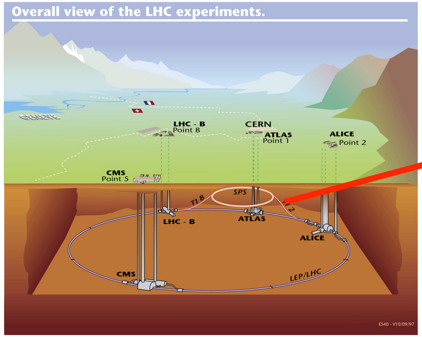
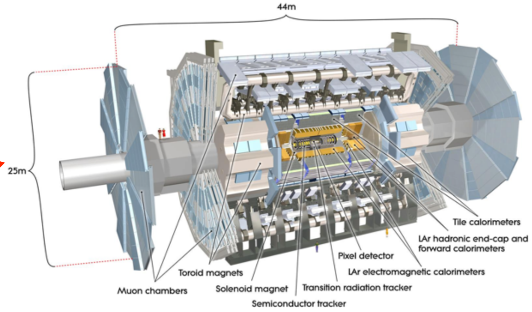
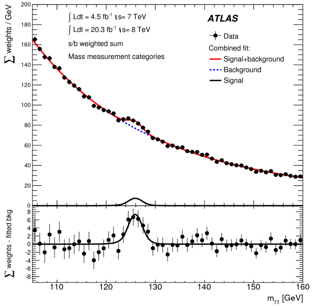
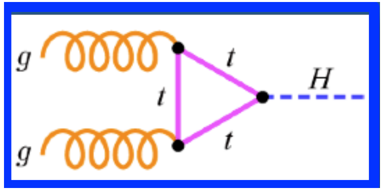
Challenging the Standard Model with Experiments at the LHC









Al Goshaw

Duke University, Durham USA

May 23, 2017

Duke University

University of Durham

Durham NC vs Durham UK

experiment

theory

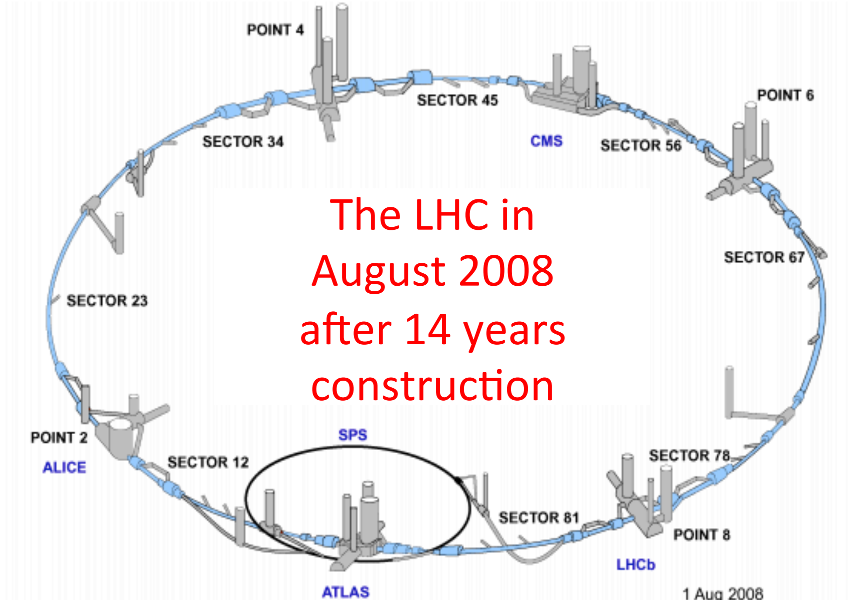
The Institute for Particle Physics Phenomenology

Outline

- The Large Hadron Collider (LHC) (1990 to 2017)
- The Standard Model(SM) discovery (1897 to 2012)
- The theory of the SM in a nut-shell
- Recent results from the LHC (2017)

The Large Hadron Collider
1990 to 2017

The history and status of the LHC



The LHC in August 2008 after 14 years construction

Dipoles of 15 m length

- A 27 kilometer ring consists of 1232 dipole 392 quadrupole magnets.
- The superconducting dipoles provide 8.3 T magnetic fields when at 1.9 K .
- The counter-rotating proton beams are focused to collide at a design proton-proton center of mass energy of 14 TeV.

The history and status of the LHC

Lynn Evans in August 2008

“The whole machine is now cold and in the final stage of commissioning.

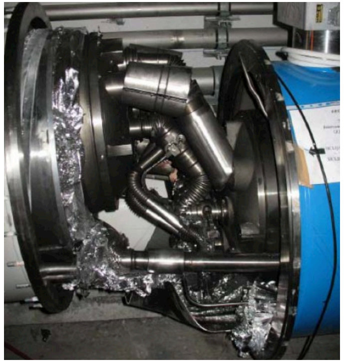
Approximately one month from now the first beam will be injected into the full machine and beam commissioning will begin.”

The machine will be trained to 14 TeV during the winter shutdown.

The best laid plans …

The history and status of the LHC

- During LHC start up in September of 2008 a junction between two magnets carrying a current of 7kA failed resulting in a cascade that damaged a chain of ~ 30 magnets.
  Repairs and re-commissioning took over a year.



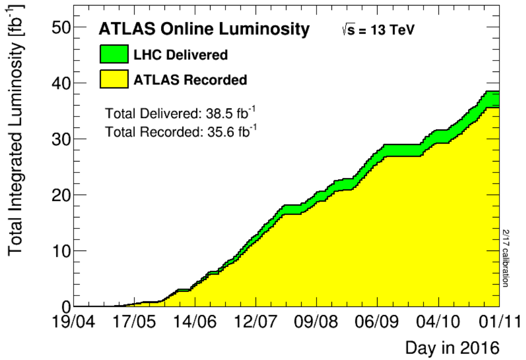
- LHC operation re-started in 2010 and ran through 2012 with proton-proton collisions at a reduced center of mass energy of 7 (latter 8) TeV.
  This is referred to as "Run 1".
  The Higgs boson was discovered using this data.

- A shutdown of two years (2013-2014) was required to install new junctions between magnets and many new safety features to finally allow the LHC to operate near the design CM energy.

The history and status of the LHC

- Operation at a cm energy of 13 TeV started in April 2015, with a plan to run for ~ 3 years. This is referred to as Run 2.

- A sample of 13 TeV data (40 fb^{-1}) delivered in 2015+2016 is currently being analyzed.
  The full Run 2 data set after 2017+2018 LHC running is projected to be about 130 fb^{-1} .

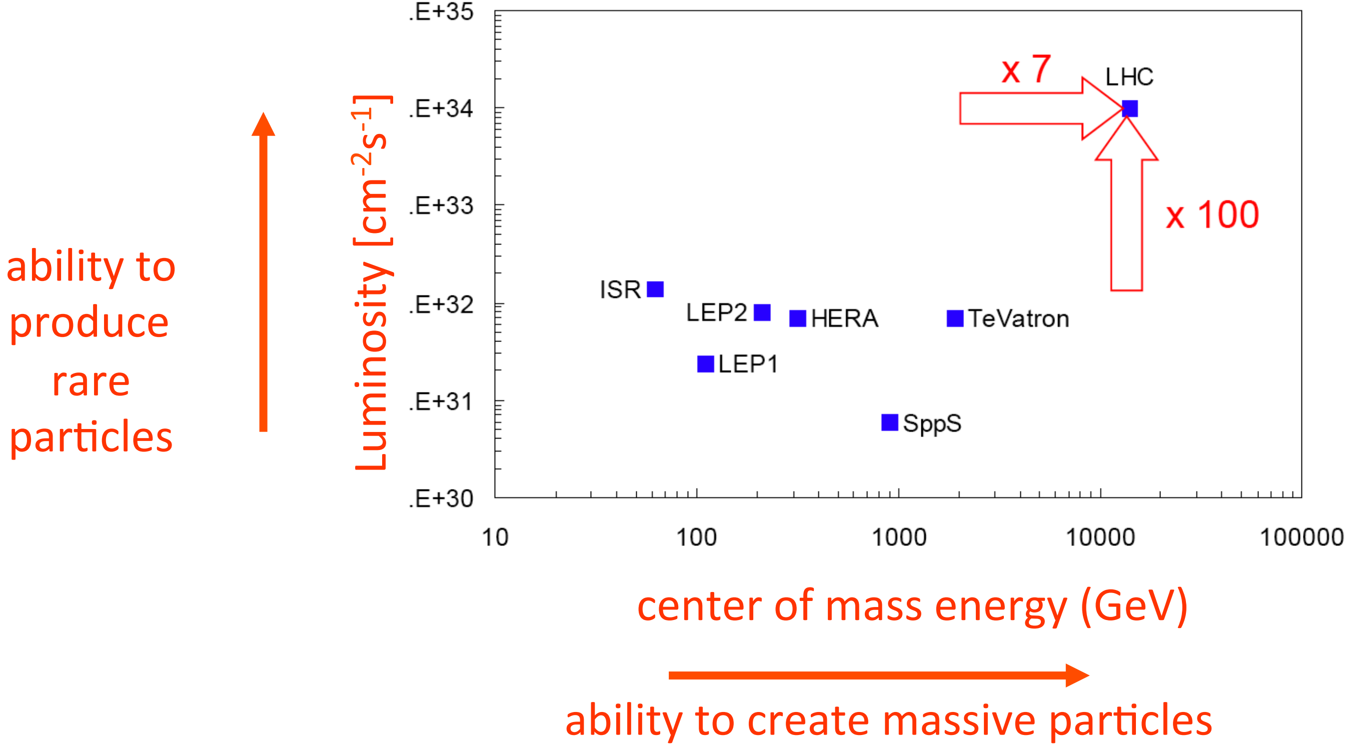


- The increase of cm energy from 8 → 13 TeV plus higher integrated luminosity in Run 2 results in a large increase in sensitivity over Run 1 for new particles that have masses in the multi-TeV range.

This has opened a new window for challenging predictions of the Standard Model.

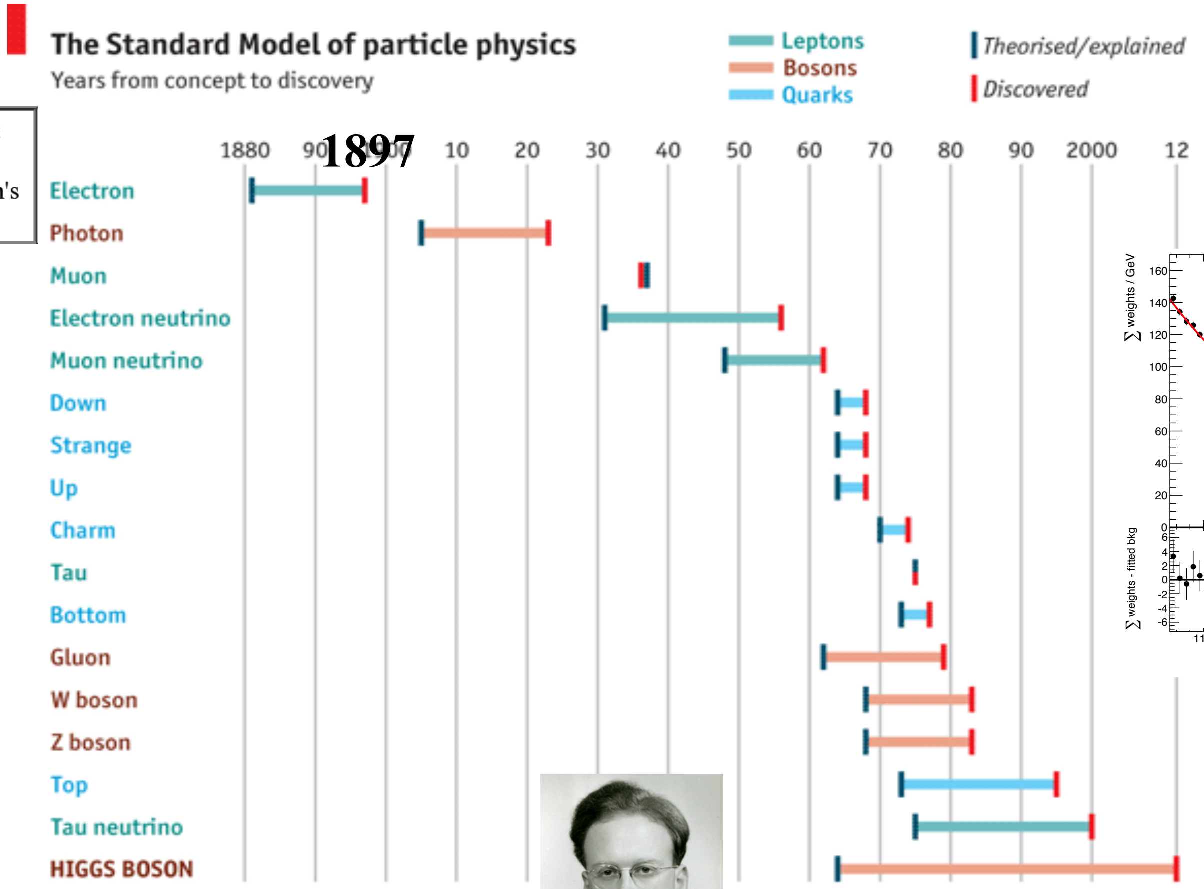
The history and status of the LHC

Comparison to previous accelerators

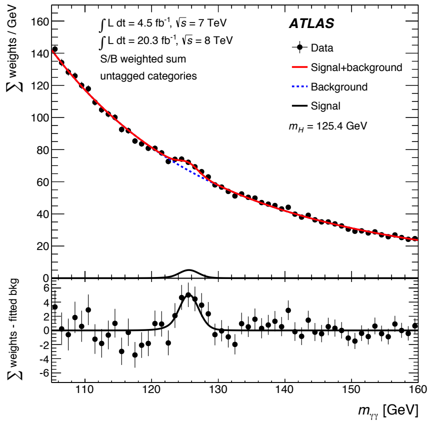


The Standard Model
(1897 to 2012)

"To the electron -- may it never be of any use to anybody." -- JJ. Thomson's favorite toast



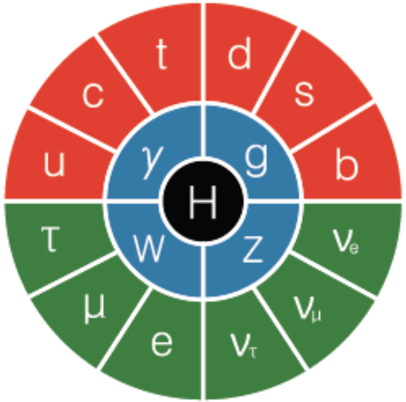
$H \rightarrow \gamma\gamma$



1964

2012

The Standard Model



The Higgs is the linchpin that holds it all together

Many speculations about theories beyond the Standard Model (BSM)

BSM theories

experimental confirmations

The take-away message: the SM has proven to be very durable

Structure of the Standard Model

SM theory in a nut-shell …

- Demand that kinematics be Poincare invariant of course …
- Then speculate that the dynamics must be invariant under simple special unitary symmetry groups: U(1) SU(2) SU(3)
  But symmetry of what ?
- At this point a combination of experimental input and theoretical insight (resulting in Nobel prizes) must enter:
  - $U(1)_Q$ → quantum electrodynamics (QED)
  - $SU(2)_L \times U(1)_Y$ → electroweak (EWK)
  - $SU(3)_C$ → quantum chromodynamics (QCD)
- The choice of "L" for a left-handed (V-A) weak interaction is driven by experiment (to introduce parity violation). This requires (if the theory is to be renormalizable) that the number of quark and lepton generation must be equal.

SM theory in a nut-shell …

- At this point you are stuck as the unbroken symmetries of the SM require the W and Z boson (and the fermions) to have zero mass. This was a problem since the W and Z boson with masses near 100 GeV and the zero-mass photon are companions in the electroweak sector.

- Enter many theoretical speculations on how to introduce electroweak symmetry breaking into the basic dynamic structure of the SM.

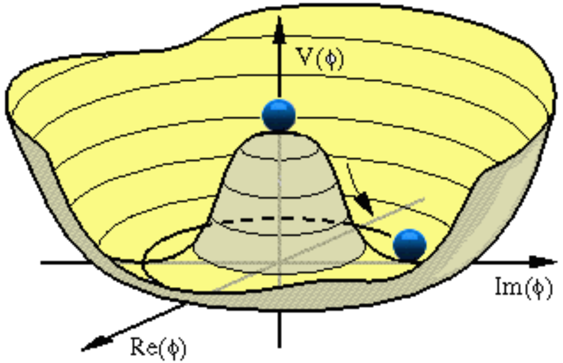
SM theory in a nut-shell …

- In 1964 several theorists working independently (1-4) postulated a new ubiquitous field carried by a spin zero boson with an unusual interaction potential.

- One of the theorists was Peter Higgs from the University of Edinburgh.

$$V(\phi) = \mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2 \qquad \mu^2 < 0 \qquad \lambda > 0$$

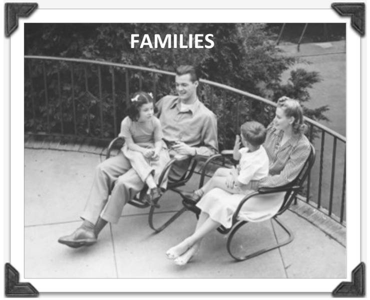
- His first publication attempt was rejected as not warranting rapid communication to the science community.



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

SM theory in a nut-shell …

- Over the years experimental information required that the SM be extended (but not broken) by introducing three families of quarks and leptons, along with the ability to to introduce CP violation.



$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix}$$

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$$

more ?

How many parameters are required in the SM?

- Number of masses = 12
- Number of coupling strengths = 2
- Number of quark mixing parameters = 4
- One QCD CP violating parameter (Λ_{QCD}) = 1 (seems to be ~ zero ?)

  → 19 parameters to be determined from experiment

- Once the 19 parameters are fixed the SM theory makes predictions. But the calculations are difficult and now require theoretical teams (read IPPP) that are of the size of (early) experimental teams.

Could the SM be super-sized?

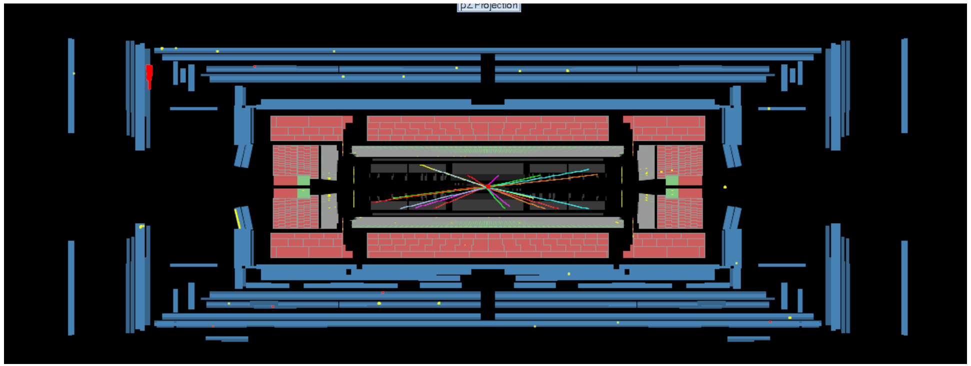
- There are known features of elementary particles that are not included in the "standard" SM.
  - What about massive neutrinos ? Could you add these?

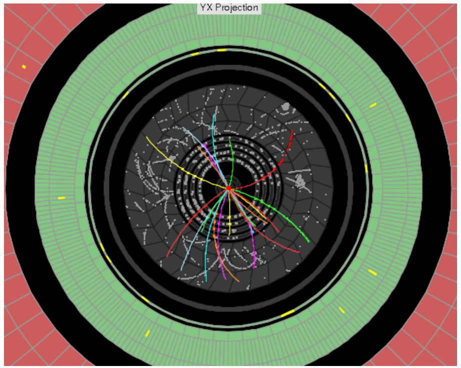
→ 26 parameters to be fixed by experiment (+ 3 massive neutrinos) (+ 4 for neutrino mixing)

- Adding an additional symmetry proposed by Peccei and Quinn $U(1)_{PQ}$ allows removal of the the strong QCD parameter, and when broken leads to the prediction of a light weakly interacting particle (a Goldstone boson in this case called an axion) that could provide a candidate for dark matter.

~~Λ_{QCD}~~

SM tests at the LHC





First p + p collisions recorded in ATLAS in 2017

Challenging the predictions of the SM

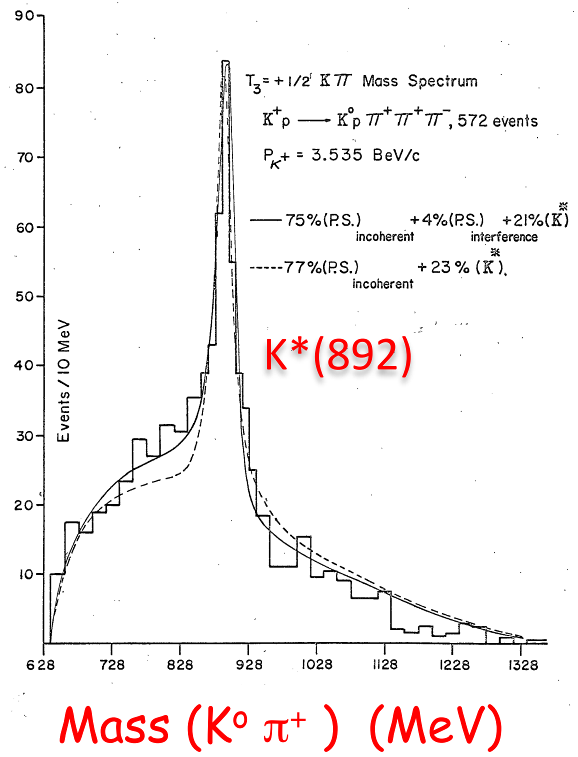
- The SM's structure and the experimental parameters required for making predictions are known.
- To test the SM (theory) against experiments (Nature) requires:

1. Experiments at the LHC (and elsewhere) providing data that allow high precision measurements.
   - now scanning distance scales down to ~ 10^{-4} fermi
   - now probing mass scales in the multi-TeV range (masses ~ 20x those of the most massive particles in the SM)

2. Theory calculations done with high precision using the theory provided by the SM. The IPPP is a world leader in providing these.

In the good old days …

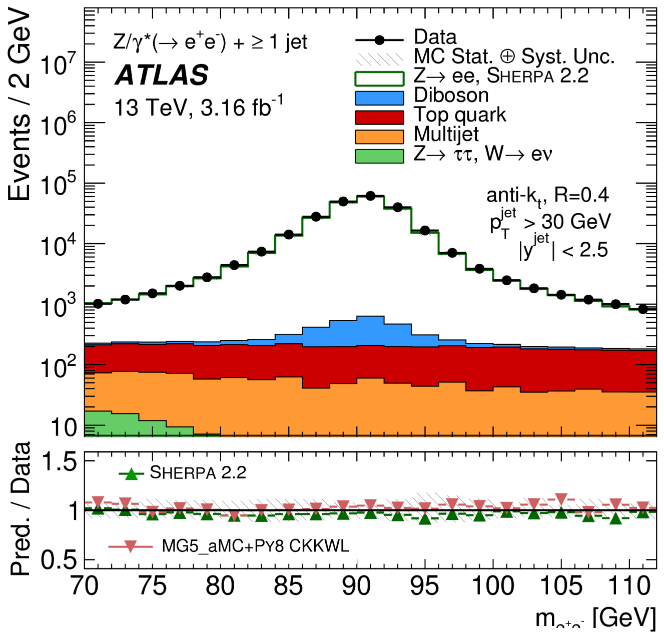
- When the SM was being developed, searches for resonant states of hadrons were all the experimental vogue. These provided the first evidence for quarks. Here is the study of an excited state of the K meson. →
  - Data analysis done on an IBM 705 computer (vacuum tubes).
  - Data analysis and calculations done from scratch not canned programs (IBM punch cards).
  - Plots made using pen-and-ink.



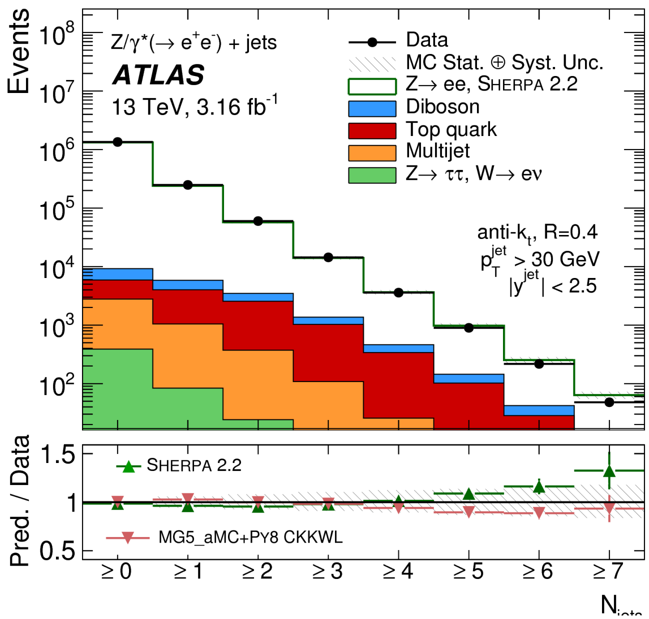
- The current "resonance" searches at the LHC are similar – just up the energy scale by ~100-1000, analyze the data with a 1000 cores of modern computers and use root for calculations and plotting.

And now … p + p → Z($e^+ e^-$) + ≥ 1 jet at 13 TeV

arXiv:1702.05725



Mass ($e^+ e^-$) (GeV)

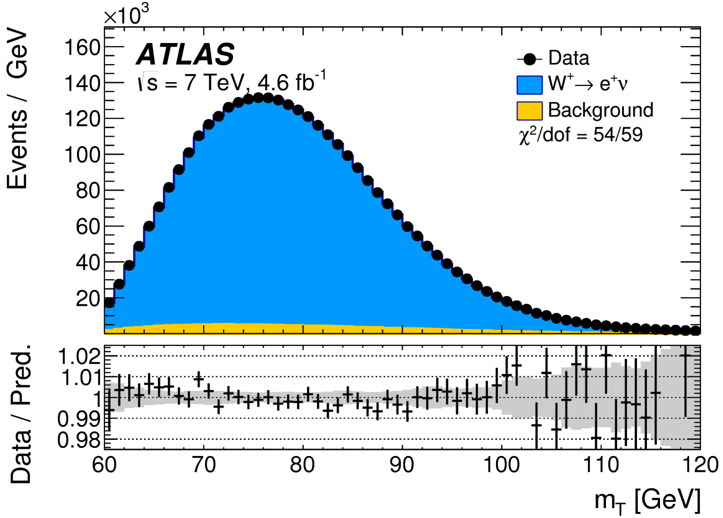


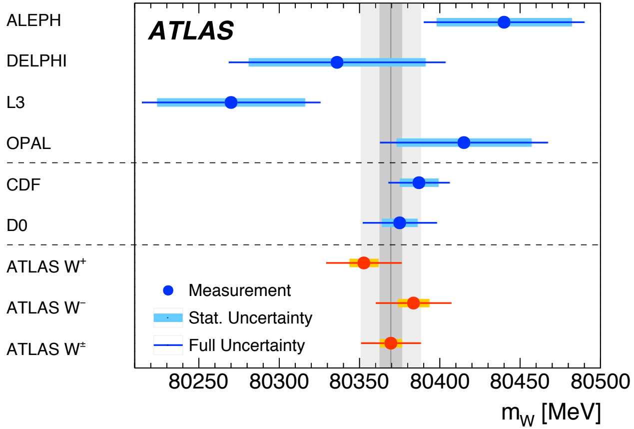
Number of jets with Et > 30 GeV

SM ✓

Measuring the W mass from p + p → W(l ν) + X at 7 TeV

arXiv:1701.07240

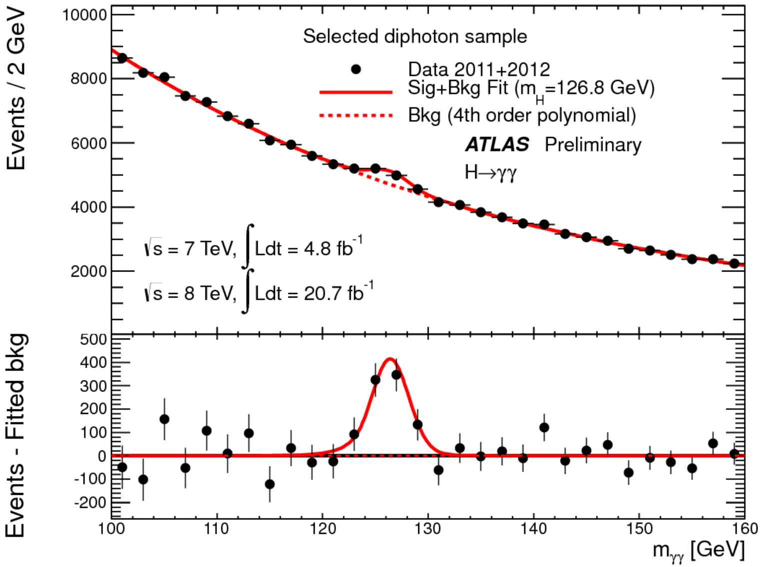


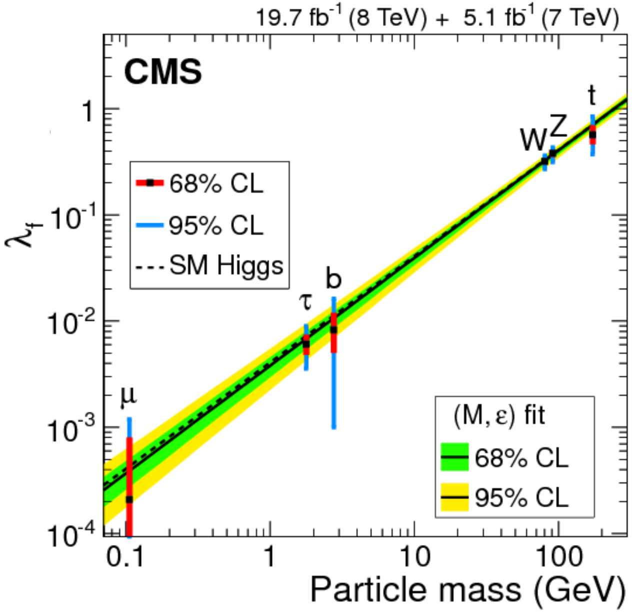


Transverse mass $e^+ \nu$ (GeV)

$$m_W = 80370 \pm 7\,(\text{stat.}) \pm 11\,(\text{exp. syst.}) \pm 14\,(\text{mod. syst.})\ \text{MeV}$$
$$= 80370 \pm 19\ \text{MeV},$$

Production of the SM Higgs boson





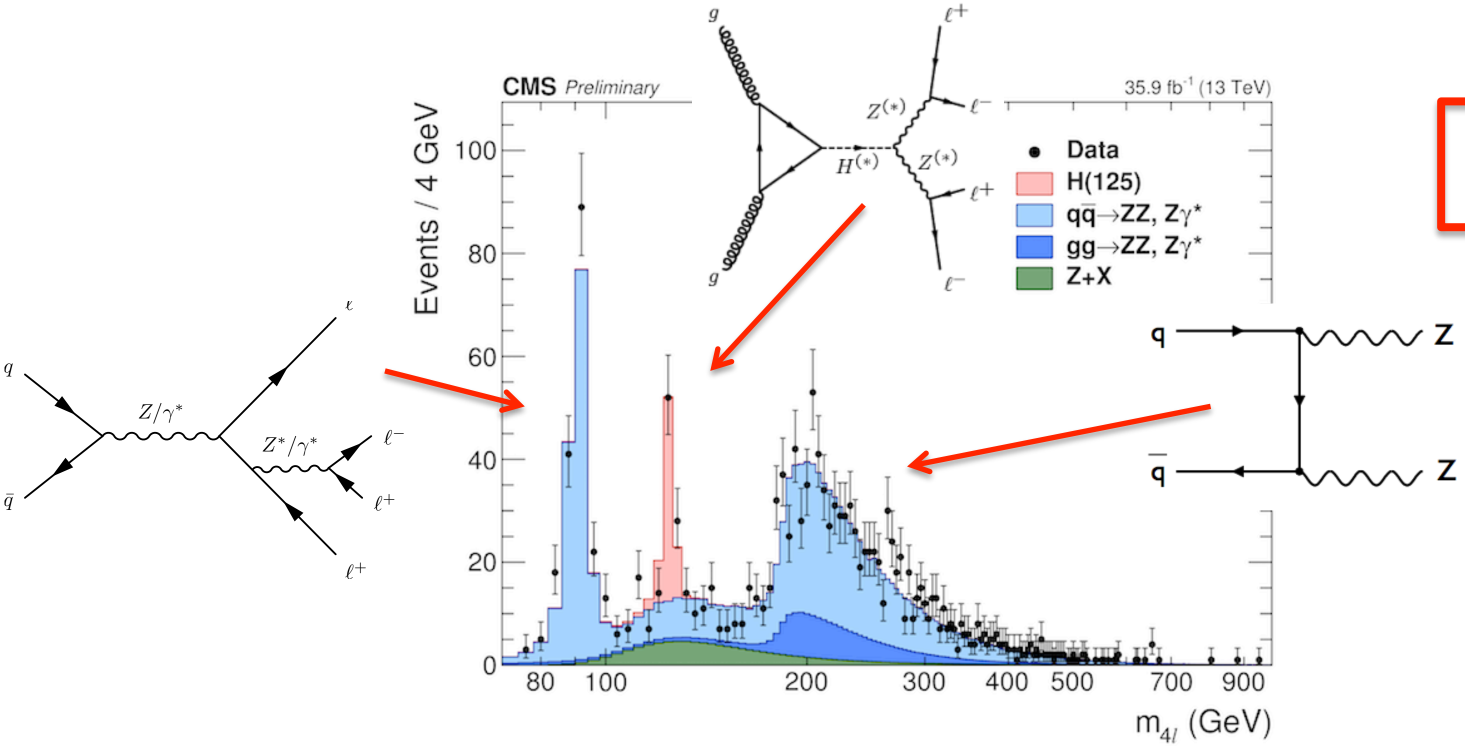
SM ✓

The Higg's boson mass from combined ATLAS and CMS measurements:

125.09 + 0.21 (stat) + 0.11 (syst) GeV

A SM electroweak survey in one measurement

- Recent CMS result on 13 TeV p + p → 4 charged leptons + X

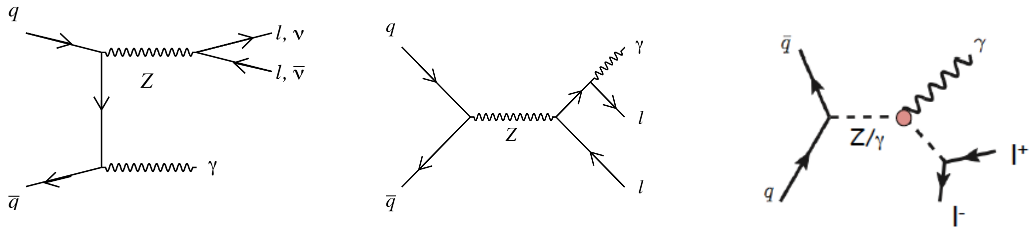


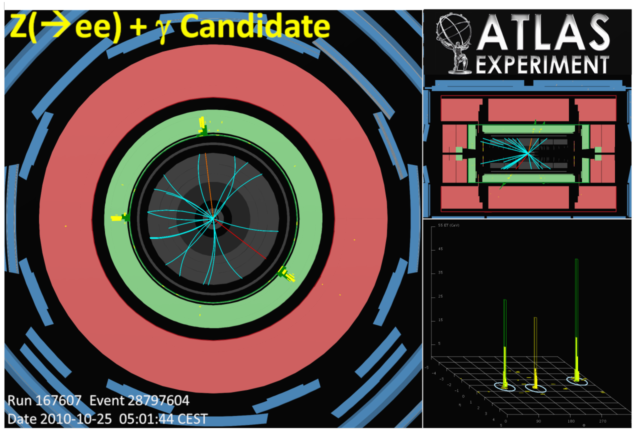
SM ✓

Production of a of Z boson plus a photon

Phys.Rev. D 93 112002 (2016)

- ATLAS has made a detailed study of the production of a Z boson with one or two high energy photons.



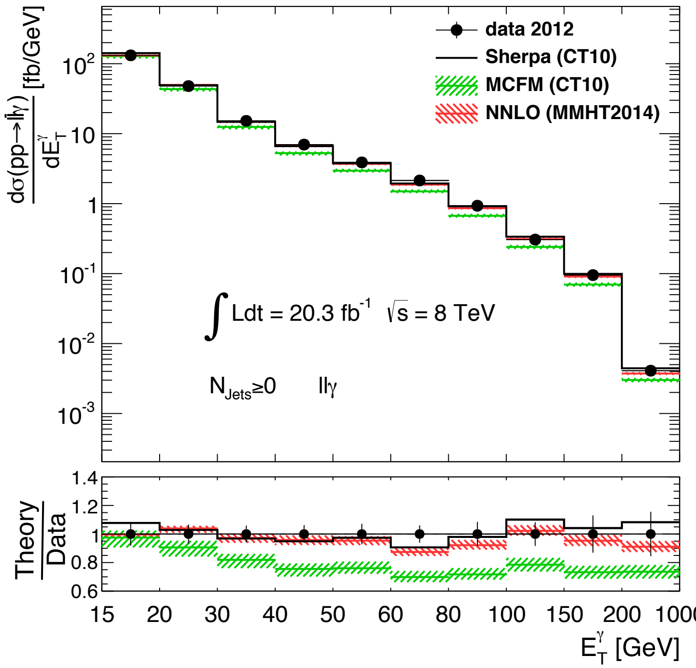


- Precision tests of SM theory calculations at higher order in perturbation (NNLO).

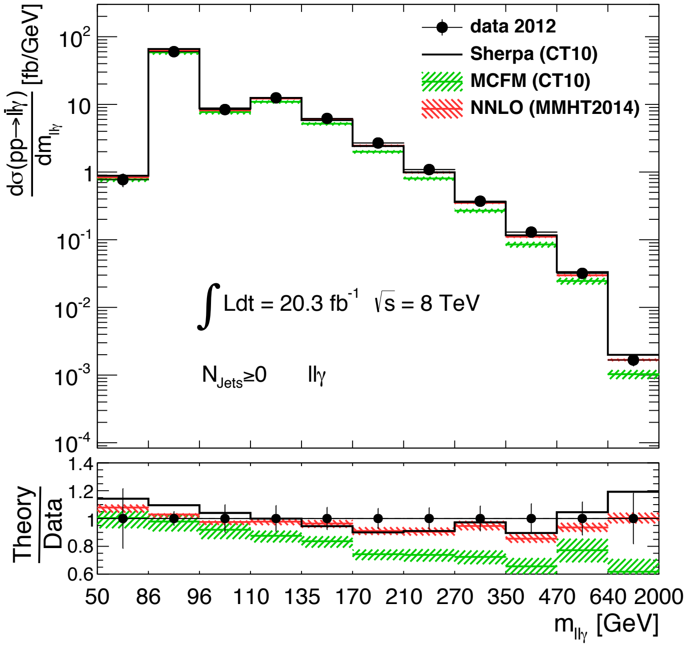
- Search for SM-forbidden triple gauge couplings

Production of a of Z boson plus a photon

- p + p → Z + γ + X √s = 8 TeV ATLAS



$E_T(\gamma)$



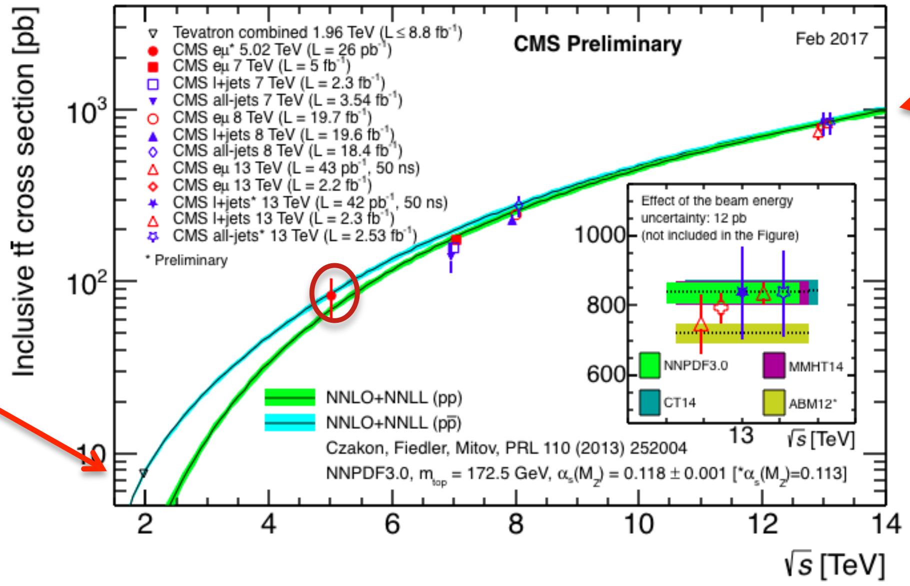
$M(l^+ l^- \gamma)$

SM ✓

Top quark pair production at the LHC

- Yesterday's big discovery, Nature's most massive elementary particle, is today's calibration …

Top quark's discovered by CDF/D0 at the Tevatron In 1995



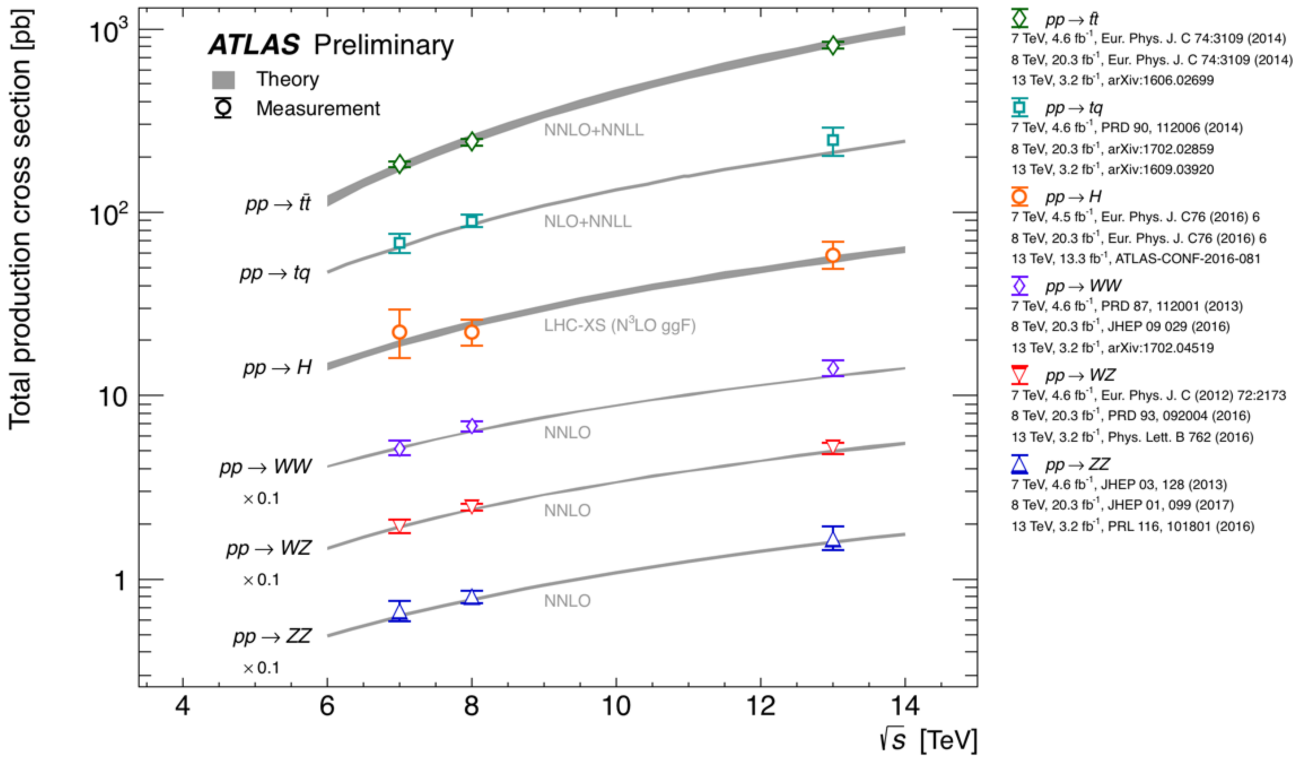
Top quark pairs produced at a 10 Hz rate at the LHC In 2017

CMS: 835 ± 33 pb

Theory: 816 ± 42 pb

SM ✓

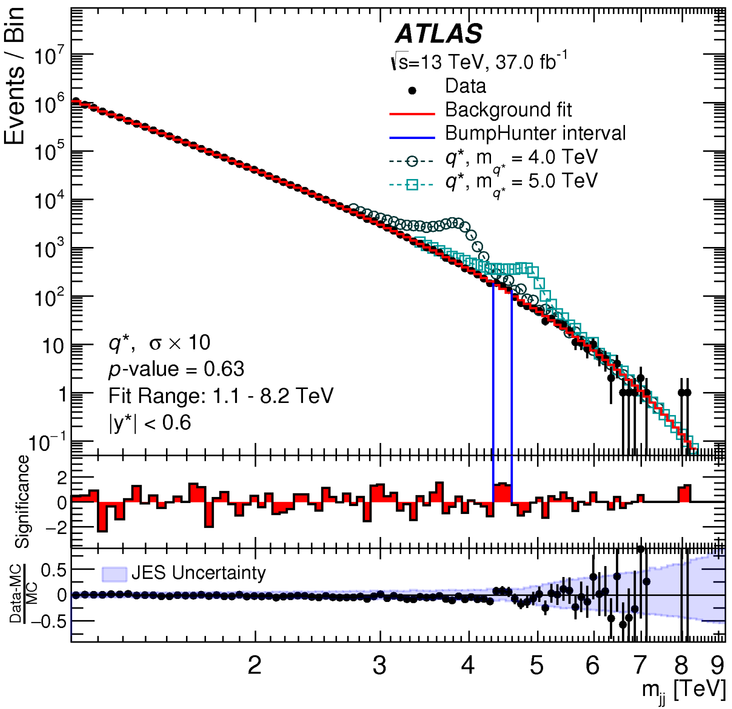
Check of SM particle production cross sections vs pp collisions cm energy



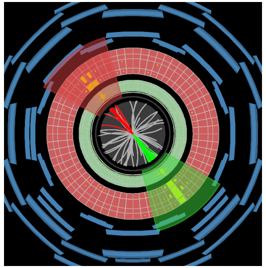
SM ✓

Production of dijets and search for quark sub-structure

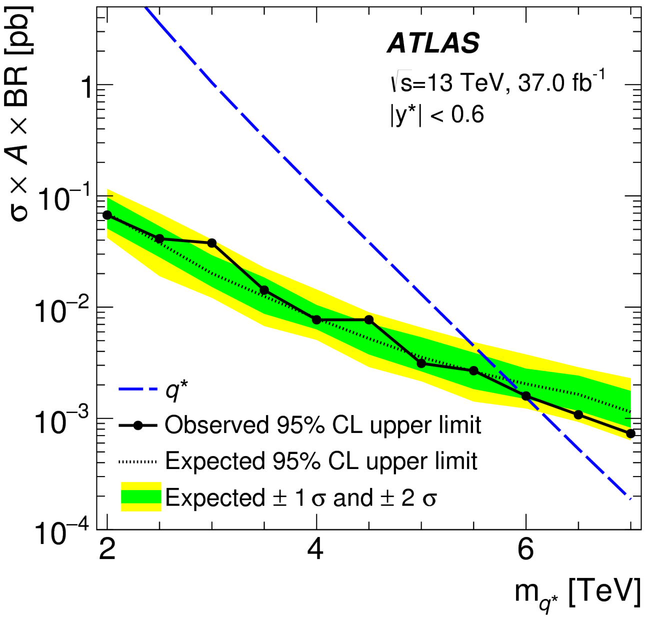
arXiv:1703.09127



Di-jet mass (TeV)

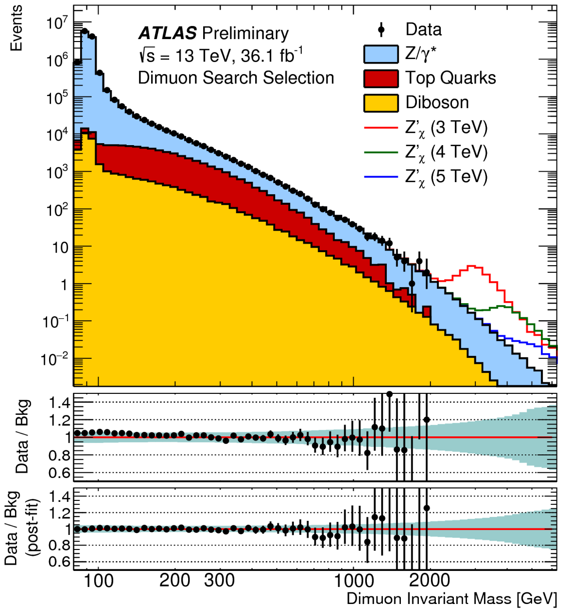


No excited quark state with mass < ~ 6 TeV



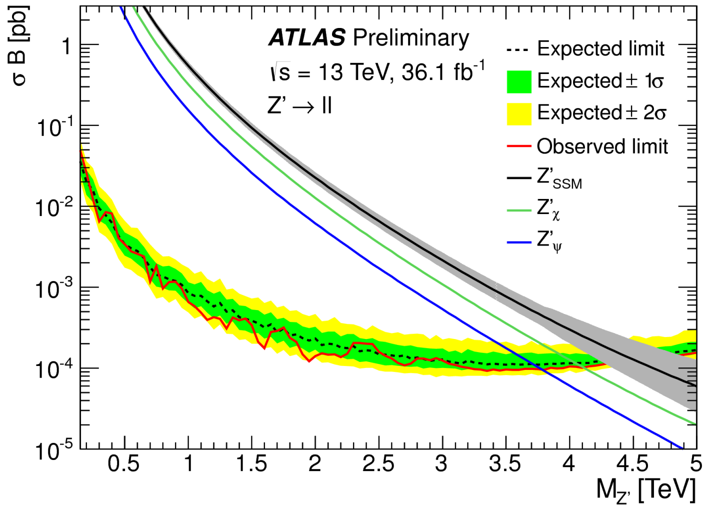
Production of muon pairs and search for new gauge bosons

ATLAS-CONF-2017-027



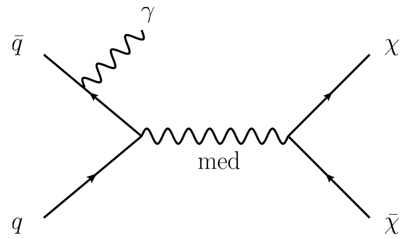
$M(\mu^+ \mu^-)$ (TeV)

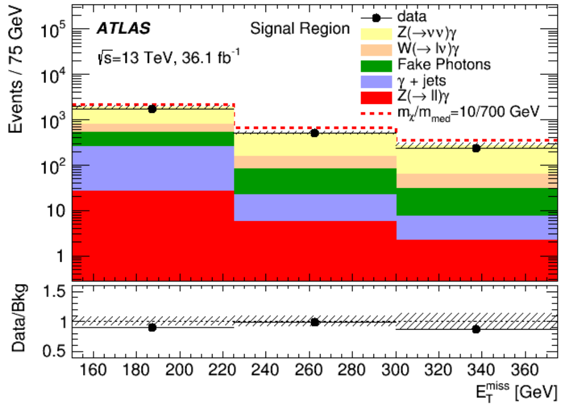
Exclude simple models of neutral gauge boson with mass < ~ 3.7 TeV



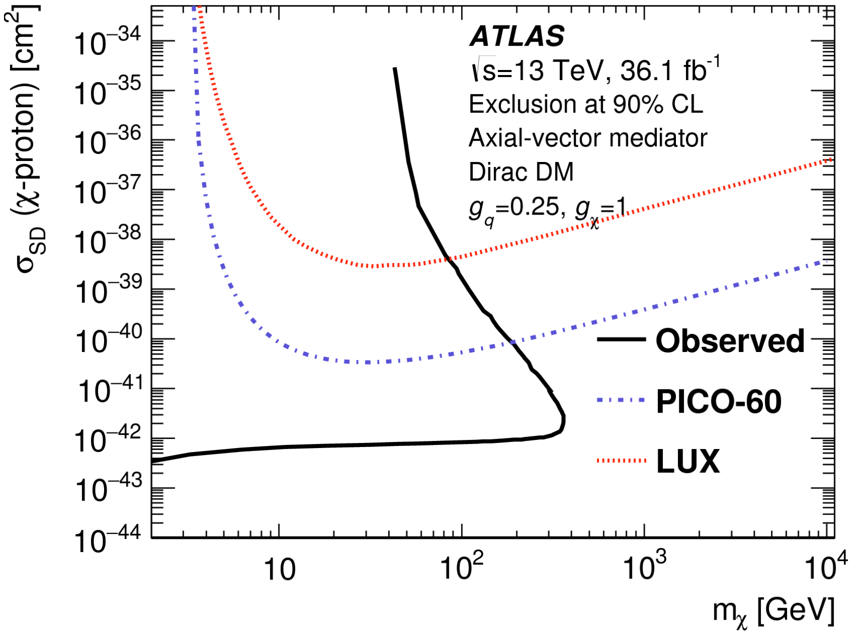
Search for dark-matter production using high Et photon with missing energy

arXiv:1704.03848





E_t^{miss} (GeV)



Mass of dark matter particle (GeV)

Summary and what's next

- It took from 1897 to 2012 to gradually reveal the particle content and structure of the Standard Model.

- Current data from the LHC finds no discovery-level deviations from SM predictions.

- A next challenge will be provided by 13 TeV LHC data that will accumulate to ~ 130 fb^{-1} by the end of 2018.

- This is a wonderful opportunity to explore if the SM will survive in its present form.

- Or perhaps put a smile on our hard working theorists ….

… anyone willing to bet ?