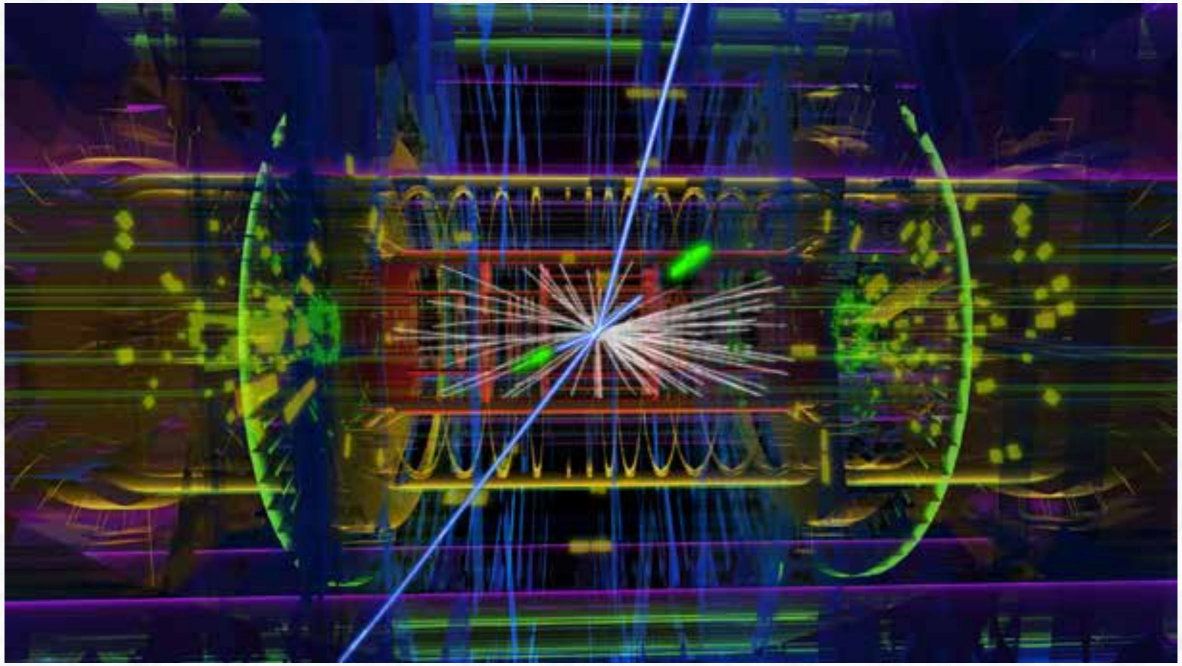
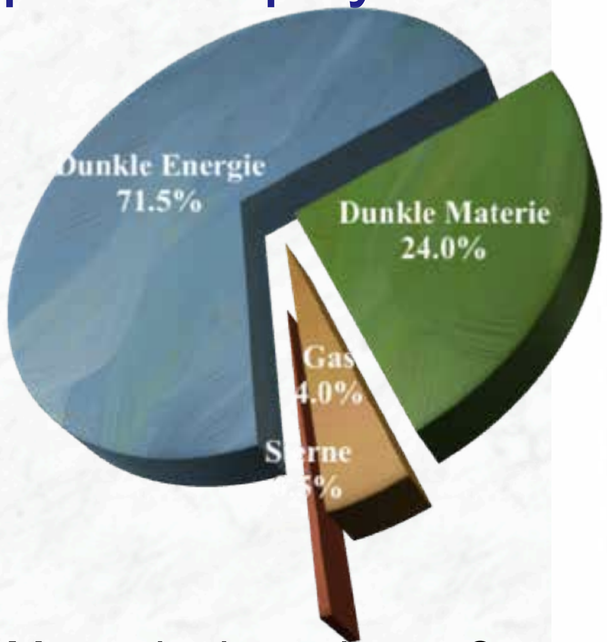
Physik am Large Hadron Collider

-Von der Entdeckung des Higgs-Teilchens zur Suche nach Neuer Physik-



Prof. Karl Jakobs
Physikalisches Institut
Universität Freiburg

Key questions of particle physics



1. Mass

What is the origin of mass?
Does the Higgs particle exist?

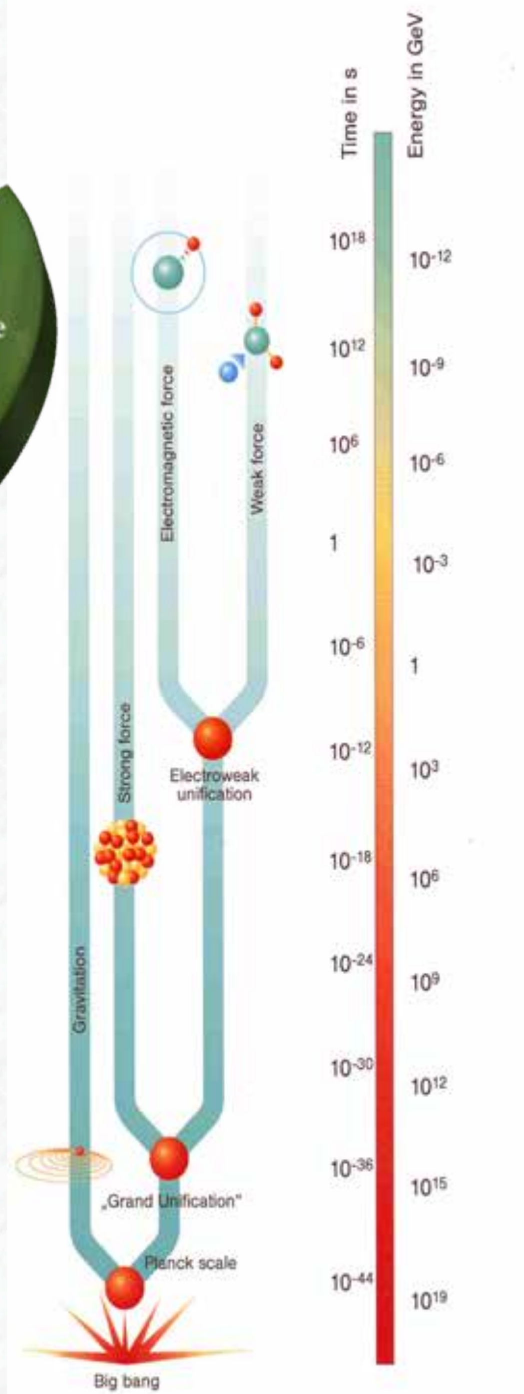
2. Unification

- Can the interactions be unified?
- Are there new types of matter, e.g. supersymmetric particles ? Are they responsible for the Dark Matter in the universe?

3. Flavour

- Why are there three generations of particles?
- What is the origin of the matter-antimatter asymmetry (Origin of CP violation)

Answers to some of these questions are expected on the TeV energy scale, i.e. at the LHC

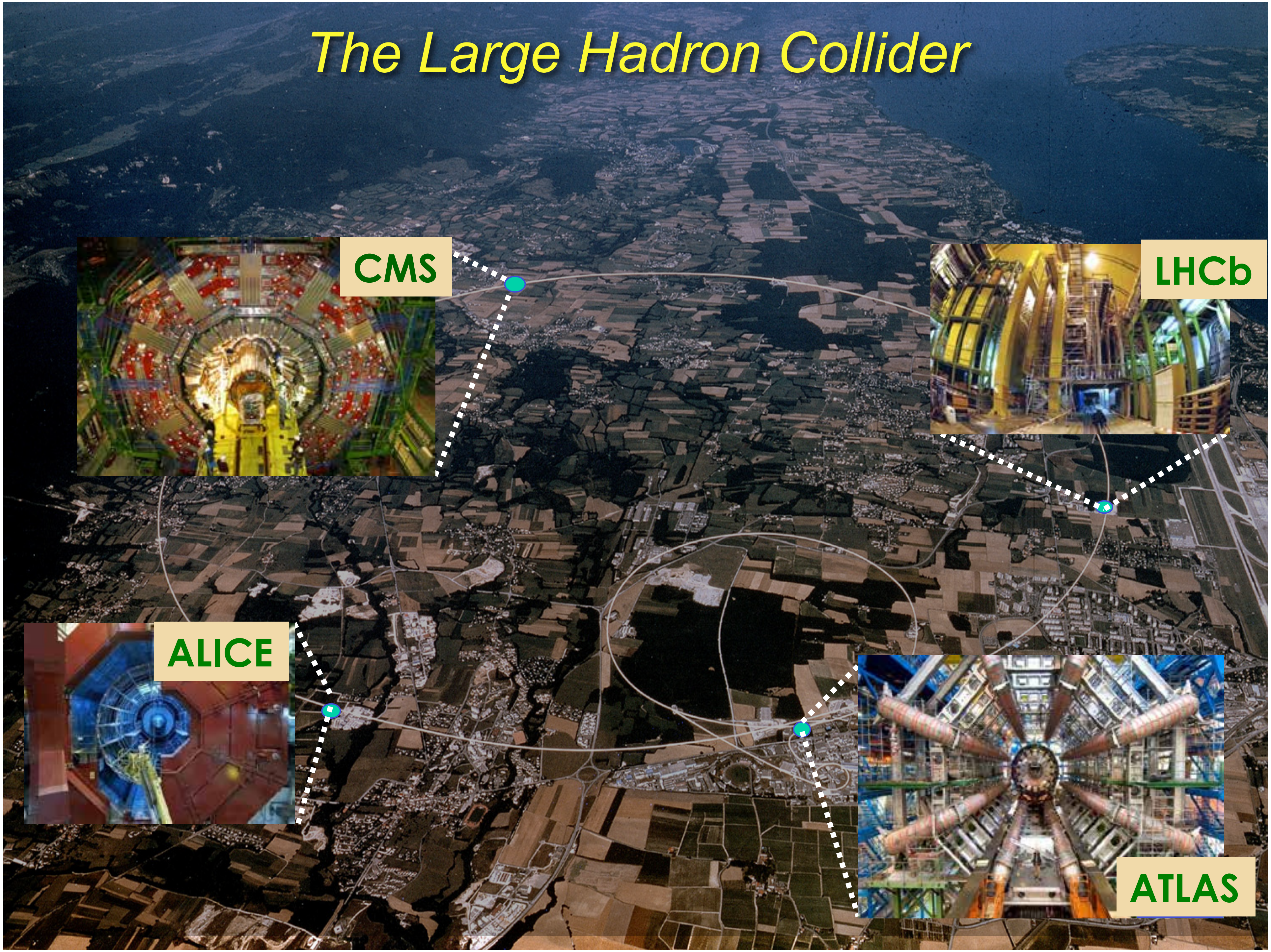


Nobel-Preis für Physik 2013:

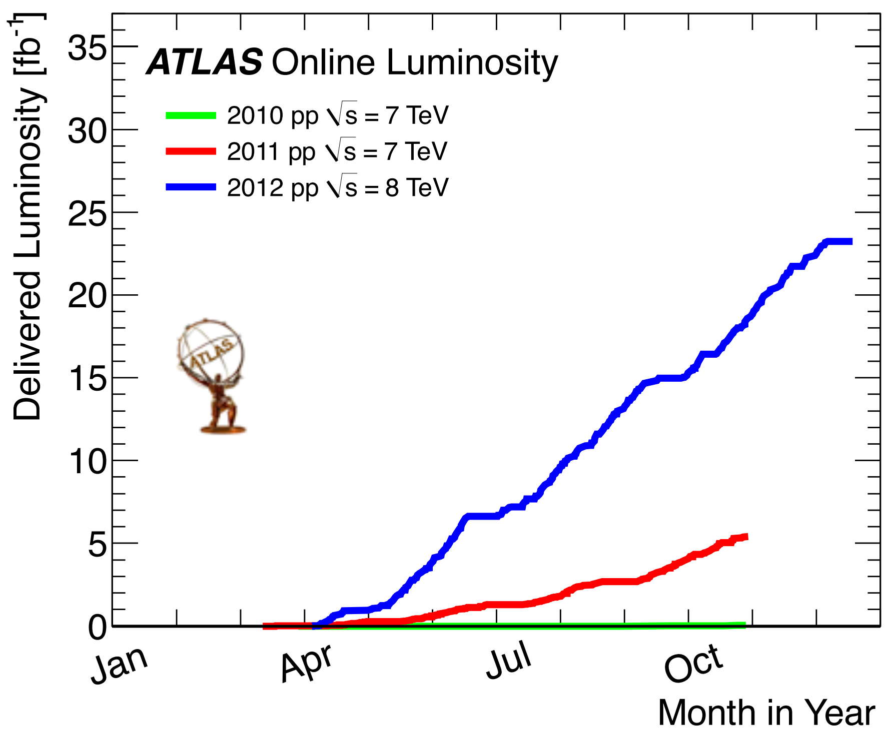
François Englert und Peter Higgs

“ … for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of sub-atomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN’s Large Hadron Collider.”

The Large Hadron Collider



Data taking at the LHC (2010-2012)



Until end 2012:

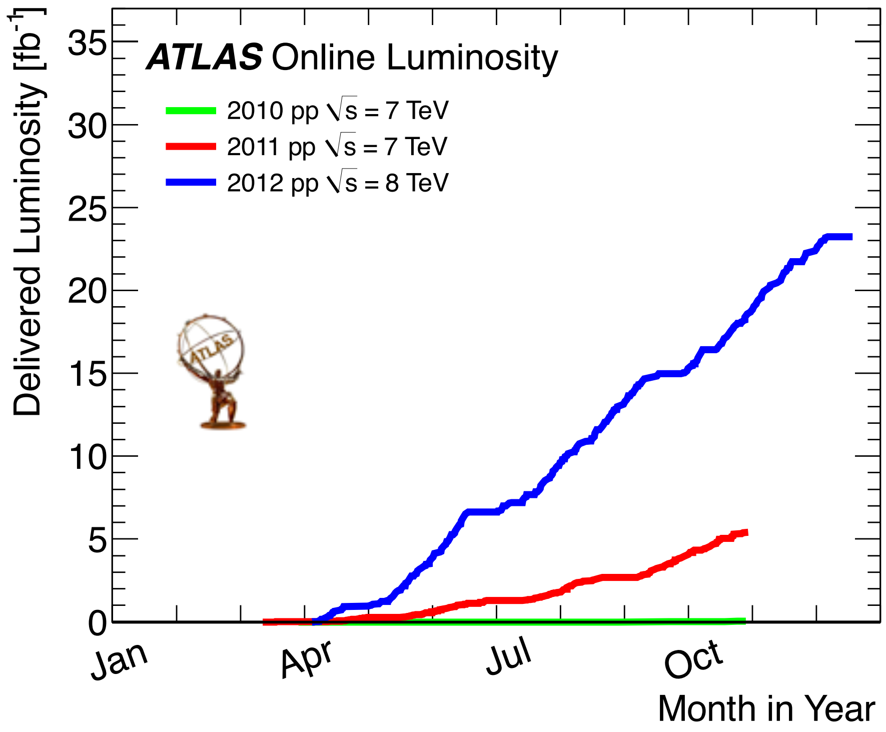
> 10^{15} pp collisions
~10^{10} pp collisions recorded

$25 \cdot 10^6$ $Z \rightarrow \mu\mu$ decays produced

Steve Meyers at "Physics at LHC 2012":

"The first two years of LHC operation have produced sensational performance: well beyond our wildest expectations. The combination of the performance of the LHC machine, the detectors and the GRID have proven to be a terrific success story in particle physics."

Data taking at the LHC (2010-2012)



Until end 2012:

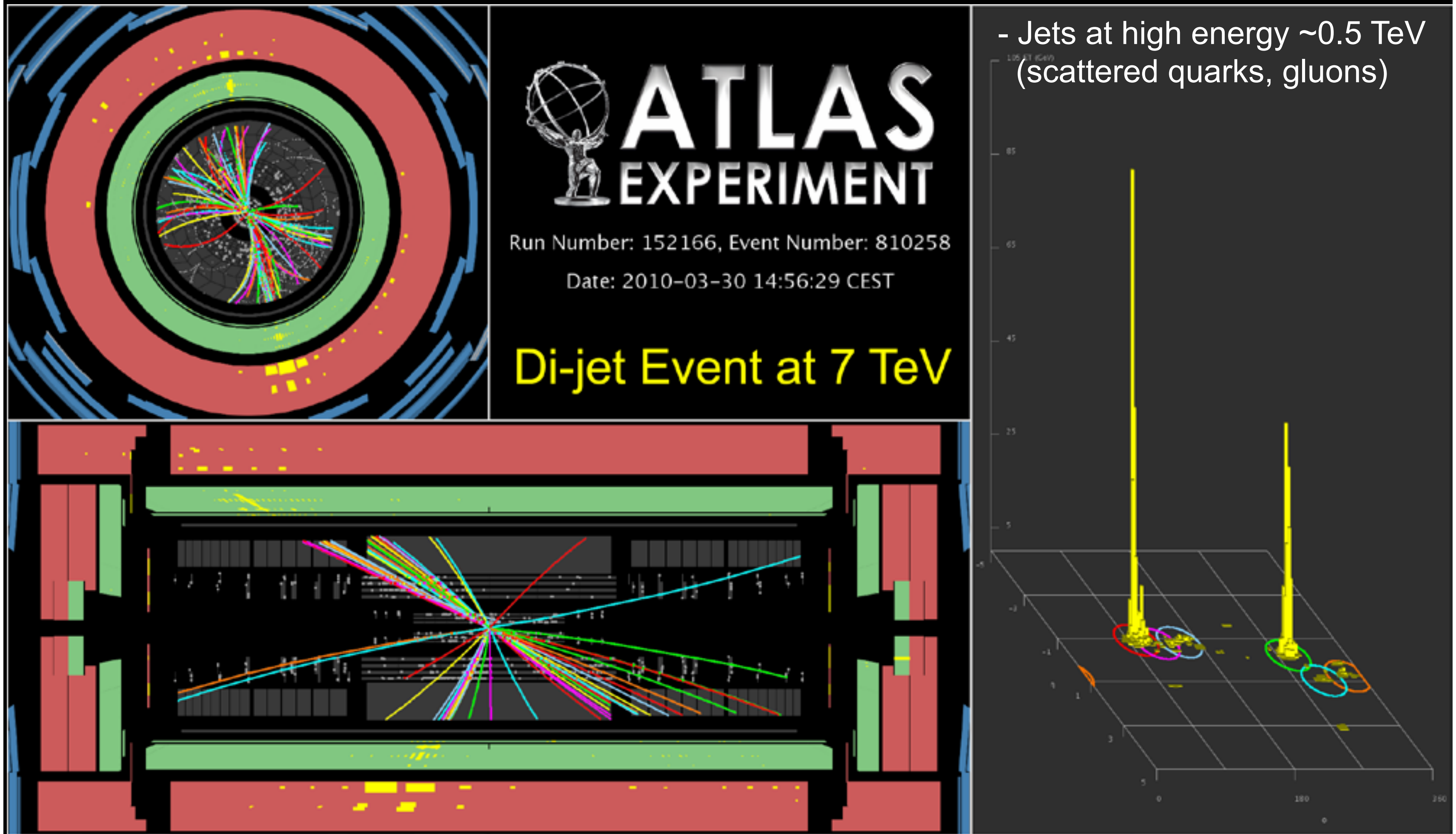
> 10^{15} pp collisions
~10^{10} pp collisions recorded

$25 \cdot 10^{6}$ Z → $\mu\mu$ decays produced

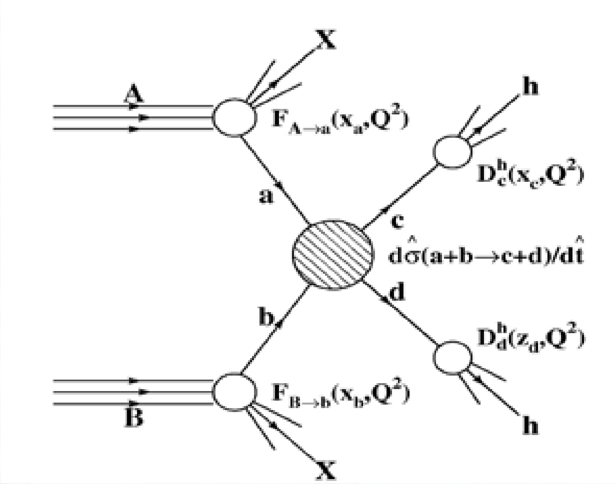
- Excellent LHC performance
  Peak luminosities > 7 10^{33} cm^{-2} s^{-1} (world record, 2012)

- Excellent performance of the experiments:
  - Data recording efficiency ~93.5%
  - Working detector channels >99%
  - Speed of data analysis

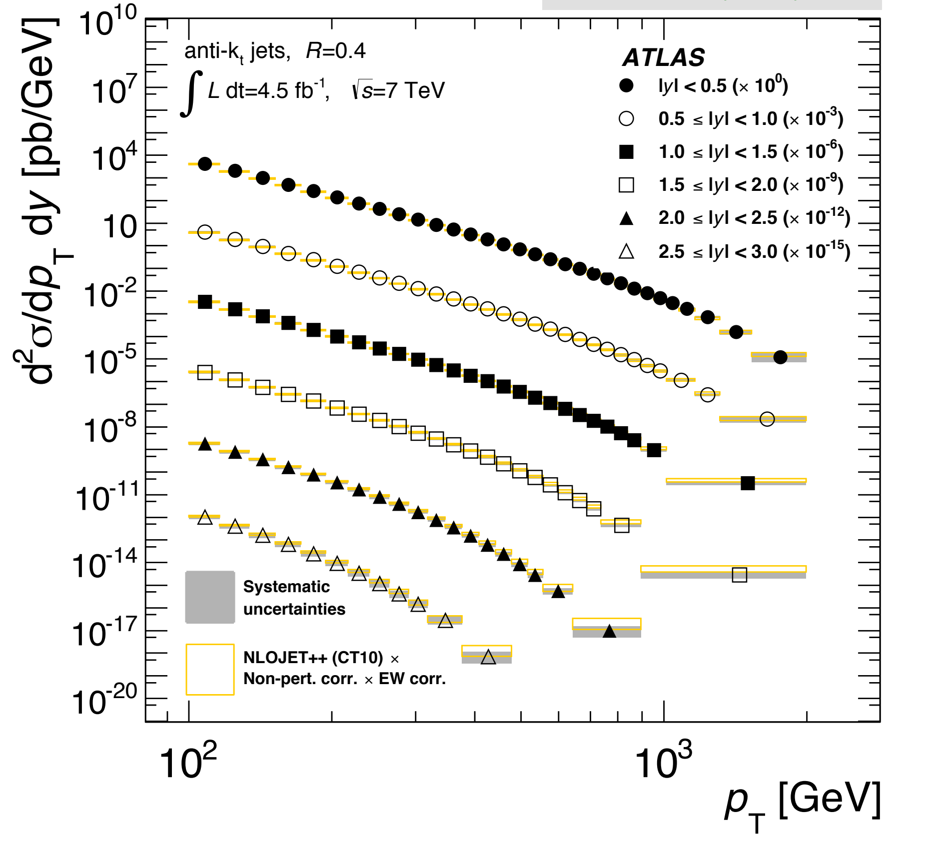
Since 30. March 2010: collisions at 7/8 TeV
(....first interesting physics events)



Double differential cross sections, as a function of p_T and rapidity y (full 2011 data set)

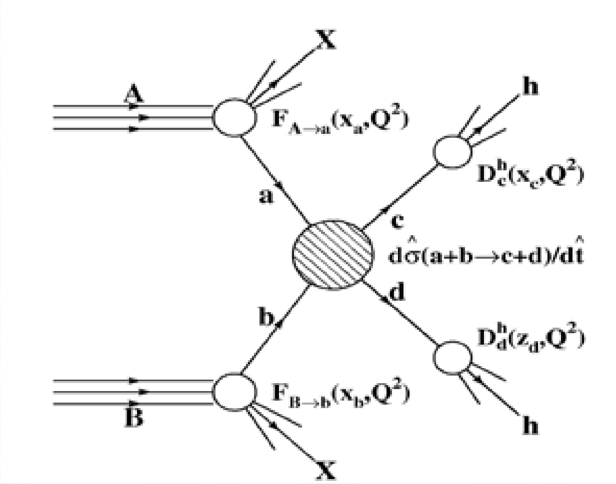


JHEP 1502 (2015) 153

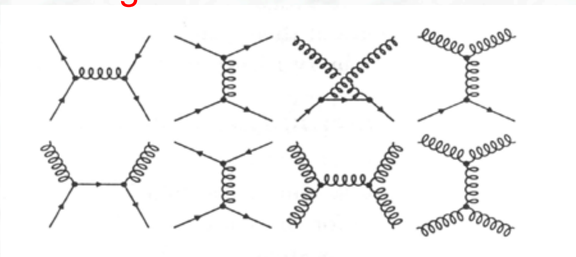


rapidity
$$y = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right) = \tanh^{-1}\left(\frac{p_z}{E}\right)$$

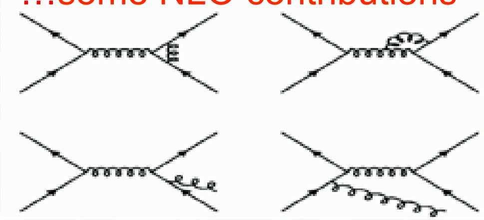
Double differential cross sections, as a function of p_T and rapidity y (full 2011 data set)



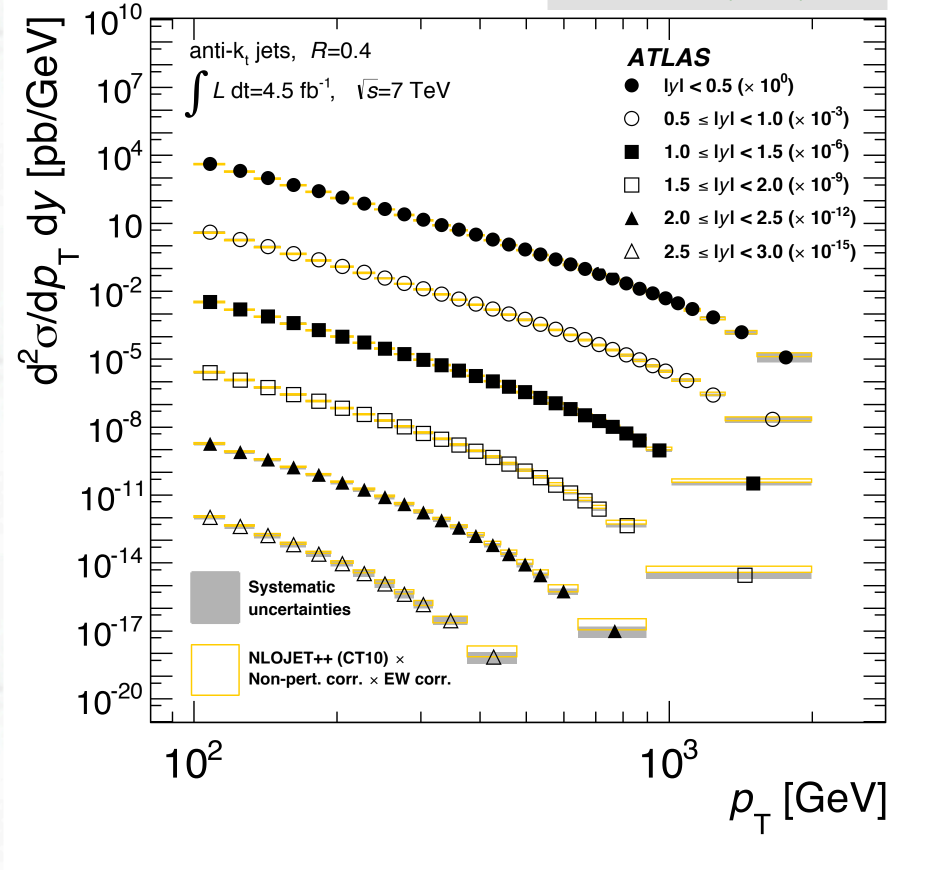
Leading order



…some NLO contributions



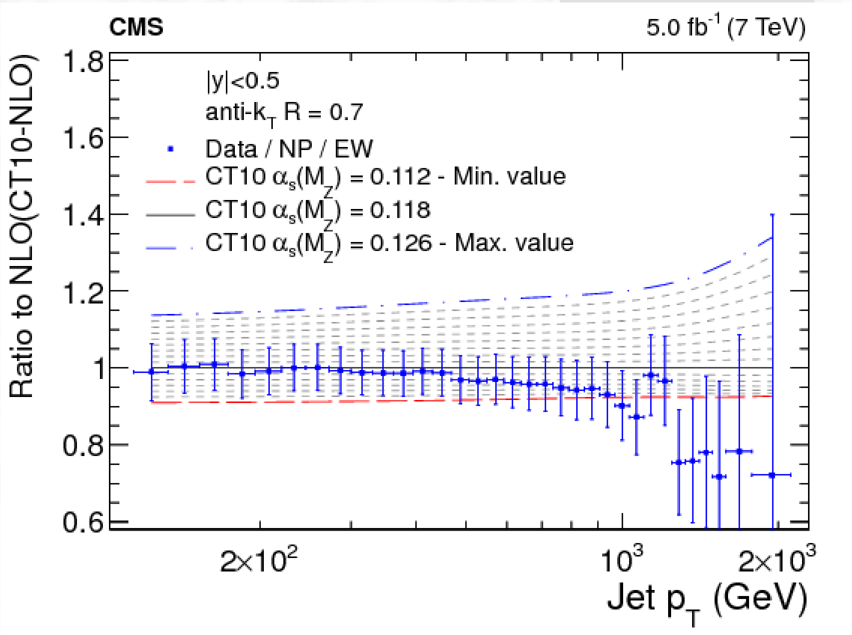
JHEP 1502 (2015) 153

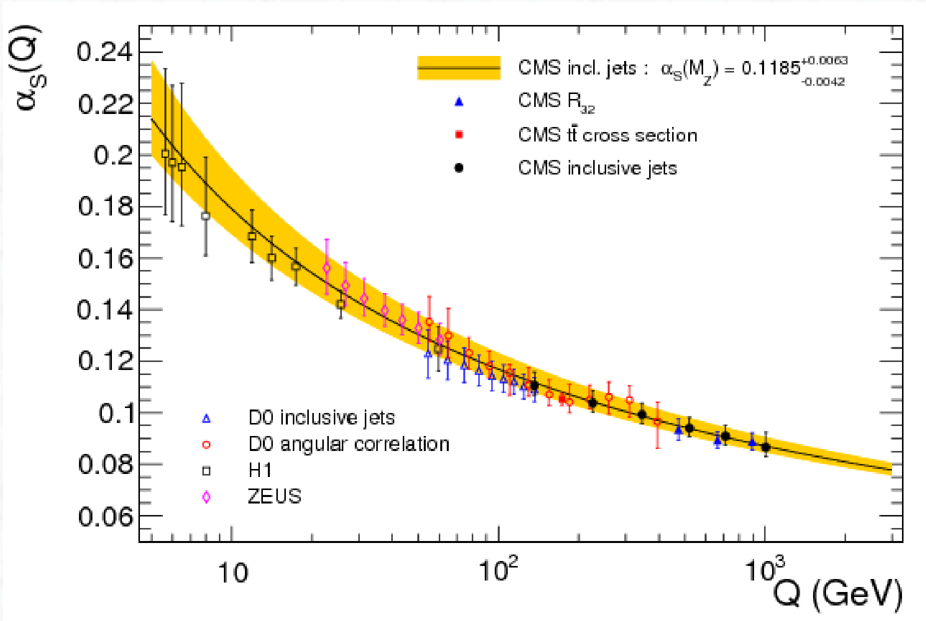


- Data are well described by NLO perturbative QCD calculations (NLOJet++), within the experimental and theoretical uncertainties

Towards precision tests of QCD at the LHC

arXiv:1410.6765





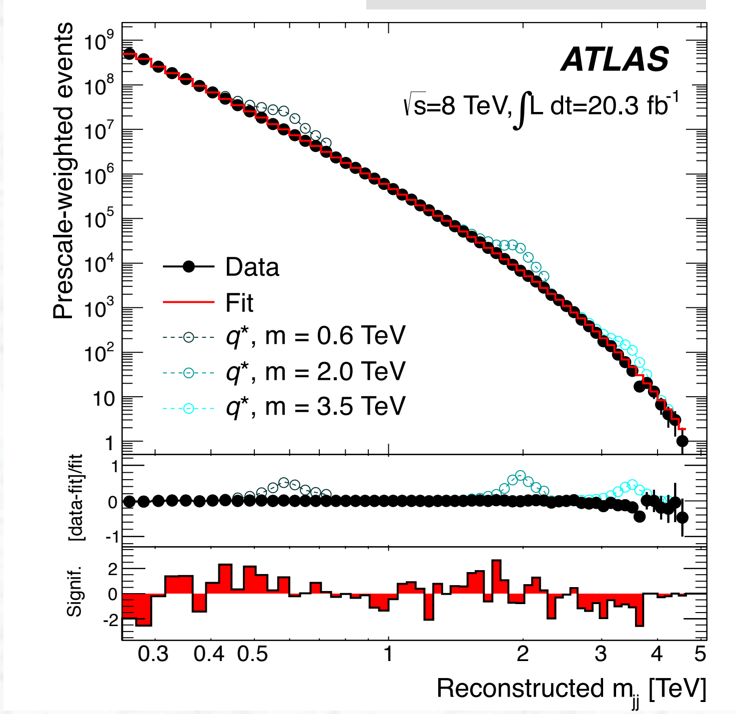
$$\alpha_s\,(m_Z) = 0.1185 \pm 0.0019\,(\mathrm{exp})\ ^{+0.0060}_{-0.0037}\,(\mathrm{theo})$$

In addition: Sensitivity to New Physics

- Di-jet mass spectrum provides large sensitivity to new physics

  e.g. resonances decaying into qq, excited quarks q*, ….

JHEP 1405 (2014) 059

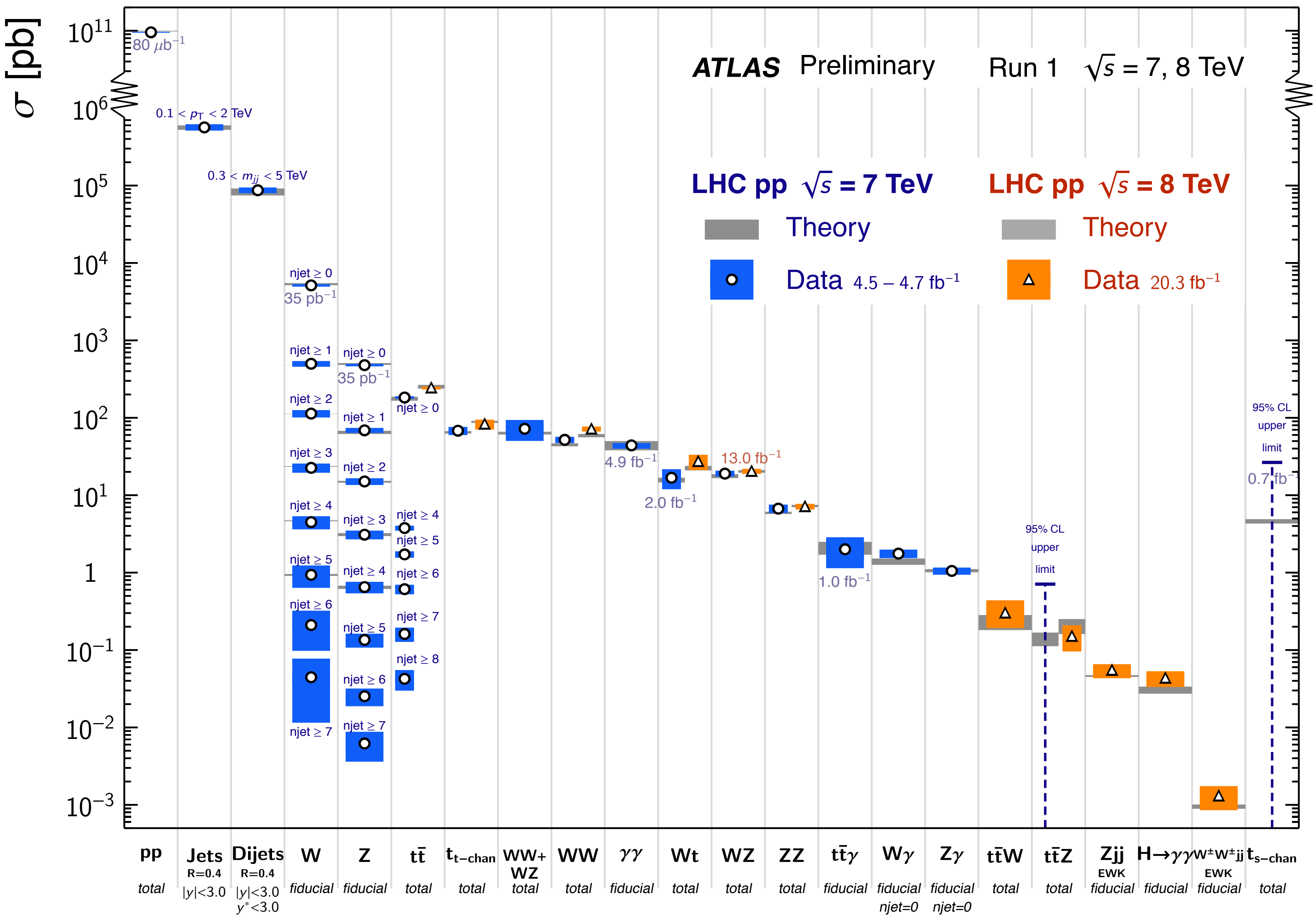


CDF (Tevatron), L =1.13 fb^{-1}: 0.26 < m_{q*} < 0.87 TeV
$\sqrt{s}$ = 1.96 TeV
ATLAS (LHC), L = 0.000315 fb^{-1} exclude (95% C.L) q* mass interval
$\sqrt{s}$ = 7 TeV 0.30 < m_{q*} < 1.26 TeV

ATLAS (LHC), L = 20.3 fb^{-1}, 8 TeV: exclude (95% C.L.) m_{q*} < 4.09 TeV

Standard Model Production Cross Section Measurements

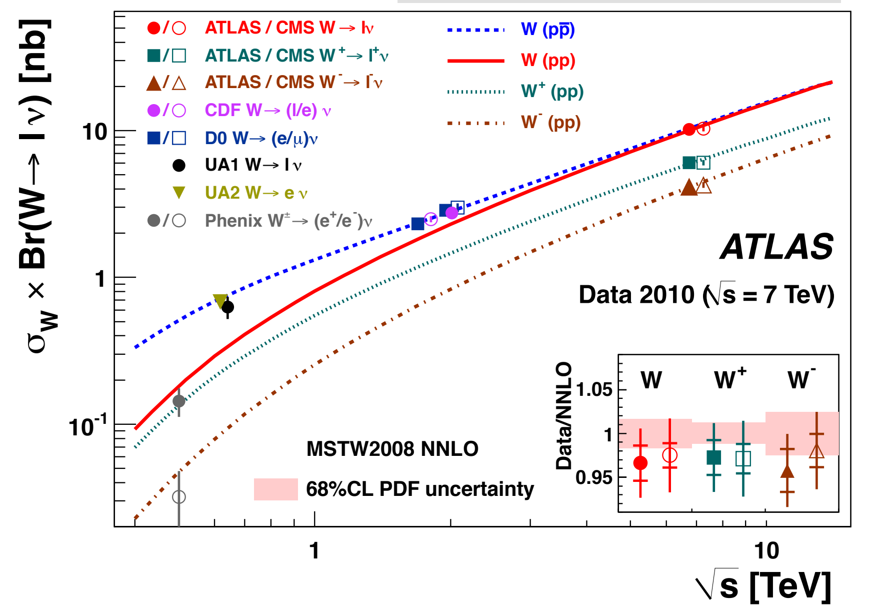
Status: July 2014

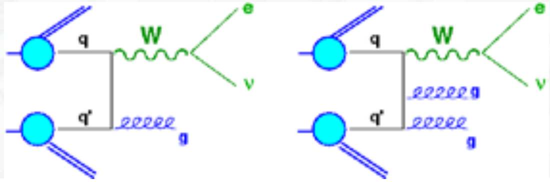


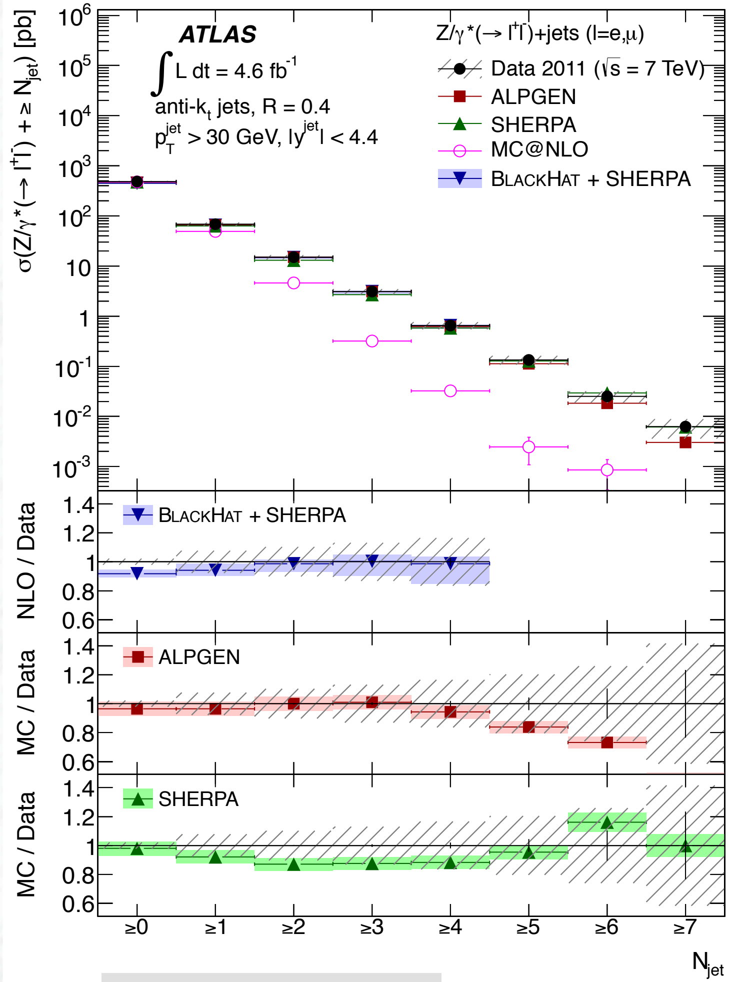
(For theorists: *LHC: = Long and Hard Calculations*)

Production of W and Z bosons at the LHC

Phys. Rev. D85 (2012) 072004



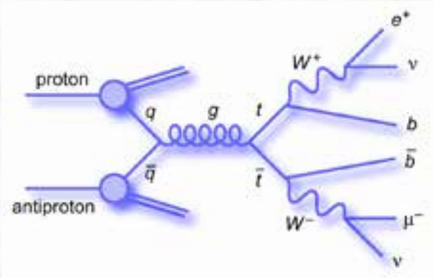


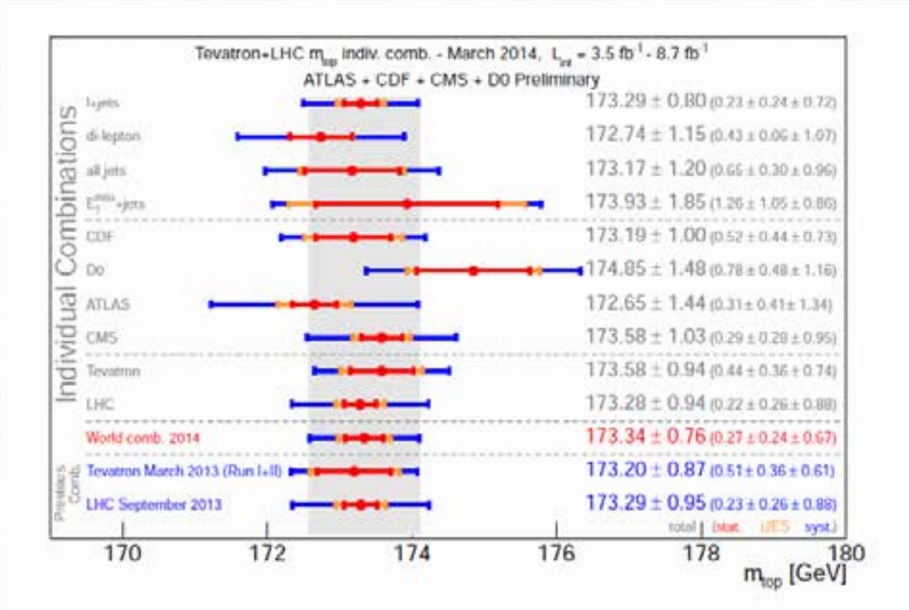


JHEP 1307 (2013) 032

Theoretical predictions (NNLO accuracy) in very good agreement with the experimental measurements

Top Quarks mass: precision physics

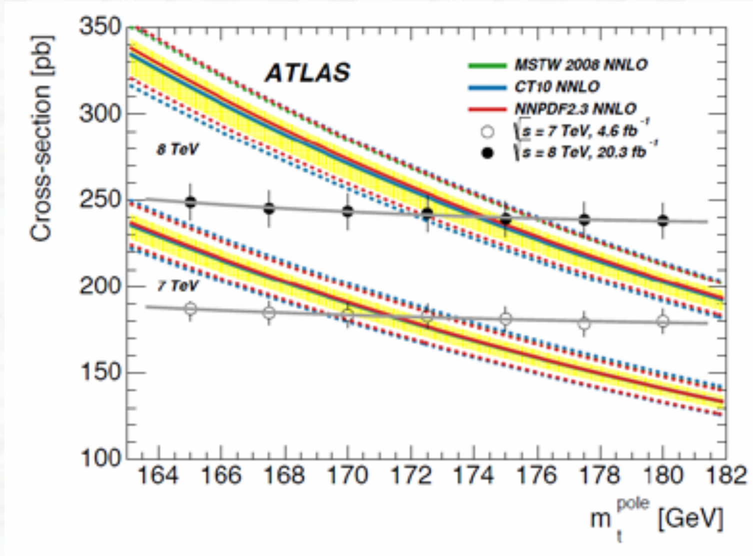




ATLAS + CMS: m_t = 173.29 ± 0.95 GeV

World combination: m_t = 173.34 ± 0.76 GeV

Precision: ±0.55% (LHC), ±0.44% (world)

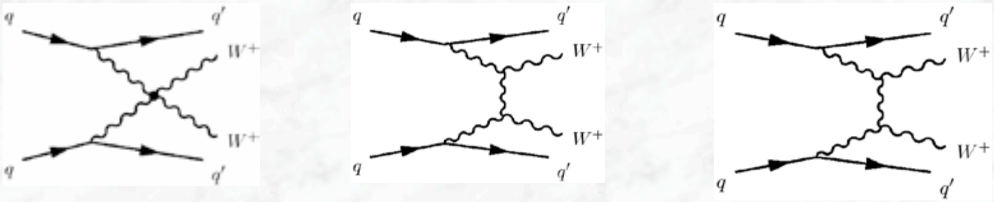


Top quark mass measurement from cross section:

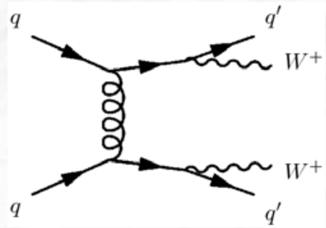
$$\boxed{m_t^{\text{pole}} = 172.9^{+2.5}_{-2.6}\ \text{GeV}}$$

Evidence for El.weak $W^{\pm}W^{\pm}jj$ production

- Higgs boson needed in the SM to regularise VV scattering at high energies;
- Key experimental process: $W^{\pm}W^{\pm}$ scattering

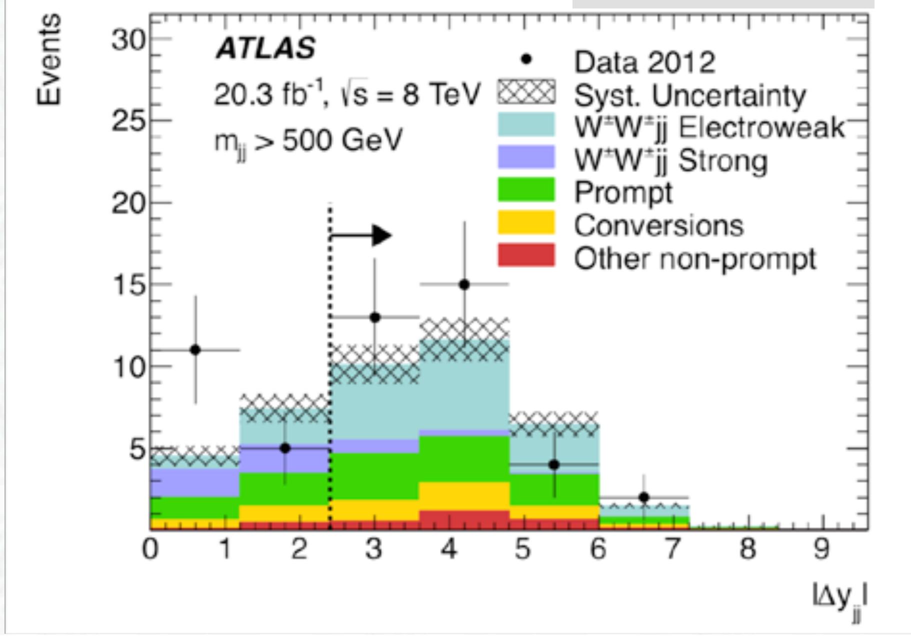


El. weak production



Strong production

PRL 113 (2014) 141803



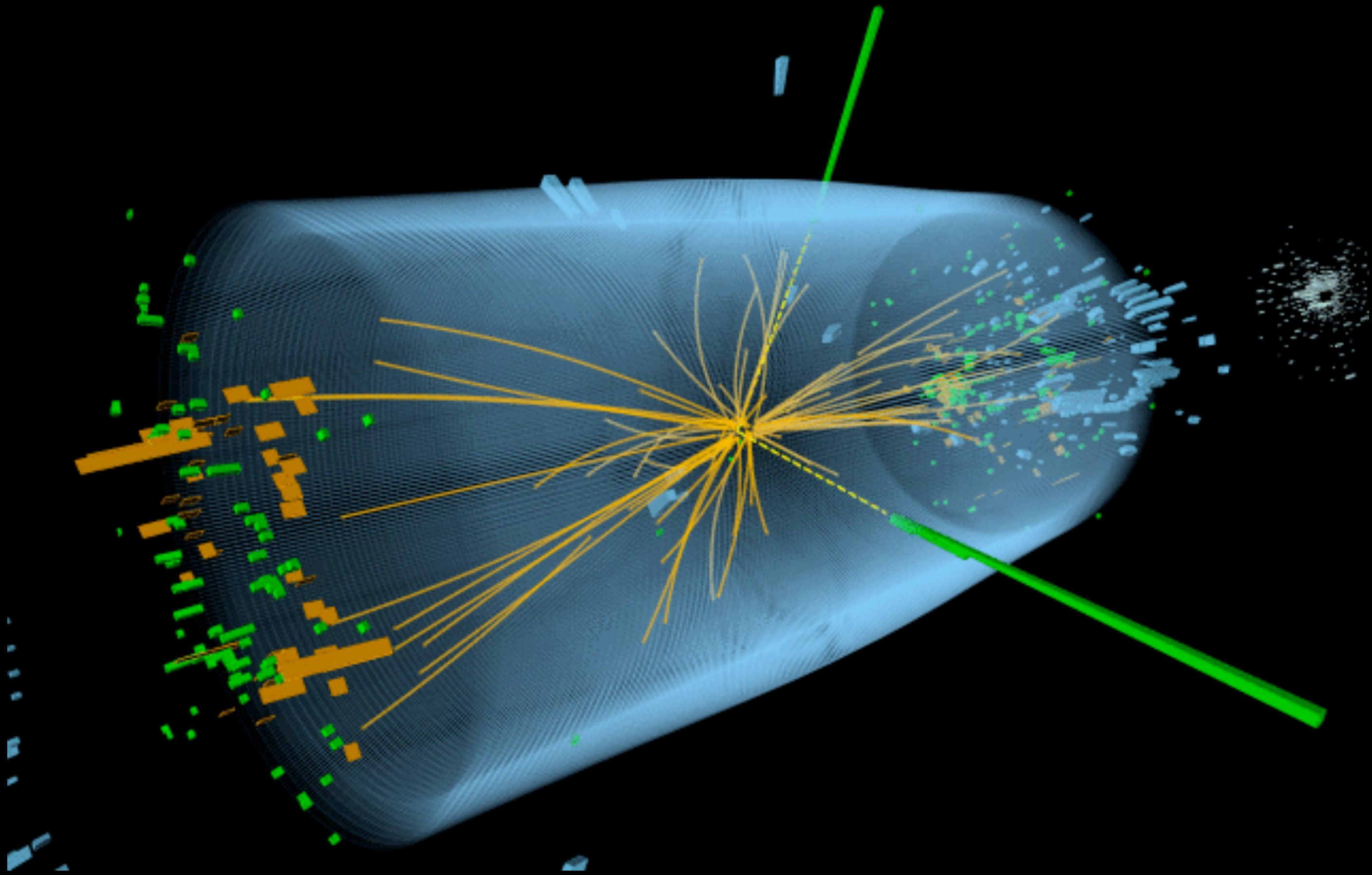
VBS enhancement by cutting on mass (m_{jj}) and rapidity separation Δy_{jj}

ATLAS: 3.6σ for el.weak production

CMS: 2.0σ PRL 114 (2015) 051801

(expected: about 3.0σ)

Discovery of a Higgs boson at the LHC



Expected number of decays in the data:
m_H = 125 GeV

~ 950 H → $\gamma\gamma$
~ 60 H → ZZ* → 4 ℓ
~ 9000 H → WW* → $\ell\nu$ $\ell\nu$

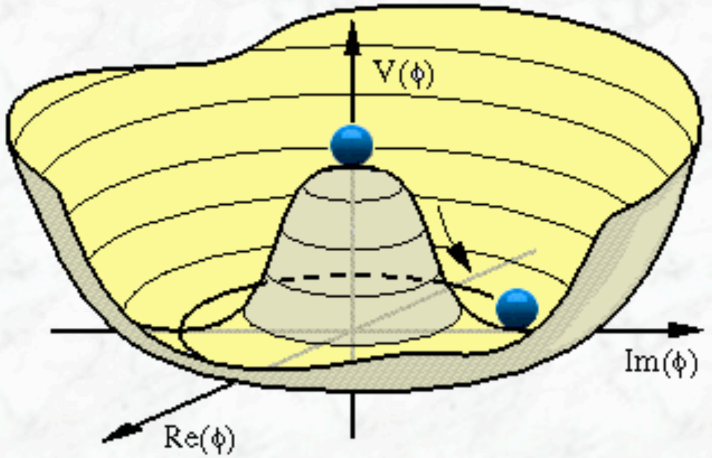
The Brout-Englert-Higgs Mechanism

R. Brout (1964)

P. Higgs (1964)

F. Englert and R. Brout. Phys. Rev. Lett. 13 (1964) 321;
P.W. Higgs, Phys. Lett. 12 (1964) 132, Phys. Rev. Lett. 13 (1964) 508;
G.S. Guralnik, C.R. Hagen, and T.W.B. Kibble. Phys. Rev. Lett. 13 (1964) 585.

The Brout-Englert-Higgs Mechanism



Complex scalar (spin-0) field ϕ with potential:

$$V(\phi) = \mu^2(\phi^* \phi) + \lambda(\phi^* \phi)^2$$

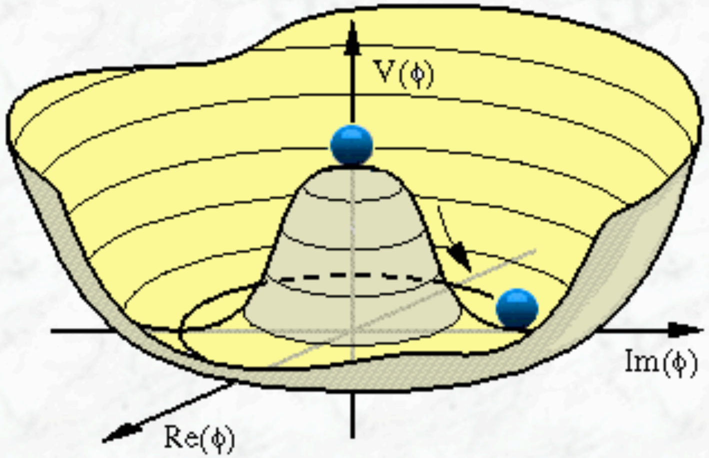
For $\lambda > 0$, $\mu^2 < 0$:
"Spontaneous Symmetry Breaking"

→ Omnipresent Higgs field: vacuum expectation value $v \approx 246$ GeV

→ Higgs Boson (mass not predicted, except $m_H <$ ~1000 GeV)

→ Particles acquire mass through interaction with the Higgs field

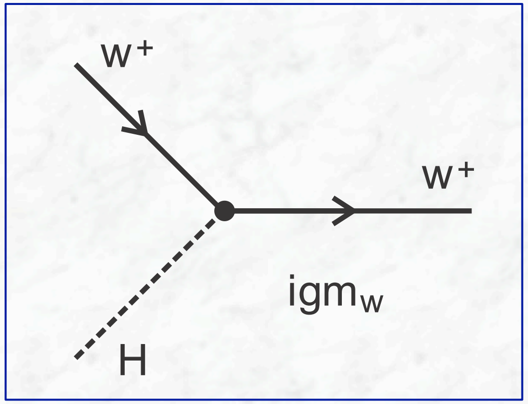
The Brout-Englert-Higgs Mechanism

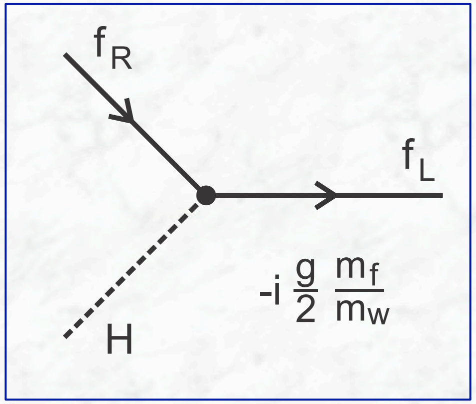


Complex scalar (spin-0) field ϕ with potential:

$$V(\phi) = \mu^2(\phi^*\phi) + \lambda(\phi^*\phi)^2$$

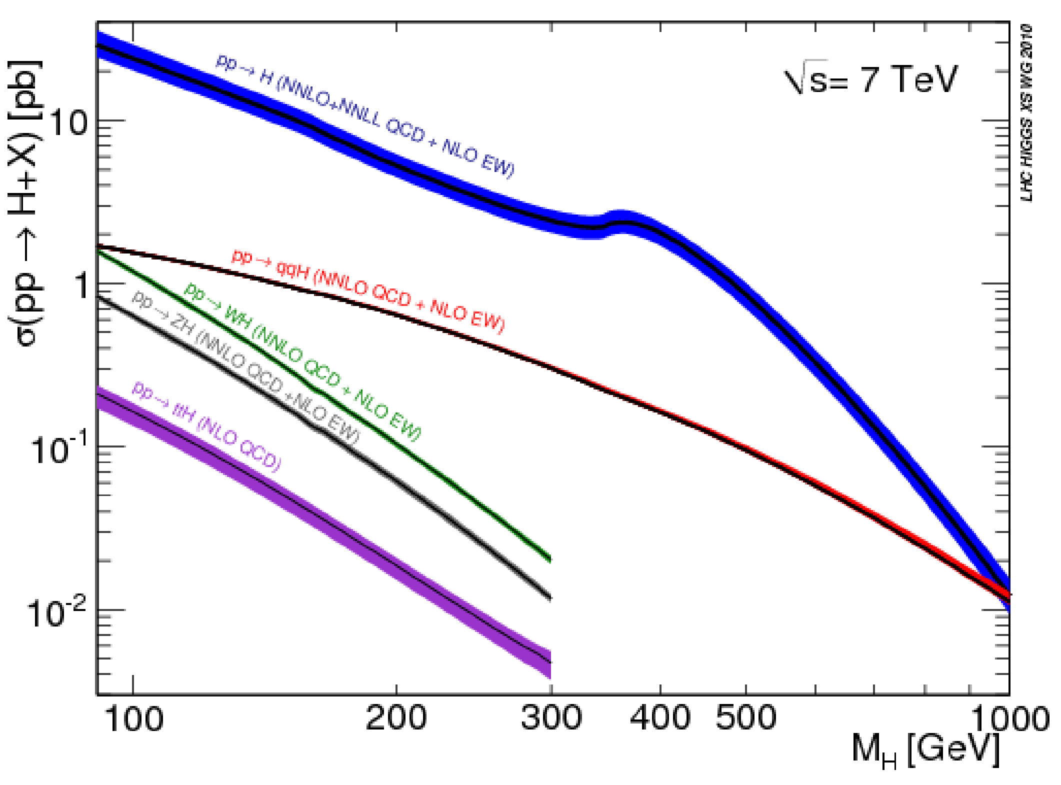
For $\lambda > 0$, $\mu^2 < 0$:
"Spontaneous Symmetry Breaking"

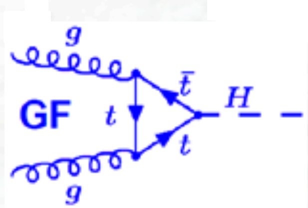




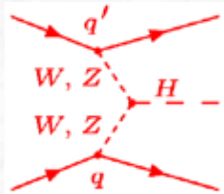
- Couplings proportional to mass

Higgs Boson Production at the LHC

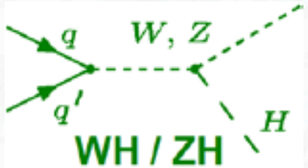




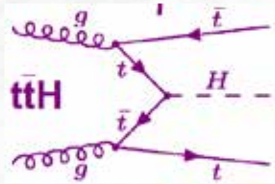
Gluon fusion



Vector boson fusion



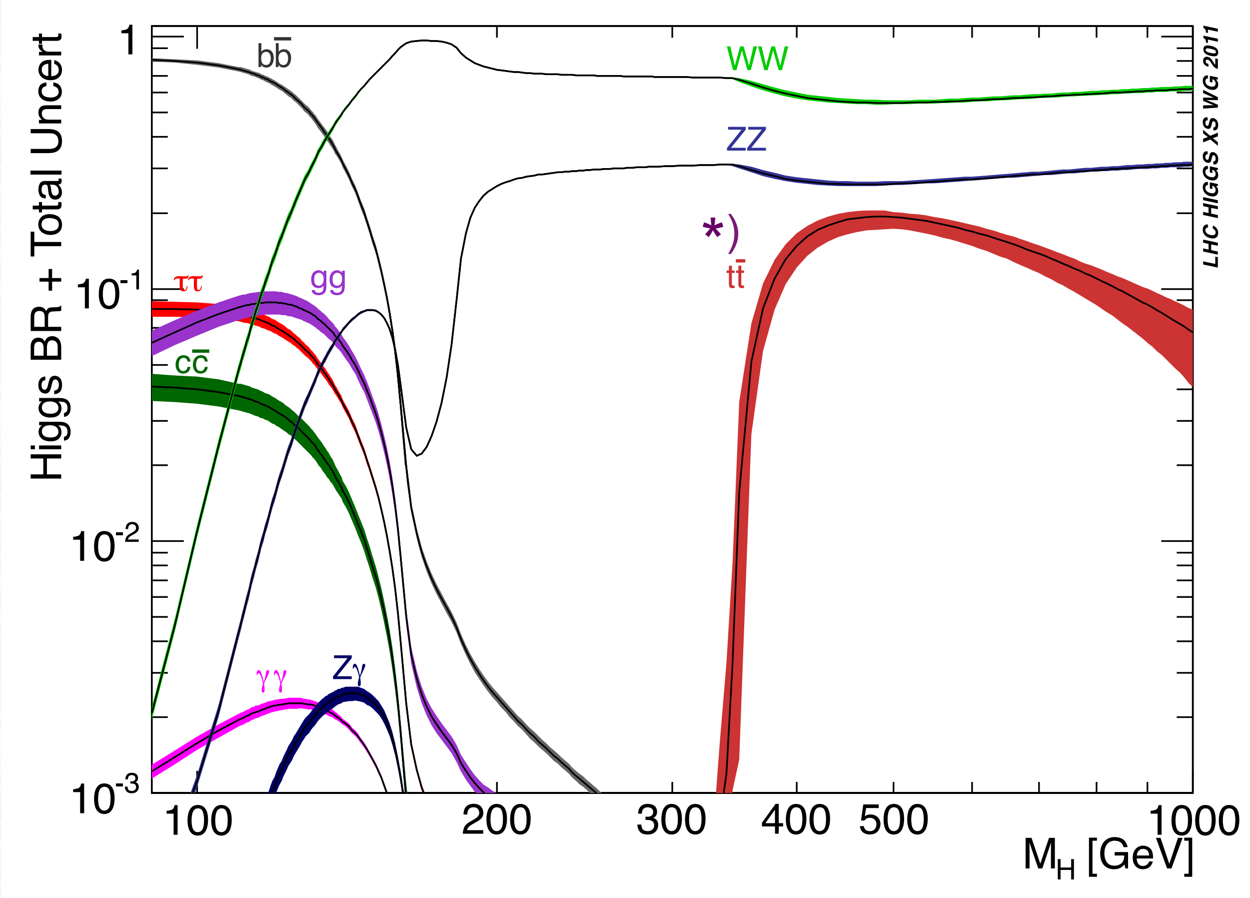
WH/ZH associated production



tt associated production

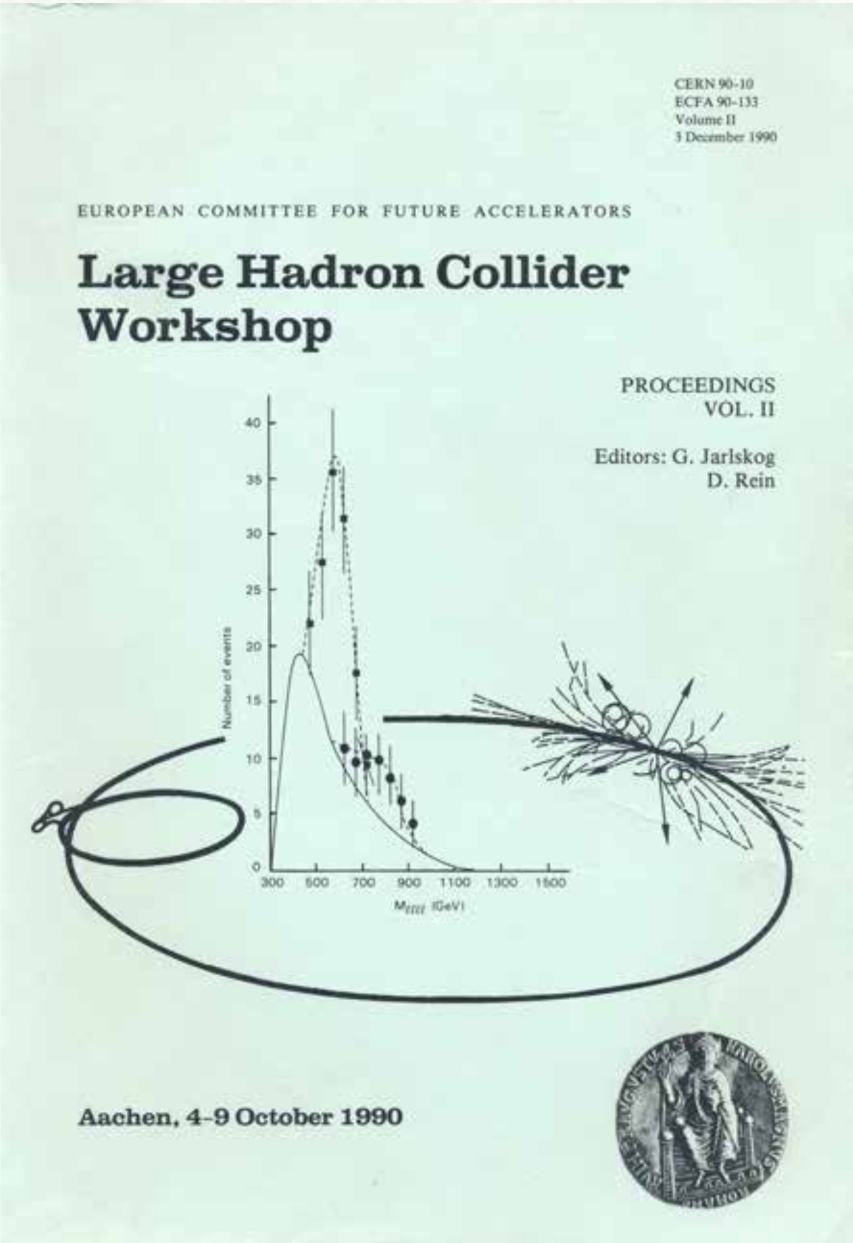
*) LHC Higgs cross-section working group;
(N)NLO calculations: Huge theory effort

Higgs Boson Decays



*) LHC Higgs cross-section working group

The first serious studies



EXPERIMENTAL REVIEW OF THE SEARCH FOR THE HIGGS BOSON

Daniel Froidevaux

This review will limit its scope to the search for the Standard Model Higgs boson, H, at the LHC, for $\sqrt{s}$ = 16 TeV. Integrated luminosities of 10^5 pb^{-1} per year of running will be used throughout, unless otherwise stated.

The search for charged Higgs bosons will be covered by the top physics working group [1], and the search for scalar or pseudoscalar neutral Higgs bosons from the Minimal Supersymmetric Standard Model has been summarised in a theoretical overview [2], since no detailed experimental simulations have yet been carried out in this context.

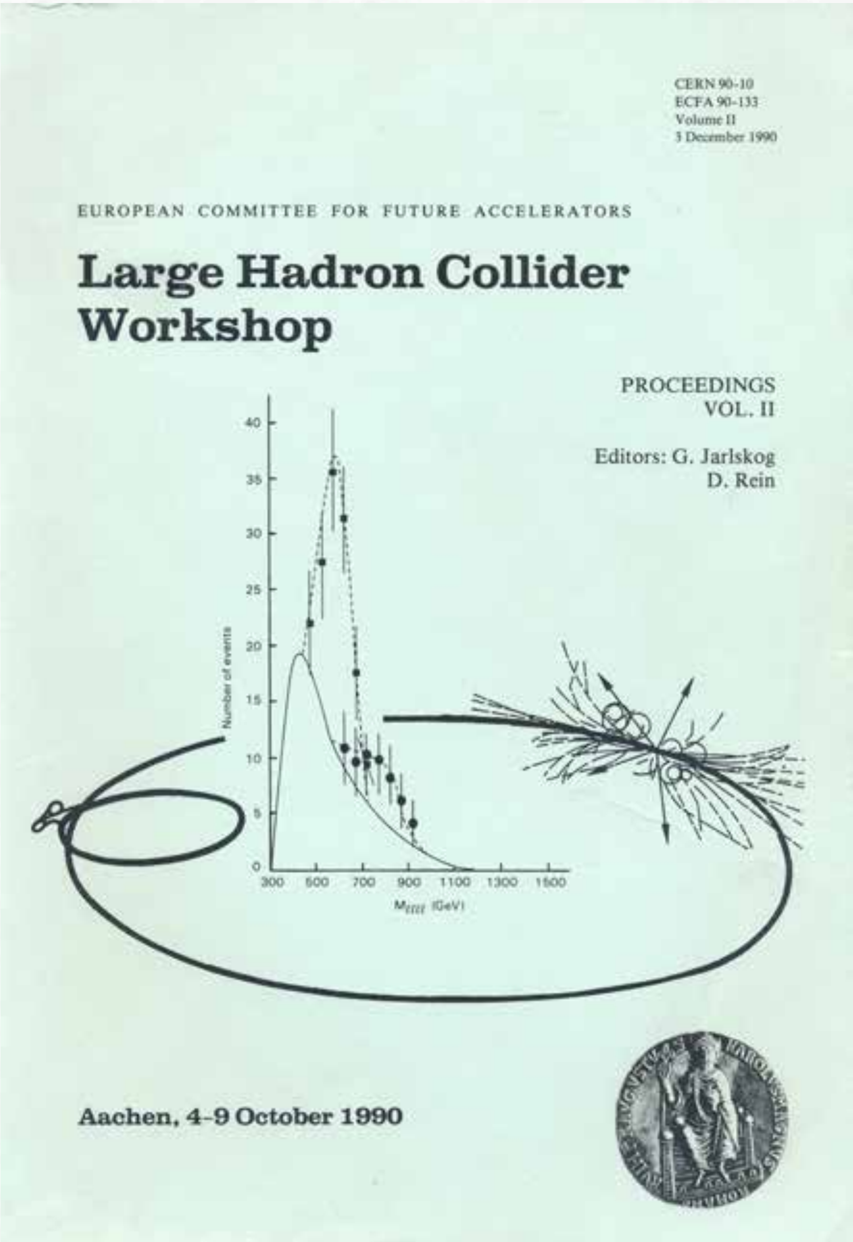
This review would not have been possible without the work of many people, theorists and experimentalists, who have participated in the Higgs working group studies for the Aachen workshop over a relatively short period of about 9 months. It will be divided into four main chapters :

1. $H \to ZZ, Z^*Z^* \to$ 4 leptons
M. Della Negra, D. Froidevaux, K. Jakobs, R. Kinnunen, R. Kleiss, A. Nisati and T. Sjöstrand

2. Intermediate mass Higgs
a) $H \to \gamma\gamma$, WH with $W \to \ell\nu$, $H \to \gamma\gamma$, and ZH with $Z \to \ell\ell$, $H \to \gamma\gamma$
L. DiLella, A. Djouadi, R. Kleiss, Z. Kunszt, G. Pancheri, C. Seez, W.J. Stirling and T. Virdee
This topic is reviewed in detail in the summary given by C. Seez [3]. Only the main conclusions will be discussed here.
b) $H \to \tau\tau$
F. Anselmo, K. Bos, L. DiLella and B. Van Eijk
c) WH with $W \to \ell\nu$, $H \to jj$ or $b\bar{b}$ and ZH with $Z \to \ell\ell$, $H \to jj$ or $b\bar{b}$
L. Poggioli

3. $H \to ZZ \to \ell\ell\nu\nu$, $H \to ZZ \to \ell\ell jj$, $H \to WW \to \ell\nu jj$ for m_H large
U. Baur, D. Froidevaux, E.W.N. Glover and M.H. Seymour

Conclusions on the Higgs boson discovery potential



Intermediate mass Higgs range $120 < m_H < 2\ m_Z$:

(i) *"In this mass range, the Higgs boson can be detected in the channel $H \rightarrow ZZ^* \rightarrow \ell\ell\ \ell\ell$, provided the detector can identify low energy isolated electrons and muons"*

(ii) *"With an integrated luminosity of 10^5 pb^{-1}, a signal from $H \rightarrow \gamma\gamma$ decays can be observed for $80 < m_H < 150$ GeV. This, however, imposes severe constraints on the detector design."*

(iii) *"None of the other possible channels, which have been studied, provides any hope to discover a Higgs boson in this mass range."*

Further major physics steps

(i) The H → WW* decay channel:

1997: M. Dittmar and H. Dreiner, H → WW → ℓν ℓν as the dominant search mode at the LHC from m_H = 150 – 180 GeV, Phys. Rev. D55 (1997) 167.

1999: Established in ATLAS and CMS Physics TDRs

(ii) The qqH → qq $\tau\tau$ decay mode:

1999: D. Rainwater, D. Zeppenfeld: Vector boson fusion production at low mass, qqH → qq WW, qqH → qq$\tau\tau$

2003: ATLAS Vector boson fusion paper, EPJ-C

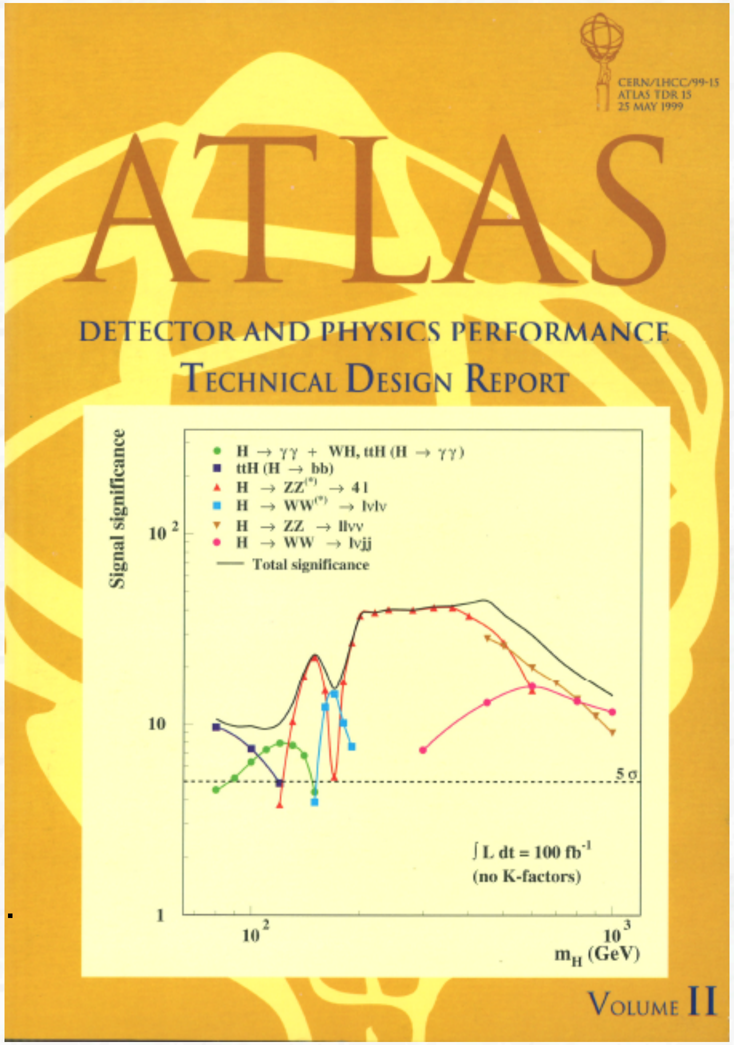
Prospects for the search for a standard model Higgs boson in ATLAS using vector boson fusion

S. Asai[8], G. Azuelos[5], C. Buttar[7], V. Cavasinni[6], D. Costanzo[6,*], K. Cranmer[9], R. Harper[7], K. Jakobs[4], J. Kanzaki[3], M. Klute[1], R. Mazini[5], B. Mellado[9], W. Quayle[9], E. Richter-Wąs[2], T. Takemoto[3], I. Vivarelli[6], Sau Lan Wu[9]

(iiii) H → bb revival

2008: J. Butterworth et al., *Jet substructure as a new Higgs search tool at the LHC*, Phys. Rev. Lett.100 (2008) 242001.

2009: ATLAS sensitivity study: ATL-PHYS-PUB-2009-088.



Little Higgs models

Composite Higgs bosons

MSSM Higgs bosons

Dark Higgs

More Higgs bosons

SUSY Higgs

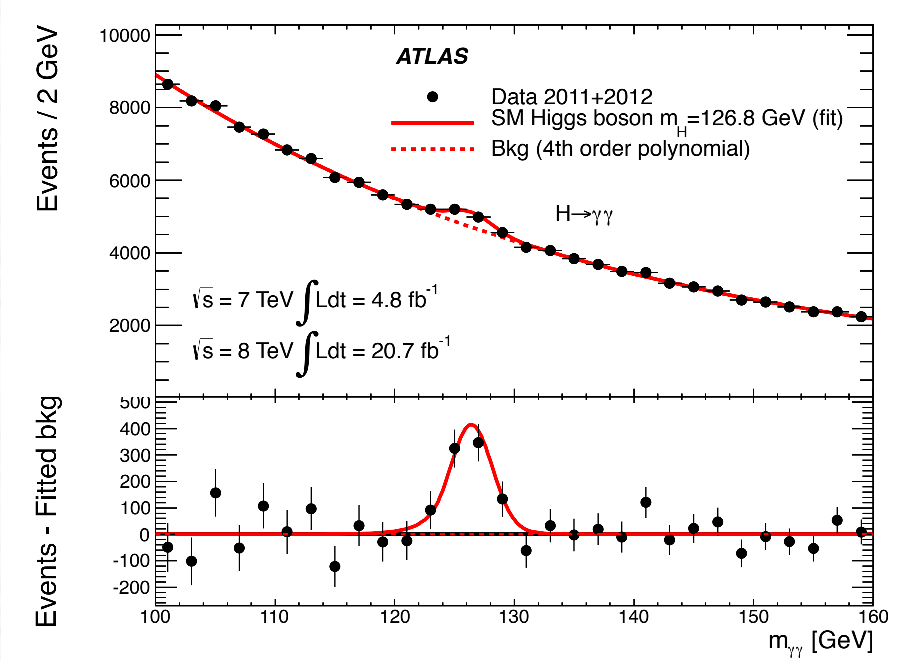
Ausgeschmierte Higgs

Heidi Higgs

No Higgs at the LHC

Result of the ATLAS search for H → $\gamma\gamma$

Phys. Lett. B726 (2013) 88

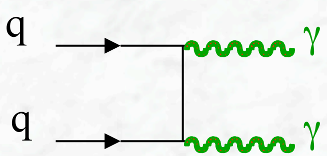


p-value for consistency of data with background-only: $\sim 10^{-13}$ (7.4σ observed)

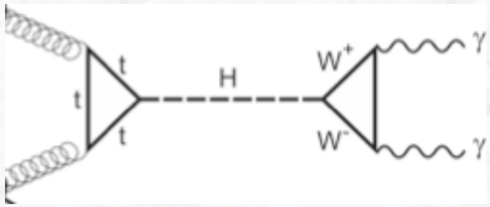
Measured signal strengths:

ATLAS: $\mu = \sigma_{obs} / \sigma_{SM} = 1.17 \pm 0.27$

CMS: $\mu = \sigma_{obs} / \sigma_{SM} = 1.14 \pm 0.26$



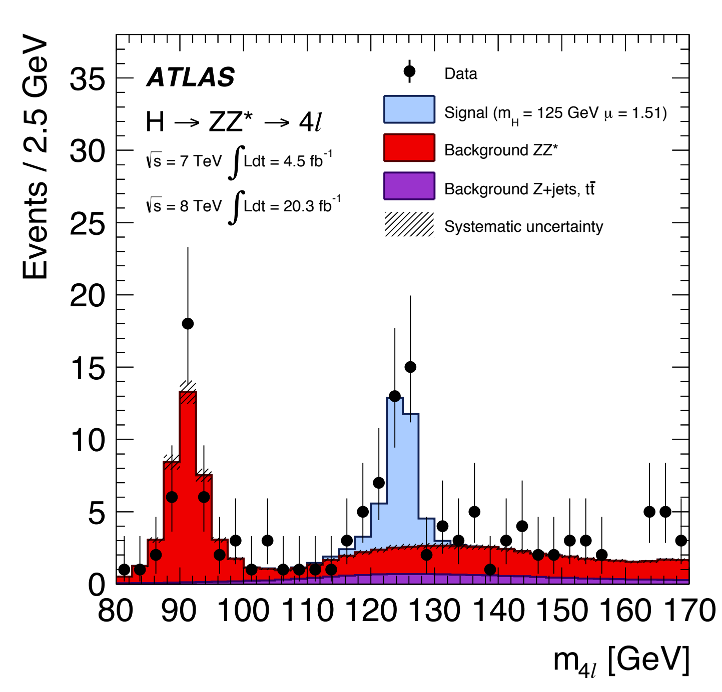
Background



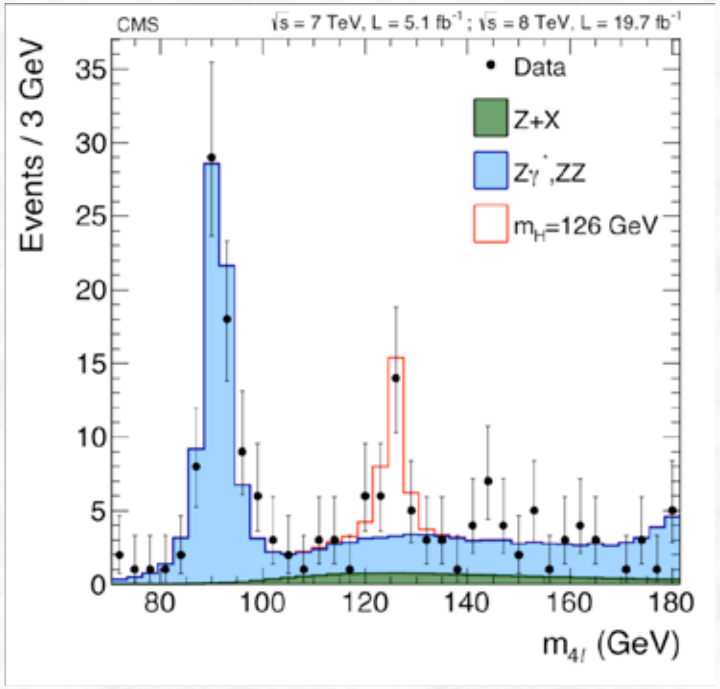
Higgs signal (main production process via gluon fusion)
(mass can be reconstructed from $\gamma\gamma$)

Reconstructed mass spectra from 4ℓ decays

Phys. Rev. D91 (2014) 012006



Phys. Rev. D89 (2014) 092007



Measured signal strengths:

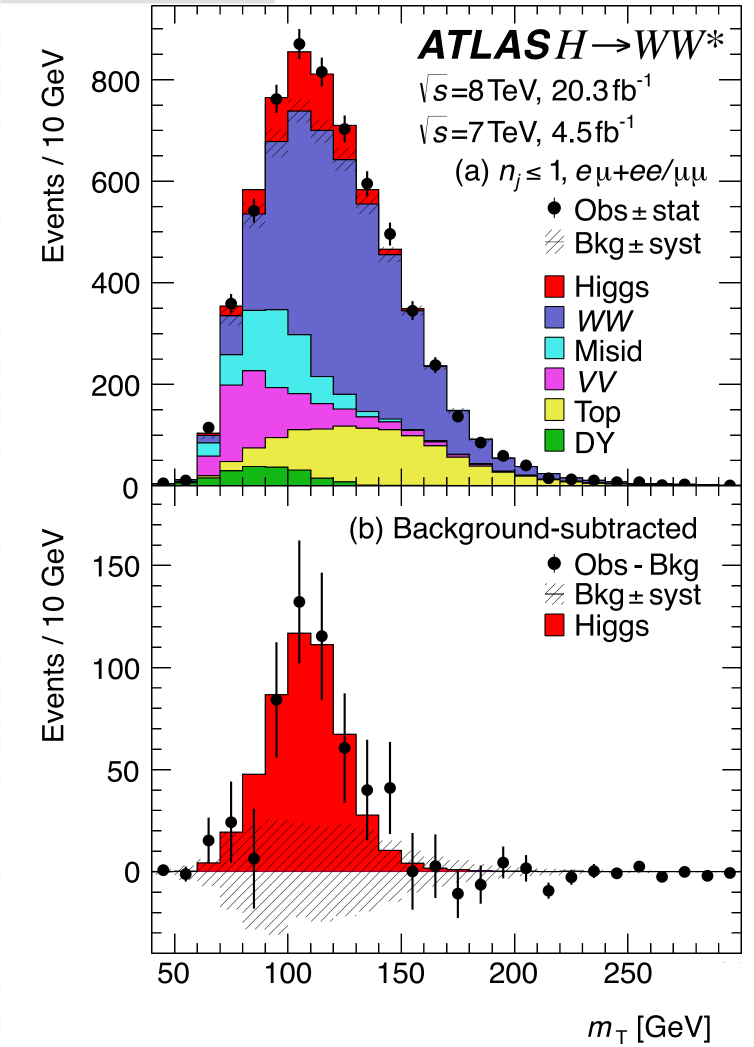
ATLAS: $\mu = 1.44^{+0.40}_{-0.33}$

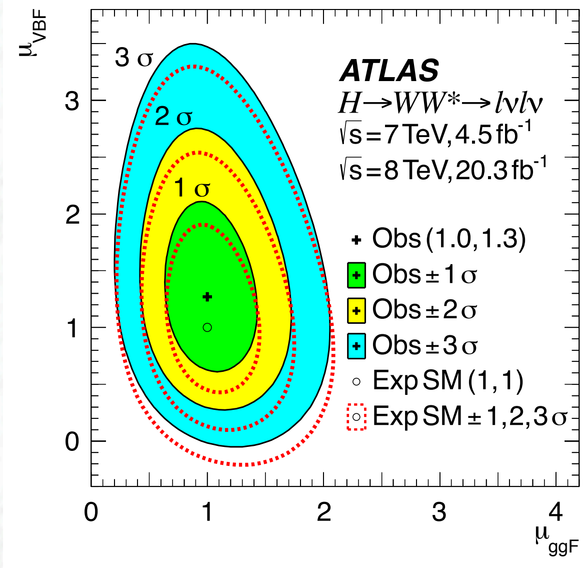
CMS: $\mu = 0.93^{+0.29}_{-0.23}$

Significance in each experiment > 6σ

H → WW* → ℓν ℓν signal

arXiv:1412.2641





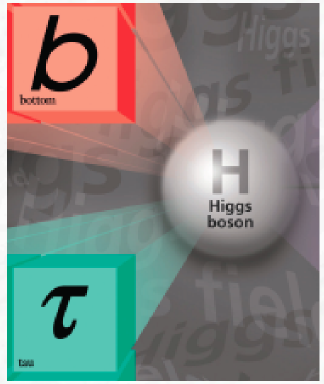
Measured signal strengths:

ATLAS: ggF: $\mu = 1.02^{+0.29}_{-0.26}$
VBF: $\mu = 1.27^{+0.53}_{-0.45}$

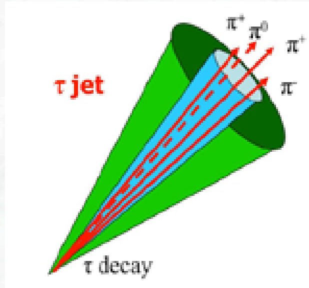
CMS: $\mu = 0.72^{+0.20}_{-0.18}$

- Very significant excess in the "transverse mass" distribution visible (6.1σ)
- Signals for both gluon-fusion (ggF) and vector-boson fusion (VBF) production

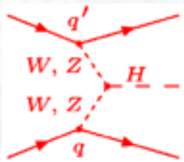
Couplings to quarks and leptons ?

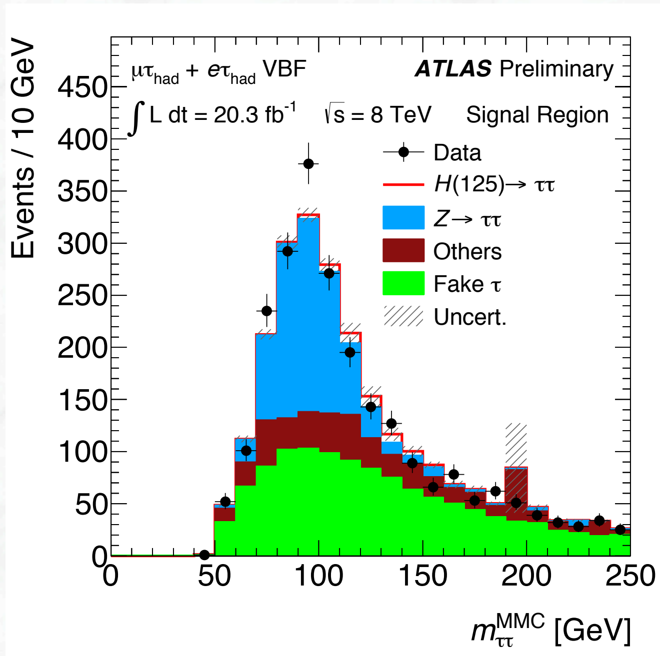


- Search for H → ττ and H → bb decays;
- Challenging signatures due to jets (bb decays) or significant fraction of hadronic tau decays

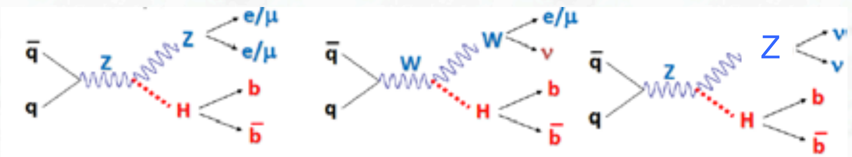


- Vector boson fusion mode essential for H → ττ decays





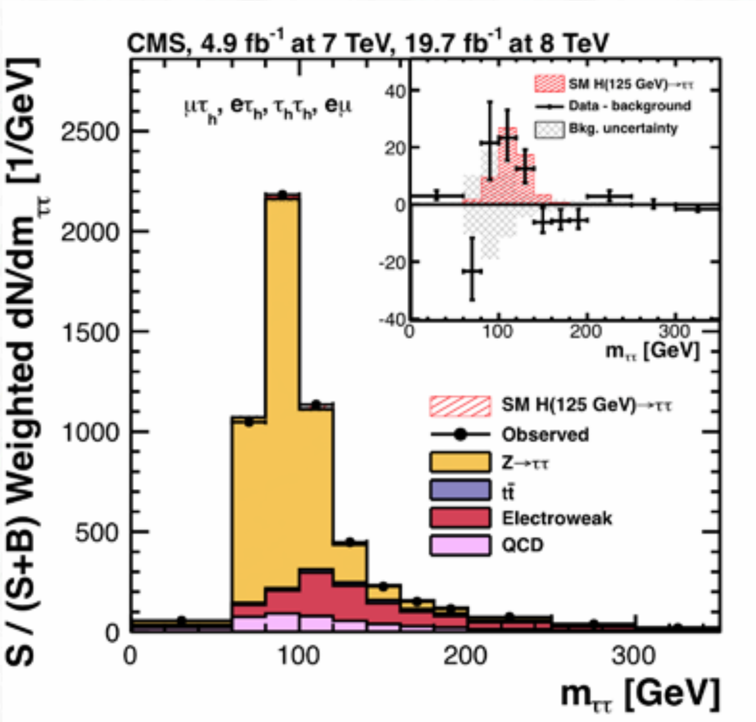
- Associated production WH, ZH modes have to be used for H → bb decays



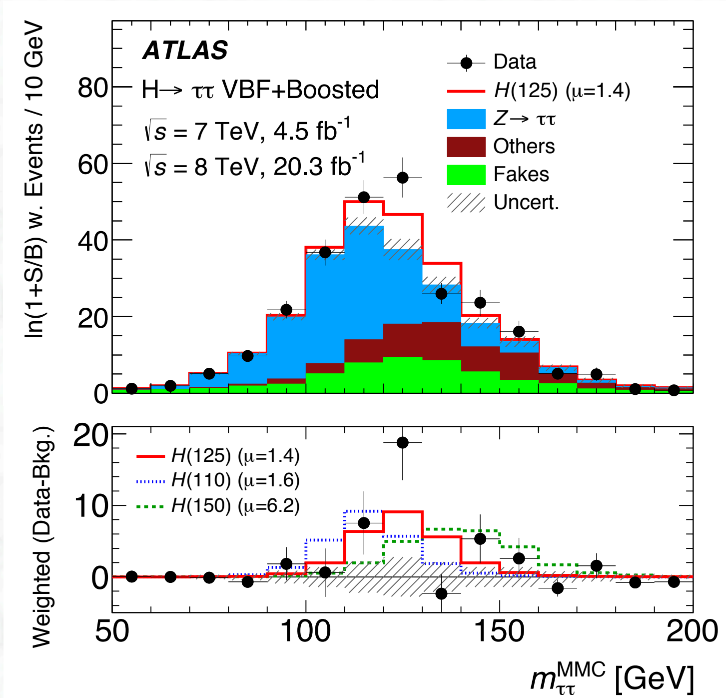
- Exploitation of multivariate analyses

Evidence for H → ττ decays

JHEP 1405 (2014) 104



arXiv:1501:04943 (2015)



$m_{\tau\tau}$ distribution, events weighted by ln (1+S/B)

Measured signal strengths:

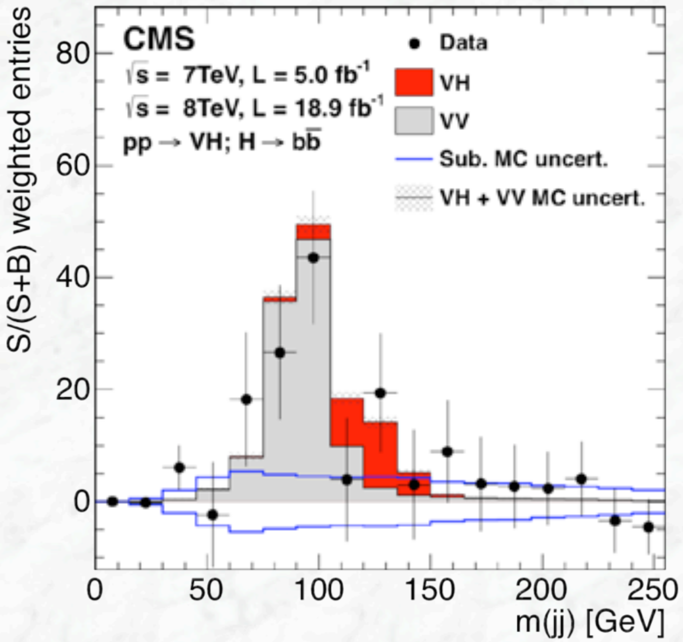
ATLAS: $\mu = 1.43^{+0.43}_{-0.37}$ (4.5σ)

CMS: $\mu = 0.78 \pm 0.27$ (3.2σ)

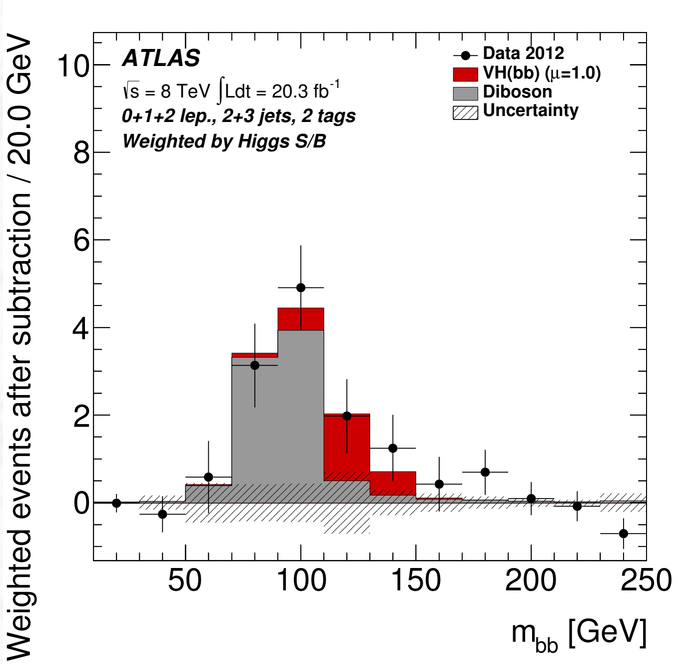
One of the most important LHC results in 2014

Results on the search for H → bb decays

Phys. Rev. D89 (2014) 012003



JHEP 1501 (2015) 069



Reconstructed m_{bb} signals (after subtraction of major backgrounds)

- Reference signal from WZ, and ZZ with Z → bb seen
- Positive, but non-conclusive Higgs boson signal contribution observed

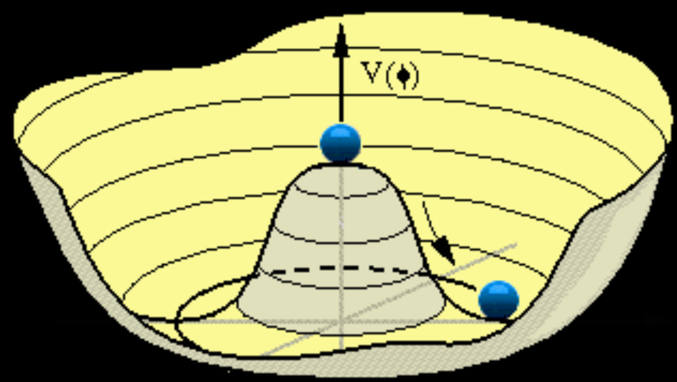
Signal strengths:

ATLAS: $\mu = 0.50 \pm 0.36$

CMS: $\mu = 1.0 \pm 0.5$

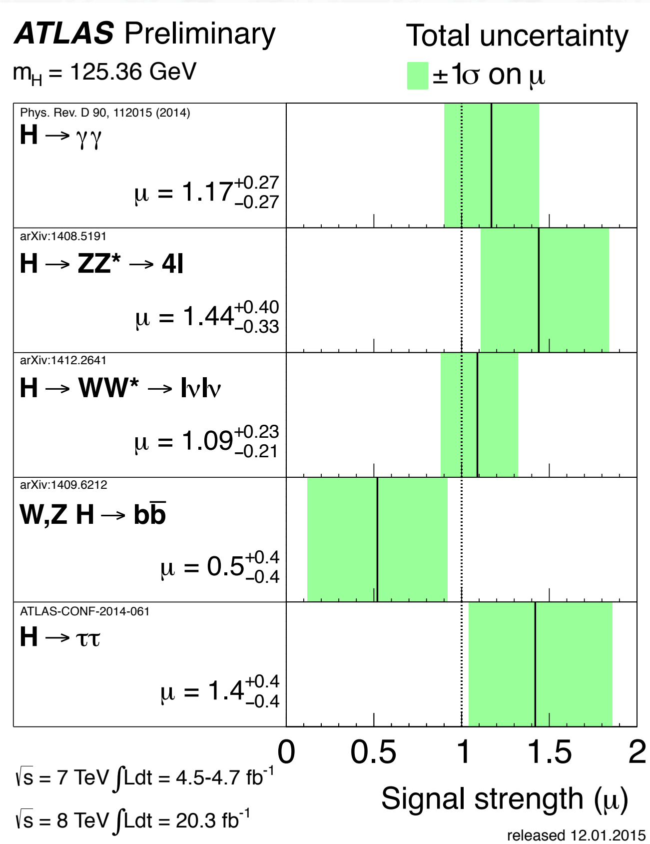
Properties of the New Particle

Is it the Higgs Boson of the Standard Model?



Signal strength in individual decay modes

-normalised to the expectations for the Standard Model Higgs boson-



ATLAS 2015

ATLAS: $m_H = 125.36 \pm 0.37$ (stat) ± 0.18 (syst) GeV

CMS: $m_H = 125.03 \pm 0.27$ (stat) ± 0.14 (syst) GeV

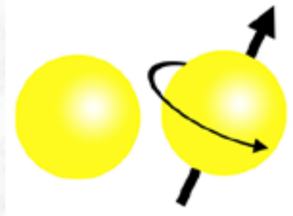
Signal strengths:

ATLAS: $\mu_{ges} = 1.30 \pm 0.17$ (prel.)

CMS: $\mu_{ges} = 1.00 \pm 0.14$ (new)

- Data are consistent with the hypothesis of the Standard Model Higgs boson
- If ATLAS and CMS combined: clear evidence for coupling to fermions

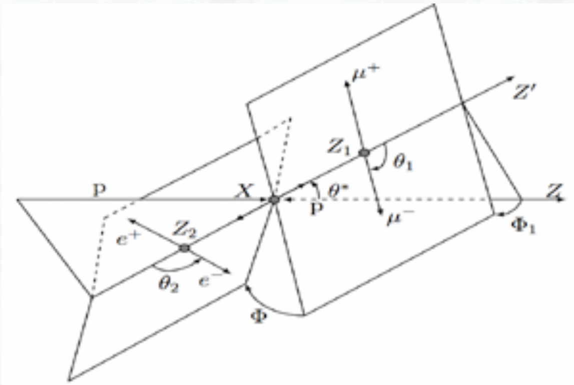
Spin and CP

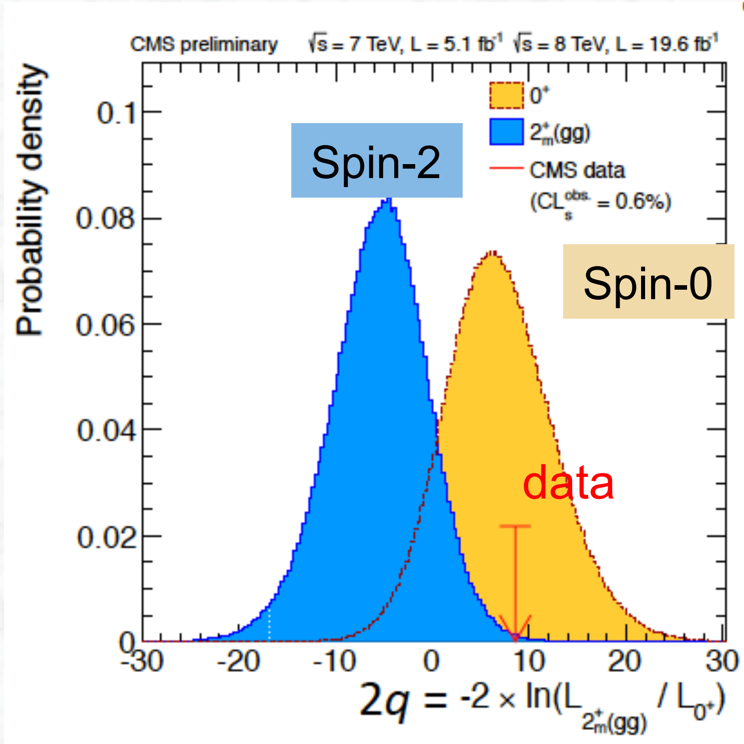


- Standard Model Higgs boson: $J^P = 0^+$

  → strategy is to falsify other hypotheses (0^-, 1^-, 1^+, 2^-, 2^+)

- Angular distributions of final state particles show sensitivity to spin



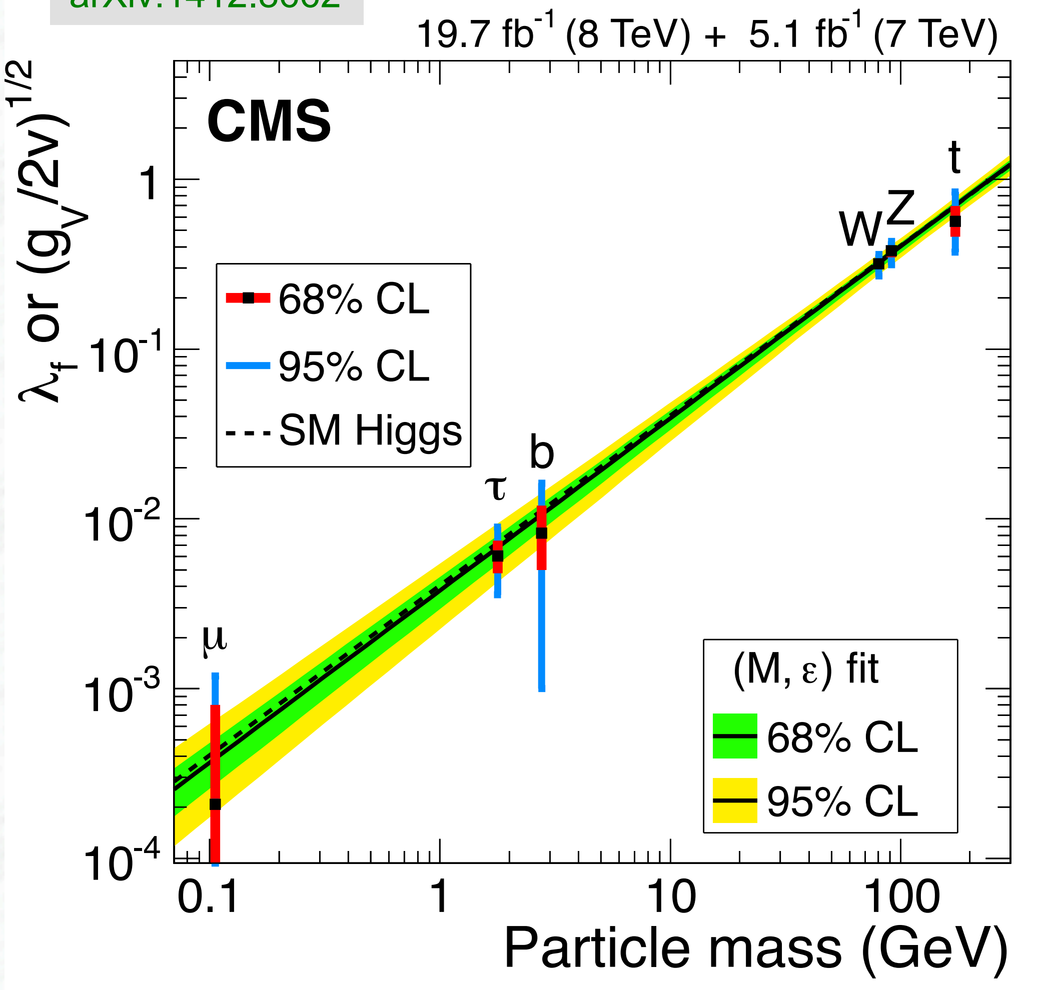


Data strongly favour the spin-0 hypothesis of the Standard Model

(Alternatives can be excluded with confidence levels > 99%)

CMS results on Higgs boson couplings

arXiv:1412.8662

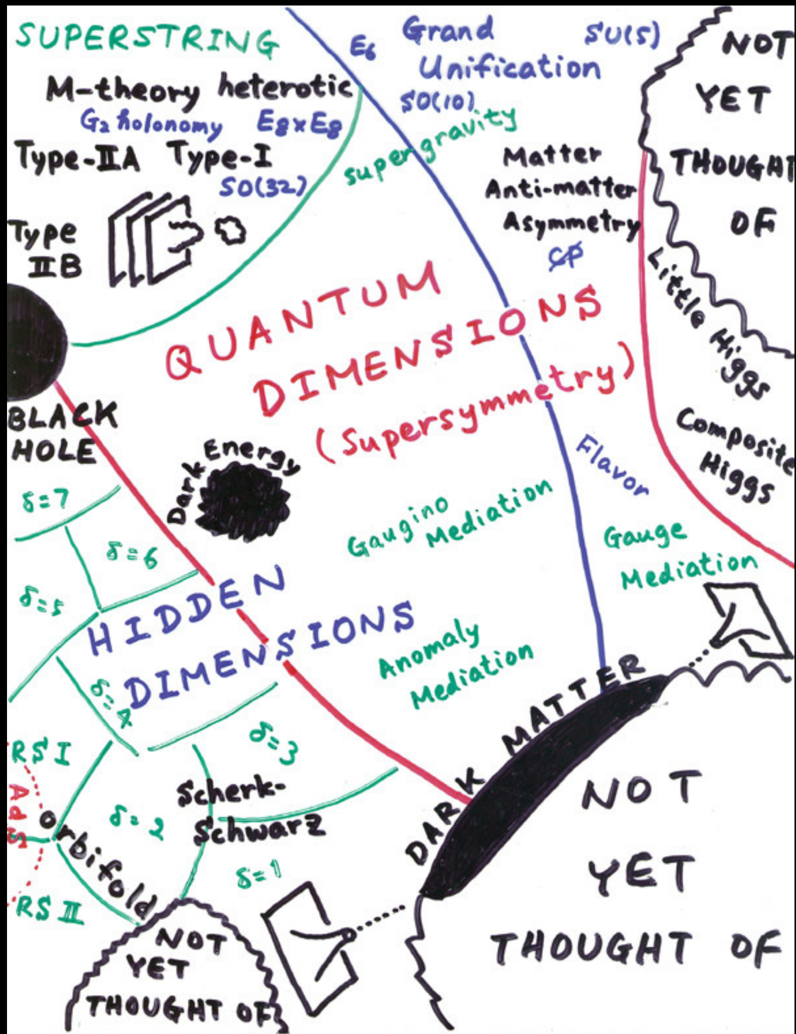


λ = Yukawa coupling for fermions

√g/2v = couplings for W/Z bosons

For the first time, non-universal, mass-dependent couplings observed

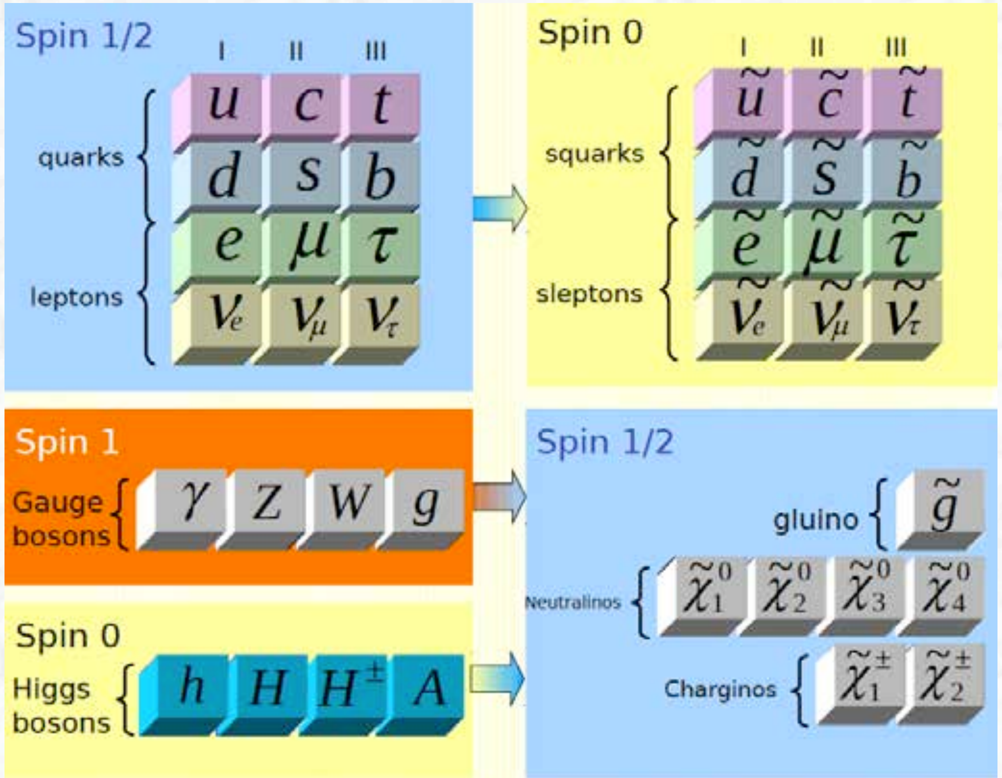
Physics Beyond the Standard Model

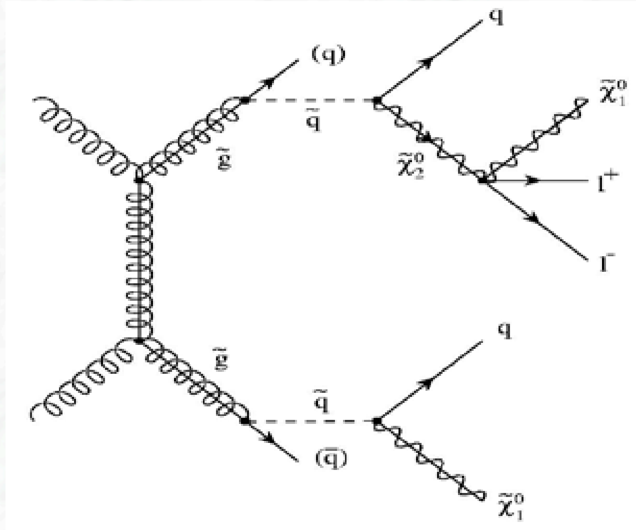


Hitoshi Murayama, IPMU Tokyo & Berkeley

Supersymmetry

SM particles **SUSY particles**





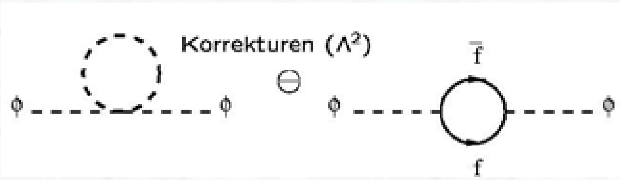
Final states with jets, E_T^{miss}, (and leptons)

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

R-parity conservation: SUSY particles produced in pairs
Decays into the Lightest SUSY Particle (LSP)

Why do we like SUSY so much?

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

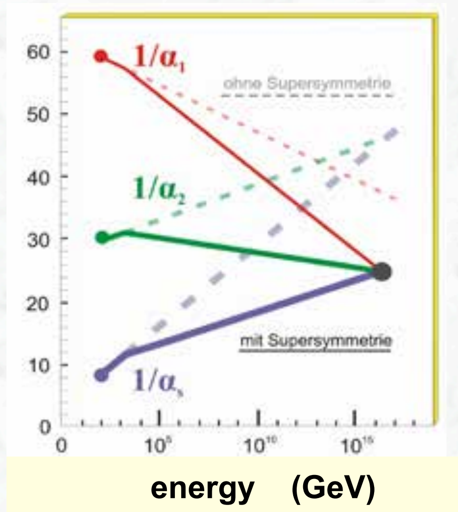


$$\Delta m_H = f(m_B^2 - m_f^2)$$

→ $\boxed{m_{SUSY} \sim 1 \text{ TeV}}$

(Hierarchy or naturalness problem)

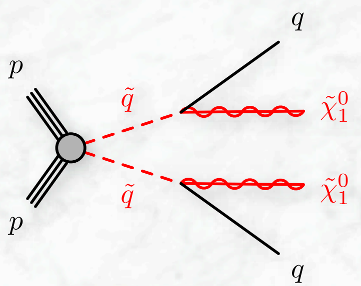
2. Unification of coupling constants of the three interactions seems possible



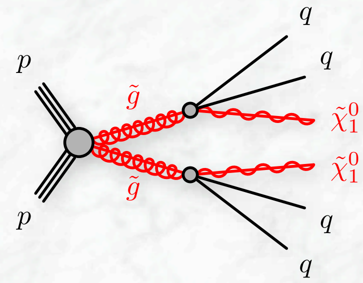
3. SUSY provides a candidate for dark matter

The lightest SUSY particle (LSP)

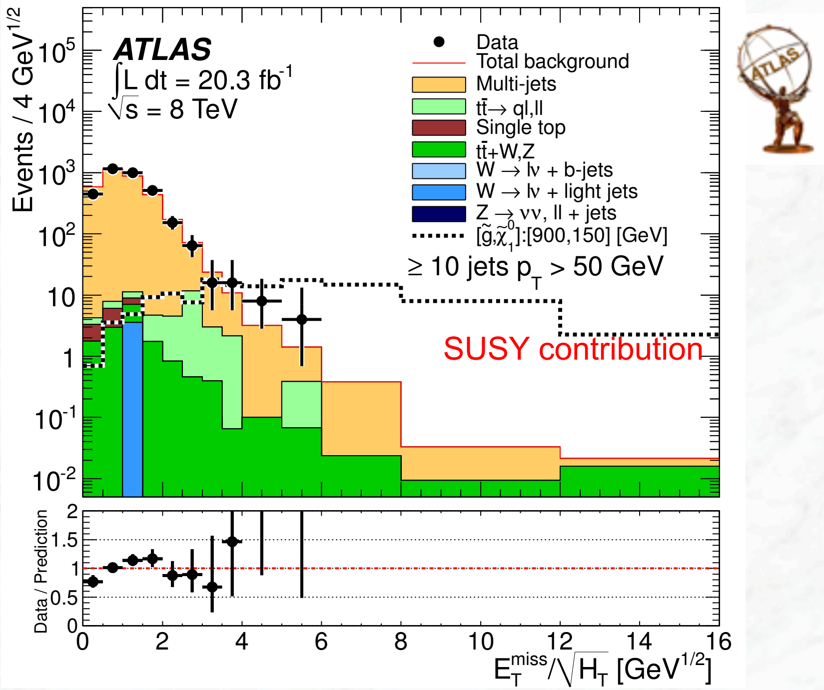
4. A SUSY extension is a small perturbation, consistent with the electroweak precision data



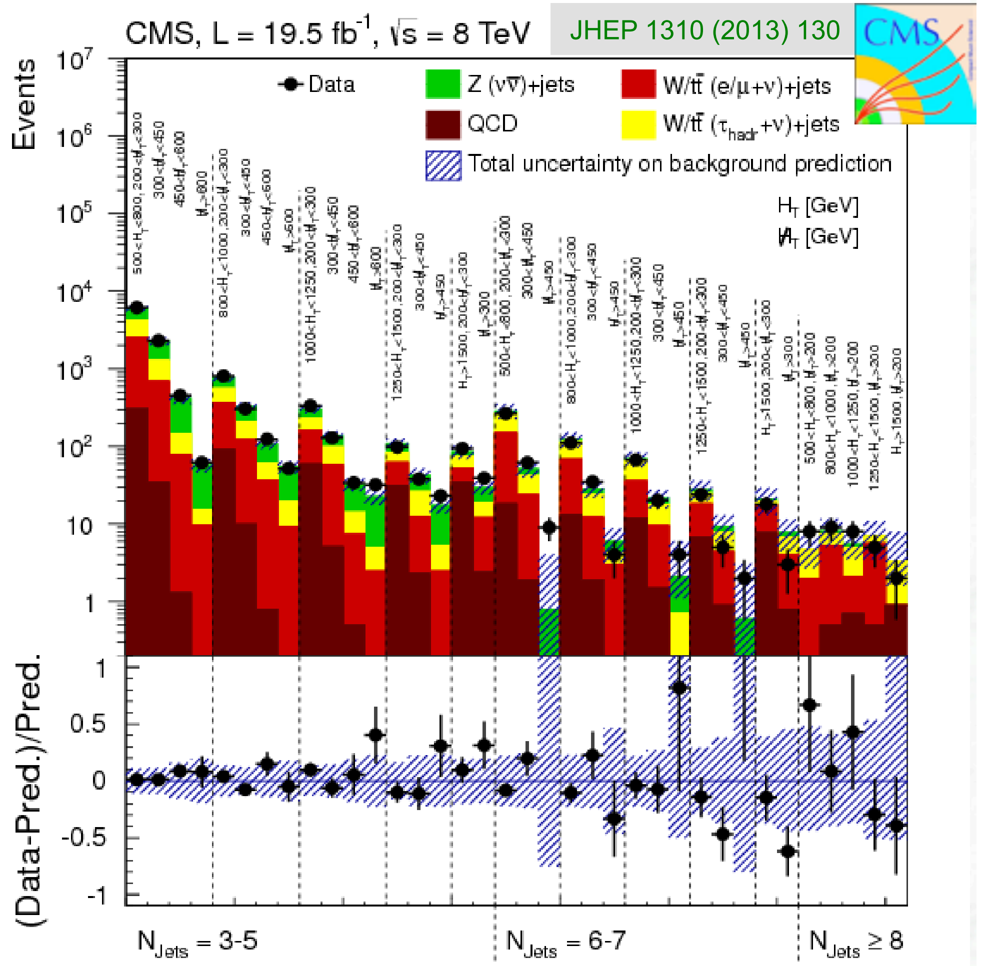
Search for Squarks and Gluinos



JHEP 1310 (2013) 130



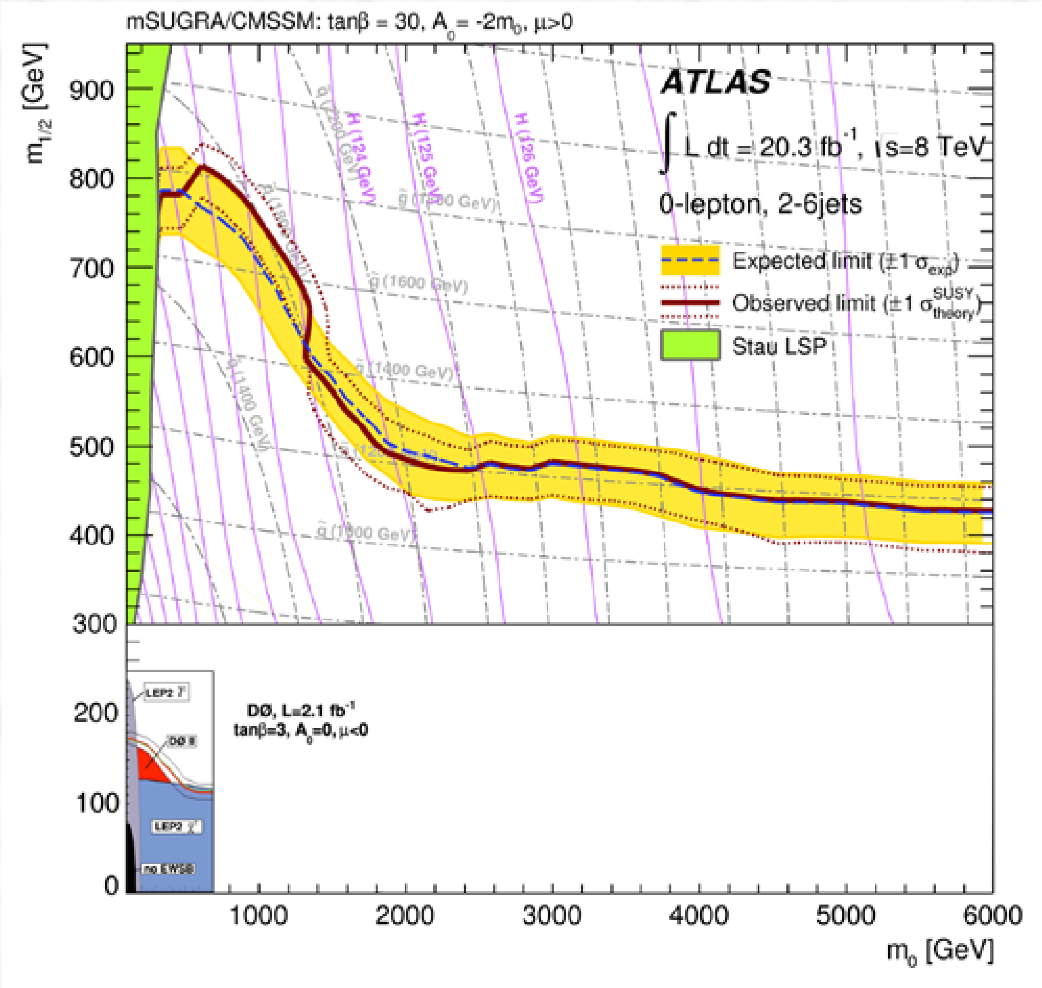
JHEP 1310 (2013) 130



$E_T^{miss} / \sqrt{H_T}$ = missing transverse energy normalized to the square root of the total transverse energy (H_T) seen in the event

Data are in agreement with predictions from Standard Model processes

Limits of light squark and gluino masses

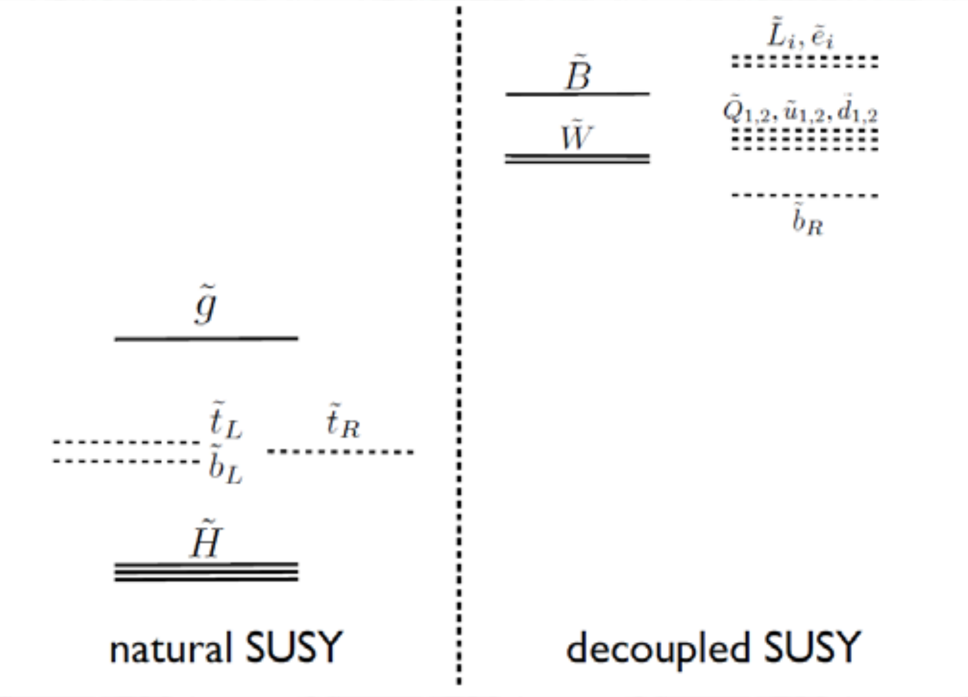


mSUGRA / CMSSM interpretation: tan β = 30, A_0 = -2m_0, μ> 0

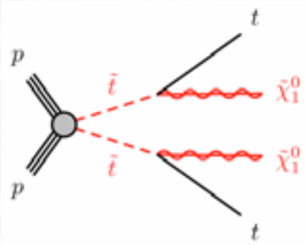
For equal mass light-flavour squarks (of first and second generation) and gluinos with masses below about 1650 GeV are excluded

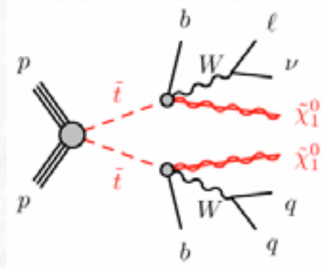
The special role of top squarks (stops)

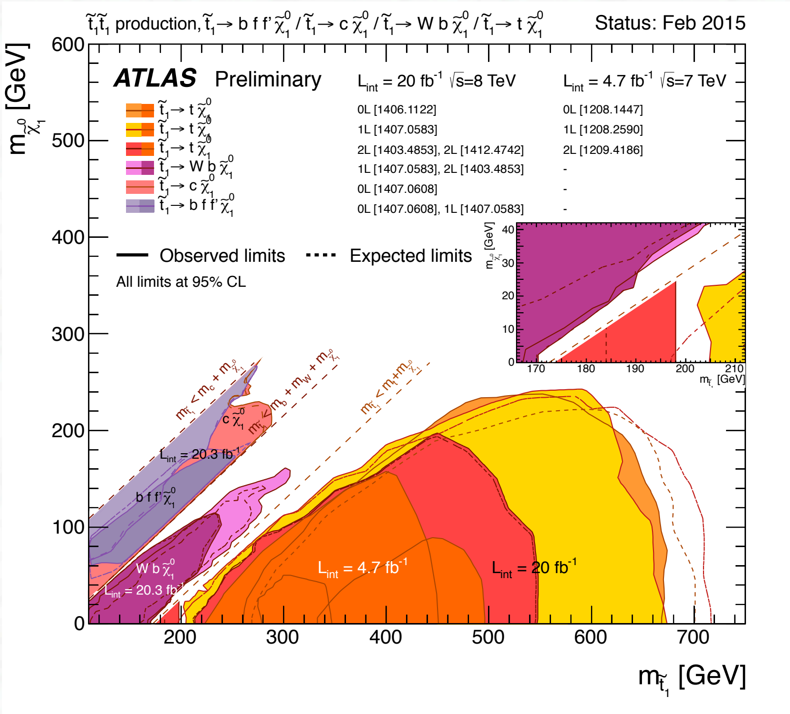
- The partners of the top (bottom) quarks might be the lightest squarks, whereas all other squarks might be too heavy to be produced at the LHC;
- Light stops could solve the so-called "hierarchy" problem (cancellation of large quantum corrections to the Higgs boson mass) "Natural SUSY"

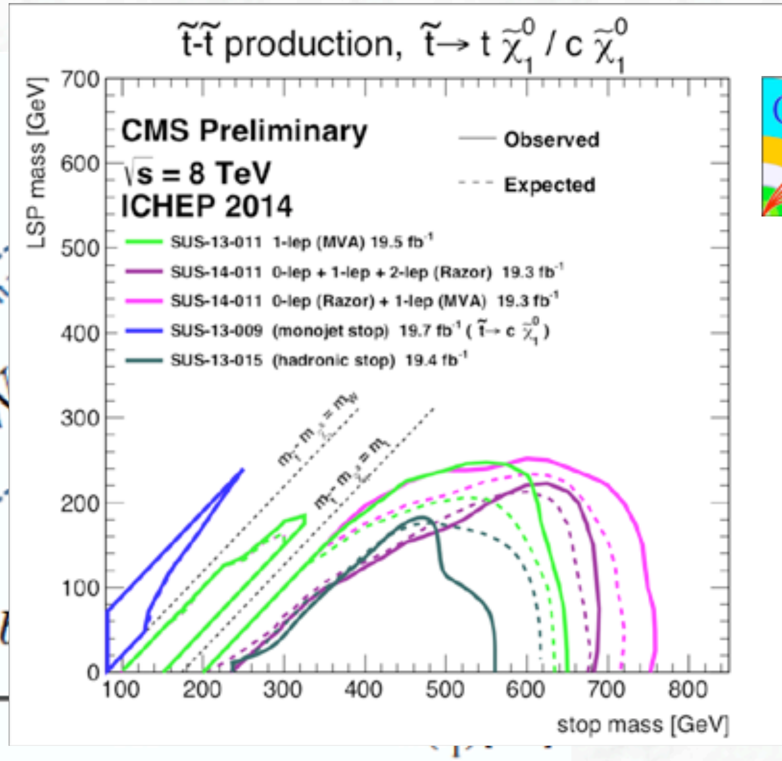


Status of top squark searches

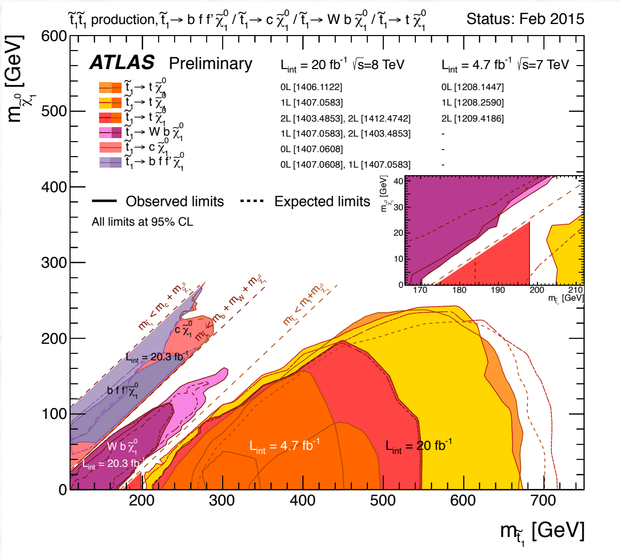








- Weaker mass limits for partners of the top quark (lower production rate, tt background)
- Parameter coverage not yet complete!

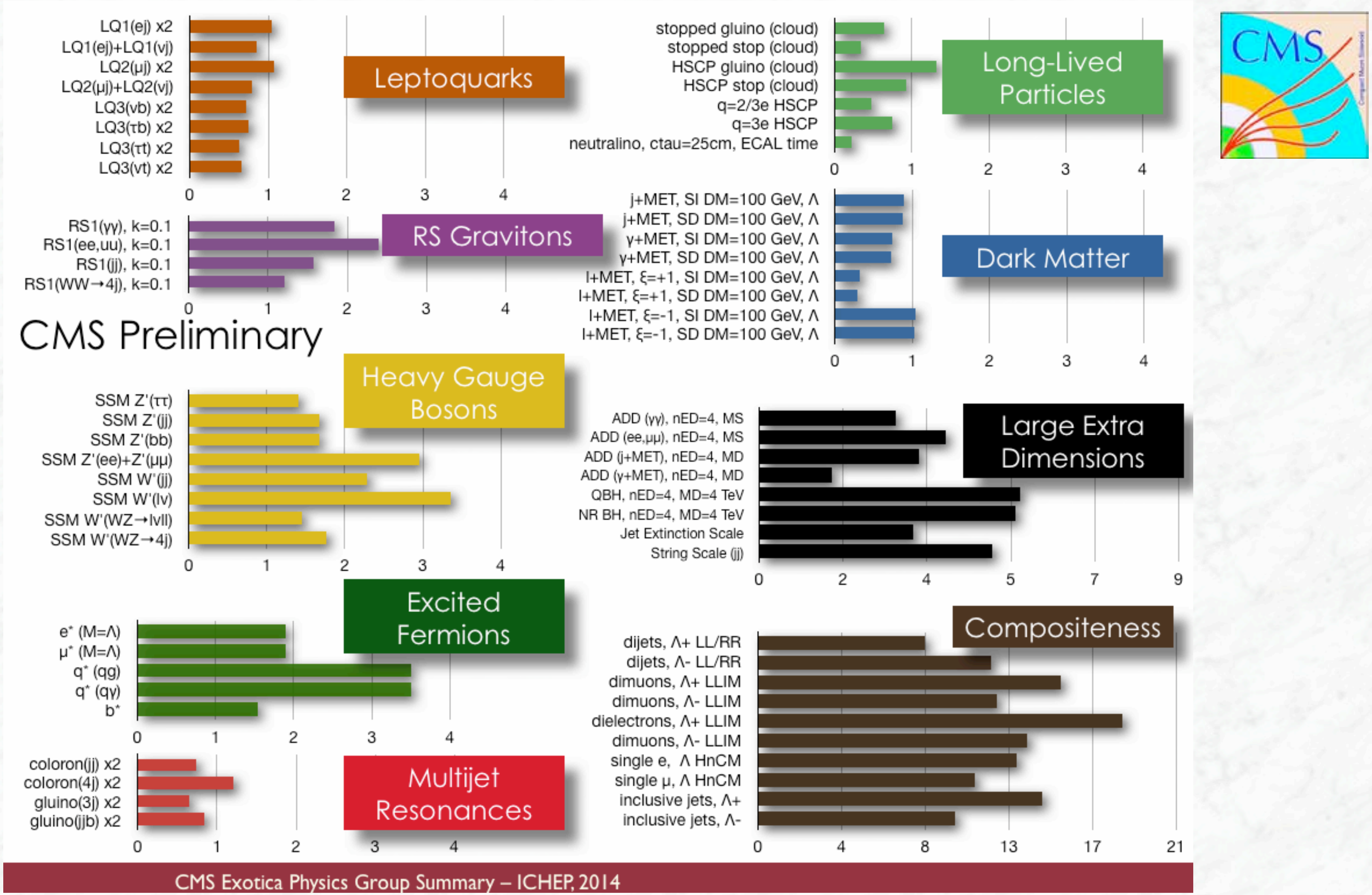


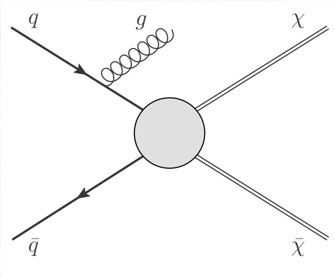
Is SUSY dead?

- *"Under attack from all sides, but not dead yet."*
- Some of the simplest models are ruled out, however, interpretations rely on many simplifying assumptions.
- Plausible "natural" scenarios still not ruled out;

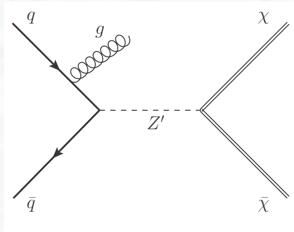
  Light stop and/or R-parity violating scenarios have fewer constraints.
- Search for Charginos and Neutralinos (el.weak production) needed at high luminosity / energy

Results from other Searches for New Physics



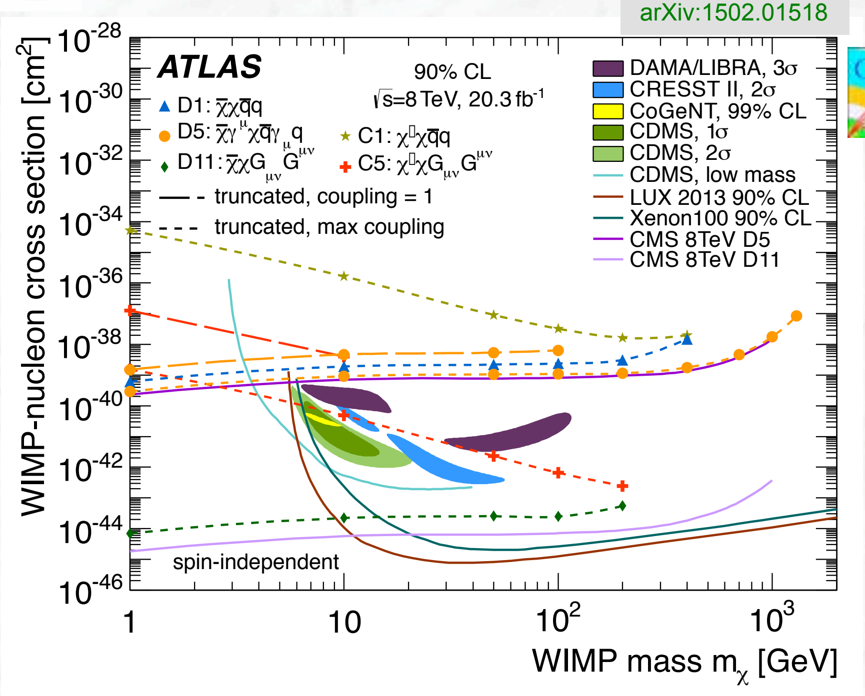


Direct Search for Dark Matter using Monojet signature



- Coupling of weakly interacting massive particles (WIMPs) is described as a contact interaction using an effective field theory approach;
- WIMP assumed to be either a Dirac fermion or a scalar;
  Limits given for different operators

arXiv:1502.01518



Name	Initial state	Type	Operator
C1	qq	scalar	$\frac{m_q}{M_\star^2}\chi^\dagger\chi\bar{q}q$
C5	gg	scalar	$\frac{1}{4M_\star^2}\chi^\dagger\chi\alpha_s(G^a_{\mu\nu})^2$
D1	qq	scalar	$\frac{m_q}{M_\star^3}\bar{\chi}\chi\bar{q}q$
D5	qq	vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$
D8	qq	axial-vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$
D9	qq	tensor	$\frac{1}{M_\star^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$
D11	gg	scalar	$\frac{1}{4M_\star^3}\bar{\chi}\chi\alpha_s(G^a_{\mu\nu})^2$

- Interesting complementary approach to understand the *nature of dark matter;*
- Close collaboration with astroparticle physics community and theory needed to understand the validity of the approach and the "translation" of results

What next ?

- The LHC will resume operation at an increased energy (at $\sqrt{s}$ = 13 – 14 TeV) in March / May 2015 (higher energy and higher luminosity)

- A new energy range will be explored !!

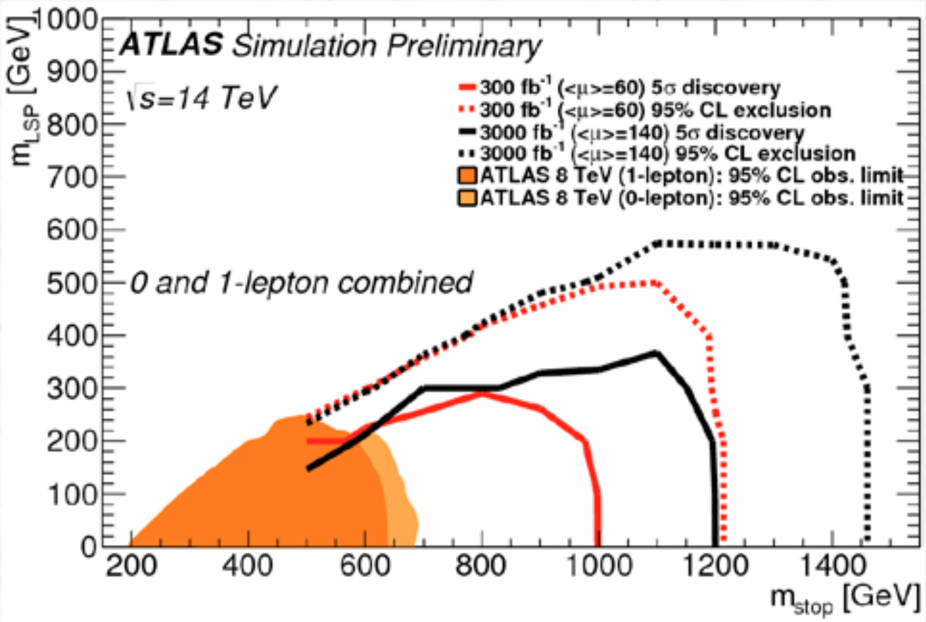
Major physics topics:
(i) Extend the searches for New Physics

(ii) Precise measurements of the
Higgs boson profile

(iii) Additional Higgs bosons?

(iv) Scattering of vector bosons

(v) Precision measurements
(m_W, m_{top}, Higgs couplings)



Conclusions

- With the operation of the LHC at high energies, particle physics has entered a new era
- Performance of the LHC and the experiments is superb
- A milestone discovery announced in July 2012

  Strong evidence that the new particle is the long-sought Higgs boson of the Standard Model;
  We moved from the discovery to the measurement phase;

- So far no signals from New Physics, however, only a small fraction of the parameter space at reach at the LHC has been explored;
- Higgs particle might be portal to new physics
- Exciting times ahead of us, with new, unexplored energy regime in reach