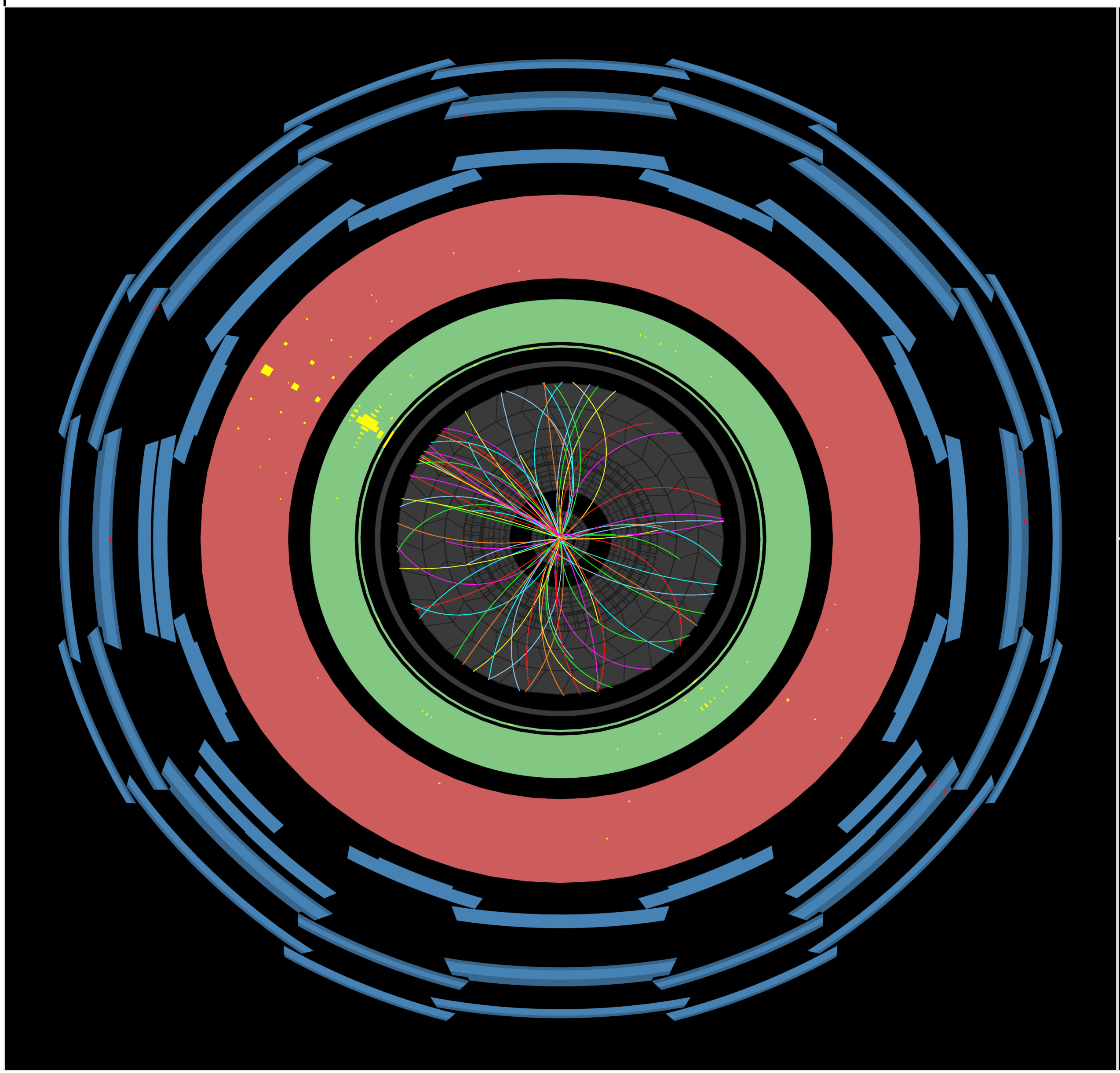
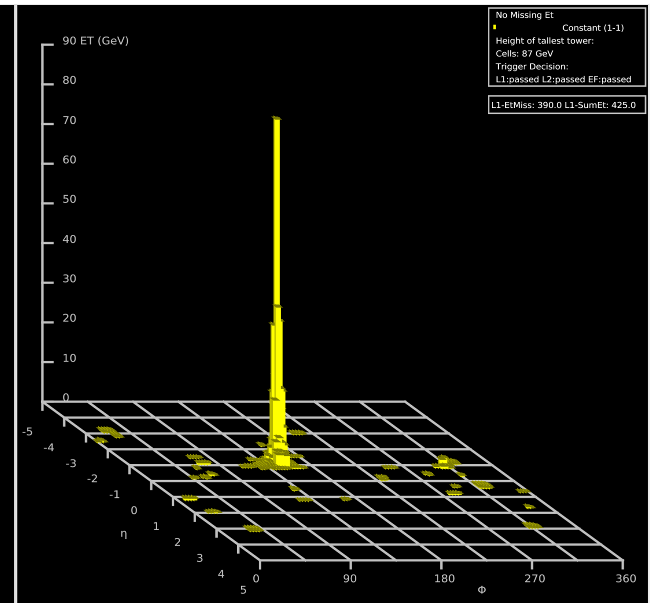
ATLAS Review and Main Results

Ryszard Stroynowski
Southern Methodist University





On behalf of the ATLAS Collaboration

Standard Model

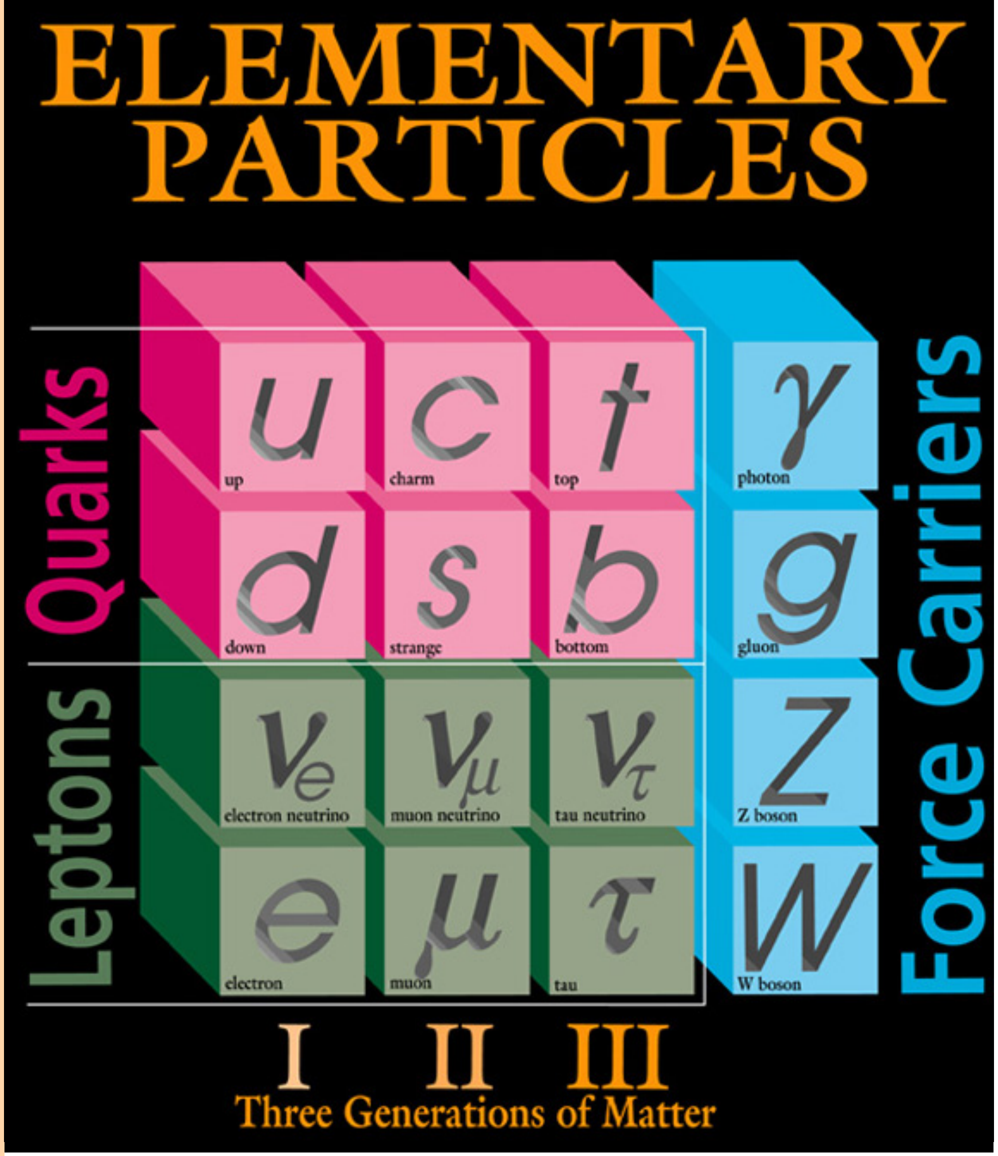
Matter is made of quarks and leptons

- Their interactions are governed by Gauge theories
  - $SU(2)_L \times U(1)$ Electroweak
  - & $SU(3)$: Strong

The forces are transmitted by Gauge bosons:

- $\gamma, W^{\pm}, Z^0$: Electroweak
- *Gluon* : Strong

- Particles receive mass through interaction with the Higgs boson



Standard Model Lagrangian

$$\mathcal{L}_{GWS} = \sum_f (\bar{\Psi}_f(i\gamma^\mu \partial\mu - m_f)\Psi_f - eQ_f\bar{\Psi}_f\gamma^\mu\Psi_f A_\mu) +$$

$$+\frac{g}{\sqrt{2}}\sum_i (\bar{a}_L^i \gamma^\mu b_L^i W_\mu^+ + \bar{b}_L^i \gamma^\mu a_L^i W_\mu^-) + \frac{g}{2c_w}\sum_f \bar{\Psi}_f \gamma^\mu (I_f^3 - 2s_w^2 Q_f - I_f^3\gamma_5)\Psi_f Z_\mu +$$

$$-\frac{1}{4}|\partial_\mu A_\nu - \partial_\nu A_\mu - ie(W_\mu^- W_\nu^+ - W_\mu^+ W_\nu^-)|^2 - \frac{1}{2}|\partial_\mu W_\nu^+ - \partial_\nu W_\mu^+ +$$

$$-ie(W_\mu^+ A_\nu - W_\nu^+ A_\mu) + ig' c_w (W_\mu^+ Z_\nu - W_\nu^+ Z_\mu|^2 +$$

$$-\frac{1}{4}|\partial_\mu Z_\nu - \partial_\nu Z_\mu + ig' c_w (W_\mu^- W_\nu^+ - W_\mu^+ W_\nu^-)|^2 +$$

$$-\frac{1}{2}M_\eta^2 \eta^2 - \frac{g M_\eta^2}{8 M_W}\eta^3 - \frac{g'^2 M_\eta^2}{32 M_W}\eta^4 + |M_W W_\mu^+ + \frac{g}{2}\eta W_\mu^+|^2 +$$

$$+\frac{1}{2}|\partial_\mu \eta + i M_Z Z_\mu + \frac{ig}{2c_w}\eta Z_\mu|^2 - \sum_f \frac{g}{2}\frac{m_f}{M_W}\bar{\Psi}_f \Psi_f \eta$$

The problems with the Standard Model

- What is the origin of the electroweak symmetry breaking
- Loop corrections blow up at high energies
- Where is the Higgs boson ?

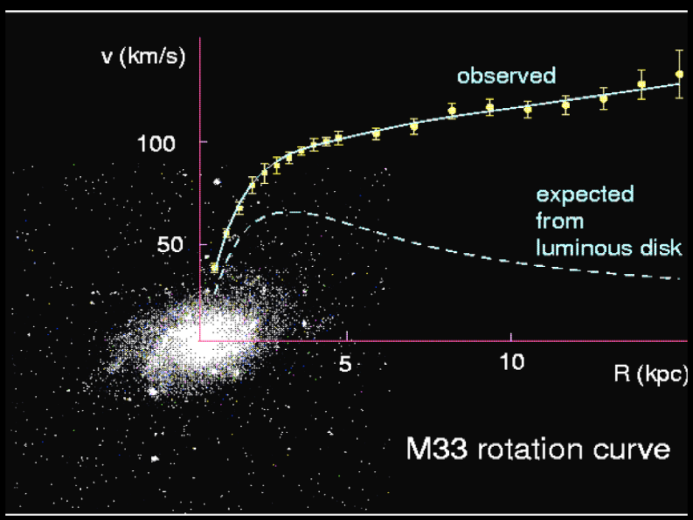
Expect new physics at the energy of ~ 1 TeV

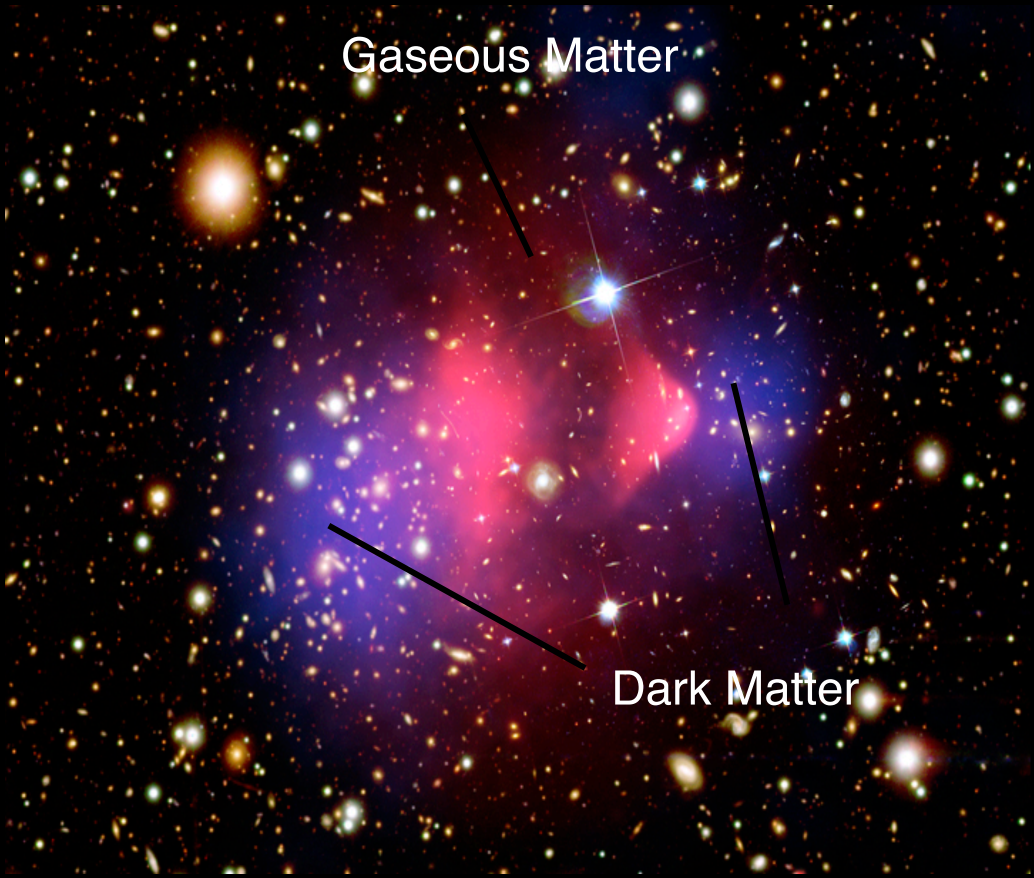
The problem of the origin of mass

- The problem of mass scales
- Dark matter
- Evolution of the universe
- Particle-antiparticle asymmetry in the universe
- Unification of gravity with the other forces

Dark Side of the Universe: Dark Matter

Dark (invisible) matter!



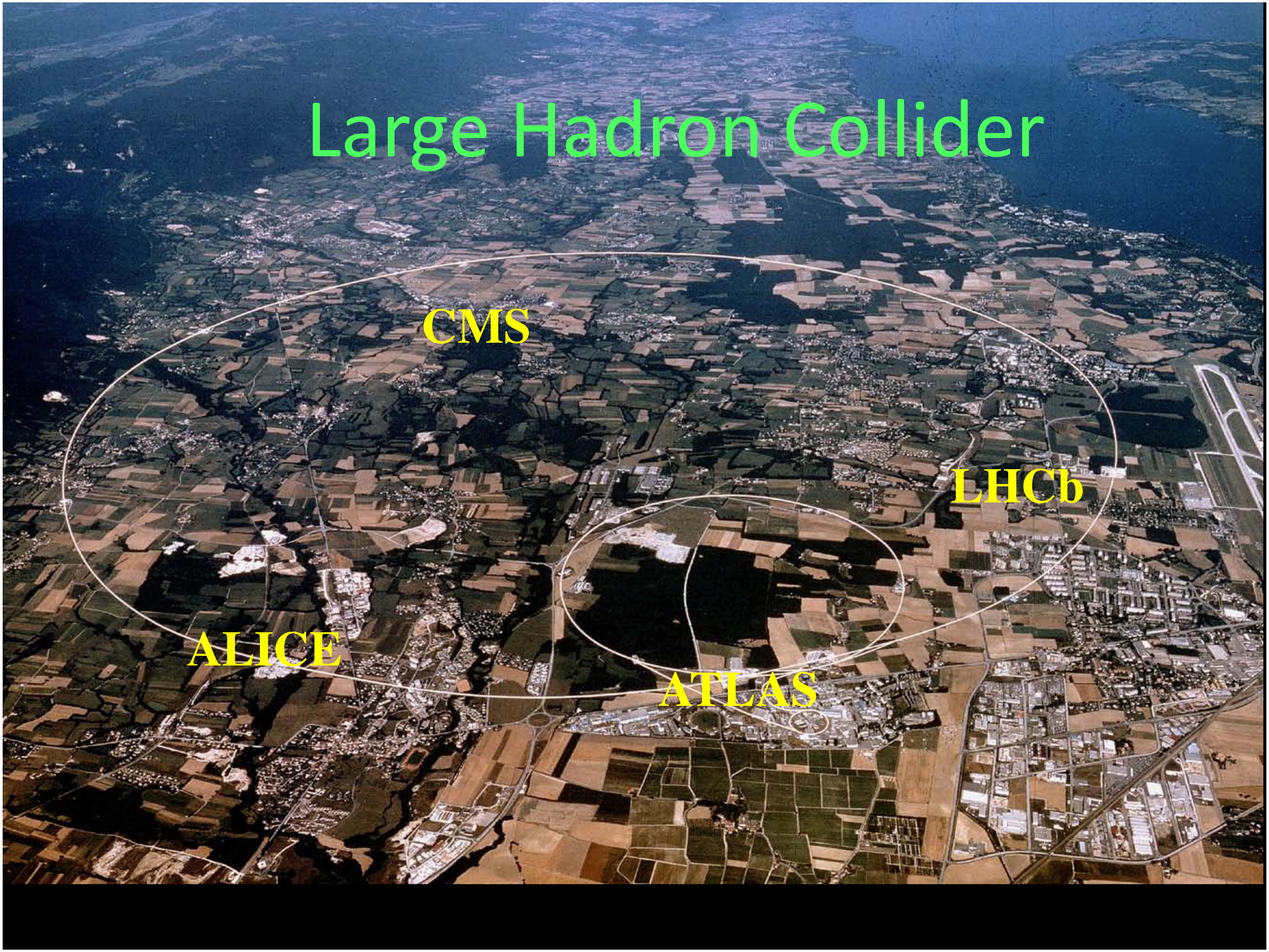


Dark Matter appears to be weakly interacting massive particle
Lightest SUSY particle has these properties !

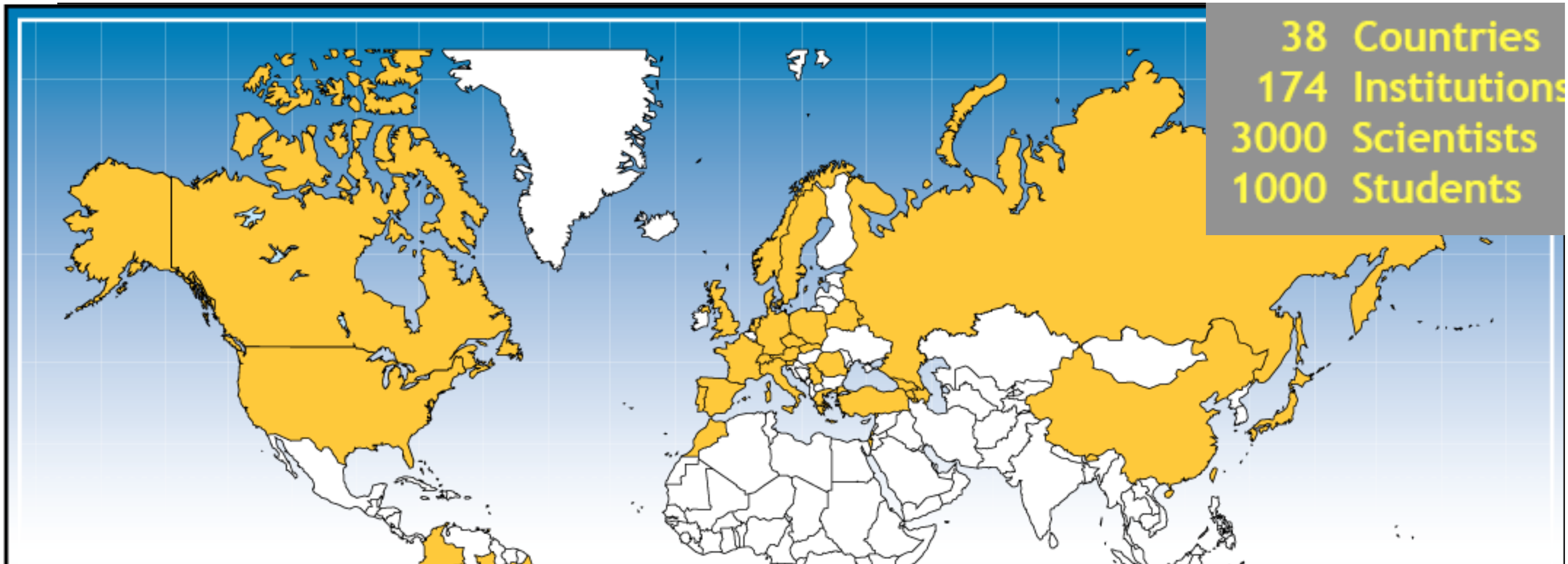
WIMPs ?

Why High Energy Accelerators?

- Reproducible results
- Large mass $E=mc^2$
- Spatial resolution $\lambda=h/p$
- **Elementary particles may be a source of dark matter**

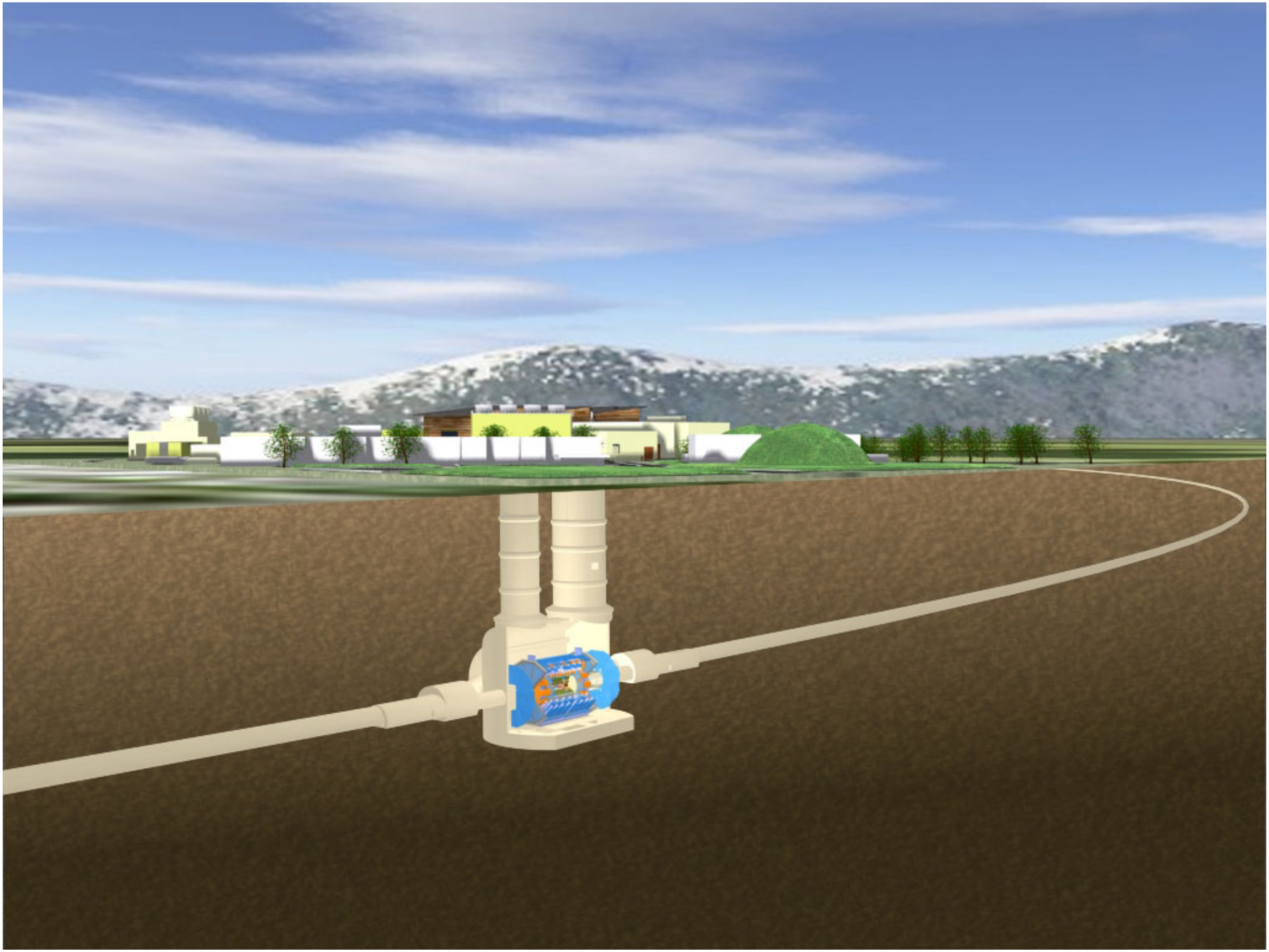

Large Hadron Collider
CMS
LHCb
ALICE
ATLAS


ATLAS
Collaboration
July 2010



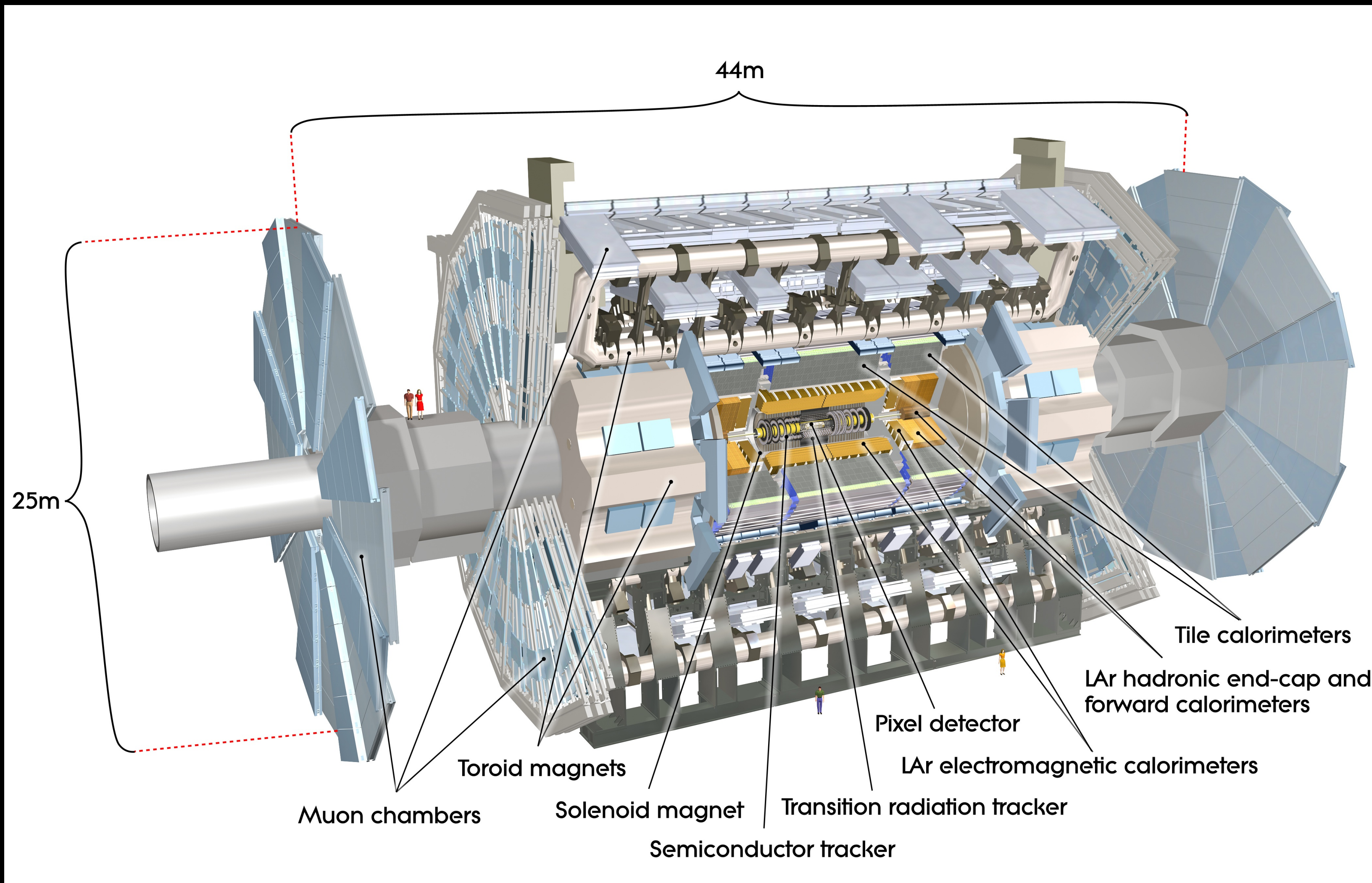
38 Countries
174 Institutions
3000 Scientists
1000 Students

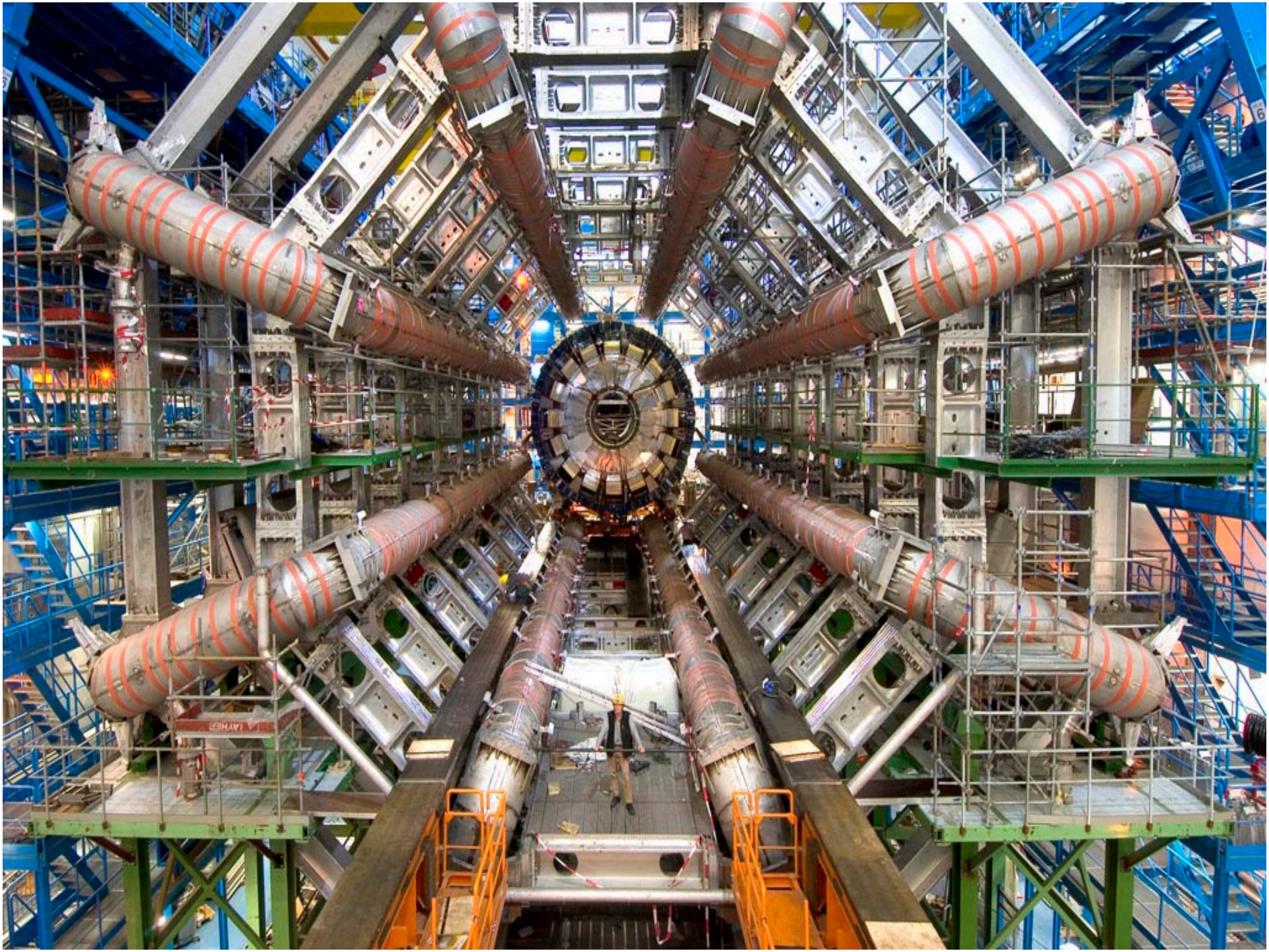
Albany, Alberta, NIKHEF Amsterdam, Ankara, LAPP Annecy, Argonne NL, Arizona, UT Arlington, Athens, NTU Athens, Baku, IFAE Barcelona, Belgrade, Bergen, Berkeley LBL and UC, HU Berlin, Bern, Birmingham, UAN Bogota, Bologna, Bonn, Boston, Brandeis, Brasil Cluster, Bratislava/SAS Kosice, Brookhaven NL, Buenos Aires, Bucharest, Cambridge, Carleton, CERN, Chinese Cluster, Chicago, Chile, Clermont-Ferrand, Columbia, NBI Copenhagen, Cosenza, AGH UST Cracow, IFJ PAN Cracow, SMU Dallas, UT Dallas, DESY, Dortmund, TU Dresden, JINR Dubna, Duke, Edinburgh, Frascati, Freiburg, Geneva, Genoa, Giessen, Glasgow, Göttingen, LPSC Grenoble, Technion Haifa, Hampton, Harvard, Heidelberg, Hiroshima IT, Indiana, Innsbruck, Iowa SU, Iowa, UC Irvine, Istanbul Bogazici, KEK, Kobe, Kyoto, Kyoto UE, Lancaster, UN La Plata, Lecce, Lisbon LIP, Liverpool, Ljubljana, QMW London, RHBNC London, UC London, Lund, UA Madrid, Mainz, Manchester, CPPM Marseille, Massachusetts, MIT, Melbourne, Michigan, Michigan SU, Milano, Minsk NAS, Minsk NCPHEP, Montreal, McGill Montreal, RUPHE Morocco, FIAN Moscow, ITEP Moscow, MEPhI Moscow, MSU Moscow, LMU Munich, MPI Munich, Nagasaki IAS, Nagoya, Naples, New Mexico, New York, Nijmegen, Northern Illinois, BINP Novosibirsk, Ohio SU, Okayama, Oklahoma, Oklahoma SU, Olomouc, Oregon, LAL Orsay, Osaka, Oslo, Oxford, Paris VI and VII, Pavia, Pennsylvania, NPI Petersburg, Pisa, Pittsburgh, CAS Prague, CU Prague, TU Prague, IHEP Protvino, Regina, Rome I, Rome II, Rome III, Rutherford Appleton Laboratory, DAPNIA Saclay, Santa Cruz UC, Sheffield, Shinshu, Siegen, Simon Fraser Burnaby, SLAC, South Africa, Stockholm, KTH Stockholm, Stony Brook, Sydney, Sussex, AS Taipei, Tbilisi, Tel Aviv, Thessaloniki, Tokyo ICEPP, Tokyo MU, Tokyo Tech, Toronto, TRIUMF, Tsukuba, Tufts, Udine/ICTP, Uppsala, UI Urbana, Valencia, UBC Vancouver, Victoria, Waseda, Washington, Weizmann Rehovot, FH Wiener Neustadt, Wisconsin, Wuppertal, Würzburg, Yale, Yerevan



ATLAS Detector

2T solenoid, toroid system
Tracking to $|\eta|$=2.5, calorimetry to $|\eta|$= 4.9



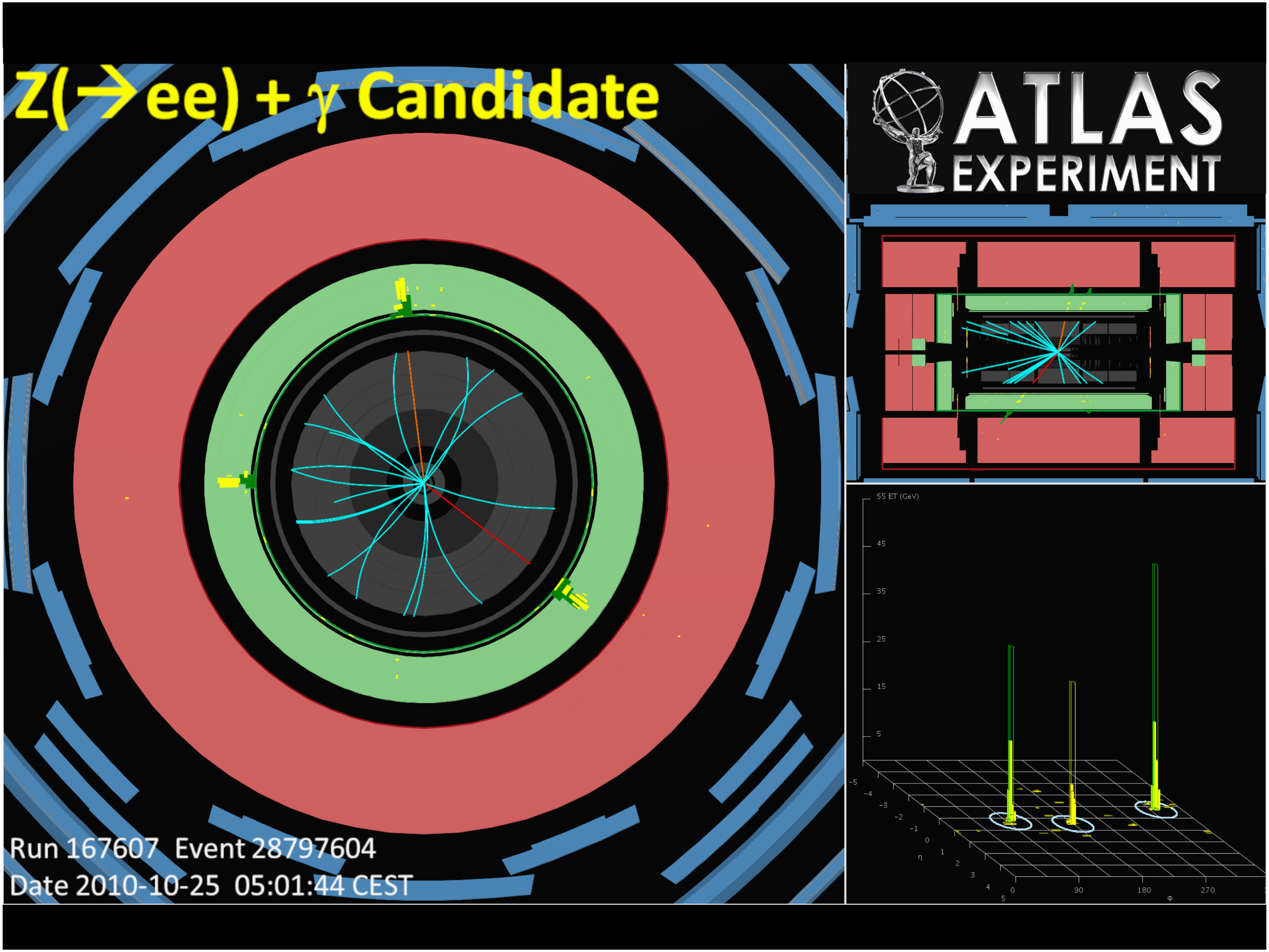


[redacted]

ATLAS Experimental observables

Electron	isolated track with matching em cluster η, φ from tracking, energy from calorimeter
Muon	isolated, combined track (ID and muon spectrometer)
Photon	isolated em cluster (no track) pointing to the vertex
2 tracks conversion:	2 electrons fitted to separated vertex
1 track conversion:	1 TRT track with with high ionization

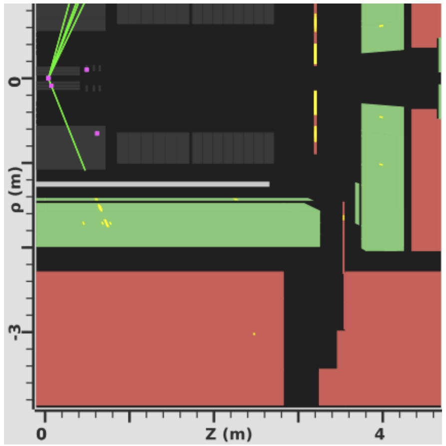
Tau (hadronic)	tracking + calorimeter signal shape
Jet	energy deposits in calorimeters anti-k_T algorithm, p_T(jet) > 25 GeV
b-jet	jet with displaced vertex, $L / \sigma(L) > 5.7$
E_T^{miss}	energy imbalance in transverse plane from topological clusters in the calorimeters



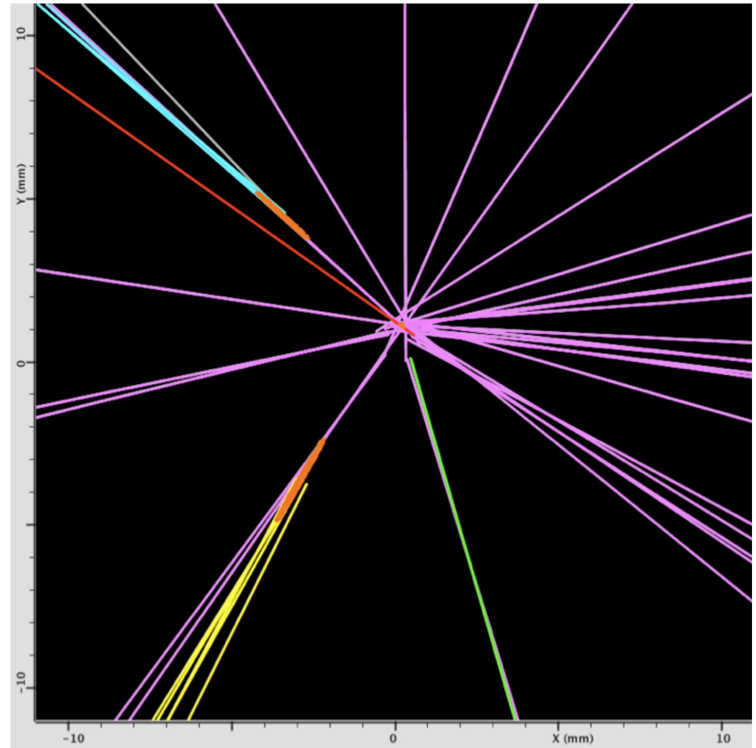
Z(→ee) + γ Candidate
ATLAS
EXPERIMENT
Run 167607 Event 28797604
Date 2010-10-25 05:01:44 CEST
55 ET (GeV)
45
35
25
15
5
-5
-4
-3
-2
-1
0
1
2
3
4
5
η
0
90
180
270
Φ

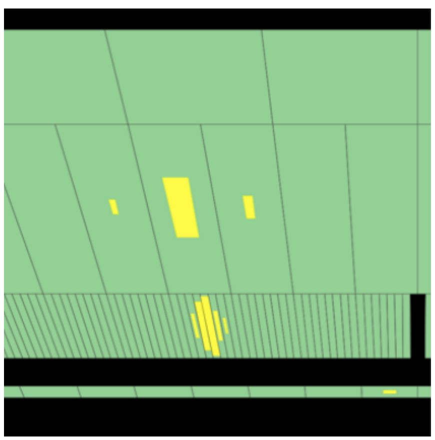
Signatures

electron

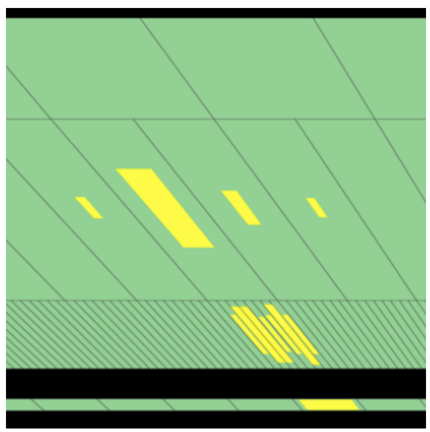


b-jet



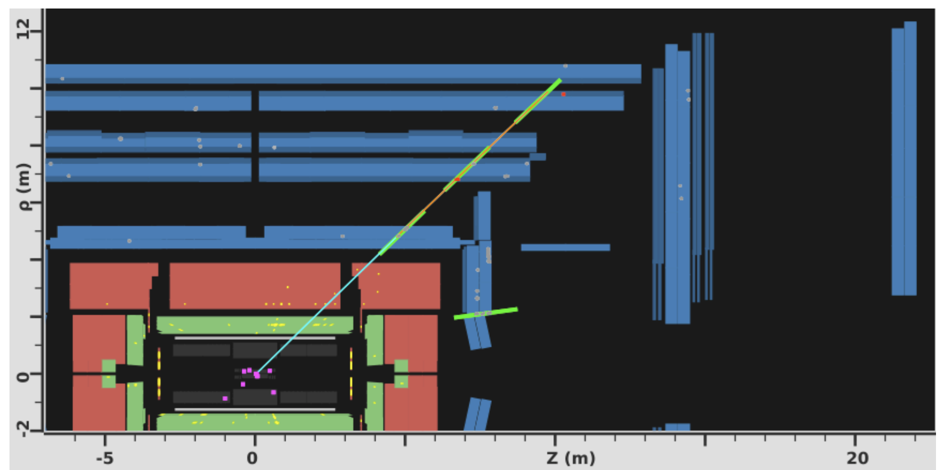


photon



π^0

muon

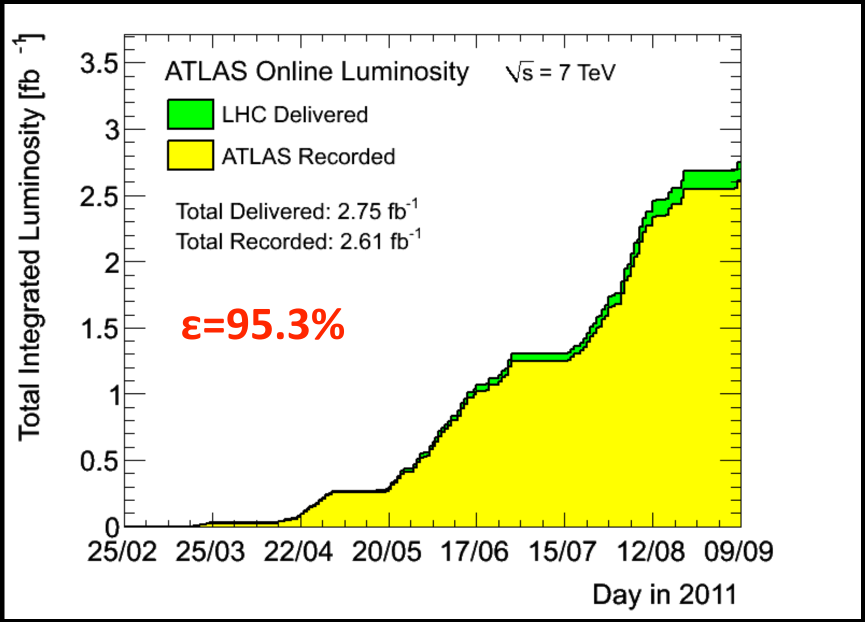


Details

Detector

- **In time LAr pileup** multiple (4-20) interactions per bunch crossing
  → requirements: precise vertex determination, photon pointing, spatial isolation of electron and photons
- **Out of time pileup** calorimeter signal collection time spans up to 8 bunch crossings
  → signal shape matching with expectations
- **Photon conversions** about 60% of photons converts in the tracker material before reaching calorimeter
  → early conversions reconstructed from 2 tracks, energy measured in the calorimeter
  → late conversions reconstructed from single tracks in TRT
- **Cosmic muons** removed by the vertex and timing constraints
- **Calorimeter calibration**
  - electrons - Use calibration signals + Geant4 simulations based on test beam results + "tag and probe" signals from J/psi + Z
  - photons - use Geant4 simulation + fudge factors to fix shower shape
  - muons - simulations + J/psi and Z signals
  - jets - simulations
  - missing ET - simulations

Data Collection



Superb LHC performance

Data collection efficiency >95%

2010		46 pb^{-1}
2011	March	295 pb-1
	July	1.50 fb^{-1}
	August 31	**2.61** fb^{-1}

Luminosity measured with calorimeters + several dedicated detectors. Calibrated with the Van der Meer beam-beam scans.

$\Delta L/L = \pm 3.4\%$ (2010)
$\Delta L/L = \pm 3.7\%$ (2011, preliminary)

$$N_{ev} = \int L dt \, \sigma \, A \, \varepsilon$$

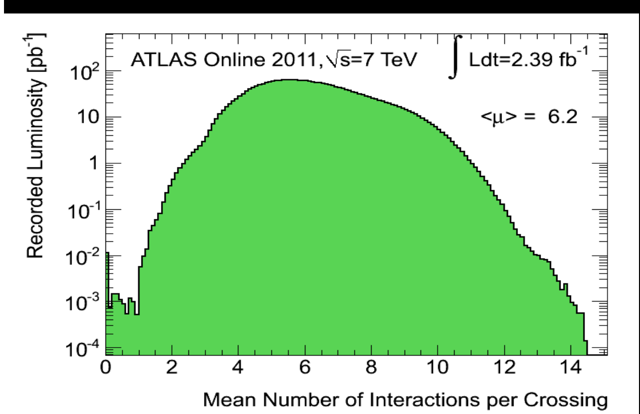
Trigger and pileup

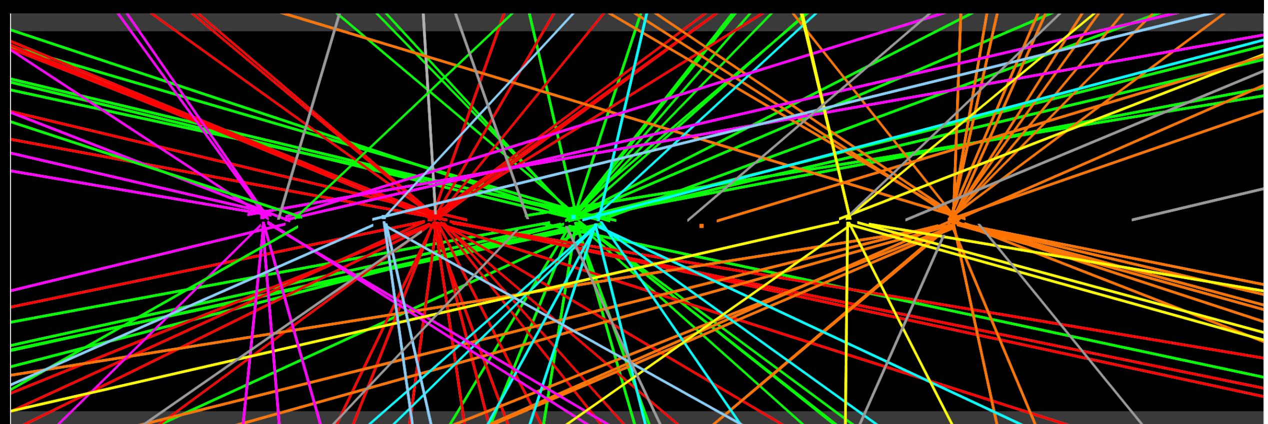
Primary triggers

Inclusive electrons	pT > ~~20 GeV~~ 22 GeV
Inclusive muons	pT > 18 GeV
Inclusive jets	pT > 180 GeV
Missing energy	E_T^{miss} > 60 GeV
Diphotons	p_T > 20 GeV

\+ several additional and monitoring triggers

Pileup 5-14 interactions per beam crossing on average





7 vertices

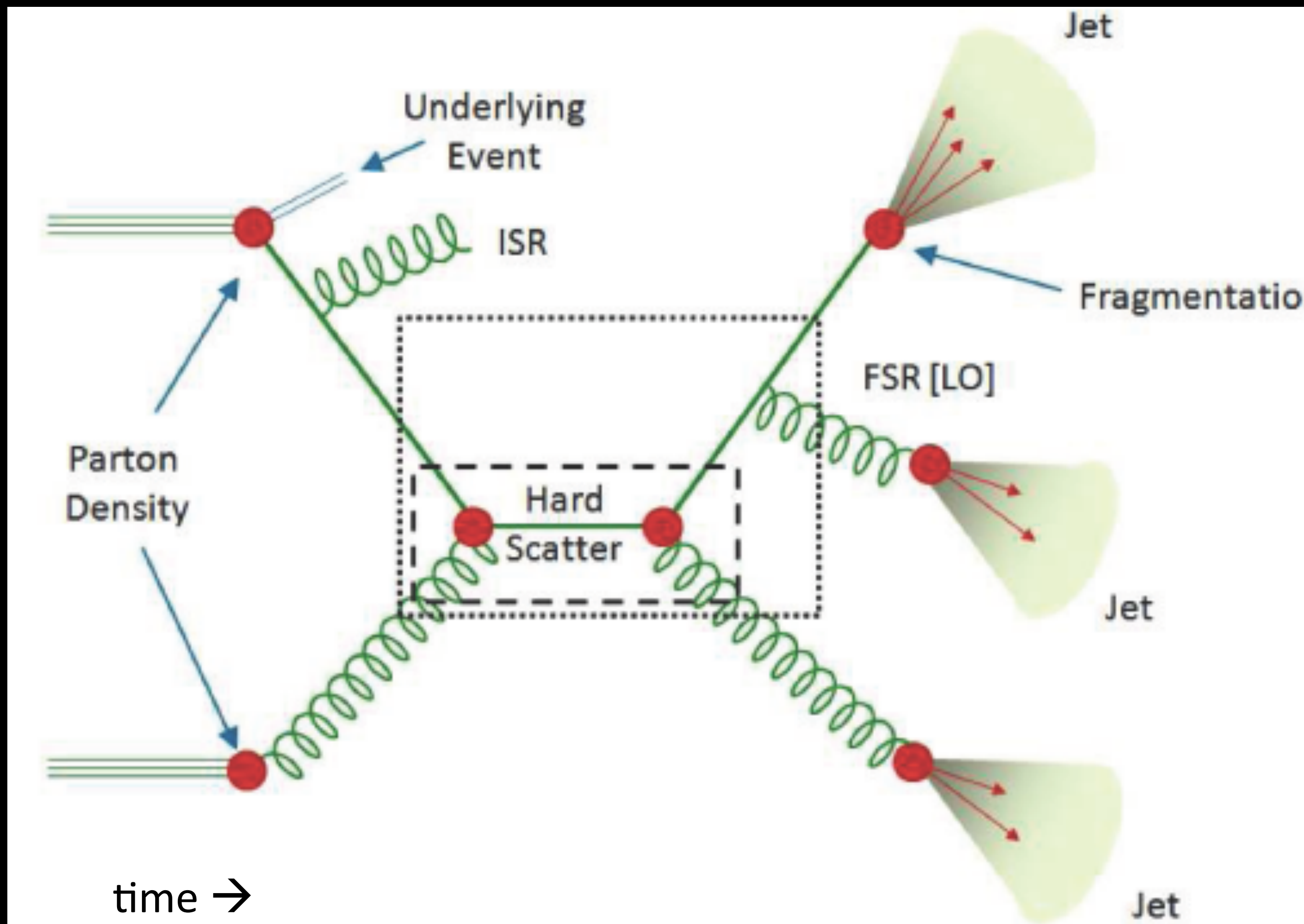
Physics results

- *Impossible to discuss all recent results. Within last 18 months ATLAS Collaboration produced 74 journal papers and 240 conference notes. The following are selected recent highlights only.*

- *General method of searching for new physics is to look for deviations from the expectations and to interpret the results within a specific model.*

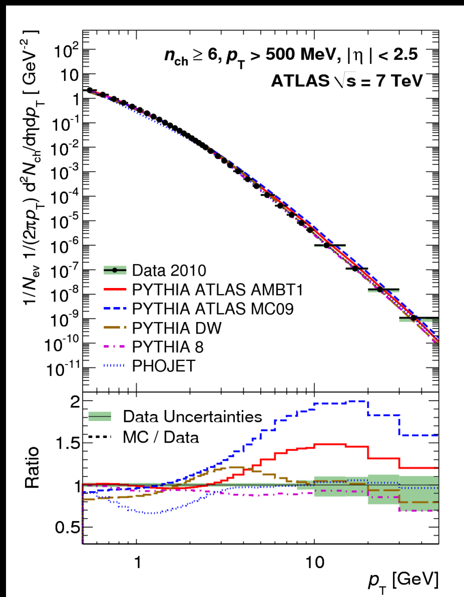
- *First step is to verify that we understand well the "known" physics:*
multiplicity, particle spectra, jet distributions, vector boson production, t tbar production, ……

QCD and the Standard Model

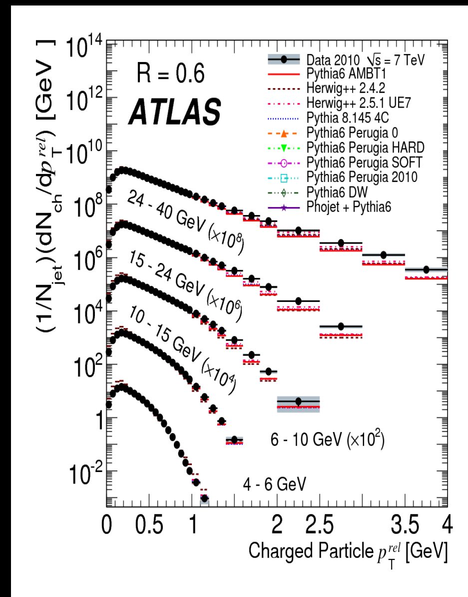


from N. Varelas, EPC2011

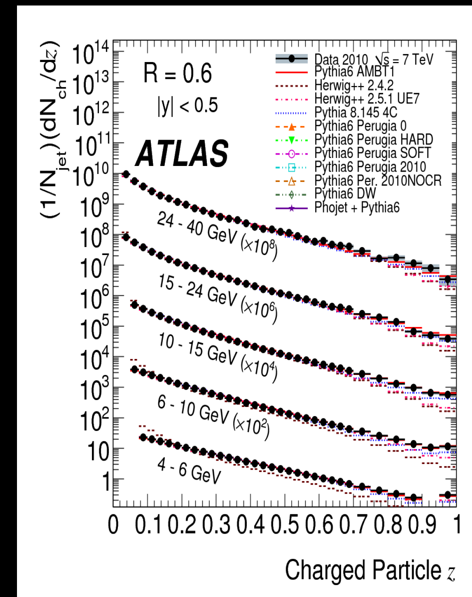
QCD - particle and jet production



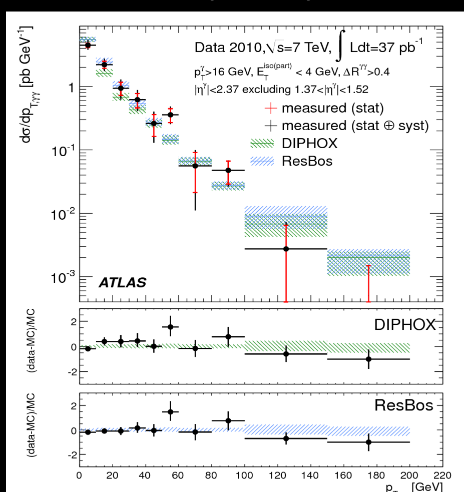
multiplicity



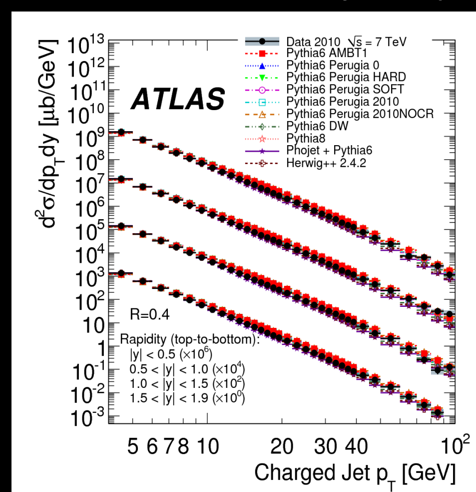
Particles within jets, pt



jets, fragmentation



diphotons



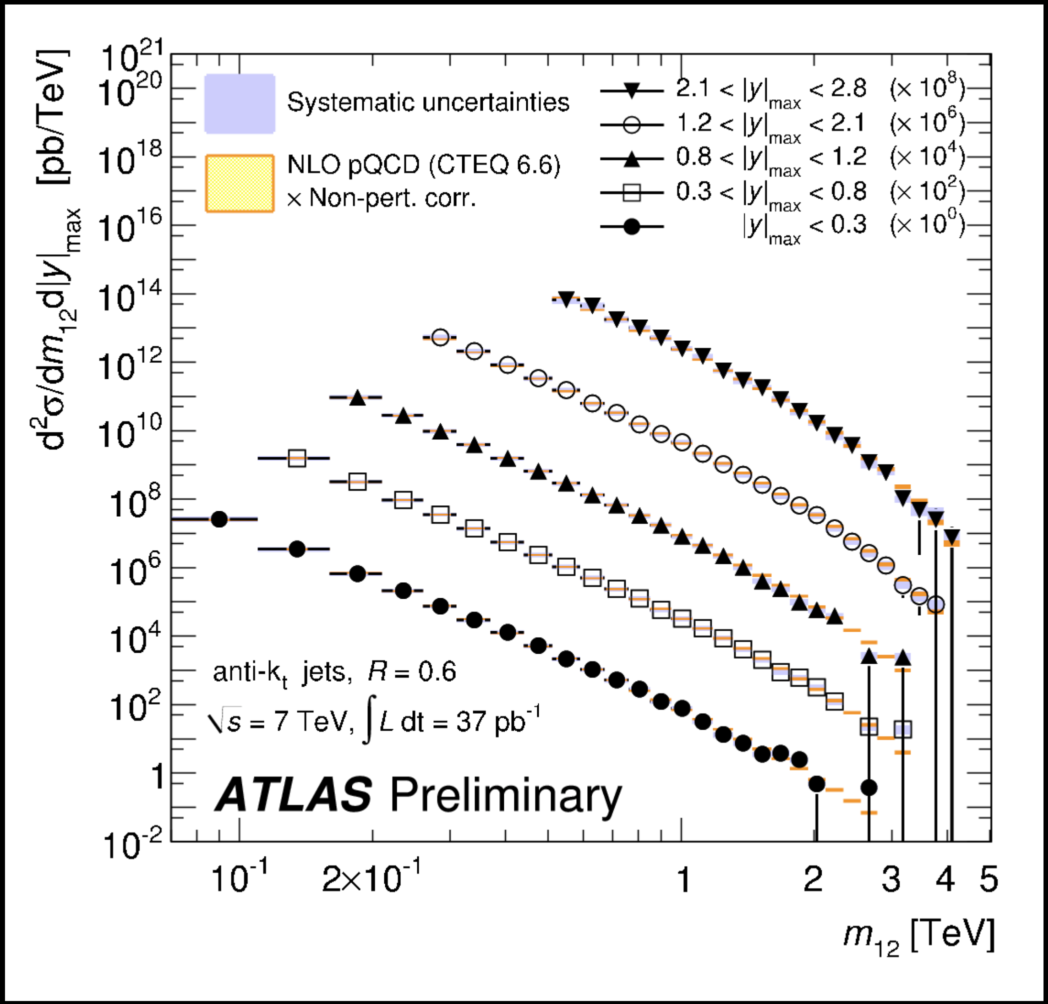
Jets, pt

Impressive agreement of data with QCD Monte Carlo predictions over many (up to 12) orders of magnitude.

arXiv1107.3311

Dijet mass cross section

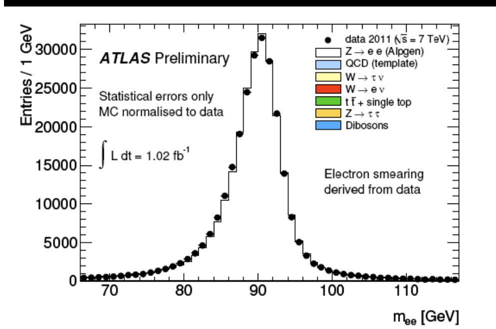
Comparison to NLO + non-perturbative corrections

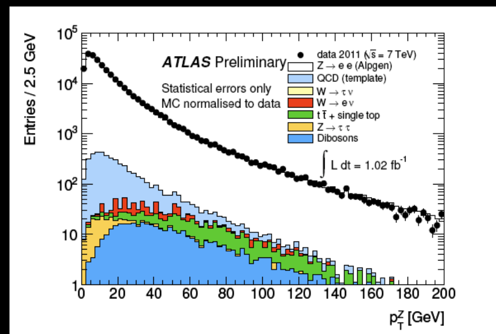


ATLAS-CONF-2011-047

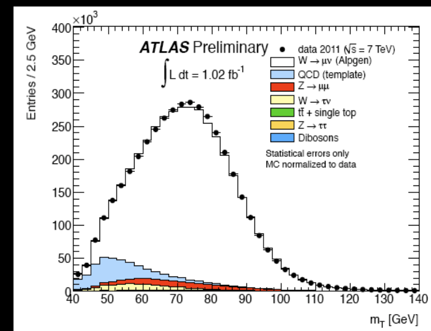
Gauge bosons

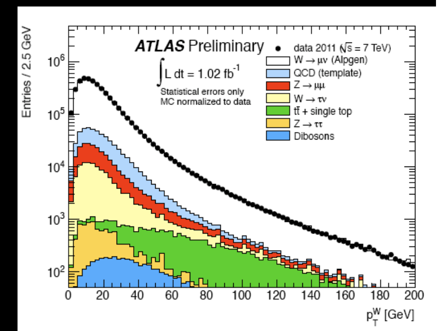
Z → e e



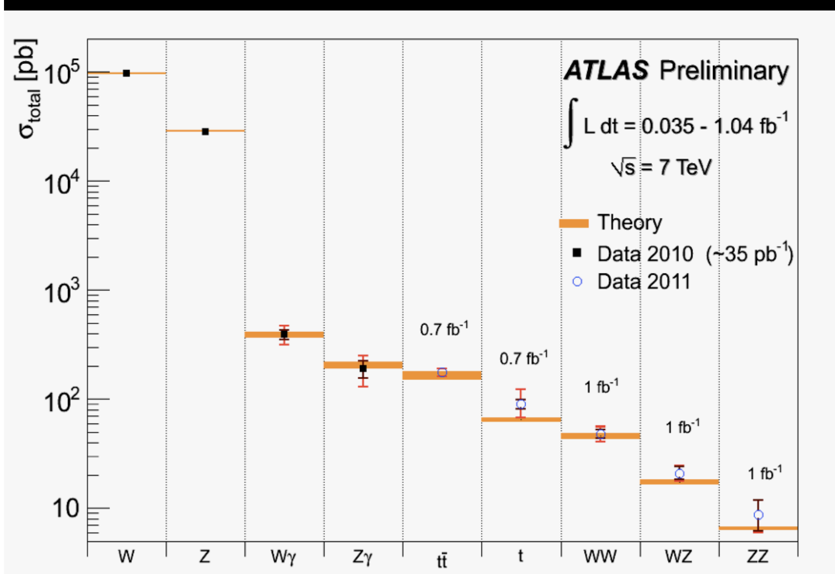


W → μ ν



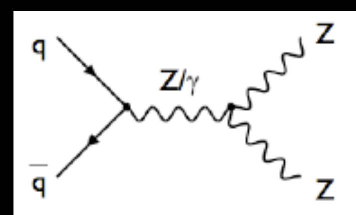


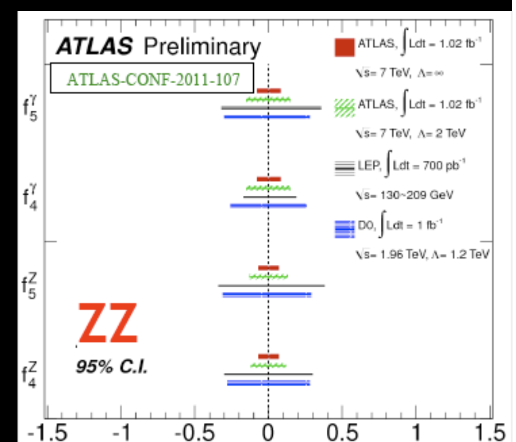
Cross sections



Theory - NLO or higher

Triple gauge coupling





No deviations from SM

SUPERSYMMETRY

- Extension of the Standard Model (SM) - solves many theoretical problems unification of gauge couplings, cancellation of fermion and boson contributions to Higgs mass (hierarchy problem),….

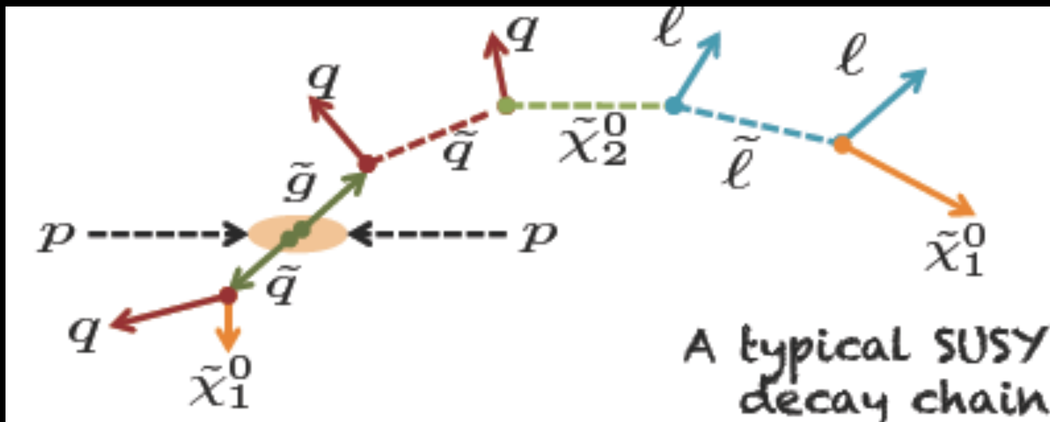
- Each SM particle has a partner with spin that differs by ½.

- If R parity is conserved $R = (-1)^{2j+3B+L}$ SUSY particles are produced in pairs and lightest one is stable.

- The minimal extension of the SM (MSSM) introduces 105 new parameters. SUSY is predictive about spins and couplings but says nothing about the masses.

- Large number of models with additional assumptions that reduce the numbers of free parameters (e.g., mSUGRA, CMSSM have 5 parameters). For most of the models a typical decay chain has lowest mass supersymmetric neutral particle that escapes the detection
  → missing energy (E_T^{miss}). Bonus: dark matter candidate

SUSY

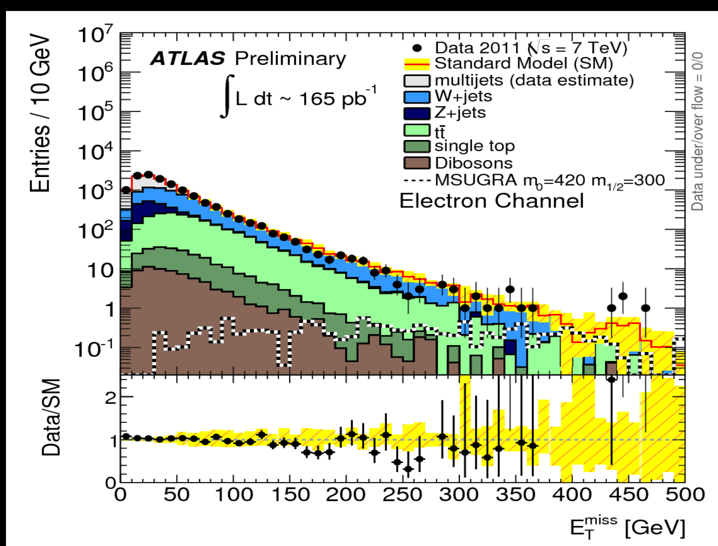


Example: squark decay
Signature E_T^{miss} + leptons + 3 jets

ATLAS-CONF-2011-090

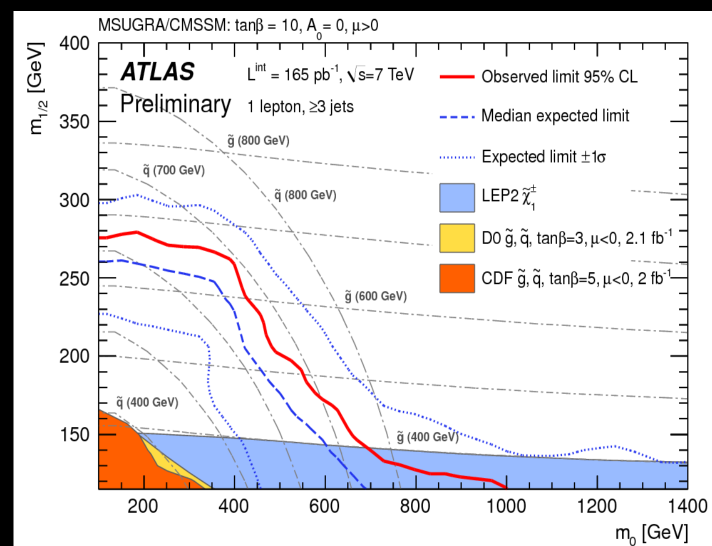
Electron with $p_T > 25$ GeV and at least 3 jets with $p_T > 60, 25, 25$ GeV.

Observed and expected 95% CL exclusion limits



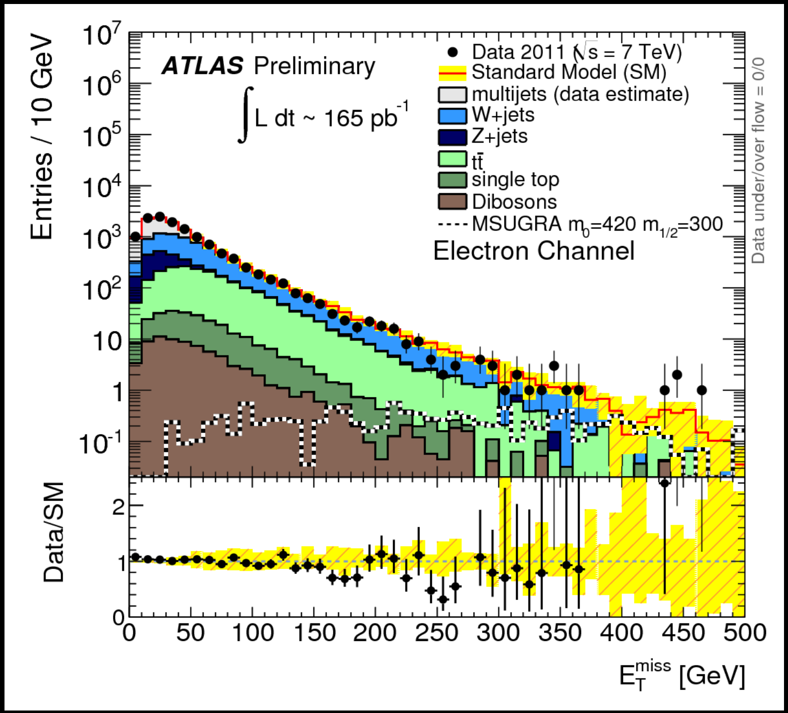
Missing E_T

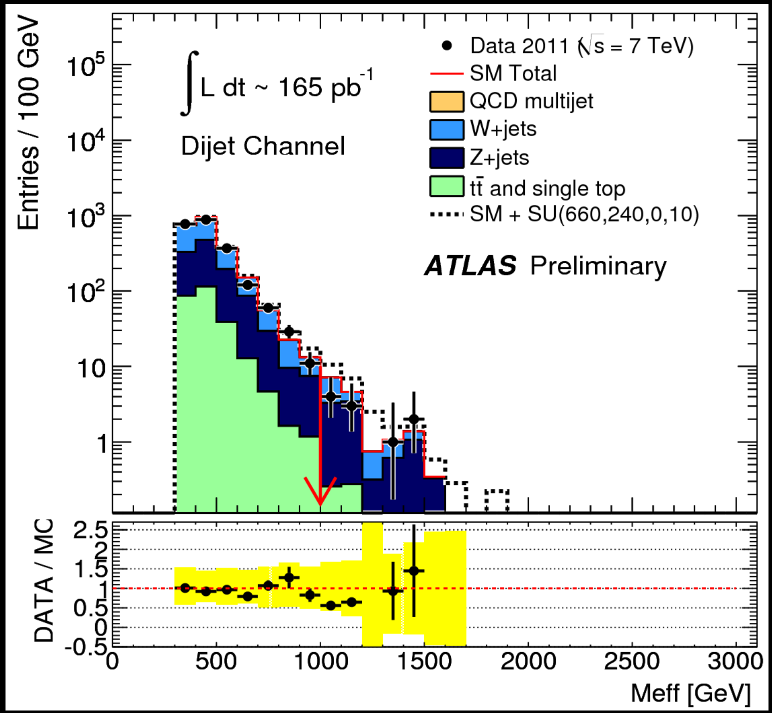
universal scalar mass



gaugino mass

SUSY cont.





Missing E_T

Events with one lepton + jets

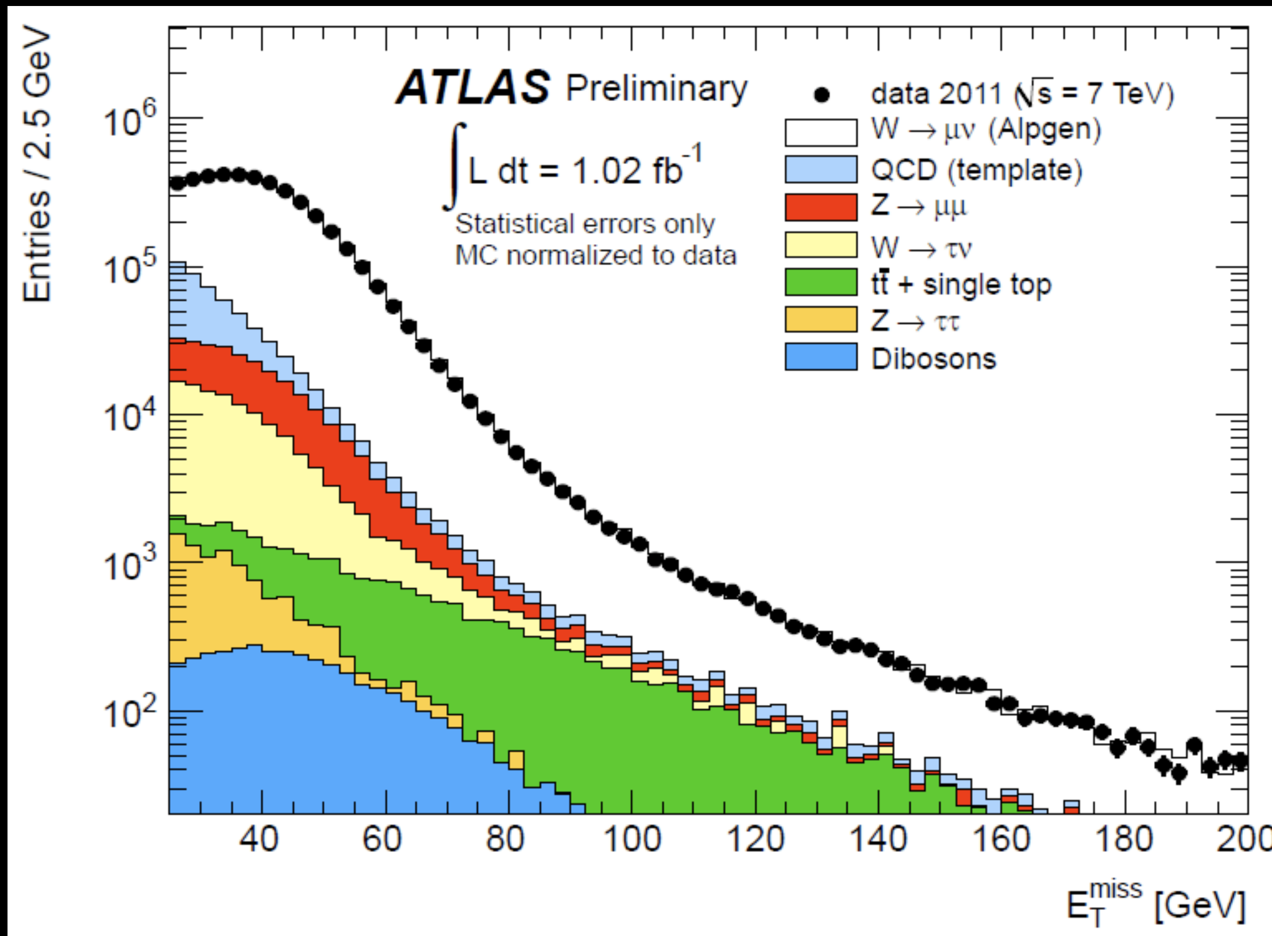
ATLAS-CONF-2011-090

Search for squarks and gluinos

Events with jets and no leptons

ATLAS-CONF-2011-086

Missing Transverse Energy, E_T^{miss}



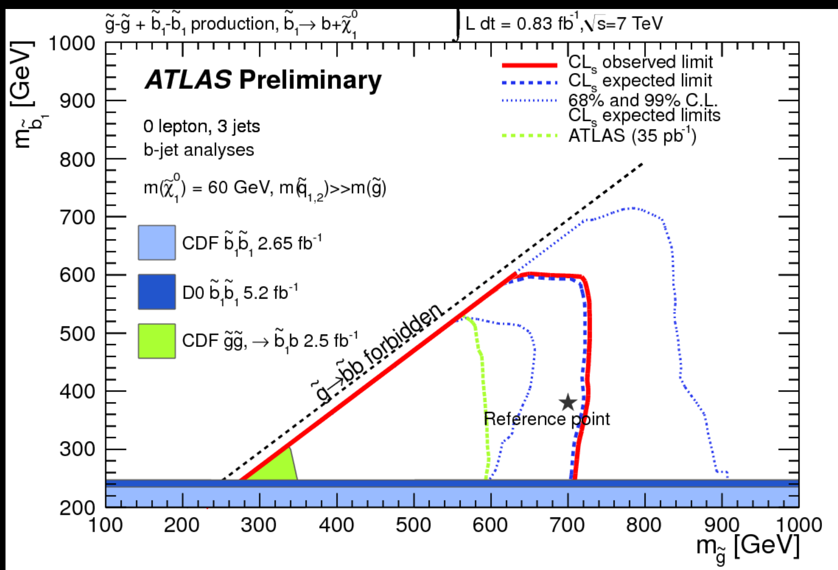
SM - W → μν: Missing transverse energy spectrum.

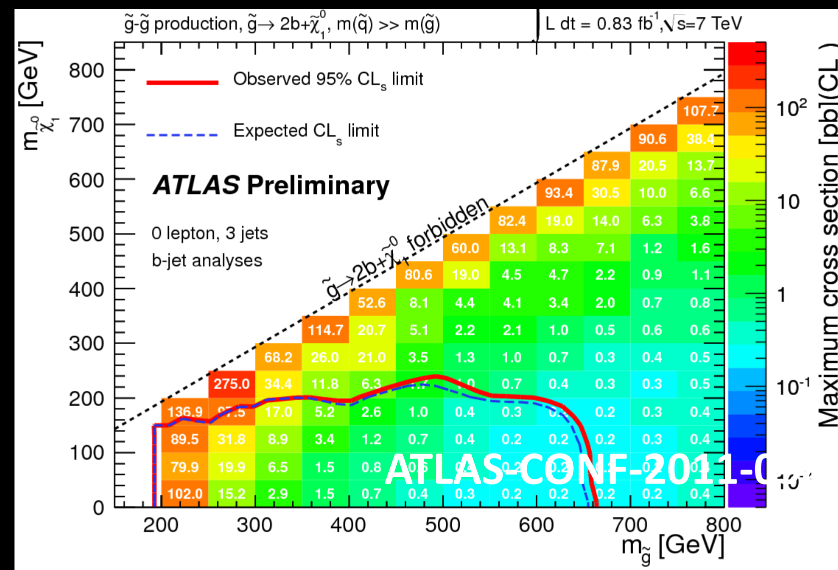
No sign of deviation from known processes

More SUSY exclusion limits

Models with large mixing of right handed and left-handed squarks expect large cross section
For heavy quark jets. Signature: b-jets, no leptons and and large missing $E_{T.}$

ATLAS-CONF-2011-098





Observed and expected 95% CL exclusion
Limits in the mass sbottom-gluino plane

95% CL upper cross section limits in pb
for gluino masses > 200 GeV

Bump hunting

Method

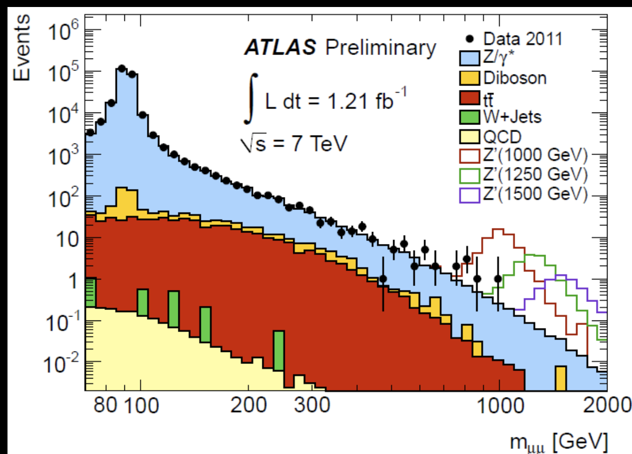
• Compare the invariant mass distribution with an expected signal from a new resonance of a fixed mass.
• For a given distribution, simulate signal and vary the mass to obtain the limit.
• Include probability of statistical fluctuations for both signal and background to compare the measured limit with an expected one.

Lepton pairs	search for Z'
Lepton + E_T^{miss}	search for W'
Di-photon	Higgs, search for gravitons, extra dimensions,…
Di-jet	search for W', Z', squarks, gluinos, excited quarks, ….
e – μ	search for exotic states
ZZ, WW	Higgs, exotic states,….

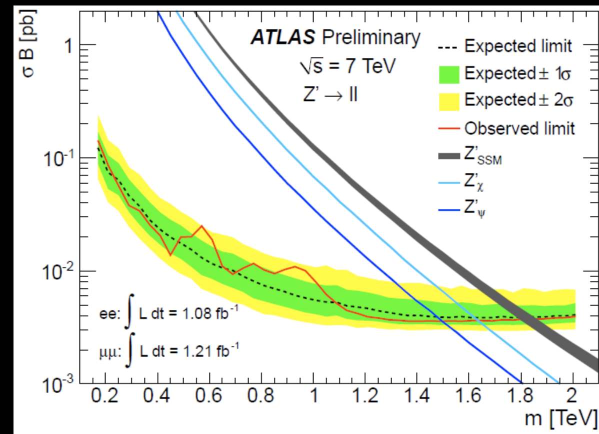
Search for sequential SM-like bosons

arXiv:1108.1316, 1582,

Z'



Di-muon mass

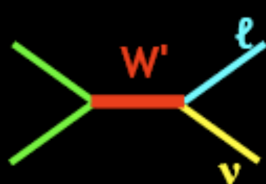


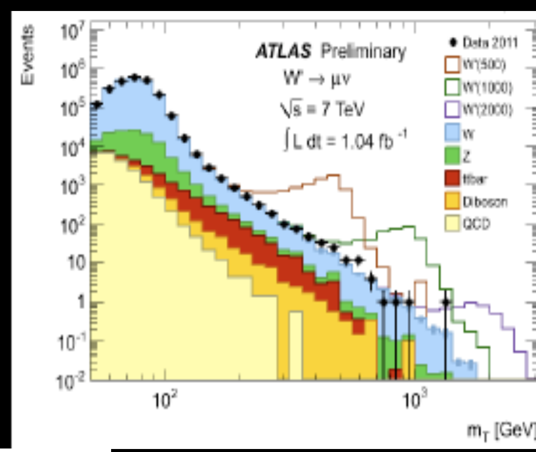
$M_{Z'}$ > 1.83 TeV @ 95% CL for SSM

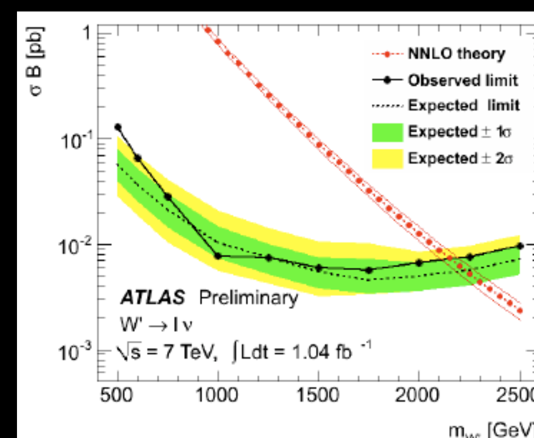
$M_{Z'}$ > 1.50 – 1.64 TeV @ 95%CL for E_6

W'

Search in transverse mass







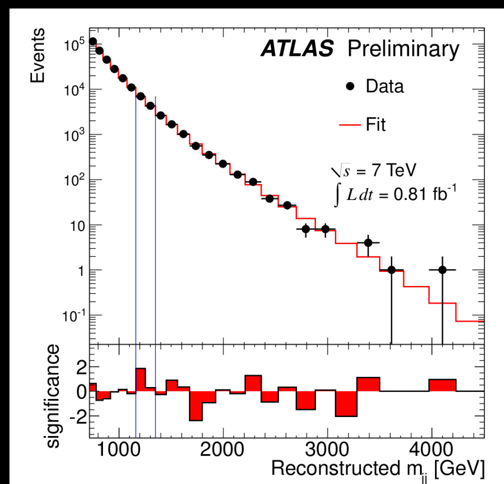
$$M_T = \sqrt{2p_T^l E_T^{miss}(1 - \cos\Delta\phi_{l,E_T^{miss}})}$$

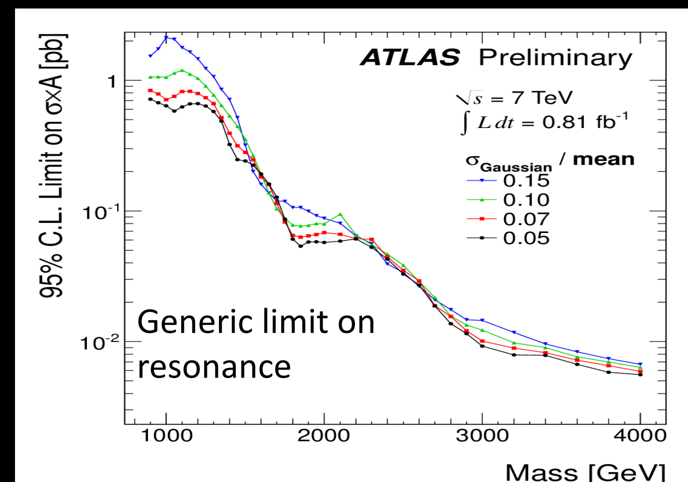
$M_{W'}$ > 2.15 TeV @ 95% CL observed

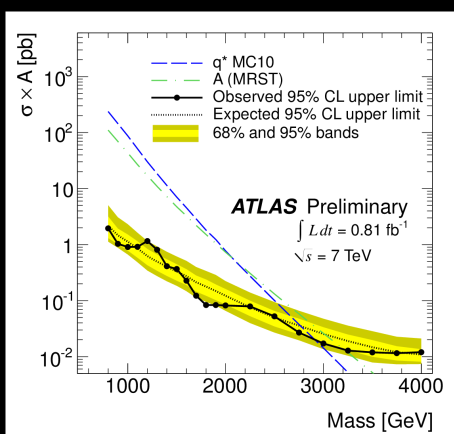
$M_{W'}$ > 2.23 TeV @ 95% CL expected

Search for di-jet resonances

Enhancement in the $m_{jet\text{-}jet}$ spectrum
Interpretation: excited quarks, axigluons, color octet scalars







95% CL limits in TeV

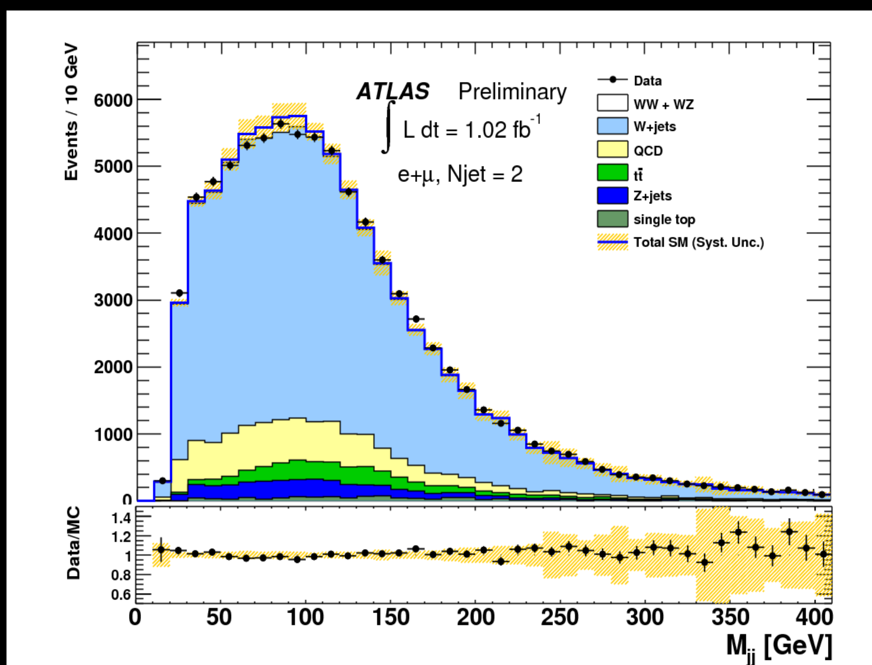
model	expected	observed
q*	2.77	2.91
axigluon	3.02	3.21
color octet	1.71	1.91

Search for di-jet resonances associated with W

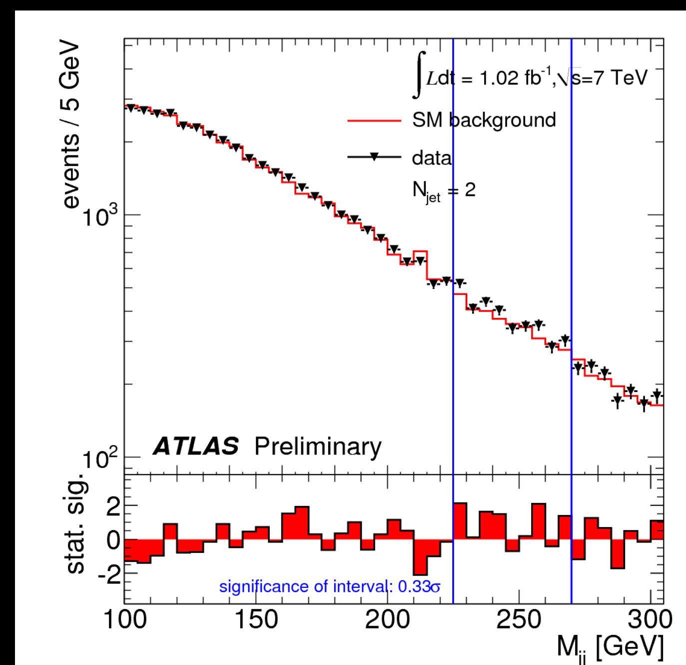
Signal: 2 jets + lepton + neutrino

ATLAS-CONF-2011-097

- electron: $E_T > 25$ GeV, $|\eta| < 2.47$, $\Delta R = 0.3$
- muon: $p_T > 20$ GeV, $|\eta| < 2.4$, $\Delta R = 0.2$
- jet: anti-k_T algorithm, $R = 0.4$, $m_T > 40$ GeV
- $E_T^{miss} > 25$ GeV



2-jet invariant mass

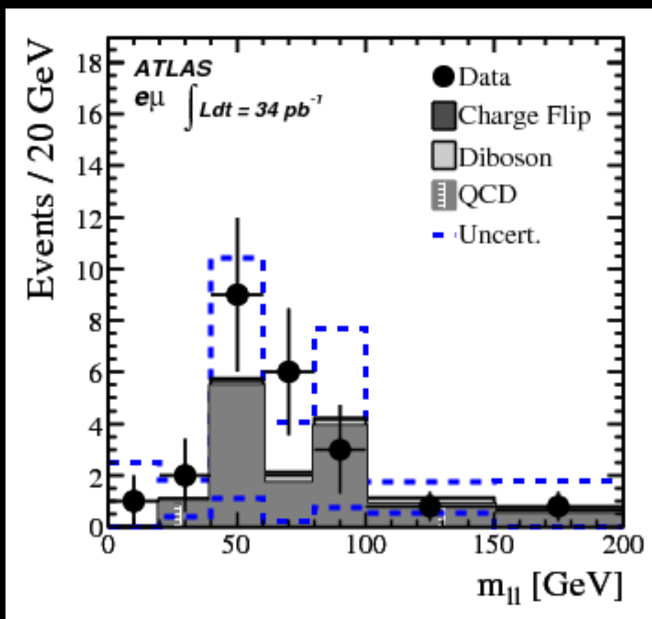


Signal/background ratio

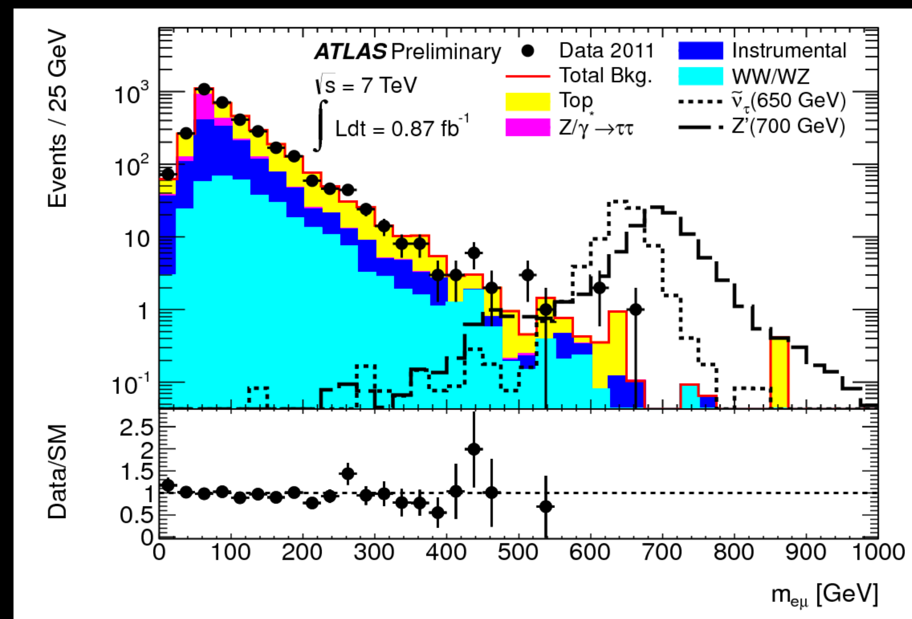
No evidence for CDF bump but the WW/WZ associated production rate is small

Search for exotics in lepton pairs

Same charge pairs



Opposite charge pairs

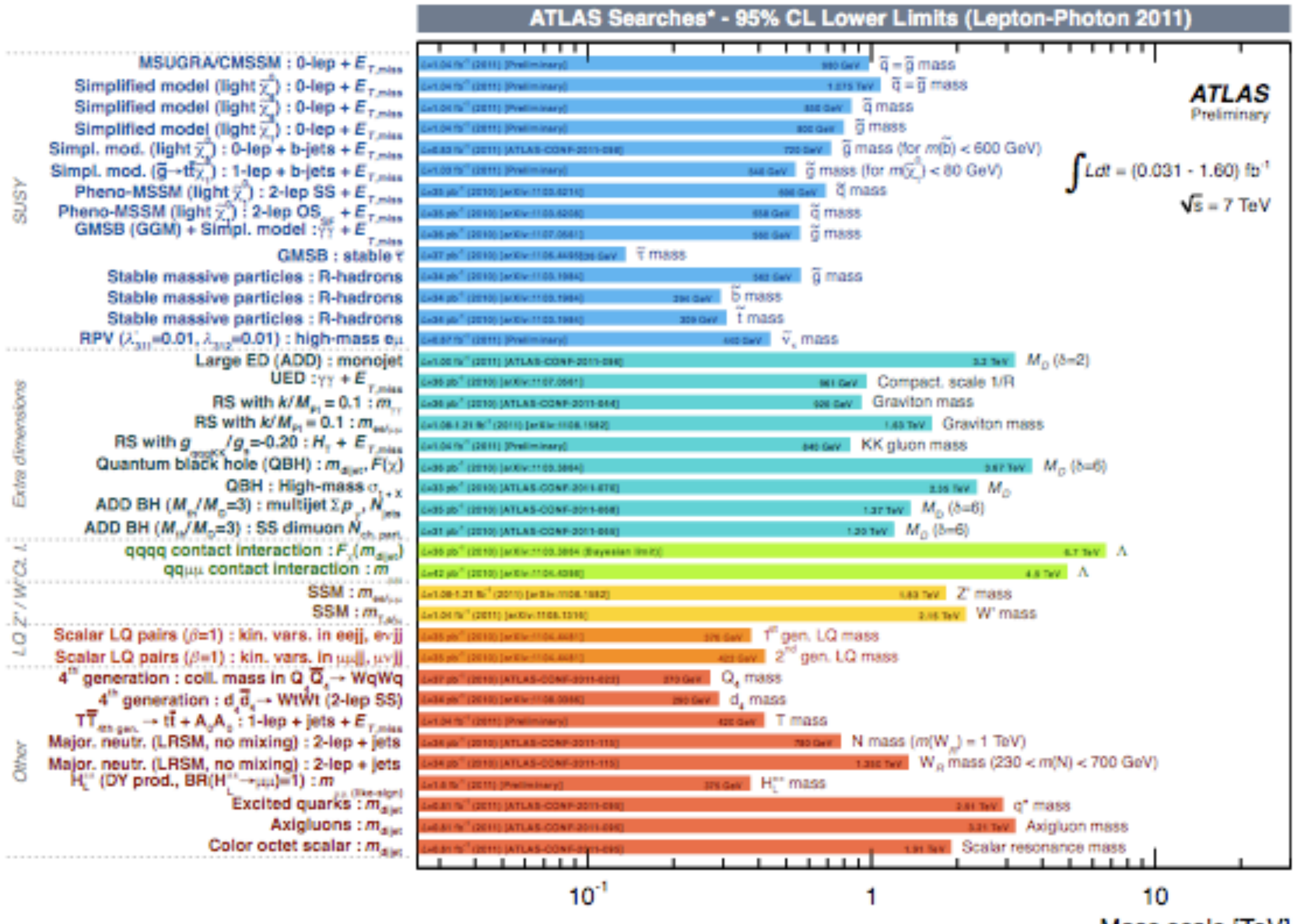


Same sign di-lepton mass sources:
- Majorana neutrinos
- universal extra dimensions
- 4th generation down-like quarks

Opposite charge e – μ resonance sources:
- sneutrions
- R-parity violating SUSY models
- Z' with lepton violating interactions

arXiv:1108.0366

ATLAS-CONF-2011-109



*Only a selection of the available results leading to mass limits shown

Higgs boson

Electroweak theory does not predict Higgs mass

Assumption that gauge boson scattering satisfies s-wave unitarity provides an upper limit

$$M_H \leq (8\pi\sqrt{2}/3G_F)^{1/2} \approx 1 \text{ TeV}$$

If bound is not satisfied weak interactions among W, Z, H become strong at 1 TeV scale.

Scalar boson

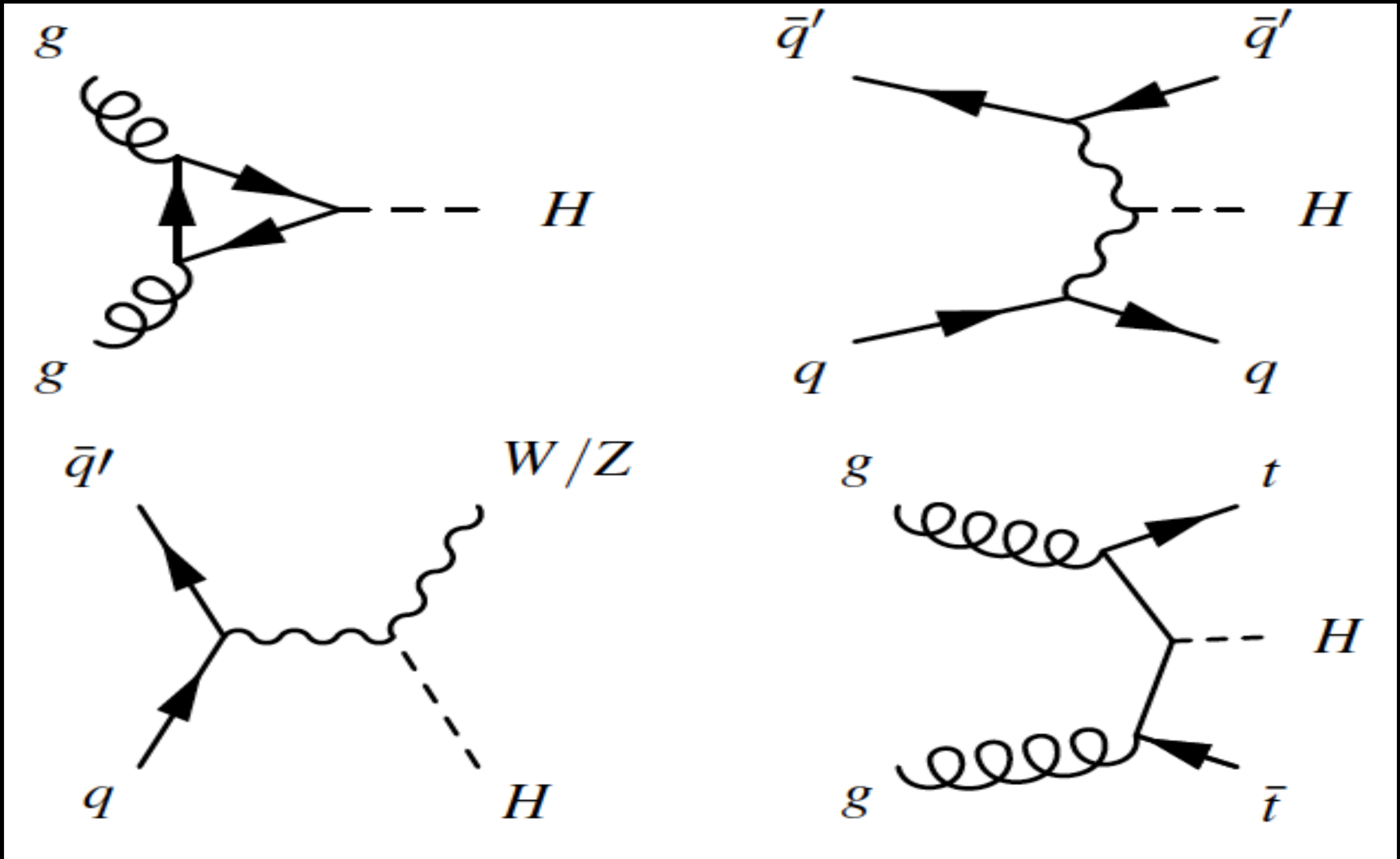
Mass dependent couplings

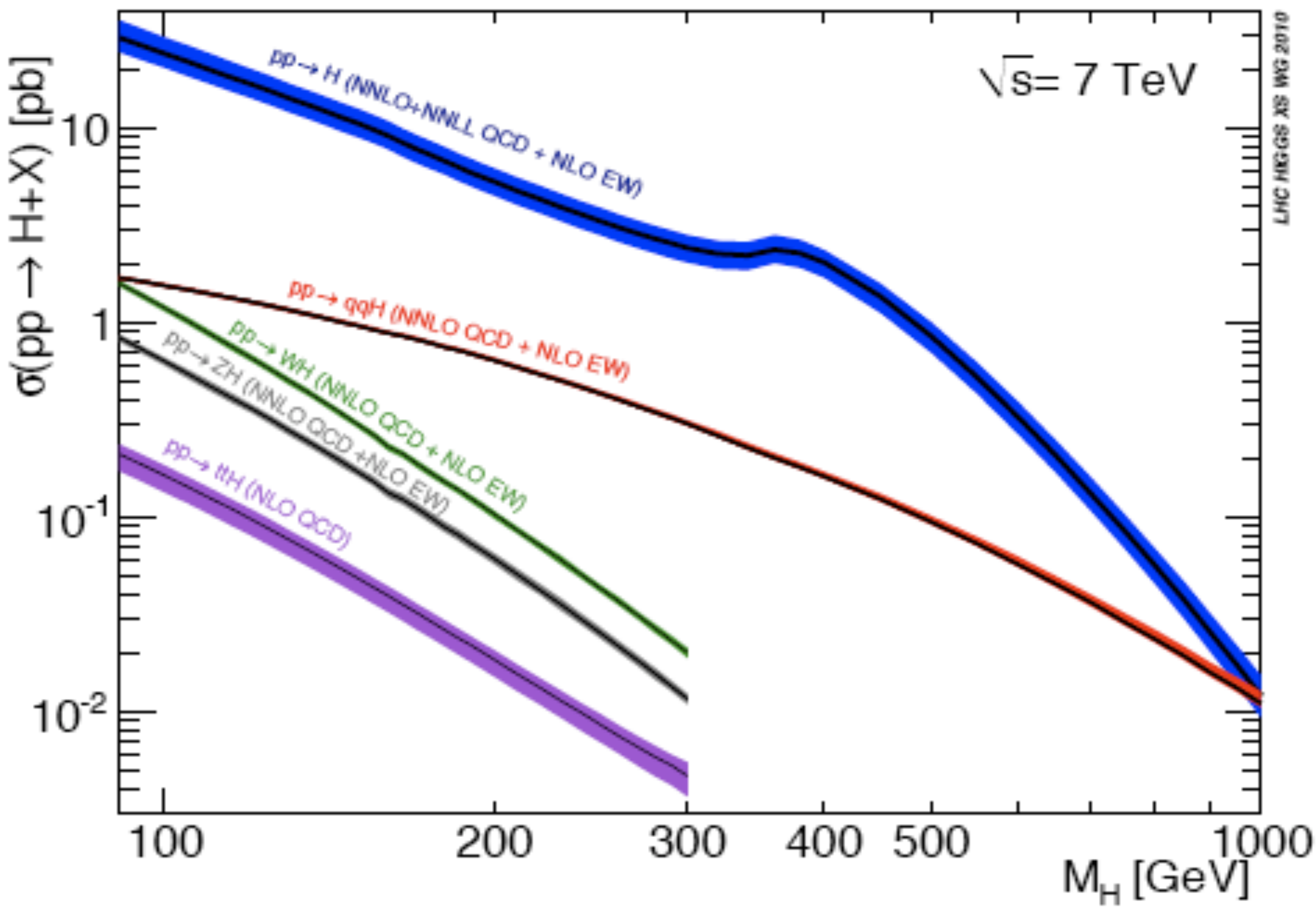
Production cross sections

Handbook of LHC Higgs Cross Sections

arXiv:1101.0593v2 [hep-ph] (work in progress)

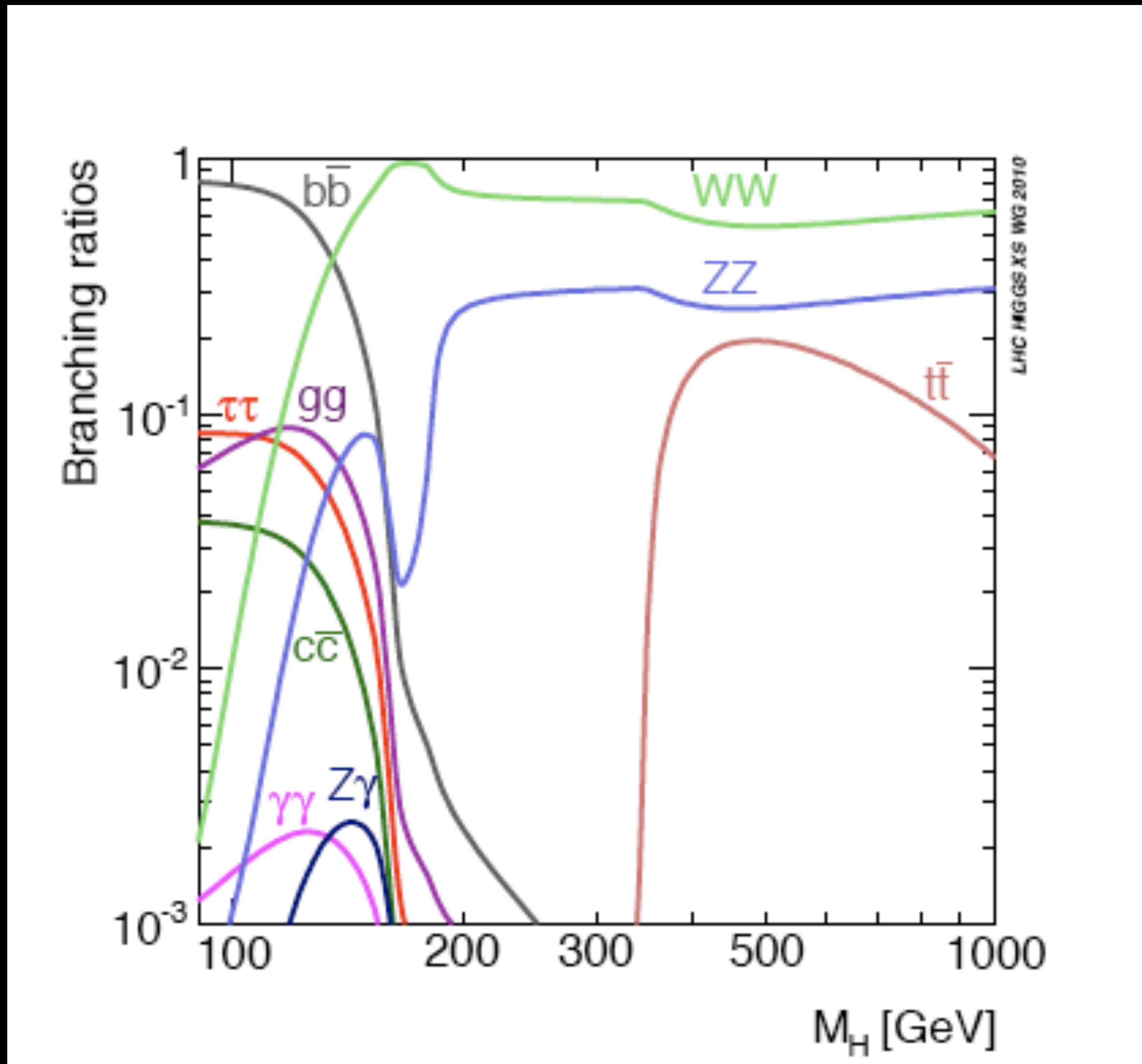
Dominant diagrams

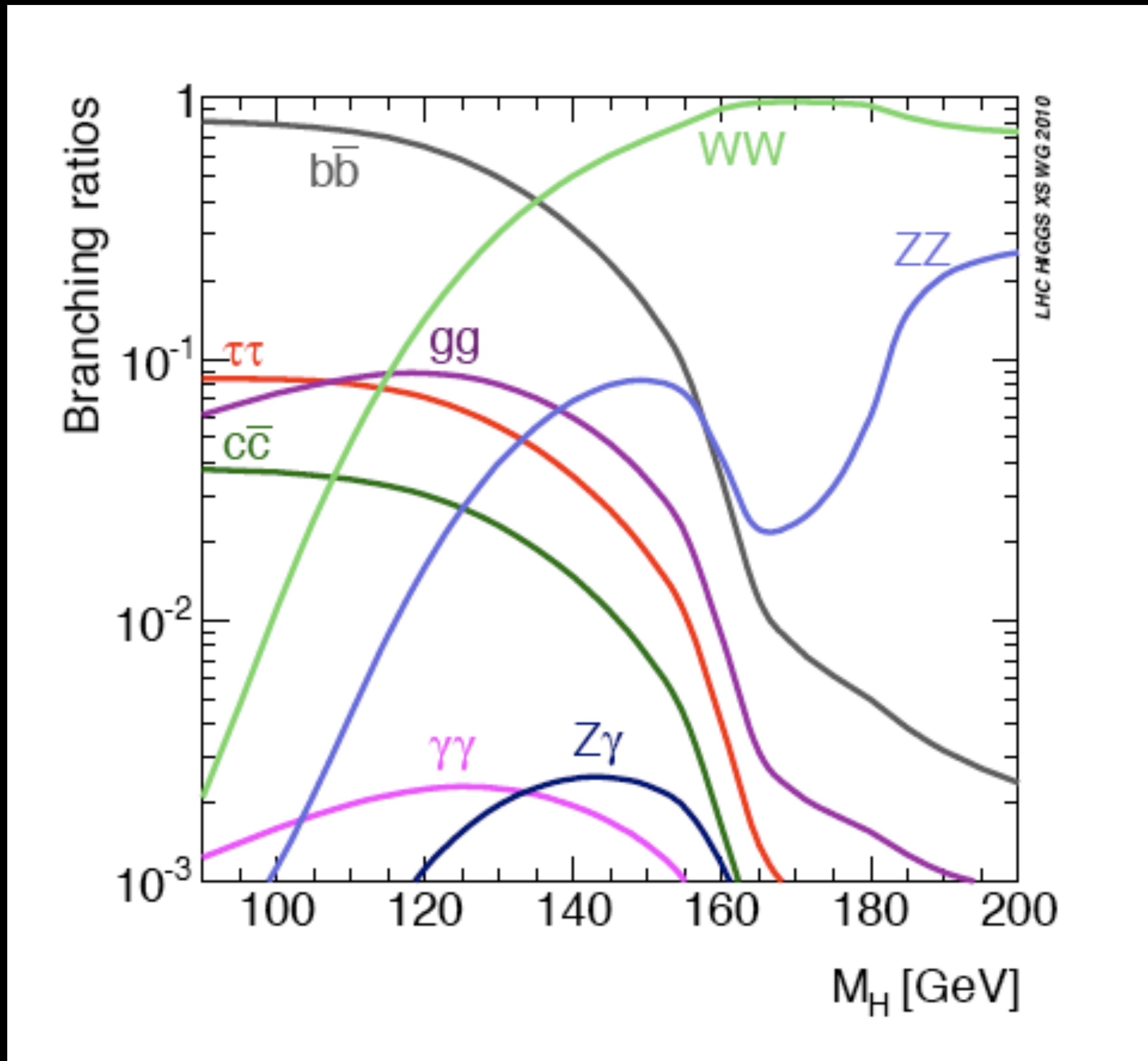




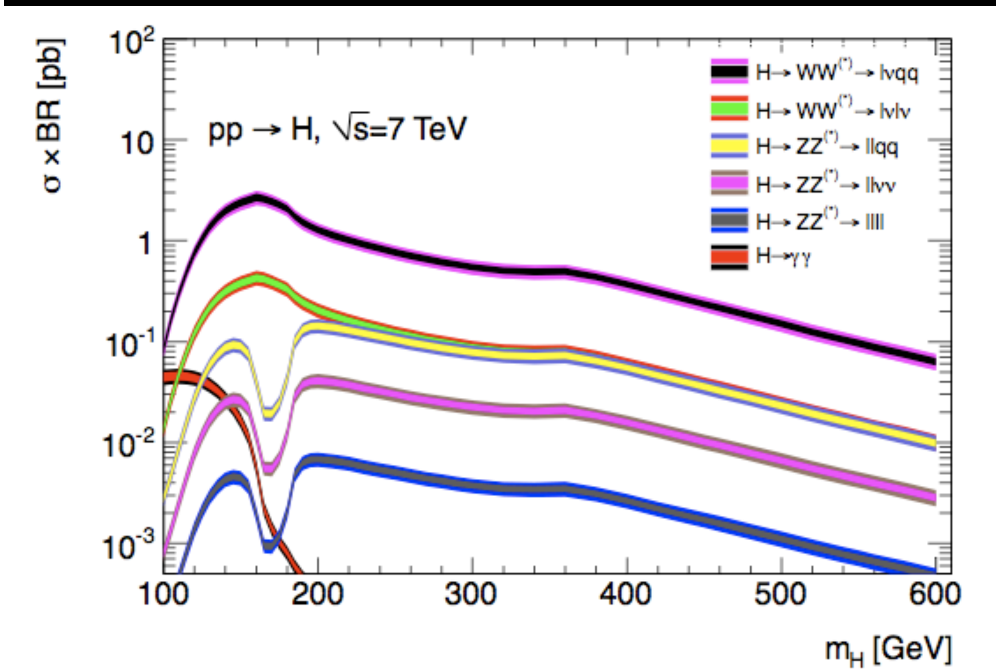
σ(pp → H+X) [pb]
√s= 7 TeV
pp→ H (NNLO+NNLL QCD + NLO EW)
pp→ qqH (NNLO QCD + NLO EW)
pp→ WH (NNLO QCD + NLO EW)
pp→ ZH (NNLO QCD +NLO EW)
pp→ ttH (NLO QCD)
LHC HIGGS XS WG 2010
10
1
10-1
10-2
100
200
300
400
500
1000
M_H [GeV]

Higgs Decays




Branching ratios
1
10-1
10-2
10-3
100
120
140
160
180
200
MH [GeV]
bb̄
WW
ZZ
ττ
gg
cc̄
γγ
Zγ
LHC HIGGS XS WG 2010

Higgs final state cross sections



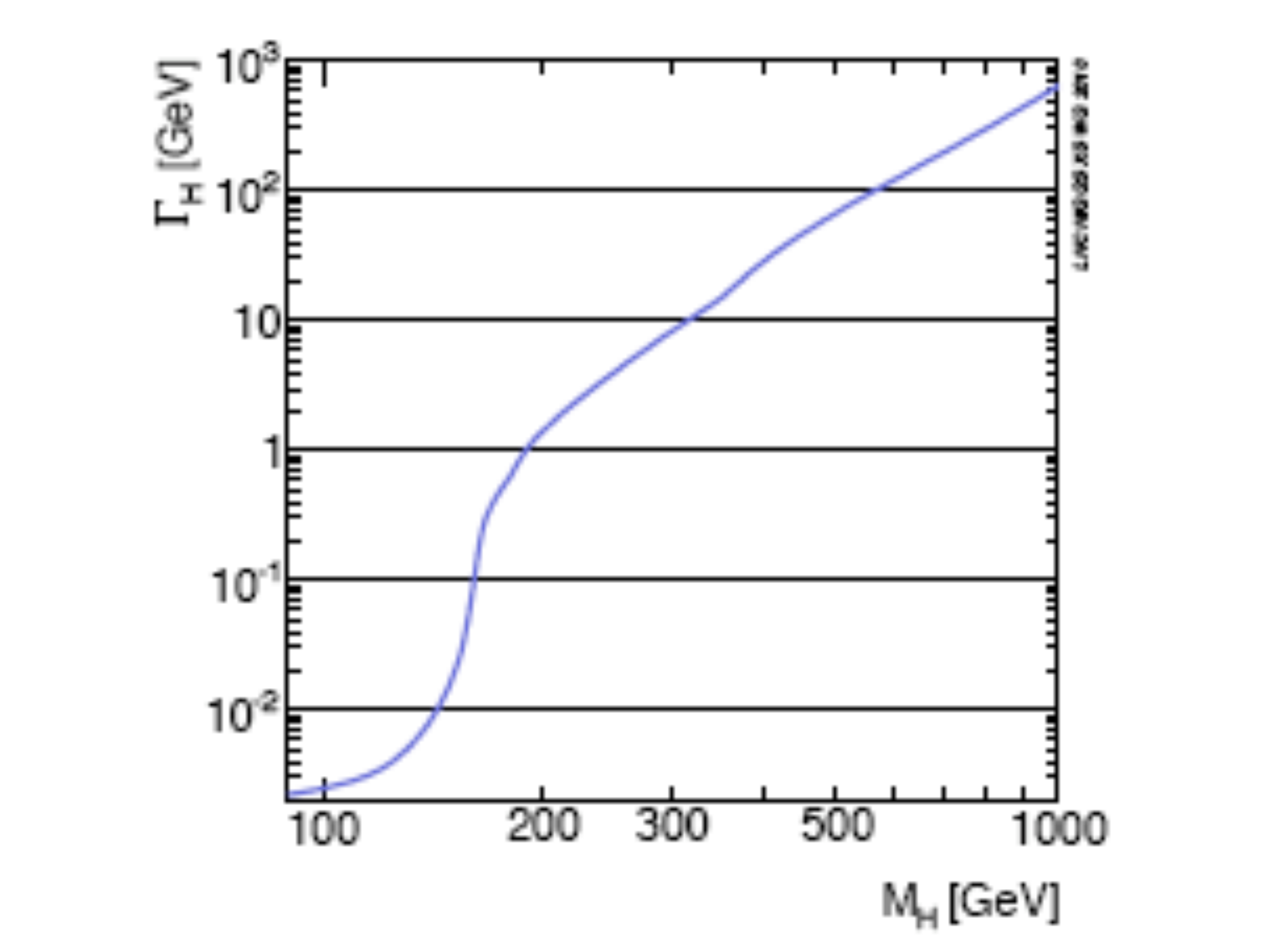
Uncertainties ~25%

- missing higher order corrections
- inner band - QCD scale (α_s)
- outer band - PDF uncertainty

If 4th generation exists all particles must be heavy

→ enhanced loop in gluon fusion Higgs production

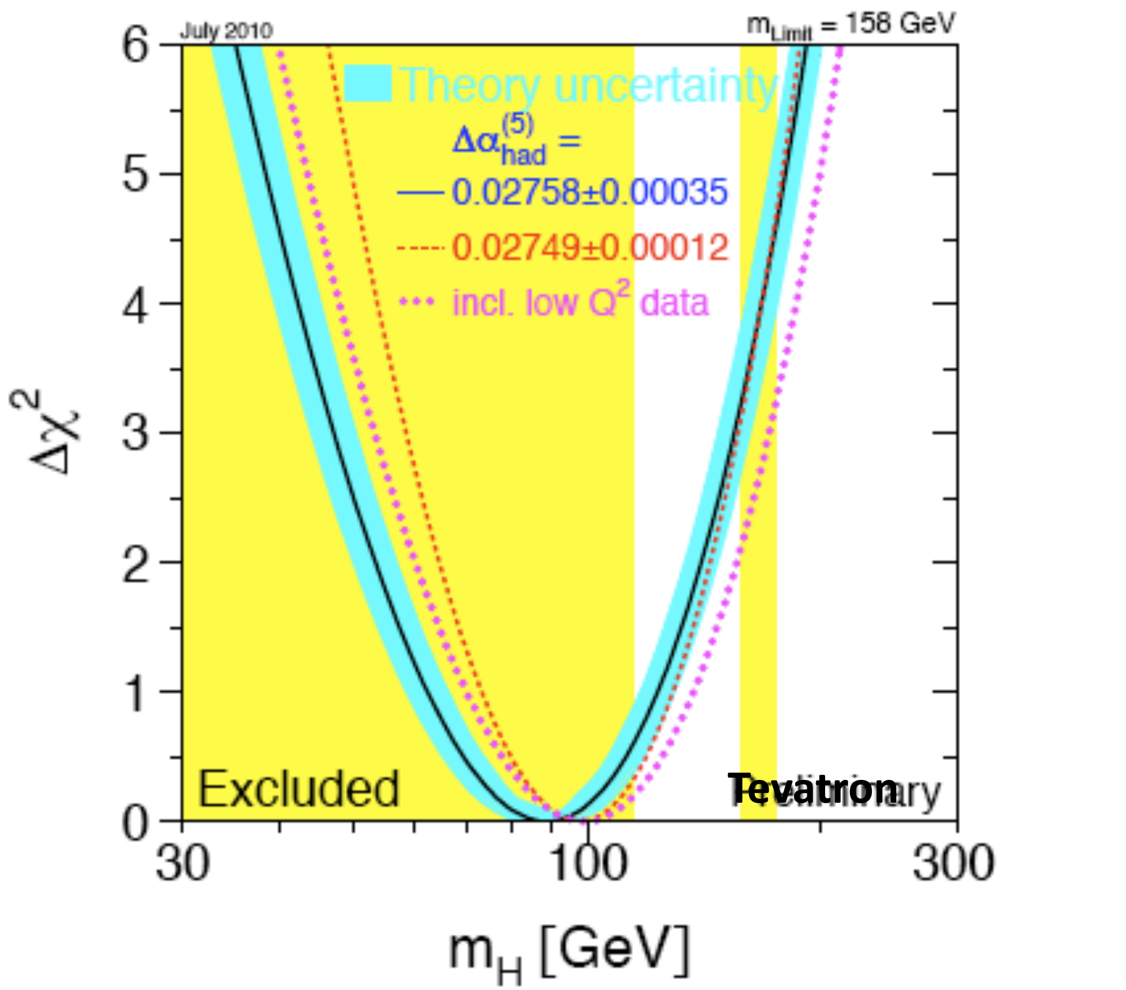
Higgs Width



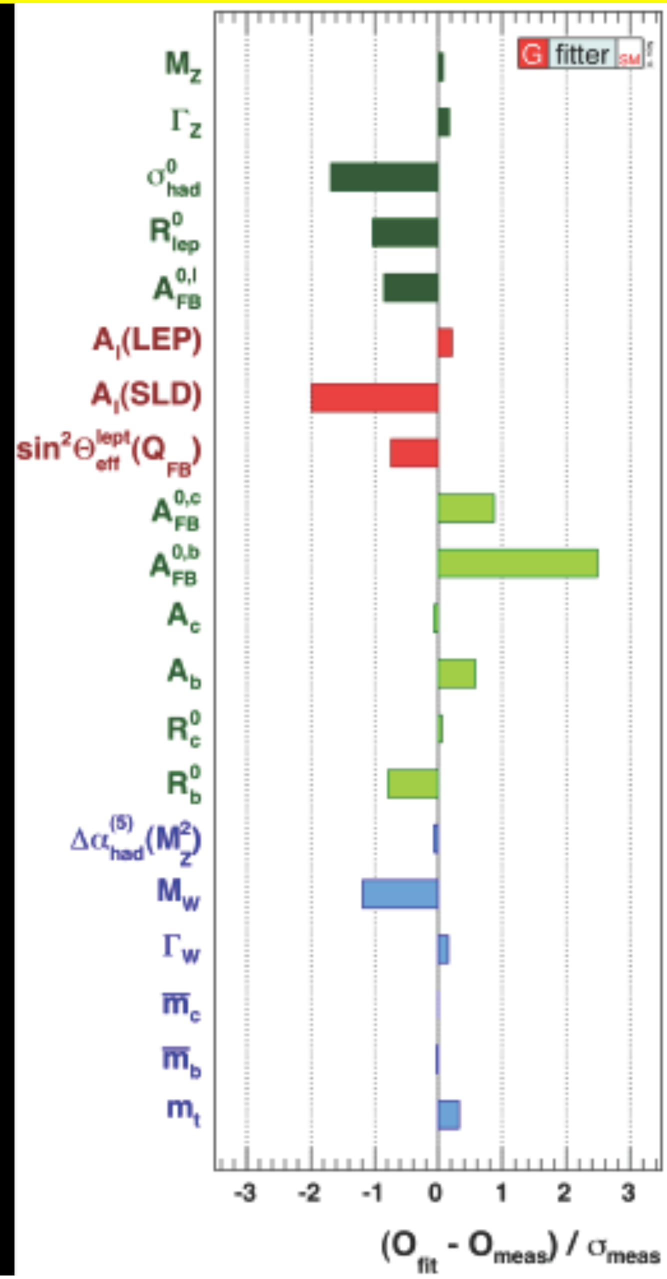
Narrow width assumed for M_H <500 GeV

Theoretical challenge – many interference effects not calculated

Standard Model parameters fit (before July 2011)



LEP: Higgs Mass m > 114.4 GeV, CL = 95%

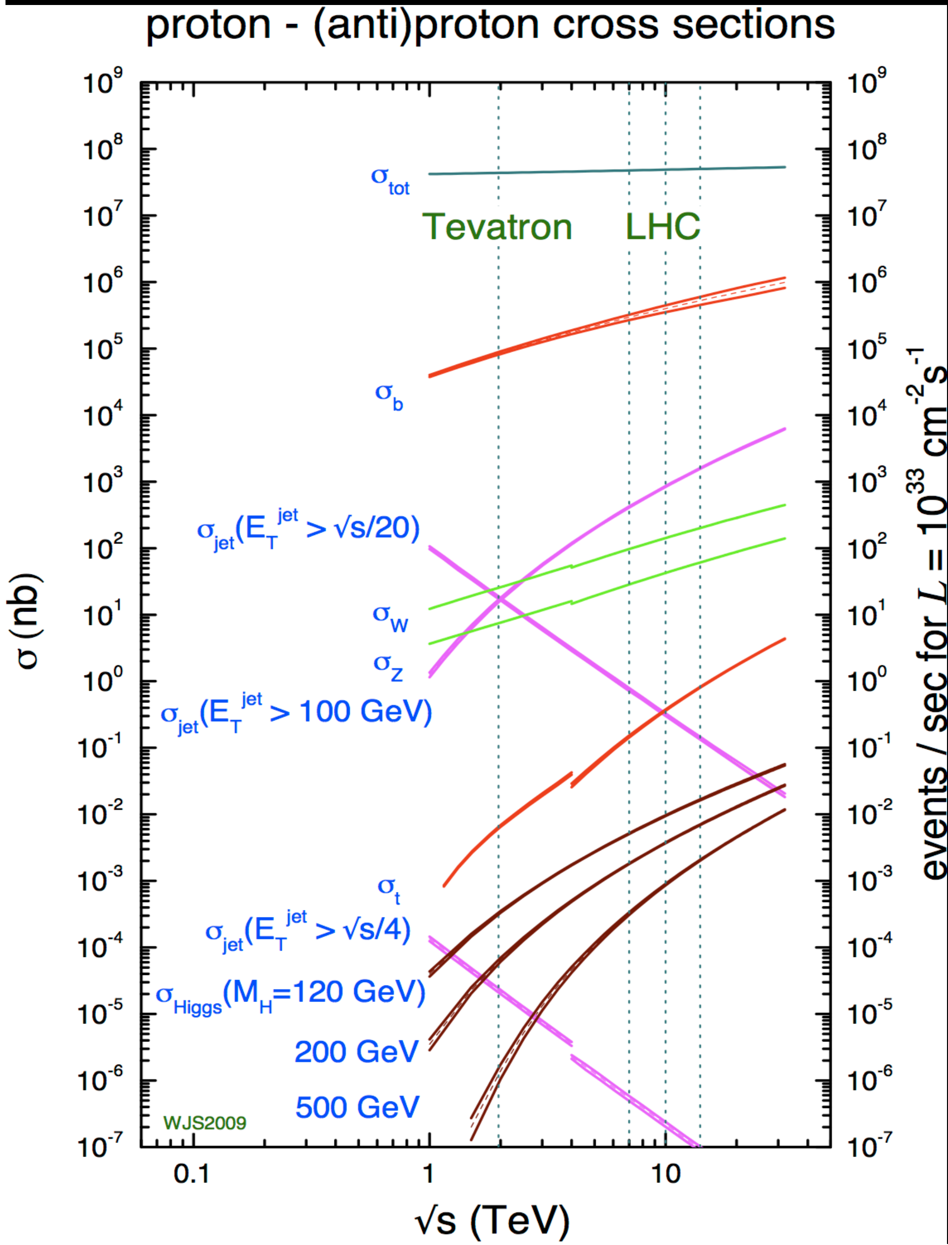


ATLAS Higgs searches

One of the main motivation for building LHC and ATLAS
ATLAS searches in many channels:

- $H \to \gamma\gamma$ — Rozmin, Renat, RS
- $H \to ZZ^* \to llll, ll\nu\nu, llqq$ ($l = e, \mu$) — Julia, Ryan, RS
- $H \to WW^* \to l\nu l\nu, l\nu qq$
- $H \to \tau\tau$
- WH/ZH, $H \to bb$
- MSSM $H \to \tau\tau$
- MSSM $H+ \to \tau$ + jets — Aidan, Steve
- ……..
- Combination of channels
- Combination with CMS

Backgrounds



Process	Dominant Backgrounds
$H\to\gamma\gamma$	$\gamma\gamma$, γ-jet
$H\to\tau\tau$	$Z\to\tau\tau$, top, EW, QCD
$H\to bb$	Vbb, V+jets, top
$H\to WW\to l\nu l\nu$	**WW**, V+jets, top
$H\to WW\to l\nu qq$	**WW**, V+jets, top
$H\to ZZ\to llll$	**ZZ**, top, Zbb
$H\to ZZ\to ll\nu\nu$	**ZZ**/WZ/WW, top, Z+jets
$H\to ZZ\to llqq$	**ZZ**/WZ/WW, top, Z+jets
MSSM $\tau\tau$	$Z\to\tau\tau$, top, EW, QCD
$H^{\pm}$	top

$H \rightarrow \gamma\gamma$

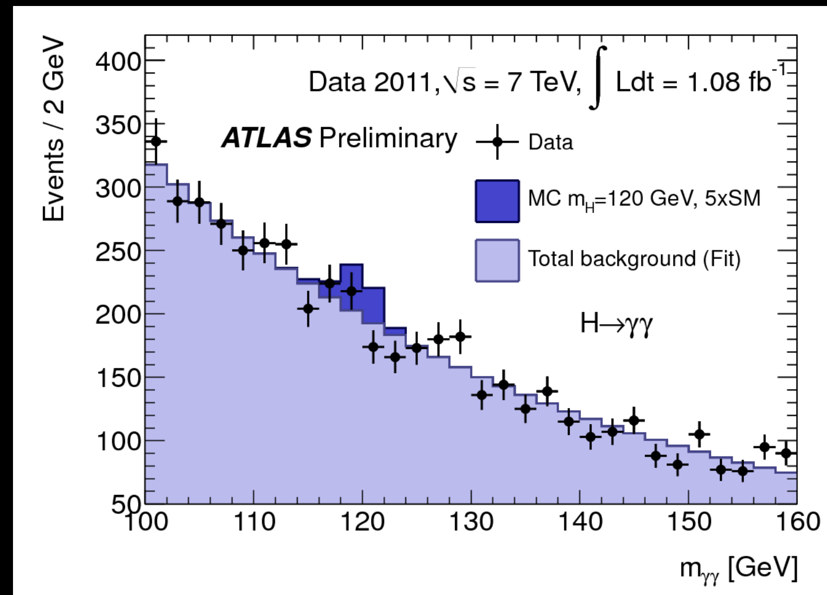
Expected signal - narrow peak

Backgrounds: $\gamma\gamma$ production

γ-jet events

jet-jet events

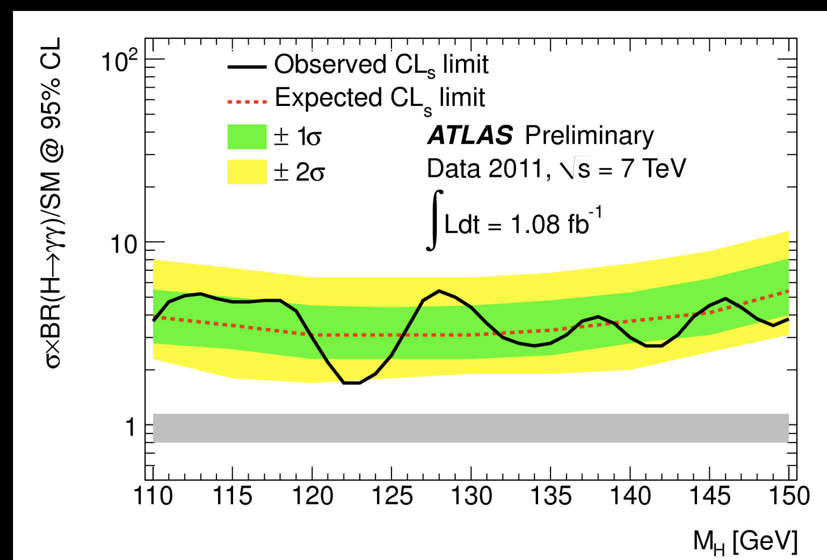
Drell-Yan



No significant excess

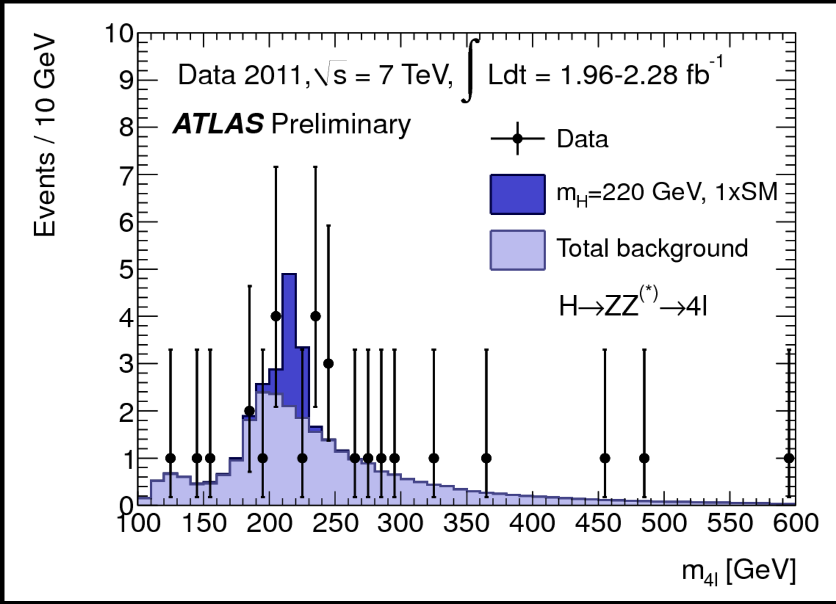
Observed upper limit

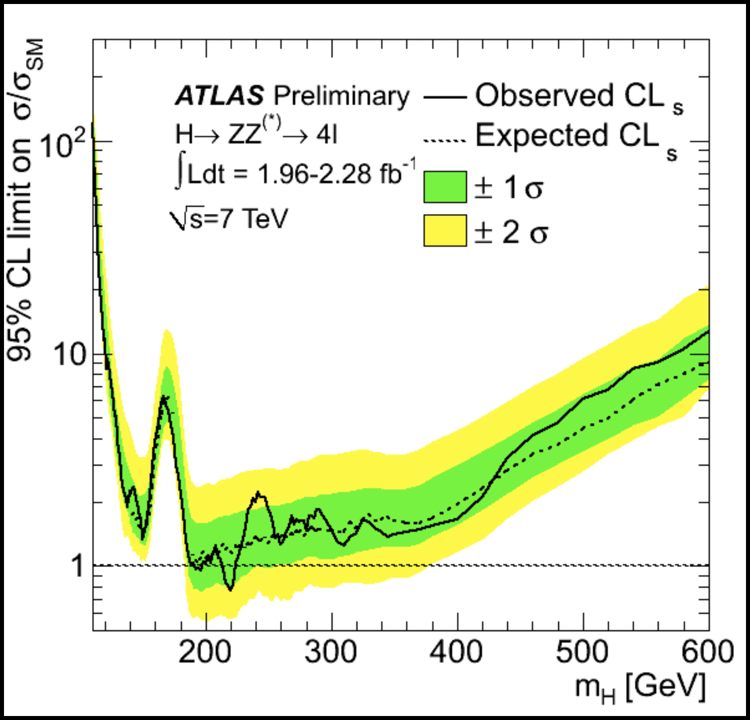
2 x σ_{SM} to 6 x σ_{SM}

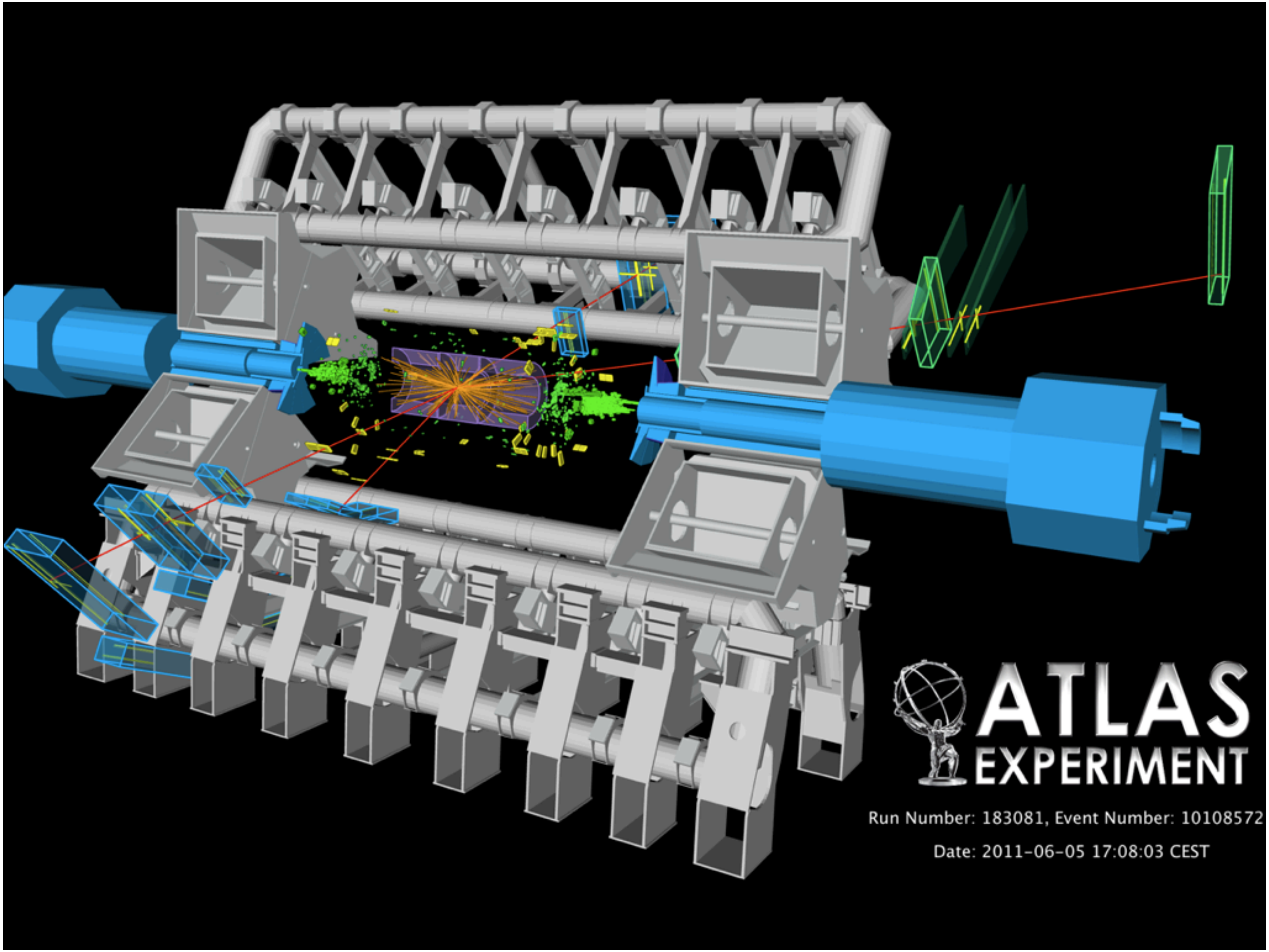


H → 4leptons: 4e, 4μ, 2e2μ, 2μ2e

Signal selection: 4 leptons with one pair of opposite charged leptons consistent with Z hypothesis
"Golden channel" because backgrounds small
Z Z*, Z + jets, t tbar

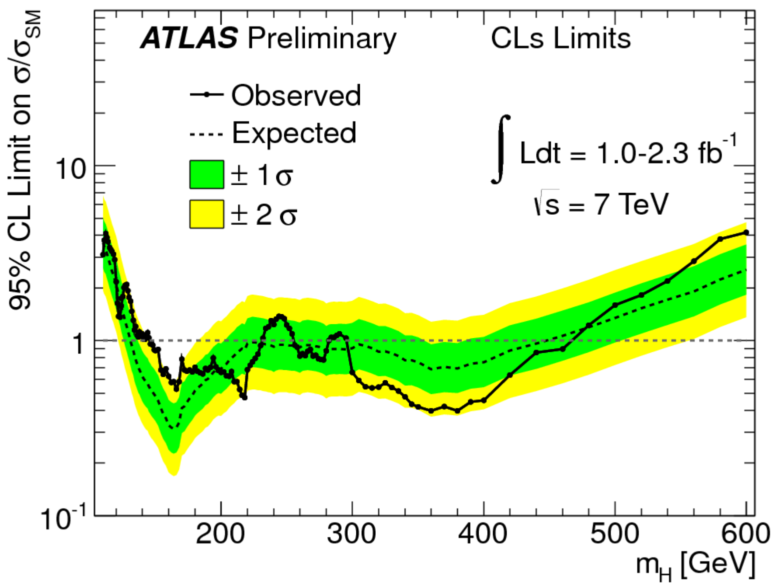


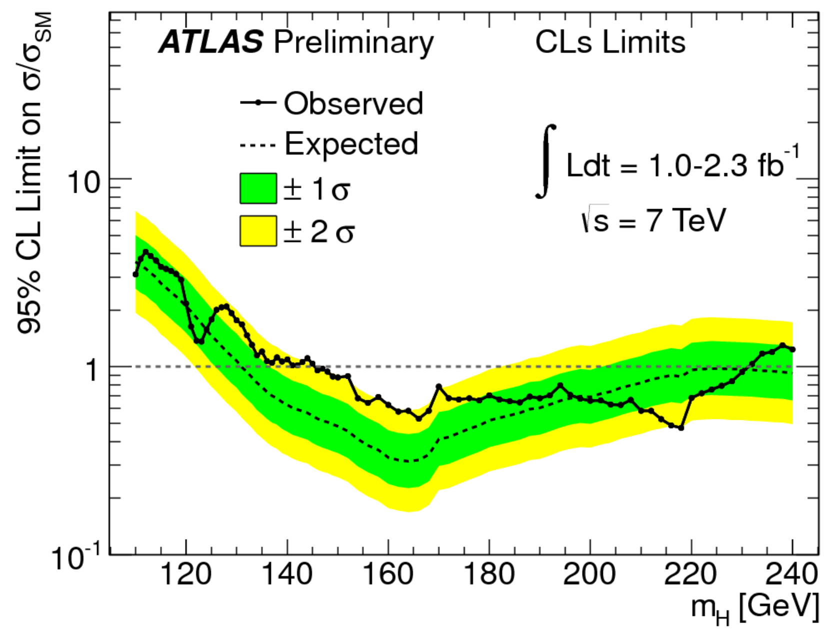



ATLAS
EXPERIMENT
Run Number: 183081, Event Number: 10108572
Date: 2011-06-05 17:08:03 CEST

SM Higgs Exclusion Limits

Combined constraints





ATLAS excludes at 95%CL

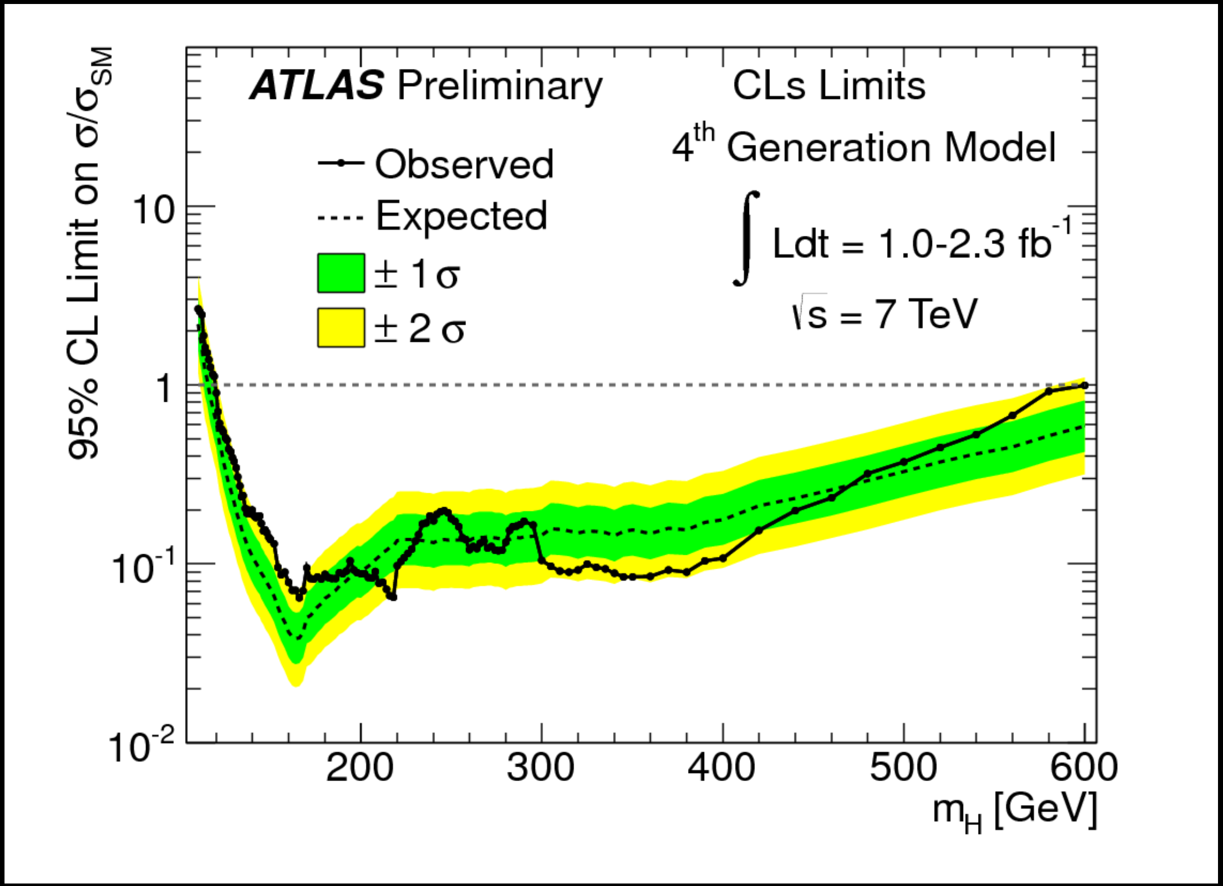
$146 < m_H < 232$ GeV

$256 < m_H < 282$ GeV

$296 < m_H < 466$ GeV

Standard Model with heavy 4th generation

Enhanced expected signal
Stronger suppression



Summary

- Limits for new physics ~ >1 TeV (>3 TeV for some exotic models).
- No evidence for Supersymmetry so far.
- Search for SM Higgs boson narrowed its possible mass range.
- LHC works better than expected. ATLAS performance is excellent. Expect 4-5 fb^{-1} before the end of the year
- Wealth of data allows for new ideas to be tested.
- Exciting times.

Backup slides

Exotic Monojets

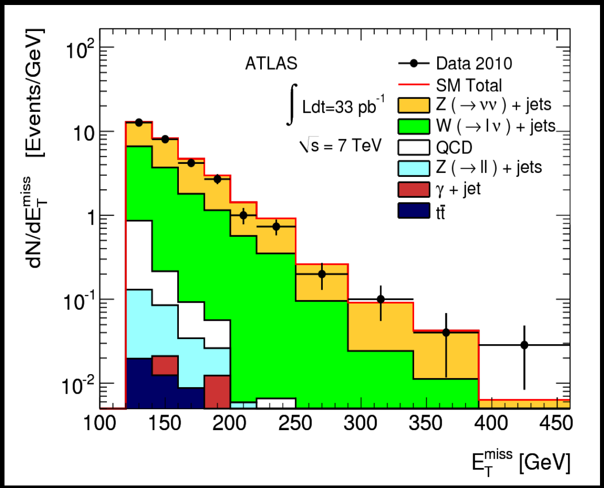
Monojet – high E_T jet + E_T^{miss}

Standard Model process: single jet + Z with Z → ν ν

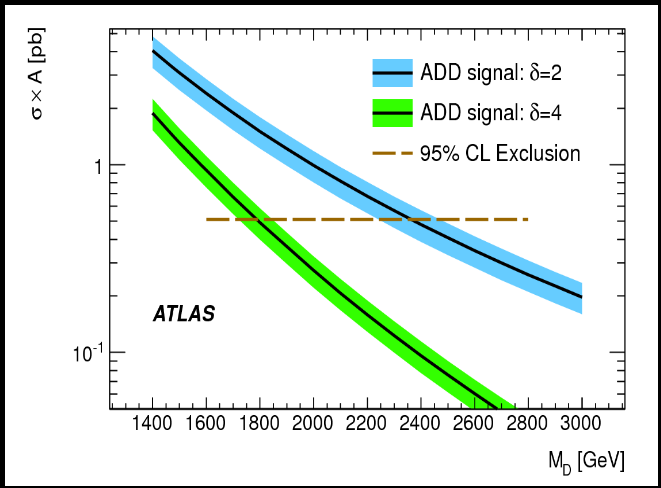
Ahmed-Arkani, Dimopulos, Dvali model with extra dimensions

monojet p_T is balanced by graviton that does not interact with detector.

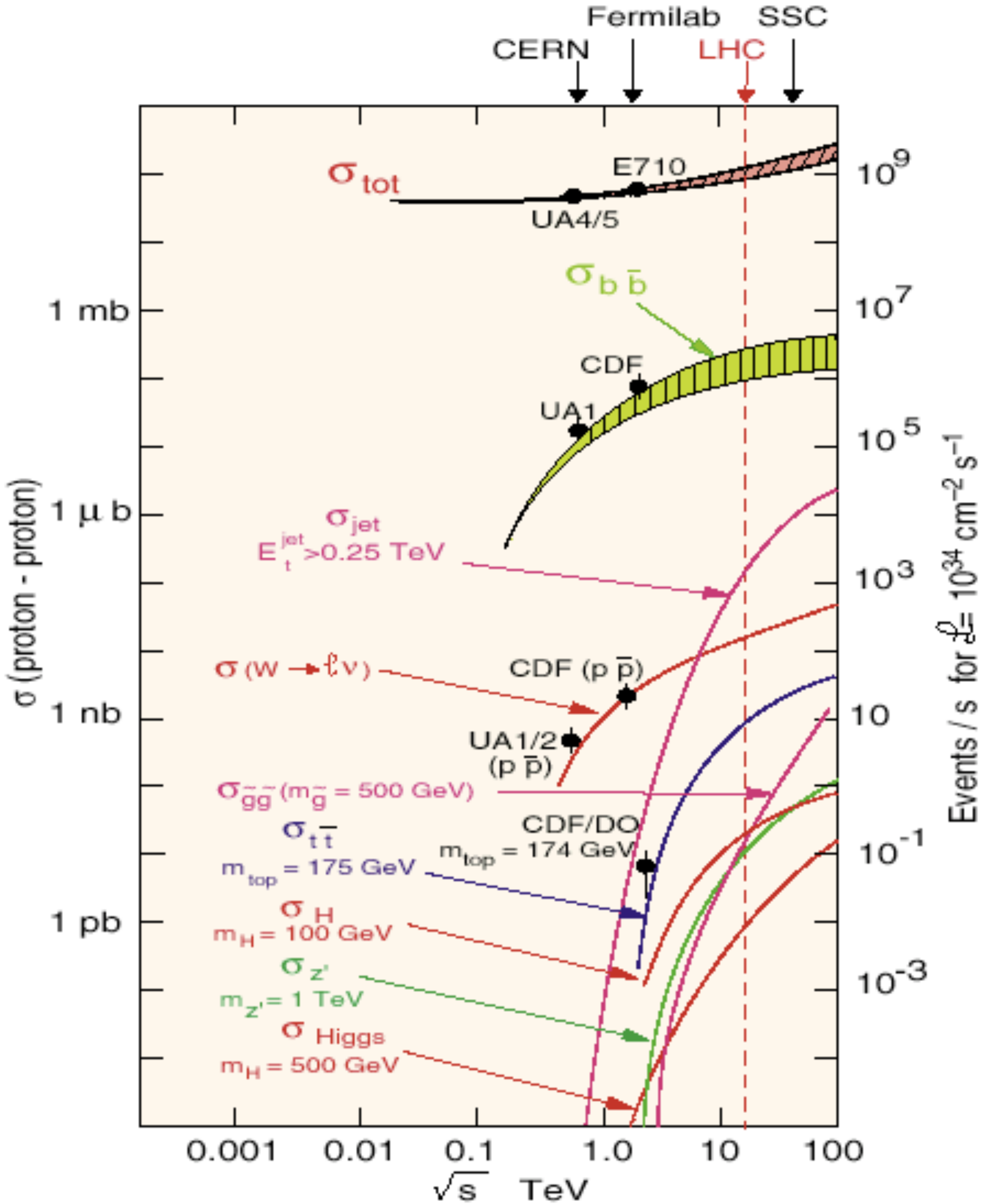
Model is characterized by M_D a 4 + n-dimensional Planck scale



No excess above SM processes

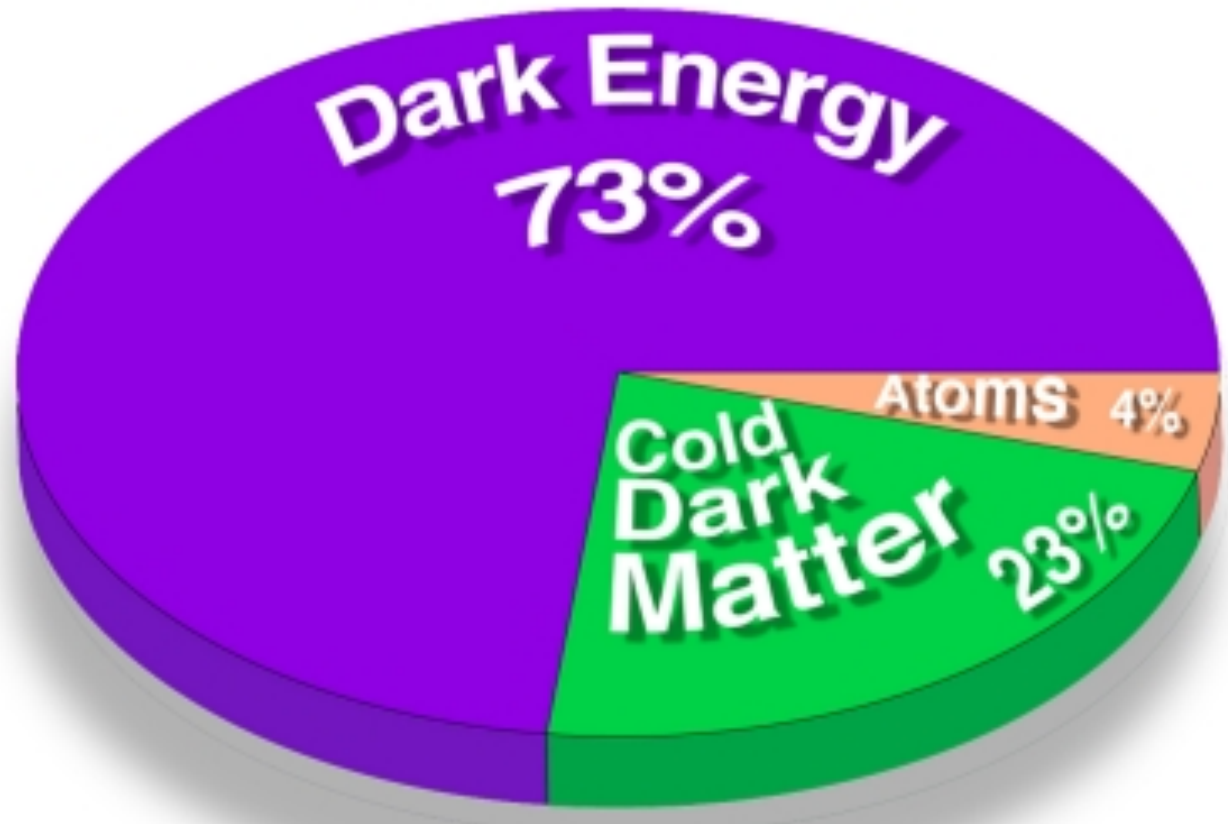


Cross section limits
for 2 and 4 extra dimensions



Fermilab
SSC
CERN
LHC
σ tot
E710
UA4/5
σ b b̄
CDF
UA1
σ jet
E t jet >0.25 TeV
σ (W → ℓν)
CDF (p p̄)
UA1/2
(p p̄)
σ g̃g̃ (m g̃ = 500 GeV)
σ t t̄
m top = 175 GeV
CDF/DO
m top = 174 GeV
σ H
m H = 100 GeV
σ z'
m z' = 1 TeV
σ Higgs
m H = 500 GeV
1 mb
1 μ b
1 nb
1 pb
σ (proton - proton)
0.001
0.01
0.1
1.0
10
100
√s TeV
10^9
10^7
10^5
10^3
10
10^-1
10^-3
Events / s for ℒ = 10^34 cm^-2 s^-1

What our Universe is made of ?



A "new" set of particles, known as "Supersymmetric particles", could explain the dark matter (but NOT the dark energy!)

Source: Robert Kirshner
Source: NASA/WMAP Science Team