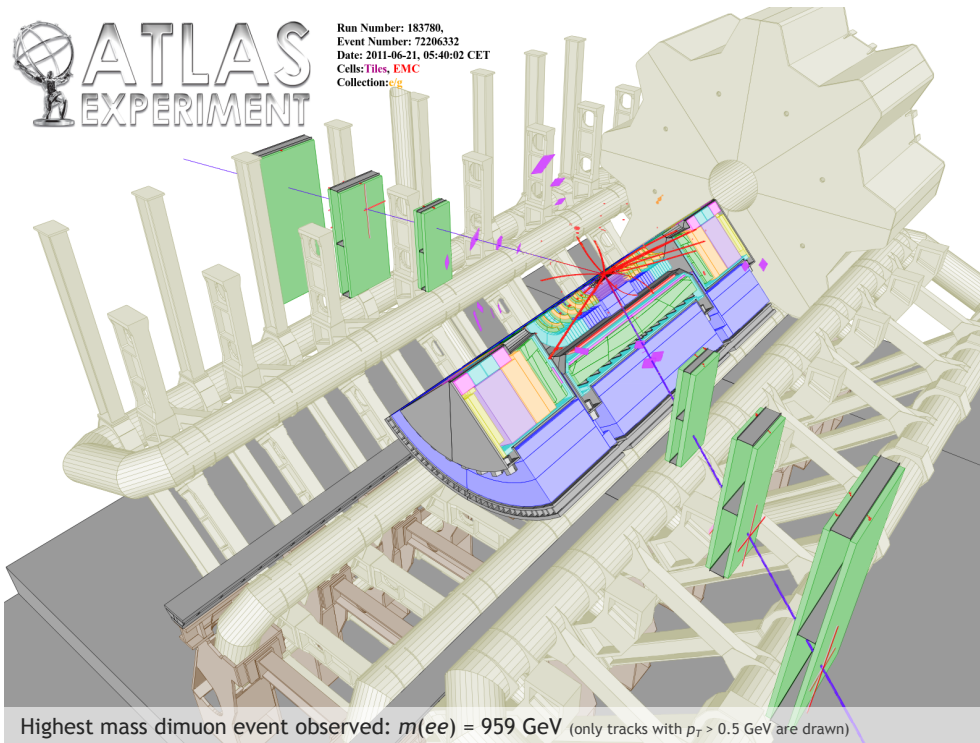
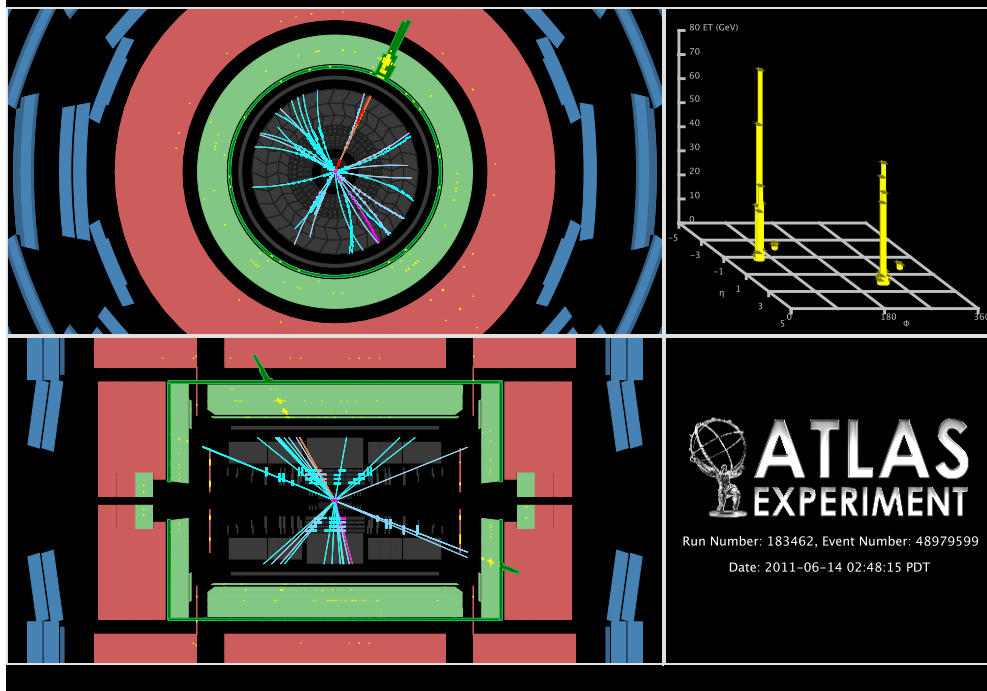


95% CL lower limit: $m(Z'_{SSM}) > 1.9 \text{ TeV}$



95% lower limit: $m(W'_{SSM}) > 2.3 \text{ TeV}^{(*)}$

Highest mass dielectron event observed: $m(ee) = 993 \text{ GeV}$ (only tracks with $p_T > 1 \text{ GeV}$ are drawn)



ATLAS and CMS have unambiguously seen top events

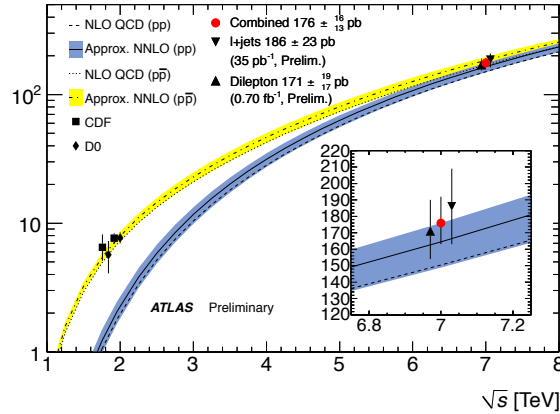
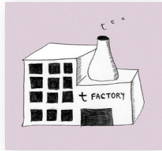
Both experiments measured cross sections and top properties

Heaviest known particle



LHC is top factory:

at 7 TeV CM energy: ~25 times larger cross section than at Tevatron



First precision measurements of top cross section and mass at LHC
Searches for new physics in top production and decay

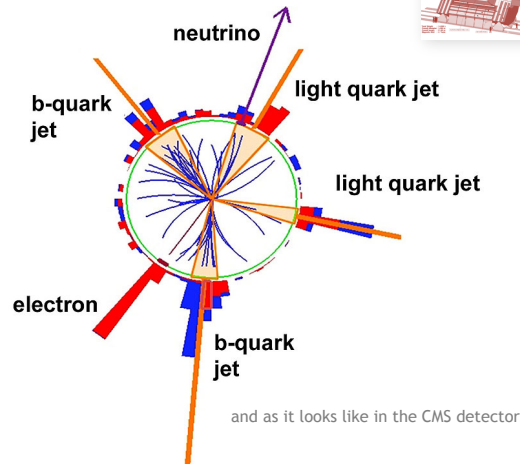
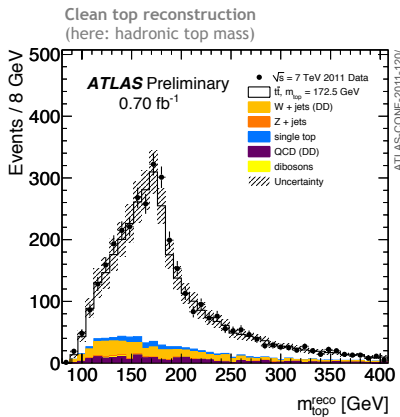
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ATLAS and CMS have unambiguously seen top events

Both experiments measured cross sections and top properties



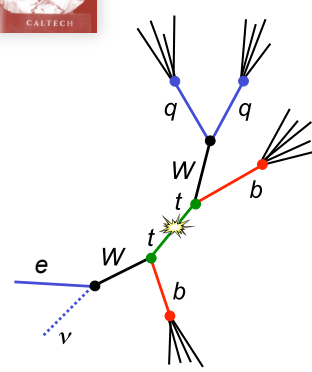
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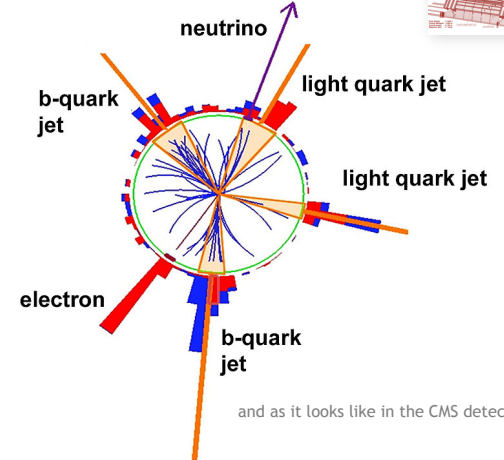
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ATLAS and CMS have unambiguously seen top events

Both experiments measured cross sections and top properties



Sketch of top pair production and decay...



and as it looks like in the CMS detector

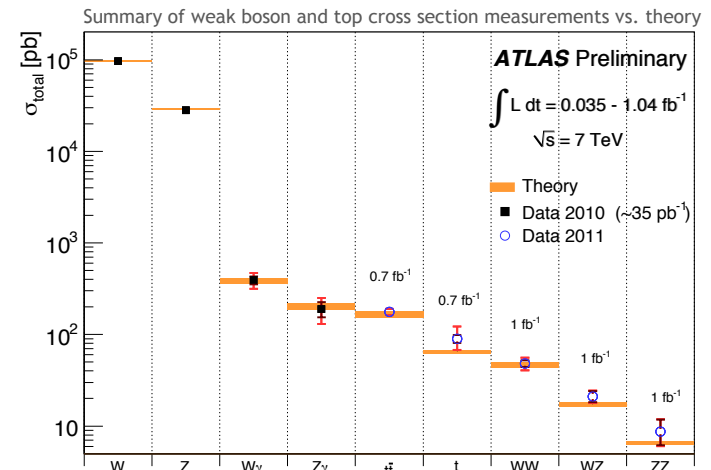
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Electroweak and QCD measurements

Lots of truly novel results at unexplored centre-of-mass energies



Berkeley Colloquium, Oct 17, 2011

Andreas Hoecker - Particle Physics at Year Two at the LHC

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Lots of truly novel results at unexplored centre-of-mass energies

Lots of truly novel results at unexplored centre-of-mass energies

ATLAS
EXPERIMENT

Run Number: 183081, Event Number: 10108572
Date: 2011-06-05 17:08:03 CEST

Stanford Seminar, March 2011 Andreas Hoecker – Quest for the Higgs boson, last of the particles? 56

The Higgs boson has been searched for at many accelerators

Best pre-LHC 95% CL limits from LEP (CERN, 1989–2000) and Tevatron (Fermilab, 1990–2011):

$$m_H > 114 \text{ GeV}$$
$$156 \text{ GeV} < m_H < 177 \text{ GeV}$$

Tevatron Run II Preliminary, $L \leq 8.6 \text{ fb}^{-1}$

95% CL Limit/SM

LEP Exclusion

Tevatron Exclusion

Expected

Observed

$\pm 1\sigma$ Expected

$\pm 2\sigma$ Expected

SM=1

July 17, 2011

$m_H (\text{GeV}/c^2)$

Stanford Seminar, March 2011

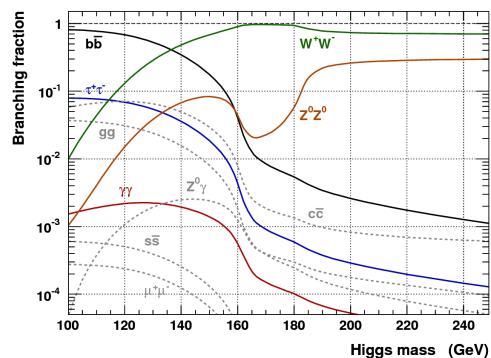
Andreas Hoecker – Quest for the Higgs boson, last of the particles?

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Higgs production and decay probabilities predicted vs. Higgs mass by SM

A Feynman diagram illustrating the decay of a Higgs boson (H) into two photons (γ). The Higgs boson is represented by a dashed line entering a shaded circular loop from the left. The loop contains a fermion (f), indicated by the label f inside the loop. Two solid lines exit the loop to the right, representing the decay products. The top solid line is labeled W, Z, q, l, g, γ , and the bottom solid line is labeled $\bar{W}, Z, \bar{q}, \bar{l}, g, \gamma$.

58

Dependence of the branching fractions on M_H drives search strategy

Associated leptons provide trigger signal as they help to reduce huge QCD background, $s(bb) \sim O(100 \mu b)$

Simulated $H \rightarrow \gamma\gamma$ event (CMS)

Andreas Hoecker - Particle Physics at Year Two at the LHC

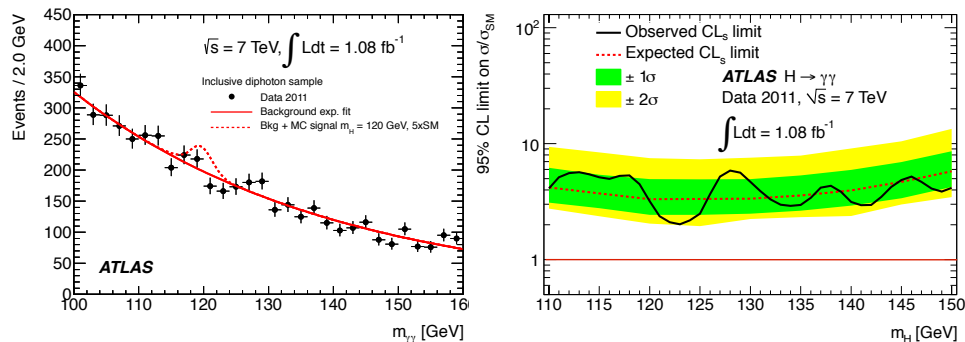
60

$H \rightarrow \gamma\gamma$: clean discovery channel for light Higgs

$\sigma \times \text{BR}$ (115 / 140 GeV | $\sqrt{s}=7$ TeV) $\approx$ 48 / 28 fb

ATLAS arXiv:1108.5895, CMS-PAS-HIG-11-021

Signal selection: need excellent photon energy resolution, and efficient & pure photon identification



Not yet sensitive to SM Higgs, but can search for, eg, “fermiophobic” Higgs boson

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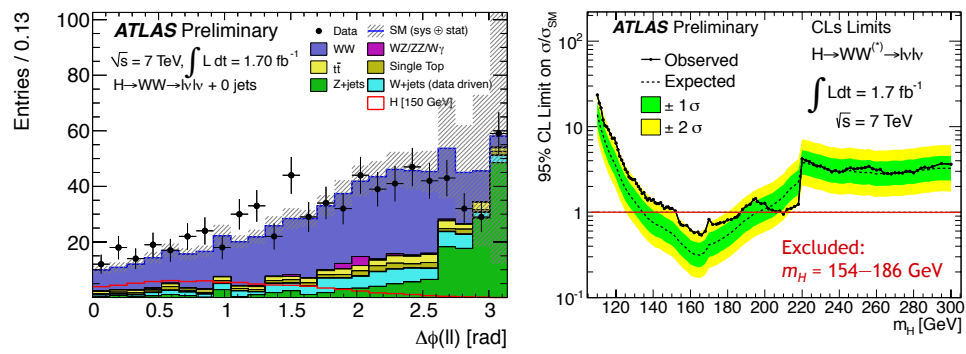
61

$H \rightarrow WW^{(*)} \rightarrow 2(e, \mu) + 2\nu$: not clean, but abundant

$\sigma \times \text{BR}$ (120 / 165 / 200 GeV | $\sqrt{s}=7$ TeV) $\approx$ 120 / 400 / 200 fb

ATLAS-CONF-2011-134

Signal selection: reconstruct transverse Higgs mass, exploit W polarisation (leptons emitted in same dir.)



Excess of events observed in 0-jet channel — not a significant Higgs signal

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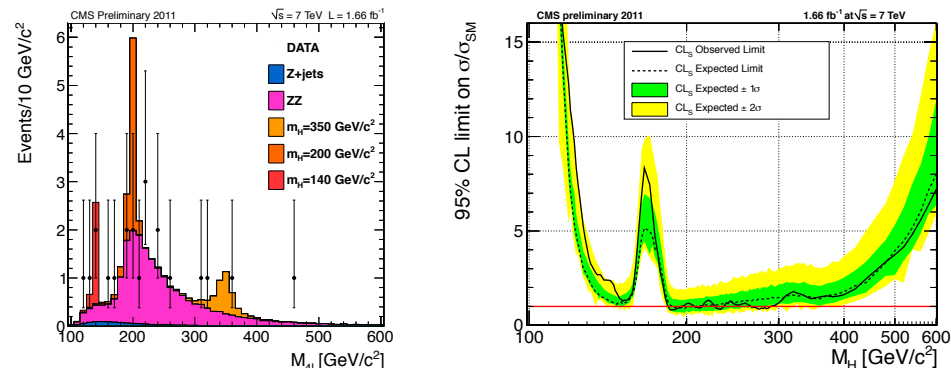
63

$H \rightarrow ZZ^{(*)} \rightarrow 2(e, \mu) + 2(e, \mu)$: “golden channel”

$\sigma \times \text{BR}$ (120 / 140 / 200 GeV | $\sqrt{s}=7$ TeV) $\approx$ 1.3 / 4.2 / 6.8 fb

ATLAS arXiv:1109.5945, CMS-PAS-HIG-11-015

Signal selection: precisely reconstruct mass of Higgs from 4 leptons, exploit on-shell Z mass constraint



Sensitivity to SM Higgs getting interesting...

Berkeley Colloquium, Oct 17, 2011

Andreas Hoecker - Particle Physics at Year Two at the LHC

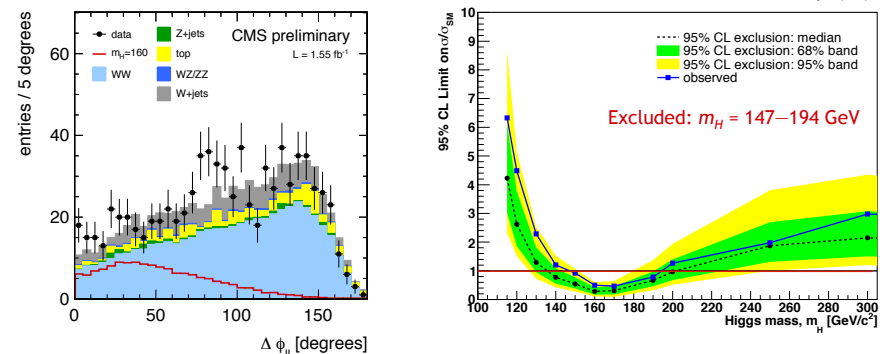
62

$H \rightarrow WW^{(*)} \rightarrow 2(e, \mu) + 2\nu$: not clean, but abundant

$\sigma \times \text{BR}$ (120 / 165 / 200 GeV | $\sqrt{s}=7$ TeV) $\approx$ 120 / 400 / 200 fb

CMS-PAS-HIG-11-014

Same plots from CMS ...



Excess of events observed in 0 and 1-jet channel — not a significant Higgs signal

Berkeley Colloquium, Oct 17, 2011

Andreas Hoecker - Particle Physics at Year Two at the LHC

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$H \rightarrow WW^{(*)} \rightarrow 2(e, \mu) + 2\nu$: not clean, but abundant

$\sigma \times \text{BR} (120 / 165 / 200 \text{ GeV} \mid \sqrt{s}=7 \text{ TeV}) \approx 120 / 400 / 200 \text{ fb}$

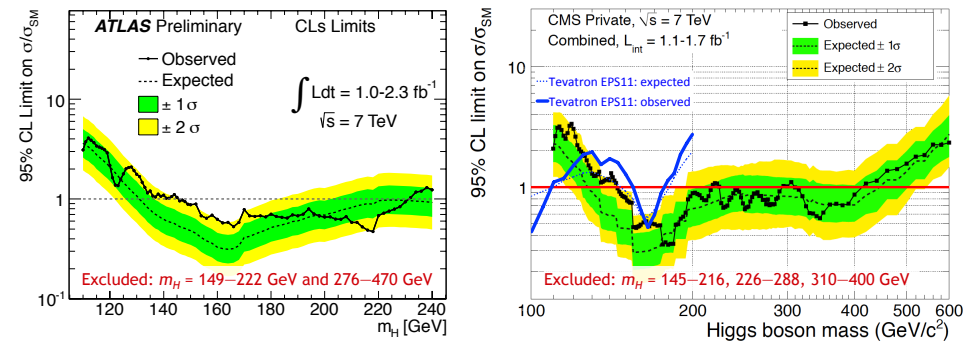


Combining all channels (status: Lepton-Photon 2011)

At high mass also $WW \rightarrow llqq$ and $ZZ \rightarrow ll\nu\nu$ channels contribute

ATLAS-CONF-2011-135, CMS-PAS-HIG-11-022

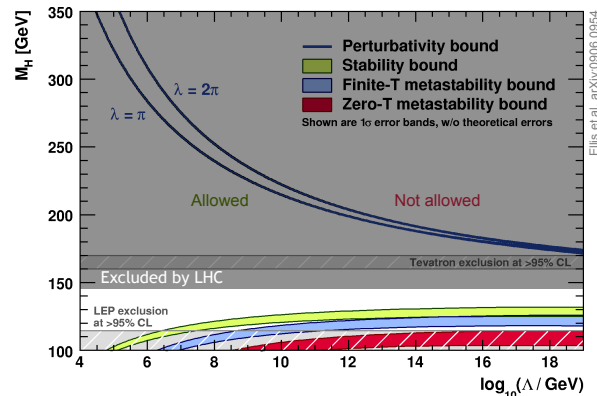
All results combined (left: ATLAS – low mass region, right: CMS – all masses)



All experiments see some excess at ~140–150 GeV, but appears too weak to be SM Higgs

Combining all channels (status: Lepton-Photon 2011)

Compare with constraints from perturbativity and (meta)stability



The SM Higgs must steer a narrow course between two disastrous situations if the SM is to survive up to the Planck scale $M_P \sim 2 \times 10^{18} \text{ GeV}$

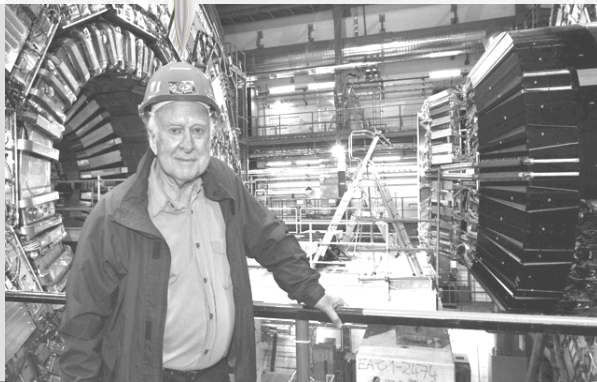
Combining all channels

Much more to come!

Next public milestones:

- Hadron collider conference in Paris in November 2011
- CERN council meeting in December 2012 (first $\sim 5 \text{ fb}^{-1}$ results expected)
- Moriond conference, France, in March 2012: full analysis of 2011 data expected

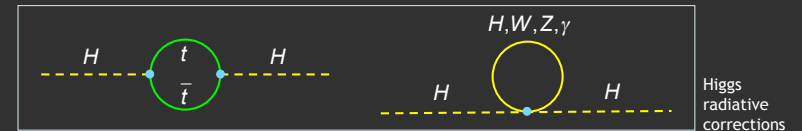
Unfortunately, there is a problem with the Higgs!



P. Higgs at CMS

The Mass of the Scalar is Unprotected

- If a Higgs boson with mass < 1 TeV is discovered, the Standard Model is complete !
- However, when computing radiative corrections to the bare Higgs mass a problem occurs:



$$\rightarrow m_H^2 = m_0^2 + \delta m_H^2 \quad \text{where:} \quad \delta m_H^2 \propto \int_0^\infty d^4k \frac{k^2 + m_t^2}{(k^2 + m_t^2)^2} + \dots$$

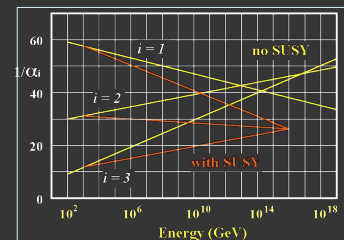
Integral quadratically divergent

- The cut-off sets the scale where new particles and physical laws must come in
- Above the EW scale we only know of two scales: GUT ($\sim 10^{16}$ GeV) and Planck ($\sim 10^{19}$ GeV)
- Such a cut-off would require an incredible amount of finetuning to keep m_H light

$$m_H^2 \stackrel{?}{=} (120 \text{ GeV})^2 = m_0^2 + C \cdot \Lambda_{\text{cut-off}}^2$$

The “Gauge Hierarchy Problem”

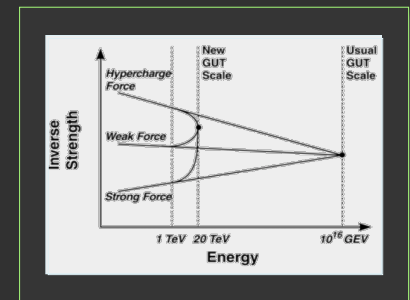
This strong dependence of the Higgs to the ultraviolet physics makes it a powerful probe to new physics



Possible solutions to the hierarchy problem:

- New physics appears not much above the EW scale and regularises the quadratic divergences

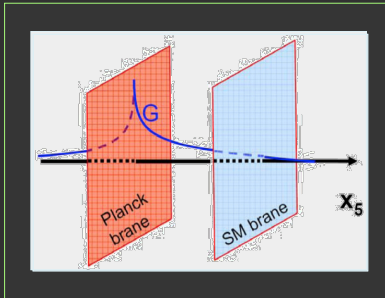
The “Gauge Hierarchy Problem”



Possible solutions to the hierarchy problem:

- New physics appears not much above the EW scale and regularises the quadratic divergences
- New physics modifies the running of the couplings, approaching GUT to the EW scale

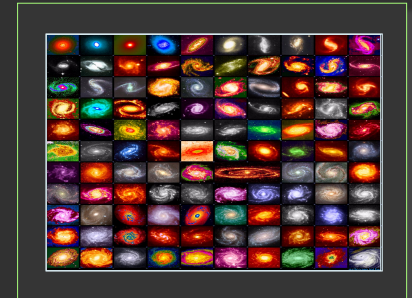
The “Gauge Hierarchy Problem”



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- Gravity is not as weak as we think, it's only diluted in our 4D world but it is as strong as EW interactions at the TeV scale in, e.g., 5 or more dimensions, $(M_{\text{Pl}})^{5D} \sim O(\text{TeV})$

The “Gauge Hierarchy Problem”



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- Gravity is not as weak as we think, it's only diluted in our 4D world but it is as strong as EW interactions at the TeV scale in, e.g., 5 or more dimensions, $(M_{\text{Pl}})^{5D} \sim O(\text{TeV})$
- The theory is finetuned: explanation for parameter values is statistical rather than dynamic (anthropic multiverse solution)

Standard Model

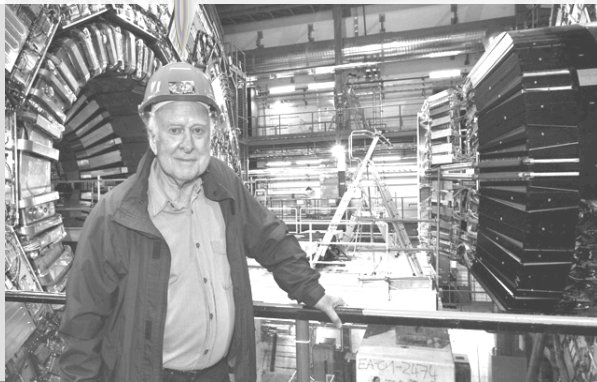
Extending the
Standard Model

Models for new physics focus on remedying the hierarchy problem and providing an explanation (particle) for dark matter. These models have names such as:

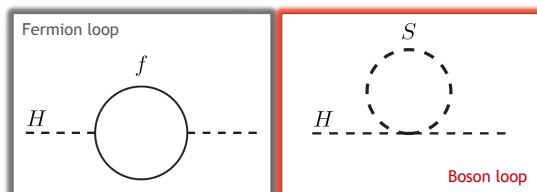
- **Supersymmetry**
- **Extra dimensions**
- **Little or composite Higgs**
- **Technicolour**

The crisis of the Standard Model calls for new physics at the TeV scale. Many models addressing the hierarchy and the dark matter problem have similar experimental signatures. Searching for them is another central pillar of the LHC physics programme.

Unfortunately, there is a problem with the Higgs!



P. Higgs at CMS



Supersymmetry (SUSY)



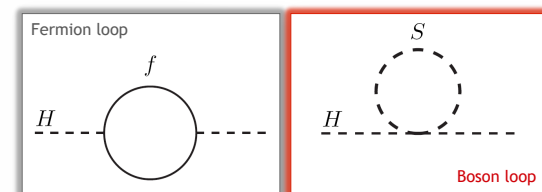
P. Higgs at CMS

Could a symmetry between fermions and bosons regularise the Higgs radiative corrections ?

Supersymmetry (SUSY)



P. Higgs at CMS



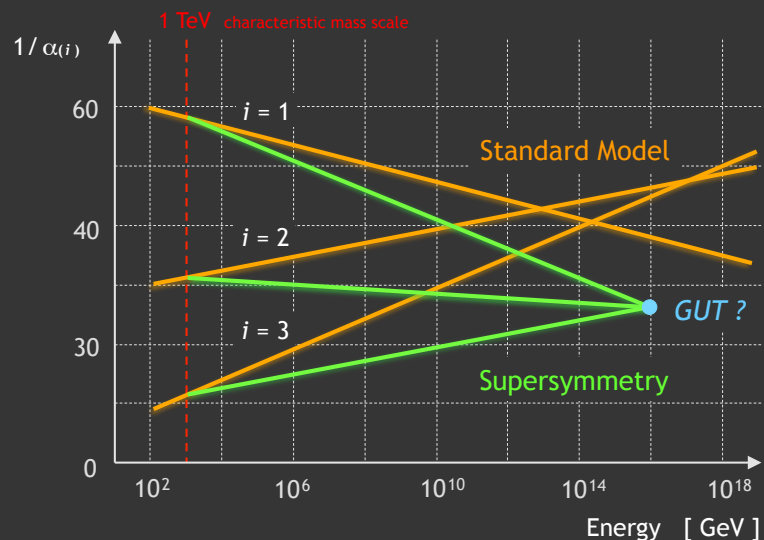
Supersymmetry (SUSY)

Fermion and boson loops contribute with **different signs** to the Higgs radiative corrections: if there existed a symmetry relating these two, this could protect the masses of the scalar Higgs

Supersymmetry realises this by transforming bosons $\leftrightarrow$ fermions

- SUSY transforms, e.g., a scalar boson into a spin- $\frac{1}{2}$ fermion, whose mass is protected
- Hence, the scalar mass is also protected (precisely through SUSY)
- This solves the naturalness and the hierarchy problems of the SM (at least technically)
- Local gauge invariance of SUSY requires existence of spin- $\frac{3}{2}$ and spin-2 particles, which naturally introduces the spin-2 graviton, assumed to mediate the gravitational force

Grand Unification of the Gauge Couplings (GUT)



SUSY has: $N_{\text{dof}}(\text{bosons}) = N_{\text{dof}}(\text{fermions})$ [cf. SM: $N_{\text{dof}}(\text{bosons}) \ll N_{\text{dof}}(\text{fermions})$]

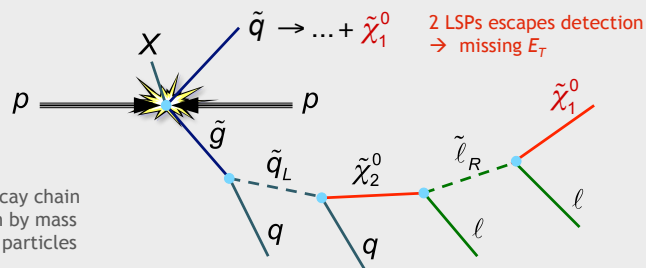
- To create *supermultiplets*, we need to add one *superpartner* to each SM particle
- Superpartners have opposite spin statistics but otherwise equal quantum numbers
- Need to introduce an additional Higgs doublet to the non-SUSY side
- SUSY breaking introduces lots (> 100) of new parameters (masses and mixing angles)

Supersymmetry (SUSY)

Spin 0	Spin 1/2	Spin 1	Spin 3/2	Spin 2
sLepton	Lepton		Gravitino	Graviton
sQuark	Quark			
Higgs	Higgsino			
	Photino	Photon		
	Zino	Z		
	Wino	W		
	Gluino	Gluon		

Characteristic SUSY Decay Cascades

- To avoid proton decay, a new conserved quantum number is introduced, which forces a SUSY particle to decay in at least in one other SUSY particle
- The lightest SUSY particle is thus stable (LSP), and must be neutral and colourless $\rightarrow$ WIMP (dark matter candidate)
- Typical **LSP is spin-1/2 neutralino**. It could also be a gravitino
- With R parity: SUSY production in pairs only $\rightarrow$ requires energy $2 \times$ SUSY mass !



SUSY searches at the LHC

Many different search channels along expected SUSY event topologies

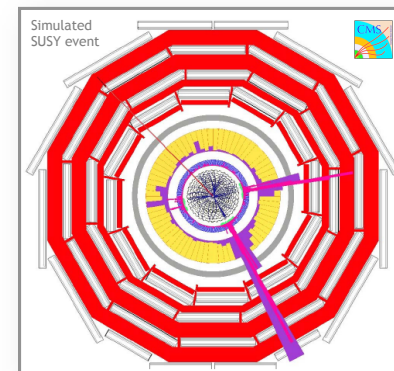
Signatures of the SUSY “cascades” are driven by masses of the SUSY particles

To good generality we can expect:

- High- p_T jets from squark & gluino decays
- Leptons from gaugino & slepton decays
- Missing energy from LSPs

This lays out an **inclusive search strategy**

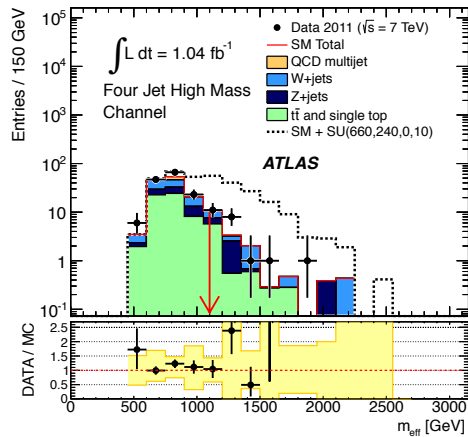
- ➡ Most of the hard analysis work consists of understanding and modeling backgrounds from SM processes !



Searches for strongly produced squarks and gluinos

... do not yet reveal a signal

ATLAS ArXiv:1109.6572, CMS-PAS-SUS-11-004



Plot shows measured sum of jet and missing transverse momenta

Heavy squarks and gluinos would lead to excess over expected SM events at high tail of distribution

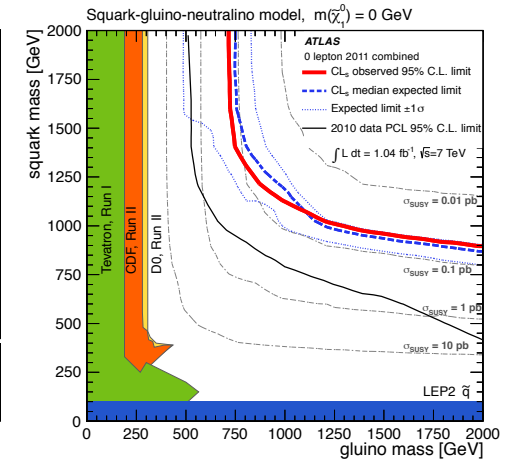
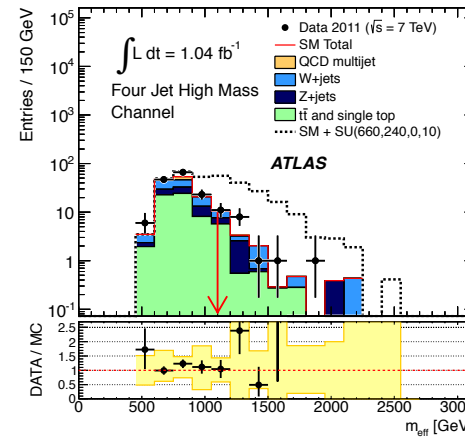
No such excess seen in current data

Can translate into limit on SUSY mass scale

Searches for strongly produced squarks and gluinos

... do not yet reveal a signal

ATLAS ArXiv:1109.6572, CMS-PAS-SUS-11-004



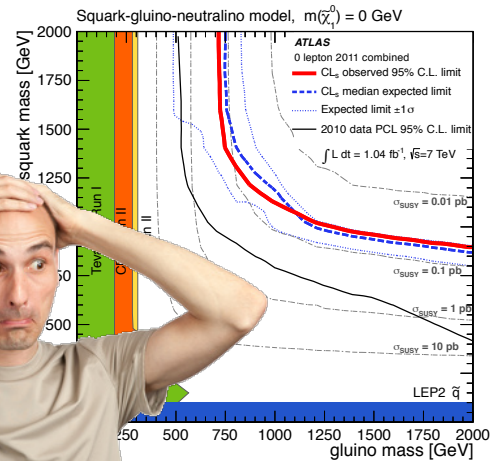
Searches for strongly produced squarks and gluinos

... do not yet reveal a signal

ATLAS ArXiv:1109.6572, CMS-PAS-SUS-11-004

Under moderate assumptions on the SUSY mass hierarchy, ATLAS (similarly CMS) excludes:

$$\begin{aligned} m(\tilde{q}) &\approx m(\tilde{g}) < 1 \text{ TeV} \\ m(\tilde{q}) &< 700 \text{ TeV} \quad (\forall m(\tilde{g}) < 2 \text{ TeV}) \\ m(\tilde{g}) &< 875 \text{ TeV} \quad (\forall m(\tilde{q}) < 2 \text{ TeV}) \end{aligned}$$



Searches for strongly produced squarks and gluinos

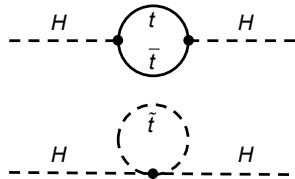
... do not yet reveal a signal

ATLAS ArXiv:1109.6572, CMS-PAS-SUS-11-004

Does SUSY hide from our analyses?

What mechanisms could camouflage strong SUSY production?

Recall: we need to cancel the Higgs virtual corrections. Most important is top loop

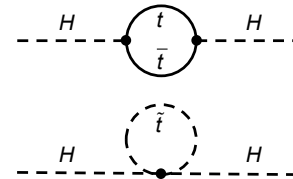


Contrary to the SM, 3rd generation squarks are lighter than 1st and 2nd generations

Does SUSY hide from our analyses?

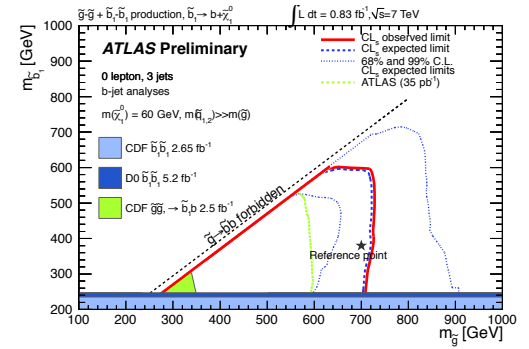
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Contrary to the SM, 3rd generation squarks are lighter than 1st and 2nd generations

→ Maybe all squarks except stop are heavy?

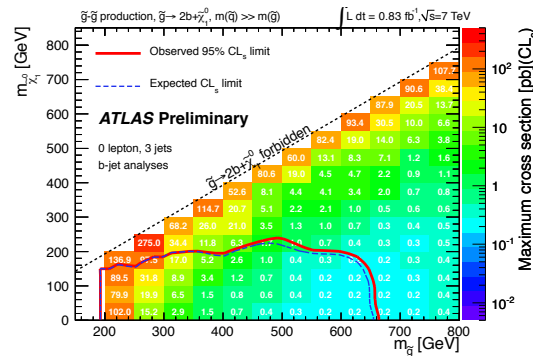


Glucinos produce stop which decays to top and neutralino. The top decays to bottom quarks that can be “tagged” in the detector

Does SUSY hide from our analyses?

What mechanisms could camouflage strong SUSY production?

Maybe the neutralinos are almost as heavy as the squarks and gluinos so that not enough missing E_T is produced in the decays to select SUSY events?



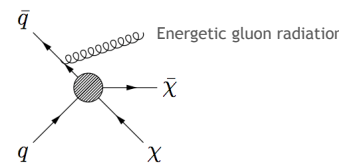
Mass degeneracy close to diagonal in plot
Little discovery reach there

Does SUSY hide from our analyses?

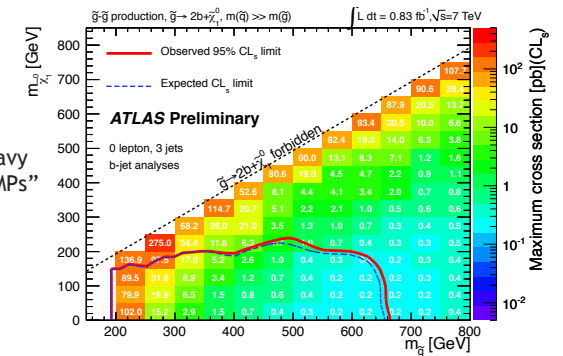
What mechanisms could camouflage strong SUSY production?

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Maybe squarks and gluinos are all too heavy and only neutralinos or dark matter “WIMPs” are produced? How can we detect them?



→ Search for mono-jets events!



Mass degeneracy close to diagonal in plot
Little discovery reach there

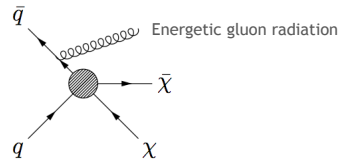
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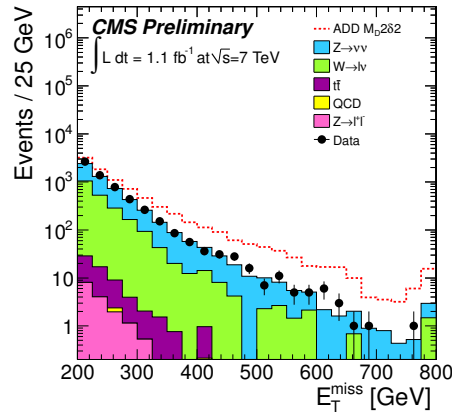
ATLAS-CONF-2011-096, CMS-PAS EXO-11-059

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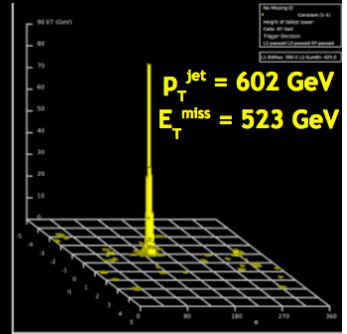
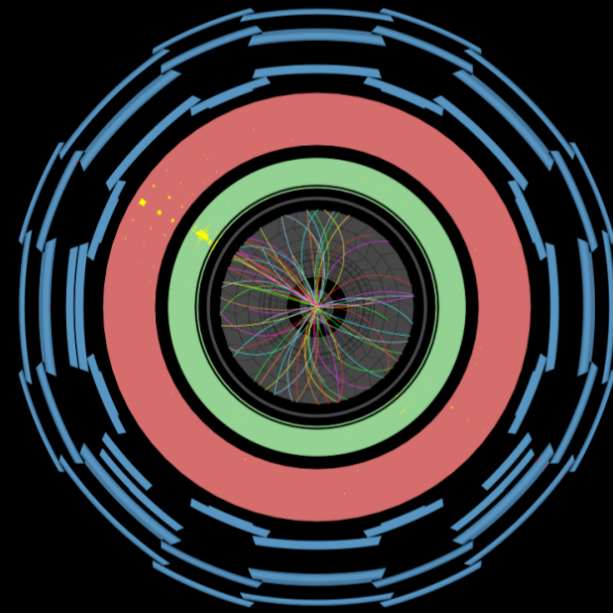
Maybe squarks and gluinos are all too heavy and only neutralinos or dark matter "WIMPs" are produced? *How can we detect them?*



→ Search for mono-jets events!



A monojet event seen by ATLAS



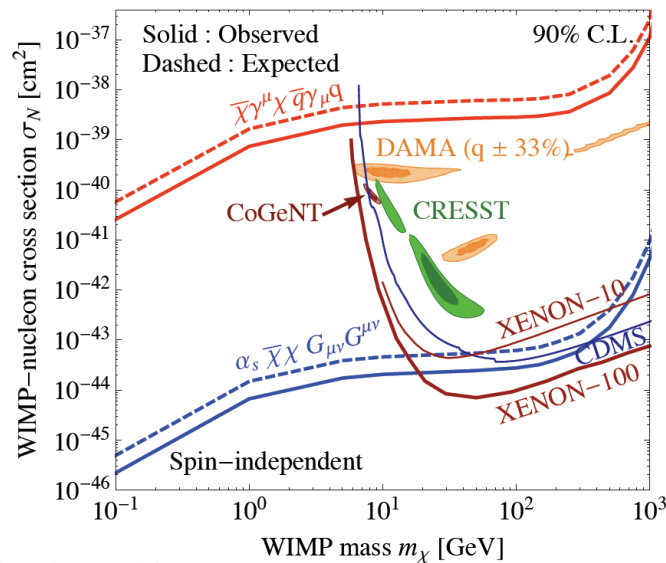
ATLAS
EXPERIMENT

Run Number: 180309, Event Number: 36060682

Date: 2011-04-27 02:33:15 CEST

A monojet event seen by ATLAS

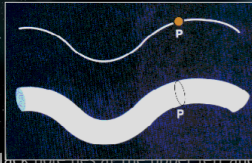
ATLAS 7TeV, 1fb⁻¹ VeryHighPt



[Fox et al., arXiv:1109.4398]

Several models other than Supersymmetry deal with the hierarchy problem, some also provide dark matter candidates, some also grand unification, some of them provide new sources of matter-antimatter violation to create the remaining matter, some may explain the hierarchy in the observed particle masses, some are only valid up to several tenth of TeV, others up to GUT scales...

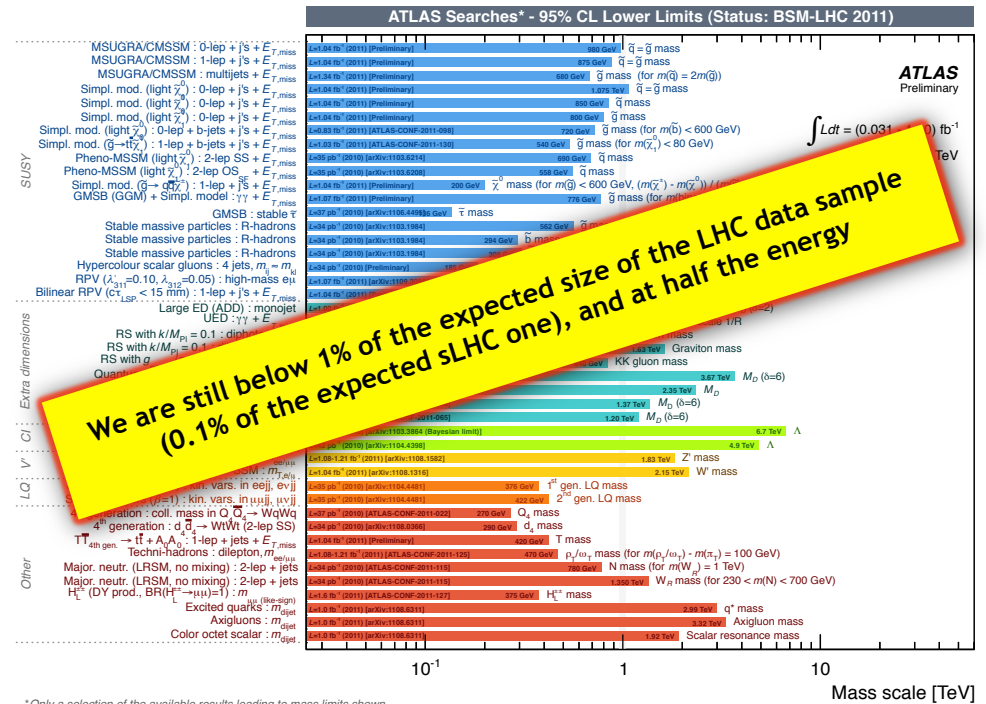
Many of these models have fascinating features. Compact extra dimensions, for example, are small, curled dimensions of micron size or much smaller. If gravitons propagate in them gravity may become strong and we should observe couplings of SM particles to gravity. If also the SM fields propagate in the extra dimensions, they may develop new high-mass states. If the new phenomena are of TeV scale we should see them. We hence must search for them at the LHC!



Artist's portrayal of the IC 10 X-1 system: the black hole lies at the upper left and its companion star is on the right

The LHC is performing marvelously
What are the next steps?

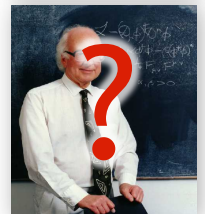
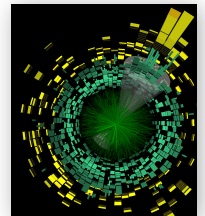
Where are we heading to



Next Steps at the LHC

One more year running at 7/8 TeV, then shutdown in 2013/2014 → ~14 TeV

- Continue running until end of October 2011 → ~5 fb⁻¹
- In November 2011: lead-lead collisions, then winter stop
- March 2012: restart with several *possible* options
 - Raise proton collision energy from 7 → 8 TeV
 - Double number of bunches in LHC
 - Reduce beam width at collision point by ~20%
 - Increase beam currents by ~25%
 - May reach average of up to 30 interactions per collision
 - Baseline expected luminosity reach: 10 fb⁻¹
- 2013/2014: repair and upgrade LHC to ~14 TeV
- Then long run until ~2018, before further upgrade





Spare slides...

Summary

The experiments are chasing the last and most important (and peculiar) particle of the Standard Model: the Higgs boson

- So far, we managed to exclude Higgs masses between 140 GeV and 470 GeV
- Precision data predict via virtual Higgs effects: $M_H = 96^{+30}_{-25}$ GeV
- Stability of the Standard Model up to the Planck mass requires $M_H > 129$ GeV

The Higgs gives mass, but renders the Standard Model unstable

- New theories exist that can stabilise the Standard Model Higgs
- Some of these theories also explain dark matter, lead to grand unification, ...
- We are mining our data for their manifestations, but none have yet been observed
- These results are corroborated by precision measurements (also from the LHC)

We are participating in the largest experiments ever built by mankind

It is our responsibility to work hard, be patient and humble, in order to observe and interpret Nature as it reveals itself to us

The Standard Model

Brout-Englert-Higgs mechanism

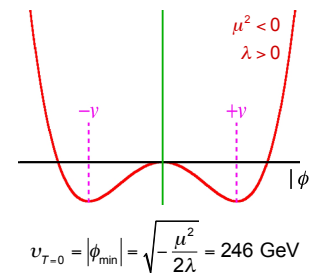
Potential $V(\phi) = \mu^2 |\phi|^2 + \lambda |\phi|^4$, ϕ scalar doublet

For $\mu^2 < 0$, the minimum moves away from $\phi = 0$

The ground state ($T = 0$) acquires a non-zero vacuum expectation value (vev) v

Perturbation theory around ground state: $\phi \propto v + H$

H is the Higgs boson. The other 3 components of the doublet ϕ are absorbed to give mass to $W^\pm$ and Z



v precisely known from muon decay

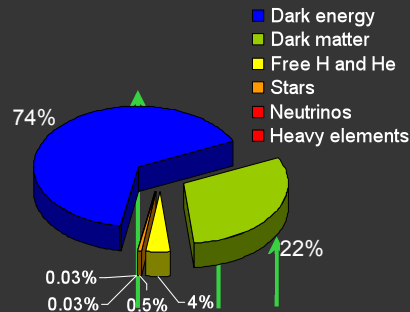
Dark Matter

- *Dark matter* does not emit or reflect sufficient electromagnetic radiation to be detected

- Evidence for dark matter stems from:

- Gravitational lensing obs.
- Rotation curves galaxies
- Anisotropy of cosmic microwave background radiation

→ 2006 Nobel Prize in Physics:
John C. Mather, and George F. Smoot
(COBE satellite)



Source: NASA WMAP Science Team, 2007

- First peak determines curvature of universe
- Second peak (ratio of odd-to-even peaks) determines reduced baryon density
- Third peak is related to dark matter density !
- ➔ Data analysis reveals a flat universe and lots of unknown matter and energy !

Dark Matter - The “WIMP Miracle”

Consider Some new particle χ

During an early *soup*, its annihilation reaction is in thermal equilibrium

$$\chi\chi \leftrightarrow f\bar{f}$$

As the *soup* expands it cools down, so that (assuming here: $m(\chi) \gg m(f)$, still remaining in thermal equilibrium)

$$\chi\chi \rightarrow f\bar{f}$$

When $\sigma_A \ll H(T)$, some χ freeze out and create weakly interacting dark matter Ω_{DM}

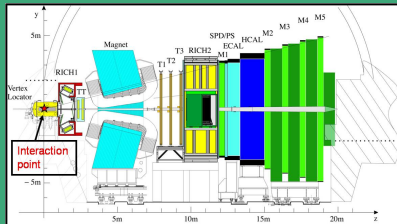
The abundance of the dark matter inverse proportional to the annihilation cross section

$$\Omega_{DM} \propto \frac{1}{\langle v\sigma_A \rangle} \propto m_\chi^2 \Rightarrow \Omega_{DM} \approx 0.1 \rightarrow m_\chi \sim 0.1 - 1 \text{ TeV}$$

COINCIDENCE ?

Dedicated B physics Experiment

LHCb



LHCb: emphasis on low- p_T physics with large forward cross section. Excellent vertex and momentum resolution, π/K separation

Physics aims: search for new physics through measurement of CP violation and rare B decays

Why Colliding Hadrons instead of e^+e^- ?

Advantage of hadron collider

- Can reach higher energies in ring (less synchrotron radiation)

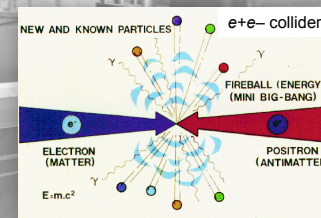
Energy loss per turn:

$$-\Delta E \approx \frac{4\pi\alpha}{3 \cdot R} \left(\frac{E}{m} \right)^4 \approx \begin{cases} 3.5 \text{ GeV for LEP-II at } E_{\text{beam}} = 104.5 \text{ GeV} \\ 6.2 \text{ keV for LHC at } E_{\text{beam}} = 7000 \text{ GeV} \end{cases}$$

High e^+e^- energy requires linear collider: *ILC, CLIC*

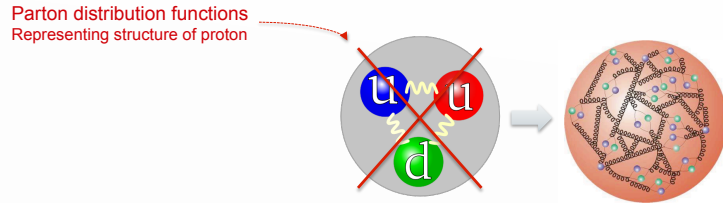
Disadvantages

- Hadrons are composites → parasitic collisions beyond hard parton scattering
- Energy and type of colliding parton unknown → kinematics partially unconstrained



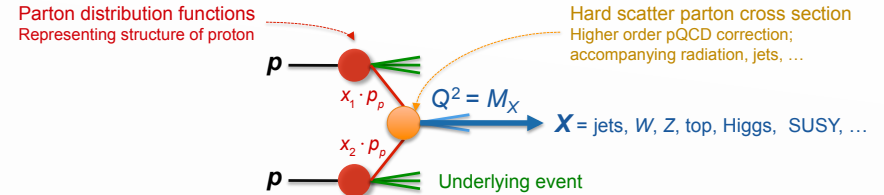
Proton-Proton Collisions

- For proton-proton collisions, cross section is convolution of Parton Density Functions (PDF) with parton scattering Matrix Element



Proton-Proton Collisions

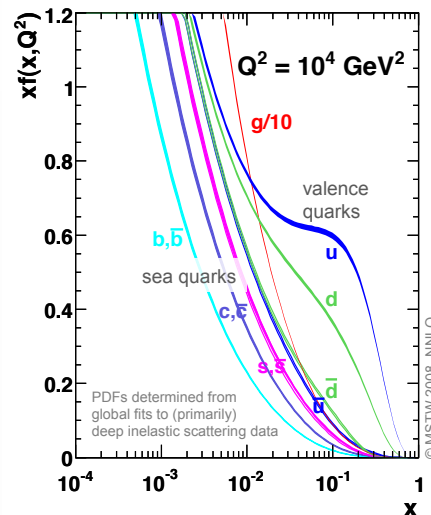
- For proton-proton collisions, cross section is convolution of Parton Density Functions (PDF) with parton scattering Matrix Element



- CM energy of parton collision: $\hat{s} = M_X^2 = x_1 \cdot x_2 \cdot s_{\text{LHC}}$
- The parton density functions rise dramatically towards low x :
 - Higher cross section at higher proton-proton collision energy
 - Low- x (eg, Higgs) dominated by gluon-gluon collisions: “gluon collider”

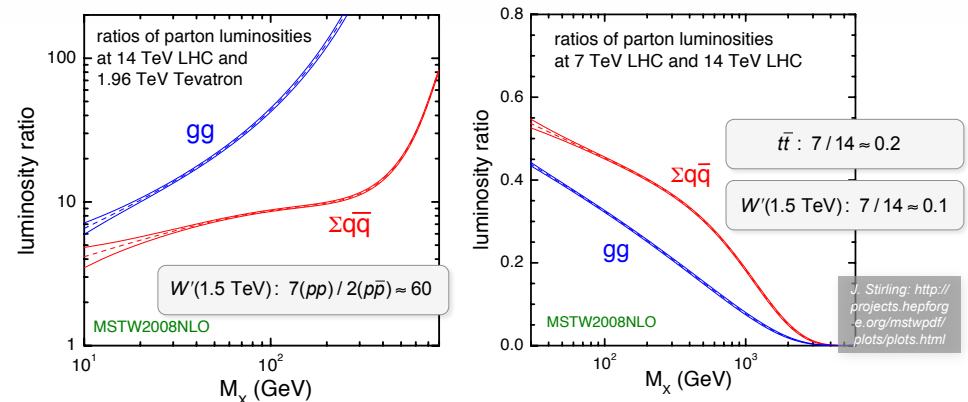
Proton-Proton Collisions

- Proton is complicated composite of valence quarks, gluons and sea quarks
- PDF depends on 2D mixture of
 - Q^2 (evolution in $\ln(Q^2)$ predicted by QCD)
 - Bjorken x momentum fraction
- CM energy of parton collision: $\hat{s} = M_X^2 = x_1 \cdot x_2 \cdot s_{\text{LHC}}$
- Typical ‘ x ’ values (assume: $x_1 = x_2$)
 - LHC ($\sqrt{s} = 14$ TeV):**
 - $M_X = 100$ GeV (1 TeV) → $\langle x \rangle = 0.007$ (0.07)
 - Tevatron ($\sqrt{s} = 2$ TeV):**
 - $M_X = 100$ GeV (1 TeV) → $\langle x \rangle = 0.05$ (0.5)
- PDFs rise dramatically towards low x
 - **larger cross sections at LHC**
 - “gluon collider”



Parton Luminosities at LHC and Tevatron

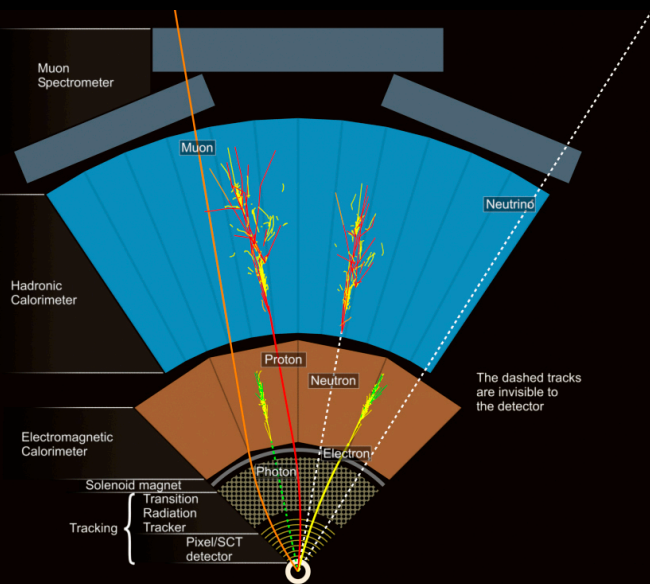
Ratio of “parton luminosities” of LHC-to-Tevatron and LHC 7 TeV-to-14 TeV



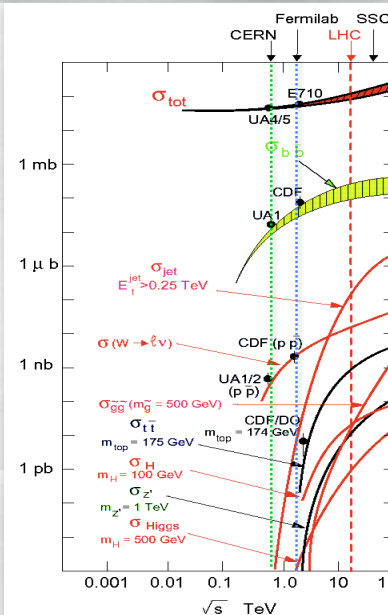
- High M_X production through gluon fusion requires large CM energy
- Less so for quark-antiquark scattering which has slow rise for $M_X < 300$ GeV

Detector Layers

Particles are detected through their interaction with the active detector materials



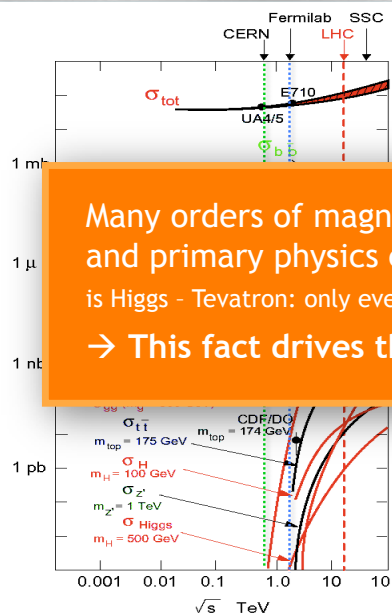
$pp(\bar{p})$ Cross Sections



Process	Cross section (nb) at 14 TeV CM energy	Production rates (Hz) at $L=10^{34} \text{ cm}^{-2} \text{ s}^{-2}$
Inelastic	10^8	10^9
$b\bar{b}$	5×10^5	5×10^6
$W \rightarrow \ell \nu$	15	150
$Z \rightarrow \ell \ell$	2	20
$t\bar{t}$	1	10
$Z' (1 \text{ TeV})$	0.05	0.5
$g\bar{g} (1 \text{ TeV})$	0.05	0.5
$H (120 \text{ GeV})$	0.04	0.4
$H (180 \text{ GeV})$	0.02	0.2

Recall: $1 \text{ pb}^{-1} \triangleq 10^{36} \text{ cm}^{-2}$
 $\Rightarrow 15 \text{ nb} \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1} =$
 $15 \text{ nb} \times 10^{-2} \text{ pb}^{-1} \text{ s}^{-1} = 150 \text{ Hz}$

$pp(\bar{p})$ Cross Sections



Many orders of magnitude between QCD background and primary physics channels (only one in five billion events is Higgs - Tevatron: only every trillionth event!)

→ This fact drives the trigger and detector design

Process	Cross section (nb) at 14 TeV CM energy	Production rates (Hz) at $L=10^{34} \text{ cm}^{-2} \text{ s}^{-2}$
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The LHC proton-proton Physics Programme

1. Mass and electroweak symmetry breaking

- Search for the Higgs Boson, measurement of its properties

2. Hierarchy in the TeV domain

- Search for new phenomena moderating the hierarchy problem
- Search for the unexpected at the high-energy frontier

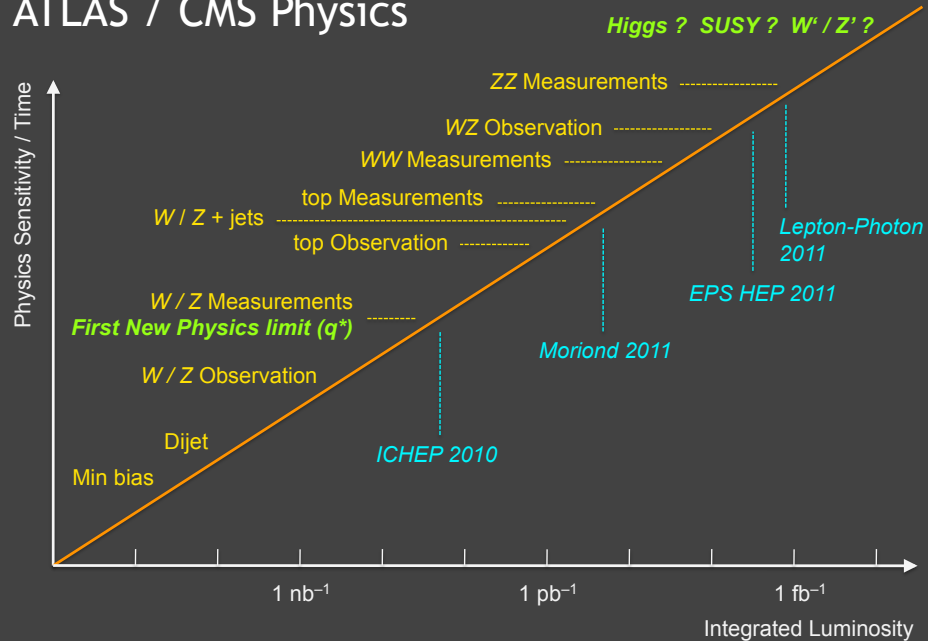
3. Electroweak unification and strong interactions

- Precision measurements and tests of the Standard Model
- Tests of perturbative QCD at the high-energy frontier

4. Flavour

- B , D mixing, rare decays and CP violation as tests of the Standard Model

ATLAS / CMS Physics



© P. Schieferdecker, Dec 17, 2010 at CERN

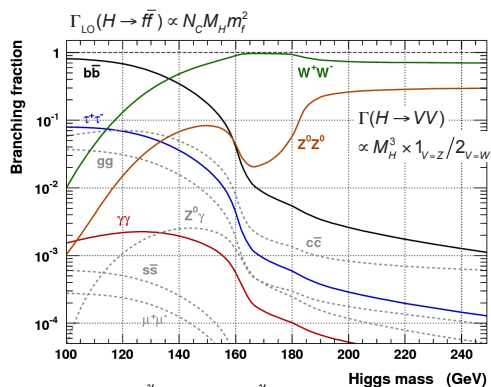
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Higgs searches at the LHC

Dependence of the branching fractions on M_H drives search strategy



$$\Gamma(H \rightarrow \gamma\gamma) \propto \alpha^2 \cdot M_H^3 \cdot |N_C Q_f^2 A_f^H + A_W^H|^2$$

For **medium to heavy Higgs**:

- Lepton final states via $WW^{(*)}$, $ZZ^{(*)}$

For **light Higgs**:

- Lepton final states via $WW^{(*)}$, $ZZ^{(*)}$
- Di-photon final state
- Di-tau final state

The dominant $H \rightarrow bb$ mode is only exploitable in association with W/Z or tt , also with strong Higgs boost

Associated leptons provide trigger signal as they help to reduce huge QCD background, $s(bb) \sim O(100 \mu b)$

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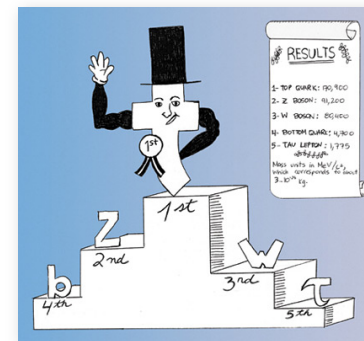
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ATLAS and CMS have unambiguously seen top events

Both experiments measured cross sections and top properties

The top quark is the heaviest known elementary particle

- Almost as heavy as a gold atom...
- It is that heavy that it decays to bW^+ before it can form hadrons: its lifetime of 5×10^{-25} s (half a yoctosecond, $\Gamma t \approx 1.5$ GeV) is smaller than hadronization time: $1/\Lambda_{QCD} \sim 3 \times 10^{-24}$ s
- When a top pair is produced at LHC, it can only fly ~ 0.1 fm within its lifetime, but the typical hadron size is 1 fm. At 0.1 fm, QCD is weak due to asymptotic freedom
- There are thus no toponium bound states
- Top is believed to be preferably involved in reactions with **heavy new physics particles**



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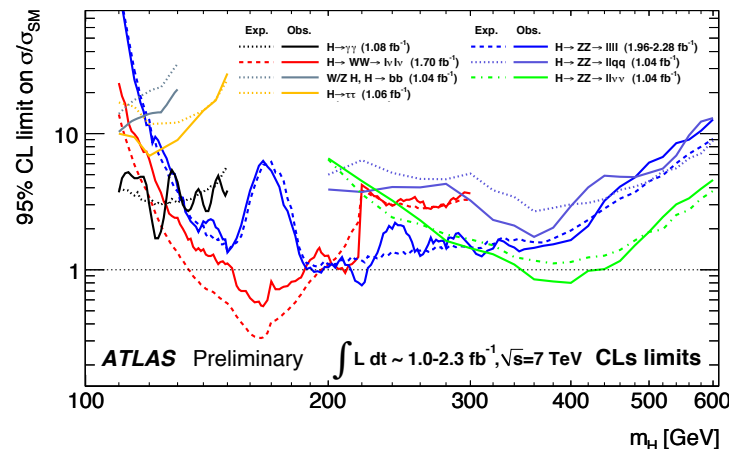
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Combining all channels (status: Lepton-Photon 2011)

At high mass also $WW \rightarrow llqq$ and $ZZ \rightarrow ll\nu\nu$ channels contribute

ATLAS-CONF-2011-135, CMS-PAS-HIG-11-022

Individual results (ATLAS)



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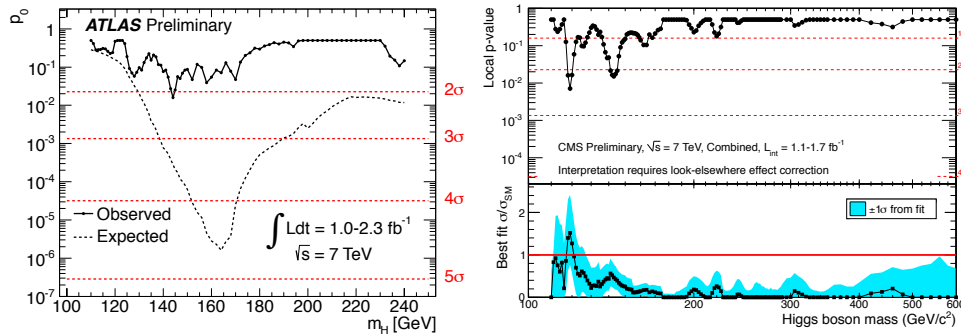
120

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ATLAS-CONF-2011-135, CMS-PAS-HIG-11-022

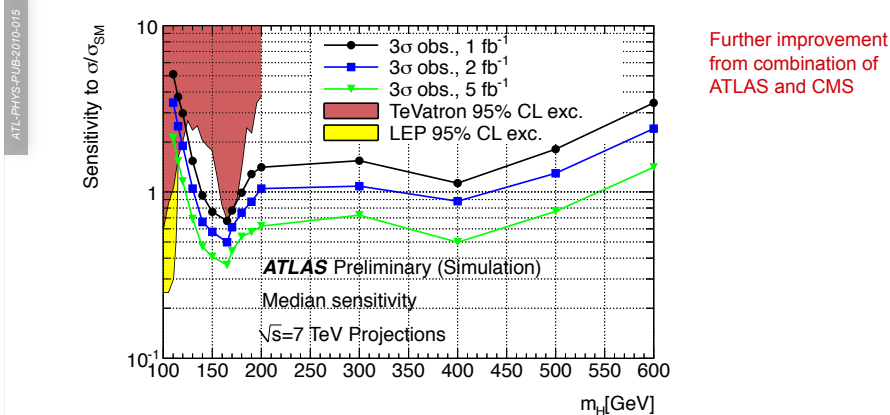
Background-only hypothesis – p-value (left: ATLAS – low mass region, right: CMS – all masses)



All experiments see some excess at ~140–150 GeV, but appears too weak to be SM Higgs

3σ Evidence Potential vs. Luminosity

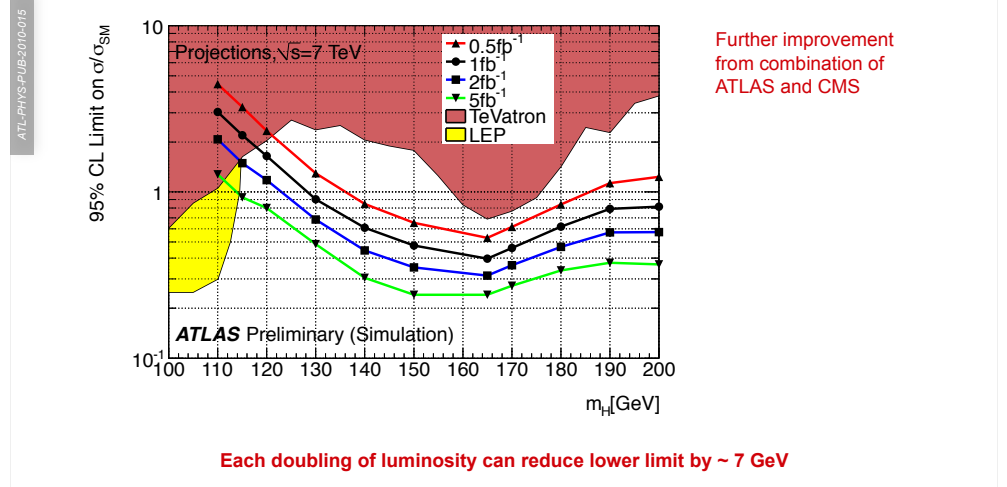
ATLAS combination of all considered channels at 7 TeV with 1, 2, 5 fb⁻¹ luminosity



For 1 fb⁻¹, 3σ evidence possible for 139–180 GeV, for ATLAS & CMS → down to 131 GeV

Exclusion Potential vs. Luminosity

ATLAS combination of all considered channels at 7 TeV with 1, 2, 5 fb⁻¹ luminosity

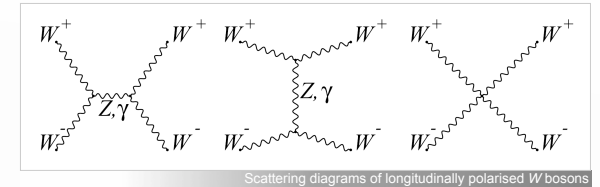


Each doubling of luminosity can reduce lower limit by ~ 7 GeV

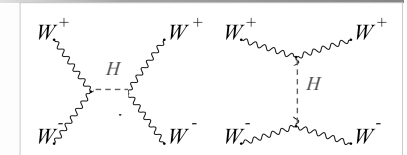
Unitarity – the Higgs Boson as UV Regulator

Unitarity problem: the amplitude of (longitudinal – since the W 's are massive) W^+W^- scattering diverges if only Z bosons and photons are exchanged:

$$\mathcal{M}_{Z,\gamma}(W_L^+W_L^- \rightarrow W_L^+W_L^-) \propto \sqrt{2}G_F \cdot (s+t)$$



$$\mathcal{M}_{Z,\gamma,H}(W_L^+W_L^- \rightarrow W_L^+W_L^-) \propto -\sqrt{2}G_F \cdot M_H^2 \cdot \left(\frac{s}{s-M_H^2} + \frac{t}{t-M_H^2} \right)$$

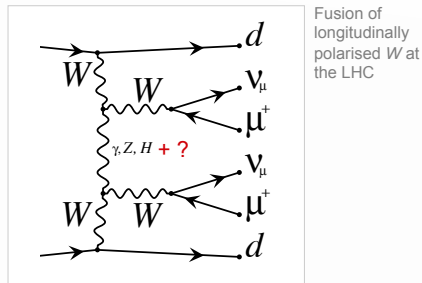


→ Higgs exchange regularises matrix element (if $M_H \leq 1/\sqrt{G_F} \sim 300$ GeV, while when doing a proper partial wave analysis of the scattering amplitude, the limit weakens)

→ Higgs is a “UV Moderator”

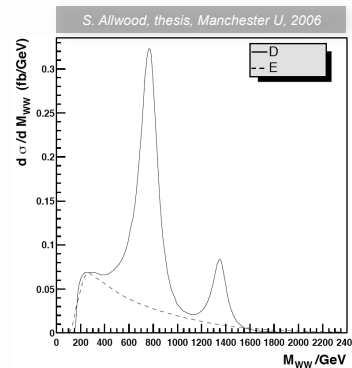
Strong WW Scattering ?

If the Higgs is very heavy, or if EW symmetry is broken by something else than a Higgs condensate (e.g., by strong interactions), W bosons would become **strongly interacting particles at TeV scale**.



Growth of scattering amplitude cancelled at $O(\text{TeV})$ by exchange of new fields

The experimental signature could be strong **WW resonances**



Strong WW Scattering ?

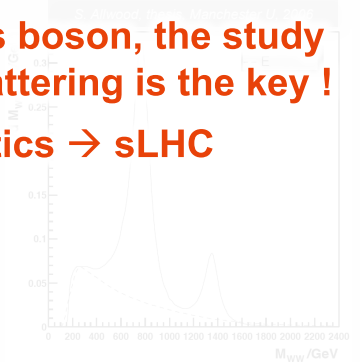
If the Higgs is very heavy, or if EW symmetry is broken by something else than a Higgs condensate (e.g., by strong interactions), W bosons would become **strongly interacting particles at TeV scale**.

If the LHC does not find a Higgs boson, the study of longitudinal gauge boson scattering is the key !

This requires large statistics → sLHC

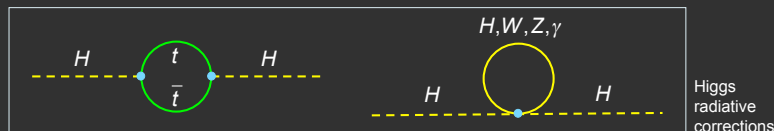
The growth of the scattering amplitude is cancelled at scale M_{SB} of $O(\text{TeV})$ (unitarity limit) by exchange of new fields from L_{SB}

The experimental signature could be strong **WW resonances**



The Mass of the Scalar is Unprotected

- If a Higgs boson with mass $< 1 \text{ TeV}$ is discovered, the Standard Model is complete !
- However, when computing radiative corrections to the bare Higgs mass a problem occurs:



$$\rightarrow m_H^2 = m_0^2 + \delta m_H^2 \quad \text{where:} \quad \delta m_H^2 \propto \int_0^\infty d^4k \frac{k^2 + m_t^2}{(k^2 + m_t^2)^2} + \dots$$

Integral quadratically divergent

- The cut-off sets the scale where new particles and physical laws must come in
- Above the EW scale we only know of two scales: GUT ($\sim 10^{16} \text{ GeV}$) and Planck ($\sim 10^{19} \text{ GeV}$)
- Such a cut-off would require an incredible amount of finetuning to keep m_H light and stable

$$m_H^2 \stackrel{?}{=} (120 \text{ GeV})^2 = m_0^2 + C \cdot \Lambda_{\text{cut-off}}^2$$

The “Gauge Hierarchy Problem”

The Gauge Hierarchy Problem...

- ...denotes this finetuning of parameters, and the strong dependence of physics at the weak scale on the physics at (presumably) much higher scale.
- If the Higgs radiative corrections are cut off at the scale of gravity, why is the scale of electroweak symmetry breaking so different from the scale of gravity? Why is $M_W \ll M_{Pl}$?
- Equivalently, why is gravity so weak? $G_F = \frac{g^2}{4\sqrt{2}M_W^2} \gg G_N = \frac{1}{M_{Pl}^2}$

Ultimately, the missing protection of the scalar Higgs boson mass is related to the **absence of a symmetry principle**. Indeed, setting the Higgs mass to zero in the SM Lagrangian, **does not restore any symmetry in the model**.

New physics models should address this. **Supersymmetry** for example offers the feature that fermionic and bosonic d.o.f. conspire to cancel the quadratic loop divergences, when the symmetry is exact

Other models, like the **Little Higgs**, interpret the Higgs as Goldstone boson of some approximate symmetry.

→ M_H becomes a deviation from some exact symmetry, and thus is **intrinsically small !**

The Mass of the Scalar is Unprotected

- If a Higgs boson with mass < 1 TeV is discovered, the Standard Model is complete !
- However, when computing radiative corrections to the bare Higgs mass a problem occurs:

Missing protection of scalar Higgs mass is related to **absence of a symmetry principle**. Setting $m_H = 0$ in SM Lagrangian, **does not restore any symmetry in the model**.

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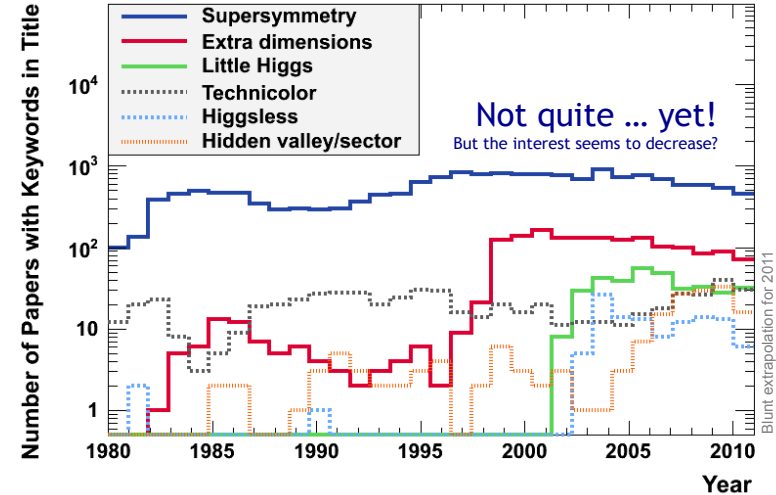
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$$m_H^2 = (120 \text{ GeV})^2 = m_0^2 + C \cdot \Lambda_{\text{cut-off}}^2$$

Paper Statistics in SPIRES

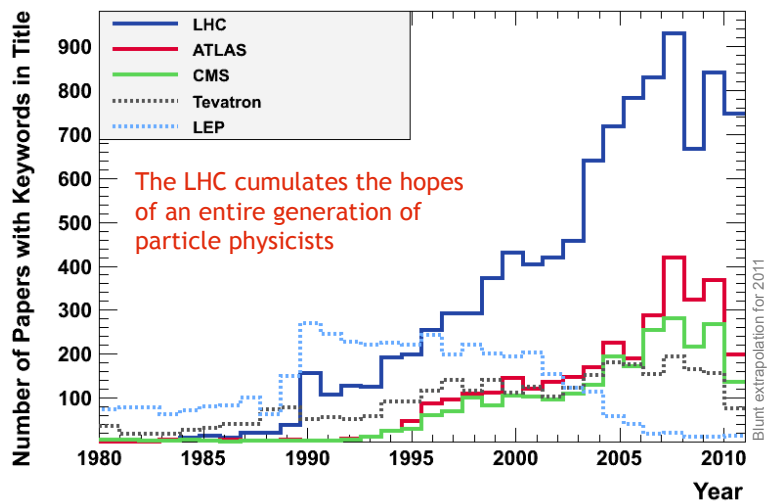
Is SUSY out already?



*Only a selection of the available results shown

Mass scale [TeV]

Paper Statistics in SPIRES



*Only a selection of the available results shown

Mass scale [TeV]