ATLAS and LHC status and future

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Outline

- PHYSICS PROGRAM AT THE LHC
  - test the Standard Model, hopefully find "physics beyond SM"
  - find clues to the EWK symmetry breaking - Higgs(ses)?

- what has and what has NOT changed after a Higgs-like boson at ~125 GeV was found by ATLAS and CMS in 2012?

Outline

- Standard Model
- ATLAS – exploratory experiment with multipurpose detector to study pp collisions at LHC at highest energies possible:
    - 7 TeV in 2011, 8 TeV in 2012, ~13 TeV from April 2015…
- Selected ATLAS results
- Summary of CMS results
- what it all means?
- FUTURE plans?

what is elementary particle physics ?

science trying to find answers to a few fundamental questions:

what is the world made of?

how does the world work?

what is world?

classical physicist's view of the world

- Time
- Space
- Matter
- Forces

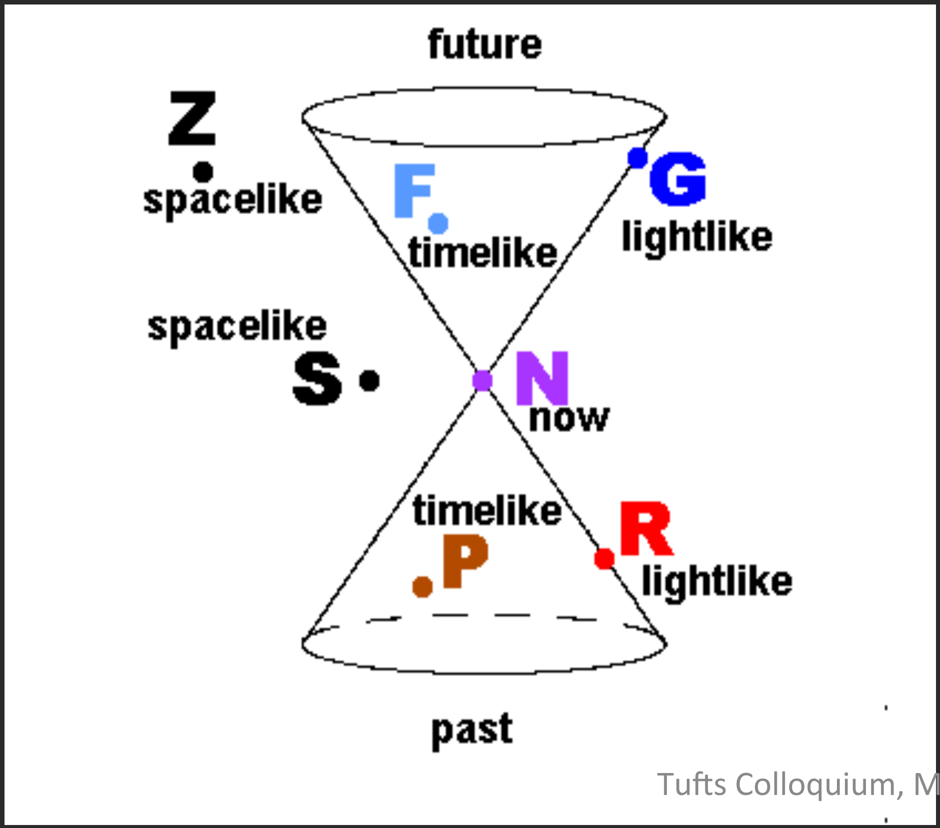
Standard Model view of the world

- space-time
- quarks and leptons
- quantum gauge fields

Path to Standard Model: Minkowski space-time

- Special Theory of Relativity - Einstein in 1905

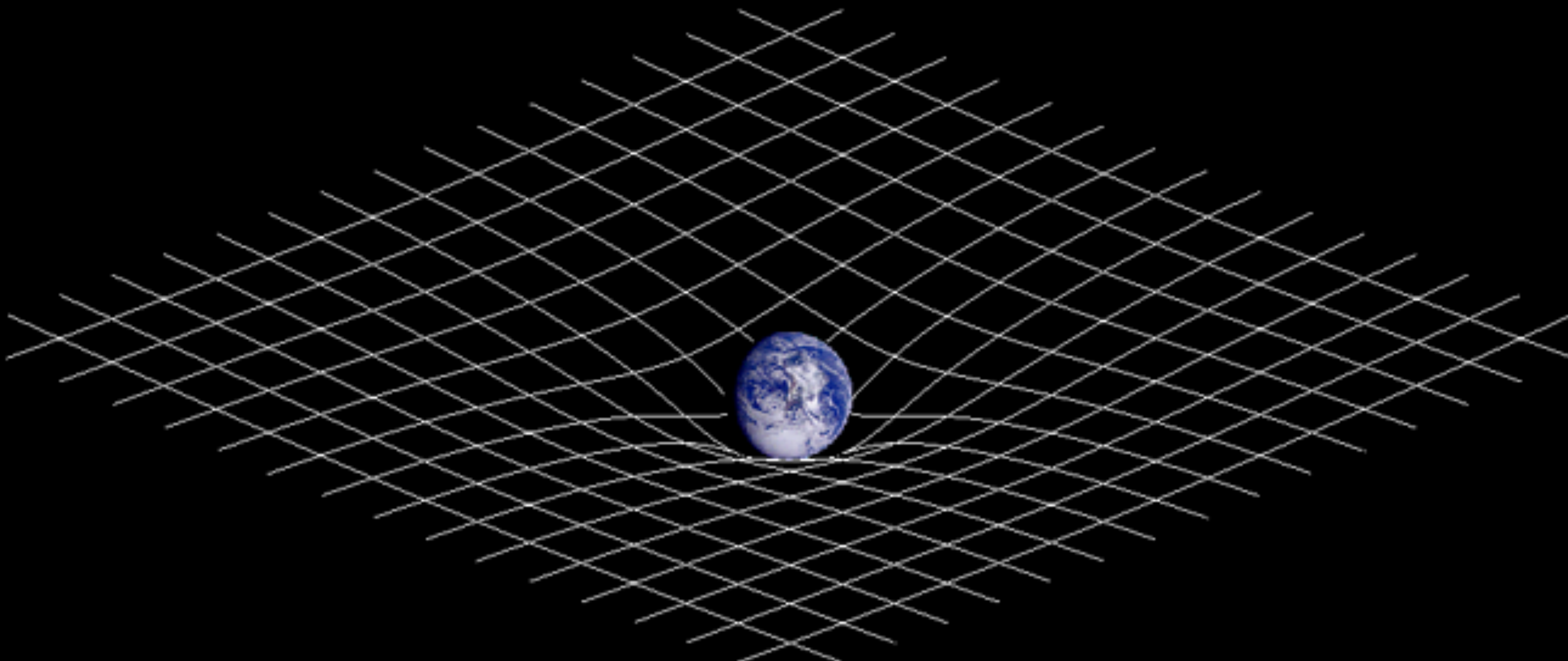
- Minkowski 1907: interpreted Einstein's Special Relativity (1905) a consequence of time and space being an unseparable 4-dimensional space-time entity ("world") - time and space no longer absolute because of the finite, and the same for all observers, speed of propagation of light or any signal



Lorentz boosts = rotations in 4-dim "world" or space-time which mix time and space coordinates
- like rotation about z axis mixes x and y coordinates (in 3-dim Euclidean space)

Path to Standard Model: General Relativity

- General Theory of relativity Einstein 1907-1915 –
  a new relativistic and geometric theory of gravity: matter tells spacetime how to curve, and curved spacetime tells matter how to move" (Wheeler)



Path to Standard Model: early attempts at Unification

- 1918 Weyl's theory of gravitation and electricity, he introduced the term gauge invariance; unification was unsuccessful; however, his idea applied to quantum mechanic became what we now call gauge theories (complex scale factor rather than real)

- 1921 Kaluza and Klein suggested that gravitation and electricity can be unified in a theory of gravity in 5-dimensional Riemannian geometry; not much support, mainly because it was introducing new dimension (Ockham's razor principle)

Path to Standard Model: Quantum Mechanics

- PHYSICS ON ATOMIC SCALE IS GOVERNED BY QUANTUM MECHANICS - no longer completely deterministic as in classical physics (Feynman : nobody understands quantum mechanics)

  at the heart of QM – noncommutativity of algebra of operators corresponding to phase space coordinates - momentum and position (Heisenberg algebra)

- periodicity of chemical elements is a quantum effect observable on macroscopic scale (periodicty of elements in the Mendeleev table)

Path to Standard Model: symmetries ⇔ conservation laws

In 1918 Emmy Noether, while working with David Hilbert and Felix Klein in Gottingen, proved two theorems (for finite continuous groups and infinite continuous groups) which are the foundations of the modern (XXth century) physics. The theorems are collectively known as "Noether's theorem"

Informally, Noether's theorem says:

symmetry <=> conservation law

Path to Standard Model: symmetries ⇔ conservation laws

Symmetries of space-time

energy is conserved if and only if (iff) the physical laws are invariant under time translations (if the form of physics laws do not depend on time)

linear momentum is conserved only iff the physical laws are invariant under space translations (if the form of physics laws do not depend on the position)

angular momentum is conserved iff the physical laws are invariant under rotations (if the physics laws do not depend on orientation; if only true about a particular direction <=> only the component of angular momentum in that direction is conserved)

Path to Standard Model: symmetries ⇔ conservation laws

symmetries observed in physics:

Symmetries of discrete space-time transformations: parity, time-reversal, charge conjugation

Symmetries of continuous space-time transformations: translational and rotational invariance and Lorentz (space-time rotations) invariance

Symmetries of permutations: lead to two kind of particles: bosons (spin=0,1,2..), which obey Bose-Einstein statistics, and fermions (spin=1/2,3/2…), which obey Fermi-Dirac statistics

Path to Standard Model: symmetries ⇔ conservation laws

gauge symmetries: "internal" symmetries inherent from the nature of the field associated with a given particle carrying such attributes as electric charge - U(1), color - SU(3), weak isospin – SU(2)… et cetera

conservation of electric charge and the existence of the electromagnetic field

<=>

invariance under phase (gauge) U(1) transformation in the "internal" space

Standard Model (~1975)

Standard Model is a gauge theory based on the following "internal" symmetries:

$$SU(3)_c \times SU(2)_I \times U(1)_Y$$

The SU(3) is an unbroken symmetry, it gives Quantum Chromo-Dynamics (QCD), a quantum theory of strong interactions, whose carriers (gluons) are massless, couple to color (strong force charge)

SU(2) × U(1) (quantum theory of electroweak interactions) is spontaneously broken by the Brout-Englert-Guralnik-Higgs-Kibble mechanism; which gives mass to electroweak bosons (massive W^+, W^-, Z° and a massless photon) and all fermions – matter particles

In the Minimal Standard Model, the Higgs sector is the simplest possible: contains one weak isospin doublet of complex Higgs fields, which after giving masses to W^+, W^-, Z° leaves a single neutral scalar Higgs particle which should be observed

Minimal Standard Model

Matter is build of fermions - quarks and leptons, three families of each, with corresponding antiparticles; quarks come in three colors, leptons are color singlets, do not couple to gluons

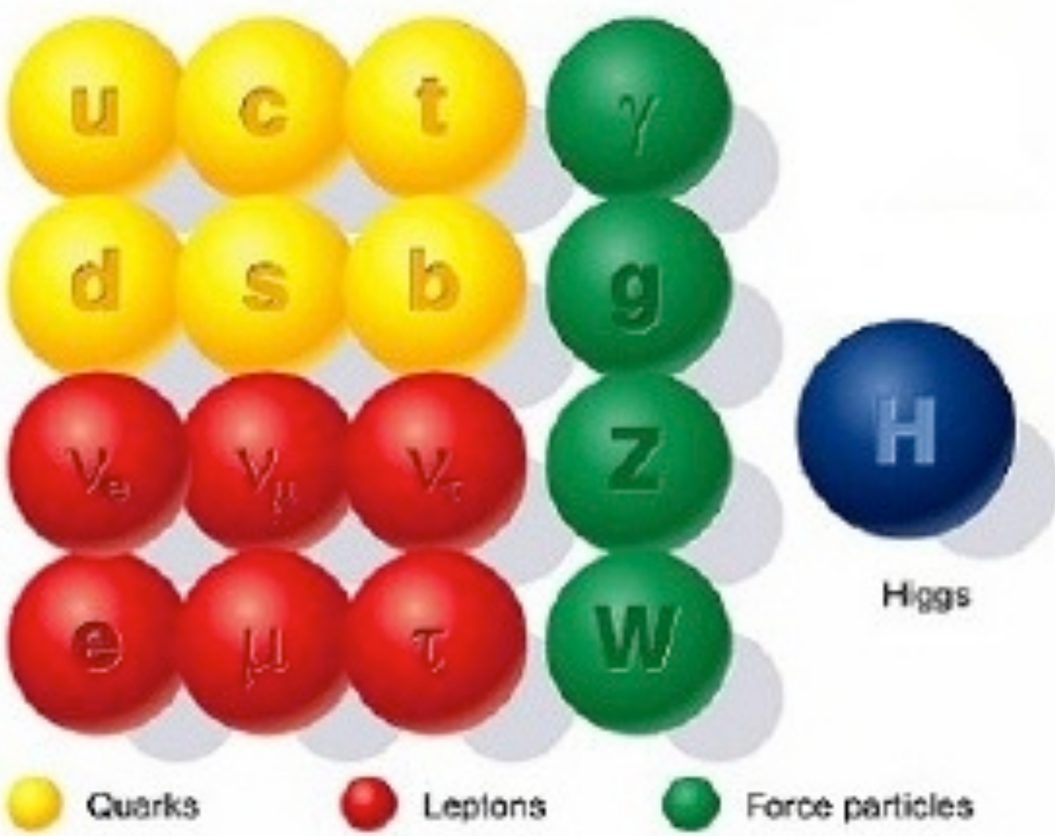
Bosons are carriers of interactions: 8 massless gluons, 3 heavy weak bosons (W,Z) and 1 massless photon

A neutral scalar Higgs field permeates the Universe and is (in some way) responsible for masses of other particles (they originate from couplings to Higgs field)

HIGGS SCALAR IT IS THE ONLY PARTICLE MISSING IN THE MINIMAL STANDARD MODEL

Minimal Standard Model

SINGLE NEUTRAL HIGGS SCALAR - THE ONLY PARTICLE MISSING IN MSM

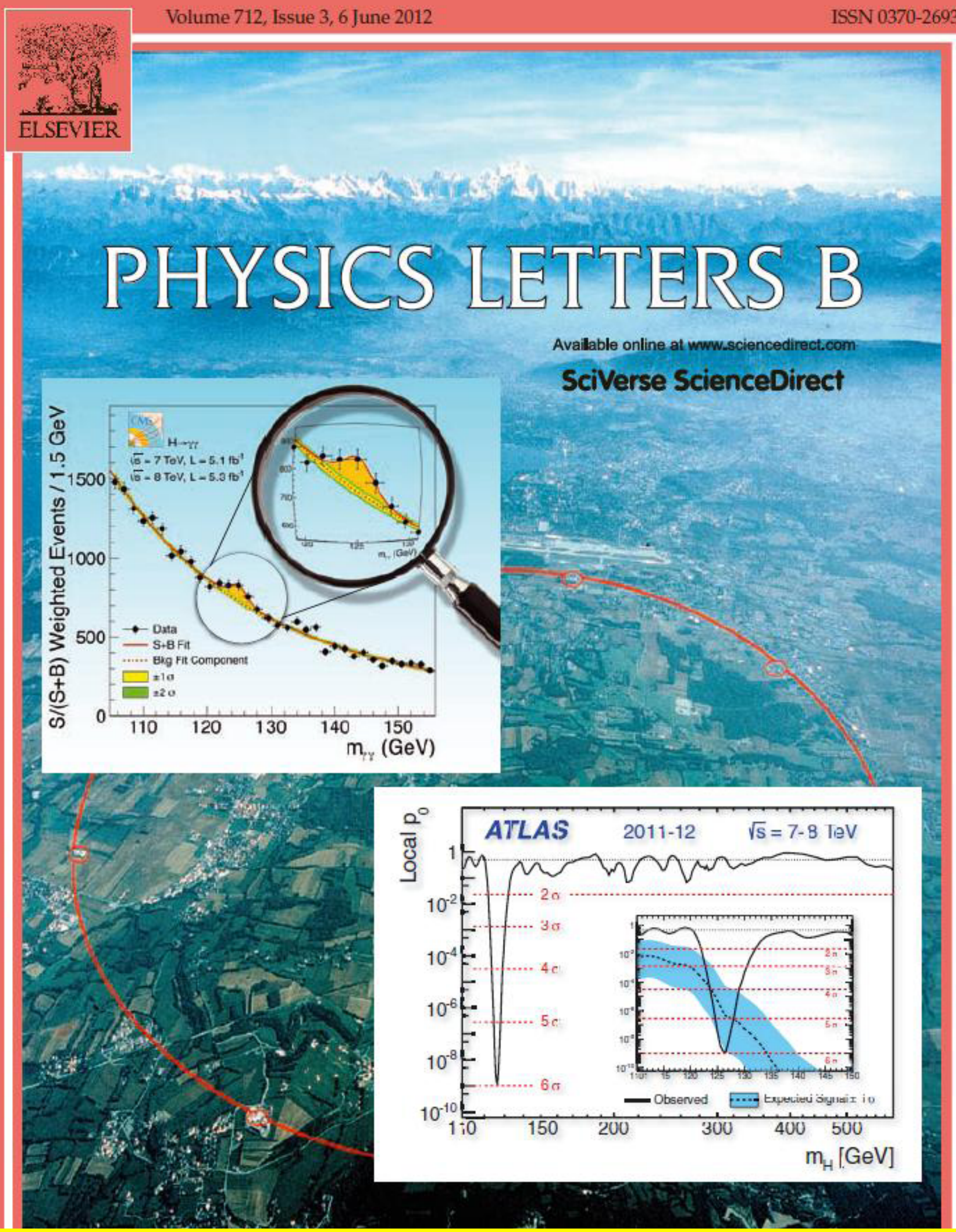


26 parameters NOT predicted by SM:

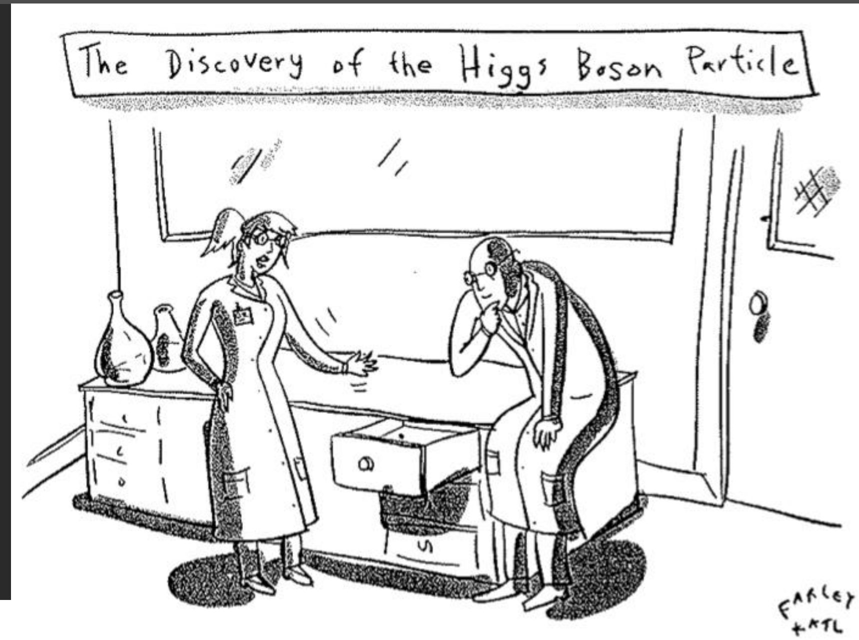
- masses of 6 quarks
- masses of 6 leptons
- coupling constants of SU(3), SU(2) and U(1)
- Higgs mass and vacuum expectation value
- Cabibbo-Kobayashi-Maskawa quark mixing angles and complex phase
- Maki-Nakagawa-Sakata lepton mixing matrix angles and complex phase
- QCD phase Θ

ALL MUST BE MEASURED !!!

4 July 2012: new boson announcement !!



Great day for the 20+ years' project !!!



"Always the last place you look!"

CERN-PH-EP-2012-218

Submitted to: Physics Letters B

Observation of a New Particle in the Search for the Standard Model Higgs Boson with the ATLAS Detector at the LHC

The ATLAS Collaboration

This paper is dedicated to the memory of our ATLAS colleagues who did not live to see the full impact and significance of their contributions to the experiment.

IS THIS THE MSM BOSON ???

Fantastic, but…many questions, some new and many old:

i) is this the Minimal Standard Model boson?? answering this question will take time and many precision measurements - with the Higgs mass known, all SM couplings can now be calculated

ii) there remain MANY unsolved problems in SM – still plenty to understand and search for

(personally, I think it would be much more interesting if Higgs boson were not there…or if the new-found particle is NOT a Minimal Standard Model boson)

STANDARD MODEL – MANY OUTSTANDING QUESTIONS

- why so many (26) free parameters: all masses, all couplings, all mixing angles and CP- violating phases

- why 6 quarks and 6 leptons - is there an additional symmetry?

- why quarks and and leptons come in three pairs (generations)?

- why is CP not an exact symmetry (or why are laws of physics not symmetrical between matter and antimatter?) perhaps related to why is our Universe matter-dominated?

- what is Dark Matter which seem to be 5-6 times more prevalent in the Universe than ordinary matter (27% vs 5%)?

- HOW TO INCLUDE GRAVITY ???

- **Standard Model just a low-energy approximation…**

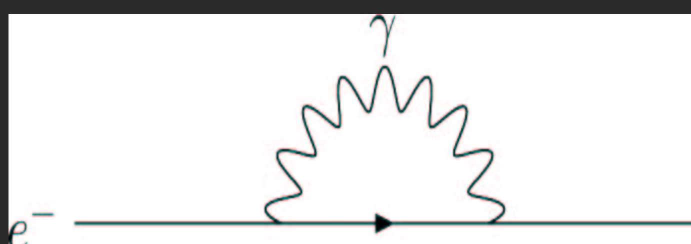
STANDARD MODEL – MANY OUTSTANDING QUESTIONS

$$\mathcal{L}_{SM} = -\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - M^2 W^+_\mu W^-_\mu -$$
$$\frac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \frac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \frac12 \partial_\mu A_\nu \partial_\mu A_\nu - igc_w(\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu \partial_\nu W^-_\mu -$$
$$W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)) - igs_w(\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu \partial_\nu W^-_\mu -$$
$$W^-_\mu\partial_\nu W^+_\mu) + A_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)) - \frac12 g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \frac12 g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu +$$
$$g^2c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) +$$
$$g^2 s_w c_w(A_\mu Z^0_\nu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu) - \frac12\partial_\mu H\partial_\mu H - \frac12 m_h^2 H^2 - \partial_\mu\phi^+\partial_\mu\phi^- -$$
$$M^2\phi^+\phi^- - \frac12\partial_\mu\phi^0\partial_\mu\phi^0 - \frac{1}{2c_w^2}M^2\phi^0\phi^0 - \beta_h\left(\frac{2M^2}{g^2} + \frac{2M}{g}H + \frac12(H^2+\phi^0\phi^0+2\phi^+\phi^-)\right) +$$
$$\frac{2M^4}{g^2}\alpha_h - g\alpha_h M\left(H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-\right) -$$
$$\frac18 g^2\alpha_h\left(H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2\right) - gMW^+_\mu W^-_\mu H -$$
$$\frac12 g\frac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \frac12 ig\left(W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)\right) +$$
$$\frac12 g\left(W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) + W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)\right) + \frac12 g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) -$$
$$ig\frac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_wMA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\frac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) +$$
$$igs_wA_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \frac14 g^2W^+_\mu W^-_\mu\left(H^2+(\phi^0)^2+2\phi^+\phi^-\right) -$$
$$\frac18 g^2\frac{1}{c_w^2}Z^0_\mu Z^0_\mu\left(H^2+(\phi^0)^2+2(2s_w^2-1)^2\phi^+\phi^-\right) - \frac12 g^2\frac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) -$$
$$\frac12 ig^2\frac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac12 g^2 s_wA_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) + \frac12 ig^2s_wA_\mu H(W^+_\mu\phi^- -$$
$$W^-_\mu\phi^+) - g^2\frac{s_w}{c_w}(2c_w^2-1)Z^0_\mu A_\mu\phi^+\phi^- - g^2s_w^2A_\mu A_\mu\phi^+\phi^- + \frac12 ig_s\lambda^a_{ij}(\bar q^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu - \bar e^\lambda(\gamma\partial + m_e^\lambda)e^\lambda -$$
$$\bar\nu^\lambda\gamma\partial\nu^\lambda - \bar u^\lambda_j(\gamma\partial+m_u^\lambda)u^\lambda_j - \bar d^\lambda_j(\gamma\partial+m_d^\lambda)d^\lambda_j + igs_wA_\mu\left(-(\bar e^\lambda\gamma^\mu e^\lambda) + \frac23(\bar u^\lambda_j\gamma^\mu u^\lambda_j) - \frac13(\bar d^\lambda_j\gamma^\mu d^\lambda_j)\right) +$$
$$\frac{ig}{4c_w}Z^0_\mu\{(\bar\nu^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar e^\lambda\gamma^\mu(4s_w^2-1-\gamma^5)e^\lambda) + (\bar d^\lambda_j\gamma^\mu(\tfrac43 s_w^2-1-\gamma^5)d^\lambda_j) + (\bar u^\lambda_j\gamma^\mu(1-\tfrac83 s_w^2 +$$
$$\gamma^5)u^\lambda_j)\} + \frac{ig}{2\sqrt2}W^+_\mu\left((\bar\nu^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) + (\bar u^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)\right) +$$
$$\frac{ig}{2\sqrt2}W^-_\mu\left((\bar e^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar d^\kappa_j C^\dagger_{\kappa\lambda}\gamma^\mu(1+\gamma^5)u^\lambda_j)\right) +$$
$$\frac{ig}{2\sqrt2}\frac{m_e^\lambda}{M}\left(-\phi^+(\bar\nu^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar e^\lambda(1+\gamma^5)\nu^\lambda)\right) - \frac g2\frac{m_e^\lambda}{M}\left(H(\bar e^\lambda e^\lambda) + i\phi^0(\bar e^\lambda\gamma^5 e^\lambda)\right) +$$
$$\frac{ig}{2M\sqrt2}\phi^+\left(-m_d^\kappa(\bar u^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m_u^\lambda(\bar u^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j)\right) +$$
$$\frac{ig}{2M\sqrt2}\phi^-\left(m_d^\lambda(\bar d^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m_u^\kappa(\bar d^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j)\right) - \frac g2\frac{m_u^\lambda}{M}H(\bar u^\lambda_j u^\lambda_j) - \frac g2\frac{m_d^\lambda}{M}H(\bar d^\lambda_j d^\lambda_j) +$$
$$\frac{ig}{2}\frac{m_u^\lambda}{M}\phi^0(\bar u^\lambda_j\gamma^5u^\lambda_j) - \frac{ig}{2}\frac{m_d^\lambda}{M}\phi^0(\bar d^\lambda_j\gamma^5 d^\lambda_j) + \bar G^a\partial^2G^a + g_sf^{abc}\partial_\mu\bar G^aG^bg^c_\mu + \bar X^+(\partial^2-M^2)X^+ + \bar X^-(\partial^2 -$$
$$M^2)X^- + \bar X^0(\partial^2 - \frac{M^2}{c_w^2})X^0 + \bar Y\partial^2Y + igc_wW^+_\mu(\partial_\mu\bar X^0X^- - \partial_\mu\bar X^+X^0) + igs_wW^+_\mu(\partial_\mu\bar YX^- -$$
$$\partial_\mu\bar X^+Y) + igc_wW^-_\mu(\partial_\mu\bar X^-X^0 - \partial_\mu\bar X^0X^+) + igs_wW^-_\mu(\partial_\mu\bar X^-Y - \partial_\mu\bar YX^+) + igc_wZ^0_\mu(\partial_\mu\bar X^+X^+ -$$
$$\partial_\mu\bar X^-X^-) + igs_wA_\mu(\partial_\mu\bar X^+X^+ - \partial_\mu\bar X^-X^-) - \frac12 gM\left(\bar X^+X^+H + \bar X^-X^-H + \frac{1}{c_w^2}\bar X^0X^0H\right) +$$
$$\frac{1-2c_w^2}{2c_w}igM\left(\bar X^+X^0\phi^+ - \bar X^-X^0\phi^-\right) + \frac{1}{2c_w}igM\left(\bar X^0X^-\phi^+ - \bar X^0X^+\phi^-\right) +$$
$$igMs_w\left(\bar X^0X^-\phi^+ - \bar X^0X^+\phi^-\right) + \frac12 igM\left(\bar X^+X^+\phi^0 - \bar X^-X^-\phi^0\right).$$

SM problems: spontaneous breaking of the electroweak symmetry by Higgs mechanism

This part of SM is the only remaining untested part of SM. Higgs-boson like particle has been observed by ATLAS and CMS in 2012; remember: the EW symmetry could be broken in a different way, not necessarily like in MSM

Difficulties with the elementary Higgs sector: suppose that SM is just an effective theory and that NEW physics is at some scale . The quantum corrections to fermion masses would depend only logarithmically on scale Λ:



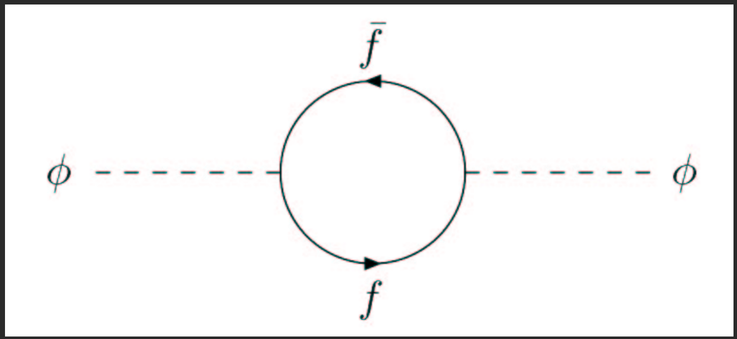
$\delta m_f \sim m_f \ln\Lambda$

SM problems: spontaneous breaking of the electroweak symmetry by Higgs mechanism

Difficulties with the elementary Higgs sector : quantum corrections to scalar particle (Higgs) exhibit quadratic dependence on scale Λ, making Higgs mass VERY sensitive to the scale of the NEW physics => fine tuning problem (or a gauge hierarchy problem). This fine tuning has to be performed for each order of perturbation theory - this is a very unpleasant feature of MSM

$$m_H^2 = - m_0^2 + g^2 \Lambda^2$$

SM cannot be valid for very large momenta, the scale Λ serves as a cutoff above which physics not contained in SM becomes important. At least one such scale, Planck scale at which gravity becomes relevant, $\Lambda = O(10^{19})$ GeV, must be present in any theory.



$\delta m_H^2 \sim \Lambda^2$

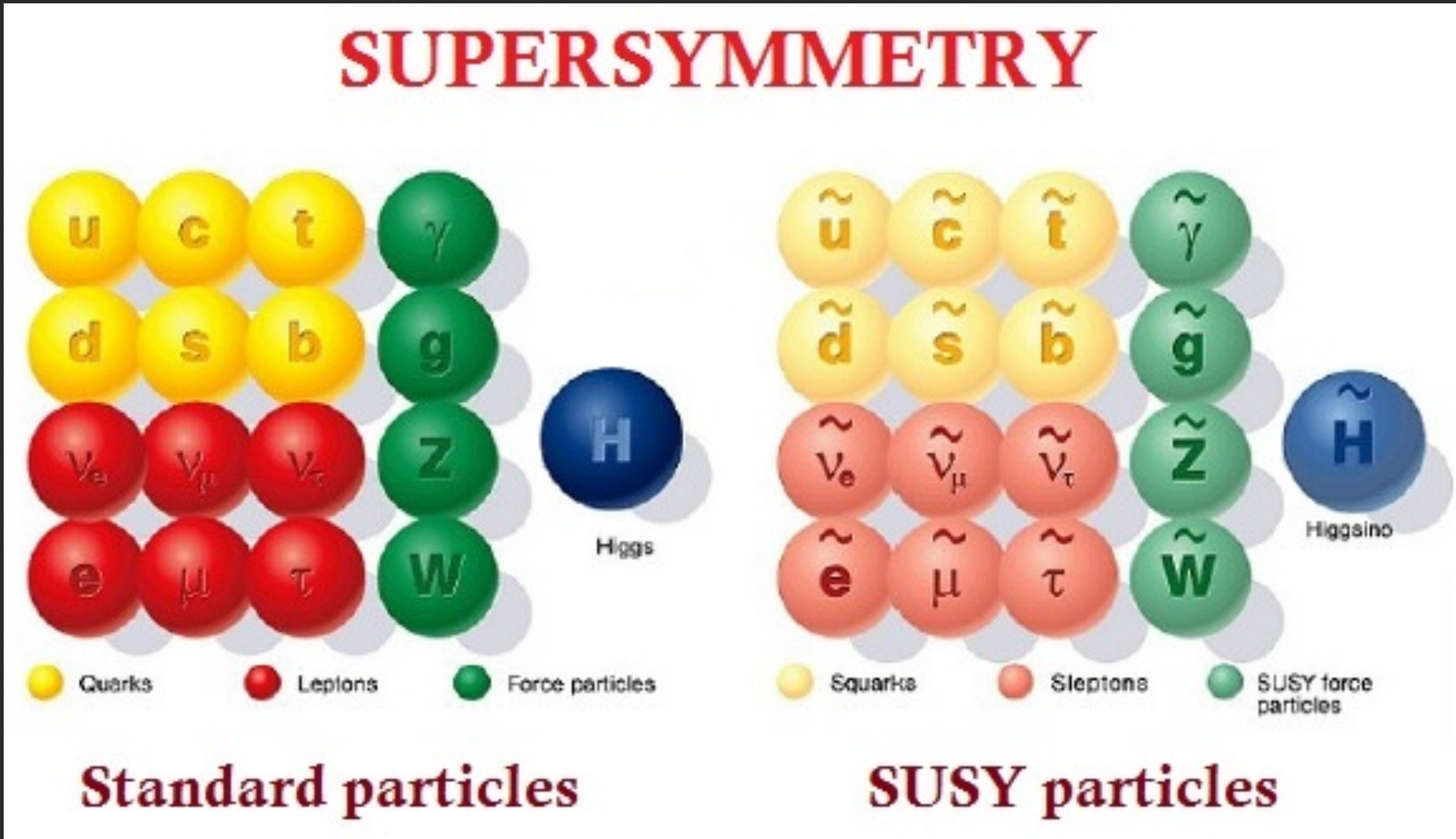
SM problems: spontaneous breaking of the electroweak symmetry by Higgs mechanism

The original problem of how to give masses to weak gauge bosons in a gauge invariant way was only partially solved by the Higgs mechanism, and the problem was transferred to a new level, where the new puzzle is how to keep Higgs mass stable against large quantum corrections from the higher energy scales

A method of controlling Higgs mass divergence other than fine tuning of parameters would be very welcomed

supersymmetry - the most elegant solution?

- Interesting fact about the scalar mass divergencies from virtual particle loops (quantum corrections) is that the
- *virtual fermions and virtual bosons contribute with opposite signs and would cancel each other exactly if for every boson there was a fermion of the same mass and charge - divergencies would cancel without any fine tuning and in all orders of perturbation theory !!*
- supersymmetry is such a symmetry: it connects bosons to fermions, it introduces a fermionic partner to every boson and vice-versa, identical in all quantum numbers;
- supersymmetry is a space-time symmetry


SUPERSYMMETRY
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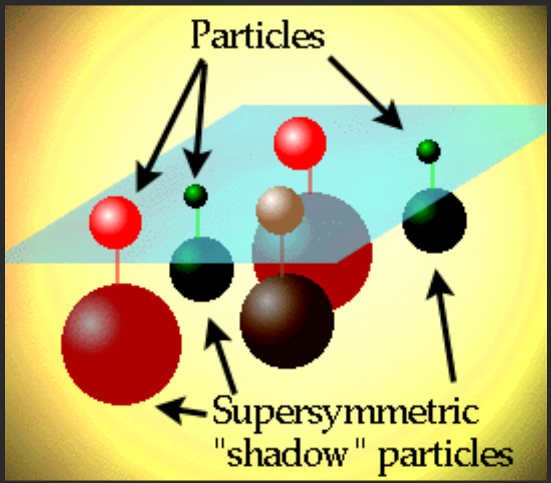
$\tilde{\mu}$
$\tilde{\tau}$
$\tilde{W}$
Squarks
Sleptons
SUSY force particles
SUSY particles

supersymmetry - the most elegant solution?

- If supersymmetry were real, it must be somehow broken as we have not yet observed superparticles. while still keeping the ability to solve the gauge hierarchy problem. Not easy, depends on the scale at which SUSY is broken, and on how it is broken. To some extent it remains still an open question

- SUSY provides a natural explanation for "dark matter"

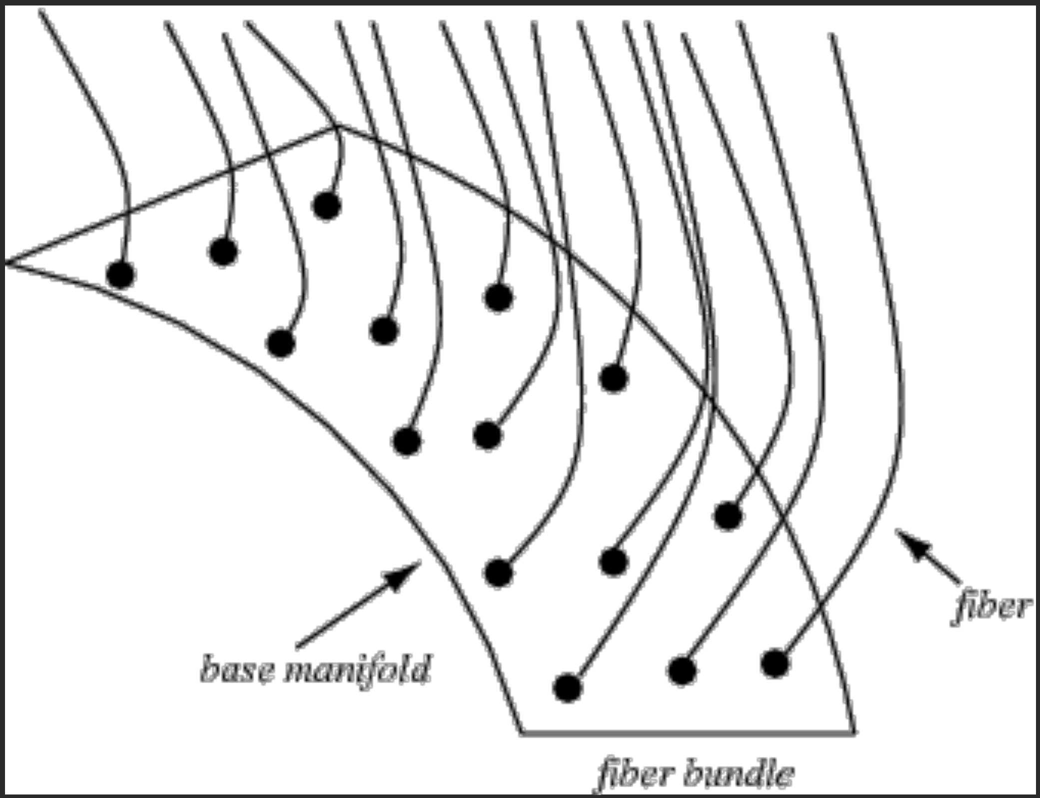
- Local supersymmetry could also be a viable theory of gravity - supergravity.



gauge theories and extra dimensions

- Geometrical picture (from ~1970: Atiyah, Singer, Donaldson, Witten, Bott…)

- In the mathematical language of fibre bundles, a gauge potential (e.g. 4-vector potential of electrodynamics, or Yang-Mills potentials for electroweak theory) is a connection in a fibre bundle, an abstract state-space of internal structure, described by a given gauge group: U(1) of EM, SU(2) of Yang-Mills theory, SU(3) for strong - superimposed on space-time. The curvature of the connection is the gauge field (e.g the field strength tensor $F_{\mu\nu}$ of electrodynamics).



gauge theories and extra dimensions

- It is a geometrical picture, very similar to Einstein's gravity, except the distortion measured by curvature is not taking place in the geometry of space-time but in the geometry of the more-dimensional "total space", imposed over space-time.

- Gauge (phase) transformations are analogous to co-ordinate transformations in Riemannian geometry of Einstein's General Relativity

- We may be living in a world which is more than just 4 dimensional (10, 11??), except we don't "see" beyond the familiar 4 space-time dimensions

gauge theories and extra dimensions

- In 1980 Scherk, Schwartz and Cremmer revived interest in Kaluza-Klein theories. They advocated that the extra dimensions should be regarded as physical, not abstract, just like the four dimensions that we are aware of.

- Cremmer and Scherk suggested that the difference between the four observed and the unobserved dimensions has its origin in a process of "spontaneous compactification" of the extra dimensions.

gauge theories and extra dimensions

- 1981 Witten noticed a remarkable fact (could be a concidence): the minimum number of dimensions for a manifold with SU(3)xSU(2)xU(1) symmetry is 7, so to construct a Kaluza-Klein theory in which those symmetries arise as components of gravity in more than 4 dimensions, one must have at least 11 dimensions. At the same time, 11 is probably the maximum number of dimensions for supergravity.

- 1984 Green and Schwartz: proved consistency of string theories only in 26 dimensions (bosonic) and 10 (supersymmetric)

- 1990 Sen, Duff, Witten: M-theory - in 11 dimensions, unites all 5 types of 10 dimensional superstring theories

gauge theories and extra dimensions

- We may be living in a world which is more than just 4 dimensional (10, 11??), except we don't "see" beyond the familiar 4 space-time dimensions

- The remaining problem is to include and quantize gravity – lots of progress, combining geometry, topology and gauge theories –

  non-commutative geometry (non-commutativity in the additional 6 mod 8 dimensions - Alain Connes)

  loop quantum gravity

Prof. George Leger (with my help) may teach a course on "Geometry, Topology and Gauge Fields" in Spring 2014

Also, Prof. Loring Tu at Tufts is an expert in topology and differential geometry, he teaches fantastic courses on "Manifolds" and related topics…

BEYOND STARDARD MODEL??

- SUPERSYMMETRY
- GRAND UNIFIED THEORIES based on larger symmetry groups, e.g. SU(5), SO(10), E_8, Monster group…
- extensions of Kaluza-Klein theory, string theory, superstring theory, branes, M-theory, loop quantum gravity, other quantum gravity theories?
- TECHNICOLOR ??

- finding Higgs does not solve SM problems

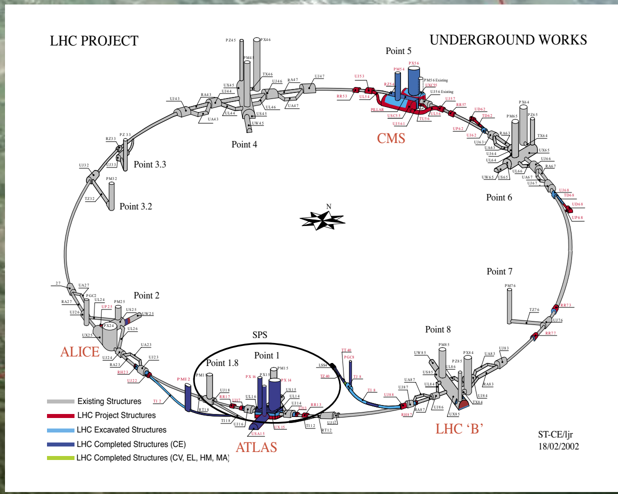
- EXPERIMENTAL DATA NEEDED BADLY!!

Large Hadron Collider at CERN

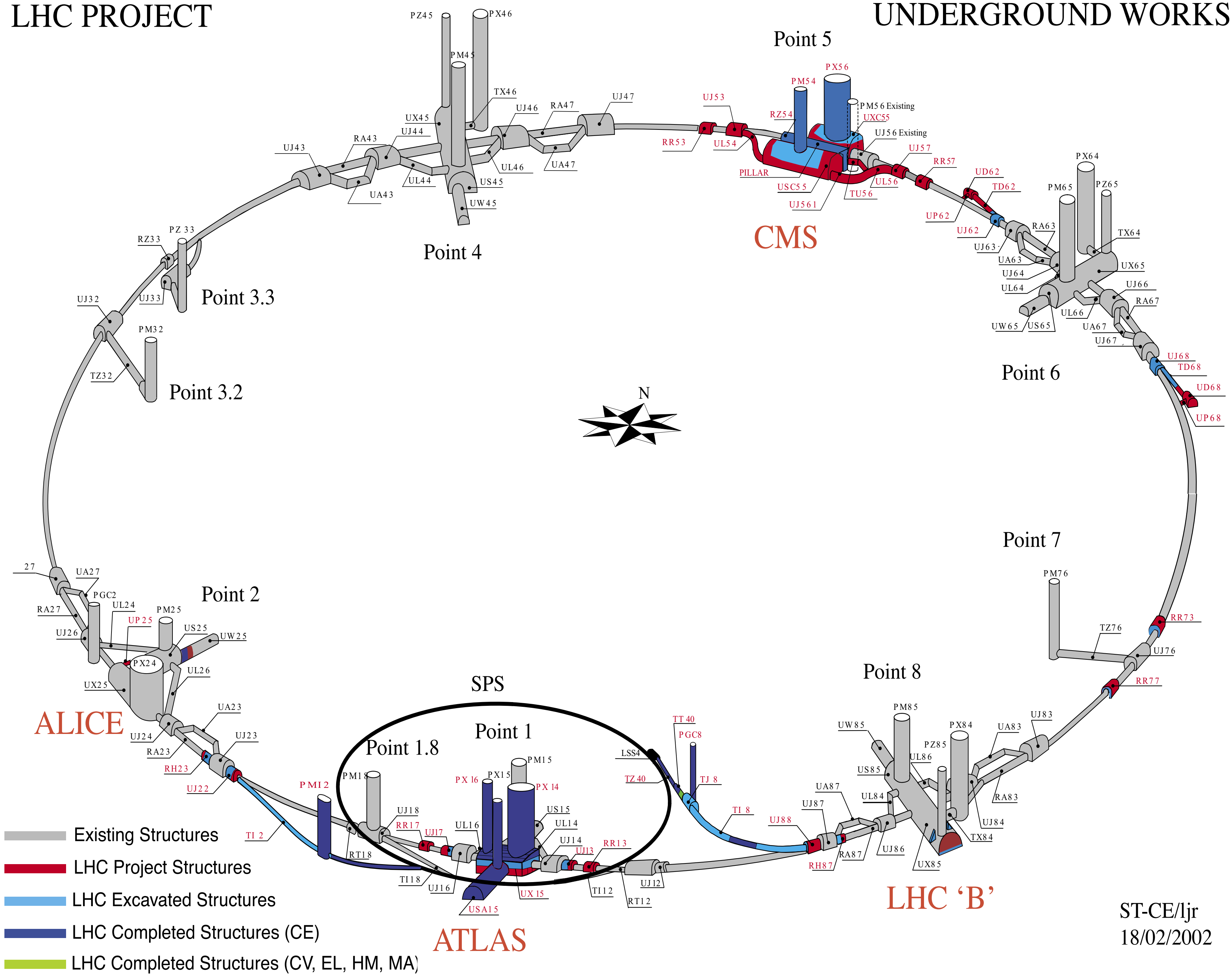
European Centre for Particle Physics, Geneva, Switzerland

Superconducting Proton Accelerator and Collider
installed in a 27km circumference underground tunnel (tunnel cross-section diameter 4m) at CERN
Tunnel was built for LEP collider in 1985
First operation in Fall 2008

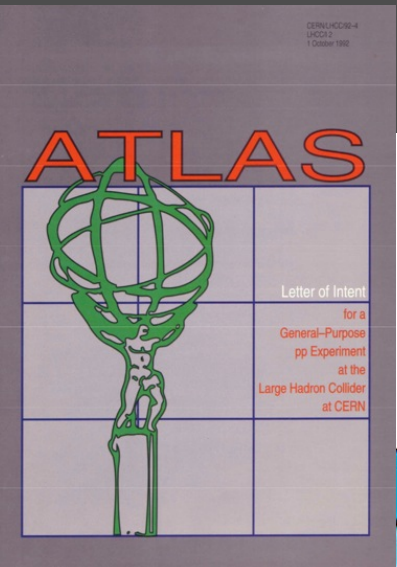
1984 : First studies for a high-energy pp collider in the LEP tunnel
1993 : cancellation of SSC
1994 : LHC approved by the CERN Council
1994 : top-quark discovered at the Tevatron
1996 : start of construction of LHC machine and experiments
2000 : closing of LEP2
2003 : Start of LHC machine and experiments installation
2009 : 23 November: first LHC collisions ($\sqrt{s}$ = 900 GeV)
2010 : 30 March: first collisions at $\sqrt{s}$ = 7 TeV
beginning of a long physics programme
2011 : hints of a new particle of mass ~125 GeV
2012 : 1st May: first collisions at $\sqrt{s}$ = 8 TeV
2012 : 4th July: discovery of a Higgs-like boson announced

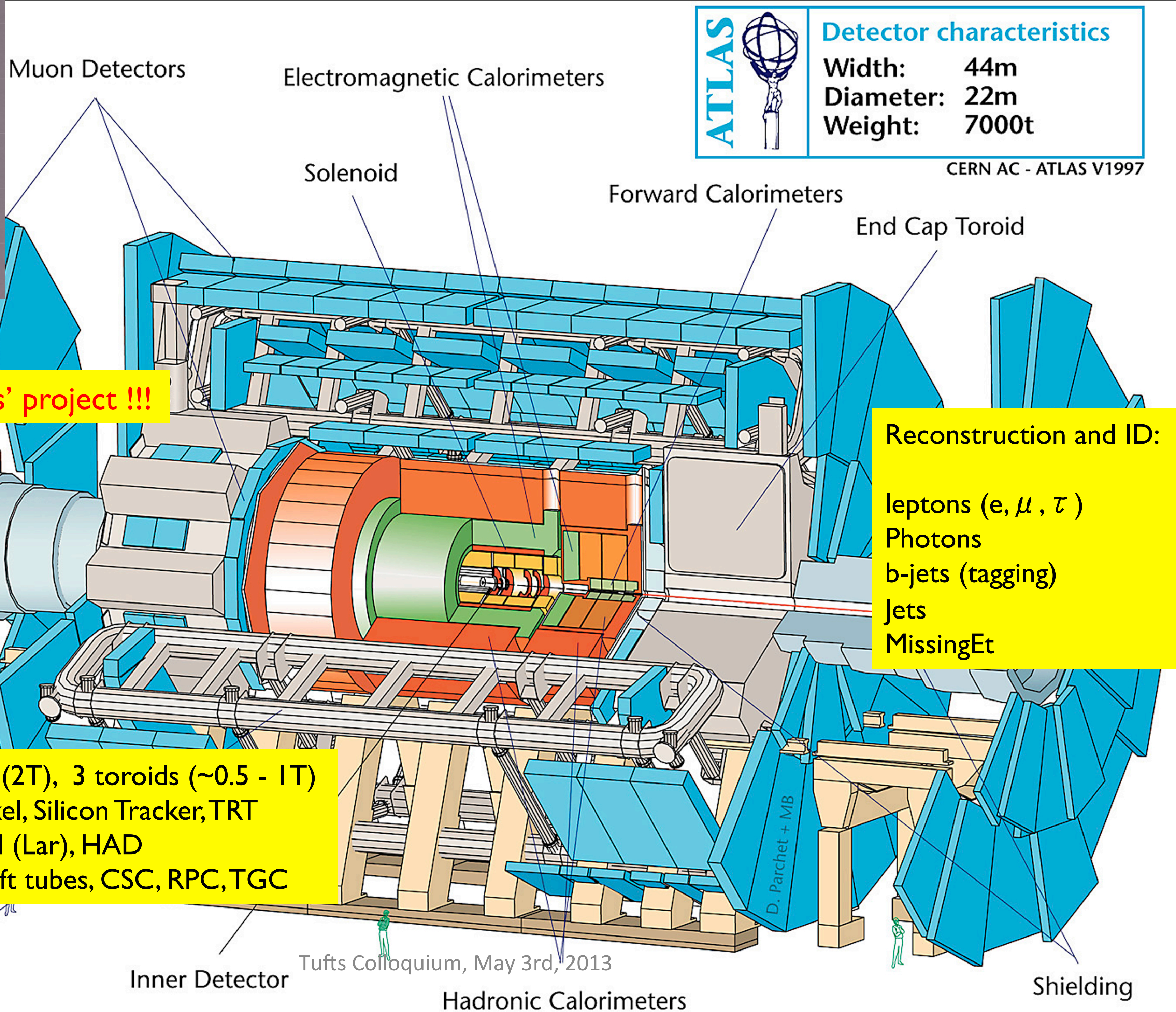


LHC PROJECT UNDERGROUND WORKS



ATLAS DETECTOR AT LHC





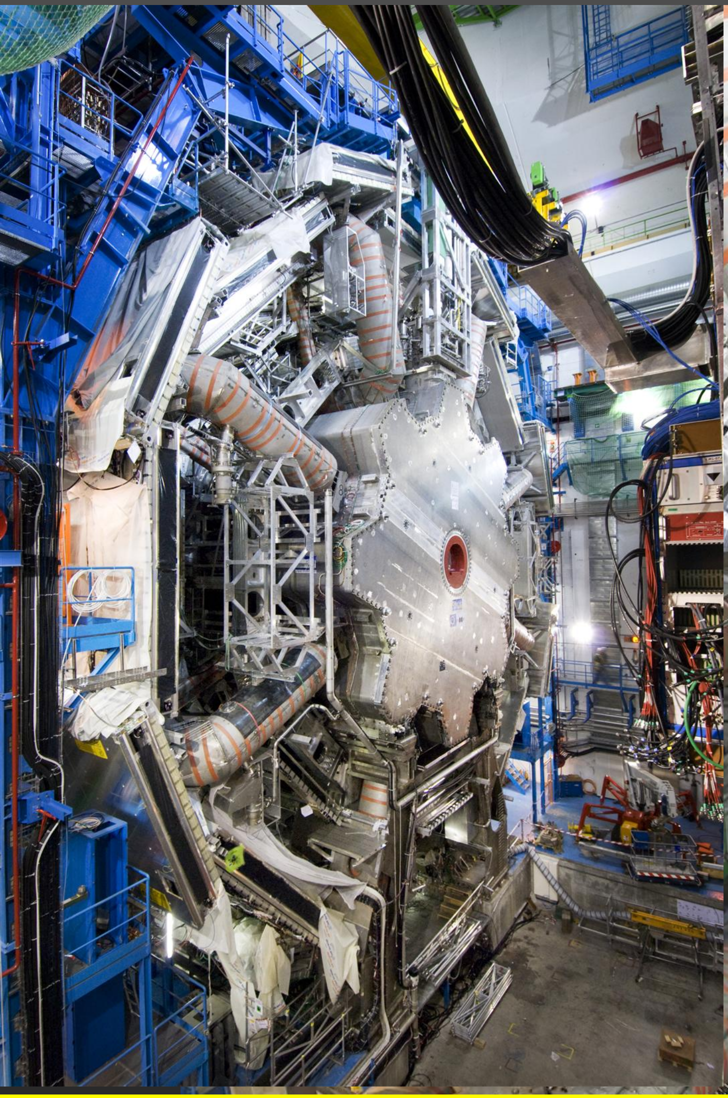
more than 20 years' project !!!

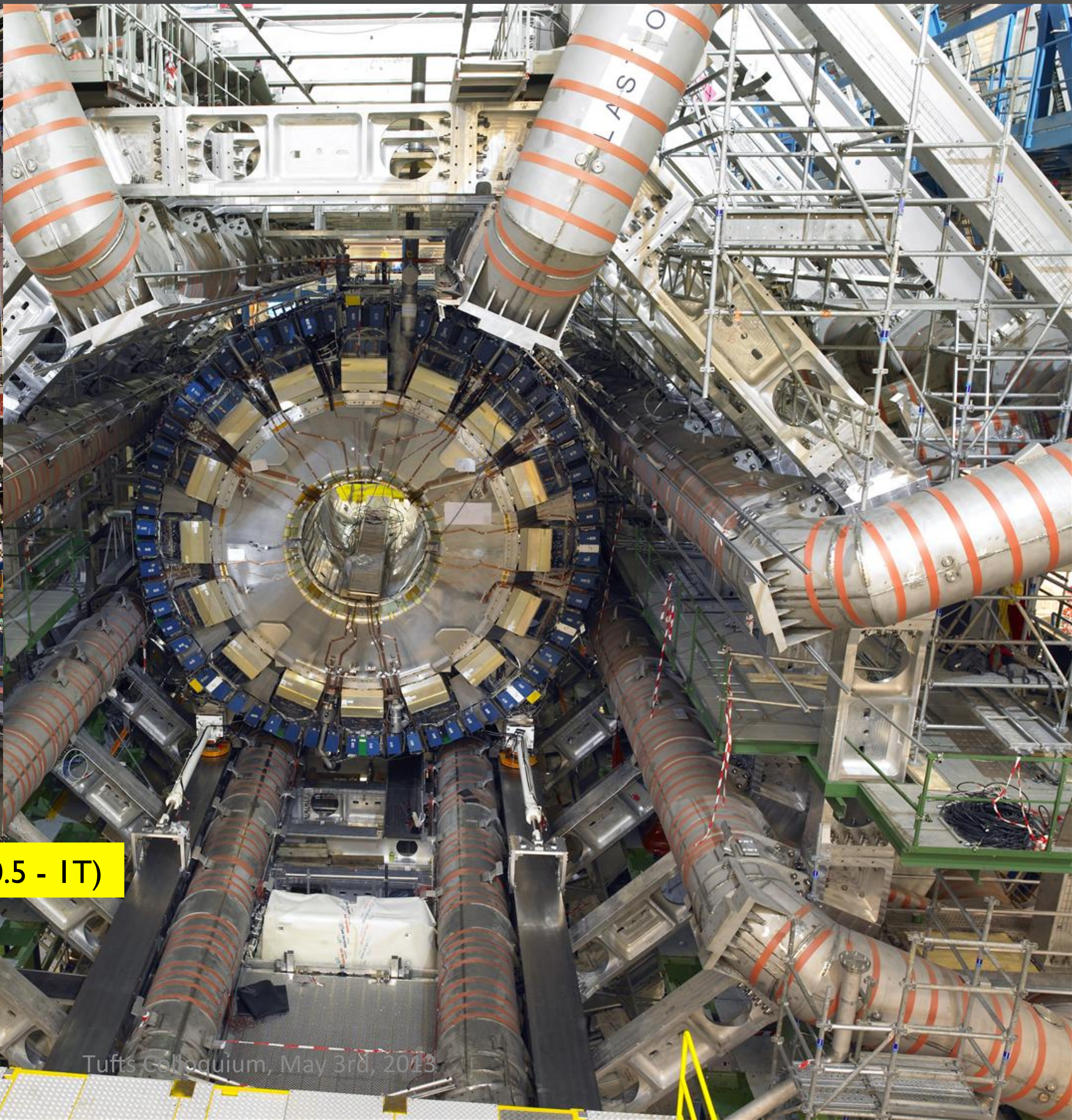
Reconstruction and ID:

leptons (e, μ , τ)
Photons
b-jets (tagging)
Jets
MissingEt

Magnets: solenoid (2T), 3 toroids (~0.5 - 1T)
Tracking: Pixel, Silicon Tracker, TRT
Calorimeter: EM (Lar), HAD
Muons: drift tubes, CSC, RPC, TGC

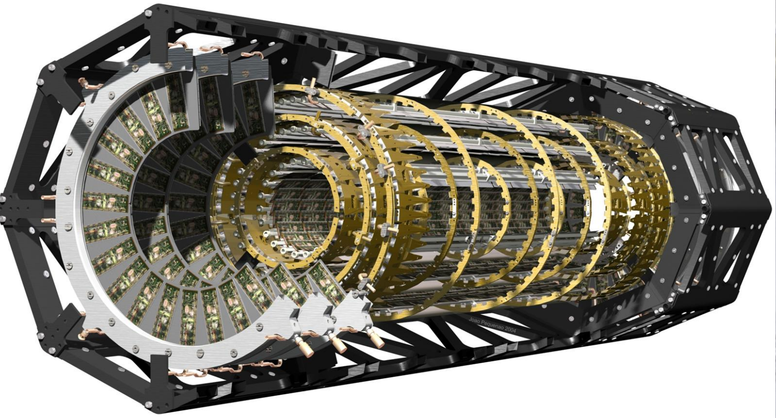
ATLAS DETECTOR AT LHC

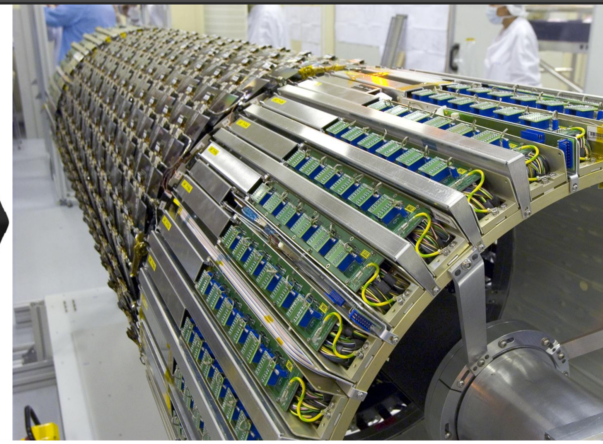


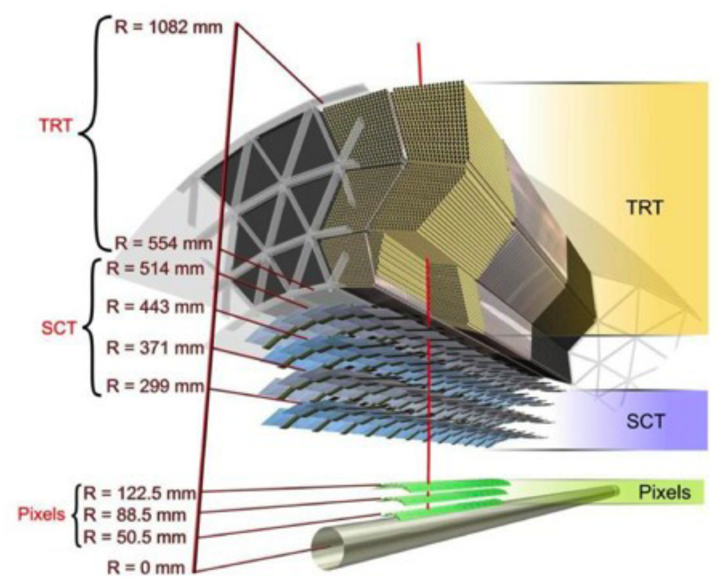


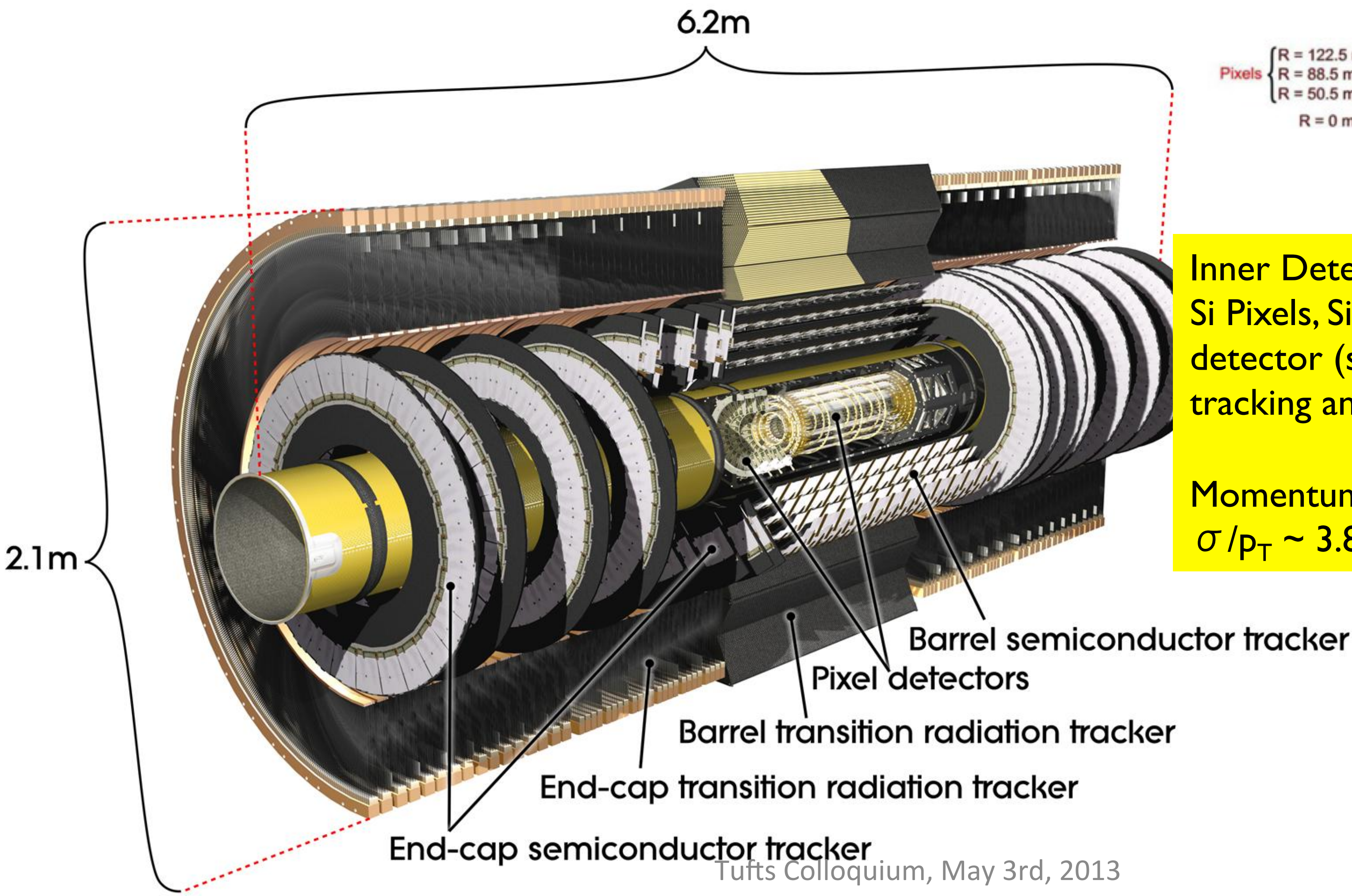
Magnets: solenoid (2T), 3 toroids (~0.5 - 1T)

ATLAS TRACKING DETECTORS





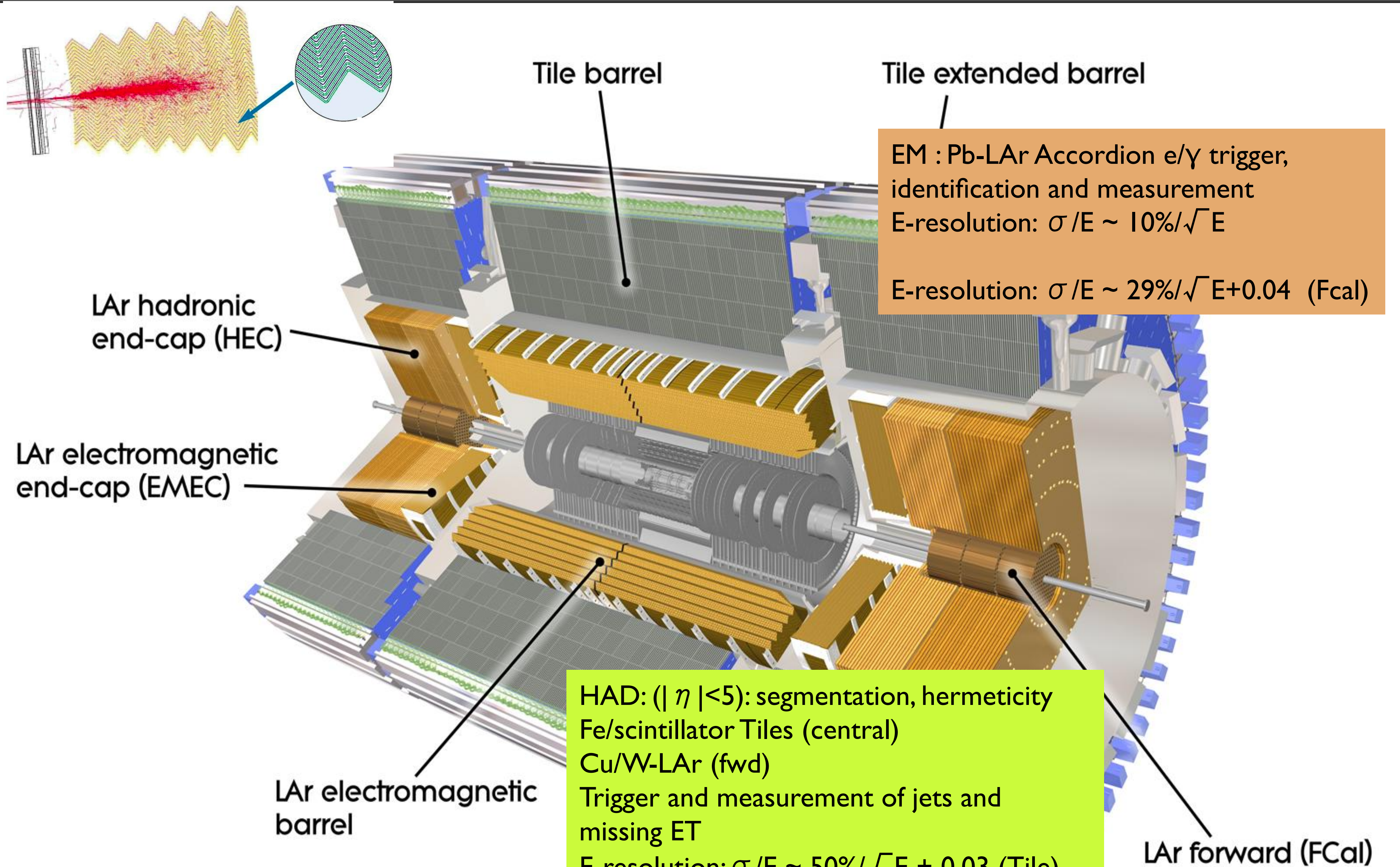




Inner Detector ($|\eta|<2.5$, solenoid B=2T): Si Pixels, Si strips, Transition Radiation detector (straws) – particle ID, precise tracking and vertexing, e/π separation

Momentum resolution:
$\sigma/p_T \sim 3.8 \times 10^{-4}\, p_T\,(\mathrm{GeV}) + 0.015$

ATLAS CALORIMETERS



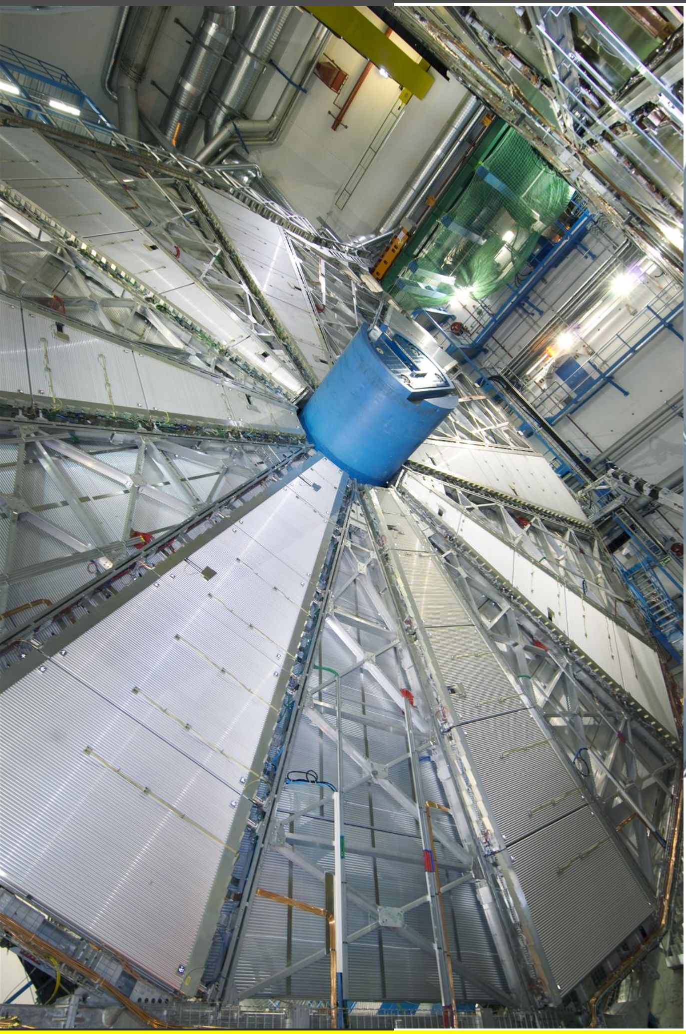
EM : Pb-LAr Accordion e/γ trigger, identification and measurement
E-resolution: $\sigma/E \sim 10\%/\sqrt{E}$

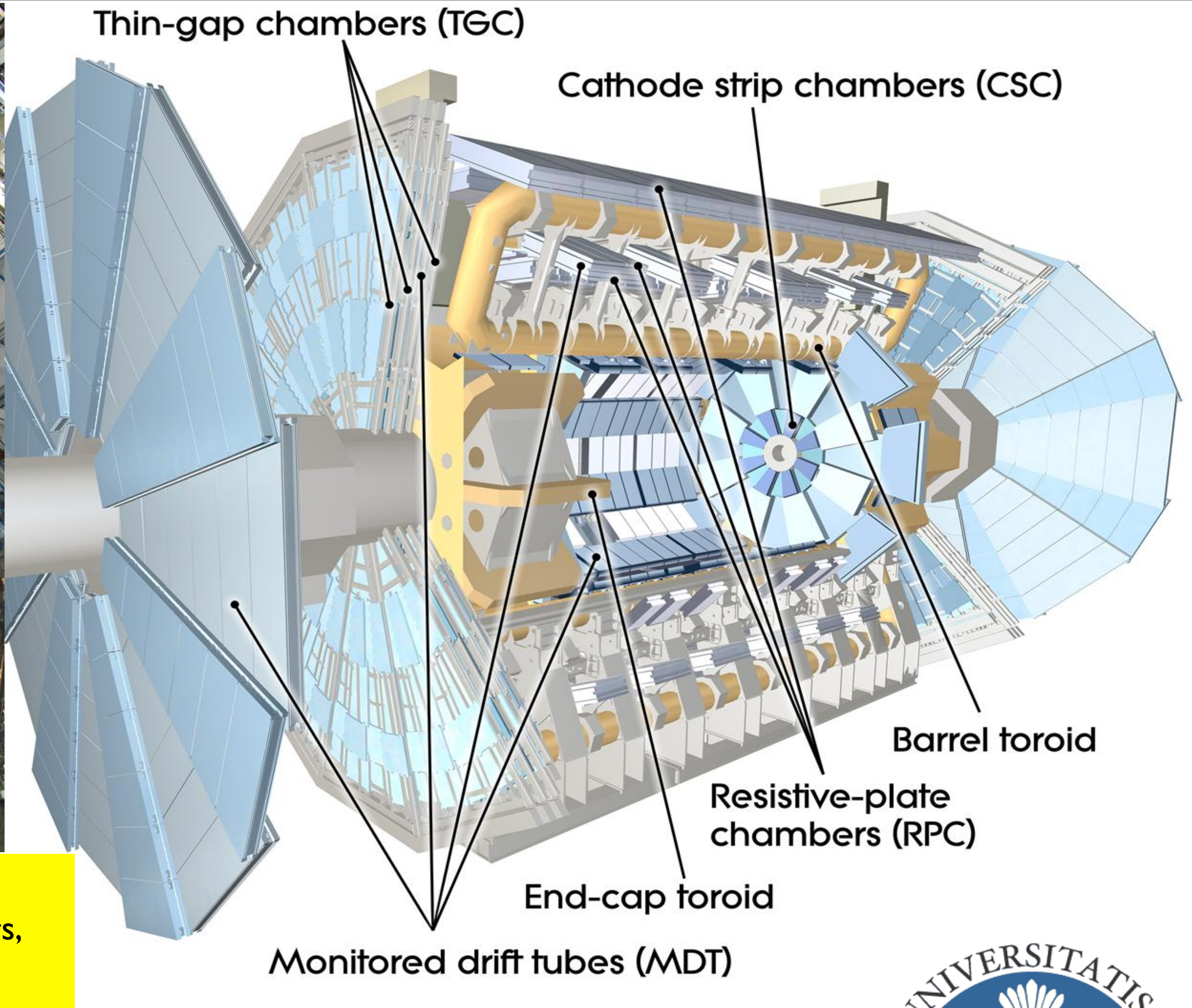
E-resolution: $\sigma/E \sim 29\%/\sqrt{E}+0.04$ (Fcal)

HAD: ($|\eta|<5$): segmentation, hermeticity
Fe/scintillator Tiles (central)
Cu/W-LAr (fwd)
Trigger and measurement of jets and missing ET
E-resolution: $\sigma/E \sim 50\%/\sqrt{E} + 0.03$ (Tile)

E-resolution: $\sigma/E \sim 95\%/\sqrt{E} + 0.08$ (FCal)

ATLAS MUON SPECTROMETER

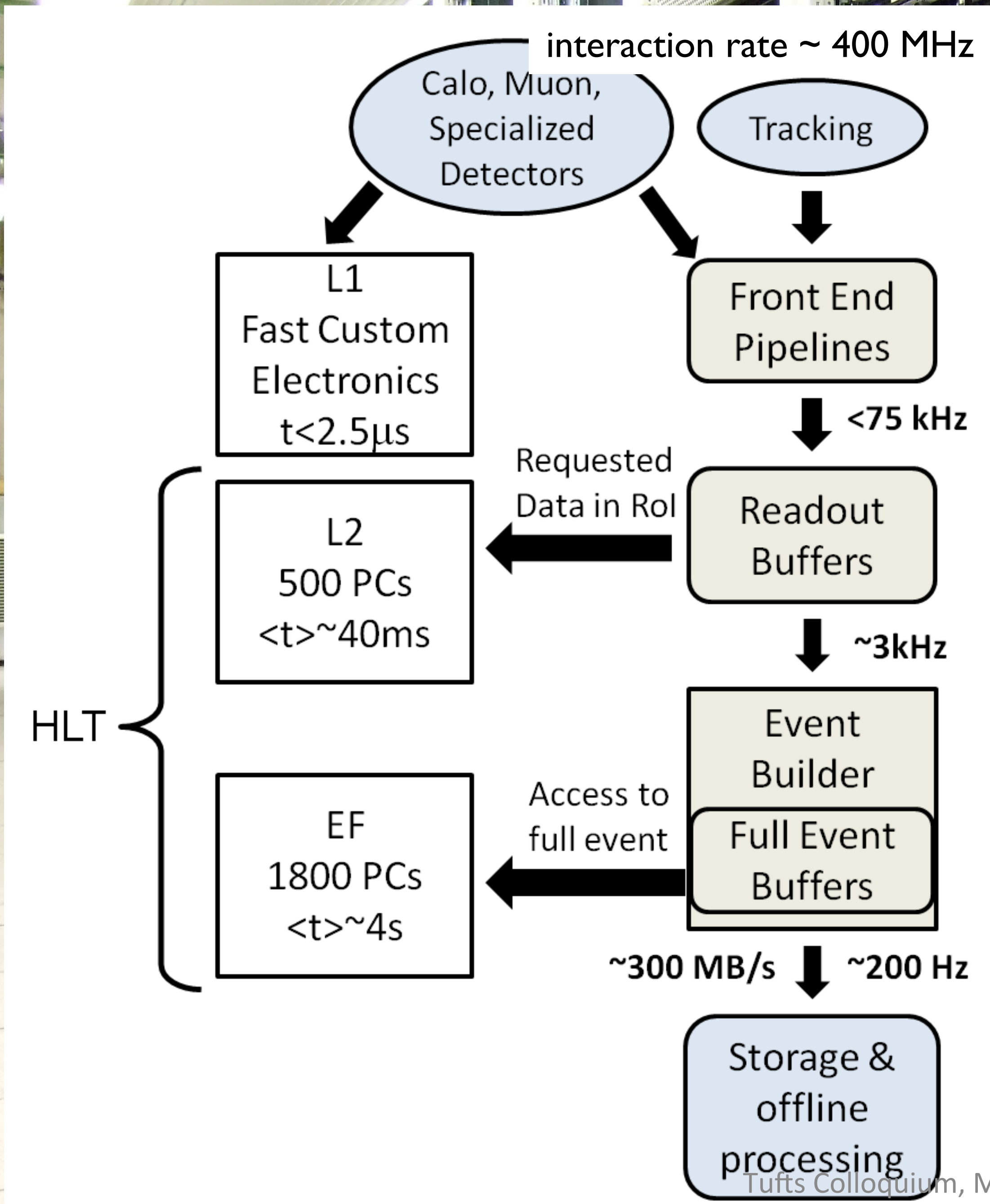




Muon coverage (| η |<2.7) : 3 air-core toroids with gas-based muon chambers, measurement (CSC, MDT) with momentum resolution
< 10% up to Eμ ~ 1 TeV
Trigger (TGC, RPC)

Tufts ATLAS Group – founding member of Boston Muon Consortium – endcap muon (BU, Brandeis, Harvard, MIT, Tufts)

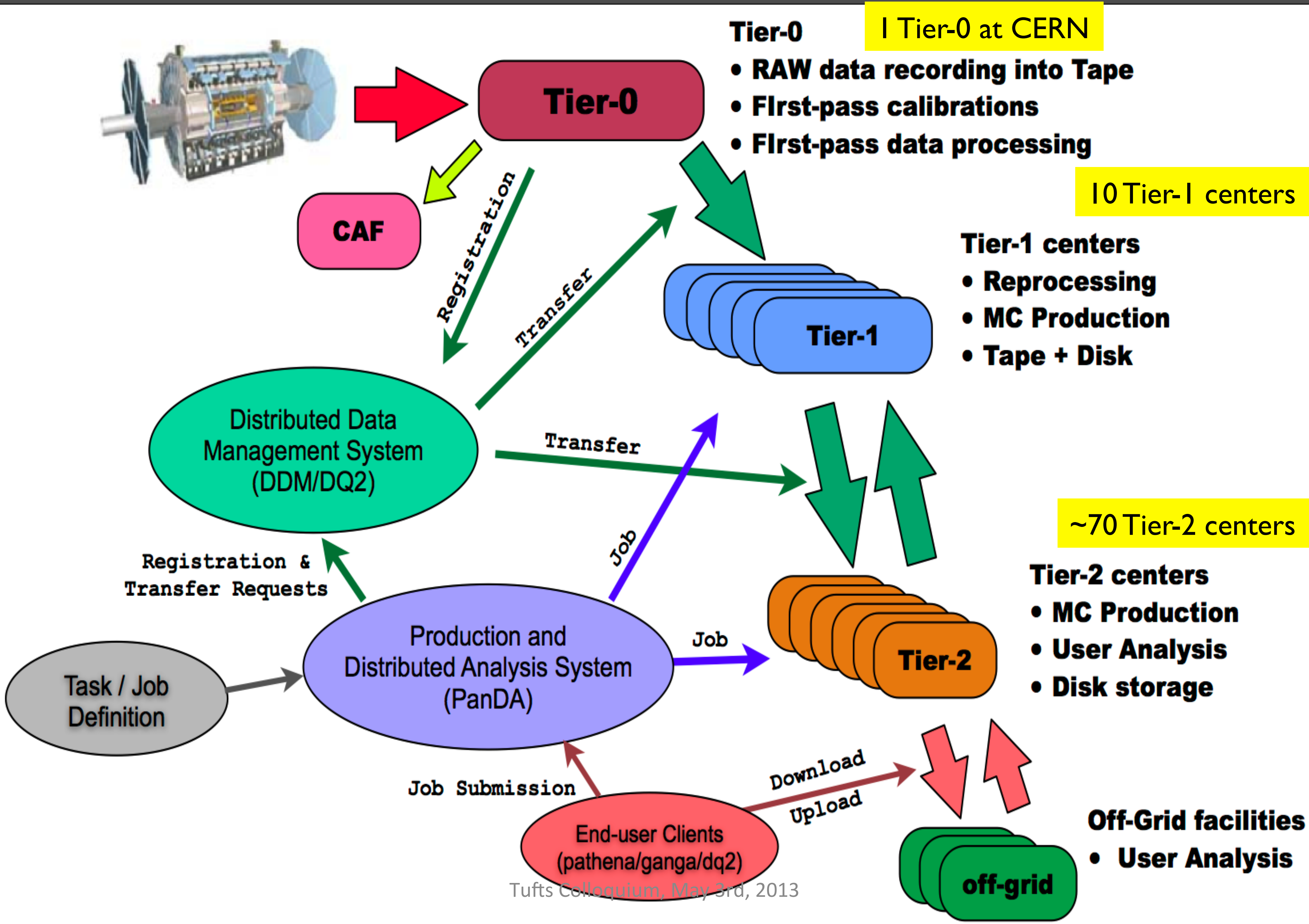
ATLAS TRIGGER AND DATA ACQUISITION SYSTEM



Number of nodes:	2000
Number of computing cores:	17000
Cooling power:	800 kW
Peak Event Building Bandwidth:	10 GB/s
Peak Storage Bandwidth:	1.6 GB/s
Amount of data in 2012:	6 PB

100 millions electronic channels
3000 km of cables

ATLAS COMPUTING



ATLAS COLLABORATION

ATLAS RESULTS ARE A TRULY COLLABORATIVE EFFORT OF MANY THOUSANDS OF PEOPLE, PHYSICISTS, ENGINEERS, PROGRAMMERS, TECHNICIANS AND STUDENTS….

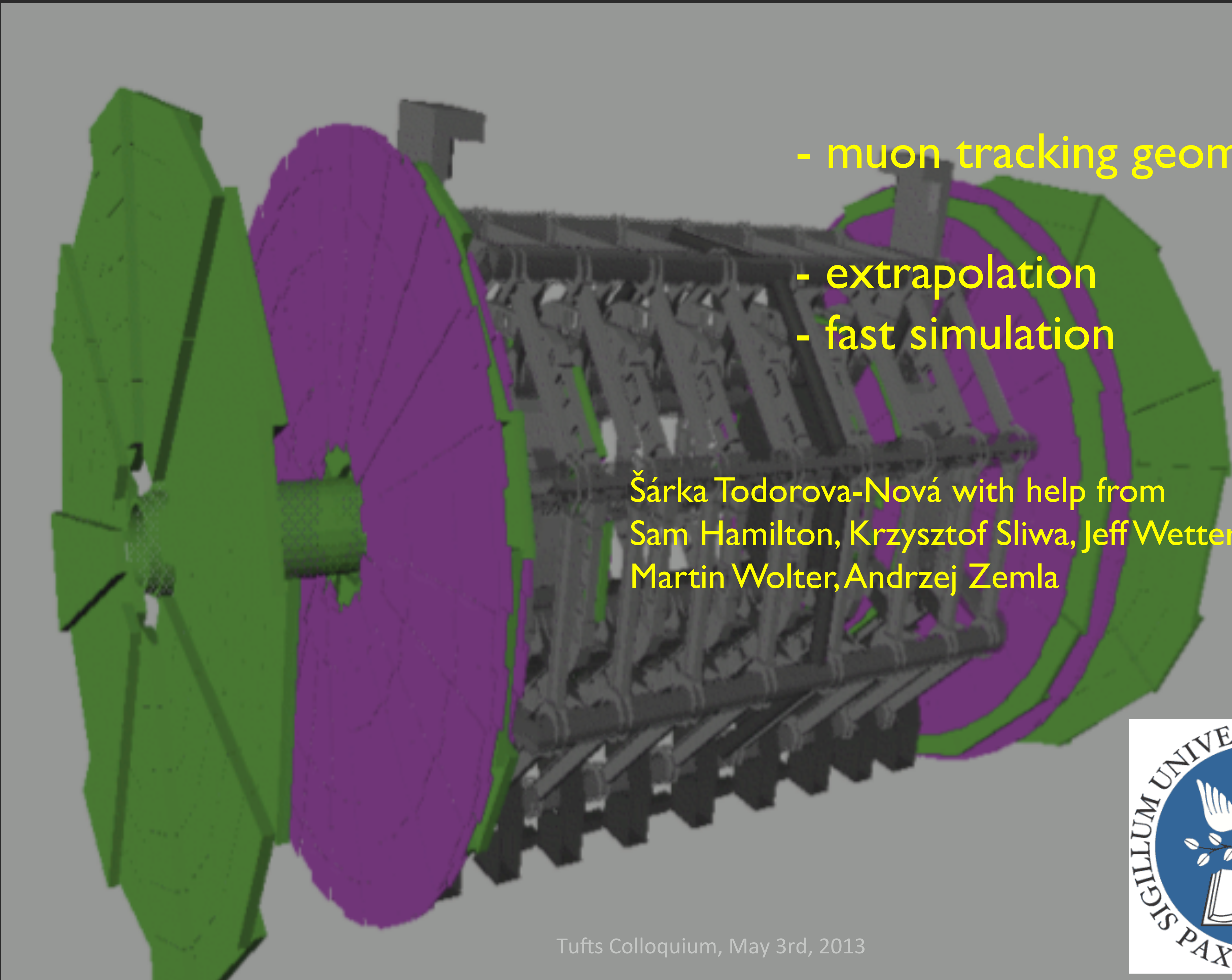
AND MANY FUNDING AGENCIES INVOLVED!!

world –wide computer grid

~3000 physicists
48 countries
177 universities
~1000 students

+ engineers
+ technicians
+ computer scientists

ATLAS SOFTWARE – muon geometry and tracking tools



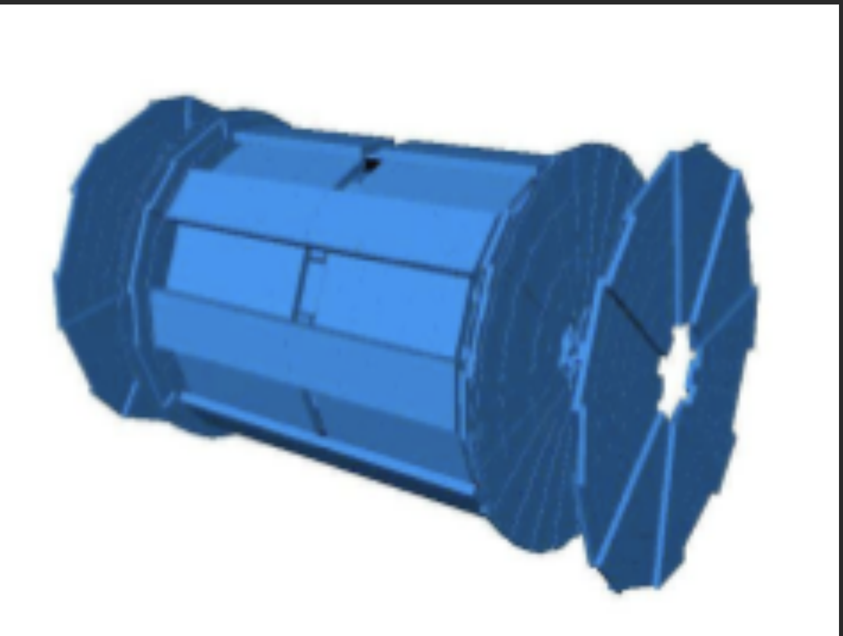
- muon tracking geometry

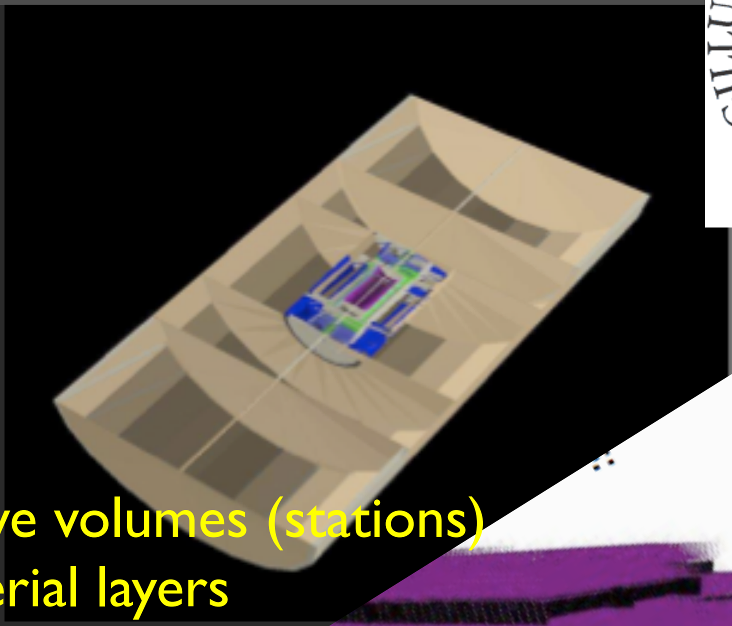
- extrapolation
- fast simulation

Šárka Todorova-Nová with help from
Sam Hamilton, Krzysztof Sliwa, Jeff Wetter,
Martin Wolter, Andrzej Zemla

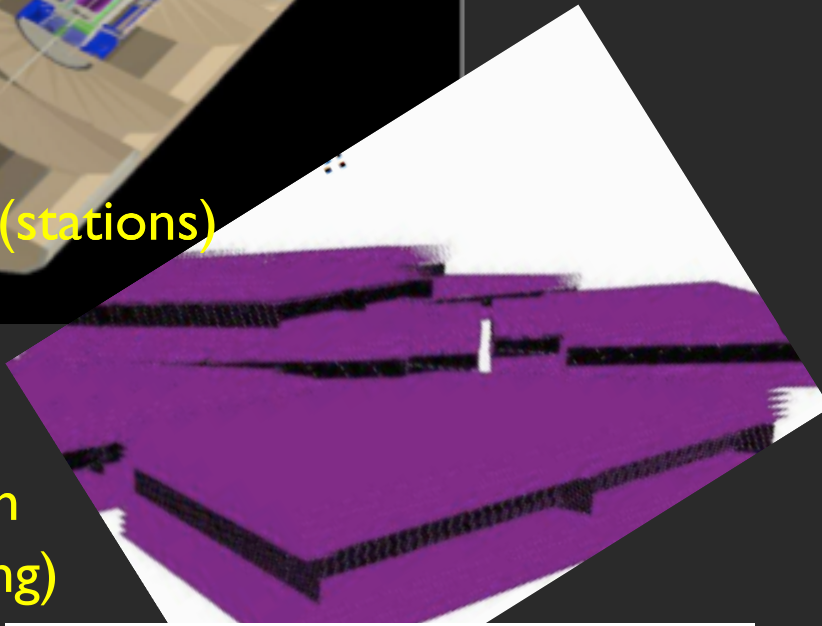
MUON TRACKING GEOMETRY

1/ ATLAS (combined, static) frame
- system of volumes covering the whole detector
- MS enveloping ID/Calo

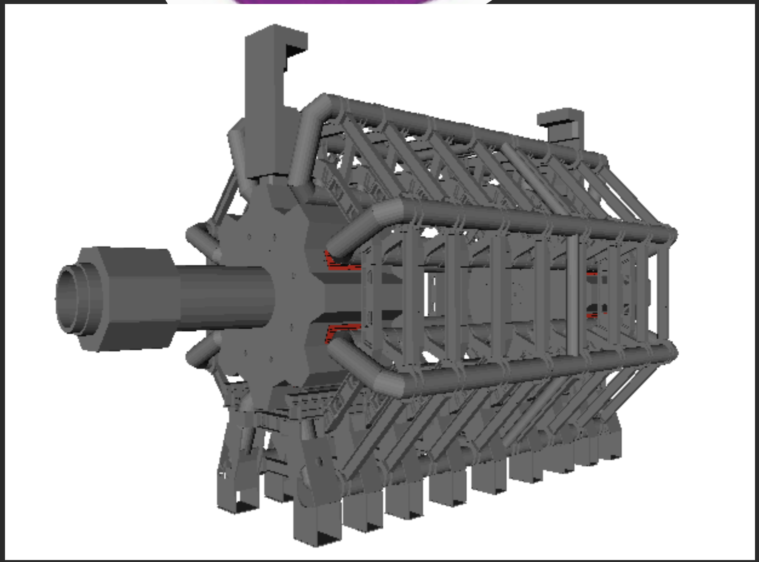




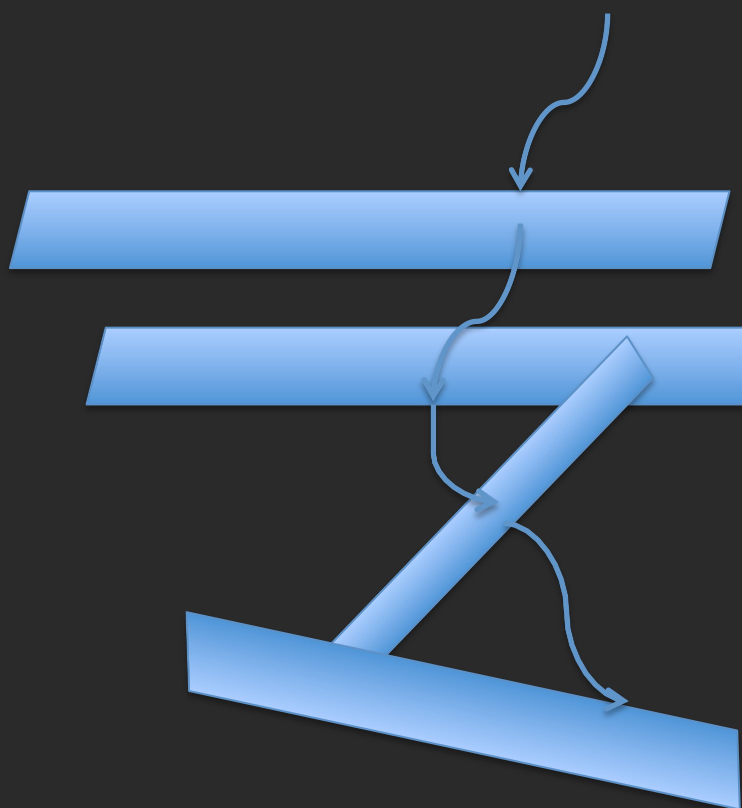
2/ active volumes (stations)
- material layers
- alignable
- complete & simplified system of active (tracking) surfaces



3/ inert material
(toroids, shieldings,
feets, supports, infrastructure ..)
Automatized transcript from the database.



Common tracking tools: extrapolator+propagator



Surface-based (local) parameters: 5 free parameters -> error matrices simplified (wrt. 6 global coordinates)

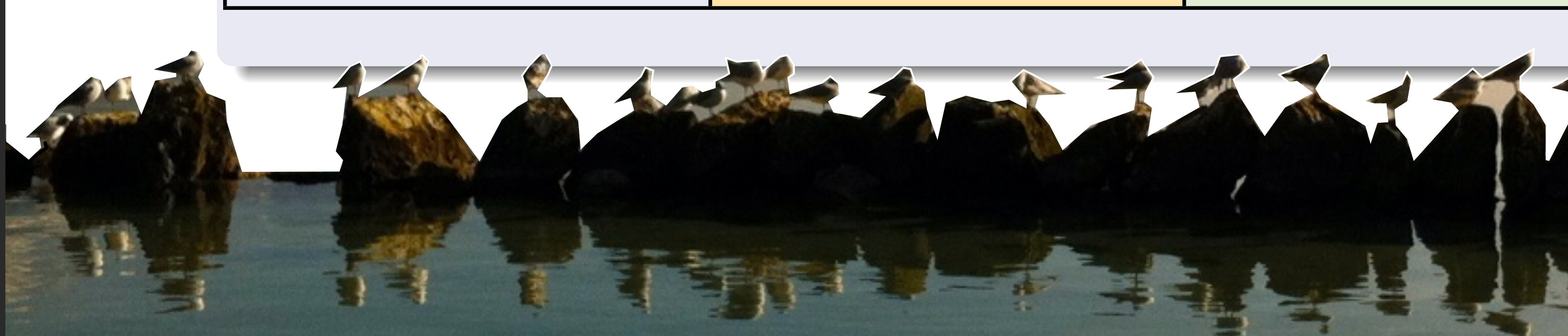
The art of finding the sequence of intersections with dense volumes boundaries and sensitive layers in rapidly fluctuating magnetic field – a lot of pioneering work done in MS

A number of simplified material options coded

Fast simulation : realistic detector response (hit based)

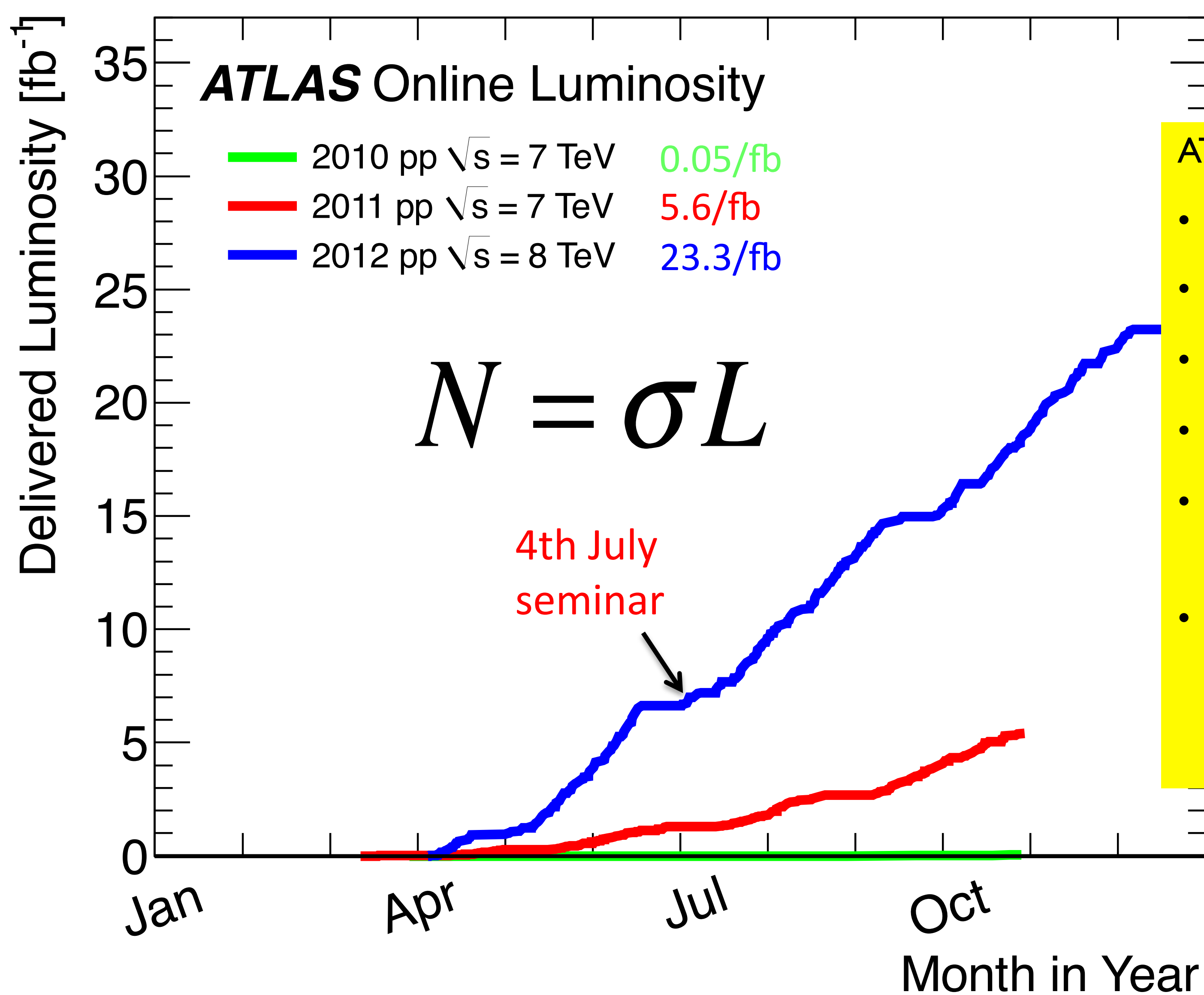
What can we do with the ISF ...

	ISF_Kernel::execute/evt	speed-up
$\mathcal{O}$ **Full Geant4** measured with 10 events	560 s	1
$\mathcal{O}$ **ATLFASTII** measured with 100 events	25 s	~25
$\mathcal{O}$ **ATLFASTIIF** measured with 1000 events	0.75 s	~750
measured with 1000 events $\mathcal{O}$ **FastGamma**	0.18 s	~3000



E. Ritsch, ISF simulation, Kernel execution time per event, ggF Higgs → γ γ

delivered luminosity– fantastic LHC performance

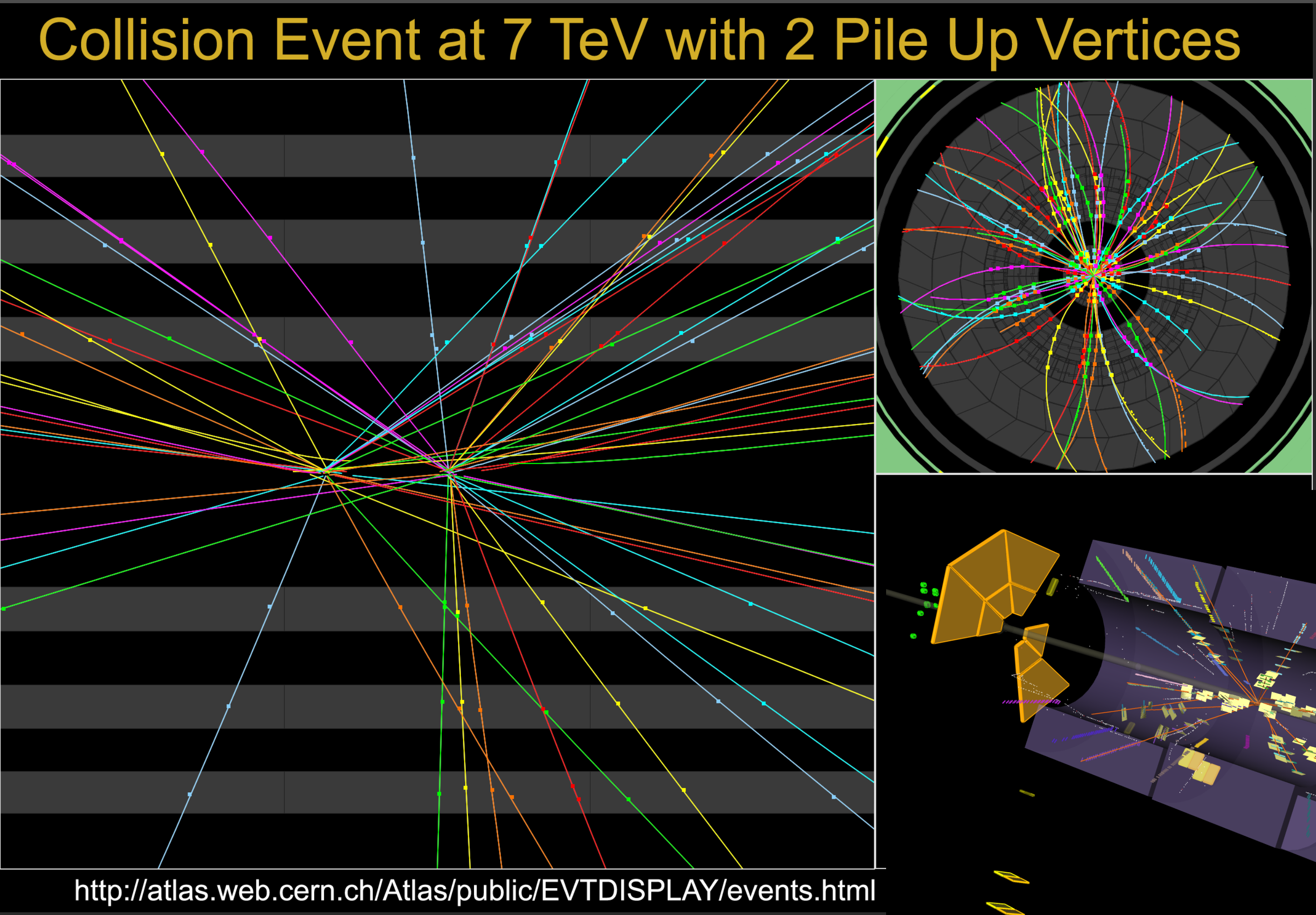


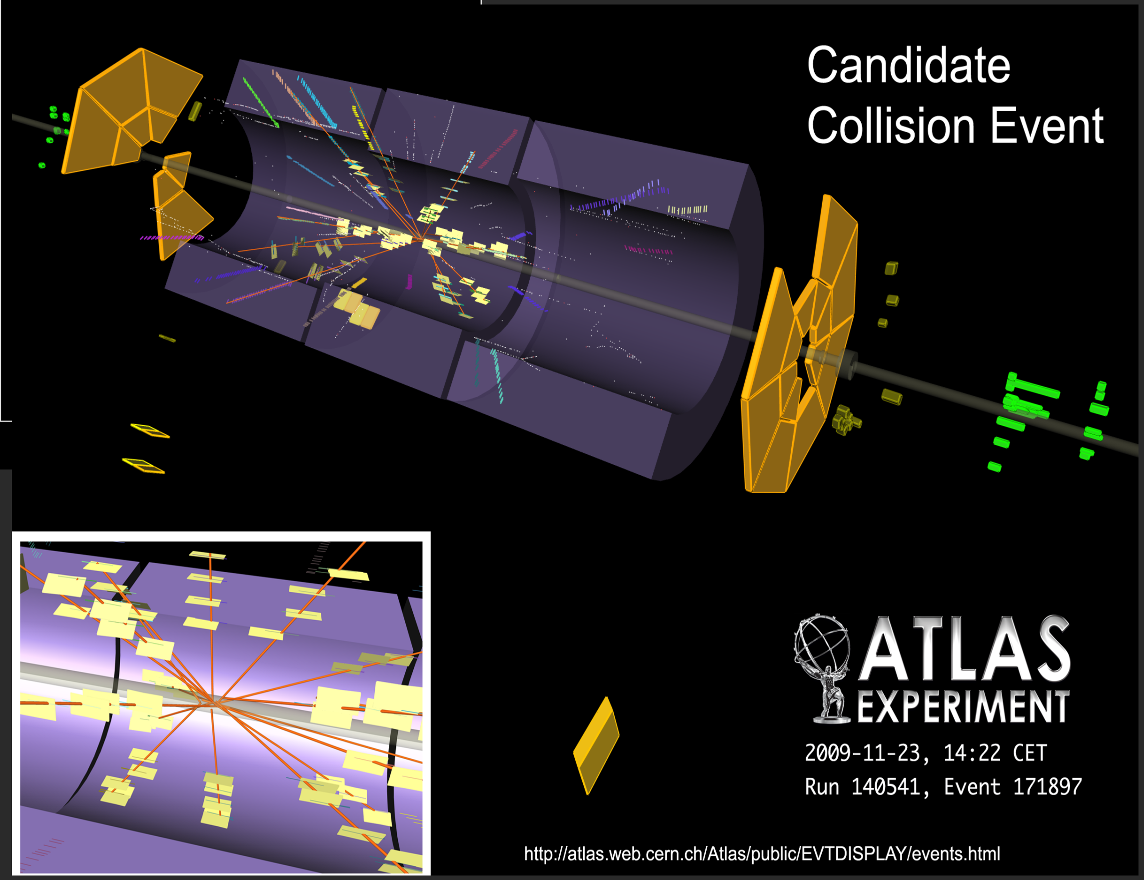
ATLAS integrated luminosity in 2012

- Peak L = 7.7×10^{33} s^{-1}cm^{-2} (Aug)
- Max L/fill: 237 pb^{-1} (June)
- Weekly record: 1350 pb^{-1} (June)
- Longest stable beams: 22.8 h (July)
- Fastest turn-around between stable beams: 2.1 h (April)
- Best weekly data-taking efficiency: 92 h (55%) (July)

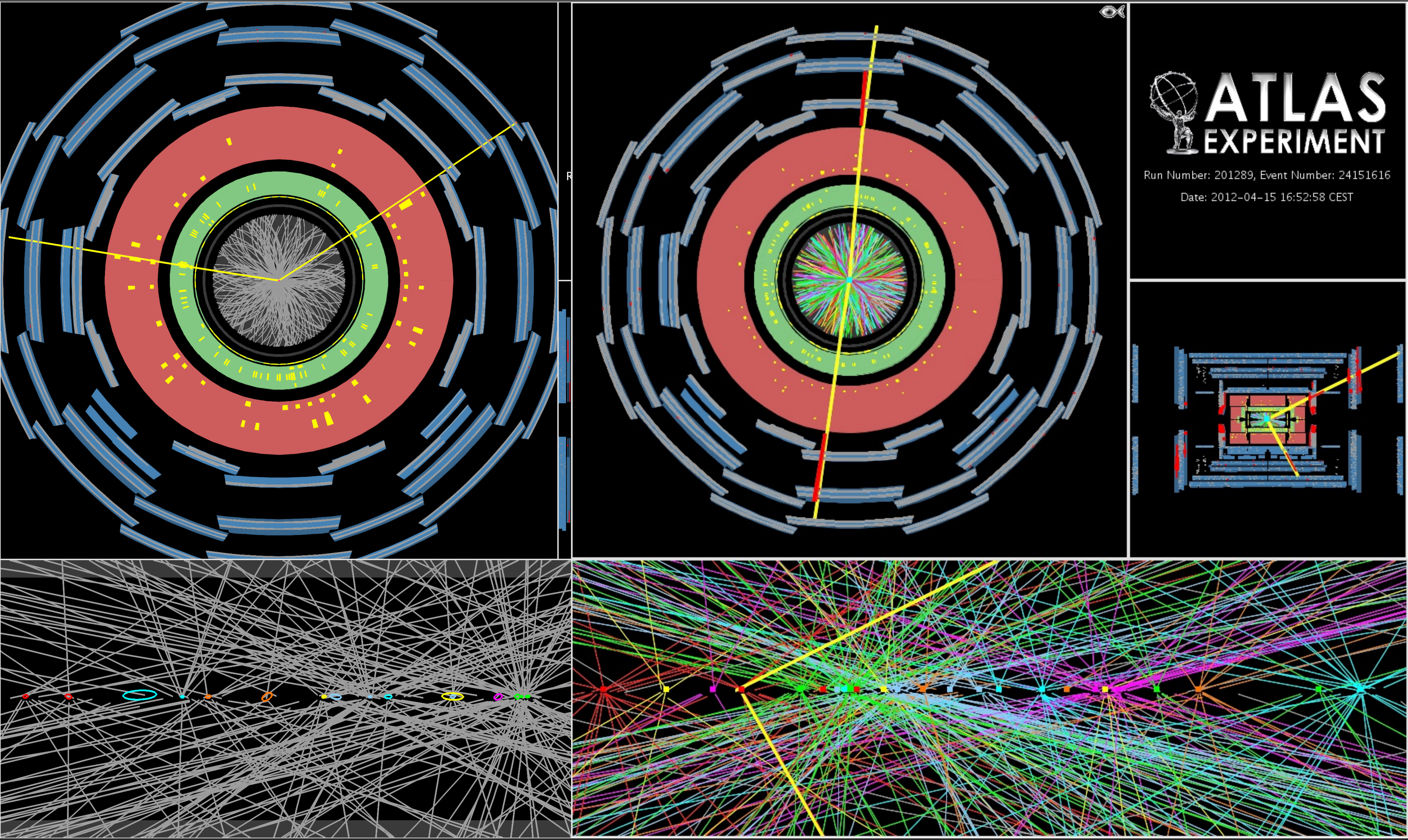
Luminosity: measured with forward detectors, calibrated with beam separation scans
Current uncertainty: 3.6%

pileup – not much difficulty in 2010-2011 TeV running





pileup – a difficulty in 2012 8 TeV running



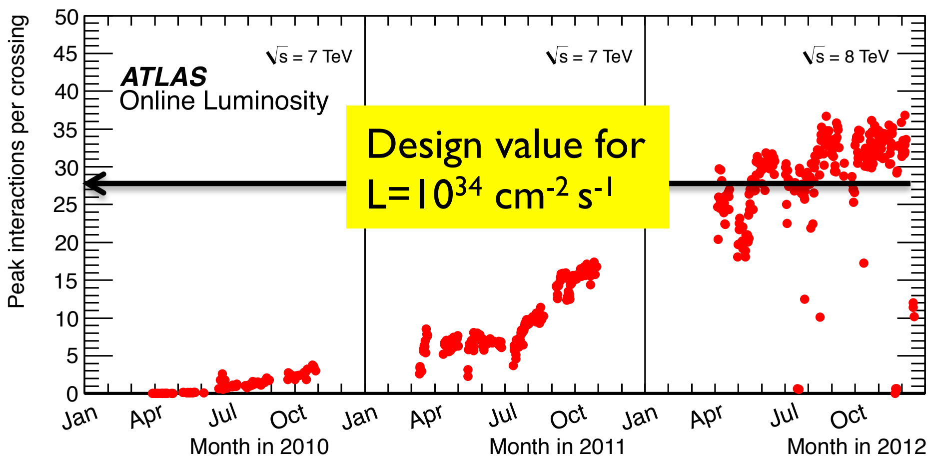
Z candidate events 2012 data, 20 (left) and 25 (right) reconstructed vertices

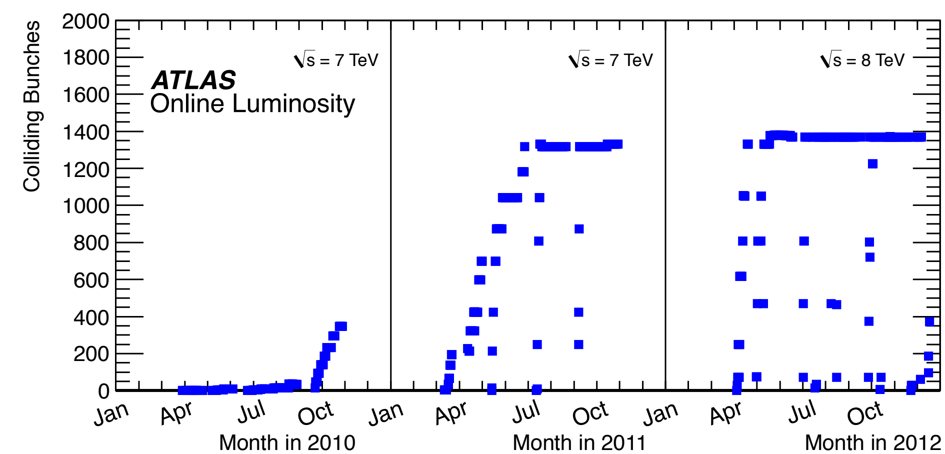
pileup

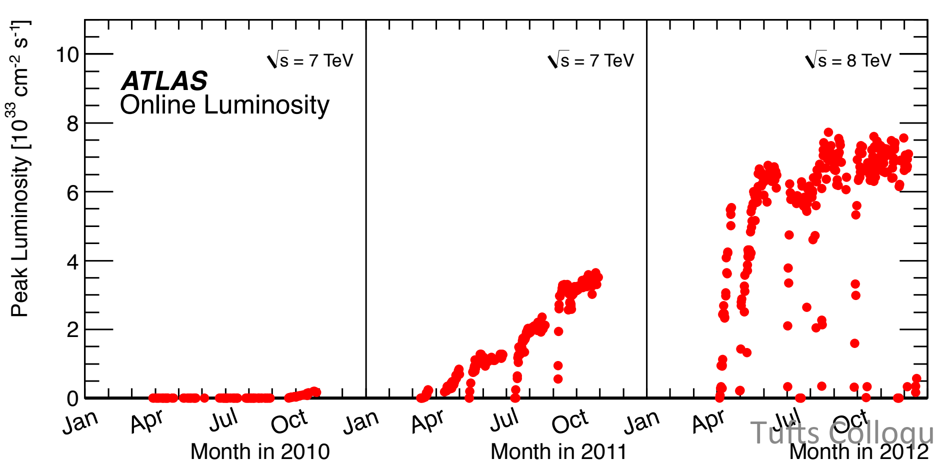
Running with 50 ns bunch spacing (rather than 25 ns) results in 2x larger pile-up for the same luminosity – lots of effort devoted to prepare for 2012 running - trigger and off-line algorithms which are pile-up "robust" needed to be developed. In general:

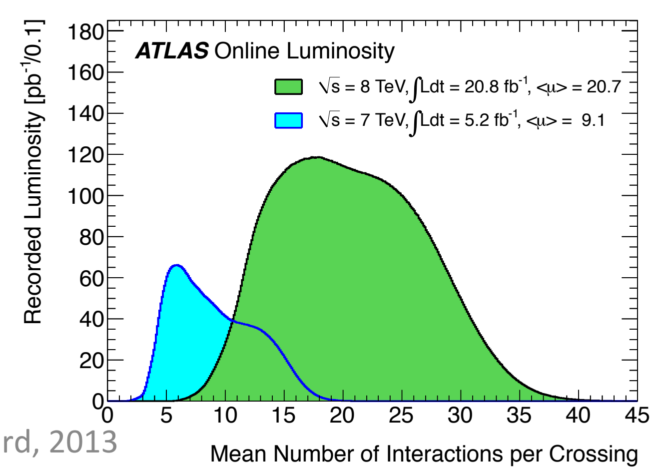
- sizable impact on jets, E_T^{miss} and tau reconstruction as well as on trigger rates and computing,
- no significant impact on tracking, muons, electrons and photons

Improved modeling of in-time and out-of-time pile-up in MC simulations
Computing challenges due to 2x higher trigger rates and large event sizes (10-50 sec/event for $\mu = 5-50$)

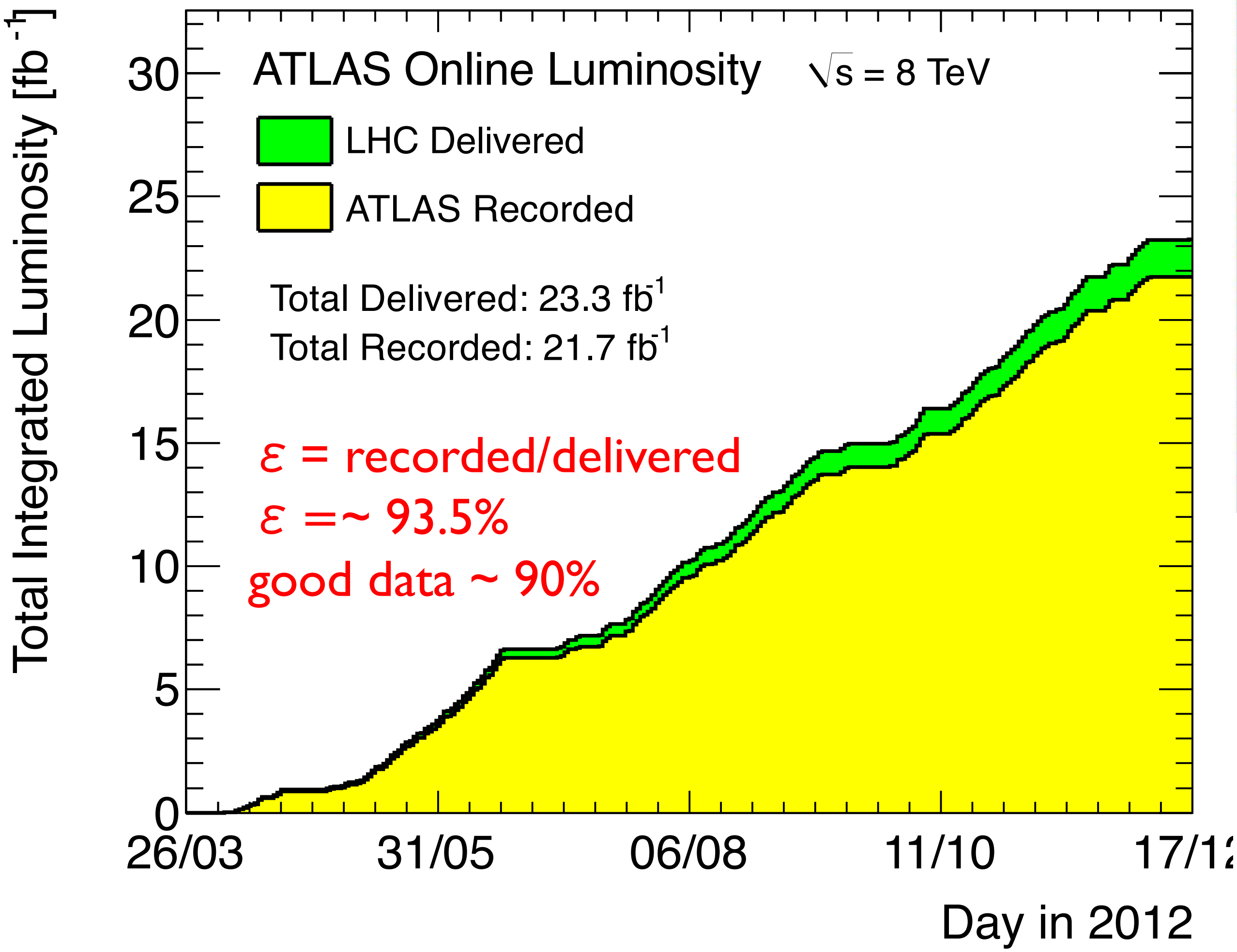








detector operation efficiency, data quality



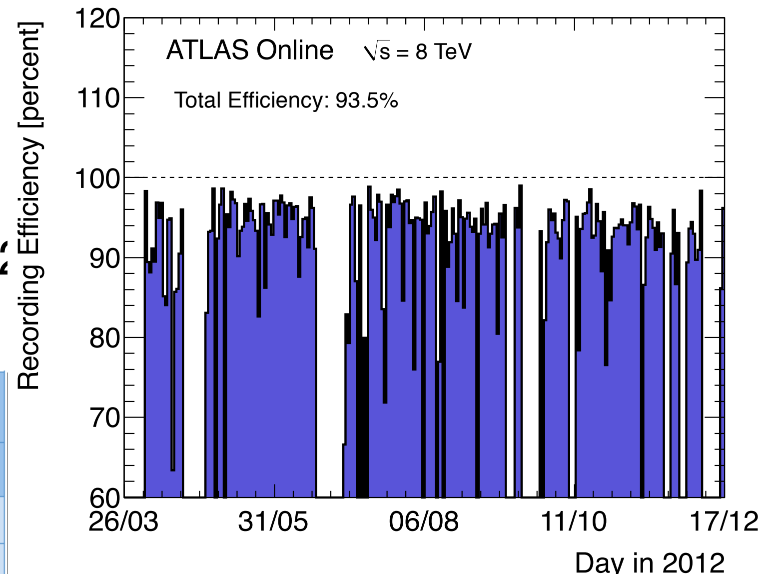
ε = recorded/delivered

ε =~ 93.5%

good data ~ 90%

Subdetector	Number of Channels	Approximate Operational Fraction
Pixels	80 M	95.0%
SCT Silicon Strips	6.3 M	99.3%
TRT Transition Radiation Tracker	350 k	97.5%
LAr EM Calorimeter	170 k	99.9%
Tile calorimeter	9800	98.3%
Hadronic endcap LAr calorimeter	5600	99.6%
Forward LAr calorimeter	3500	99.8%
LVL1 Calo trigger	7160	100%
LVL1 Muon RPC trigger	370 k	100%
LVL1 Muon TGC trigger	320 k	100%
MDT Muon Drift Tubes	350 k	99.7%
CSC Cathode Strip Chambers	31 k	96.0%
RPC Barrel Muon Chambers	370 k	97.1%
TGC Endcap Muon Chambers	320 k	98.2%

$\geq$ 95% for all systems



ATLAS p-p run: April-Sept. 2012

Inner Tracker			Calorimeters		Muon Spectrometer				Magnets	
Pixel	SCT	TRT	LAr	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
100	99.3	99.5	97.0	99.6	99.9	99.8	99.9	99.9	99.7	99.2

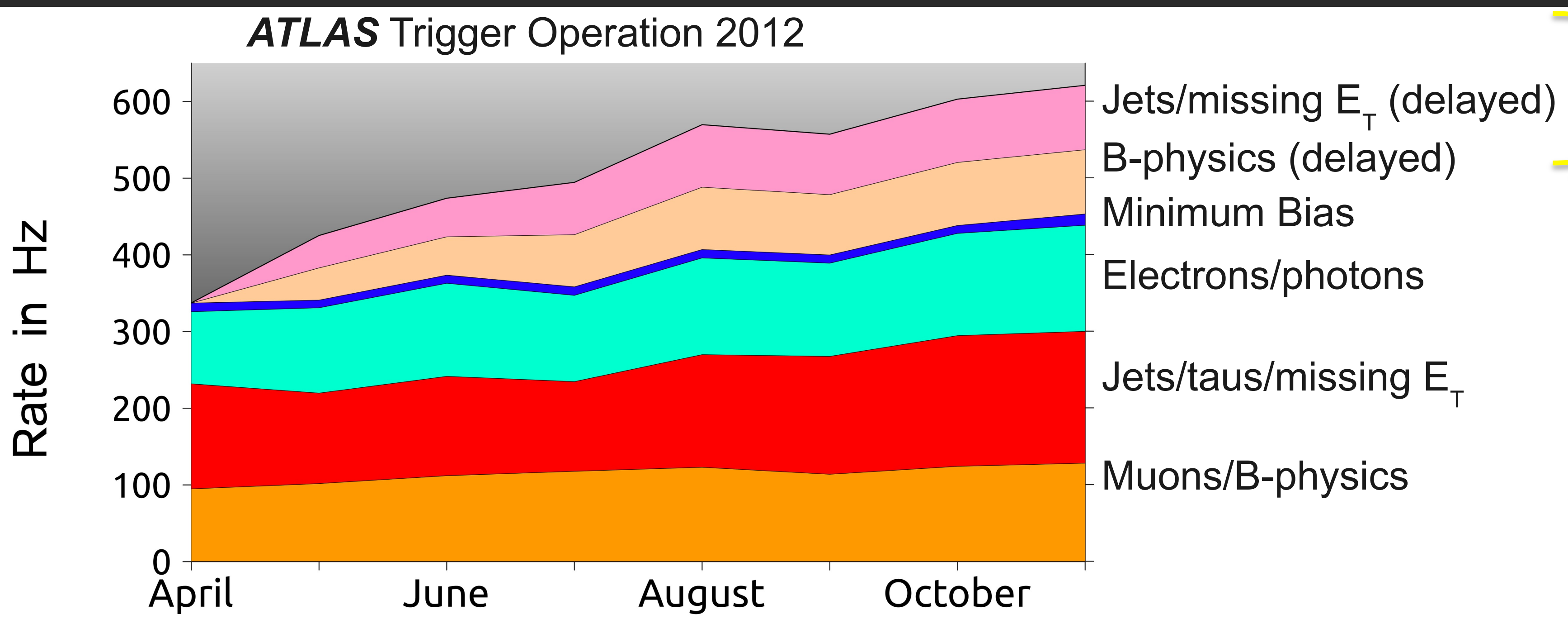
All good for physics: 93.7%

Luminosity weighted relative detector uptime and good quality data delivery during 2012 stable beams in pp collisions at $\sqrt{s}$=8 TeV between April 4th and September 17th (in %) – corresponding to 14.0 fb^{-1} of recorded data. The inefficiencies in the LAr calorimeter will partially be recovered in the future.

trigger

Baseline menu designed for $L = 8 \times 10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ and mostly unchanged during 2012 run

Average trigger table during Stable Beams:



Delayed reconstruction
[0.8 B events so far]

Prompt Tier-0 reconstruction
[2.4 B events so far]

Average rate of 400 Hz over 2012 run for prompt trigger streams
(~1700 stable beam hours)

(from A. Hoecker slides – ATLAS Status Report – LHCC, Dec 5, 2012

ATLAS – MAIN RESULTS

- precision measurements and tests of Standard Model

  QCD studies……

  WW, WZ, ZZ, Wγ, Zγ, $\gamma\gamma$ …. tt, single top

  most important background to most
  Higgs and new physics searches

  WELL UNDERWAY…

- searches for physics "BEYOND the STANDARD MODEL"

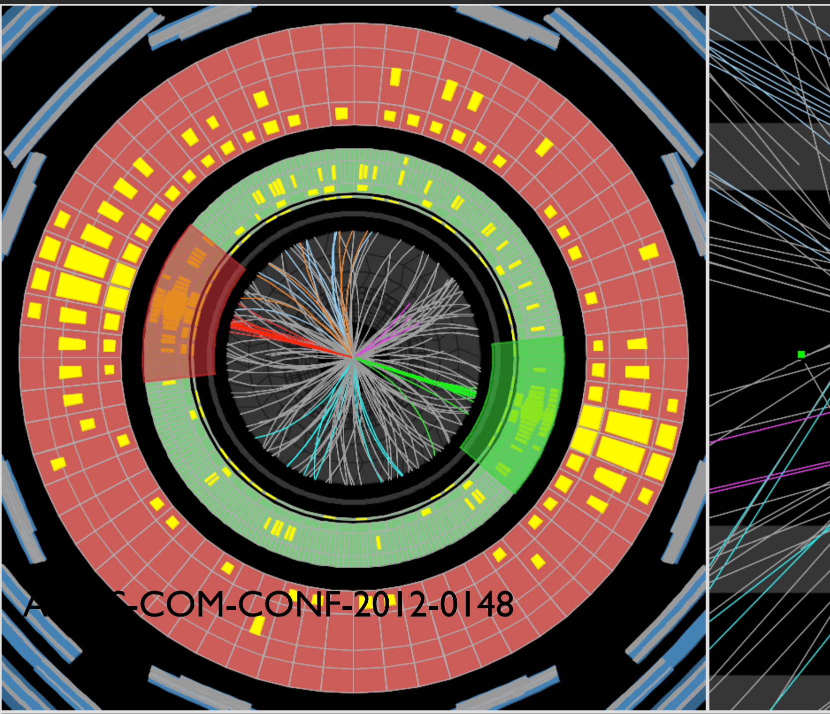
  SO FAR, NOTHING:(

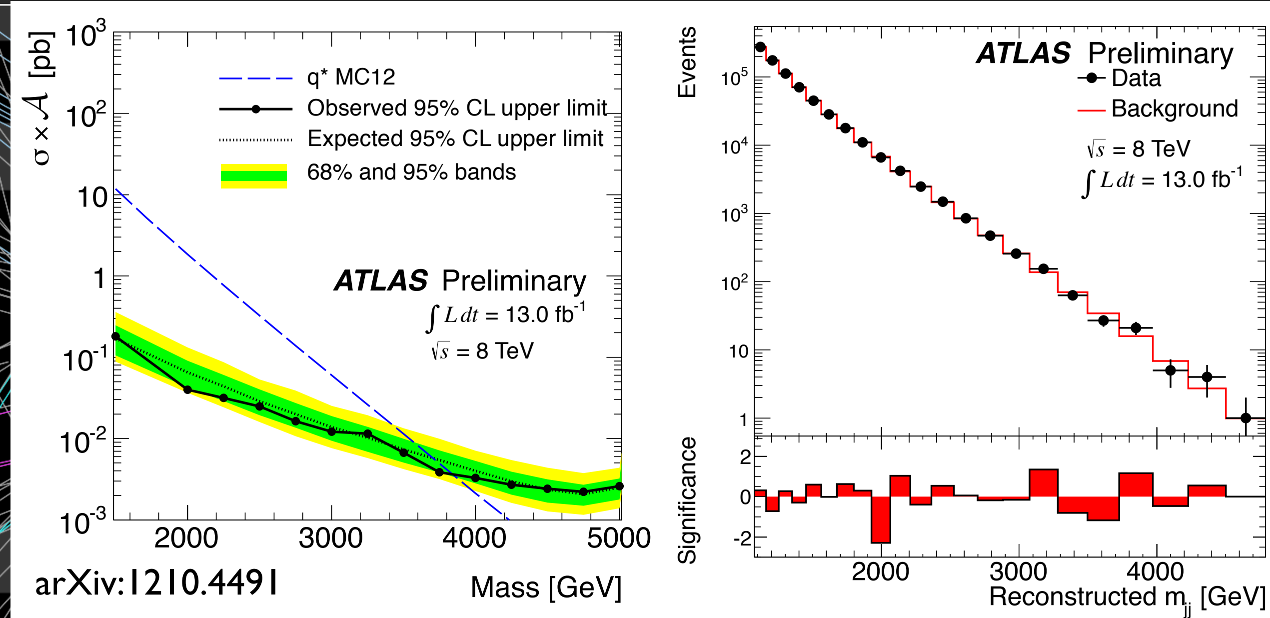
- Higgs search: new boson at ~125 GeV !!

  just one? two? spin-parity? Is this the MSM boson?

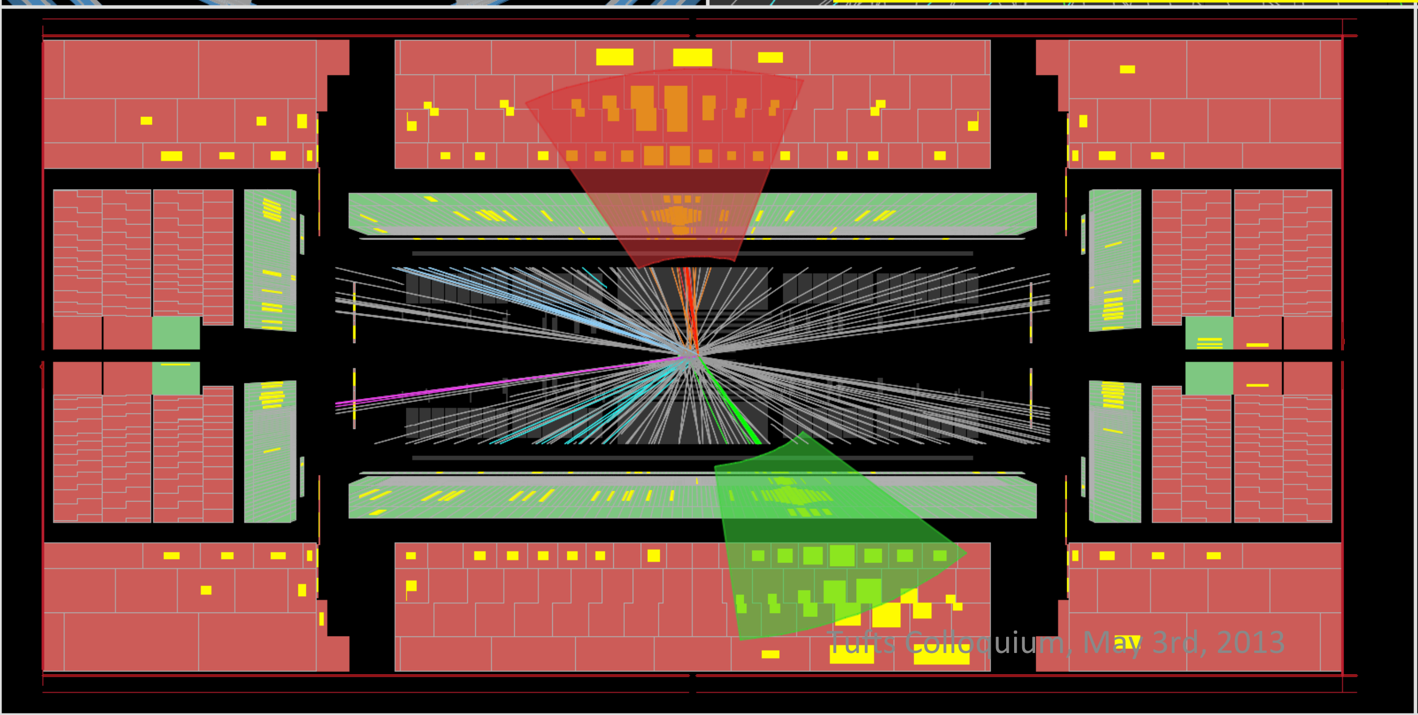
QCD jet studies

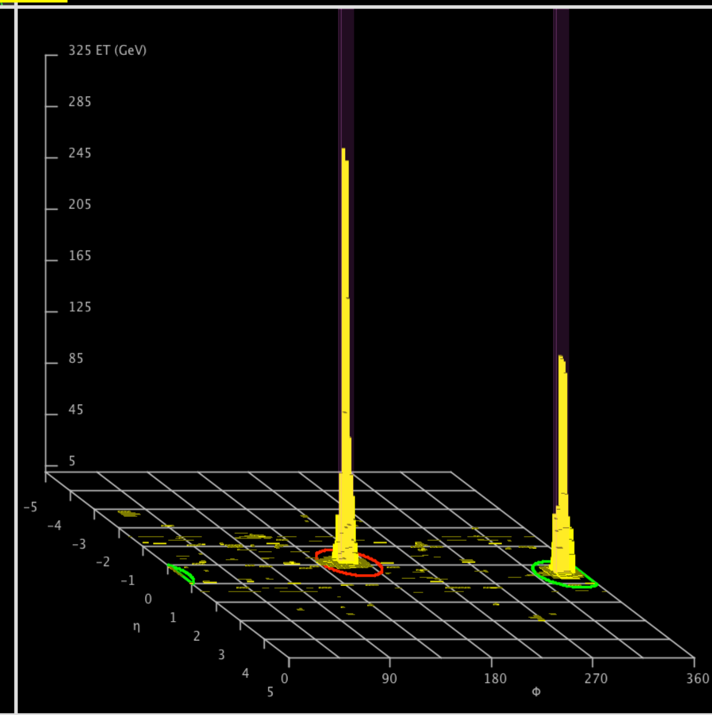
QCD: two central high-p_T jets with an invariant mass of 4.69 TeV (2012 – 8 TeV running)





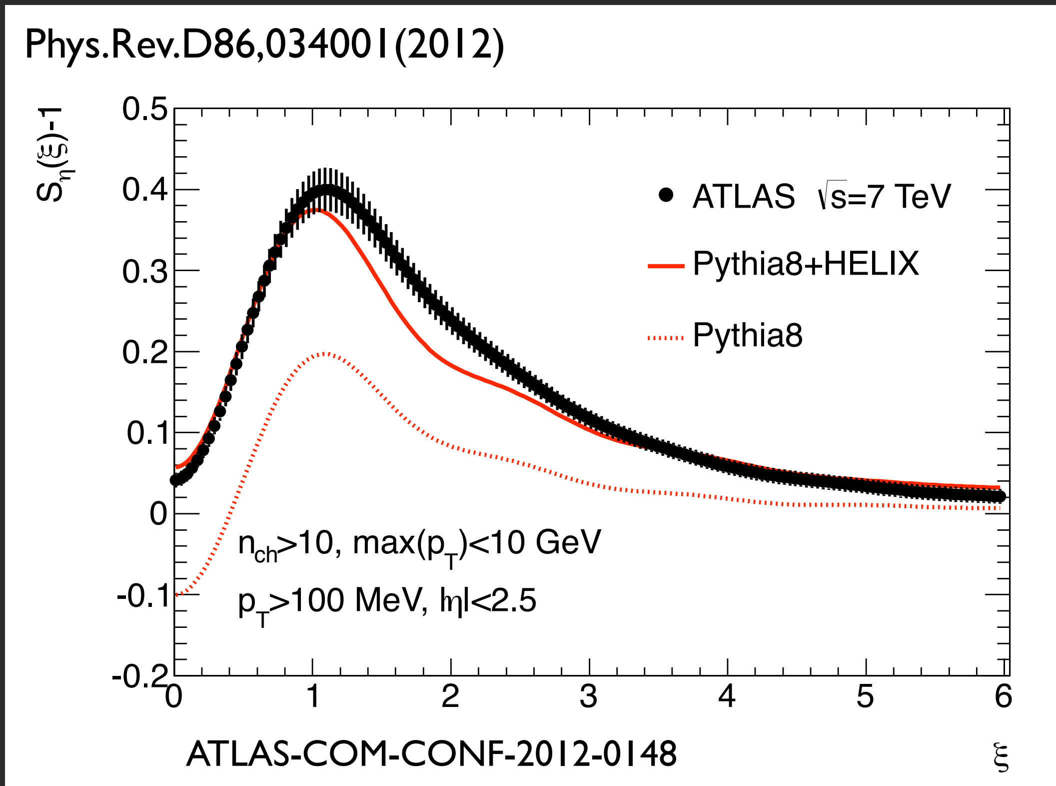
M(q*) > 3.84 TeV @95 CL

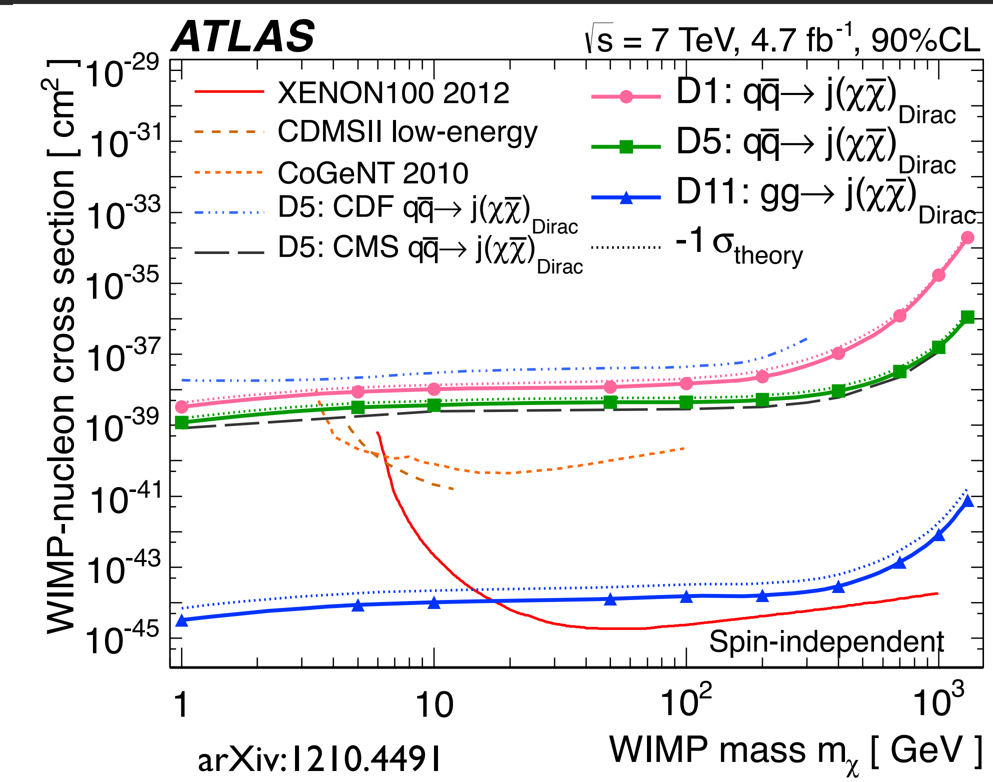




QCD track and jet studies

Helix structure of the fragmentation string – Dr Sarka Todorova





Evidence for helix structure of QCD string – should lead to improved description of fragmentation models – will benefit ALL analyses

Understanding of QCD effects is essential for all precision measurements

Monojet analysis – limits on WIMP
prof. Beauchemin

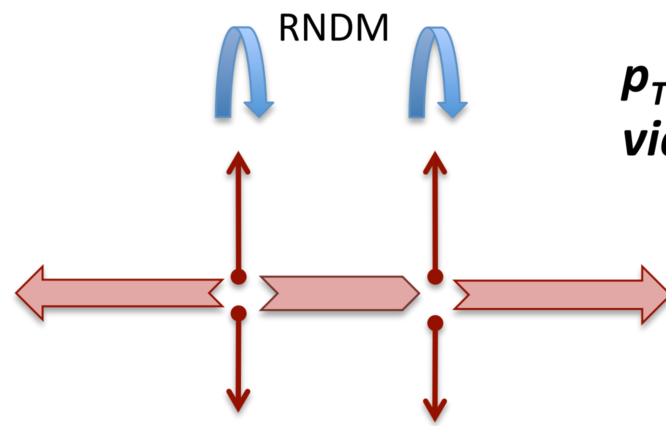
The idea of helix string [first proposed in JHEP09(1998)14.]

Bo Anderson et al.:"Is there a screwiness at the end of parton cascade ?"

Replace the standard Lund string

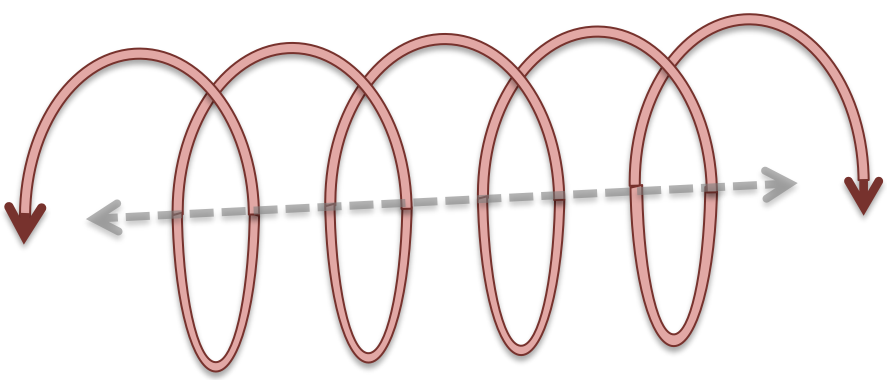
string tension $\kappa \approx 1$ GeV/fm
(longitudinal)

+



p_T generation via tunneling effect

with a helix-like ordered gluon chain & suppress p_T in the tunneling :



transverse momentum of a direct hadron ENTIRELY constrained by the spiral structure of the QCD string (2 degrees of freedom removed from the modelling)

top studies

Top is heaviest particle in the SM, and it may be playing a special role in EW symmetry breaking.

Most physics beyond the SM will show up as excess of events above the SM including 6 quarks –

TOP PRODUCTION HAS TO BE UNDERSTOOD REALLY WELL AS IT IS THE MOST IMPORTANT BACKGROUND FOR MANY OF "NEW PHYSICS" SIGNATURES

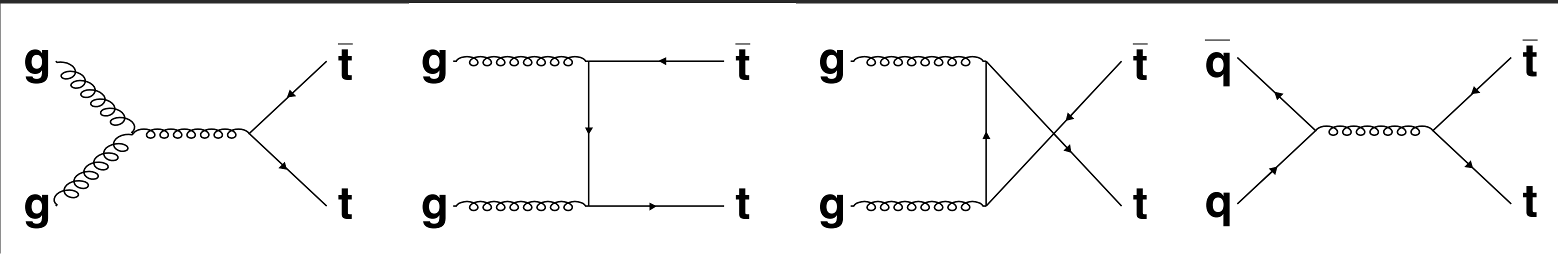
Top studies may be the best testing ground for NLO and NNLO calculations

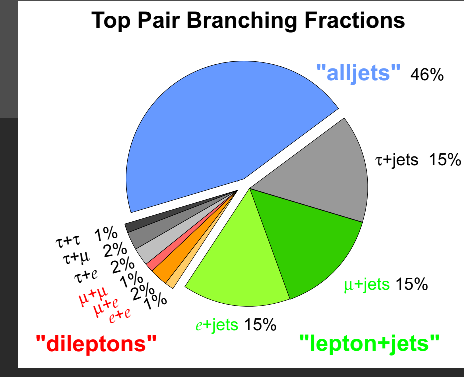
(recently lots of progress - Czakon and Mitov finished qq and qg NNLO -arXiv:1210.6832, gg – soon, may explain the ttbar charge asymmetry puzzle)

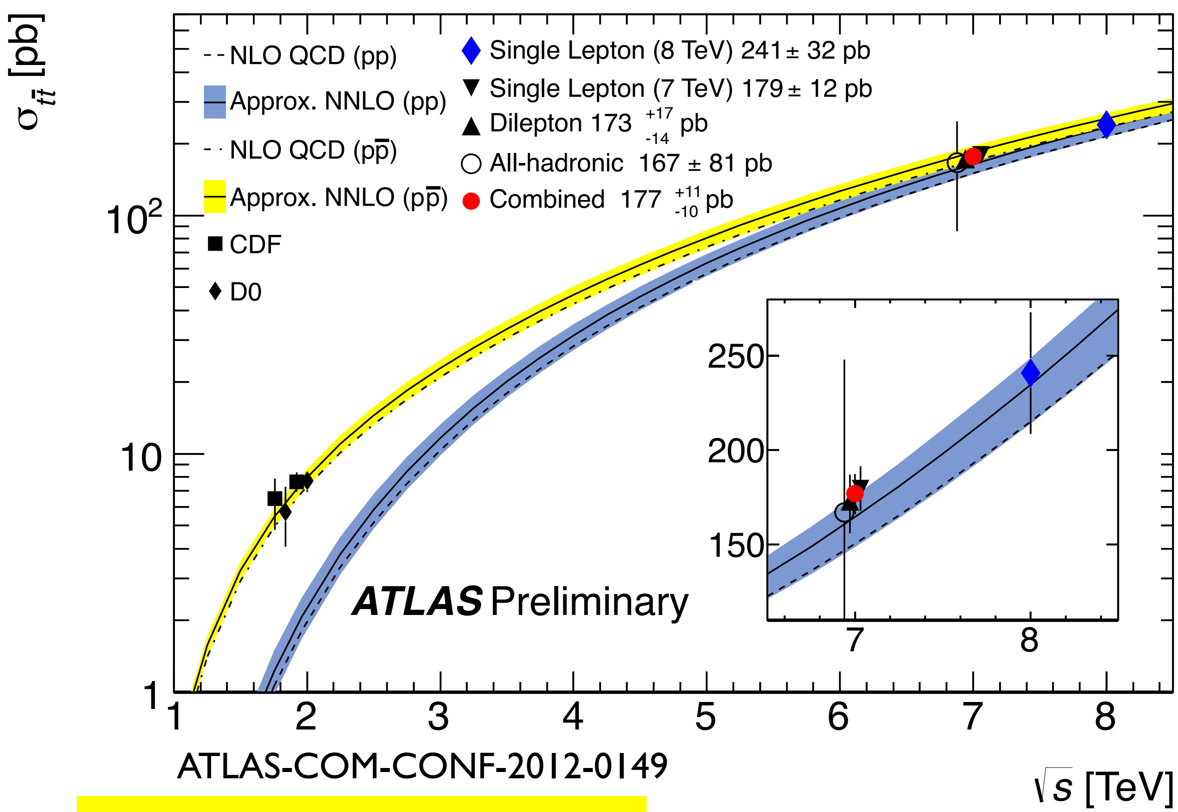
Samuel Hamilton, Jeff Wetter, Benjamin Whitehouse, Krzysztof Sliwa

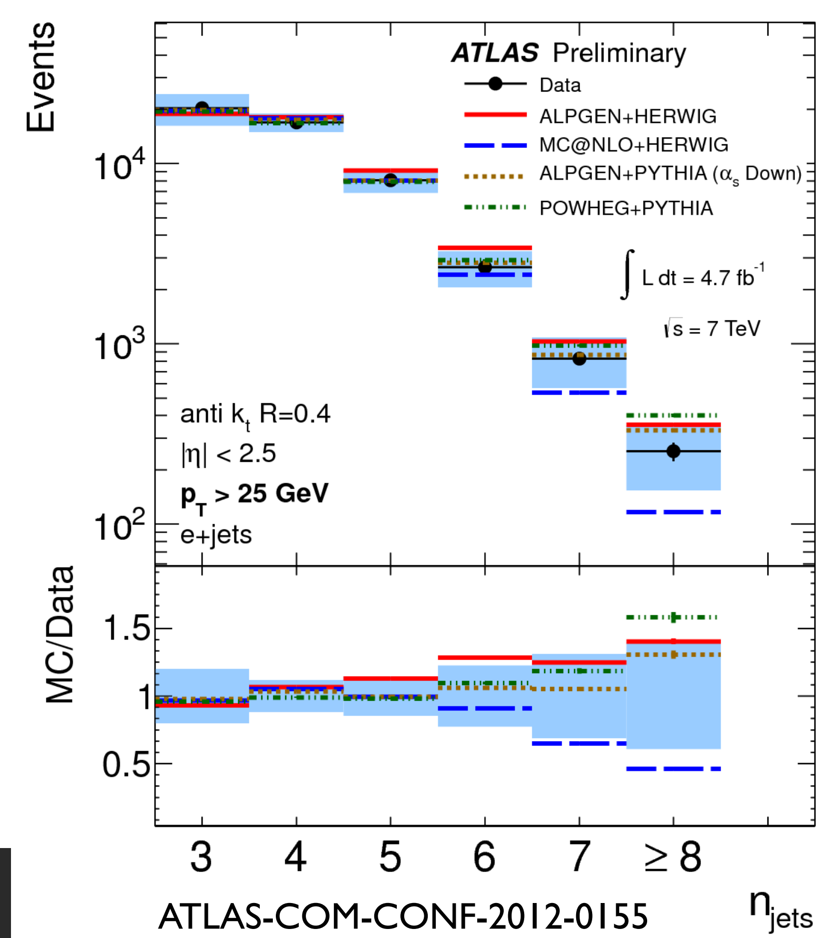
Top polarization, top cross section with a new multidimensional analysis method - event classifier based on support vector machines

top studies







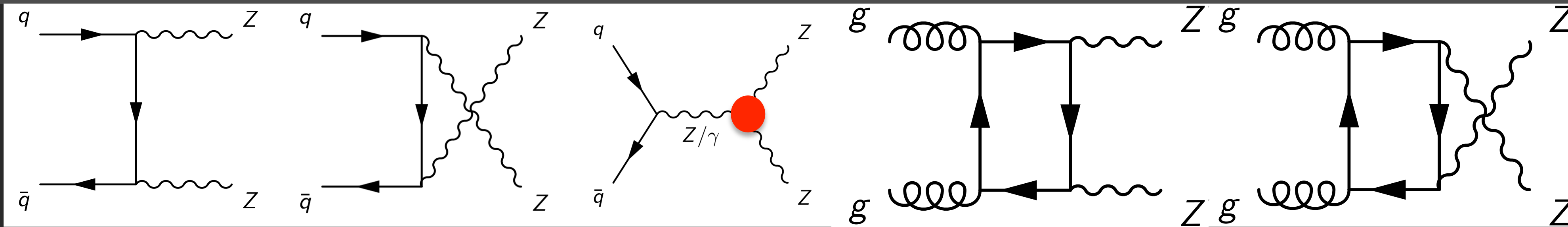


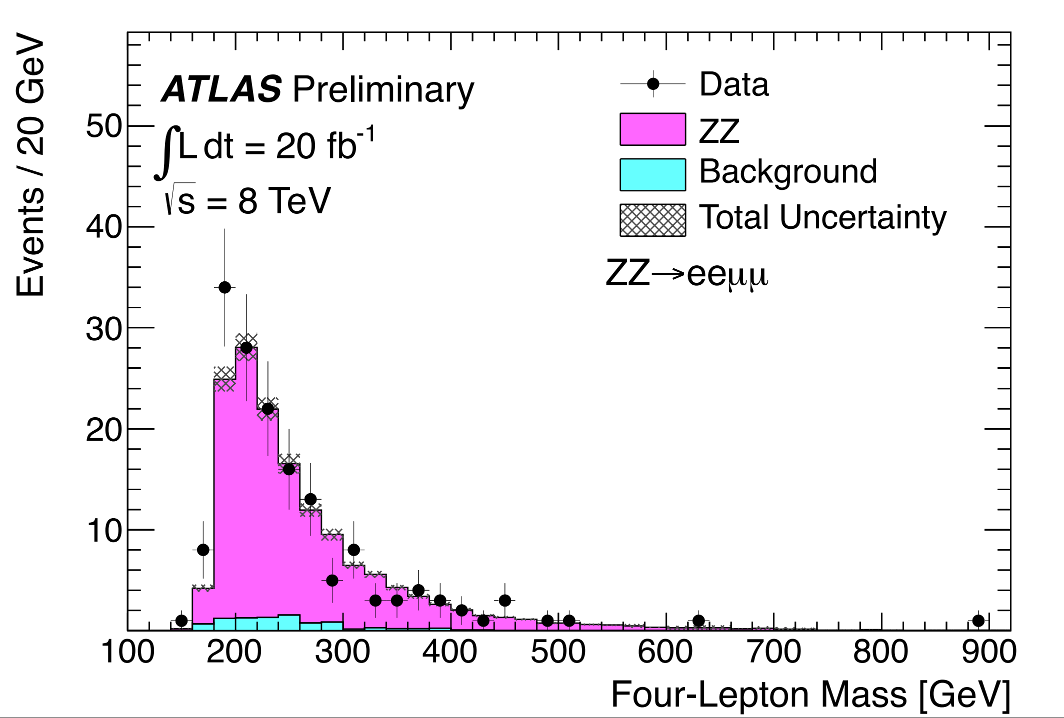
7 TeV: σ =177+11-10 pb

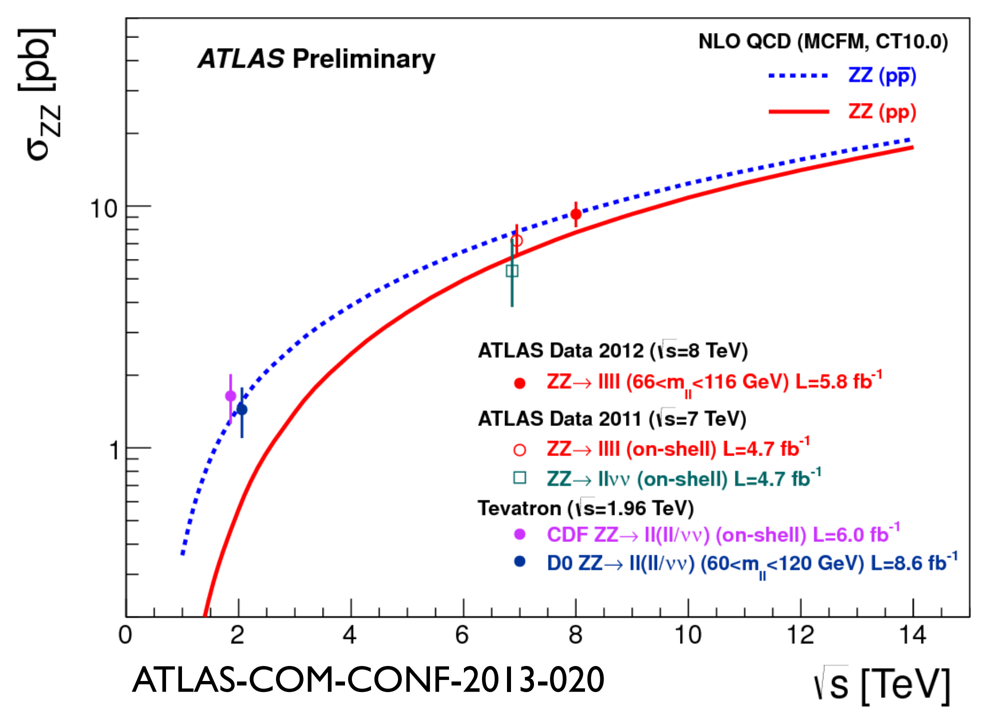
8 TeV: σ =241±32 pb

Top quark in addition to being of fundamental importance on their own, provide opportunity to test QCD calculations and improve tuning of MC – essential for all analyses

ZZ studies





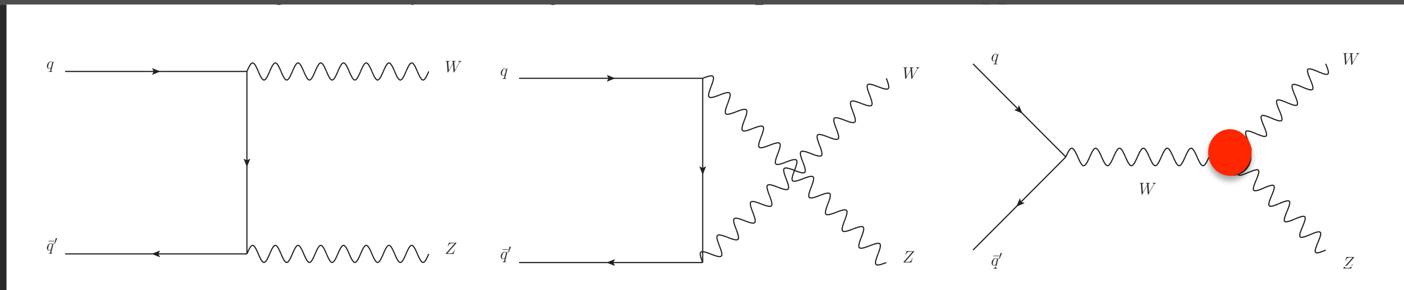


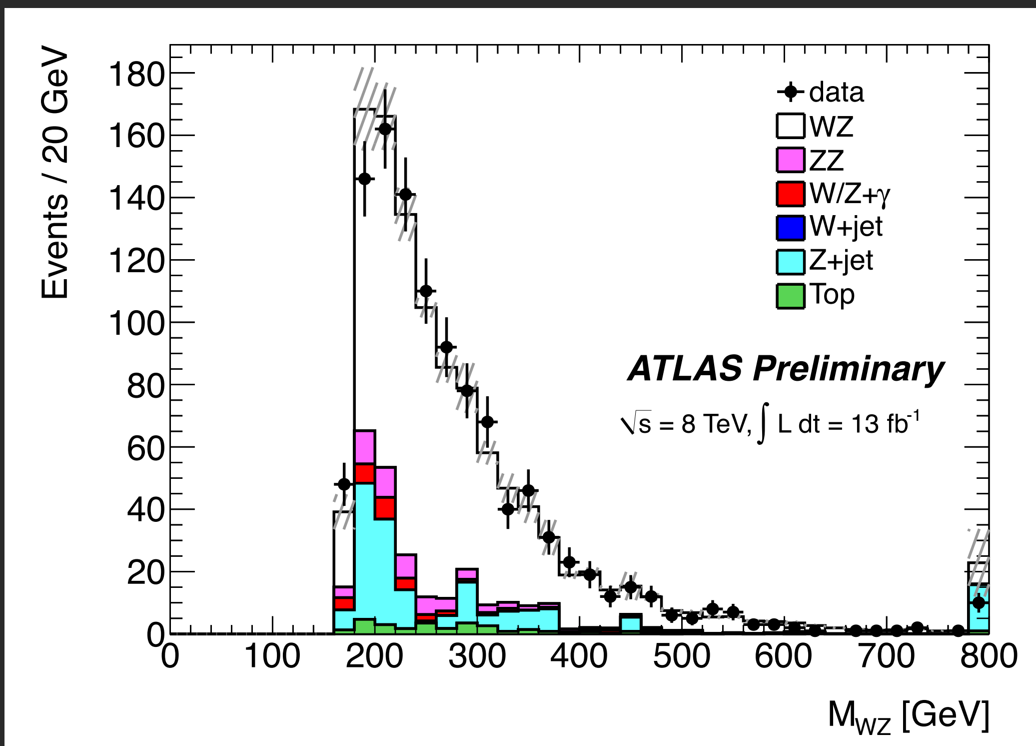
$\sigma(ZZ) = 7.1{+0.5}{-0.4}$ (stat) ± 0.3 (syst) ± 0.2 (lumi) pb

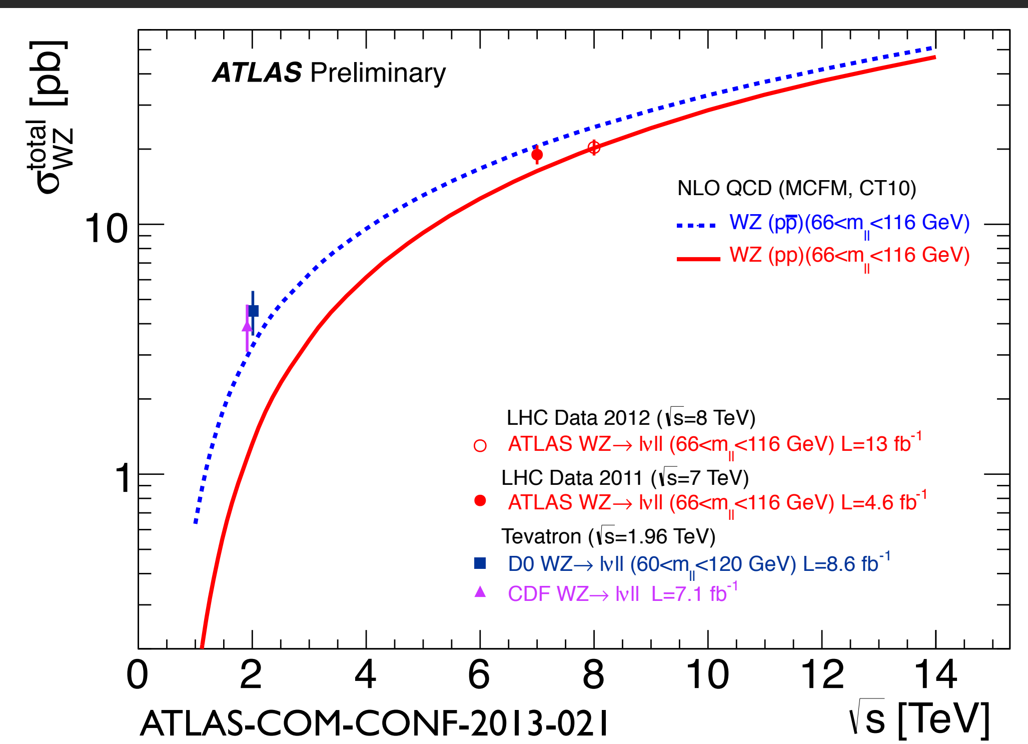
Tests of NLO SM calculations, good agreement.

Deviations could indicate physics beyond SM; neutral triple-gauge-couplings zero in SM

WZ studies





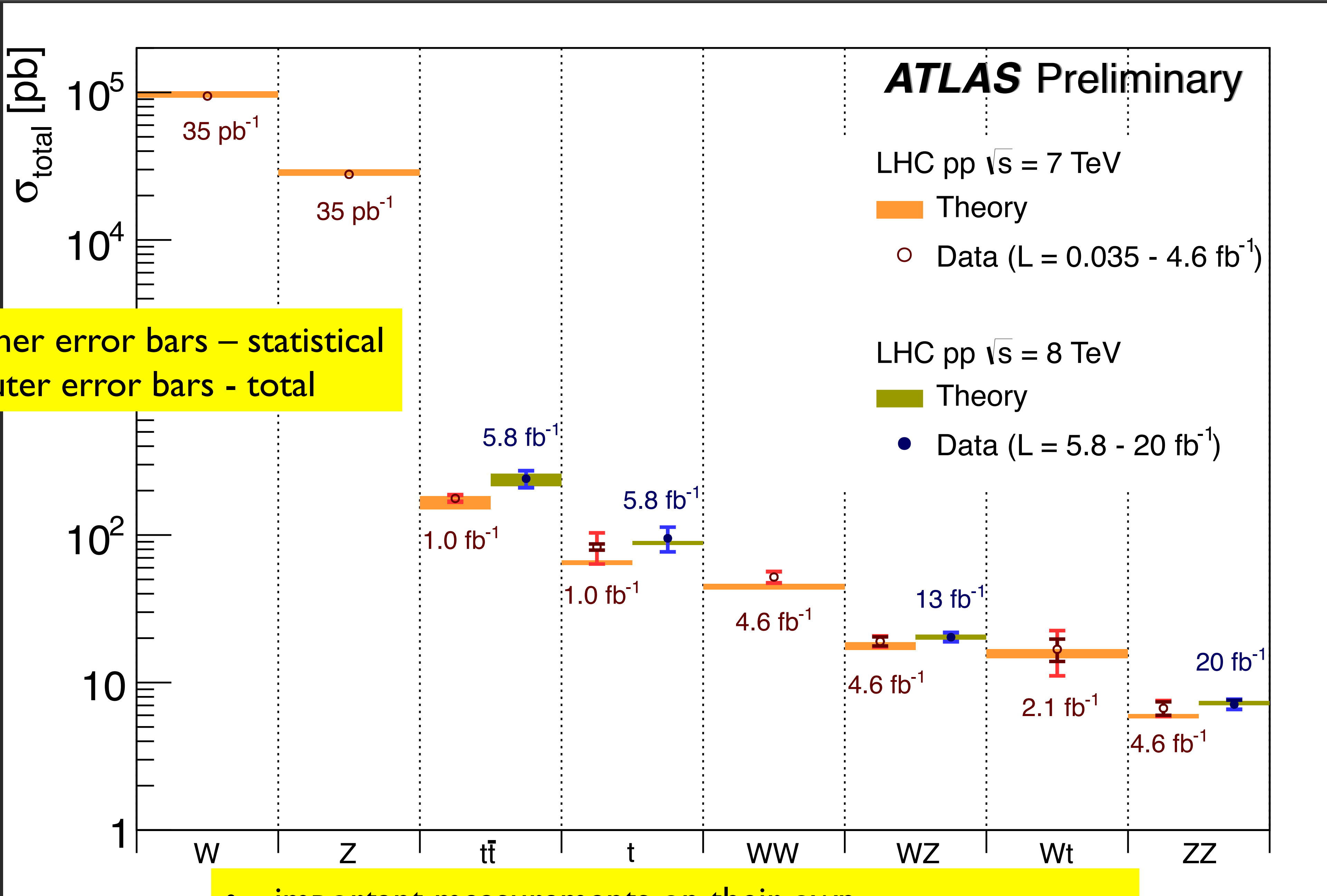


σ(WZ) =20.3+0.8-0.7(stat)+1.2-1.1(syst)+0.7-0.6(lumi)

Tests of NLO SM calculations, good agreement.

Deviations could indicate physics beyond SM; triple-gauge-couplings;

status of ATLAS electroweak and top measurements



inner error bars – statistical
outer error bars - total

- important measurements on their own
- but, most also irreducible background to Higgs searches

SUSY:

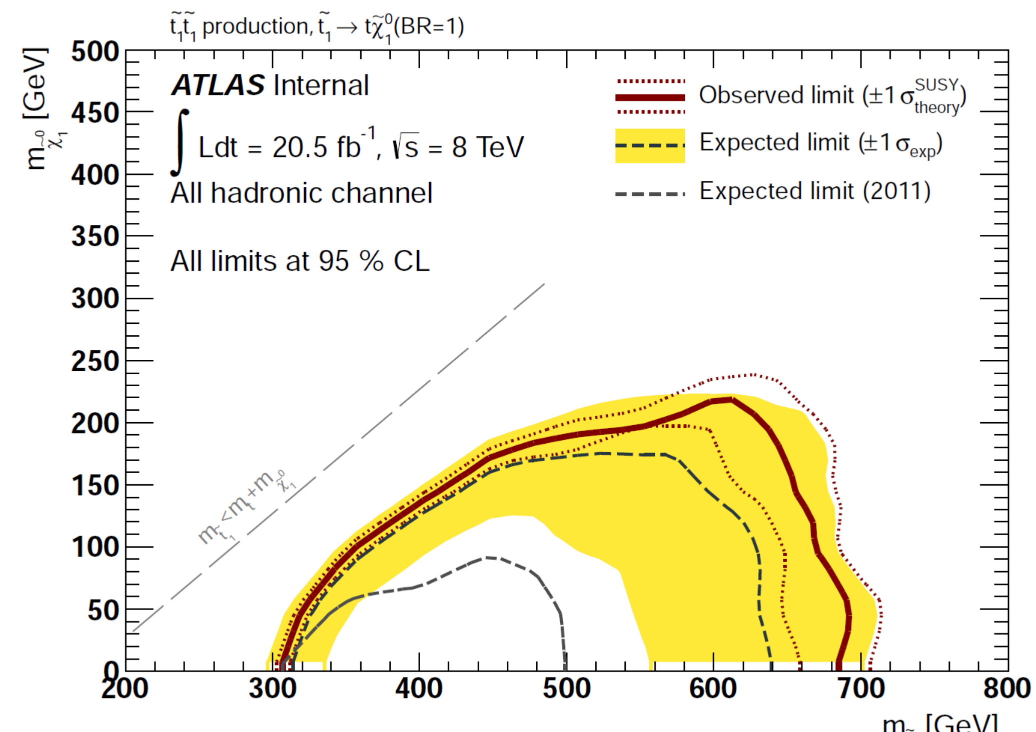
SUSY particles are expected to be produced strongly in pairs, and their decay chains invariably include a LSP, usually neutral. The typical signatures are final states with variable number of jets, also multi-leptons, same-sign leptons - almost always with large MET. Large mixing in 3rd generation of SUSY sfermions is expected, with at least one of the top squarks expected to be light.

The Minimal Supersymmetric SM is difficult to reconcile with M_H=125 GeV, as it predicts a smaller mass for its lightest neutral Higgs, h. Large part of MSSM parameter space is excluded.

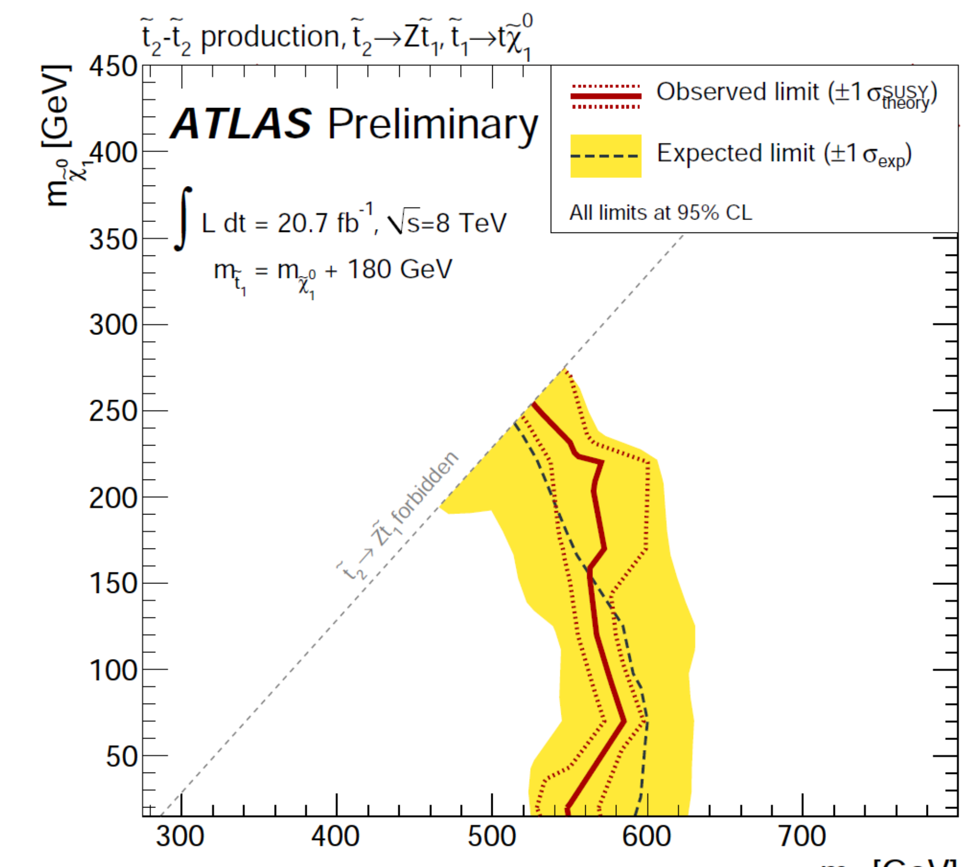
In the NMSSM, a singlet chiral superfield added to MSSM allows to alleviate the μ and the lightest Higgs mass (H_1) problem. The model has 7 physical Higgses (MSSM has 5).

Many searches for physics beyond SM look for SUSY particles.

SUSY: stop searches



ATLAS-COM-CONF-2013-024



ATLAS-COM-CONF-2013-025

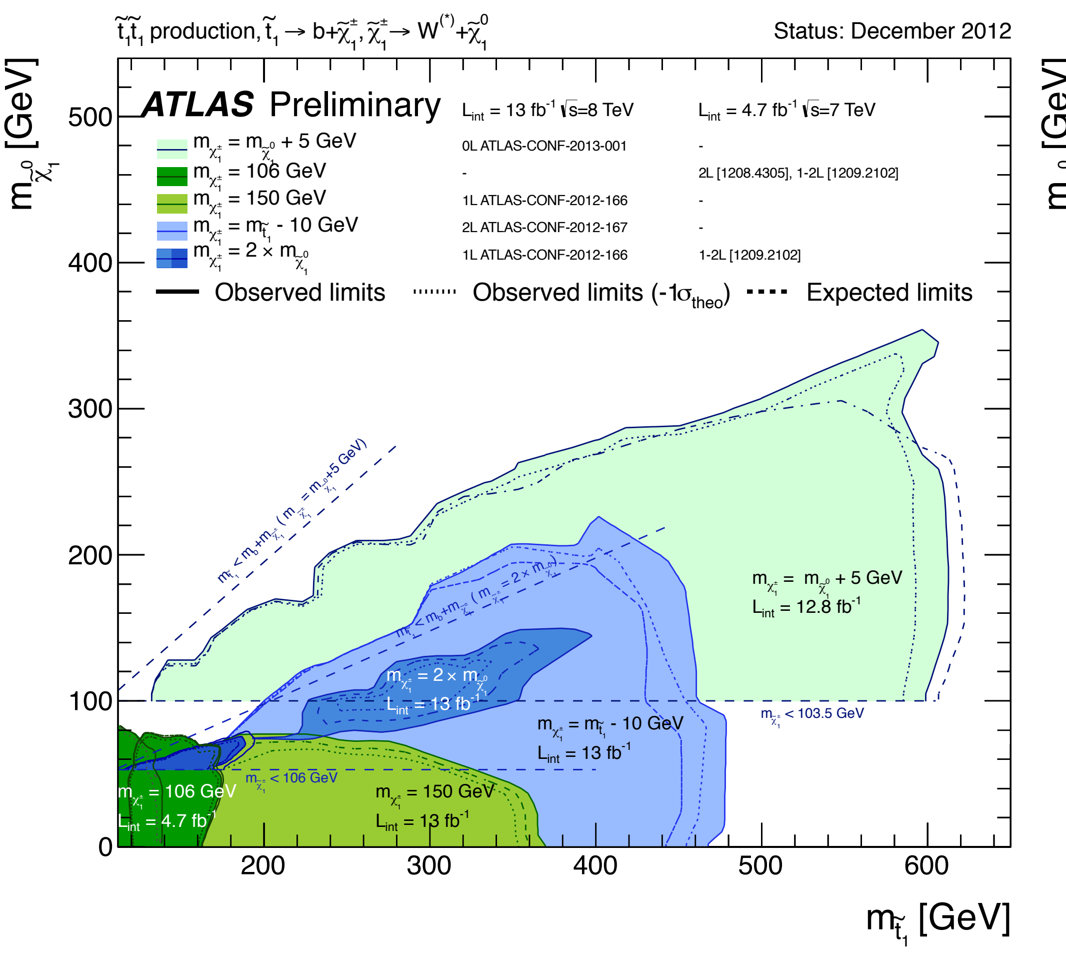
stop pair –> t+LSP+t+LSP(MET) final state (both top quark decay hadronically – jets)

320 GeV > M(stop) > 660 GeV for massless LSP

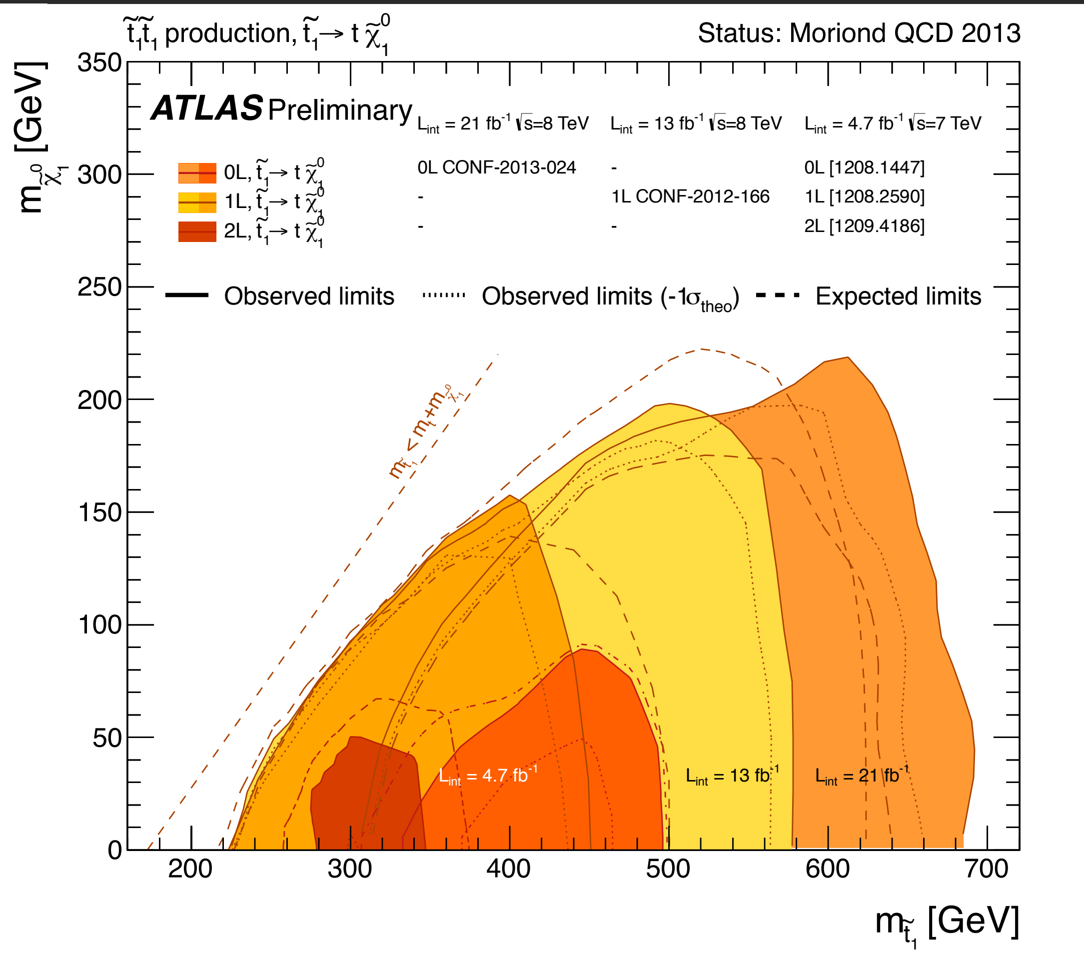
400 GeV > M(stop) > 620 GeV forM(LSP)=150GeV (95% CL)

stop pair –> Z+b+LSP(MET) final state (˜t2 –> Z˜t1 decay chain)

SUSY: stop searches



stop pair –> b+W*+LSP

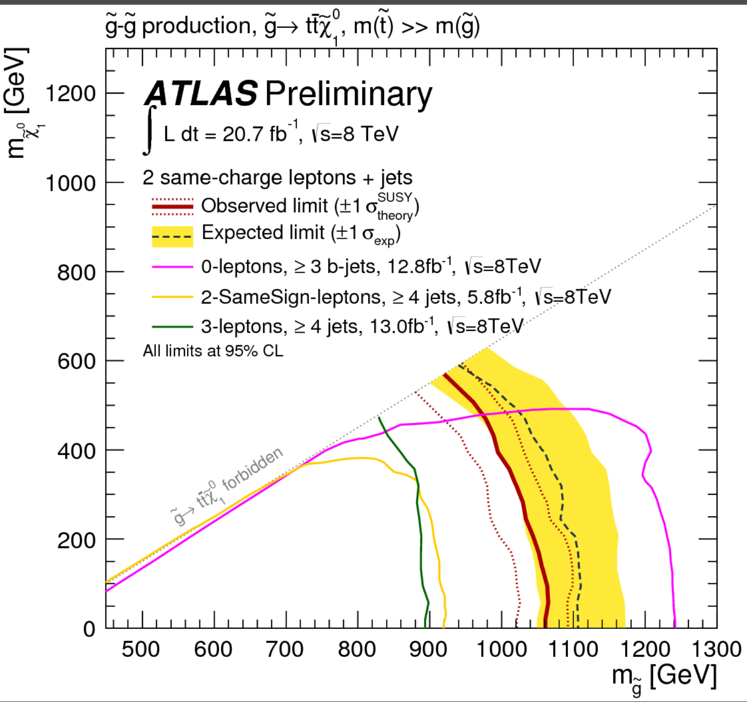


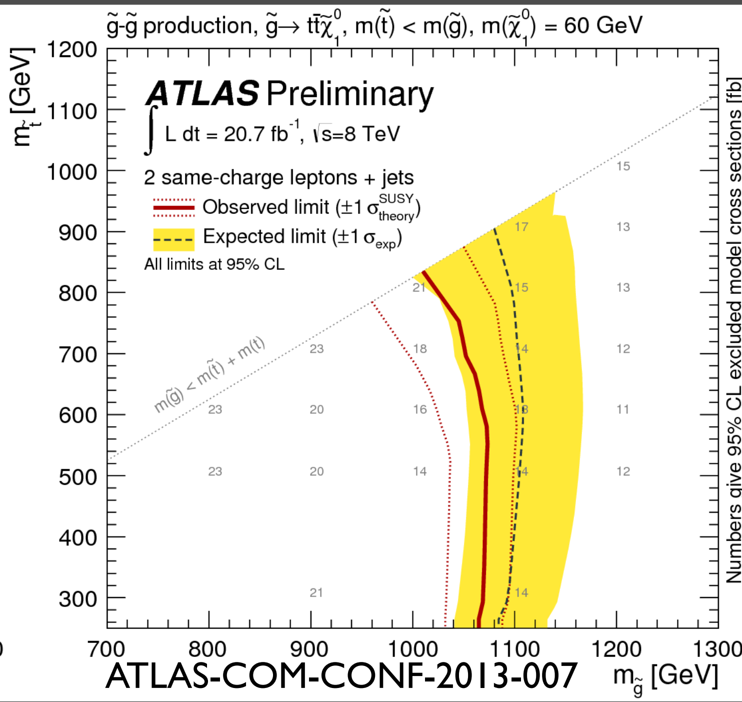
stop pair –> top+LSP

Exclusion limits at 95% CL are shown in the $\tilde{t}_1$ - $\tilde{\chi}^0_1$ mass plane.

These plots overlay contours belong to different stop decay channels, different sparticle mass hierarchies, and simplified decay scenarios – one should be careful when interpreting

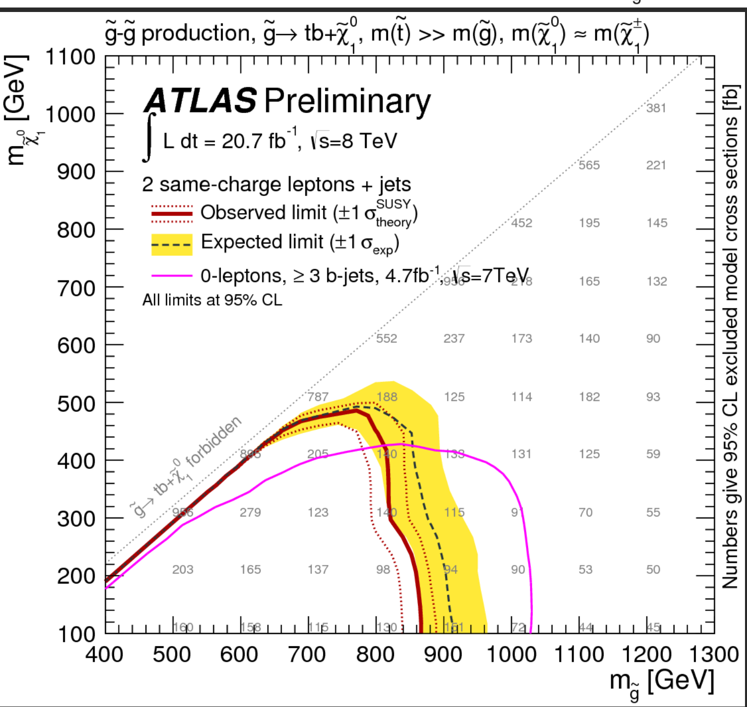
SUSY: stop searches

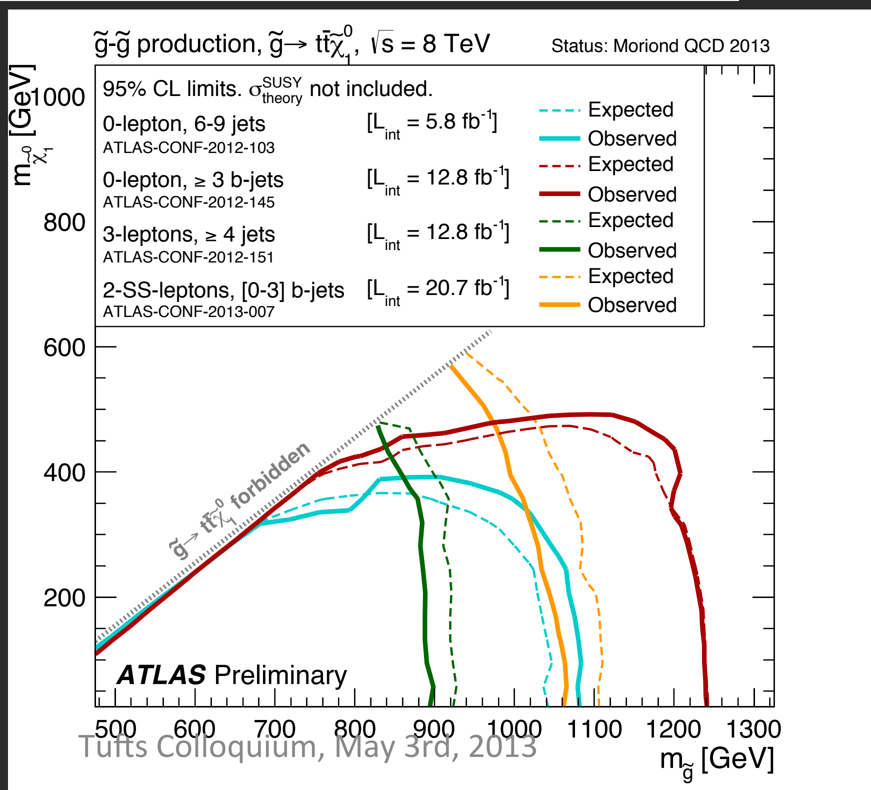




gluino mediated stop production:

same-sign dileptons, jets, varying number of b-jets

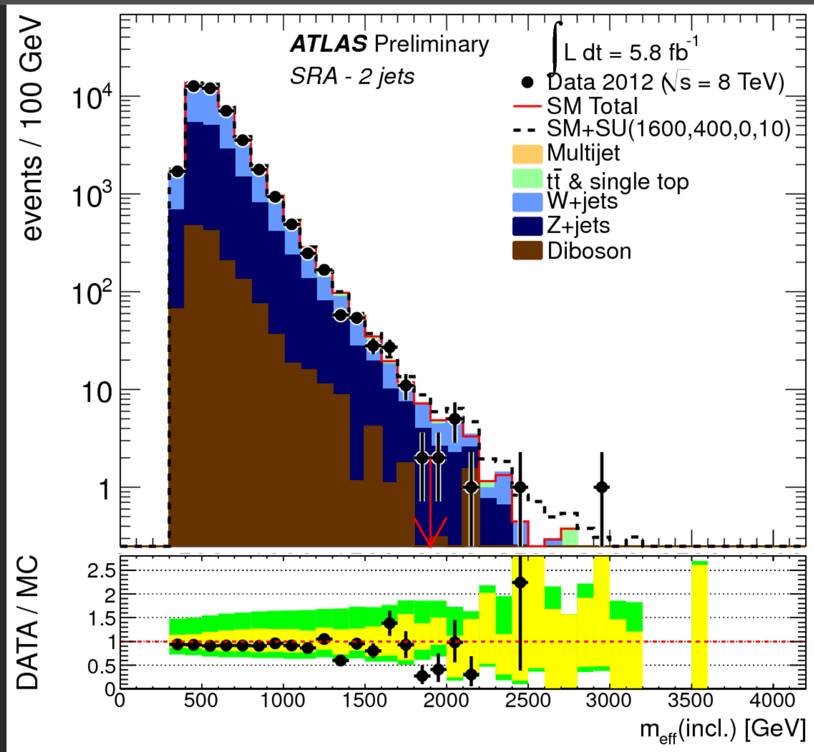


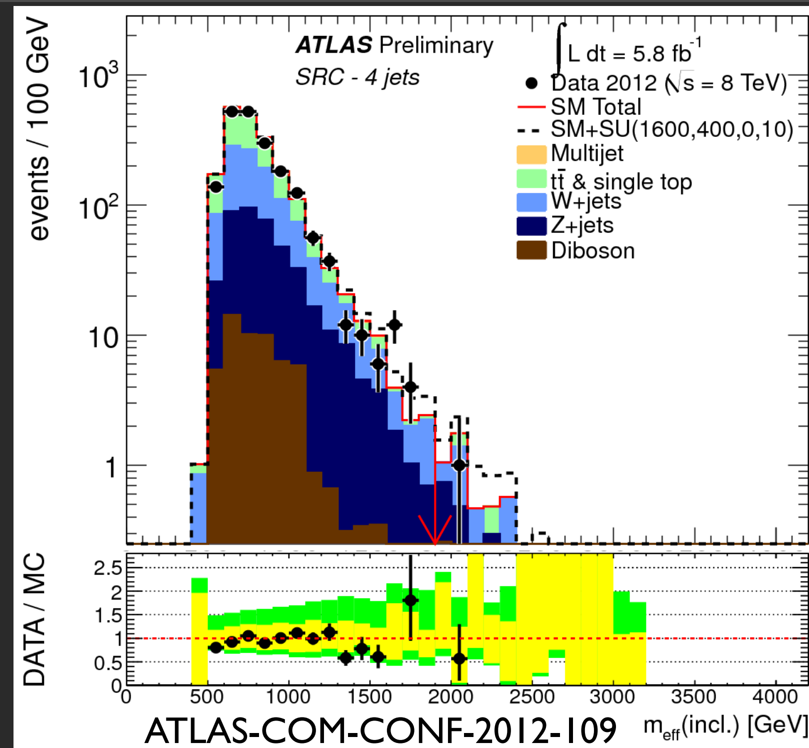


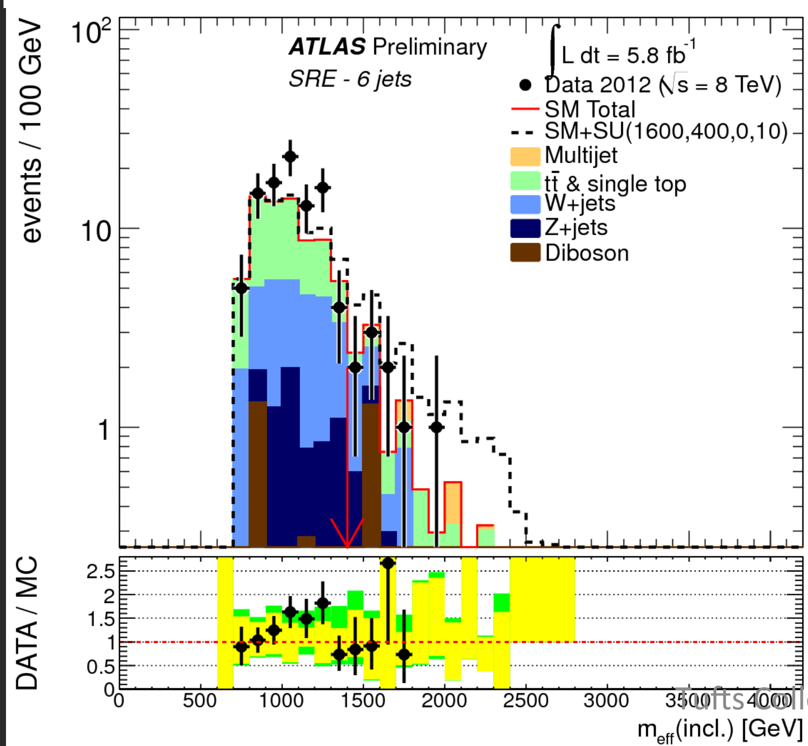
summary plot: gluino mediated stop production

0 leptons
3 leptons
2 same-sign leptons

SUSY searches –squarks and gluinos







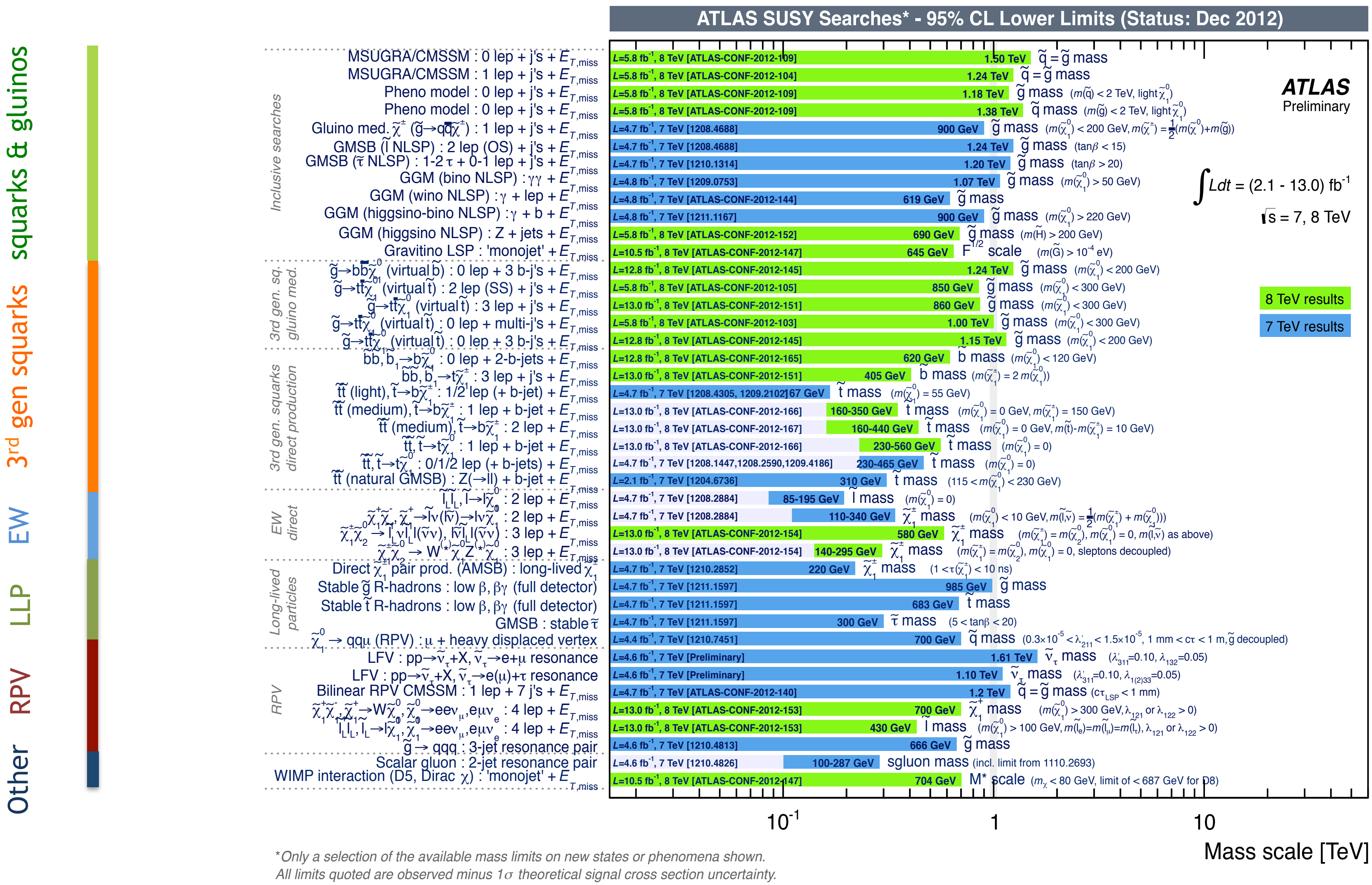
squarks and gluinos, strongly produced
1st and 2nd generation

2 jets + MET
4 jets + MET
6 jets + MET

model dependent limits (~TeV scale)

SUSY searches

"natural" SUSY, R-parity violating, and searches for long-lived particles

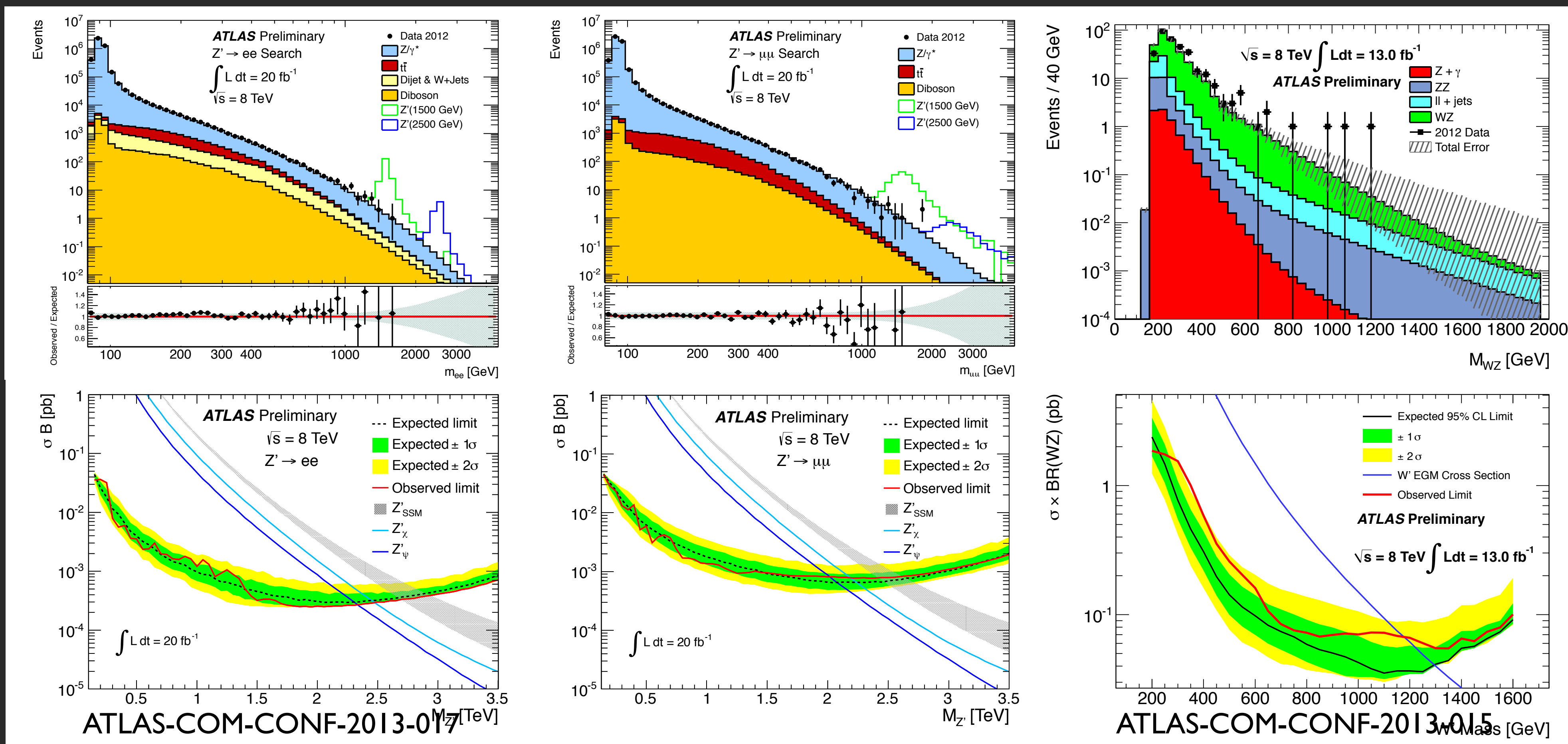


ATLAS-COM-CONF-2013-026

ATLAS-COM-CONF-2013-028

exotic: ee, μμ, WZ

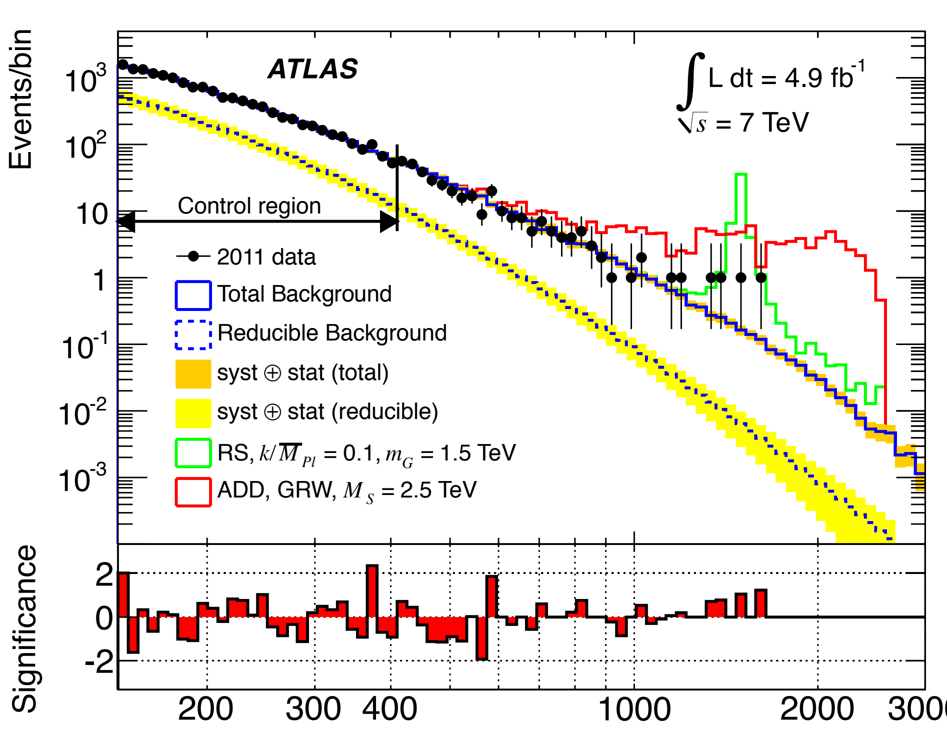
Searched for resonanses (new bosons?) in invariant mass spectra of dileptons, WZ



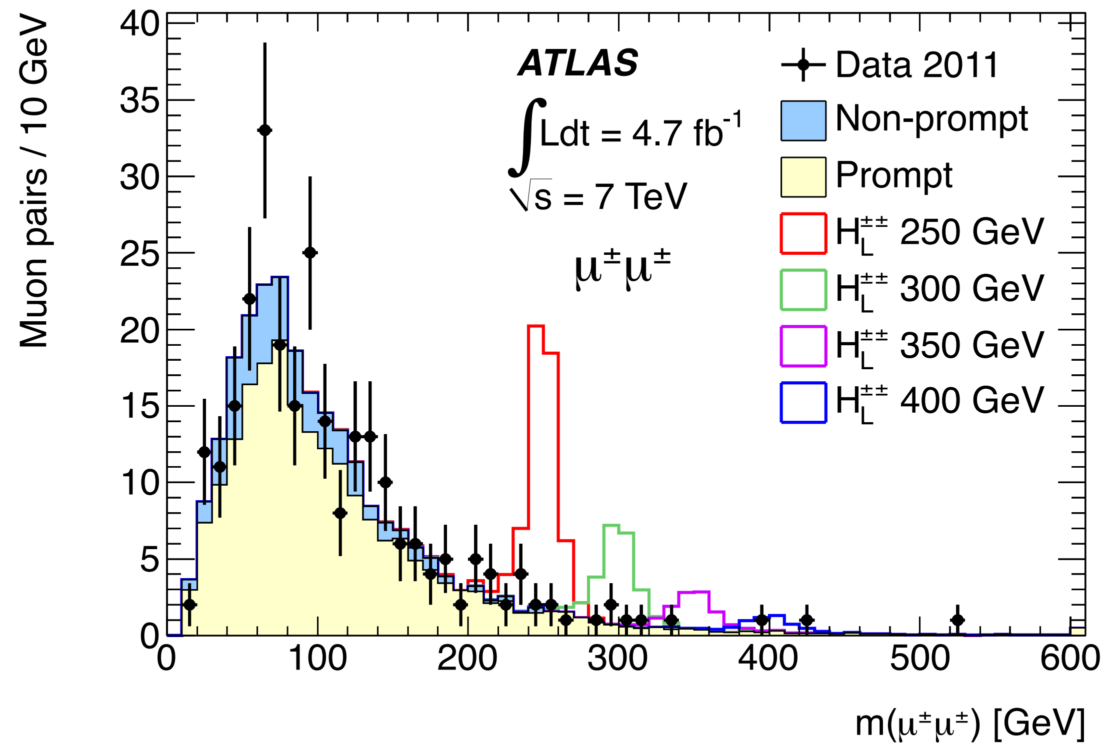
Limits (95% CL): M(Z') > 2.79 TeV (ee); M(Z') > 2.48 TeV (μμ); M(Z') > 2.86 TeV (combined)
M(W')> 1.18 TeV

exotic: $\mu^\pm\mu^\pm$ and $\gamma\gamma$ searches

Prompt photons or like-sign leptons is one of the most powerful signatures for new physics



arXiv:1210.8389

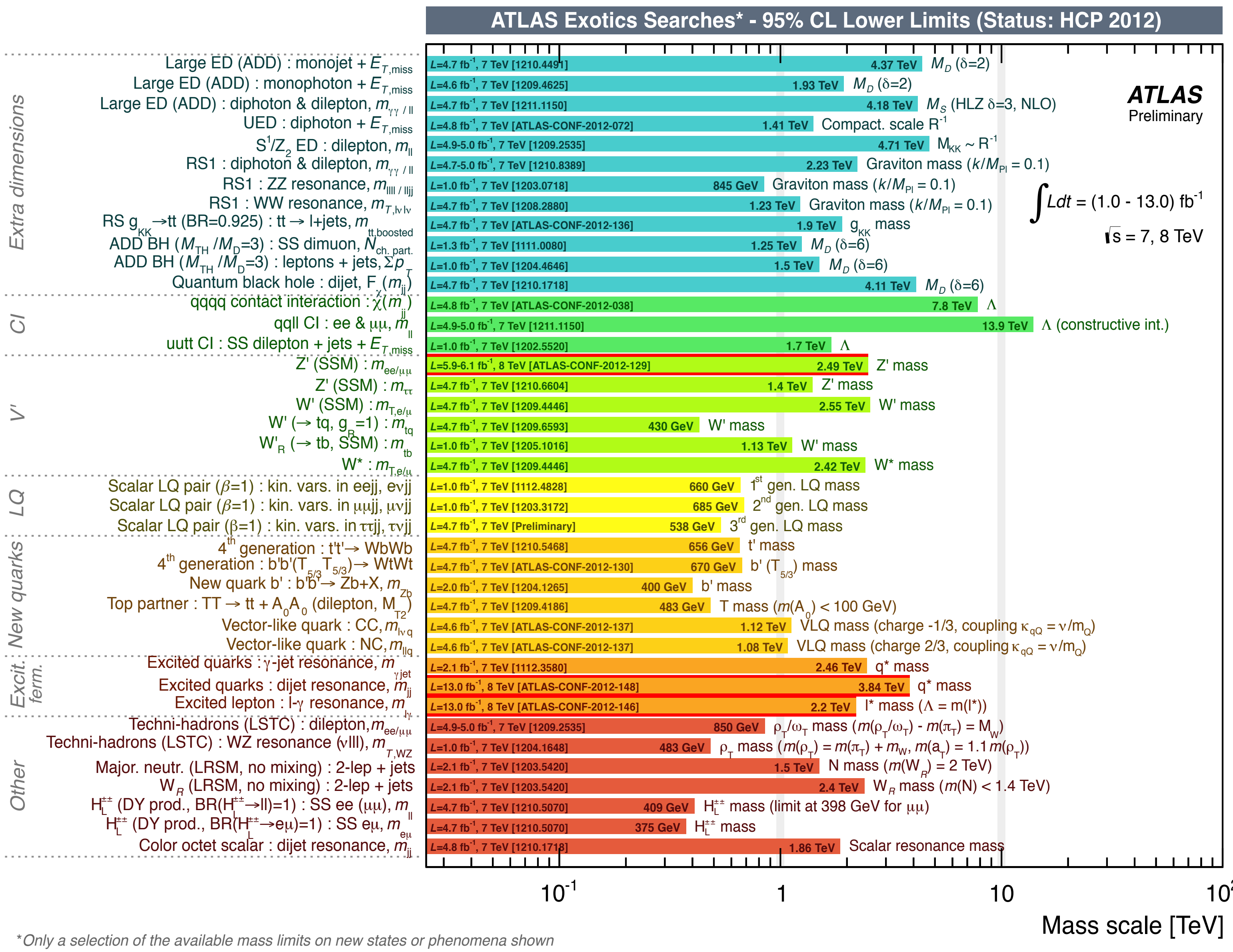


Randall-Sundrum graviton with strong coupling to SM particles would decay to a photon pair

$M(G) > 2.06$ TeV ($k/M_{Pl}=0.1$)

Doubly charged Higgs would show up as a narrow like-sign resonance

searches for new physics
specific models and model independent studies



Exotics Models:

Extra dimensions:
- RS KK Graviton
  (dibosons, dileptons, diphotons)
- RS KK gluons (top antitop)
- ADD (monojets, monophotons, dileptons, diphotons)
- KK Z/gamma boosns (dileptons)

Grand Unification symmetries
- (dielectons, dimuons, ditaus)
- Leptophobic topcolor Z' boson
  (dilepton ttbar, l+j, all had)

S8- color octet scalars (dijets)
String resonance (dijets,)
Benchmark Sequential SM Z',W'
W' (lepton+MET, dijets, tb)
W* (lepton+MET, dijets)
Quantum Black Holes (dijet)
Black Holes (l+jets, same sign leptons)
Technihadrons (dileptons, dibosons)
Dark Matter
- WIMPs (Monojet, monophotons)

Excited fermions
- q*, Excited quarks (dijets, photon+jet)
- l*, excited leptons (dileptons+photon)

Leptoquarks (1st, 2nd, 3rd generations)
Higgs -> hidden sector
- (displaced vertices, lepton jets)

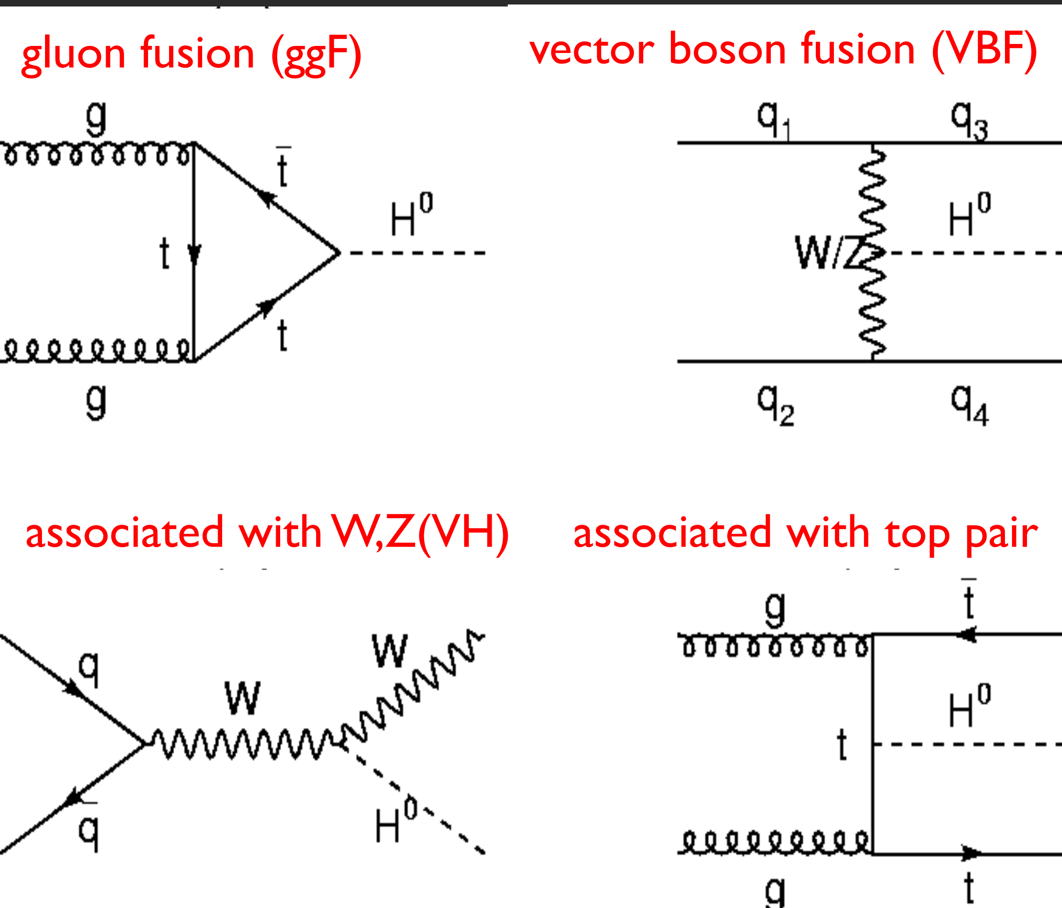
Contact Interaction
- llqq CI
- 4q CI (dijets)

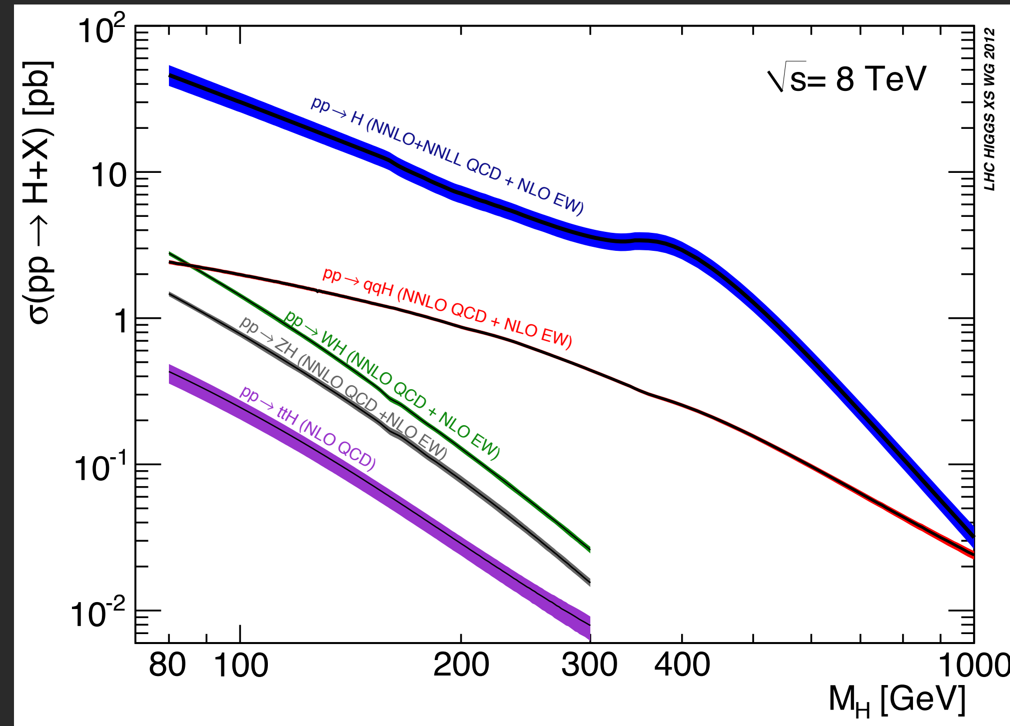
Doubly charged Higgs (
- multi leptons, same sign leptons)

4th generation
- t'->Wb, t'->ht, b'-Zb, b'->Wt
  (dileptons, same sign leptons, l+J)

VLQ-Vector Like quarks
Magnetic Monopoles (and HIP)
Heavy Majorana neutrino and RH W

MSM Higgs search and properties





gluon fusion – largest cross sections, but also large backgrounds

associated production – smaller but cleaner

VBF – even smaller but may help to improve sensitivity

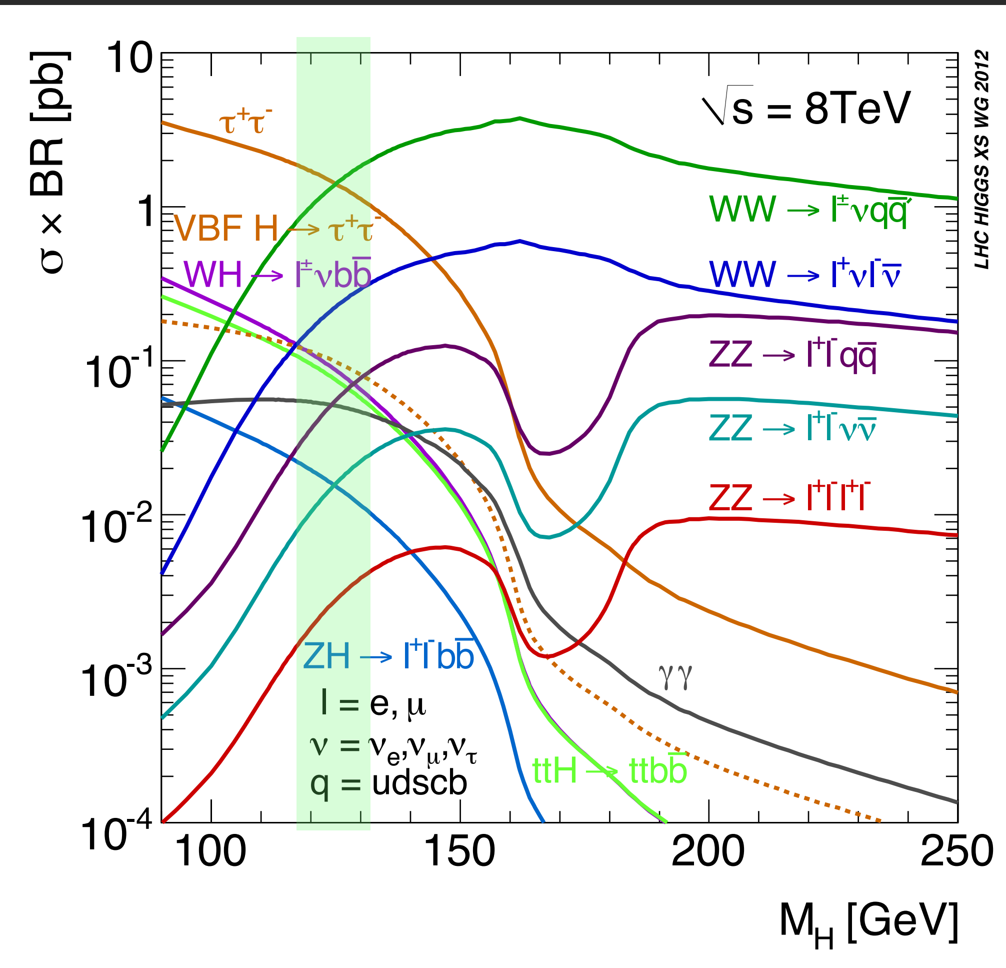
Higgs cross section higher ~1.3x at 8 TeV

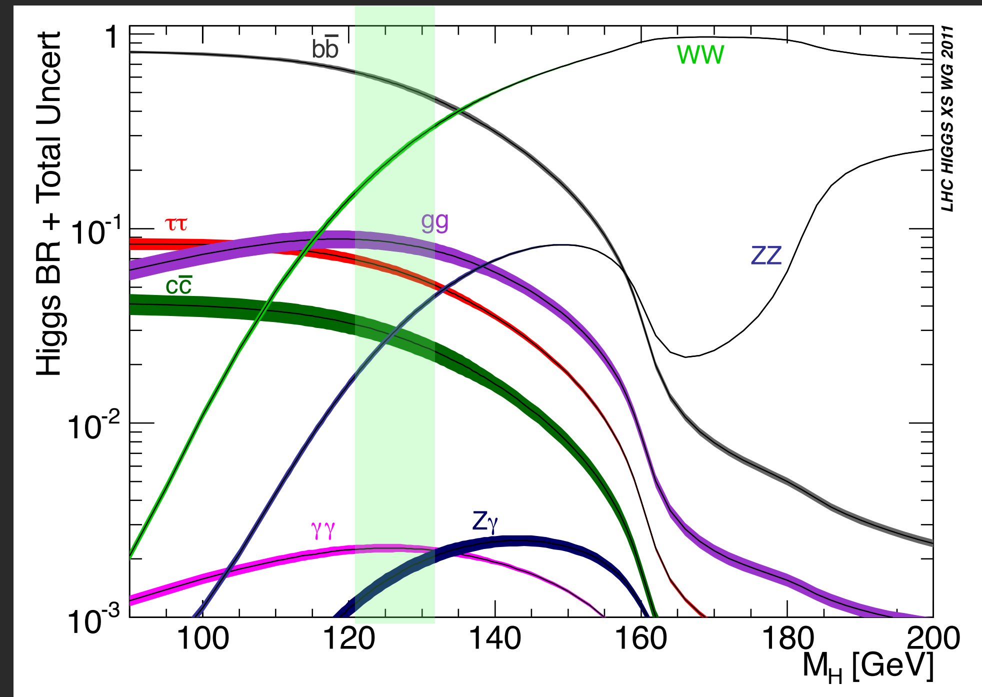
irreducible backgrounds (γγ, WW, WZ, ZZ) also higher, but a bit less

reducible backgrounds (top, Zbb) higher even a bit more

increase in sensitivity at 8 TeV
–> 1.1x - 1.15x

MSM Higgs search and properties





Most sensitive channels
for $120 < M_H < 130$ GeV:

H –>ZZ*–>4l,
H–> $\gamma\ \gamma$
H–>WW*–>l ν l ν
H–> $\tau\ \tau$
W/ZH–>W/Z bb

By some strange coincidence, M_H= 125 GeV is one of the best places to find Higgs and study its properties (from the experimental point of view) – many channels with relatively large branching fractions !

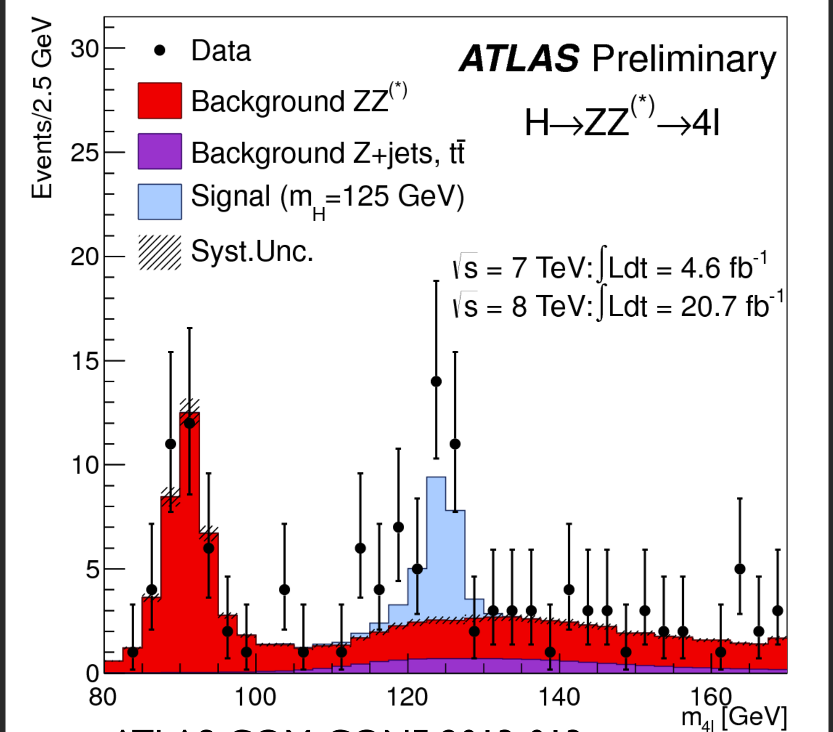
MSM Higgs search and properties

M_{4l} = 124.3+0.6-0.5(stat)
+0.5-0.3(syst) GeV

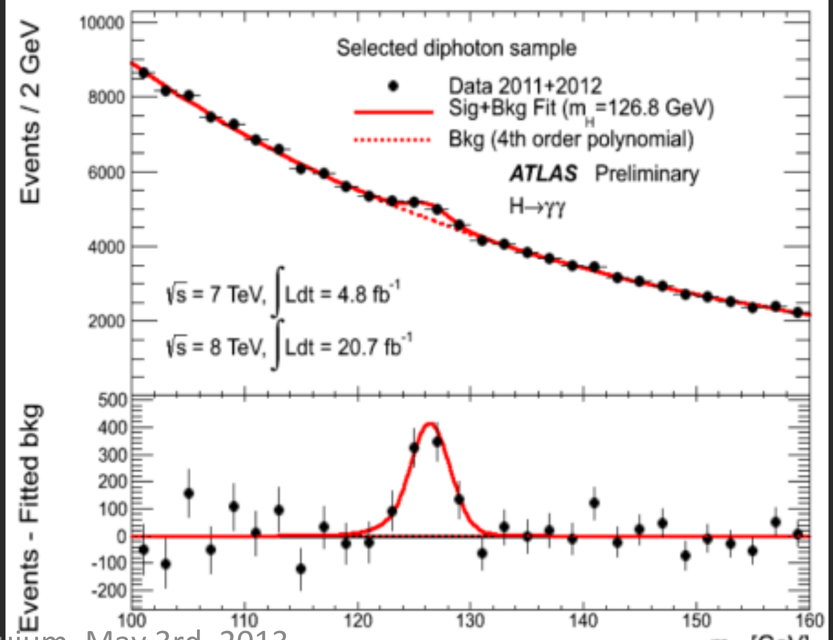
$M_{\gamma\gamma}$ = 126.8±0.2(stat)
±0.7(syst) GeV

M_H = 125.5±0.2(stat)
(4l + γγ) +0.5-0.6(syst) GeV

ΔM = 2.3+0.6-0.7(stat)
±0.6(syst) GeV



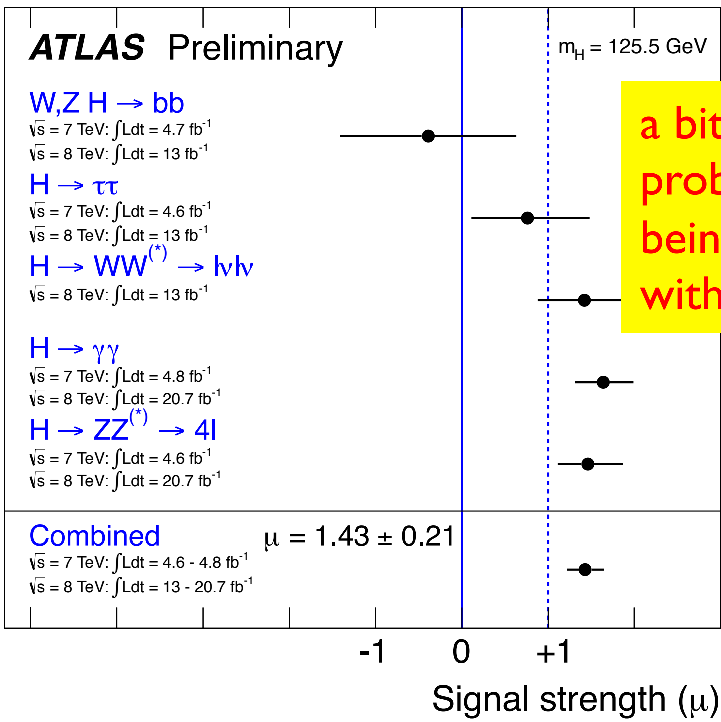
ATLAS-COM-CONF-2013-013



ATLAS-COM-CONF-2013-012

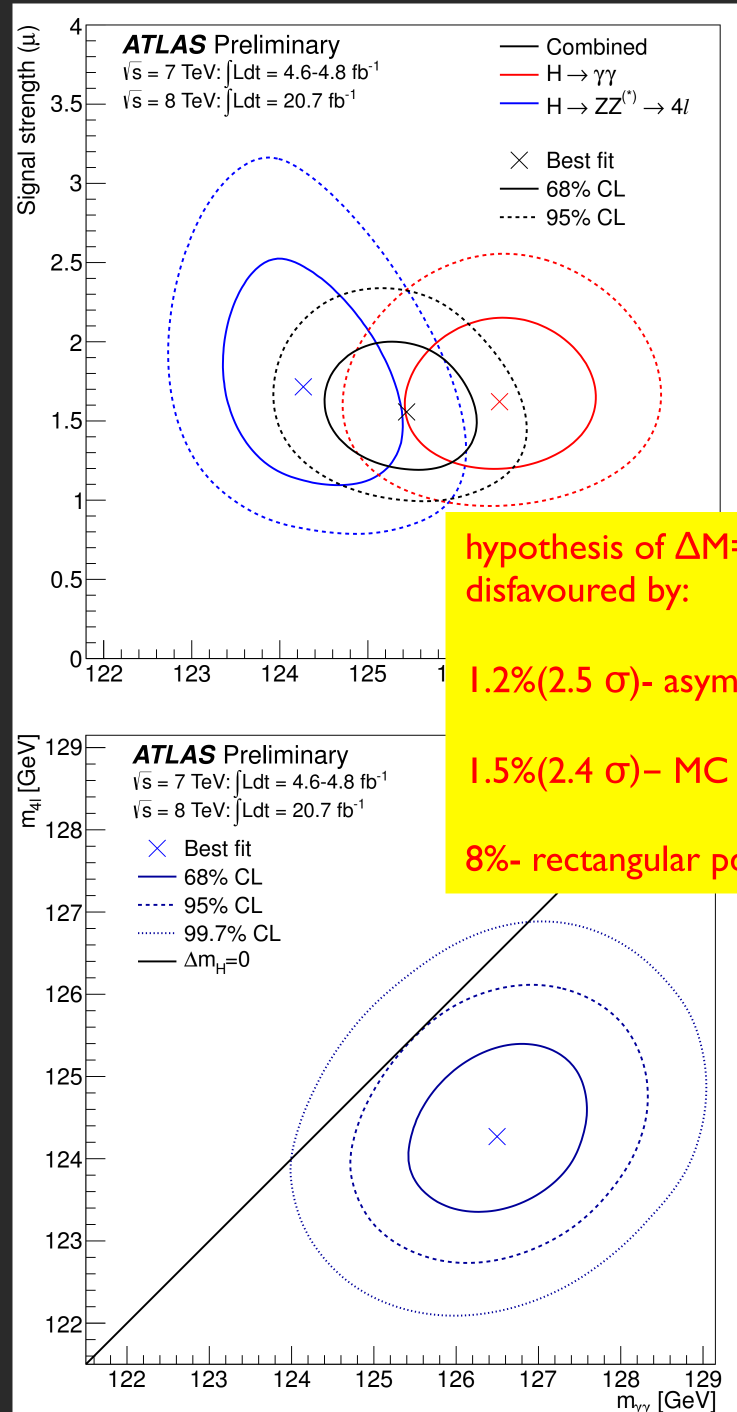
MSM Higgs search and properties

Higgs Boson Decay	μ (m_H=125.5 GeV)
$VH \to Vbb$	-0.4 ± 1.0
$H \to \tau\tau$	0.8 ± 0.7
$H \to WW^{(*)}$	1.0 ± 0.3
$H \to \gamma\gamma$	1.6 ± 0.3
$H \to ZZ^{(*)}$	1.5 ± 0.4
Combined	1.30 ± 0.20



a bit high, probability of being compatible with SM ~9%

ATLAS-COM-CONF-2013-014



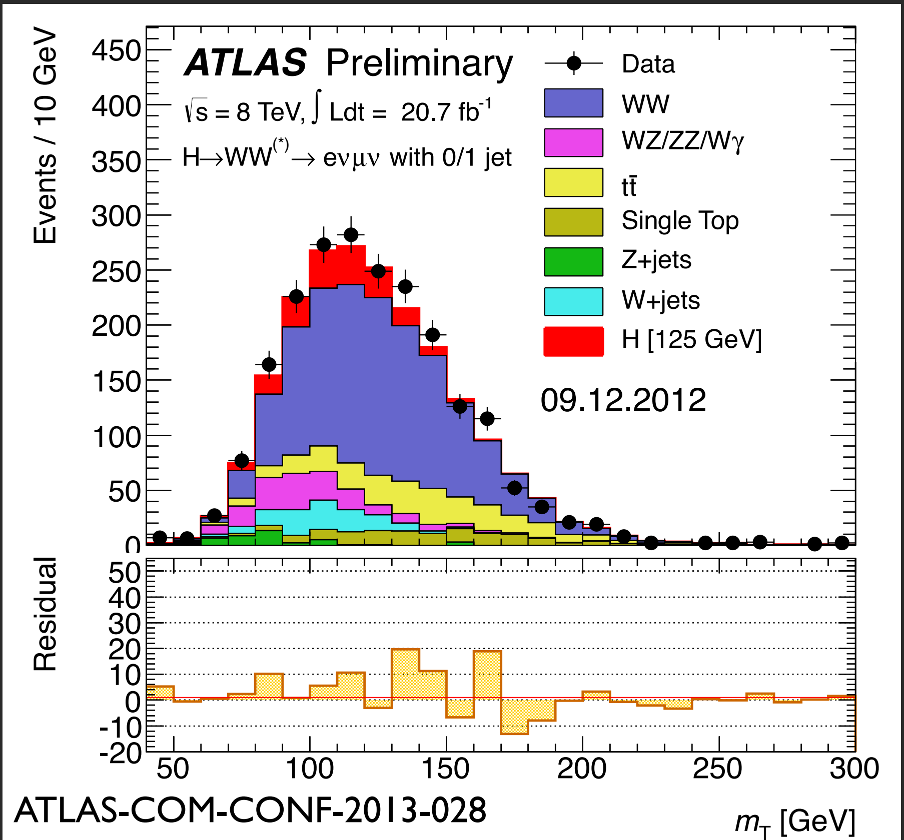
hypothesis of ΔM=0 disfavoured by:

1.2%(2.5 σ)- asymptotic assumption

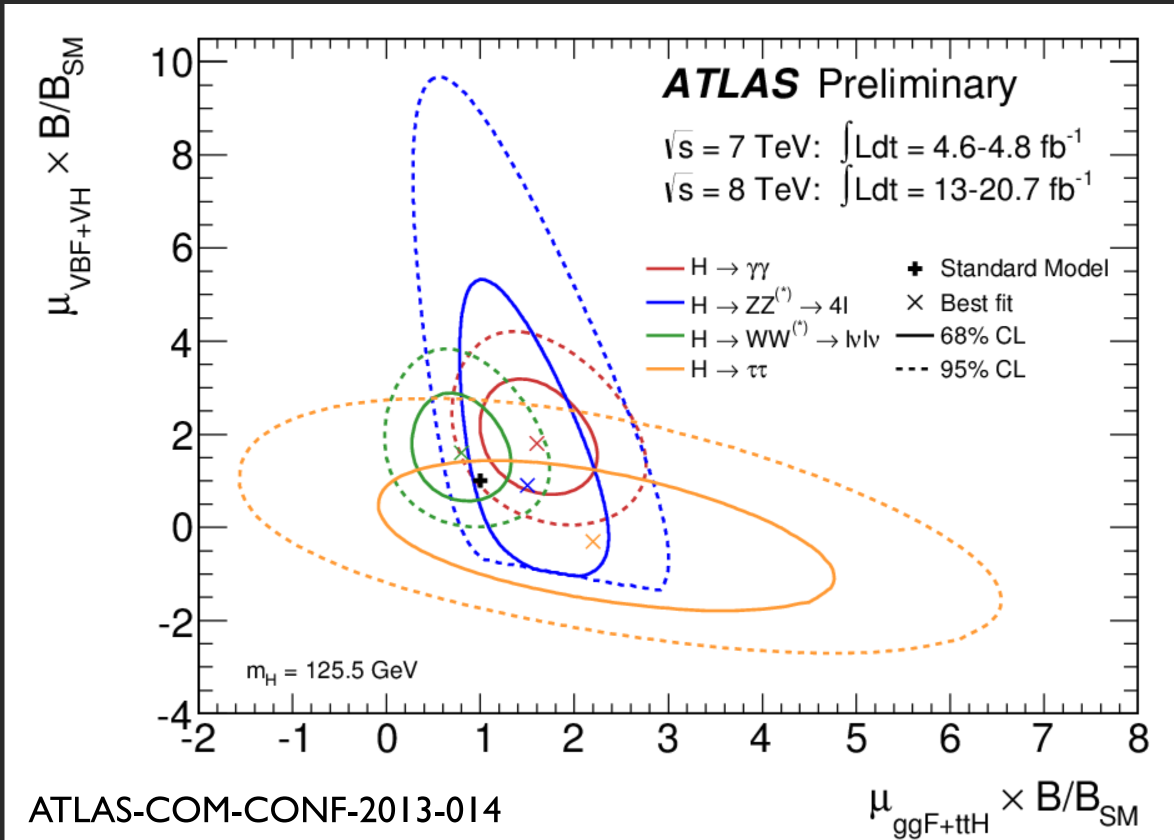
1.5%(2.4 σ)– MC ensembles;

8%- rectangular pdfs

MSM Higgs search and properties



ATLAS-COM-CONF-2013-028



ATLAS-COM-CONF-2013-014

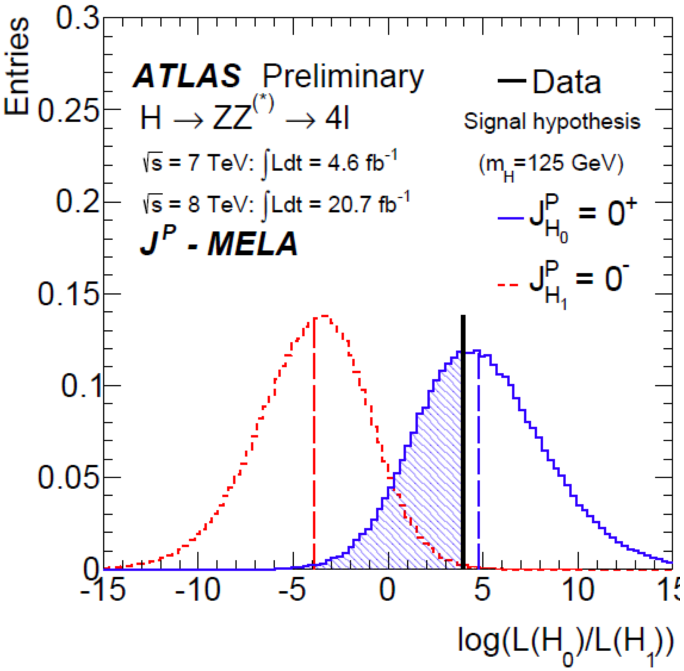
Evidence for VBF (~3.1σ)
Measurements of relative production rates very important for establishing properties of a new boson

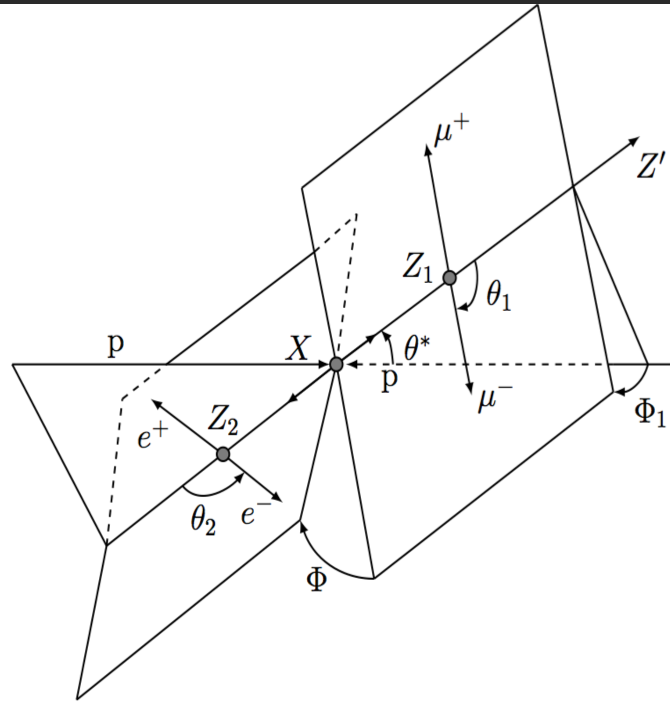
With the M_H known, all couplings can be calculated within SM –> is this a SM Higgs or not?
Expected for M_H=125 GeV at 8 TeV

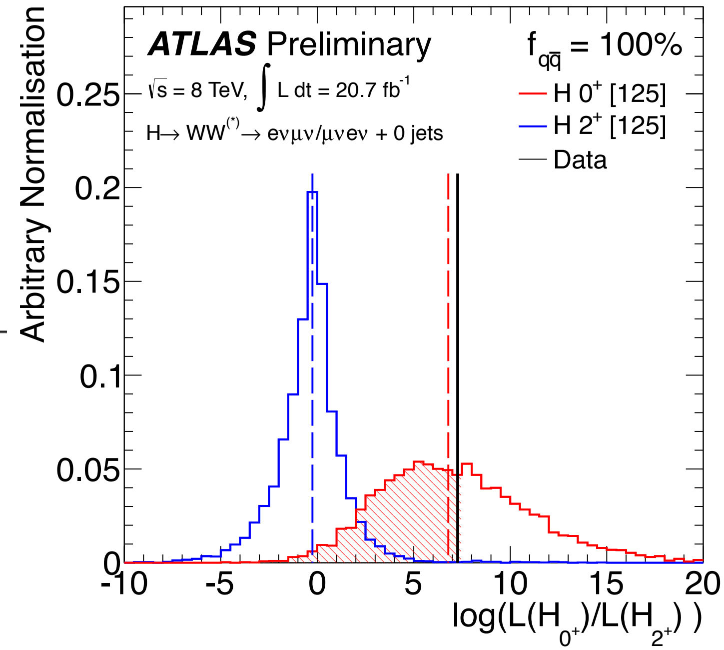
ggF	19.5 pb	fermion couplings (γγ, ZZ, WW*)
VBF	1.6 pb	boson couplings (γγ, ZZ, WW* >=2 jets)
VH	1.1 pb	boson couplings (γγ, ZZ, WW* +W,Z)
ttH	0.1 pb	fermions couplings

H -> WW*jj Vector Boson Fusion
Jeff Wetter, Ben Whitehouse, Noah Kurinsky and Krzysztof Sliwa
(analysis with svm event classifier)

MSM Higgs search and properties







spin-parity compatible with $J^{CP} = 0^+$ (as in Minimal Standard Model)

H−> γ γ : spin 2 excluded at 2.8 σ (100% gg)
(spin 1 excluded, as well, of course)

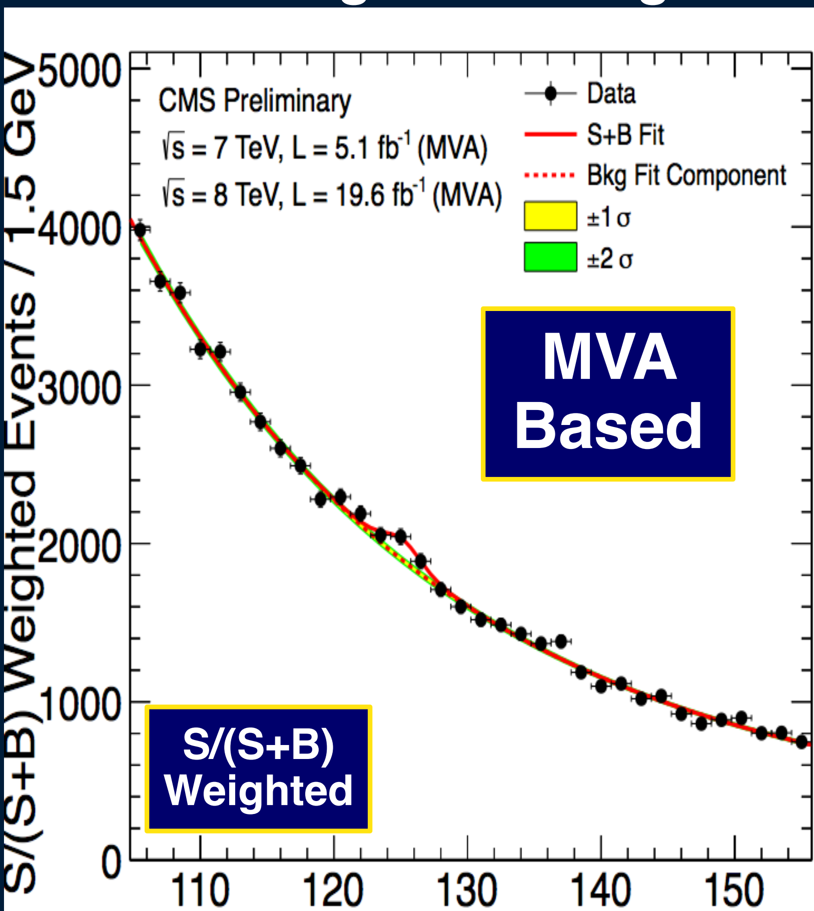
H−>4l : spin 0^- excluded at >2 σ, spin 2 excluded at 1.5- 3 σ (0-100% gg)

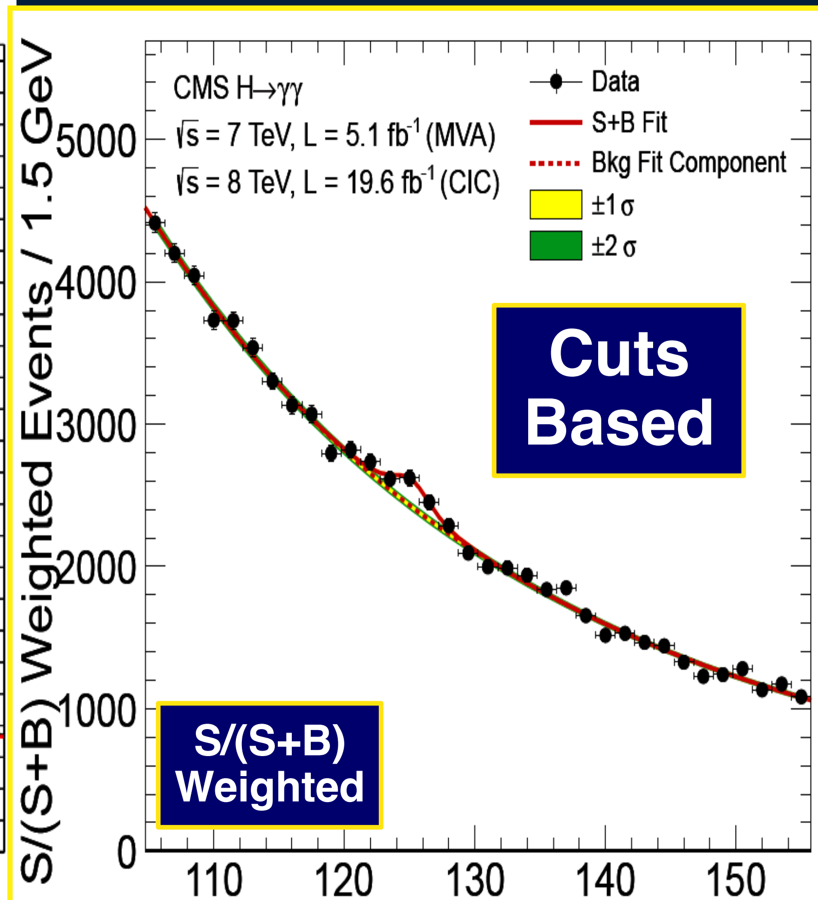
H−>WW*: spin 2 excluded at 95-99% C.L (depending on %gg)

S/(S+B) Weighted Mass Distributions

MVA and Cuts-Based Analysis Side by Side

- **Sum of mass distributions** for each event class, **weighted by S/(S+B)**
  - B is integral of background model over a constant signal fraction interval



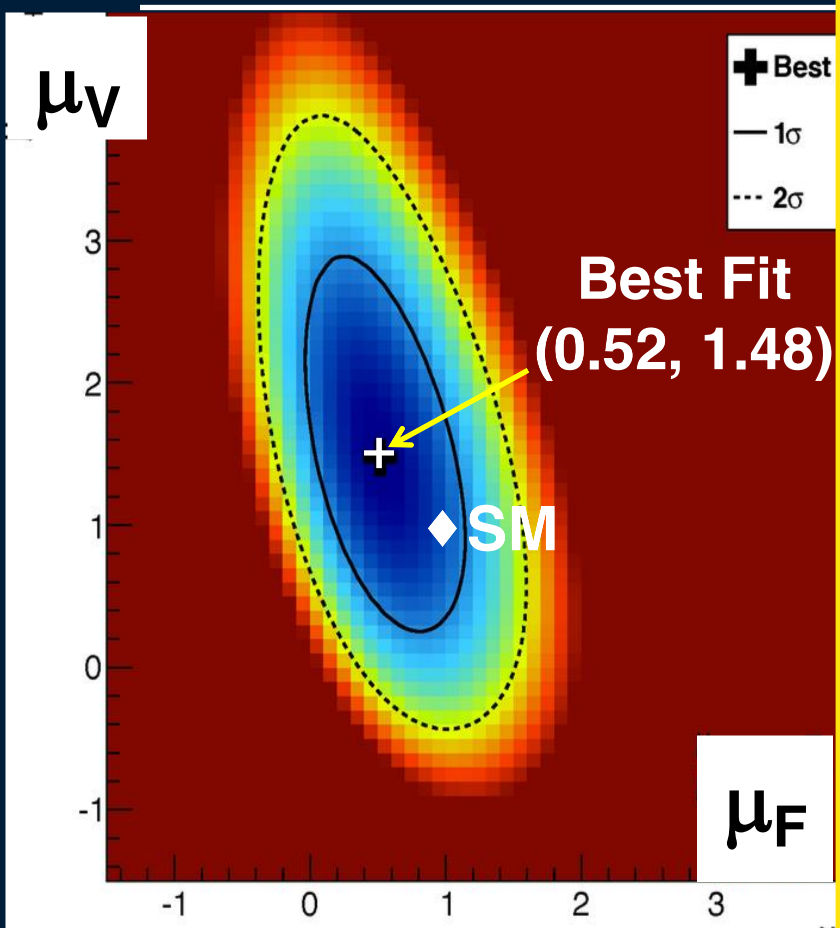


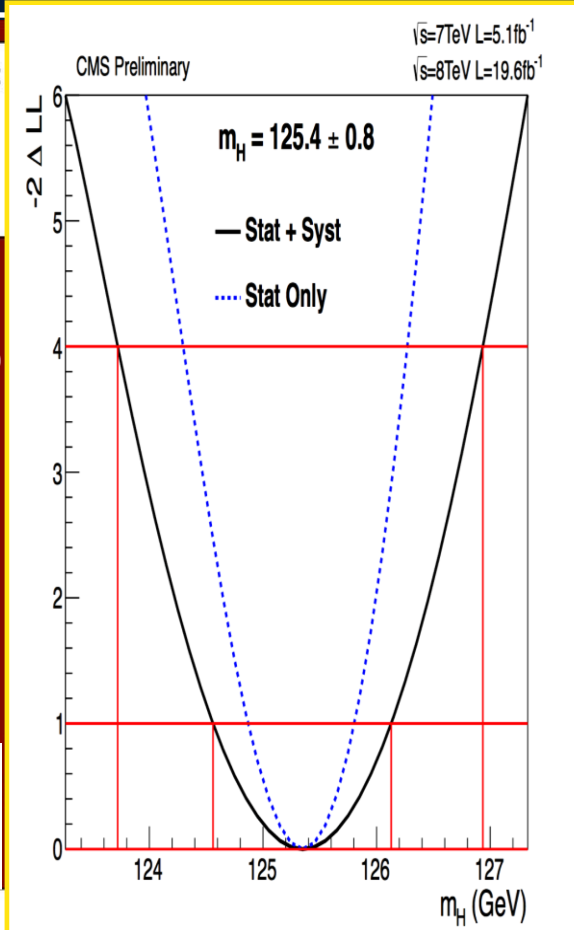
Weighting to Correctly Show S/(S+B)

An illustration: Not used to derive the quantitative Results

R.J. Barlow, "Event Classification Using Weighting Methods", J. Comput. Phys. 72 (1987) 202

H $\rightarrow\gamma\gamma$: Couplings μ_V (VBF+VH) vs μ_F (ggH+ttH) and Mass Determination





Mass measured profiling μ_V, μ_F along with all other nuisances to reduce model dependence

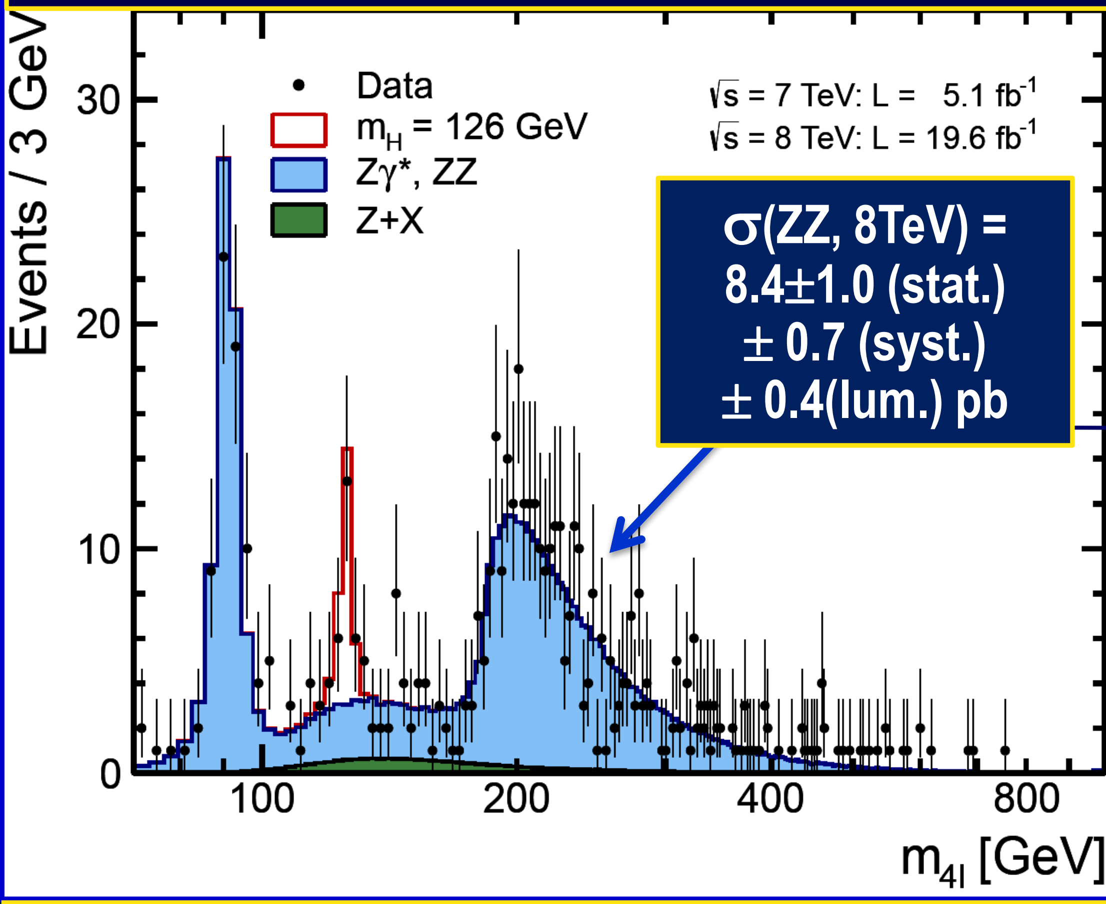
Main Systematic: Energy Scale extrapolation from M_Z to M_H ~125 GeV (0.47%)

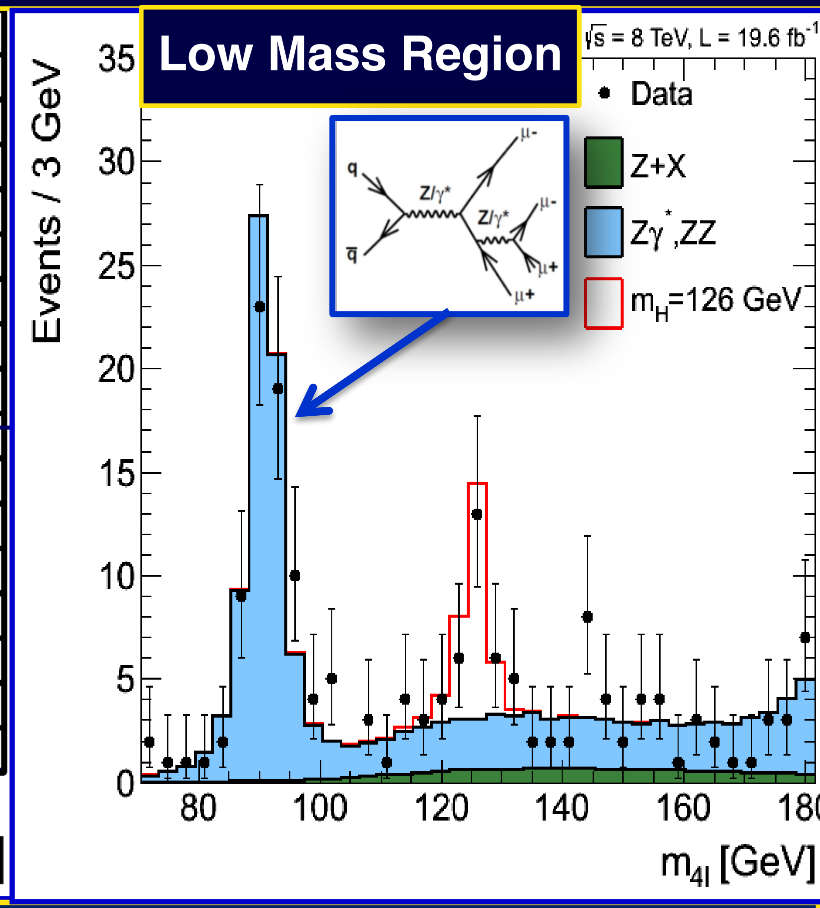
μ_V and μ_F are consistent, within 1 sigma, of SM prediction

Best Fit: Mass = 125.4 GeV ± 0.5 (stat) ± 0.6 (syst.) GeV

H ➡ ZZ(*) ➡ 4e, 4μ, 2e2μ Candidates
Mass Spectrum

Good description of Z →4L Peak, and ZZ continuum





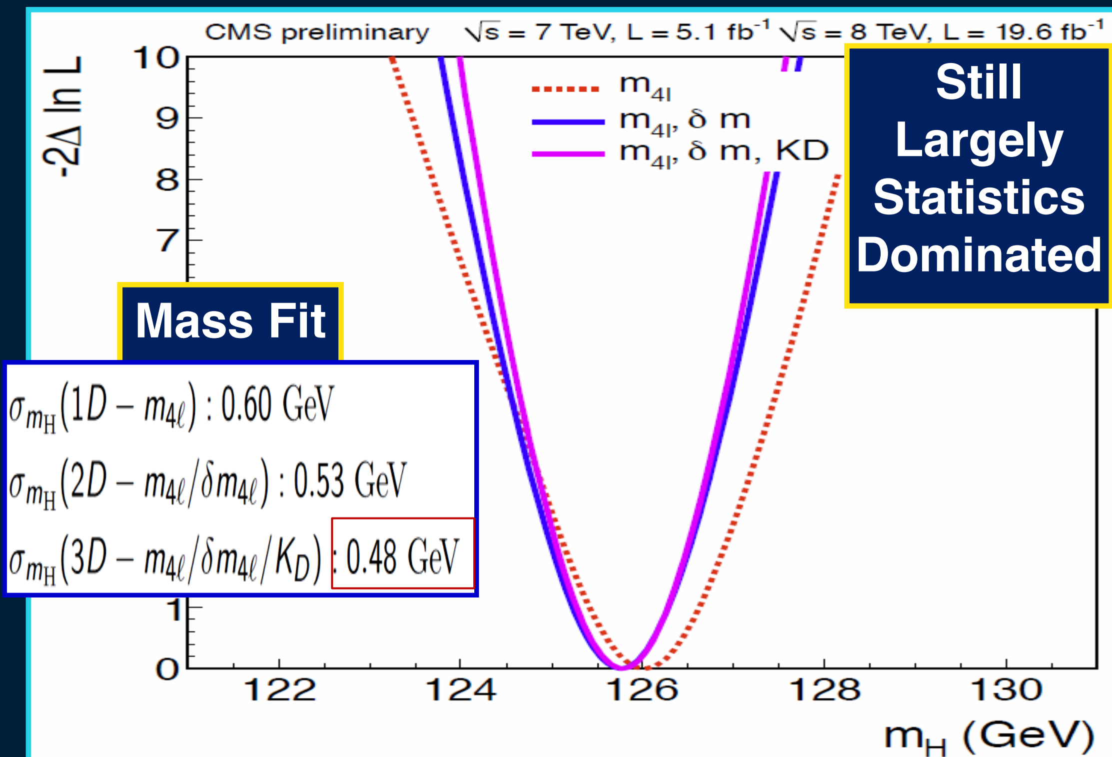
Clear Signal Peak Near 126 GeV

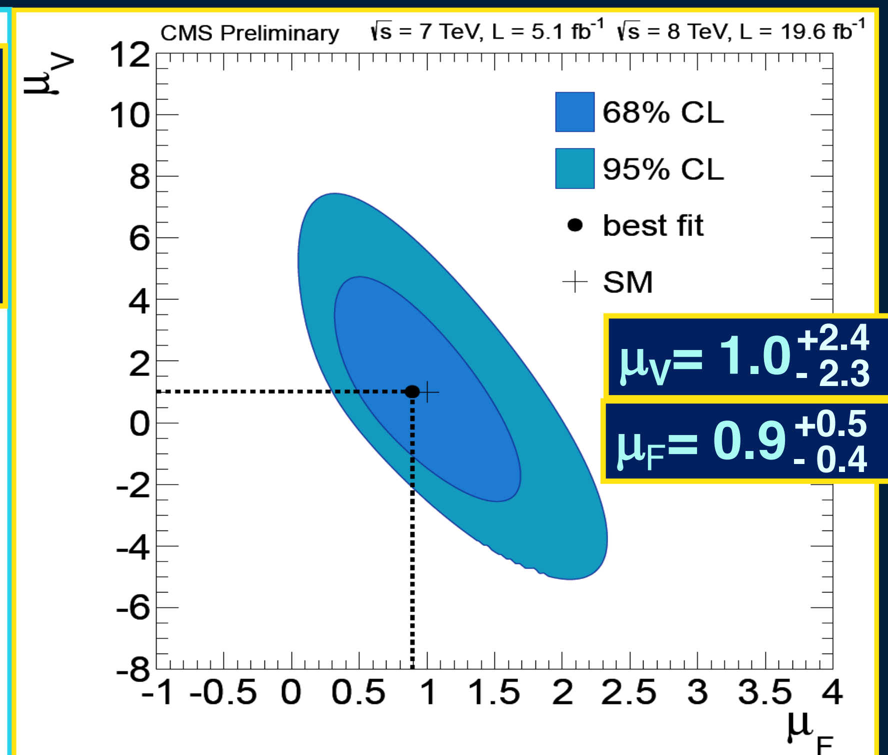
Z ➡4l Peak Provides Cross Check

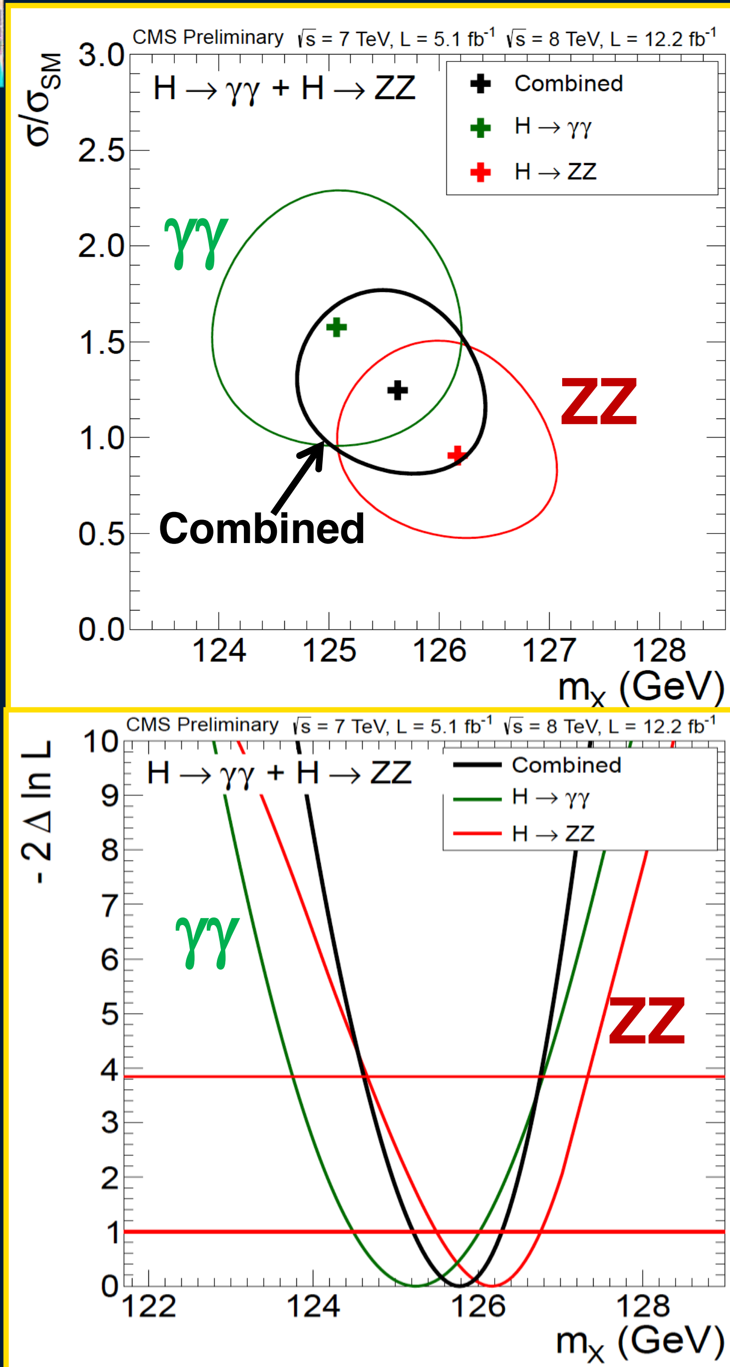
$H \rightarrow ZZ \rightarrow 4l$

Mass Fit and Coupling Factors μ_V and μ_F

1. 3D Fit (M_{4l}, K_D, δM_{4l}) for mass: $M = 125.8 \pm 0.5$ (stat) ± 0.2 (syst) GeV
2. Momentum Scale, Resolution: Studied & tuned in dilepton control samples
3. In Dijet category: P_T spectrum, V_D : used to disentangle prod. Mechanisms: Scale factors for Couplings to Vector Bosons μ_V (from VBF, ZH, WH) and to Fermions μ_F (from gg via quark loops, ttH)







Characterization of the Boson: the Mass

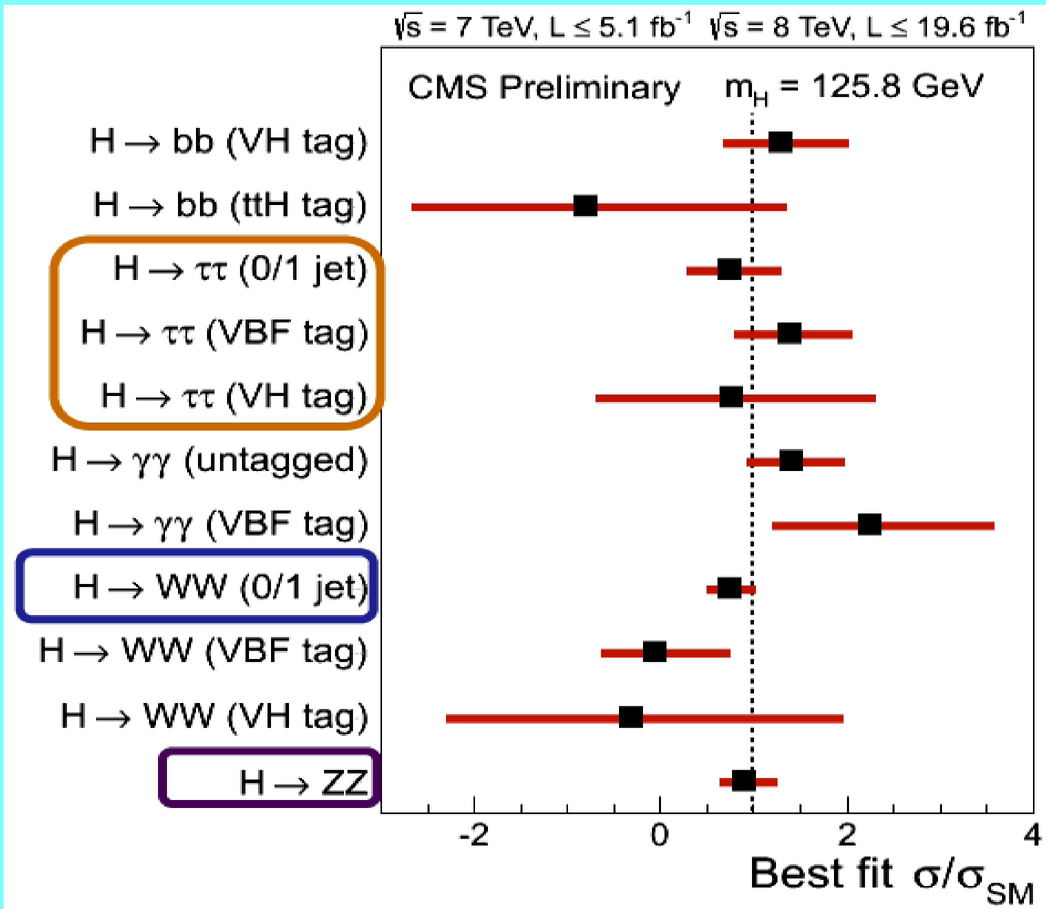
- Assume one particle, use sub-channels with good mass resolution:

  γγ(untagged), γγ(VBF), ZZ(4l)

- Do a likelihood scan for the Mass & Signal Strength
- Results are self-consistent; can be combined
- To reduce model dependence, float cross sections in 3 channels; do 1D fit for a common mass:

$m_X = 125.8 \pm 0.4(\text{stat}) \pm 0.4\ (\text{syst})$ GeV

Compatibility: Among Channels and with SM Higgs boson



New updates on some modes using the full 2011-12 dataset:

ττ, WW, ZZ

H → ττ: $\mu = 1.1 \pm 0.4$

H → WW: $\mu = 0.76 \pm 0.21$

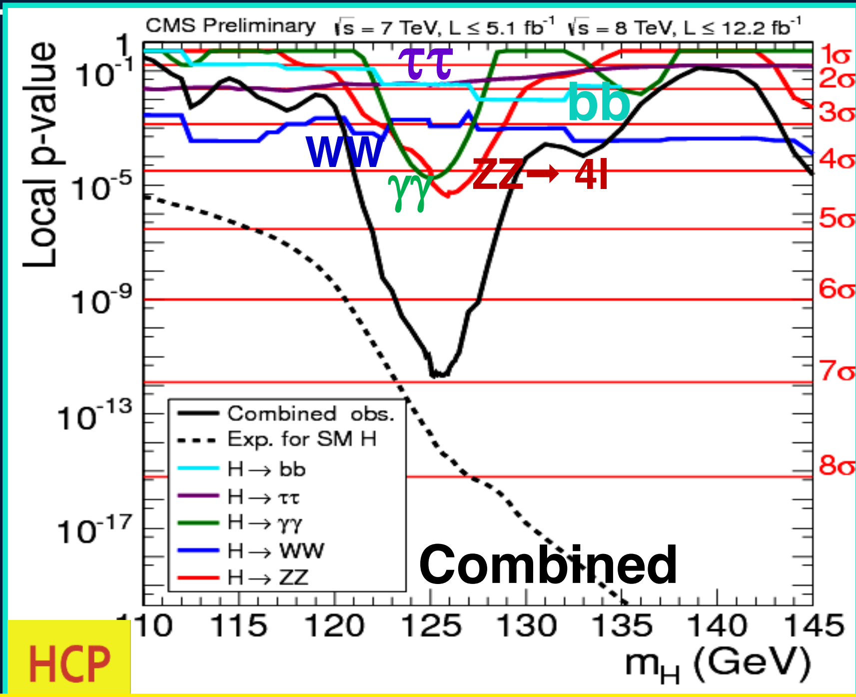
H → ZZ: $\mu = 0.91^{+0.30}_{-0.24}$

New (and older) results are compatible with the SM Higgs boson

Also Note Latest H → γγ Result on Full Dataset: $\mu = 0.78^{+0.28}_{-0.26}$

Observation of a New Boson Near 125.8 GeV

p-values and Significance by Channel HCP



	un-tagged	VBF-tag	VH-tag	ttH-tag
γγ	✔	✔		
bb			✔	✔
ττ	✔	✔	✔	
WW(lνlν)	✔	✔	✔	
ZZ(4l)	✔			

CMS-HIG-12-045

Excess at ~125.8 GeV:

Combined Significance 6.9 σ

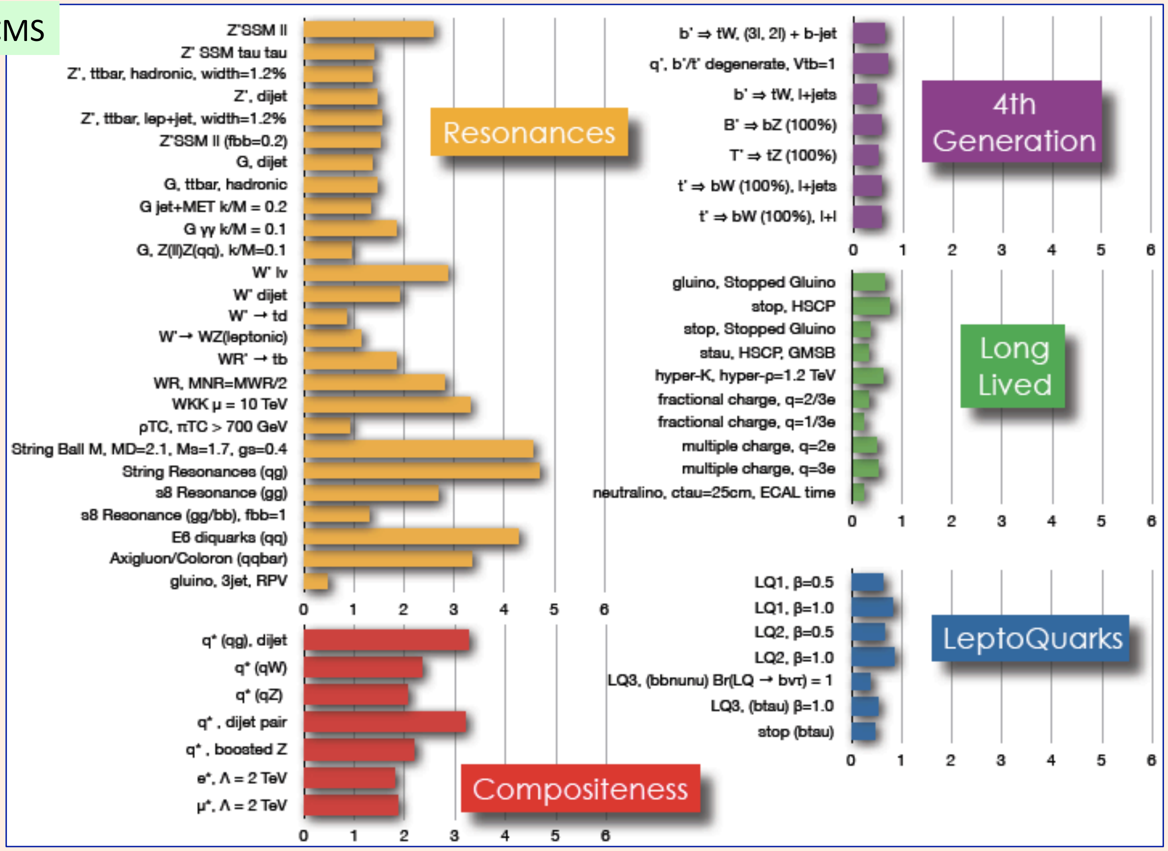
High sensitivity, high mass resolution channels: γγ + 4l

- ZZ → 4l: 4.4 σ Excess
- γγ 4.0 σ Excess

	Expected σ	Observed σ
H→ZZ	5.0	4.4
H→γγ	2.8	4.0
H→ WW	4.3	3.0
H→ bb	2.2	1.8
H → ττ	2.1	1.8
H → γγ+ZZ+WW + ττ + bb	7.8	6.9

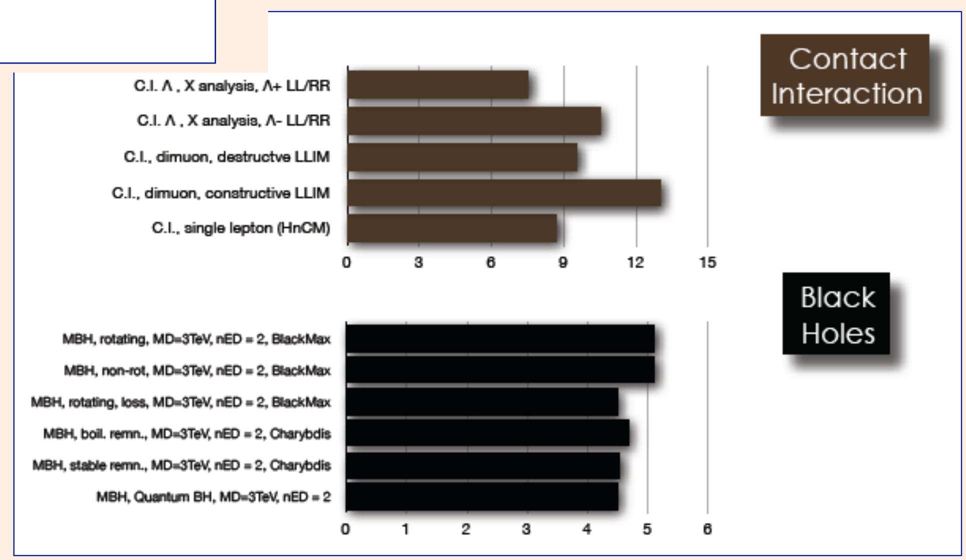
Searches for New Physics: Exotics

CMS



CMS SEARCHES for NEW PHYSICS

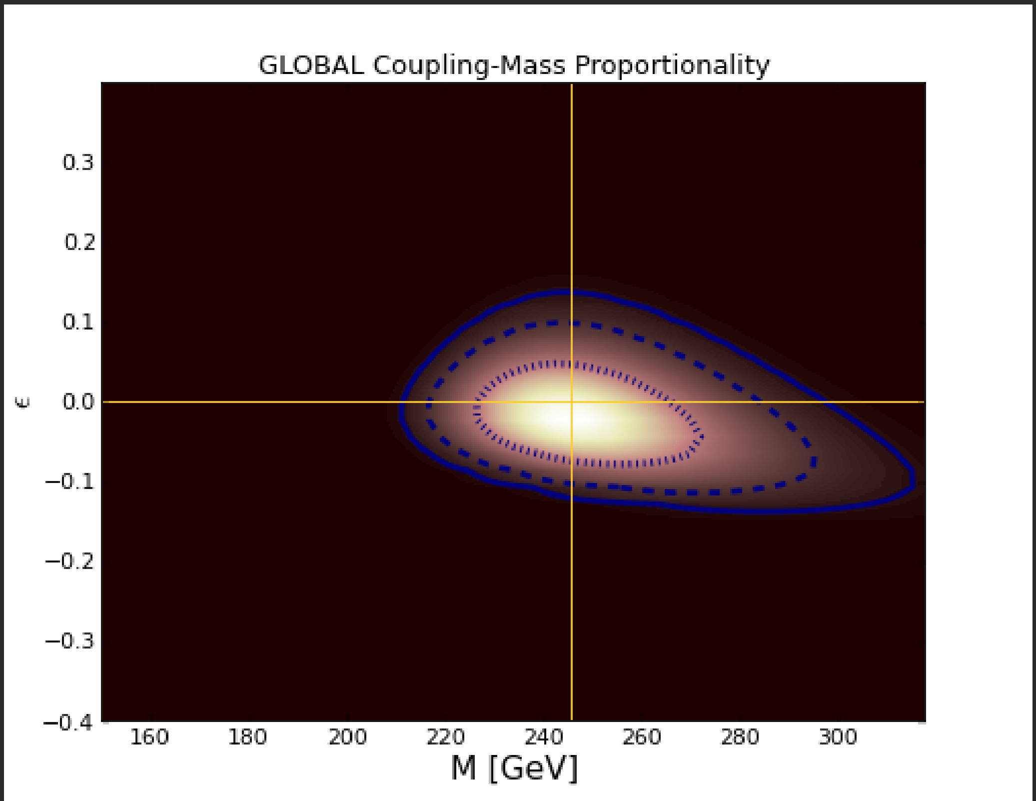
for New Physics: Exotics

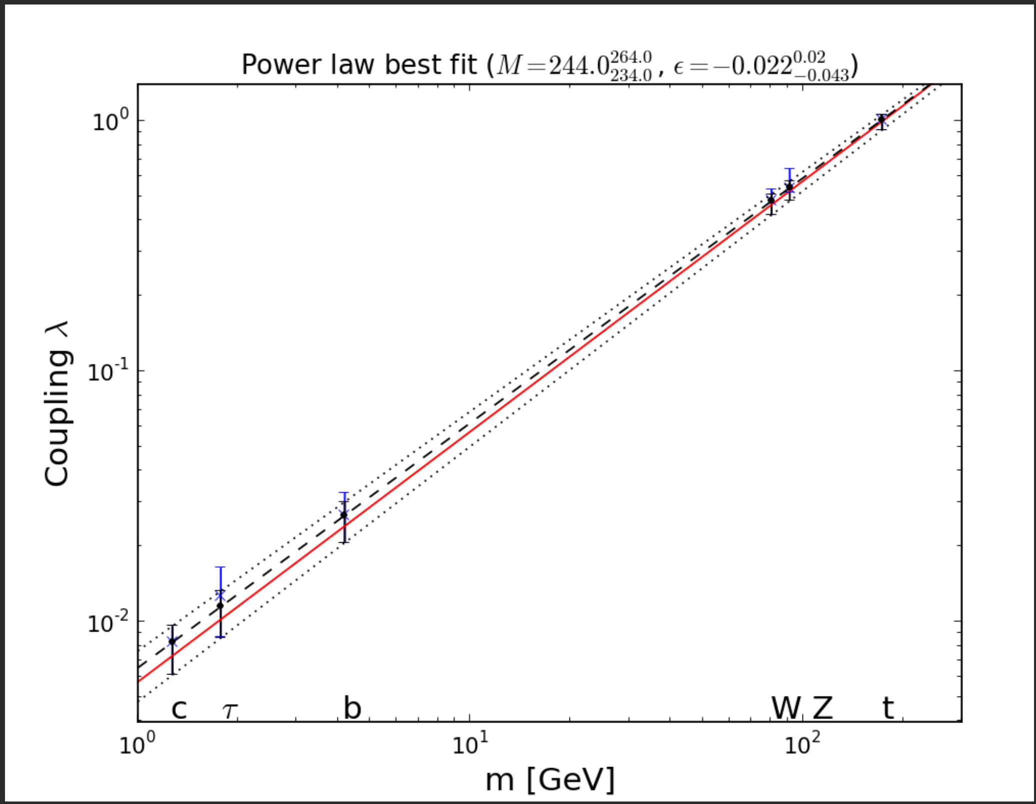


See talks from Samuel Pierre Jean Calvet and Sung Won Lee

MSM Higgs search & properties – "unofficial" combination

John Ellis and Tevong You: arXiv: 1303.38791 [hep-ph] 15 Mar 2013





LOOKS LIKE A MSM HIGGS ….

near Future – present LHC schedule

2009
2010
2011
2012
2013 LS1
2014
2015
2016
2017
2018 LS2
2019
2020
2021
2022 LS3
2023
...
2030?

✧ LHC startup, $\sqrt{s}$ = 900 GeV

$\sqrt{s}$=7~8 TeV, L=6x10^{33} cm^{-2} s^{-1}, bunch spacing 50 ns

~20-25 fb^{-1}

Go to design energy, nominal luminosity (Phase-0)

new Pixel B-layer

$\sqrt{s}$=13~14 TeV, L~1x10^{34} cm^{-2} s^{-1}, bunch spacing 25 ns

~75-100 fb^{-1}

Injector and LHC Phase-1 upgrade to full design luminosity

NSW, FTK
LVL1 trigger

$\sqrt{s}$=14 TeV, L~2x10^{34} cm^{-2} s^{-1}, bunch spacing 25 ns

~350 fb^{-1}

HL-LHC Phase-2 upgrade, IR, crab cavities?

new tracker

$\sqrt{s}$=14 TeV, L=5x10^{34} cm^{-2} s^{-1}, luminosity levelling

~3000 fb^{-1}

Higgs boson properties

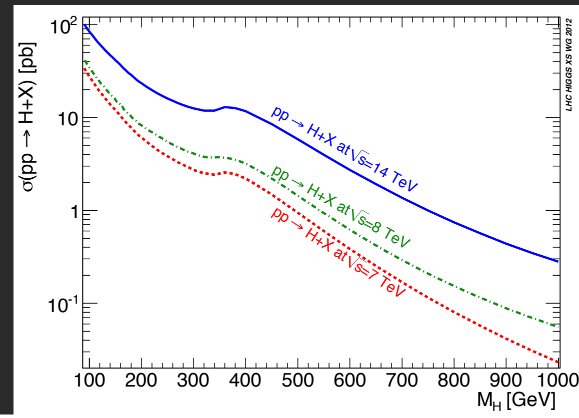
With the KNOWN mass of a new boson, the MSM couplings are calculable, and will be compared with the data

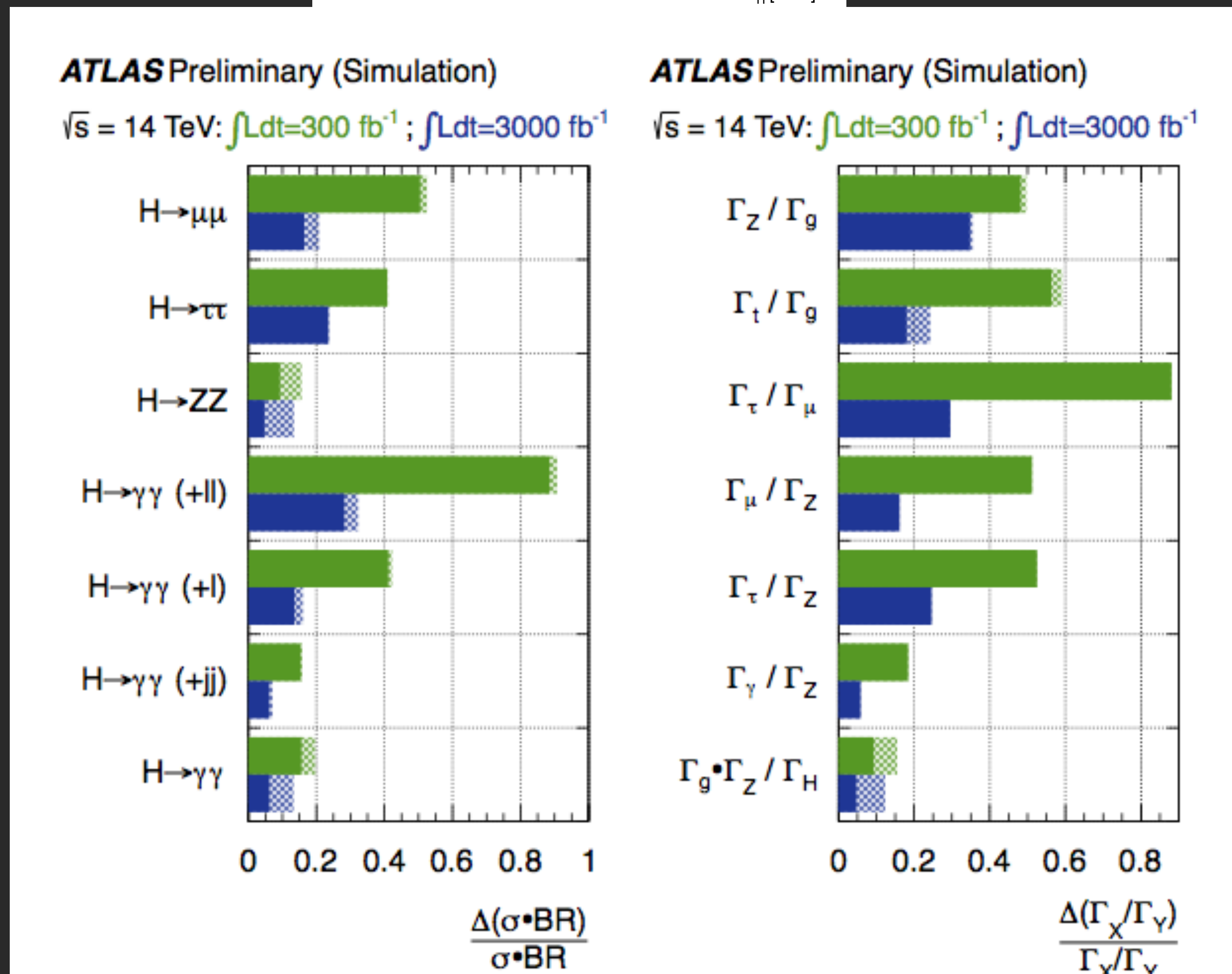
With ~300/fb- after Phase-I upgrade - the ratios of couplings will be known to within 30-50%

Spin and parity will be known with ~5σ level

HHH couplings – maybe with 3000/fb

HHHH – perhaps not at LHC





NEW PHYSICS ? FUTURE?

Of course, with the energy increase from 8 TeV to ~13 TeV, in addition to Higgs boson(s) studies, there will be another round of comprehensive searches for NMSSM and other "new physics".

This is what the physics goal of the LHC program is – to EXPLORE the new, previously unreachable, energies, and – in turn – new regions of phase space and model parameter spaces.

MORE DATA FROM 2015 at ~13 TEV

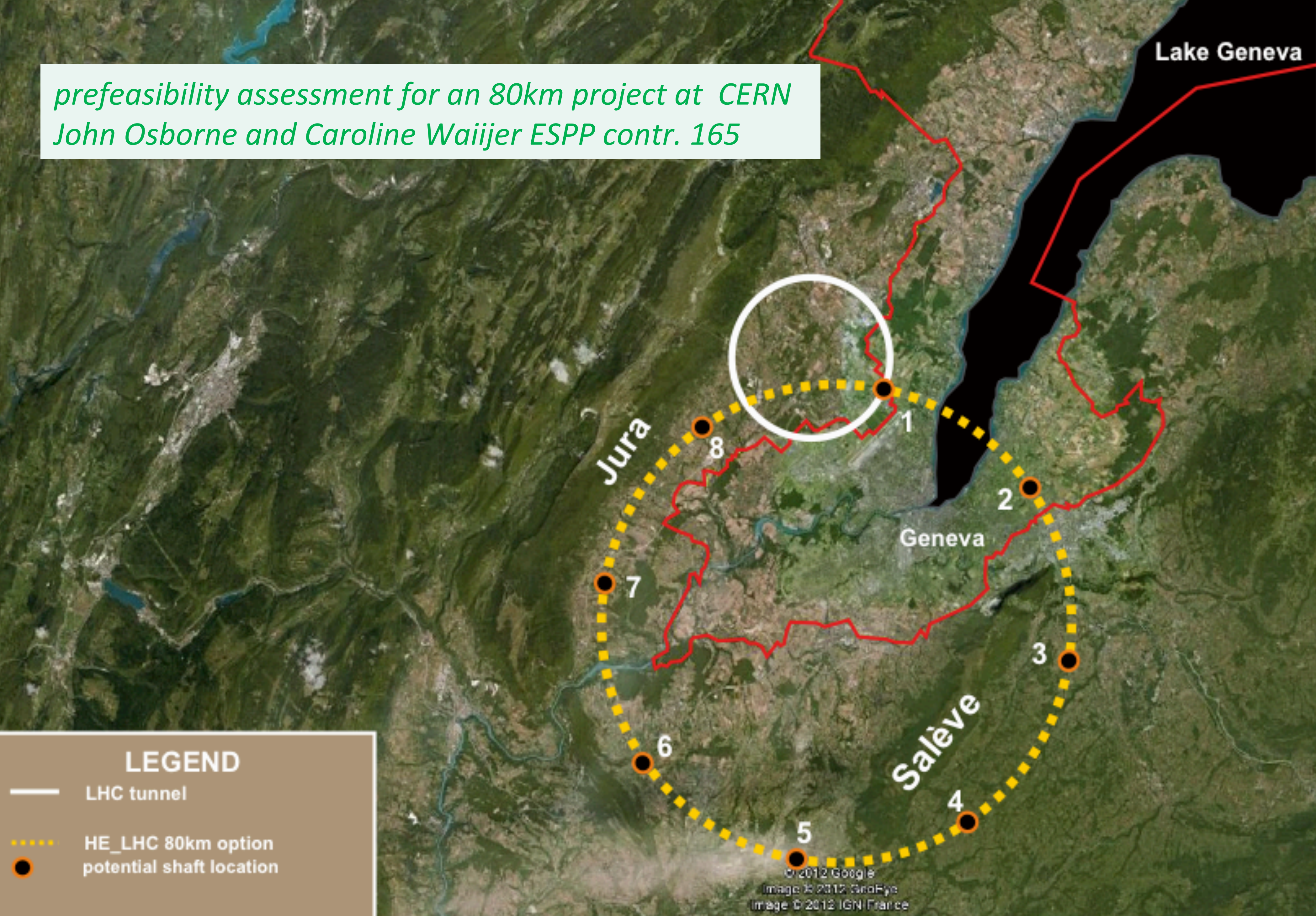
NEW PHYSICS ? FUTURE?

Finding the new boson is a great physics result, however, if it just looks like the minimal Standard Model Higgs boson – the simplest possible realization of the electroweak symmetry breaking – it will leave many unanswered questions – the fine tuning (gauge hierarchy problem) will still be with us

It is possible that with an increase of the pp collision energy from 8 TeV to 13 TeV we'll cross a threshold above which we'll observe new particles, too heavy to have been produced so far. This would be REALLY GREAT !

If not, then perhaps we'll have to turn our attention to precise measurements of the branching fractions and properties of the Higgs boson, either at LHC, or at a new e^+e^- collider, a "cleaner" environment in which to study the MSM Higgs boson

prefeasibility assessment for an 80km project at CERN
John Osborne and Caroline Waiijer ESPP contr. 165



	LEP2	LHeC	LEP3	TLEP-Z	TLEP-H	TLEP-t
beam energy E_b [GeV]	104.5	60	120	45.5	120	175
circumference [km]	26.7	26.7	26.7	80	80	80
beam current [mA]	4	100	7.2	1180	24.3	5.4
#bunches/beam	4	2808	4	2625	80	12
#e-/beam [10^{12}]	2.3	56	4.0	2000	40.5	9.0
horizontal emittance [nm]	48	5	25	30.8	9.4	20
vertical emittance [nm]	0.25	2.5	0.10	0.15	0.05	0.1
bending radius [km]	3.1	2.6	2.6	9.0	9.0	9.0
partition number J_ε	1.1	1.5	1.5	1.0	1.0	1.0
momentum comp. α_c [10^{-5}]	18.5	8.1	8.1	9.0	1.0	1.0
SR power/beam [MW]	11	44	50	50	50	50
β^*_x [m]	1.5	0.18	0.2	0.2	0.2	0.2
β^*_y [cm]	5	10	0.1	0.1	0.1	0.1
σ^*_x [µm]	270	30	71	78	43	63
σ^*_y [µm]	3.5	16	0.32	0.39	0.22	0.32
hourglass F_{hg}	0.98	0.99	0.67	0.71	0.75	0.65
ΔE^{SR}_{loss}/turn [GeV]	3.41	0.44	6.99	0.04	2.1	9.3
$V_{RF,tot}$ [GV]	3.64	0.5	12.0	2.0	6.0	12.0
$\delta_{max,RF}$ [%]	0.77	0.66	4.2	4.0	9.4	4.9
ξ_x/IP	0.025	N/A	0.09	0.12	0.10	0.05
ξ_y/IP	0.065	N/A	0.08	0.12	0.10	0.05
f_s [kHz]	1.6	0.65	3.91	1.29	0.44	0.43
E_{acc} [MV/m]	7.5	11.9	20	20	20	20
eff. RF length [m]	485	42	600	100	300	600
f_{RF} [MHz]	352	721	1300	700	700	700
δ^{SR}_{rms} [%]	0.22	0.12	0.23	0.06	0.15	0.22
$\sigma^{SR}_{z,rms}$ [cm]	1.61	0.69	0.23	0.19	0.17	0.25
L/IP[10^{32}cm^{-2}s^{-1}]	1.25	N/A	107	10335	490	65
number of IPs	4	1	2	2	2	2
Rad.Bhabha b.lifetime [min]	360	N/A	16	74	32	54
Υ_{BS} [10^{-4}]	0.2	0.05	10	4	15	15
n_γ/collision	0.08	0.16	0.60	0.41	0.50	0.51
$\Delta\delta^{BS}$/collision [MeV]	0.1	0.02	33	3.6	42	61
$\Delta\delta^{BS}_{rms}$/collision [MeV]	0.3	0.07	48	6.2	65	95

ILC Parameters

			Baseline	1st Stage	L Upgrade	TeV Upgrade A	TeV Upgrade B
Centre-of-mass energy	E_{CM}	GeV	500	250	500	1000	1000
Collision rate	f_{rep}	Hz	5	5	5	4	4
Electron linac rate	f_{linac}	Hz	5	10	5	4	4
Number of bunches	n_b		1312	1312	2625	2450	2450
Bunch population	N	$\times 10^{10}$	2.0	2.0	2.0	1.74	1.74
Bunch separation	Δt_b	ns	554	554	366	366	366
Pulse current	I_{beam}	mA	5.79	5.8	8.75	7.6	7.6
Average total beam power	P_{beam}	MW	10.5	5.2	21.0	27.2	27.2
Estimated AC power	P_{AC}	MW	162	128	205	300	300
RMS bunch length	σ_z	mm	0.3	0.3	0.3	0.250	0.225
Electron RMS energy spread	$\Delta p/p$	%	0.124	0.190	0.124	0.083	0.085
Positron RMS energy spread	$\Delta p/p$	%	0.070	0.152	0.070	0.043	0.047
Electron polarisation	P_-	%	80	80	80	80	80
Positron polarisation	P_+	%	30	30	30	20	20
Horizontal emittance	$\gamma\epsilon_x$	µm	10	10	10	10	10
Vertical emittance	$\gamma\epsilon_y$	nm	35	35	35	30	30
IP horizontal beta function	β_x^*	mm	11.0	13.0	11.0	22.6	11.0
IP vertical beta function (no TF)	β_y^*	mm	0.48	0.41	0.48	0.25	0.23
IP RMS horizontal beam size	σ_x^*	nm	474	729	474	481	335
IP RMS veritcal beam size (no TF)	σ_y^*	nm	5.9	7.7	5.9	2.8	2.7
Luminosity (inc. waist shift)	L	$\times 10^{34}$ cm^{-2}s^{-1}	1.8	0.75	3.6	3.6	4.9
Fraction of luminosity in top 1%	$L_{0.01}/L$		58.3%	87.1%	58.3%	59.2%	44.5%
Average energy loss	δ_{BS}		4.5%	0.97%	4.5%	5.6%	10.5%
Number of pairs per bunch crossing	N_{pairs}	$\times 10^3$	139.0	62.4	139.0	200.5	382.6
Total pair energy per bunch crossing	E_{pairs}	TeV	344.1	46.5	344.1	1338.0	3441.0

500 GeV Baseline

Initial 'Higg's Factory

The European Strategy for Particle Physics

Based on the Physics Briefing Book
CERN-ESG-005 , 13 January 2013

- High Energy Frontier:

Name	beams	collider geometry	√s, TeV	luminosity	Operation (years)
HL-LHC	pp	circular	14	3000 fb^{-1}	2024-2030
HE-LHC	pp	circular	26-33	100-300 fb^{-1}/year	After 2035
VHE-LHC	pp	circular	40-100	-	After 2035
LEP3	e^+e^-	circular	0.240	$1 \cdot 10^{34}$ $cm^{-2}s^{-1}$	After 2024
ILC	e^+e^-	linear	0.250→1.0	~$1 \cdot 10^{34}$ $cm^{-2}s^{-1}$	~ 2030
CLIC	e^+e^-	linear	0.500→3.0	2-$6 \cdot 10^{34}$ $cm^{-2}s^{-1}$	After 2030
TLEP	e^+e^-	circular	0.24-0.350	$5 \cdot 10^{34}$ $cm^{-2}s^{-1}$	After 2035
LHeC	$e^-(e^+)p$	circular		O(100 fb^{-1})	After 2022
γγ-collider	γγ				?
μ-collider	$\mu^+\mu^-$	circular			?

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