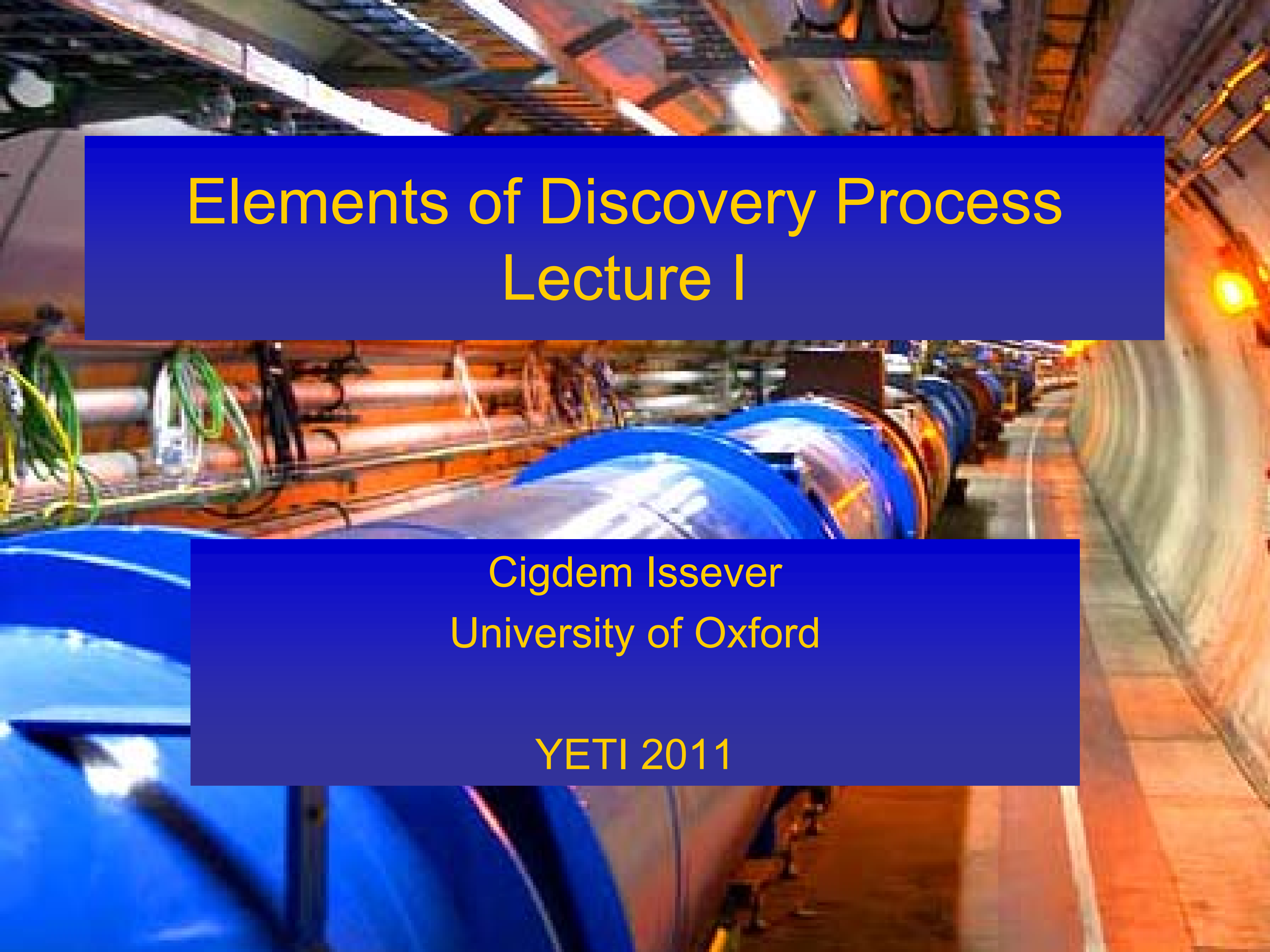


Elements of Discovery Process
Lecture I

Cigdem Issever
University of Oxford

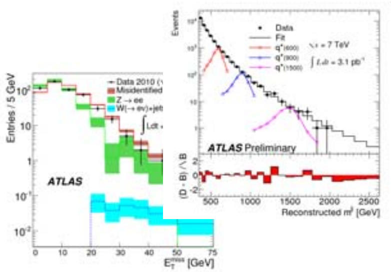
YETI 2011

Elements of Discovery Process

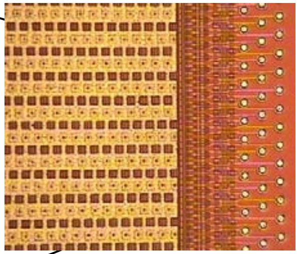
Theoretical Insight
Interplay of theory and experiment is essential

Accelerator Advances
At the LHC we can create and study new interactions

New Physics: Our Understanding of the World



New Detectors, Computing Tools
With new developments come new capabilities



Data Analysis:
Not missing the signal is key

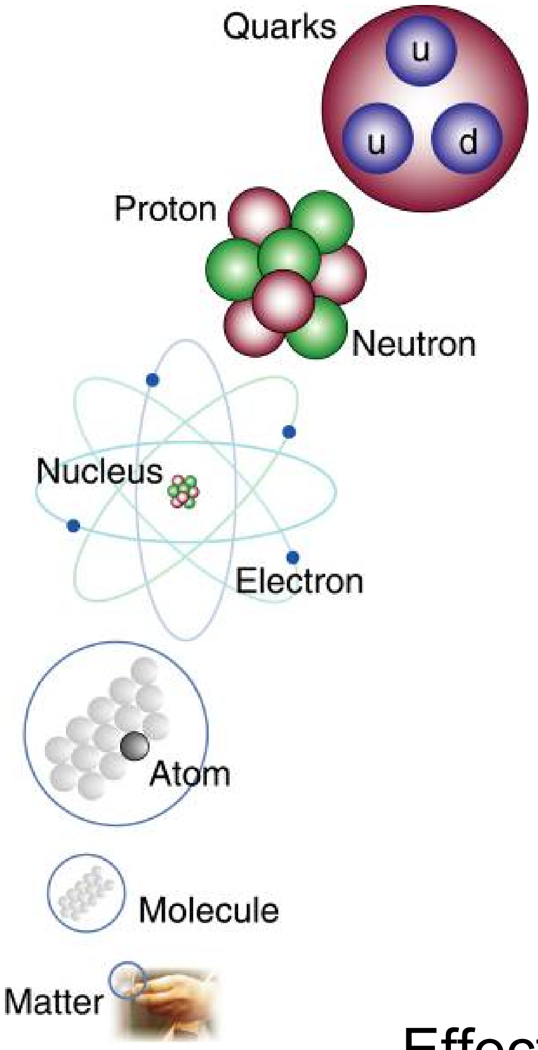
Theoretical Insight

Theoretical Insight

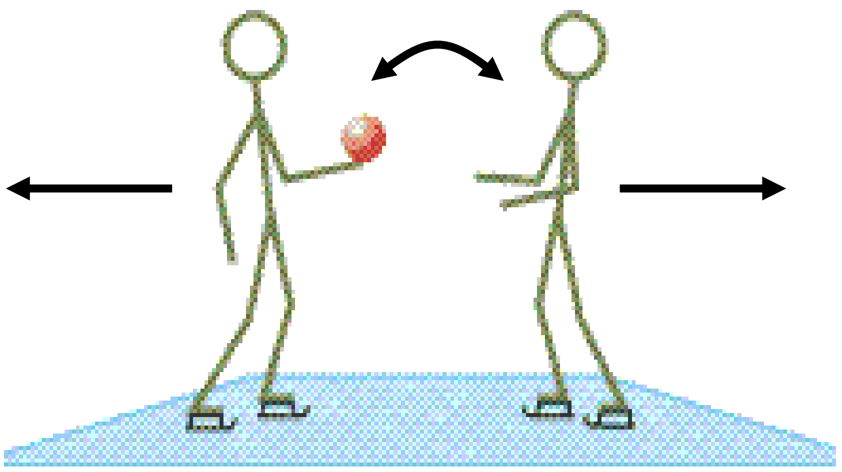
Interplay of theory and experiment is essential

Discussions, Papers, MCs….etc

The Standard Model of Particle Physics

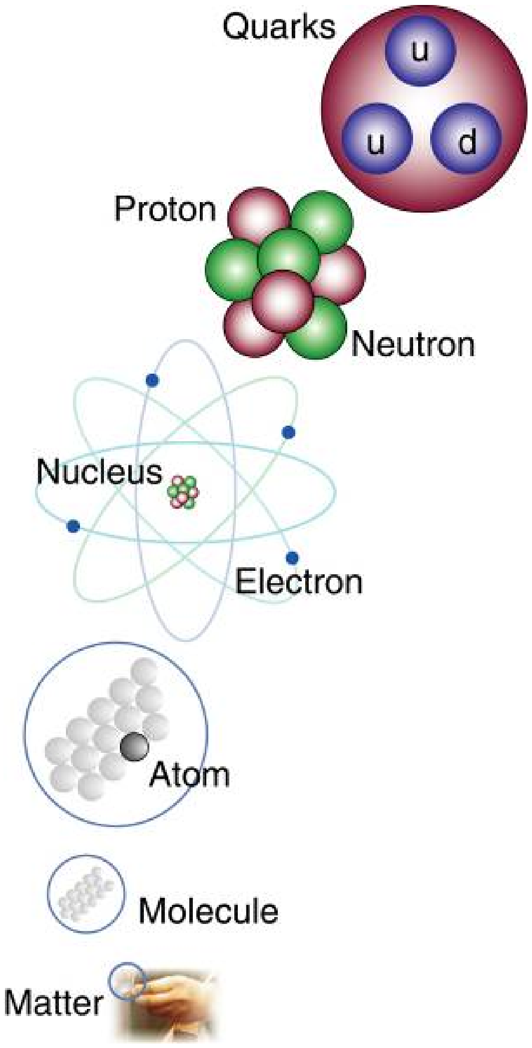


Forces due to exchange of particles:



Effect of force ~ intrinsic strength ("muscle power")
+ mass of carrier (~ range)

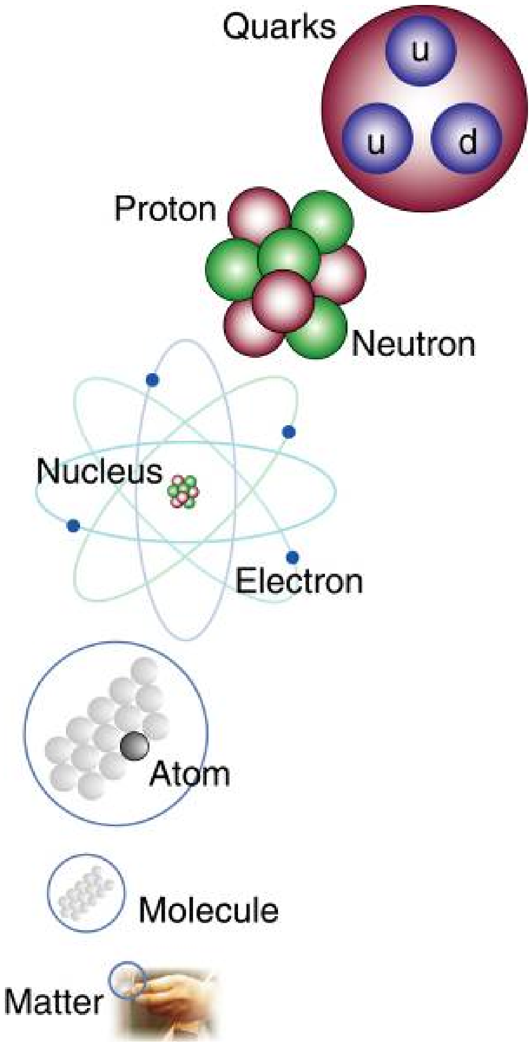
The Standard Model of Particle Physics



Gravitation electromagnetism weak force strong/nuclear force

Gravity	Electromagnetic	Weak	Strong
Graviton (not observed)	Photon	W^+, W^-, Z	Gluon
10^{-41}	1	0.8	25

The Standard Model of Particle Physics



Gravitation electromagnetism weak force strong/nuclear force

Gravity	Electromagnetic	Weak	Strong
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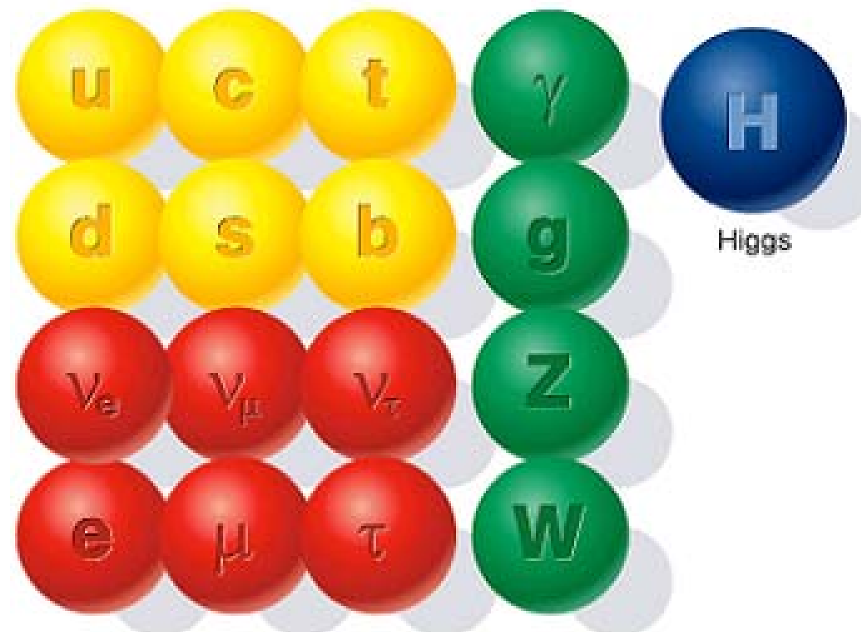
10^{-41}	1	0.8	25

Add another particle, the Higgs gives mass to other particles

The Standard Model of Particle Physics

- A few fundamental particles
- A few forces
  - mediated by bosons
- Higgs to give mass.



The Standard Model has been incredibly successful in explaining all data...
…but there are problems too.

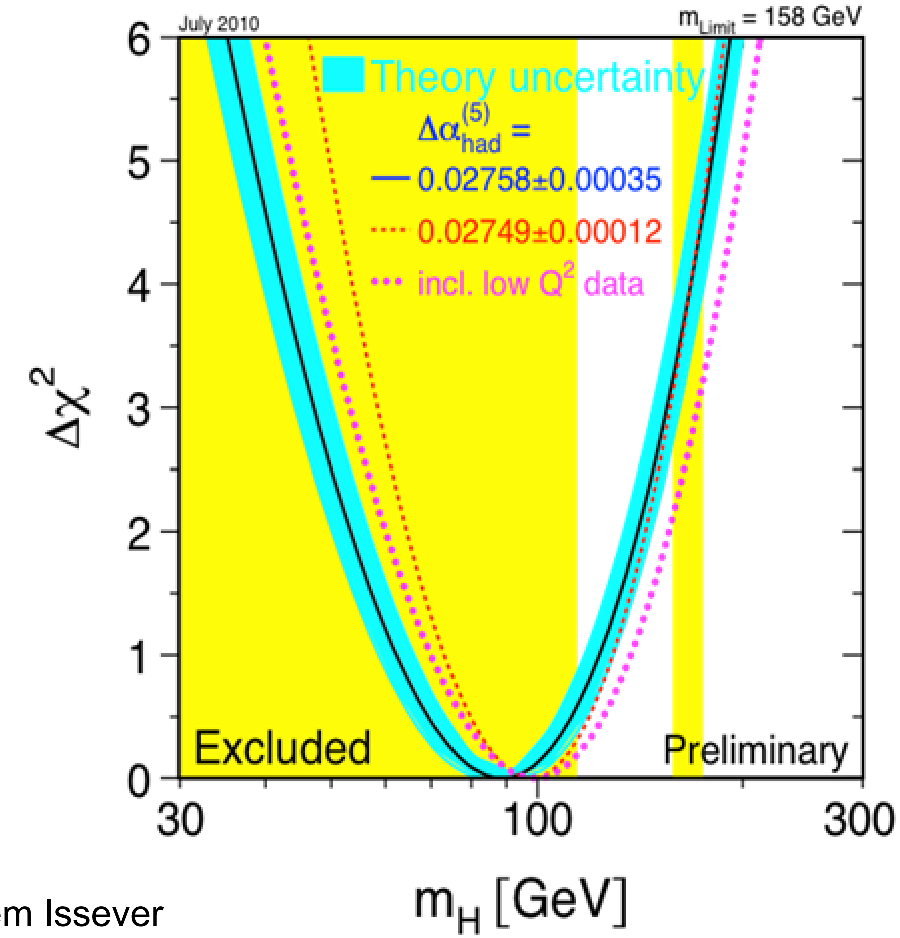
The Standard Problems: Higgs?

From precision Electroweak measurements

Mass of SM Higgs boson: $\mathbf{87^{+35}_{-26}}$ **GeV**

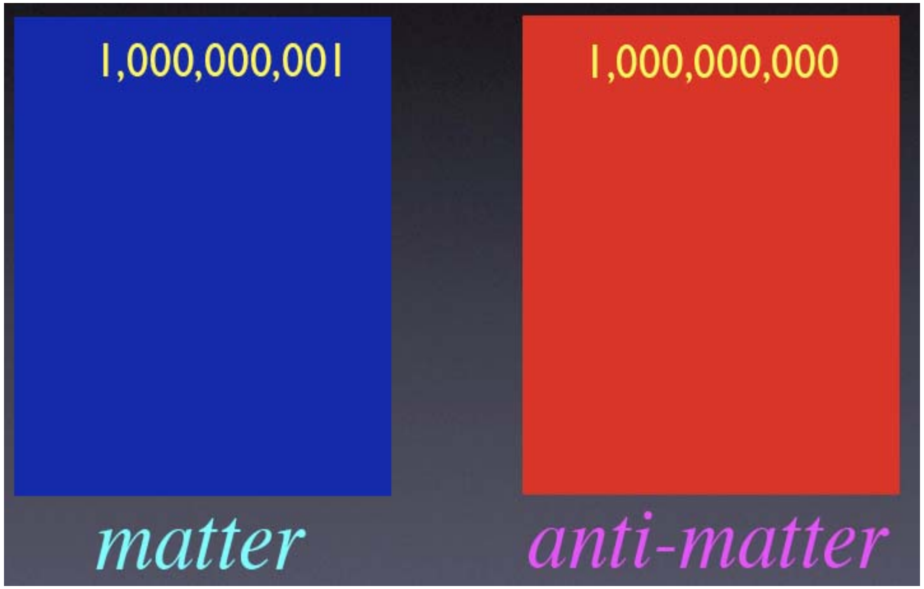
but we know $\mathbf{114 < m_H < 157}$ **GeV**

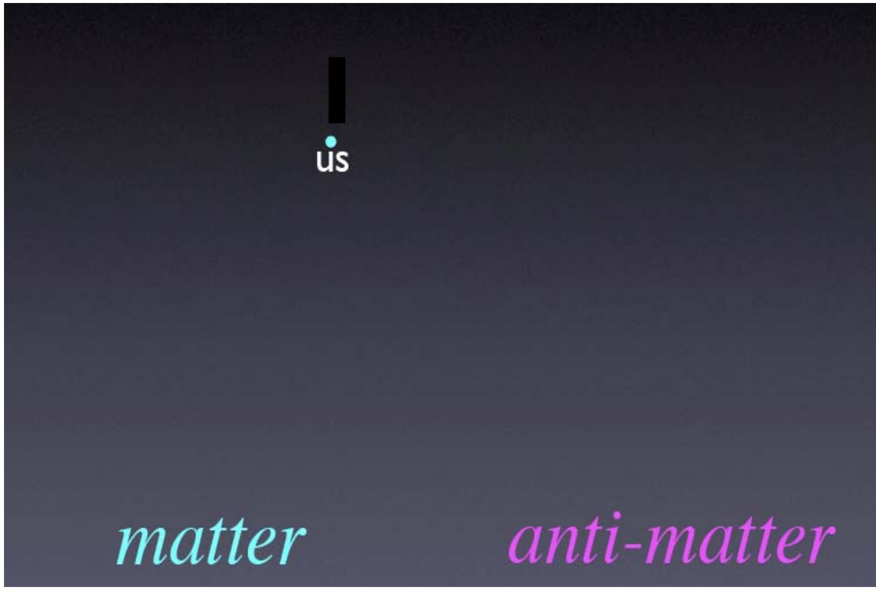
Where is the Higgs?



Standard Problems: antimatter?

What happened to all the antimatter?

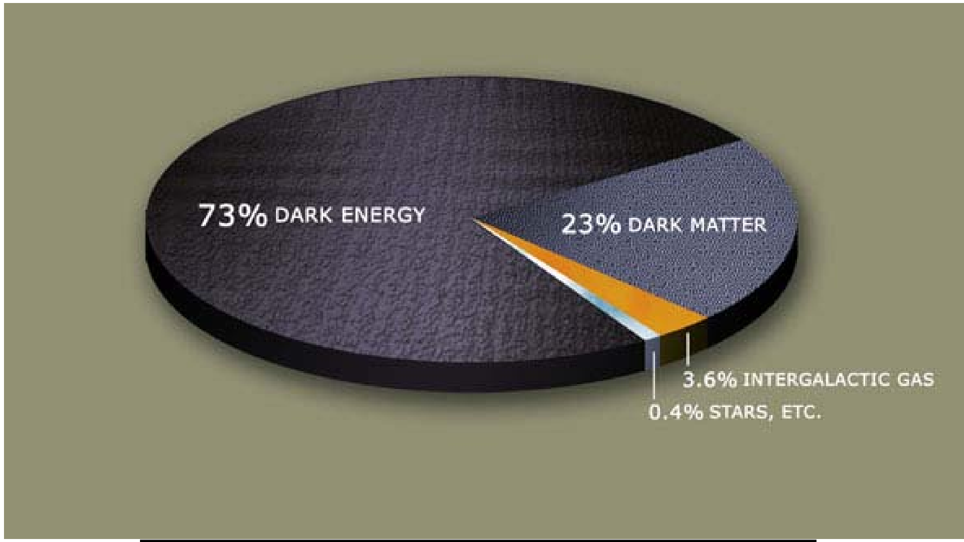


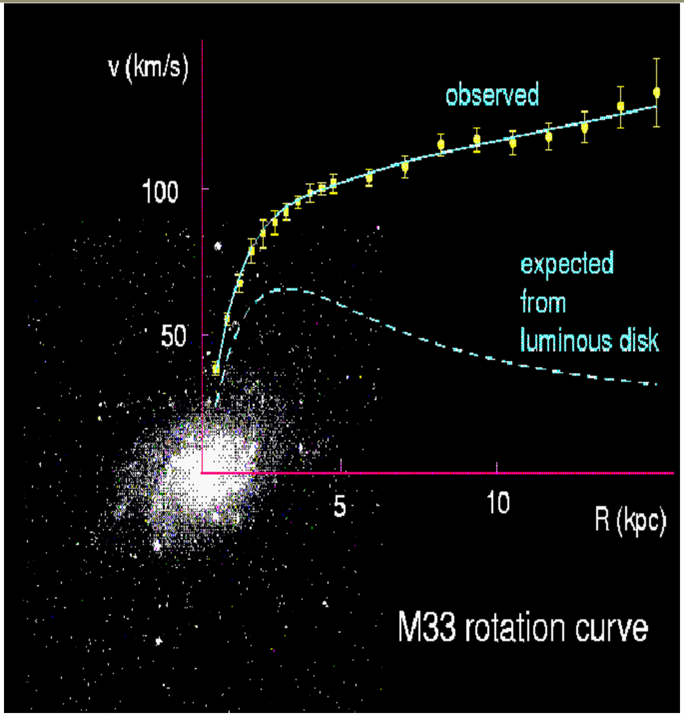


The imbalance is a trillion times bigger than the model predicts.

The Standard Problems: Dark Matter?

- 23 % Dark Matter
  - Inferred from gravitational effects
  - Rotational speed of galaxies
  - Orbital velocities of galaxies in clusters
  - Gravitational lensing
  - …..
- 73 % Dark Energy
  - Accelerated expansion of universe
- **Only 4 % made out of known matter…..**





More Problems!

“Cracks” have started to appear in the Standard Model…

Many problems identified over time

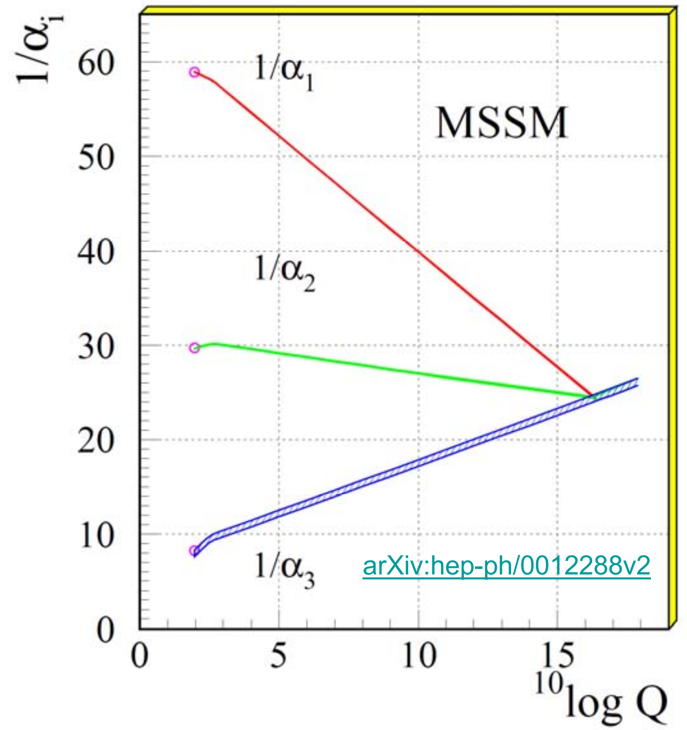
- No explanation of
  - masses,
  - coupling constants
- Why three families?
- Gravity not included
- The “hierarchy” problem, fine tuning…

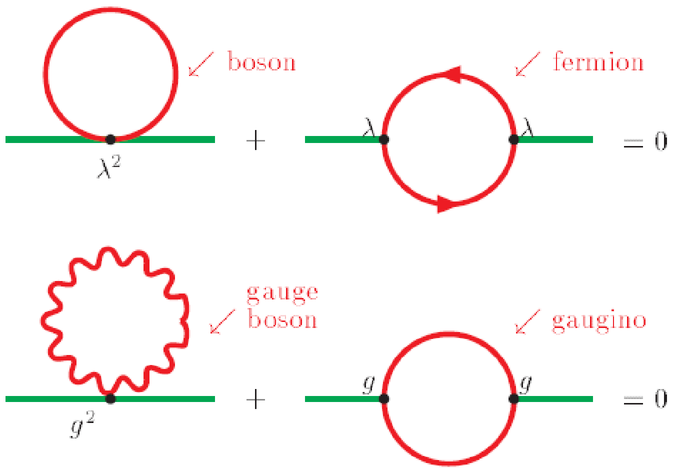
…and yet it explains the data

The Standard Model isn’t so much wrong as it is *incomplete*

Is SUSY the “next SM”?

- Supersymmetry (SUSY)
  - SM particles get partners (-spin ½)
- Unifications of forces possible
  - SUSY changes running of coupling
- Dark matter candidate exists:
  - The lightest neutral partner of the gauge bosons
- No (or little) fine-tuning require
  - cancellation of loop corrections

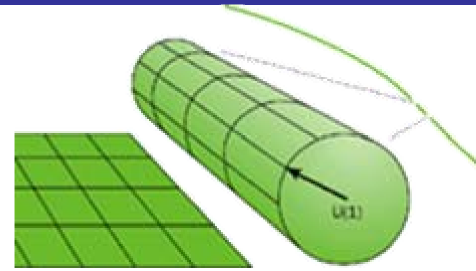




D. I. Kazakov

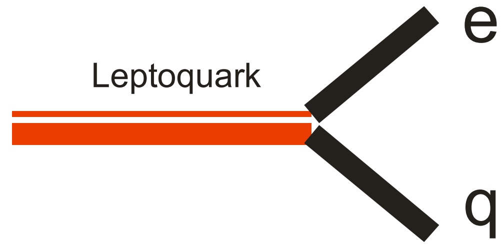
What else is there beside SUSY?

- **Extra spatial dimensions**
  - Addresses hierarchy problem
  - make gravity strong at TeV scale

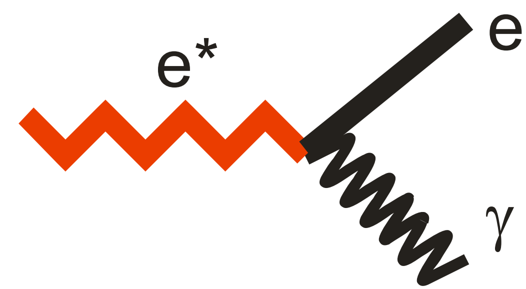


- **Extra gauge groups: Z', W'**
  - Occur naturally in GUT scale theories

- **Leptoquarks:**
  - Would combine naturally the quark and lepton sector



- **New/excited fermions**
  - More generations? Compositeness?



- something not thought of yet

Redman's Theorem

Sorting out the structure of the universe can be frustrating…

…just ask the astronomers

"Any competent theoretician can fit any given theory to any set of facts."

Quoted in M. Longair's *High Energy Astrophysics*, sect 2.5.1: "The Psychology of Astronomers and Astrophysicists": Prof. R. Redman, 1905-1975

First we need data…

S.Worm

Accelerator Advances

Accelerator Advances

At the LHC we can create and study new interactions

Accelerator Advances

- Each advance is a *revolution*…
  - but sadly only once or twice per generation
- To help understand our excitement about the LHC
  - Previous energy record-holder (Tevatron) started in 1983 - 27 years
  - LEP at CERN stopped in 2000 - 10 years ago

S.Worm

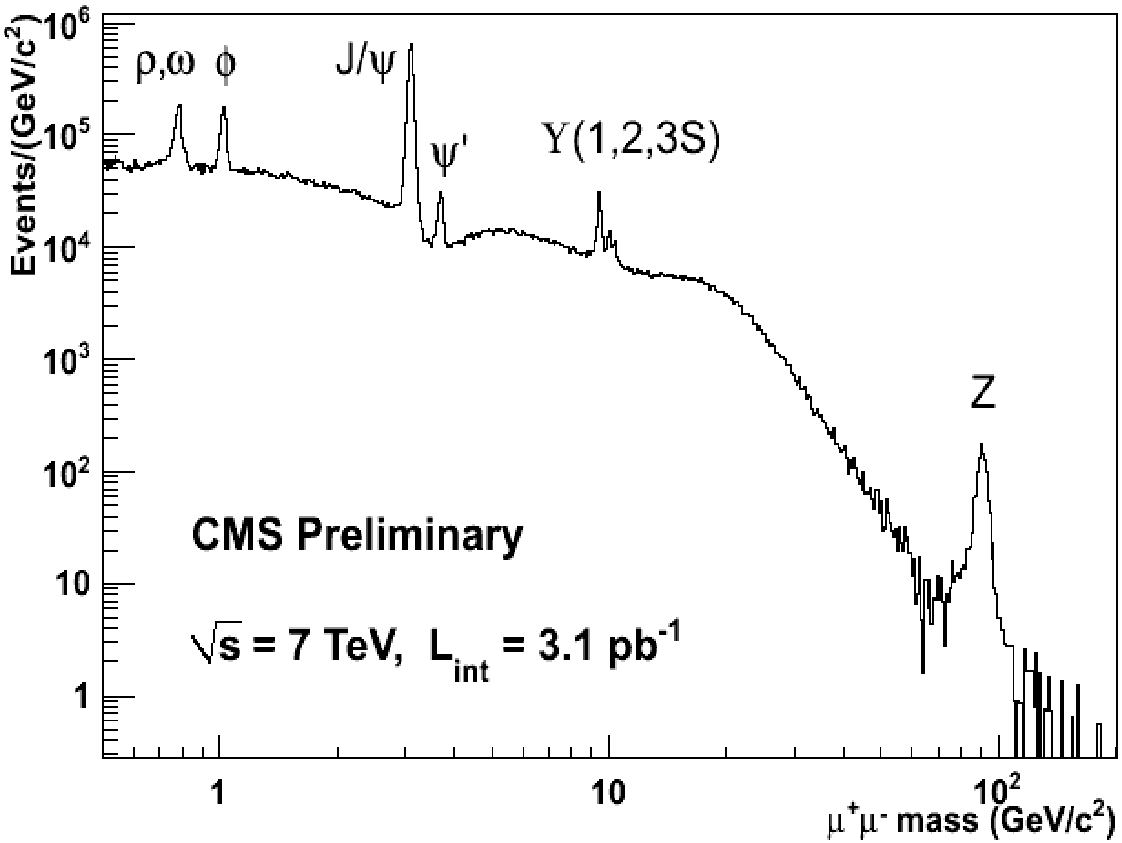
Role of Colliders

- **Colliders key tool for discovering particles we know today**
  - Anti-proton (LBNL, 1955)
  - Quarks (SLAC 1969)
  - W- and Z-boson (CERN, 1983)
  - Top-quark (FNAL, 1994)
  - … plus many more

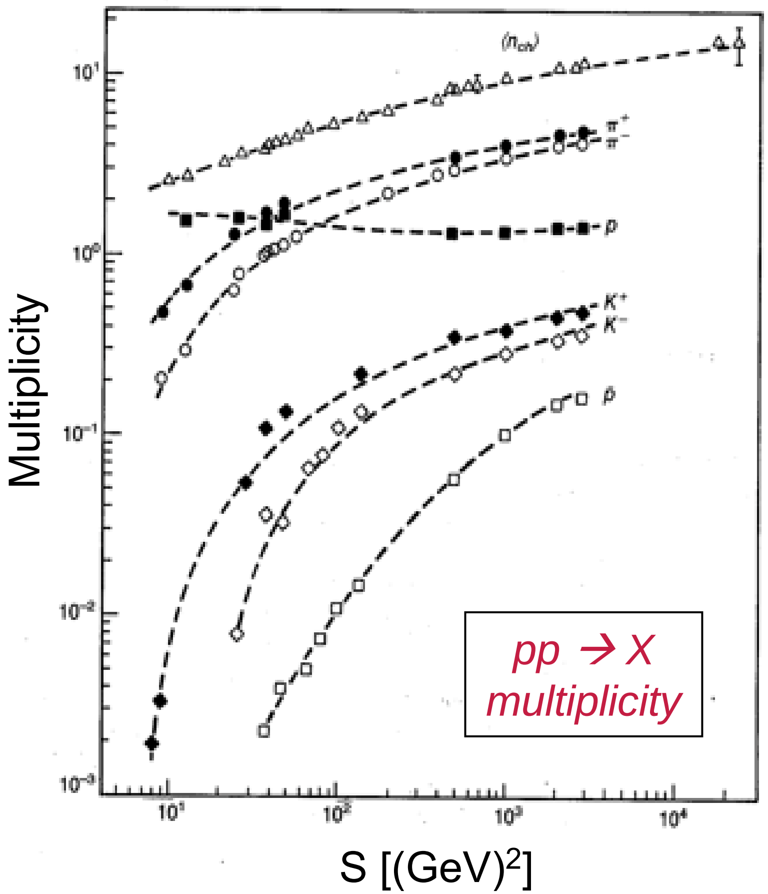
- **Basic principle follows from $E=mc^2$**
  - If collider energy ≥ mass of particle
    - particle can be produced

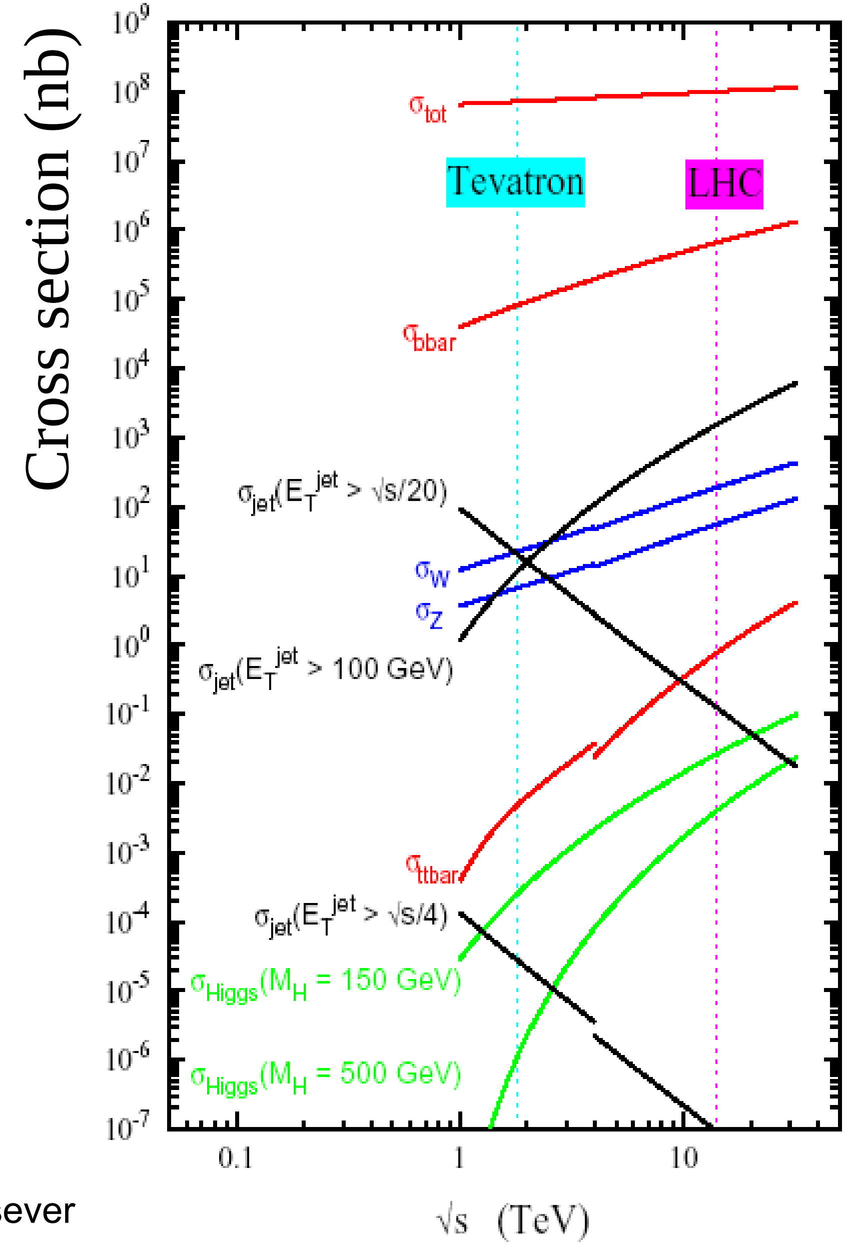
New Energy Regimes

- Each advance in territory makes new discovery possible
- Many historic examples…
- Hunting for "bumps" in the mass spectra



More energy, more particles





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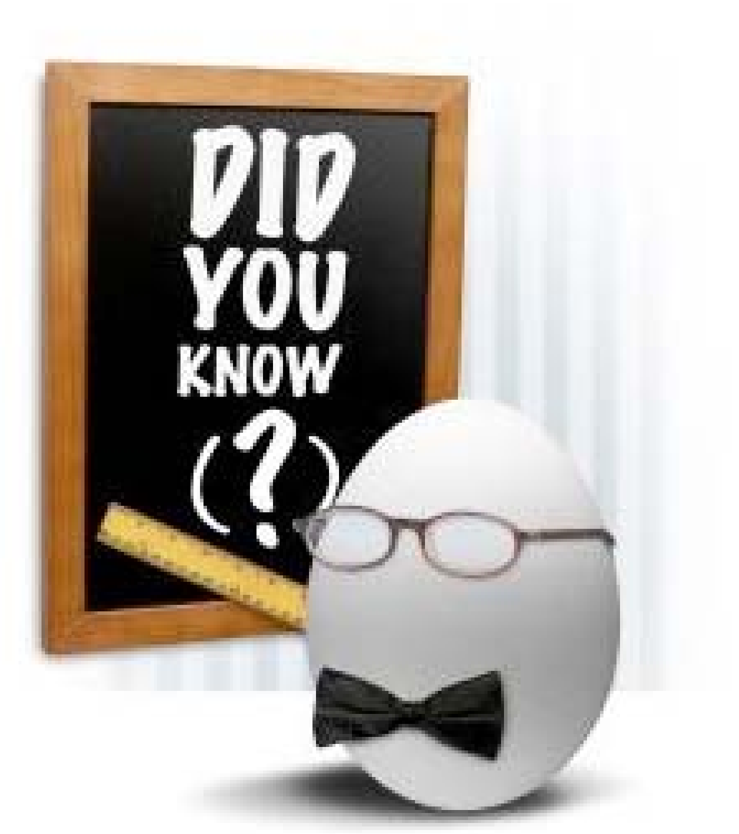
Some Fun Facts about the LHC

-



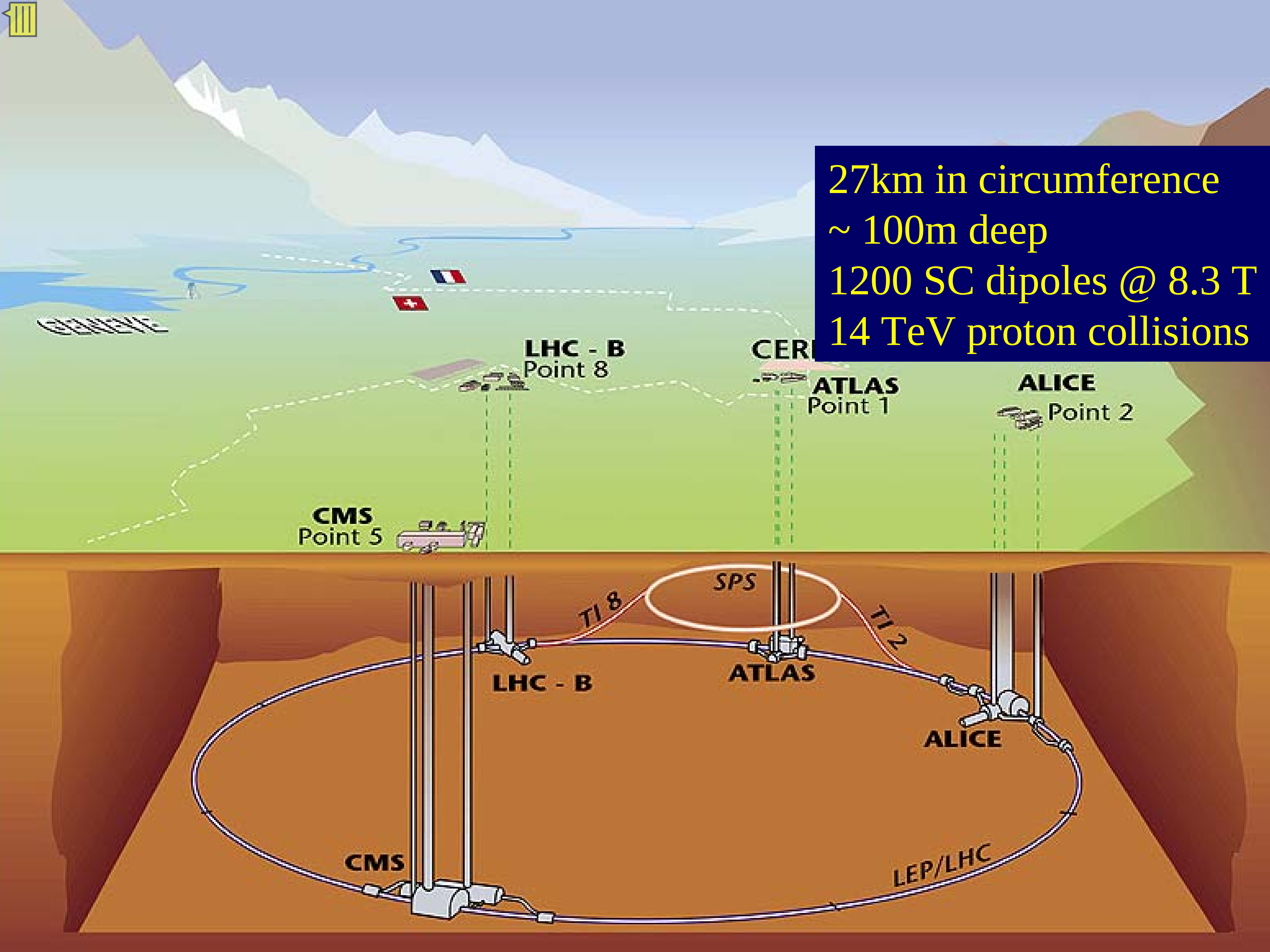
http://www.sustain.ucla.edu/media/images/facts_general.jpg

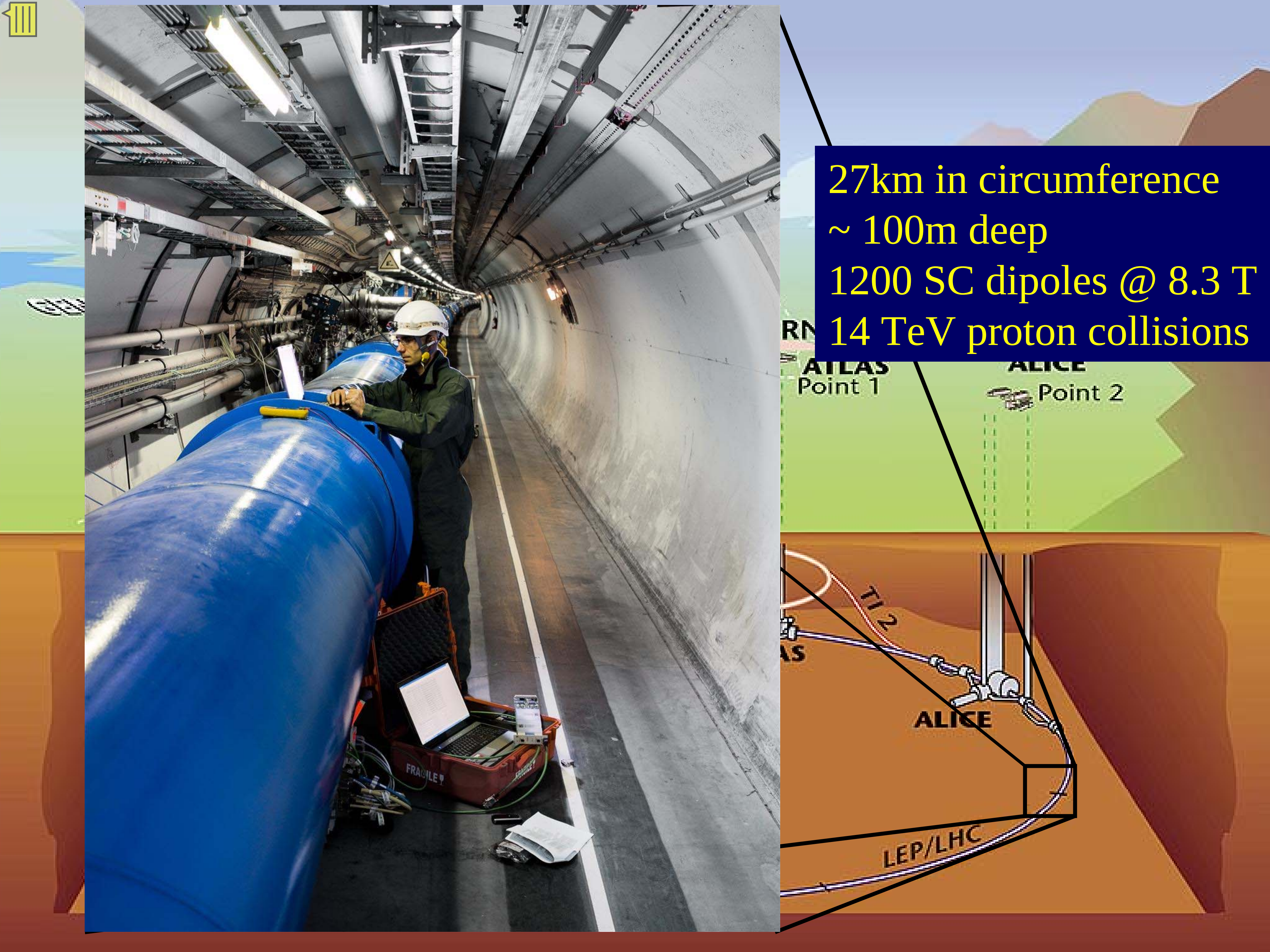
27km in circumference

~ 100m deep

1200 SC dipoles @ 8.3 T

14 TeV proton collisions





27km in circumference
~ 100m deep
1200 SC dipoles @ 8.3 T
14 TeV proton collisions

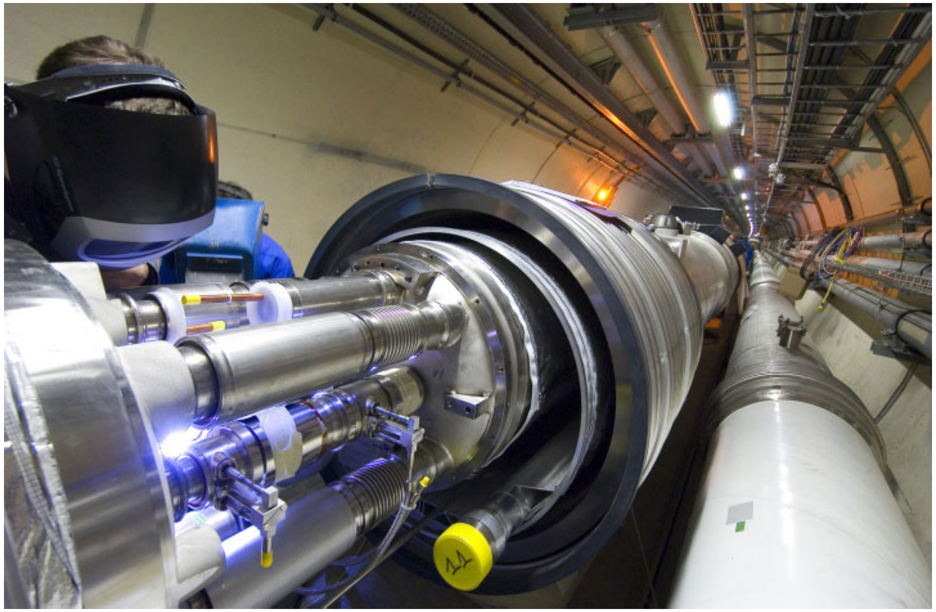
Proton on Proton Collisions at 14 TeV*

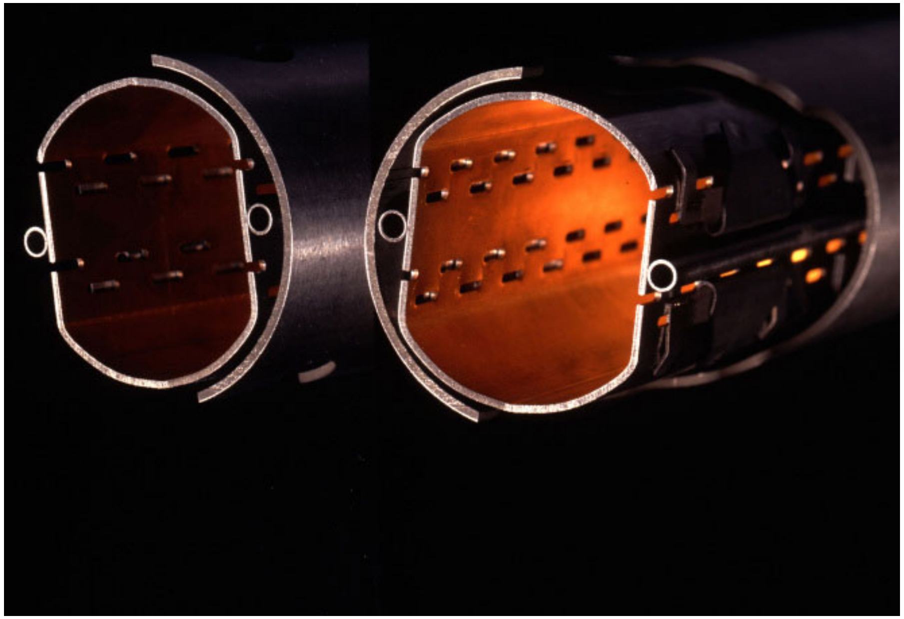
7 TeV   7 TeV

- 1 TeV ~ kinetic energy (KE) of a mosquito
- 10^{11} protons in a bunch = KE of a London bus
- LHC beam stores 700 MegaJoules

*Lead on Lead at 1150 TeV

The emptiest (largest) vacuum in the solar system

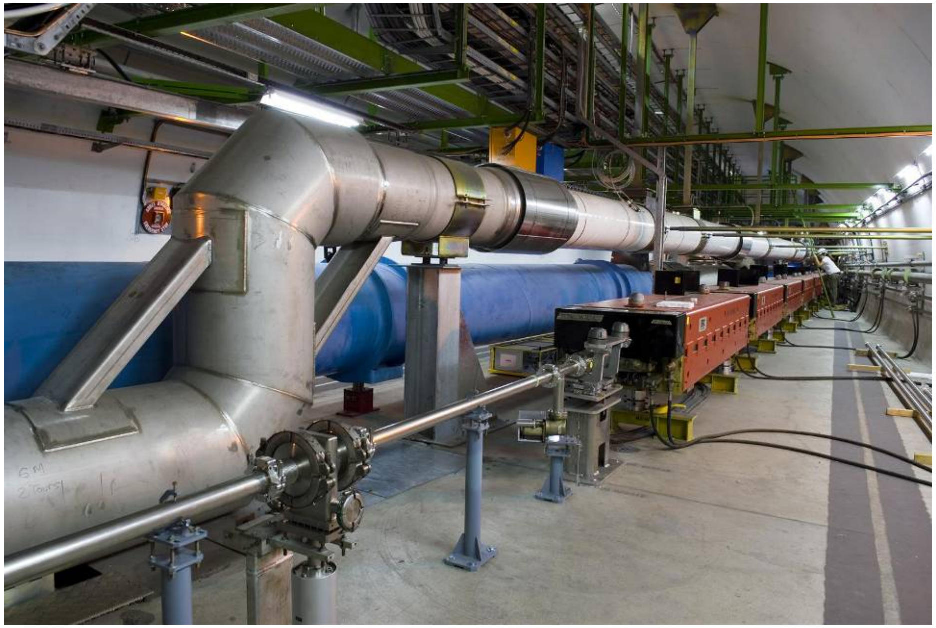




Ten times more atmosphere on the Moon than inside LHC beam pipes

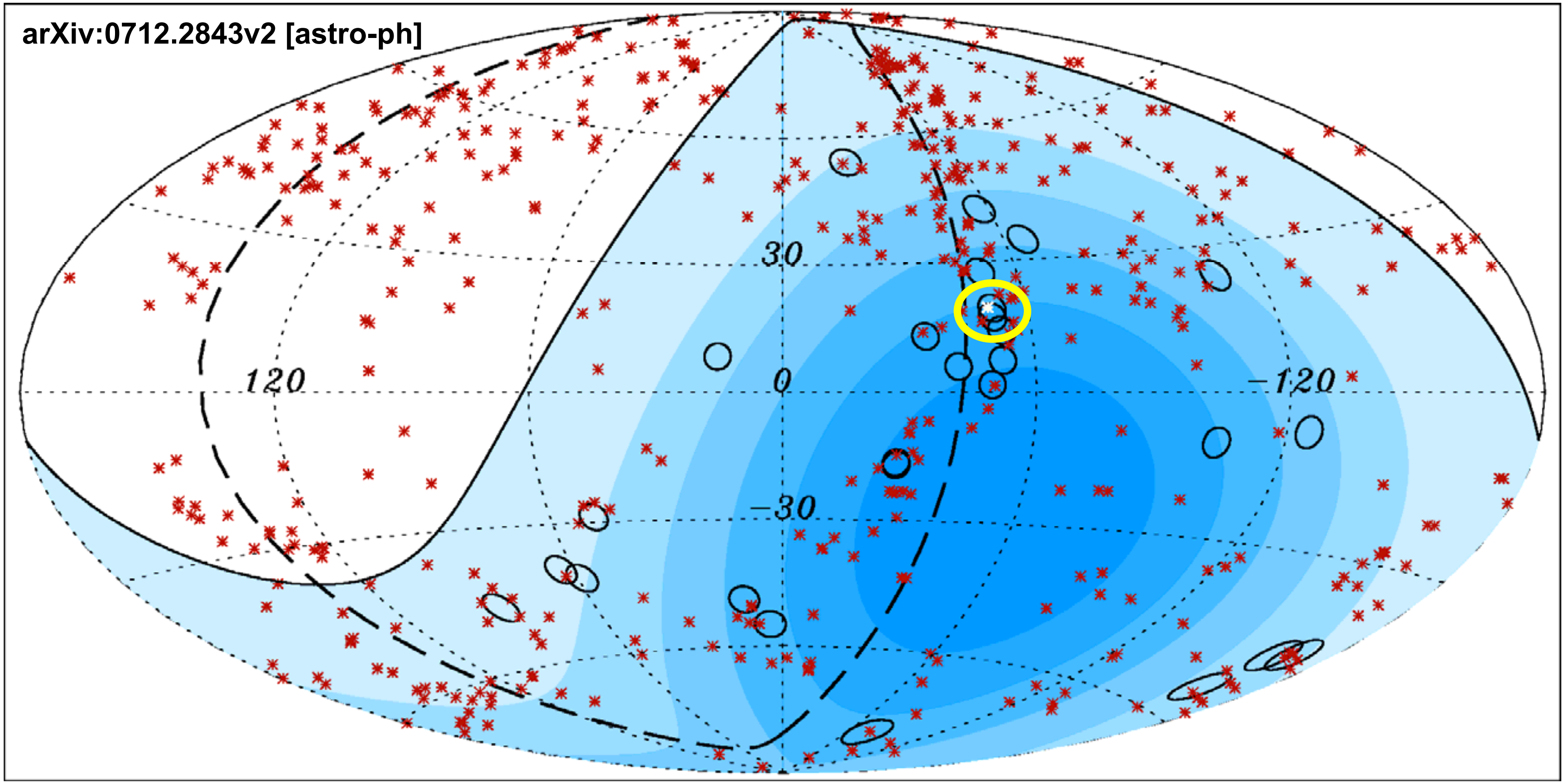
Colder than outer space

LHC operates at 1.9 K
38000 tones cool mass
120 tones of Helium



The largest refrigerator ever

Sources of ultra high energetic particles



27 highest energy cosmic rays detected by Auger 2004 - 2007

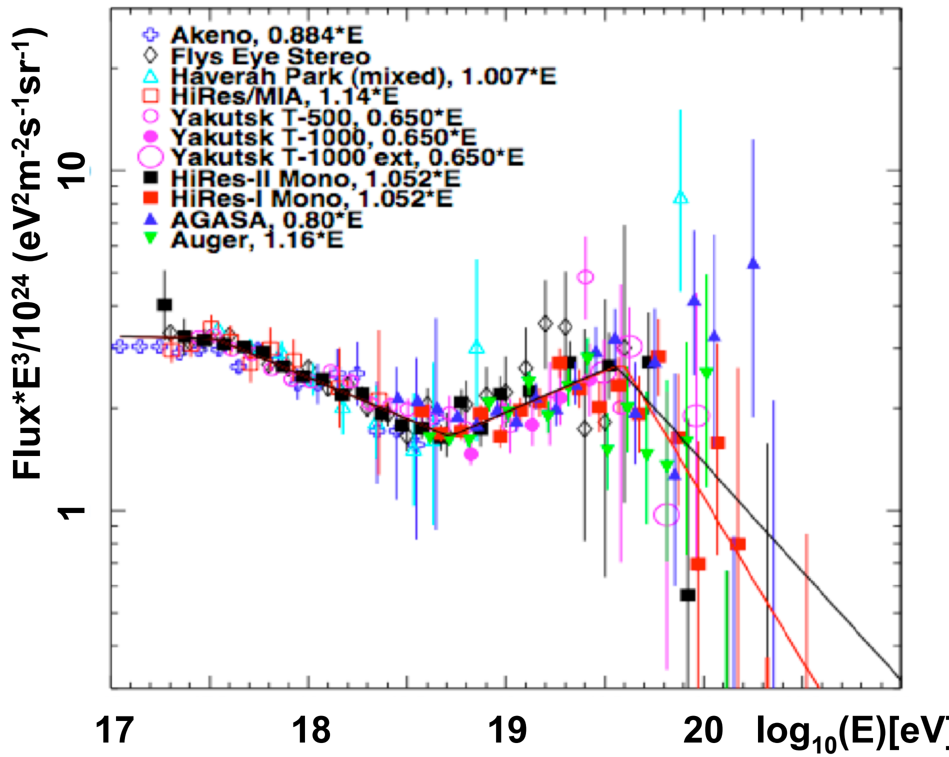
$E > 6x10^{19}$ eV=$60x10^{6}$ TeV

LHC is safe!

J. Ellis, http://indico.cern.ch/conferenceDisplay.py?confId=39099

- LHC@14 TeV=cosmic ray@10^{17}eV
- ~ 3.10^{22} cosmic rays >10^{17} e have struck Earth
- Equivalent to 10^5 LHC programmes
- Area of Sun 10^4 larger
- 10^{11} stars in galaxy
- 10^{11} galaxies in Universe
- Nature has performed 10^{31} LHC programmes
- Nature carries out 3.10^{13} LHC programmes per second

arXiv:0806.3414v2 [hep-ph]



ultra-high-energy cosmic rays up to 10^{20} eV

Luminosity

- Single most important quantity
  - Drives ability to observe new rare processes

$$L = \frac{f * n_{bunch} * N_p^2}{4\pi * \sigma_x * \sigma_y}$$

- revolving frequency f = 11245.5/s
- n_{bunch} = 2808
- N_p = 1.15 x 10^{11} Protons/Bunch
- Area of beams: $4\pi\sigma_x\sigma_y$~40 μm

- Rate of physics processes per unit time ~ L

$$N_{Obs} = \int L dt * \varepsilon * \sigma_{process}$$

Cross section; given by nature; predicted by theory

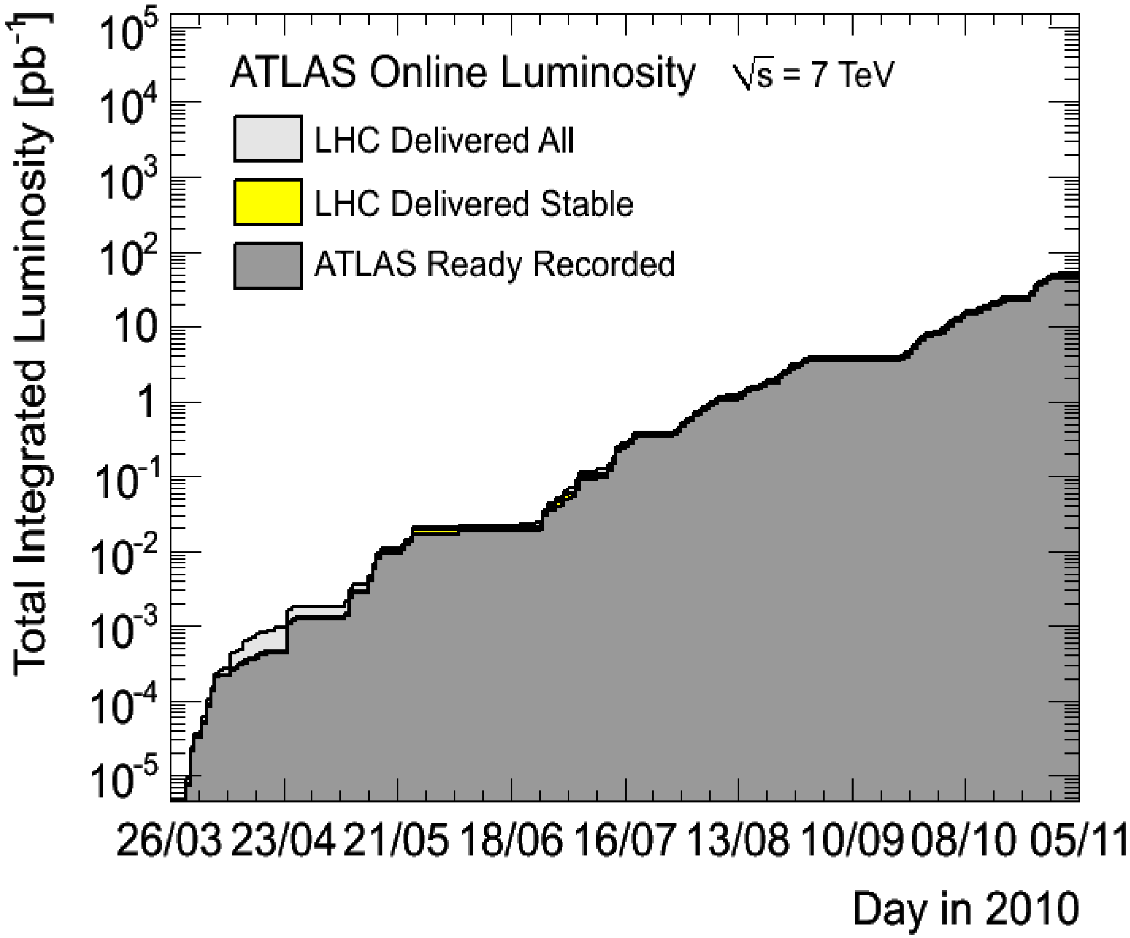
Efficiency; optimized by experimentalists

Maximize N_{obs} → max ε and L

2010 Proton Proton Collisions

- First 7 TeV collision:
  - 30.03.2010
- End of proton run:
  - 04.11.2010

$$\int_{2010} L\,dt = 45\,pb^{-1}$$



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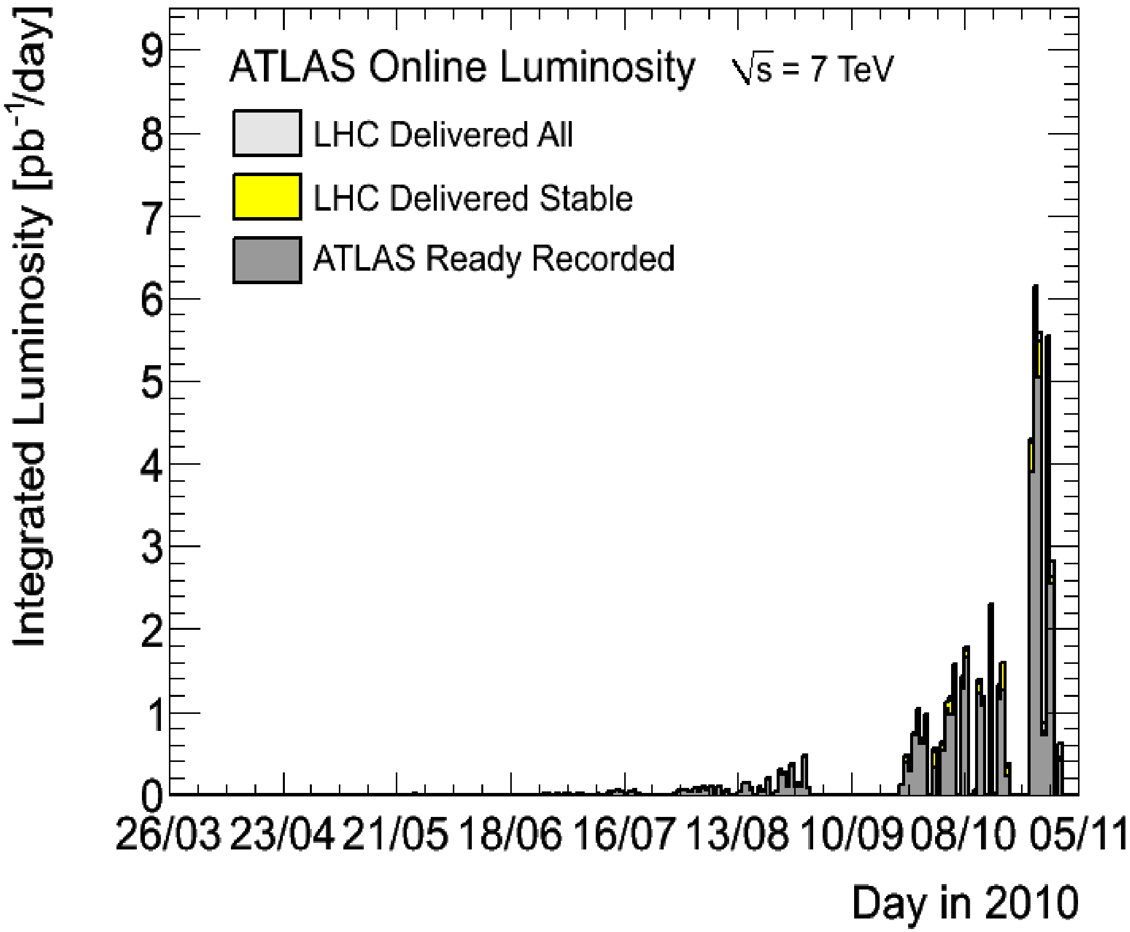

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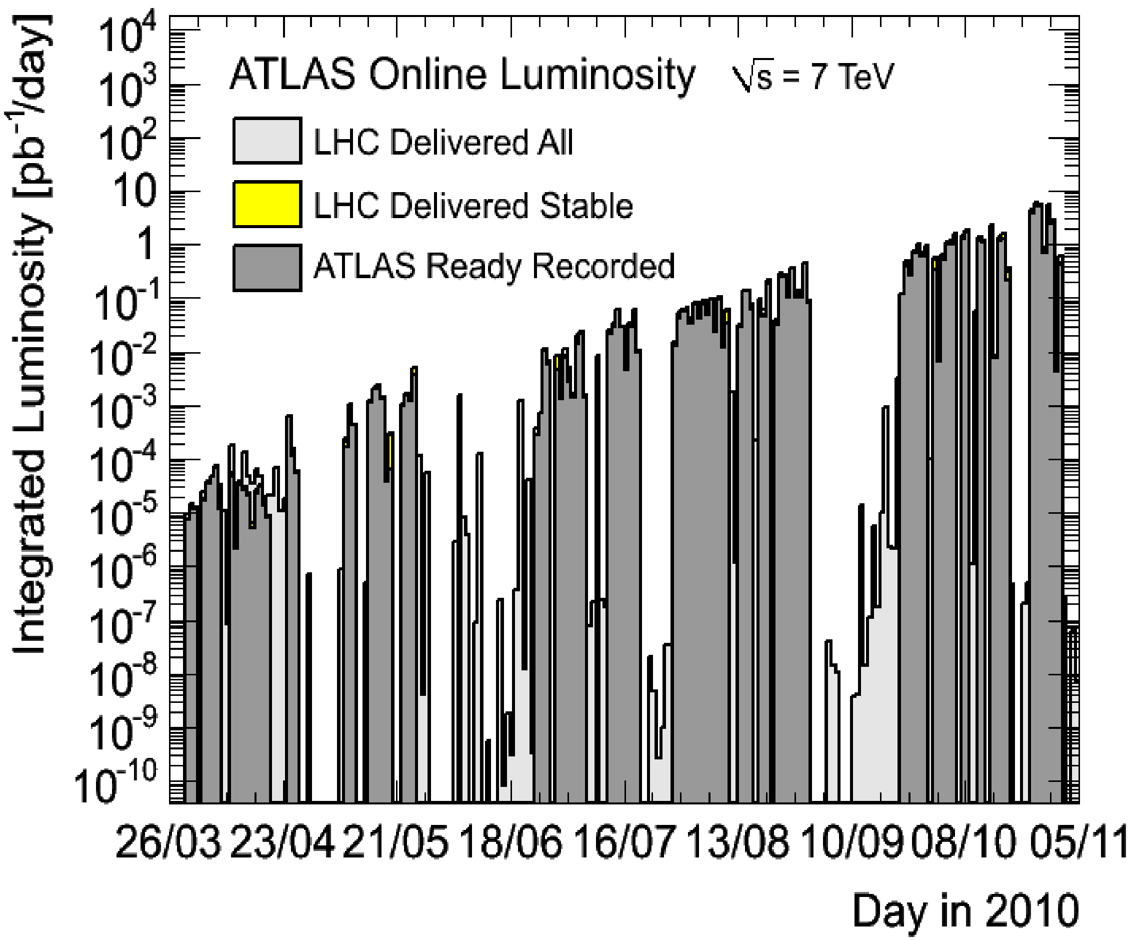
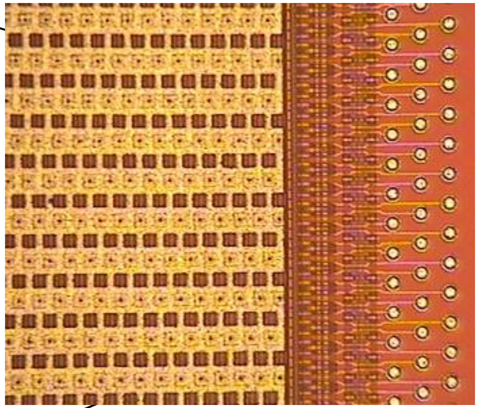


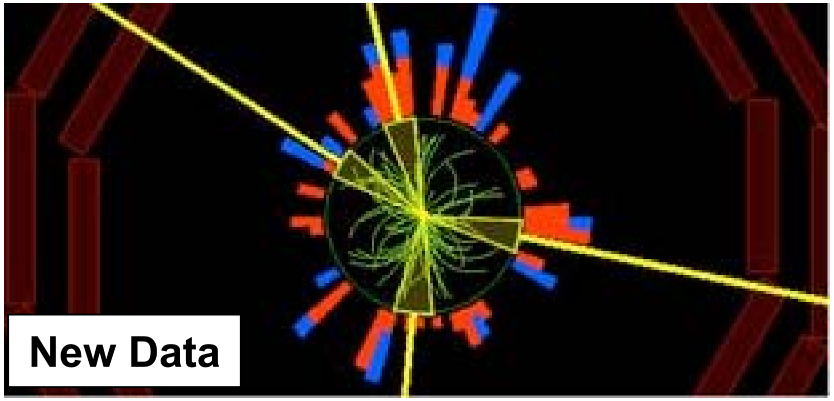
Detectors and Computing

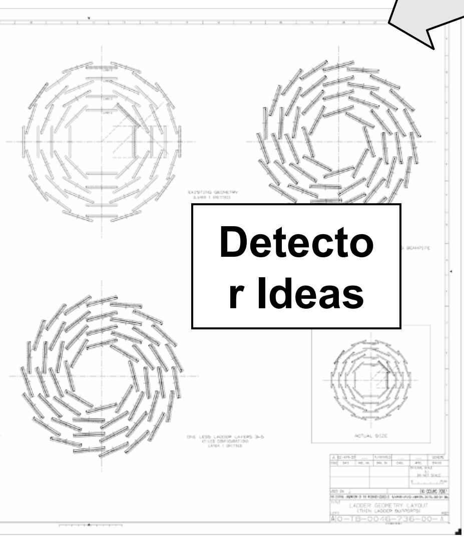
New Detectors, Computing Tools

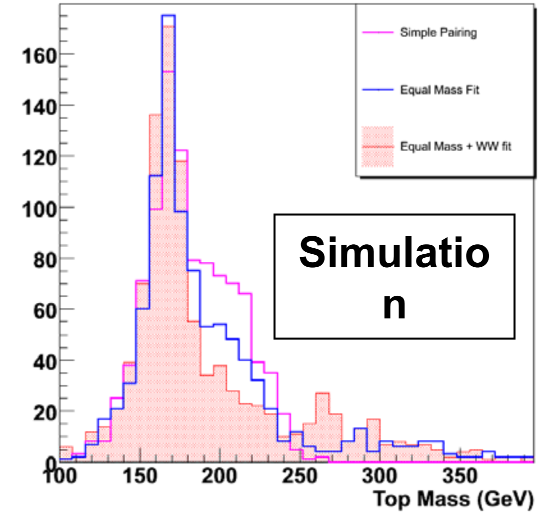
With new developments come new capabilities

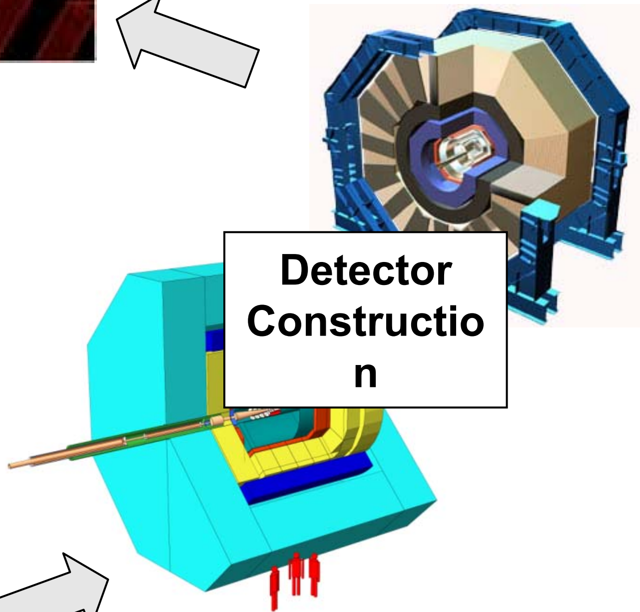


The Detector Development Loop Today



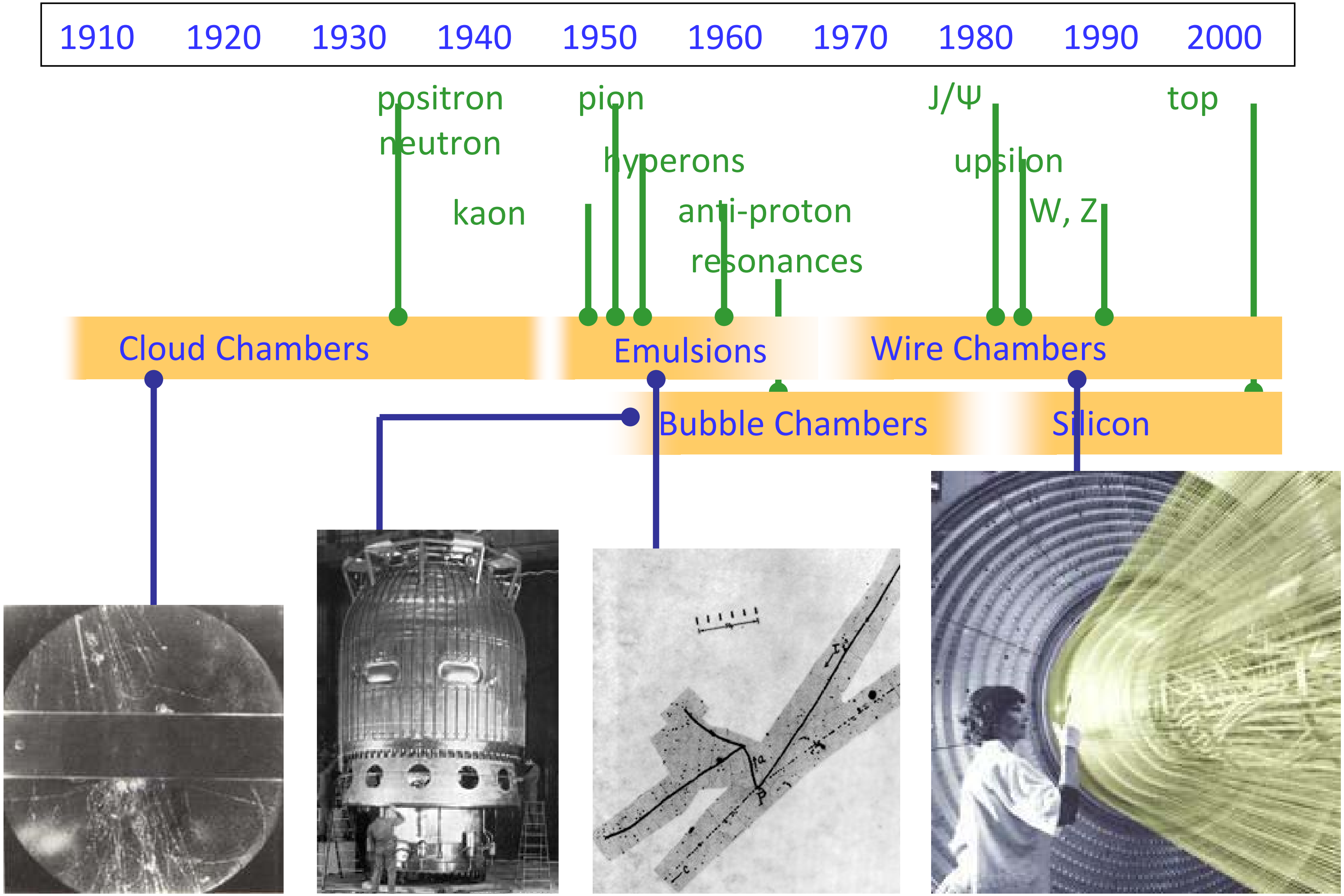




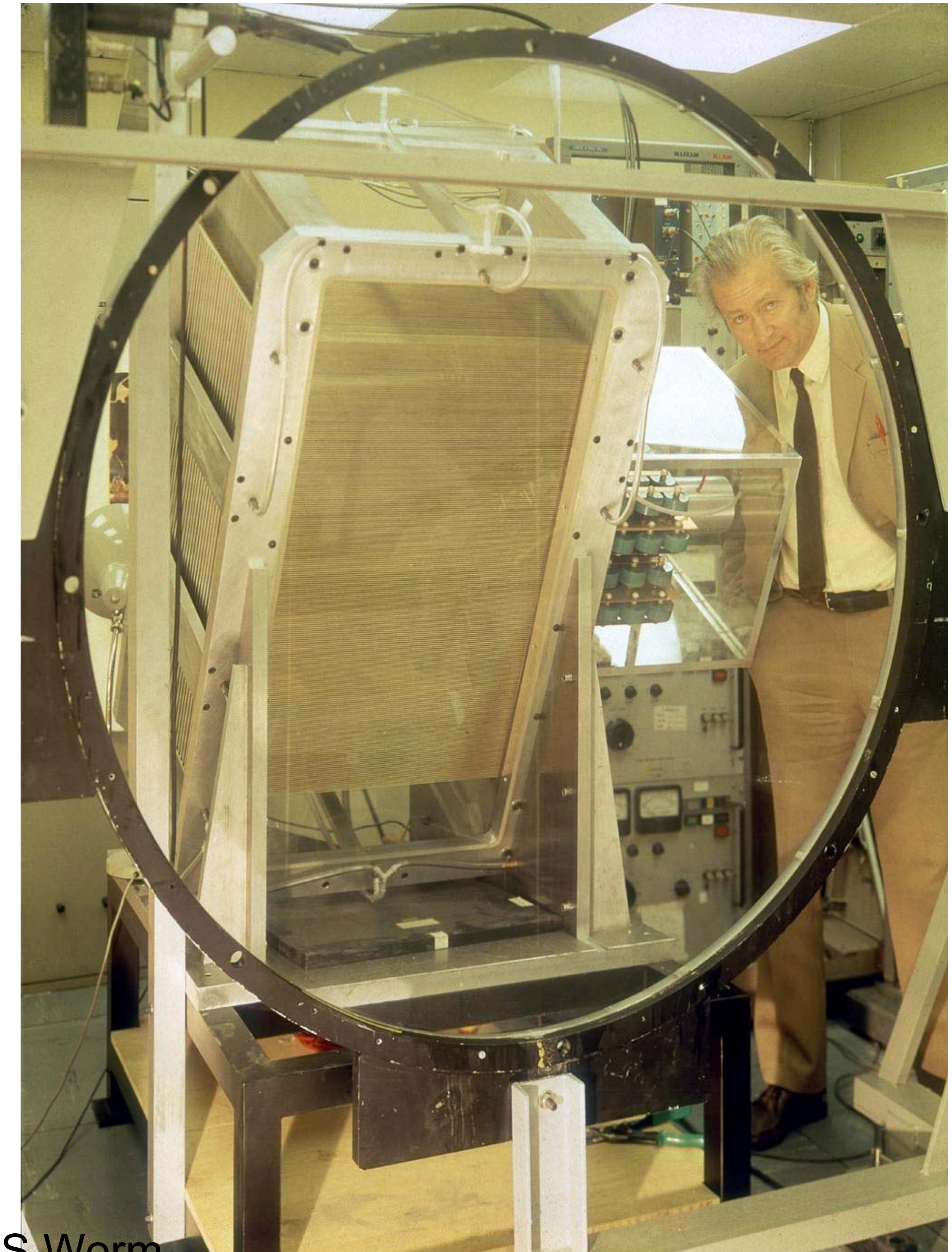


S.Worm

Interplay of Detectors and Discoveries



S. Worm



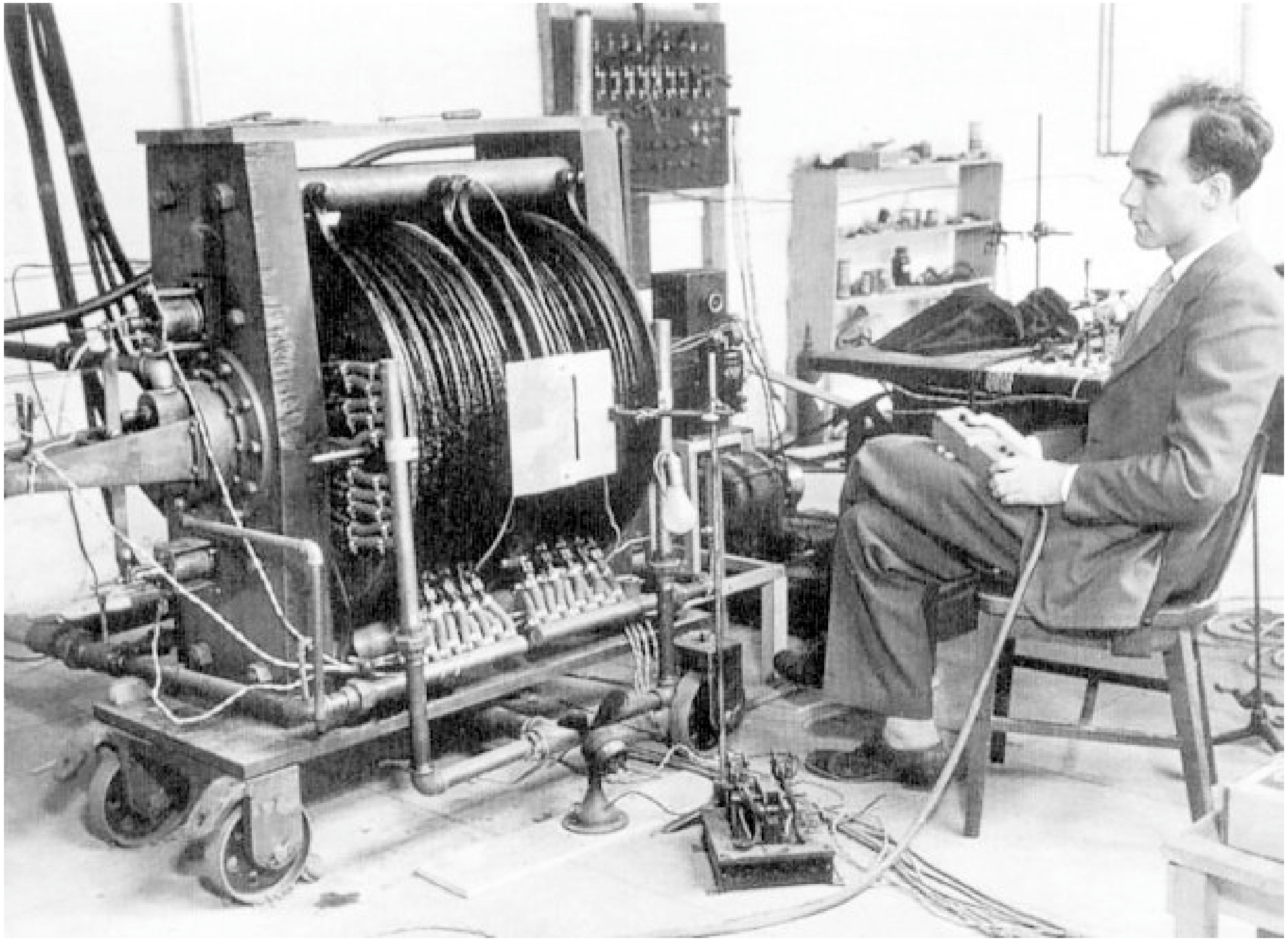
S.Worm

Georges Charpak
(1924 – 2010)

Invented Multi-wire proportional chambers (1968) which rapidly replaced bubble chambers

Nobel Prize in Physics in 1992

Searches and (old fashioned) Detectors:



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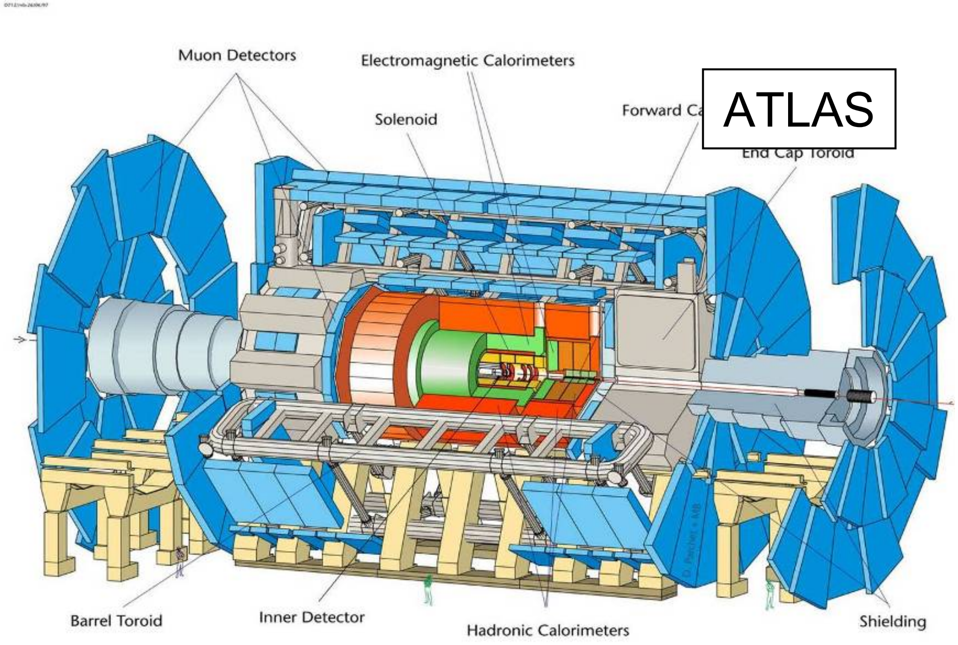
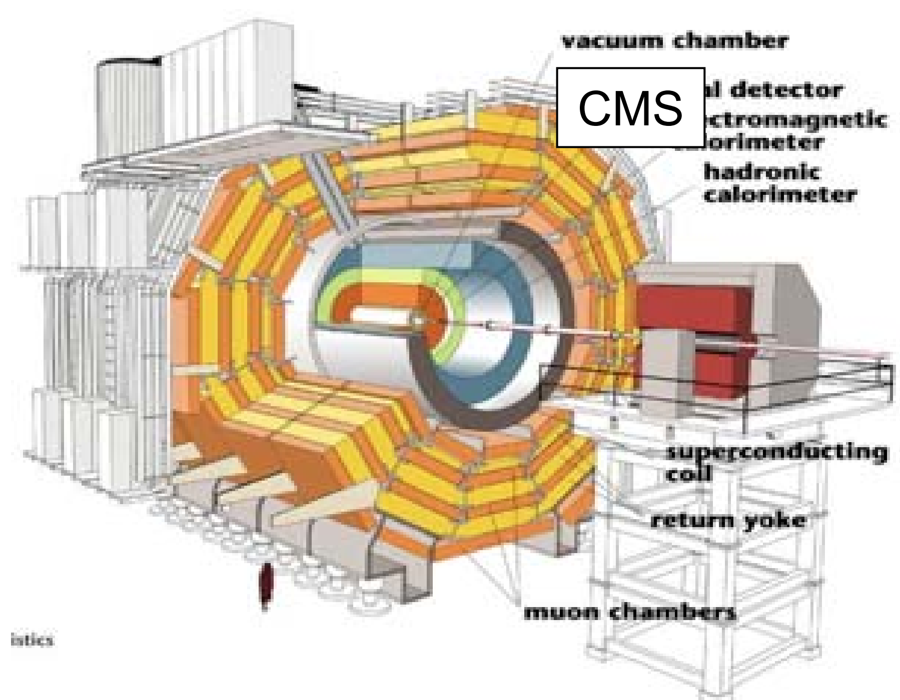
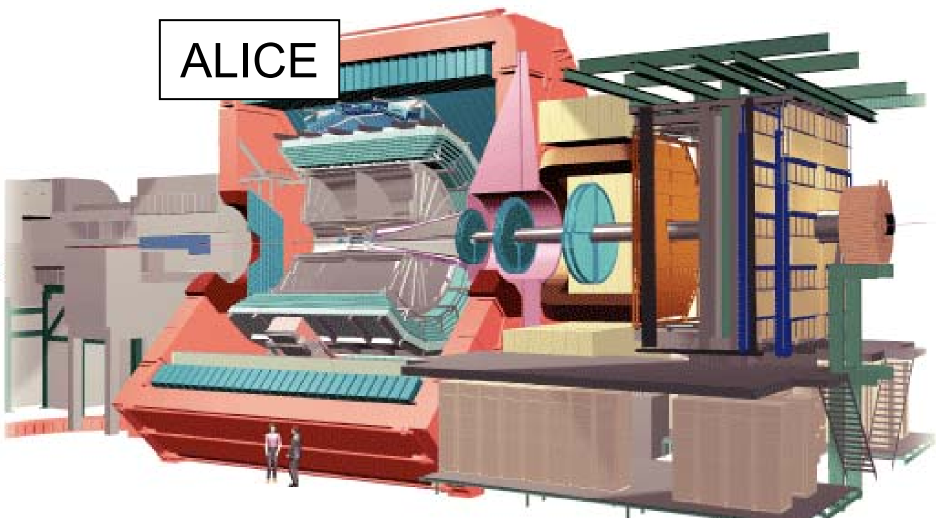
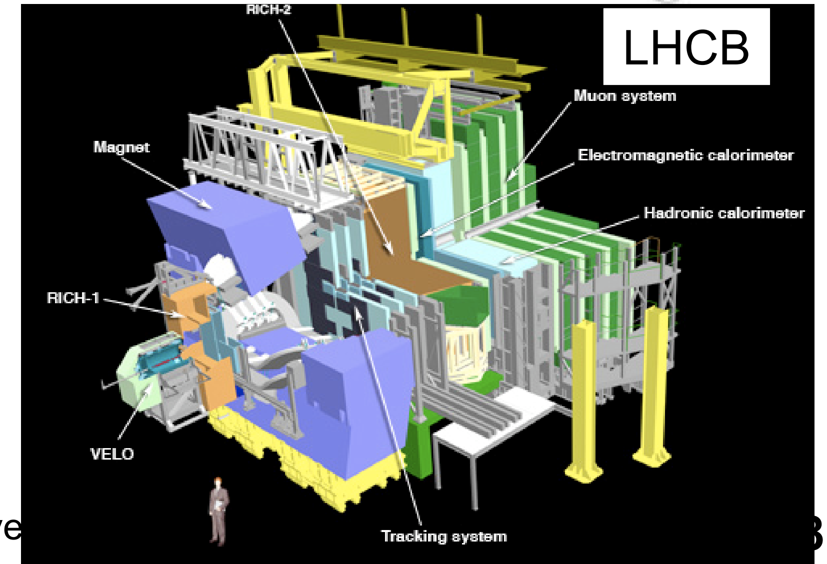
New/better detector → new physics found → Nobel prize (simple, isn't it?)

Modern Detectors

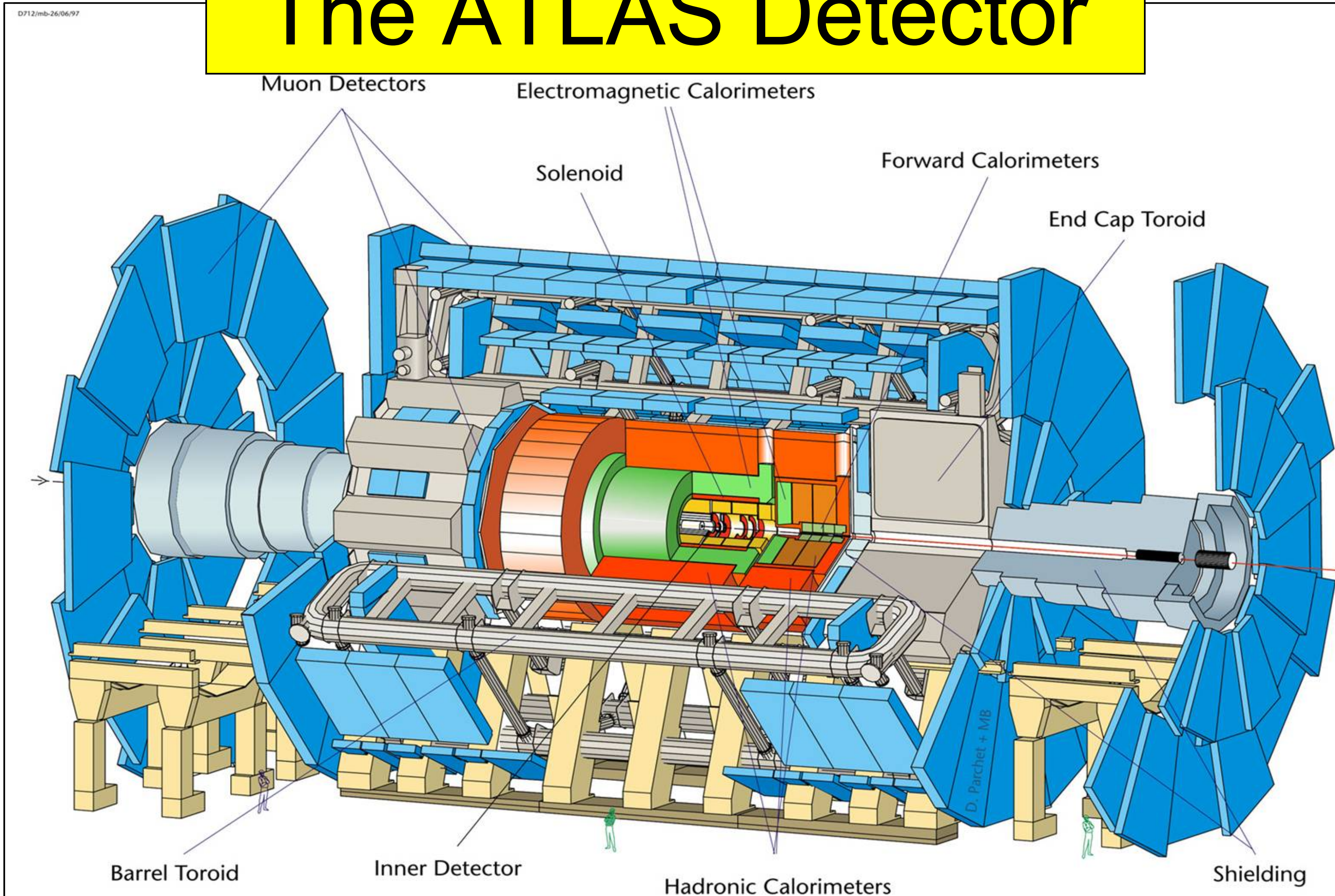








The ATLAS Detector



Diameter	25 m
Total length	46 m
Overall weight	7000 tons

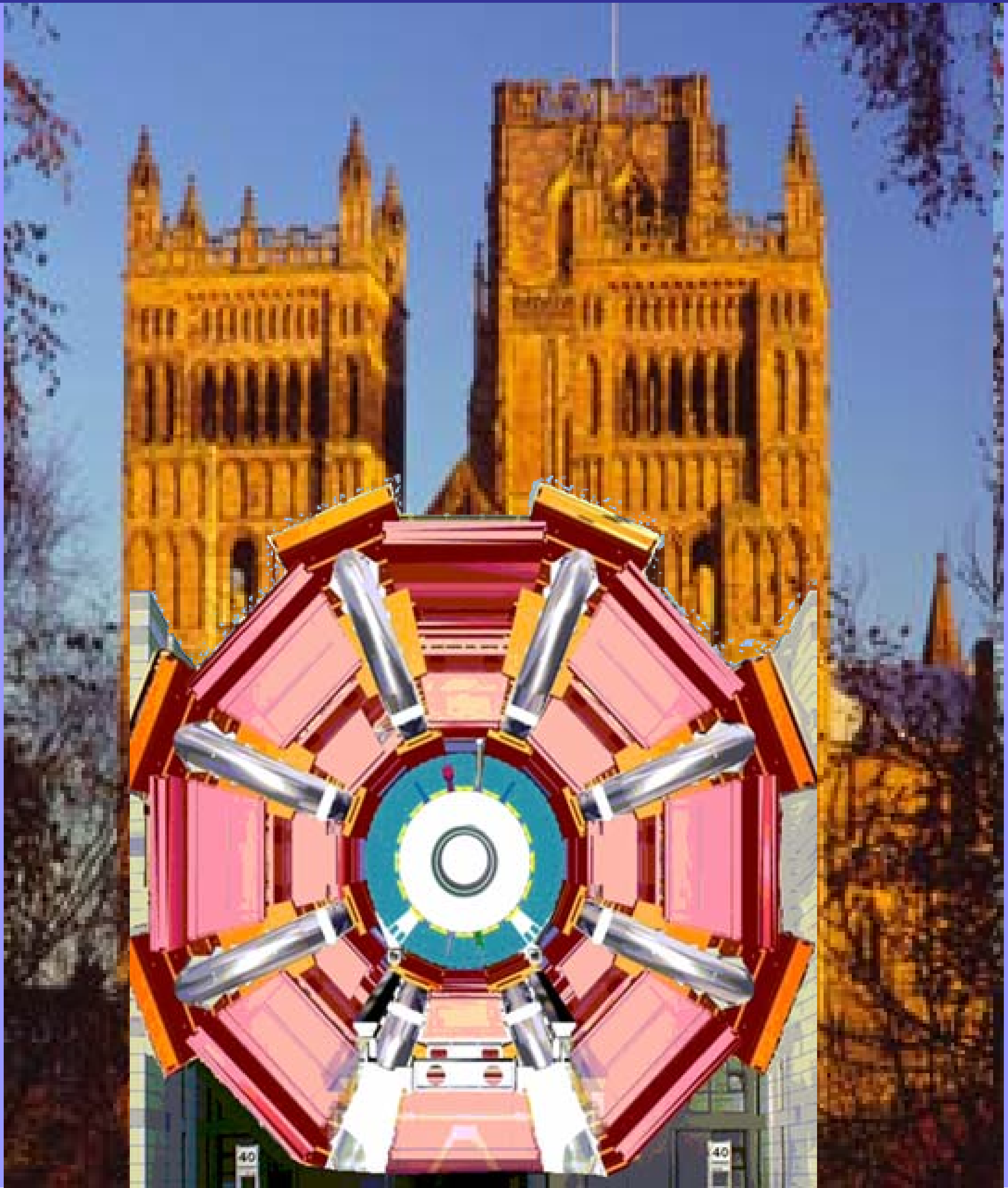
Over 2500 scientists and engineers
Nearly 40 countries
More components than a moon rocket

Detector Mass in Perspecitive

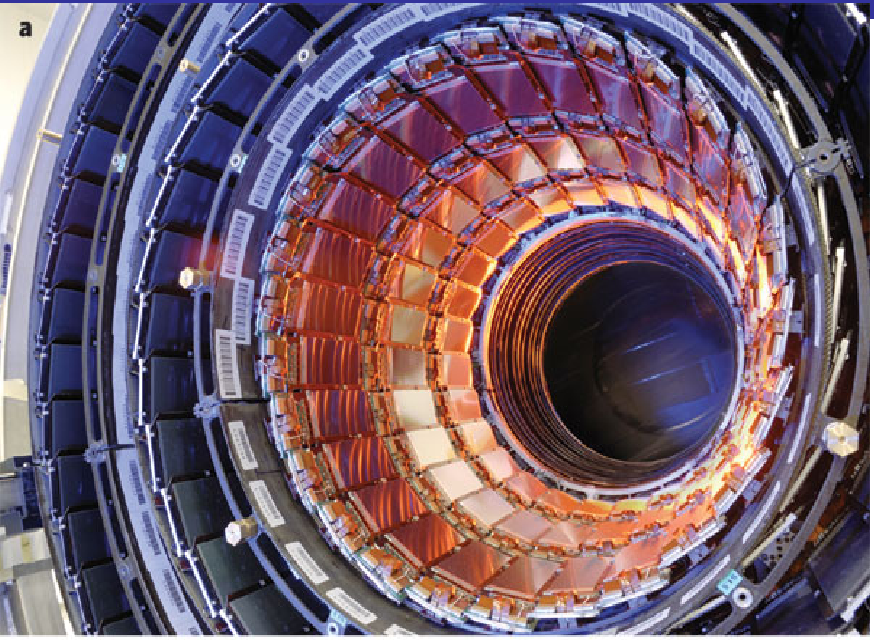
CMS is 30% heavier than the Eiffel tower

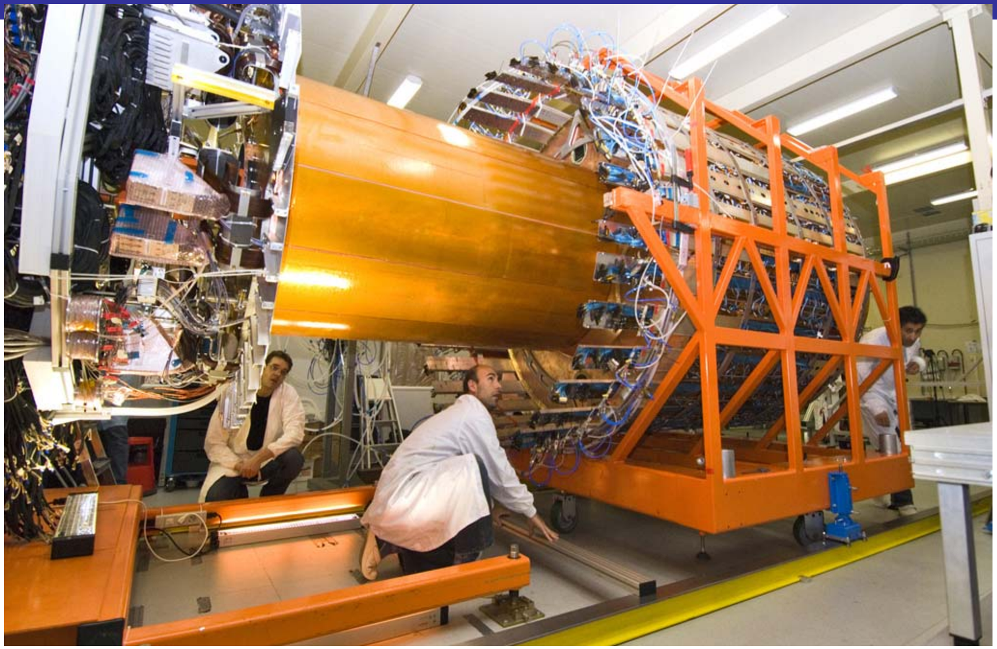
B.Heinemann

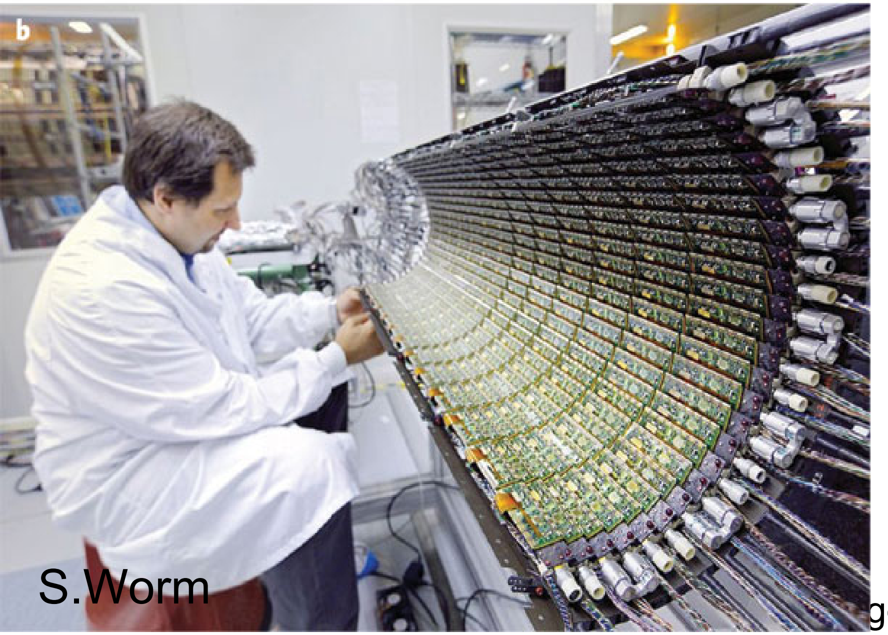
Durham Cathedral and ATLAS



Silicon Detectors



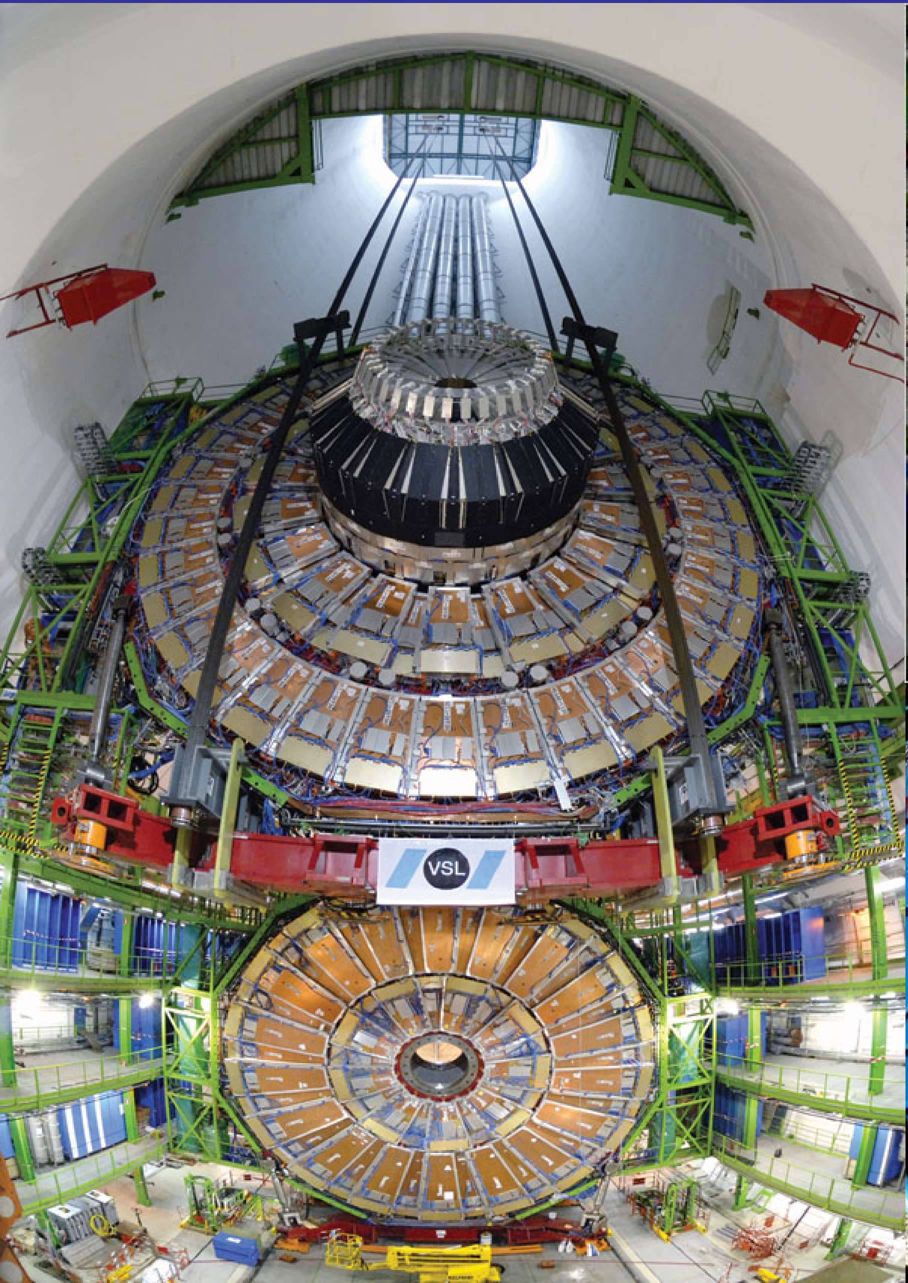


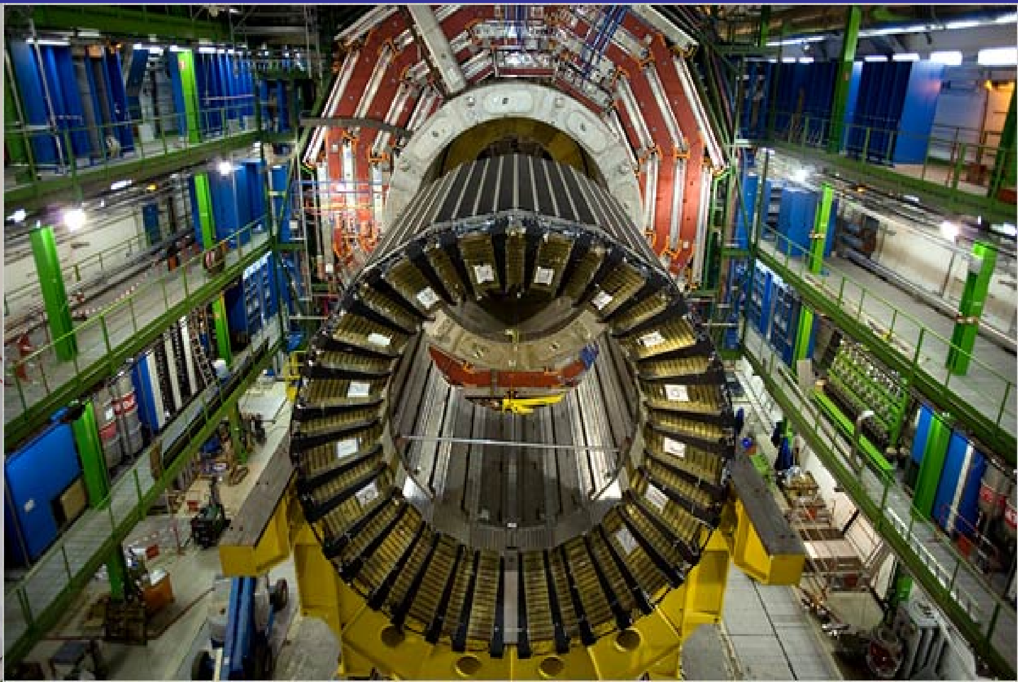


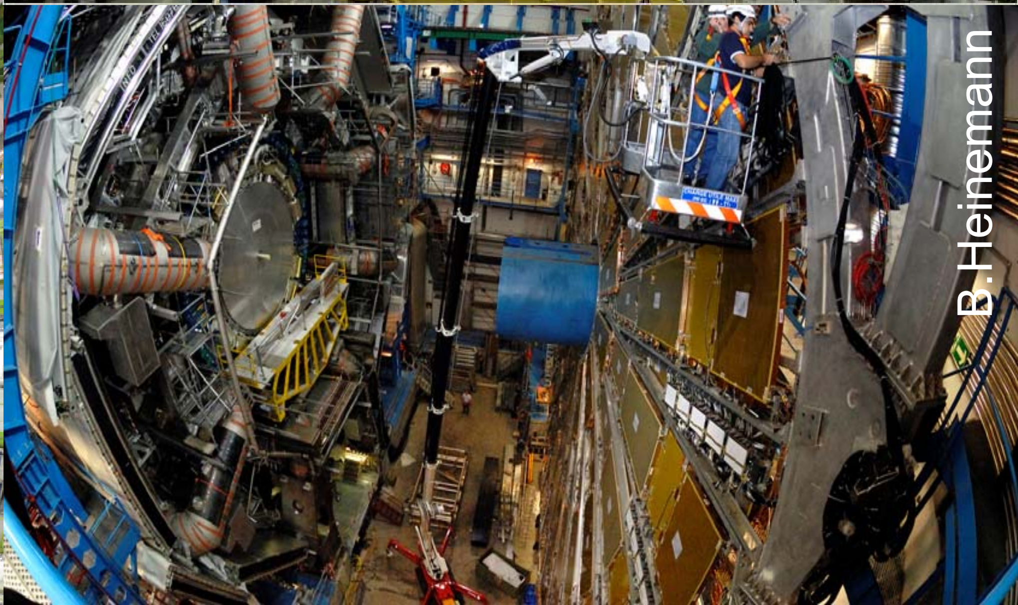
- Silicon strip and pixel detectors
  - Pixels used for first time at hadron colliders
  - Huge!
    - area of CMS silicon ~200 m^2
    - Like a football field!

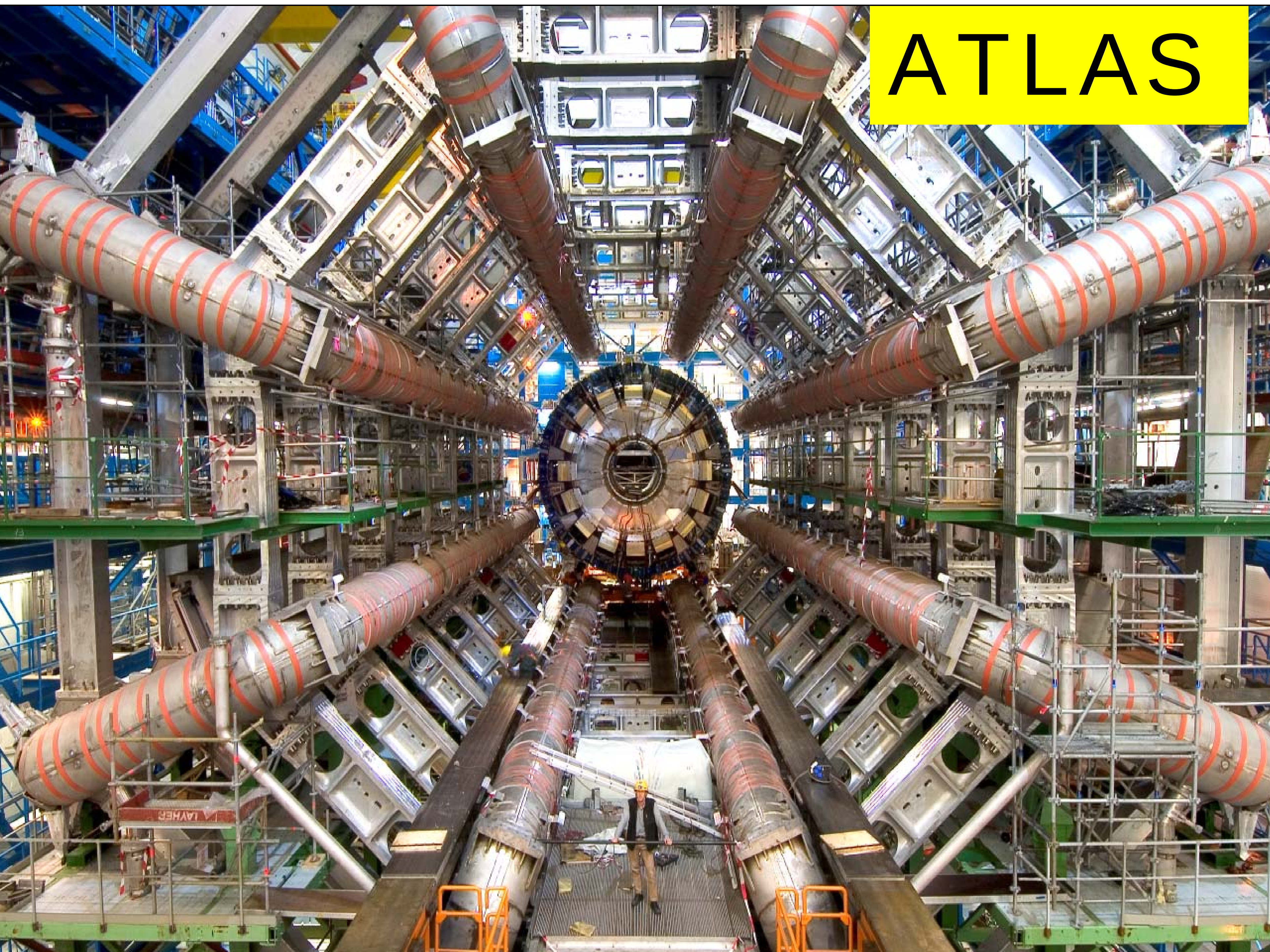
B.Heinemann

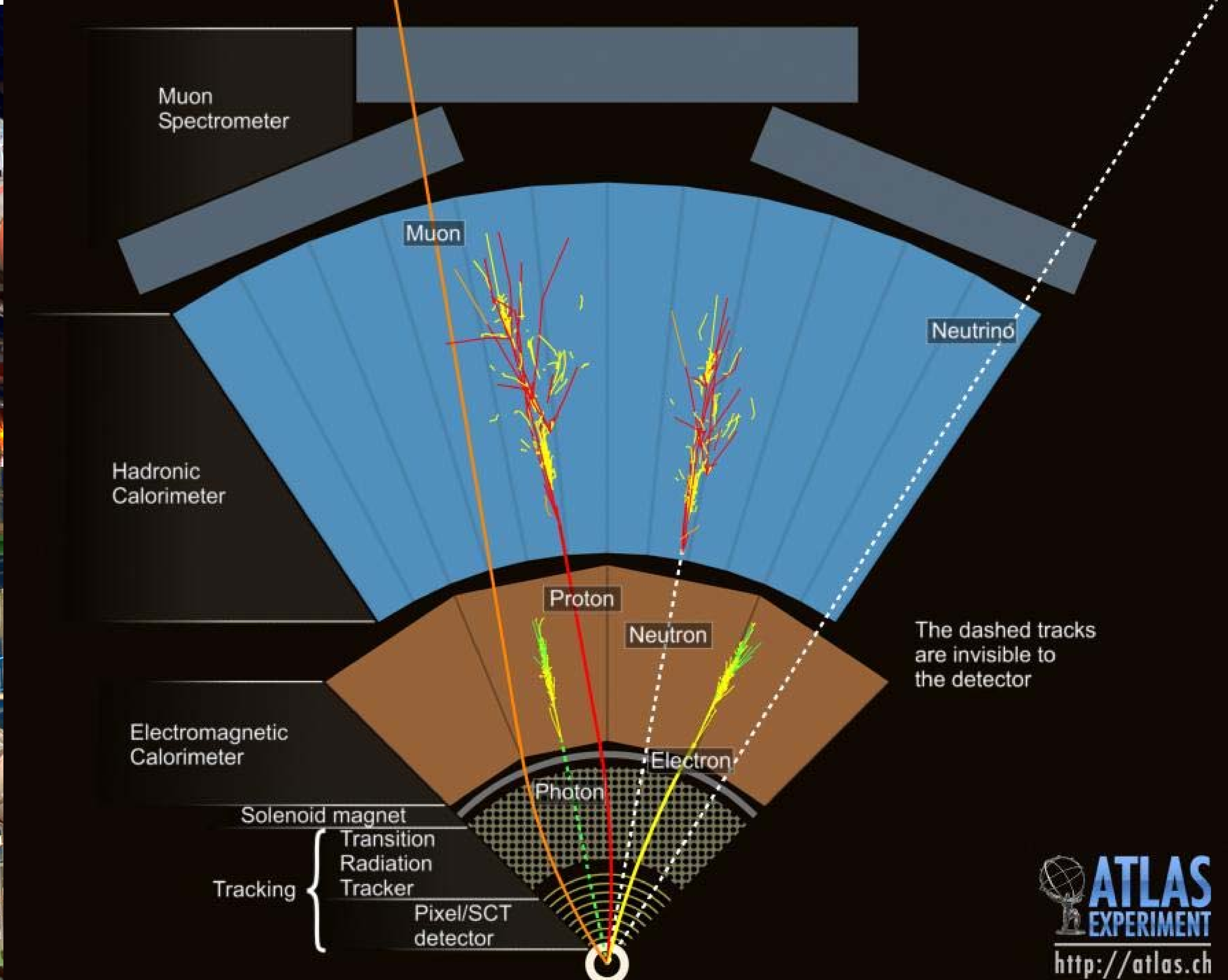
Muon Systems and Calorimeters







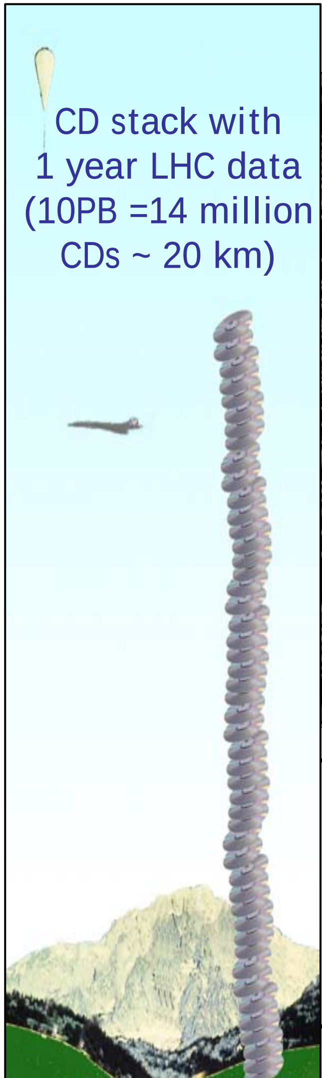

ATLAS

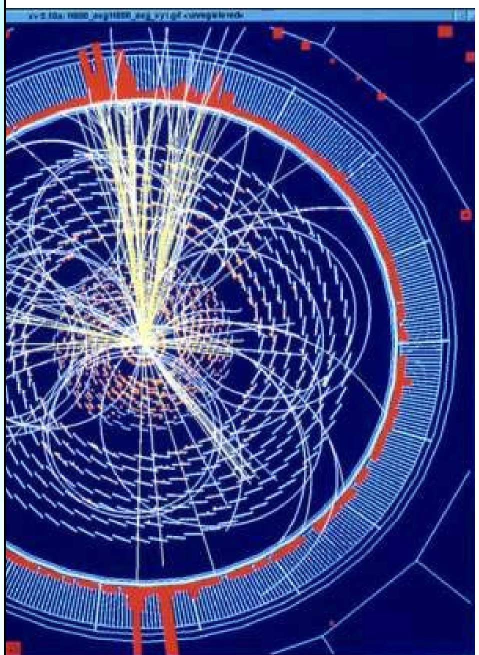


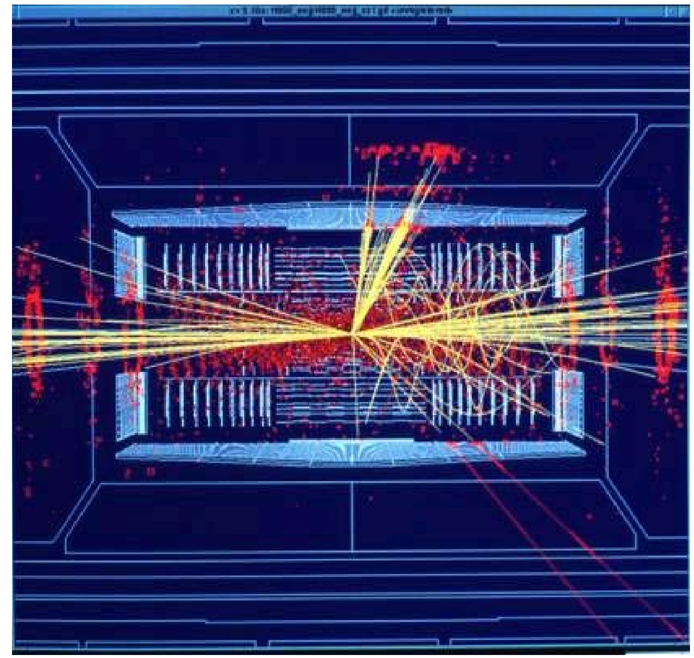
Muon Spectrometer
Muon
Neutrino
Hadronic Calorimeter
Proton
Neutron
The dashed tracks are invisible to the detector
Electromagnetic Calorimeter
Electron
Photon
Solenoid magnet
Transition Radiation Tracker
Tracking
Pixel/SCT detector
ATLAS EXPERIMENT
http://atlas.ch

Particle Collisions - "Events"

The raw data recorded is later reconstructed, filtered, and then analysed.







- ~100,000,000 electronic channels
- 600,000,000 proton-proton collisions each second
- But record only 100 one-MB events each second
- which still gives 10 PB of data recorded per year.

Finding the interesting Events

- A lot more “uninteresting” than “interesting” processes

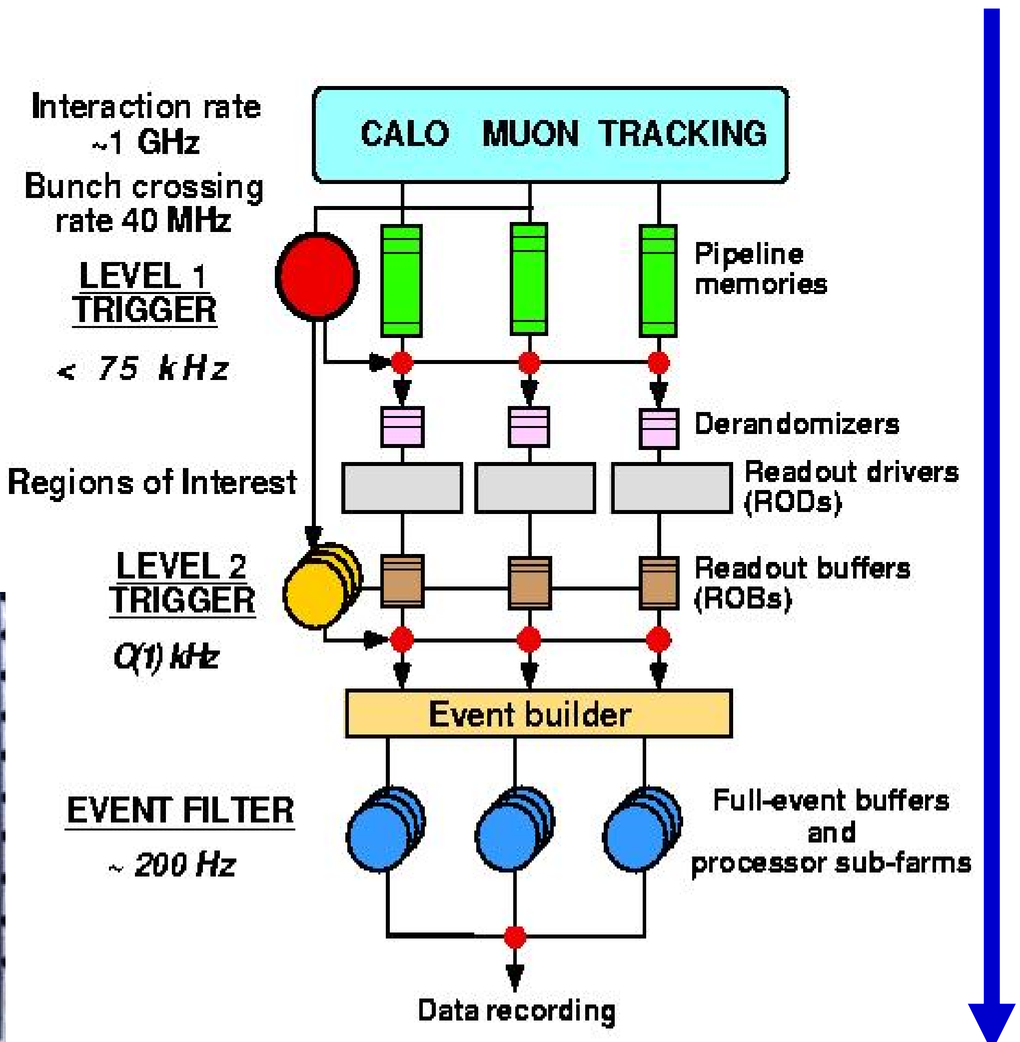
  at design luminosity ($L=10^{34}\ cm^{-2}s^{-1}$)

  - Any event: 10^9 / second
  - W boson: 150 / second
  - Top quark: 8 / second
  - Higgs (150 GeV): 0.2 / second

B.Heinemann

The Trigger Systems

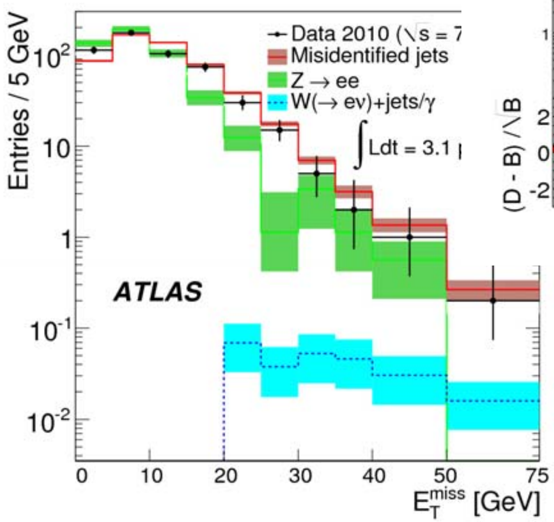
- **Trigger** filters out interesting processes
  - Makes fast decision
    - Keep
    - Not Keep
  - Crucial at hadron colliders

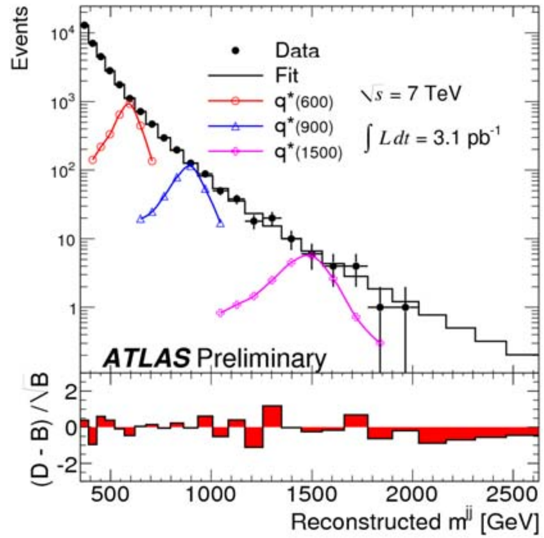


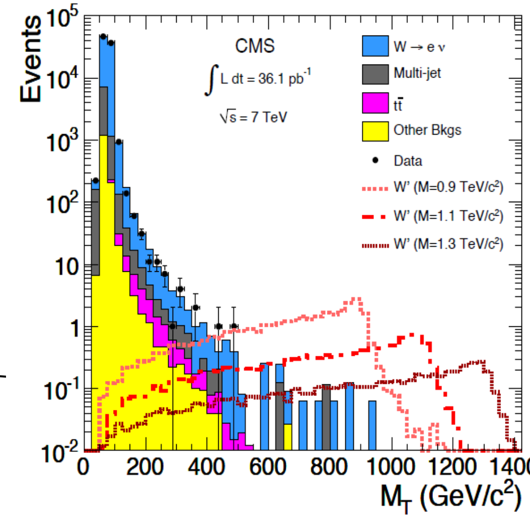
What is it for?

A.Barr

Analysis of the Data





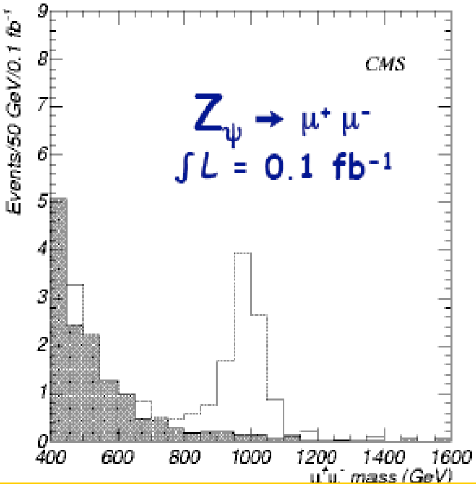


Data Analysis:

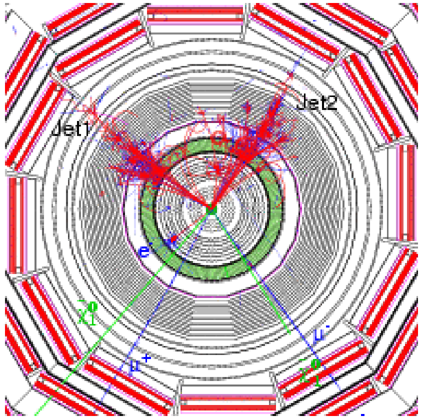
ot missing the signal is key

S. Worm

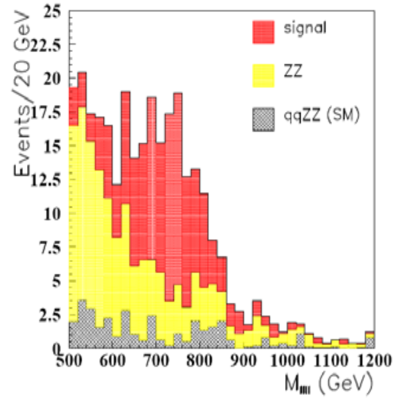
New Gauge Bosons?



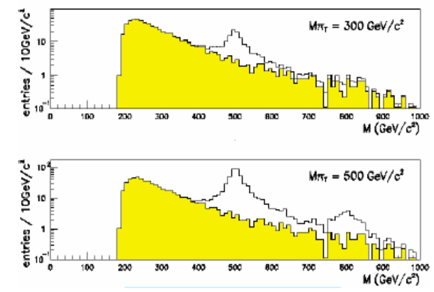
Supersymmetry



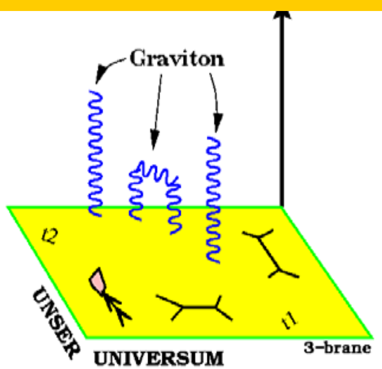
ZZ/WW resonances?



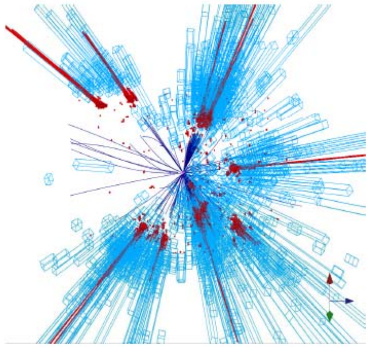
Technicolor?



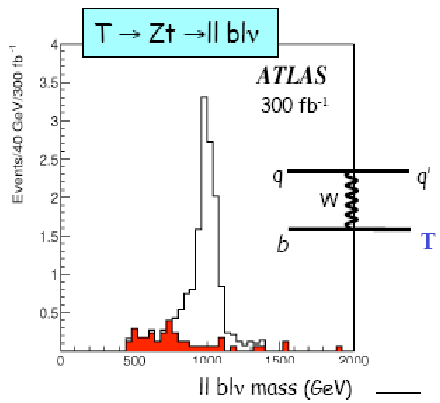
Extra Dimensions?



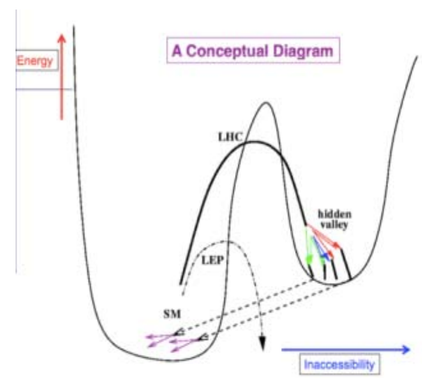
Black Holes???



Little Higgs?



Hidden Valleys?



We do not know what is out there for us…
A large variety of possible signals. We have to be ready for that

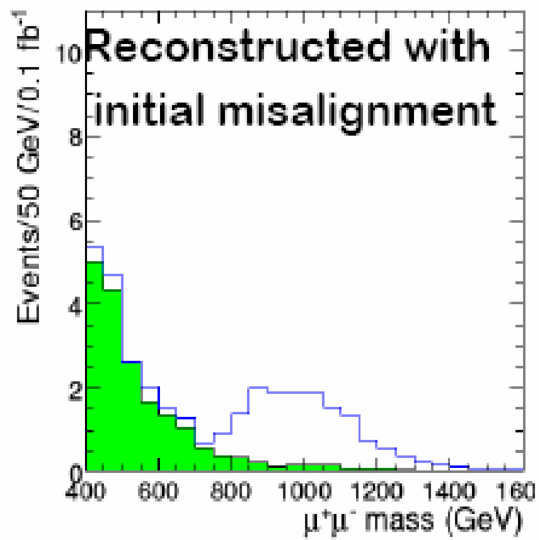
Early discoveries? E.g. Di-lepton Resonance

Plot the di-lepton invariant mass

A peak!!

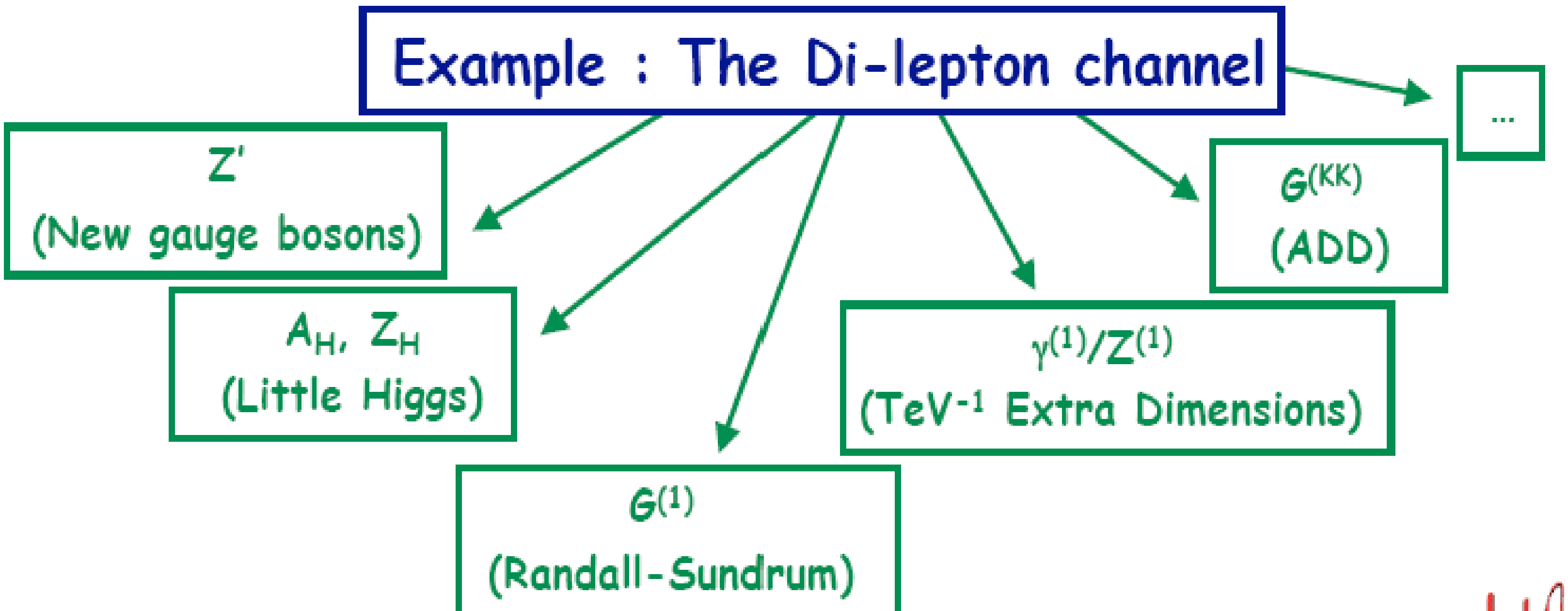
A new particle!!

A discovery!!



$pp \rightarrow \mu\mu + X$

First year of operation



How to make a Discovery?

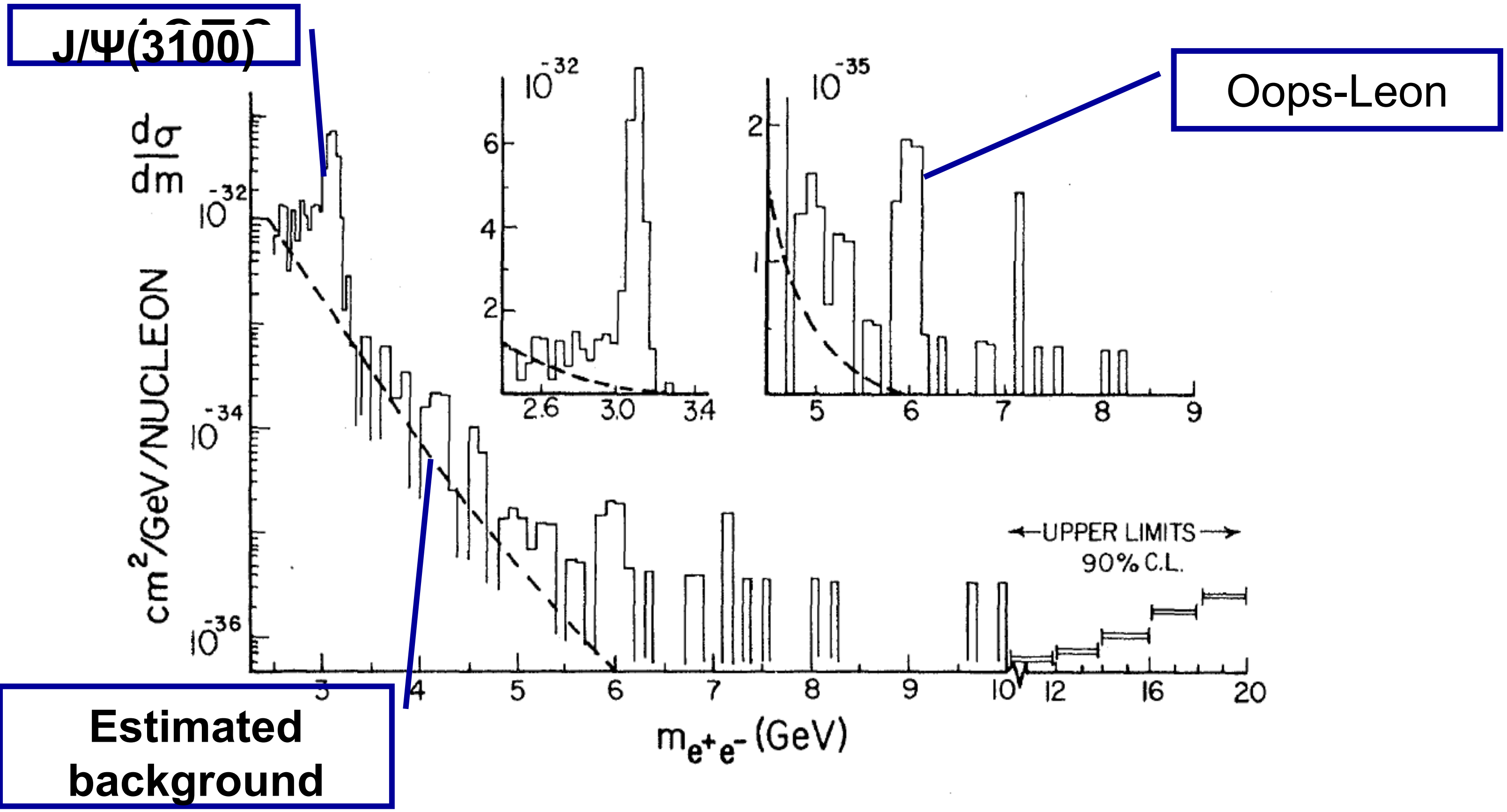
- This is a tricky business!
  - Lot's of complicated statistical tools needed at some level
- But in a nutshell:
  - Show that we have a signal that is inconsistent with being background
    - Number of observed data events: N_{Data}
    - Number of estimated background events: N_{Bg}
  - Number of observed data events to be inconsistent with background fluctuation:
    - Background fluctuates statistically: $\sqrt{N_{Bg}}$
  - Significance: $S/\sqrt{B}=(N_{Data}-N_{Bg})/\sqrt{N_{Bg}}$
    - Require typically 5σ
    - Increases with increasing luminosity: $S/\sqrt{B} \sim \sqrt{L}$
    - All a lot more complex with systematic uncertainties…

B.Heinemann

The Discovery of the Oops-Leon

Physical Review Letters 36: 1236–123

- New subatomic particle "discovered" at Fermilab in



"less than one chance in fifty" that this is due to random coincidence

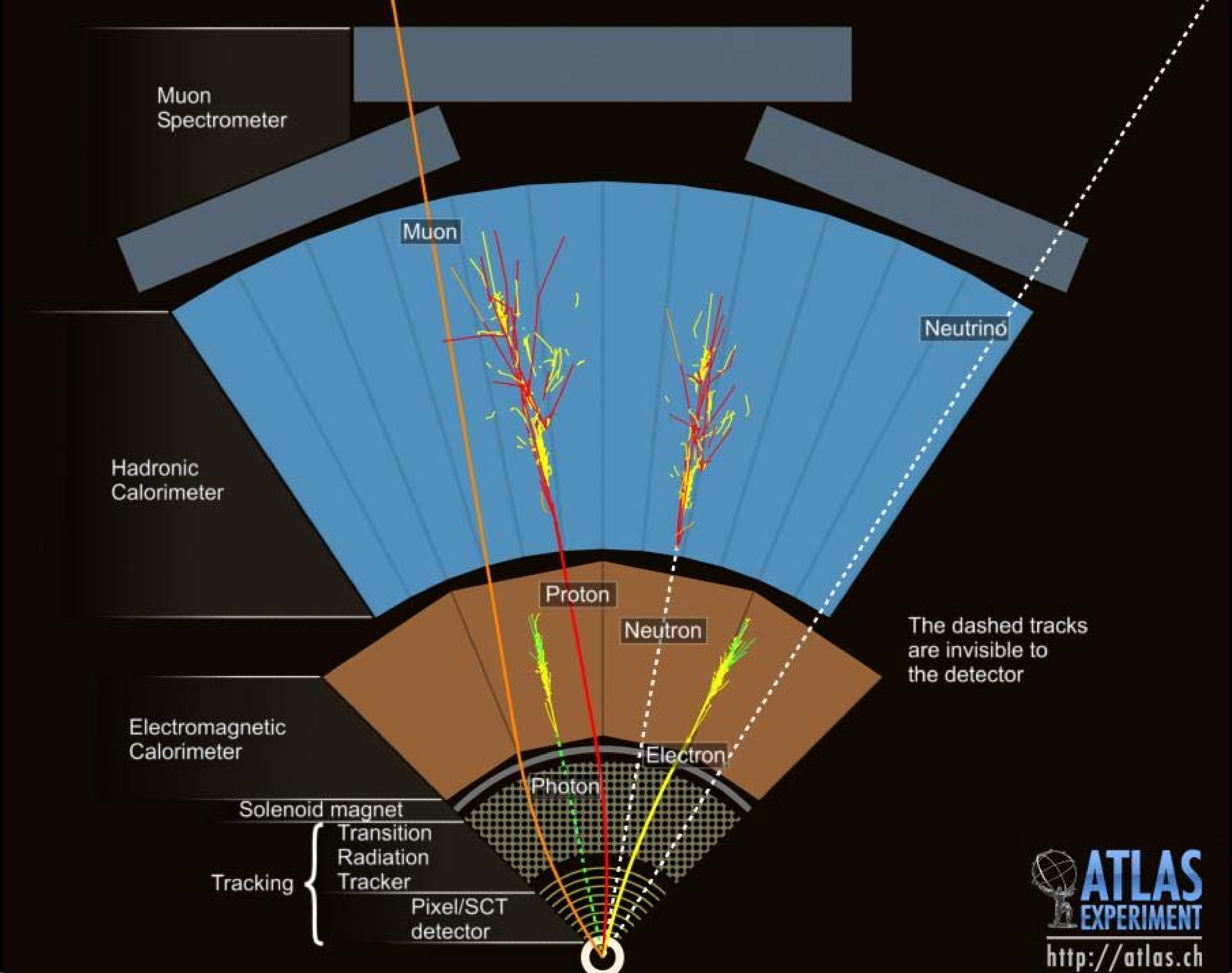
BUT 1977 data showed that is was such a coincidence

“Five-sigma Rule”

- Commonly-accepted standard (acid test)
  - $N_{obs} > 5\sigma$ above the expected level of the background
    - 99.9999% of events fall within 5σ
    - less than one in a million chance
  - Today :Oops-Leon "discovery" would have not been published.
- Five-sigma rule is far from golden
  - 5σ “discoveries” can vanish overnight

“The statistical analysis is based upon the assumption that you know everything and that everything is behaving as it should. But after everything you think of, there can be things you don't think of. **A five-sigma discovery is only five sigma if you properly account for systematics**.”

Val Fitch, 1980 Nobel Prize for discovering charge-parity violation in K mesons.


Muon
Spectrometer
Muon
Neutrino
Hadronic
Calorimeter
Proton
Neutron
The dashed tracks
are invisible to
the detector
Electromagnetic
Calorimeter
Electron
Photon
Solenoid magnet
Transition
Radiation
Tracker
Tracking
Pixel/SCT
detector
ATLAS
EXPERIMENT
http://atlas.ch

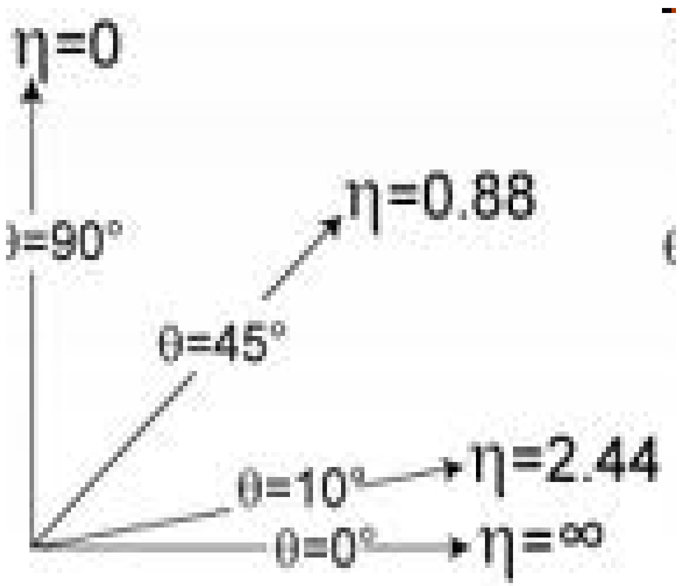
Kinematic Constraints and Variables

- **Longitudinal momentum and energy, p_z and E**
  - Visible p_z is not conserved
- **Polar angle θ**
  - θ is not Lorentz invariant

$$y = \frac{1}{2} \ln \frac{E + p_z}{E - p_z}$$

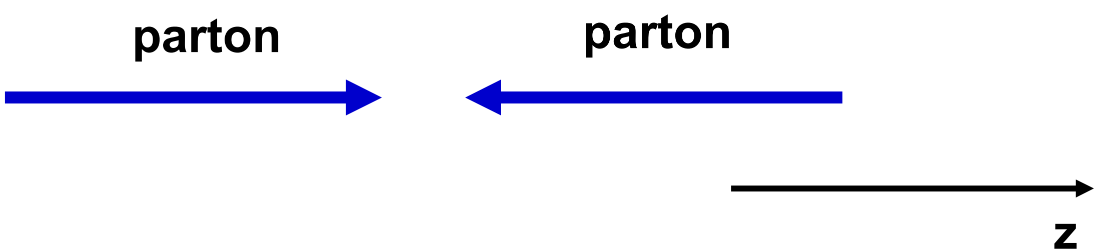
$$y = \eta = -\ln(\tan\frac{\theta}{2})$$

For M=0



Kinematic Constraints and Variables

- **Transverse momentum, pT, very useful!**
  - **Colliding** partons $p_T \approx 0$



- Vector sum p_T conserved: $\sum_i \mathbf{p}_{Ti} \approx 0$
  - **If non zero something escaped detection**
  - **Missing transverse momentum: - $\sum_i \mathbf{p}_{Ti}$**
- **Scalar sum p_T: $\sum_i |\mathbf{p}_{Ti}|$**
  - **Measure of "Umpf" in the final state**

2010 (Exotics) Searches at the LHC

- Bump Hunting
  - Dijet, dilepton, diphoton, dijet+dilepton final states
  - Excited quarks, Z', W', RS Graviton, Leptoquarks….
- Search for deviations in the tails
  - Digamma + Met final states (UED, SUSY)
  - Multi-object final states (Strong Gravity, Black Holes)
- Search for odder things
  - Long lived particles

Overview of Dijet Resonance Search

- Select inclusive dijet events, and plot dijet mass

$$m_{jj} = \sqrt{(E_{j1} + E_{j2})^2 - (\vec{p}_{j1} + \vec{p}_{j2})^2}$$

- Background: fit a smooth function to **DATA***

$$f(x) = p_1 (1 - x)^{p_2} x^{p_3 + p_4 \ln x}$$

$$x = m_{jj} / \sqrt{s}$$

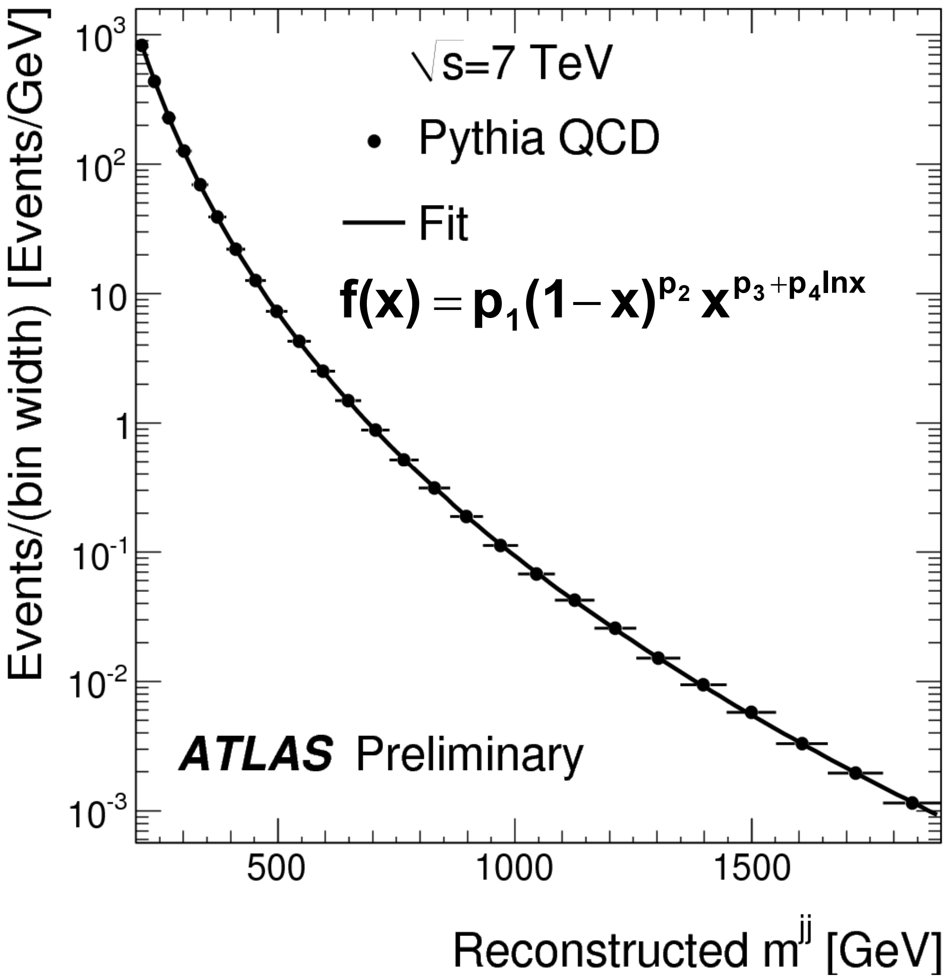
- Search for discrepancies between data and background.
- If no discrepancies found, set limits

*CDF, Phys.Rev.D79:112002,2009

Fitting MC

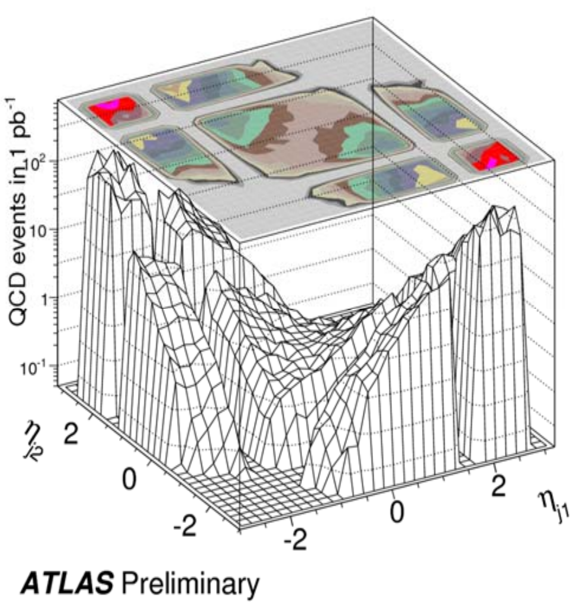
- Excellent fit to SM QCD, 7TeV
- Same for PYTHIA, ALPGEN, NLOJET++, hadron-level, reco-level..
- Same for 1.96 TeV, shown by CDF
- By construction
    - smooth,
    - monotonic
    - and goes to 0 at m = s

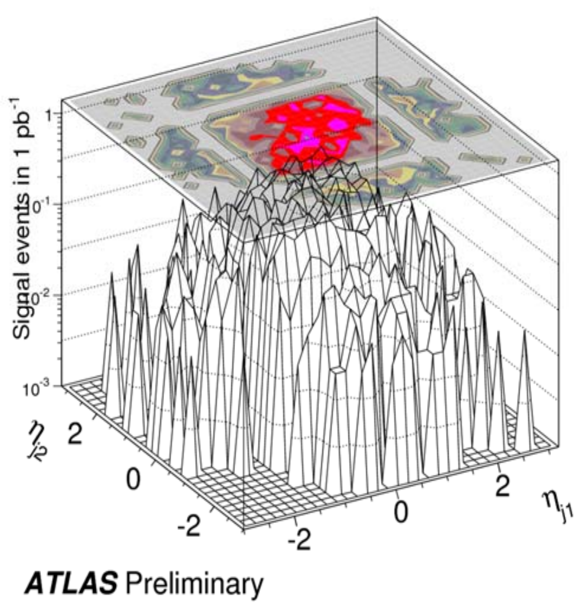
If we can't fit data something is going on.

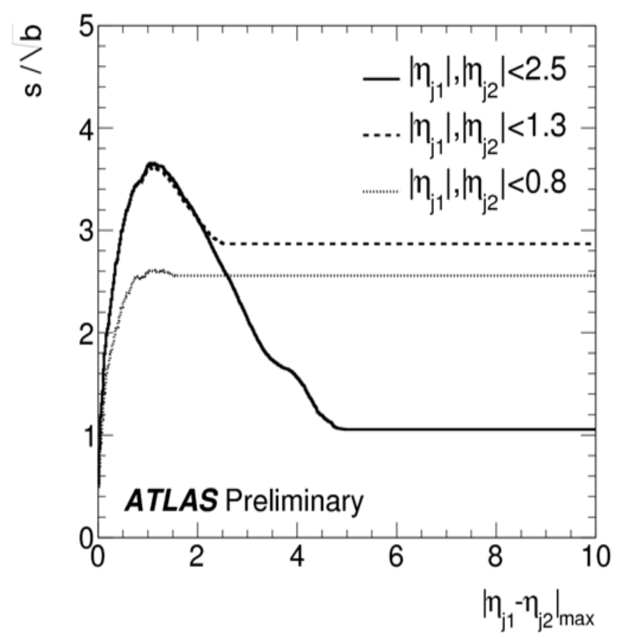


Event Selection

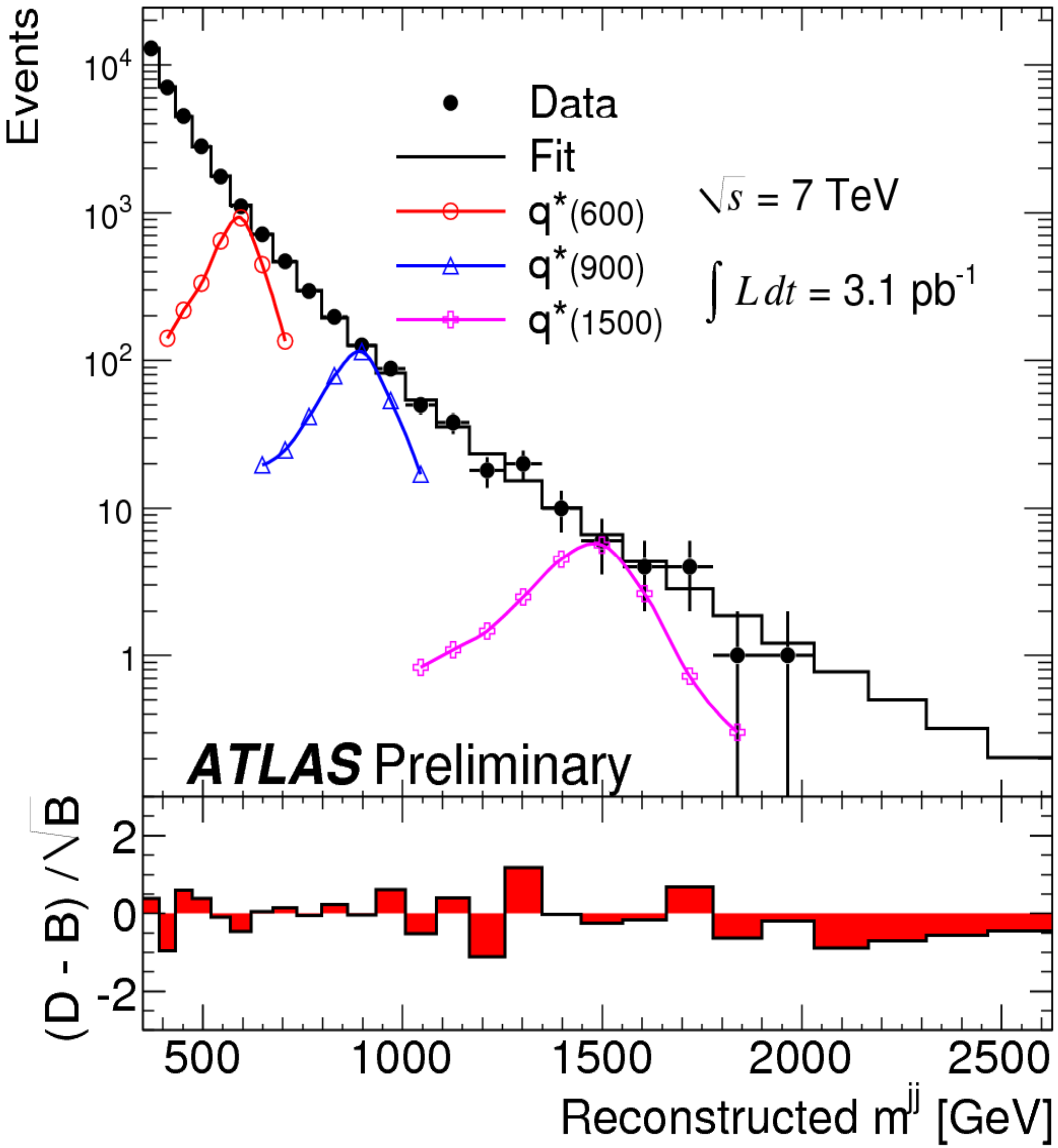
- High Data Quality
- p_T^{j1}>150 GeV
- p_T^{j2}>30 GeV
- M_{jj}>350 GeV
- Reject poorly measured jets
- |η| < 2.5 and |△η|<1.3







Data and Background



Model independent search for discrepancy

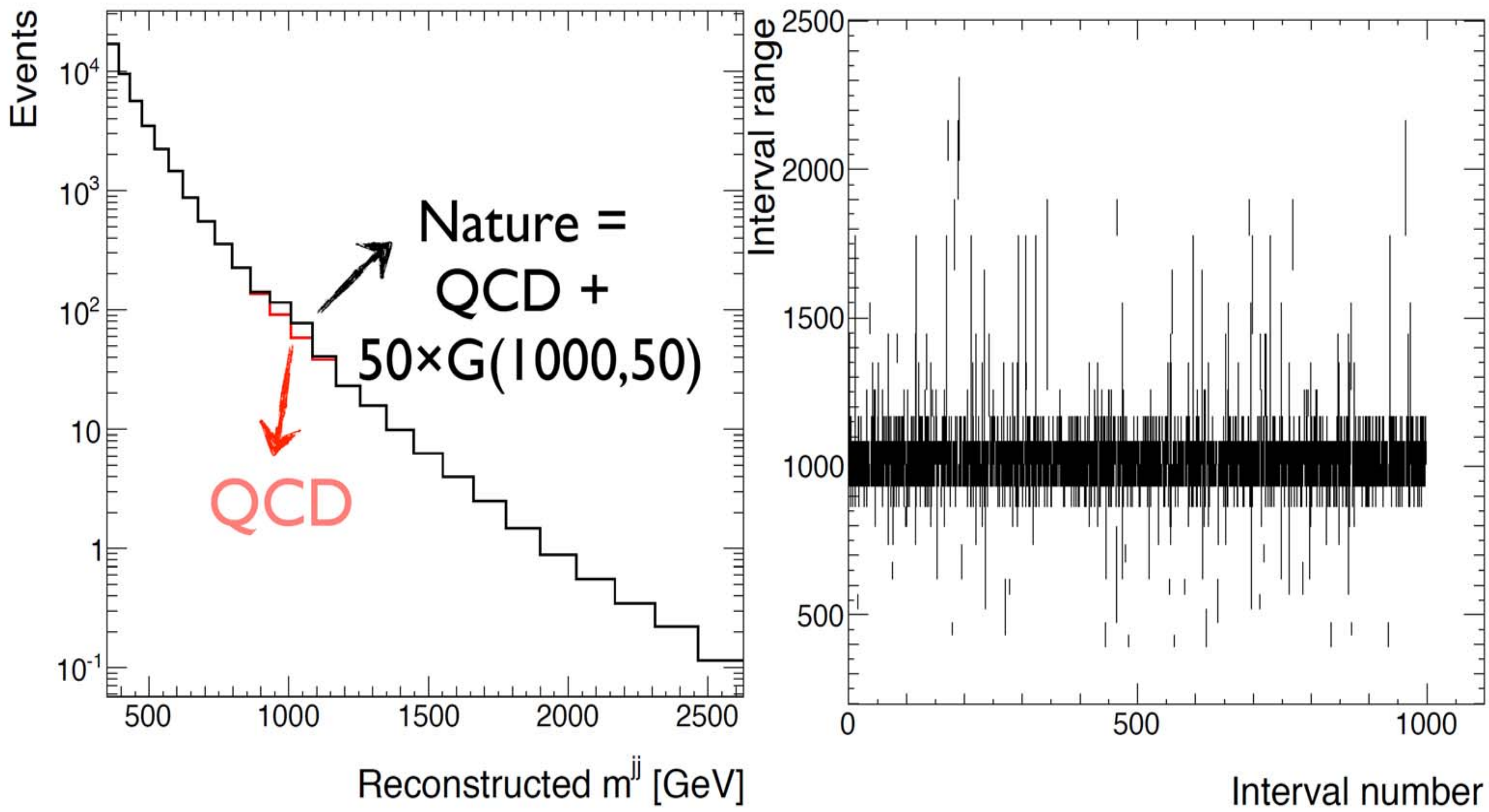
- BumpHunter *
- TailHunter*
- Likelihood, χ^2, KS, Jeffreys Divergence

*http://arxiv.org/abs/1101.0390, Phys.Rev.D79:011101,2009 and Phys.Rev.D78:012002,2008

BumpHunter and TailHunter

- **BumpHunter:**
  - scan the spectrum for a local excess
  - surrounded by agreeing sidebands.
- **TailHunter:**
  - Similar. Check all high-mass tails for an excess.
- Nothing assumed about mass, or width of the signal.

BumpHunter Demo



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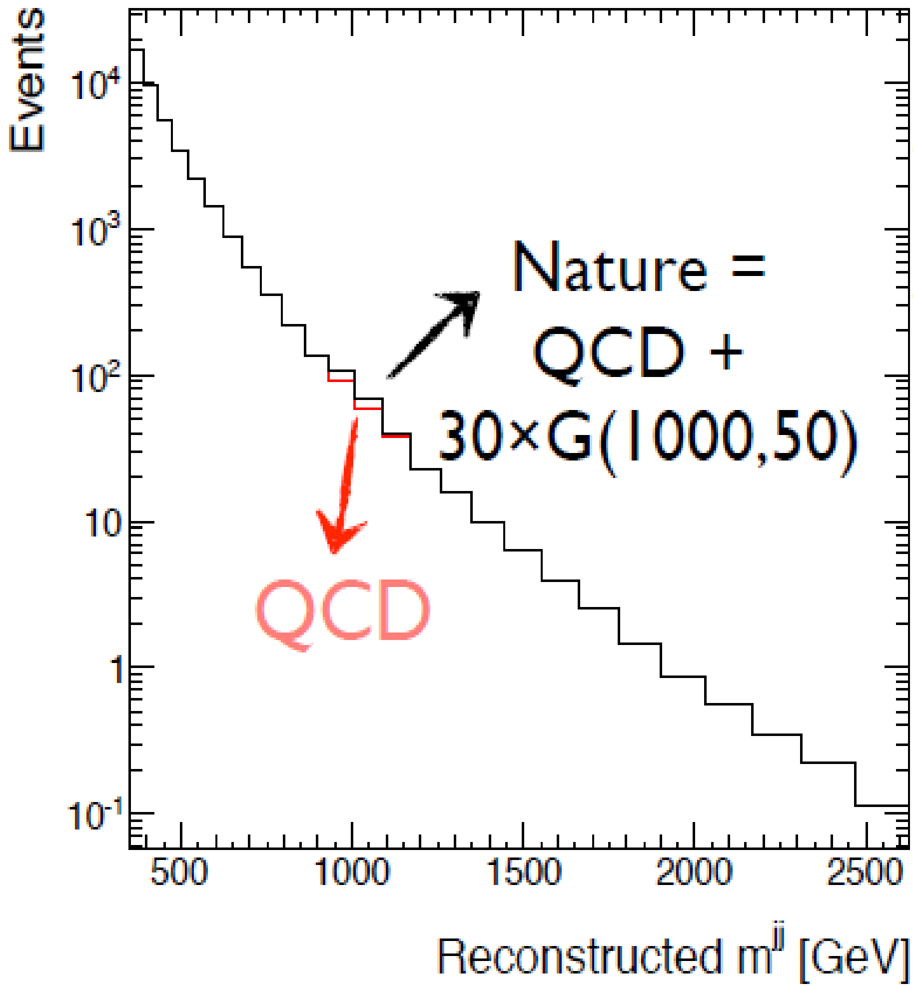
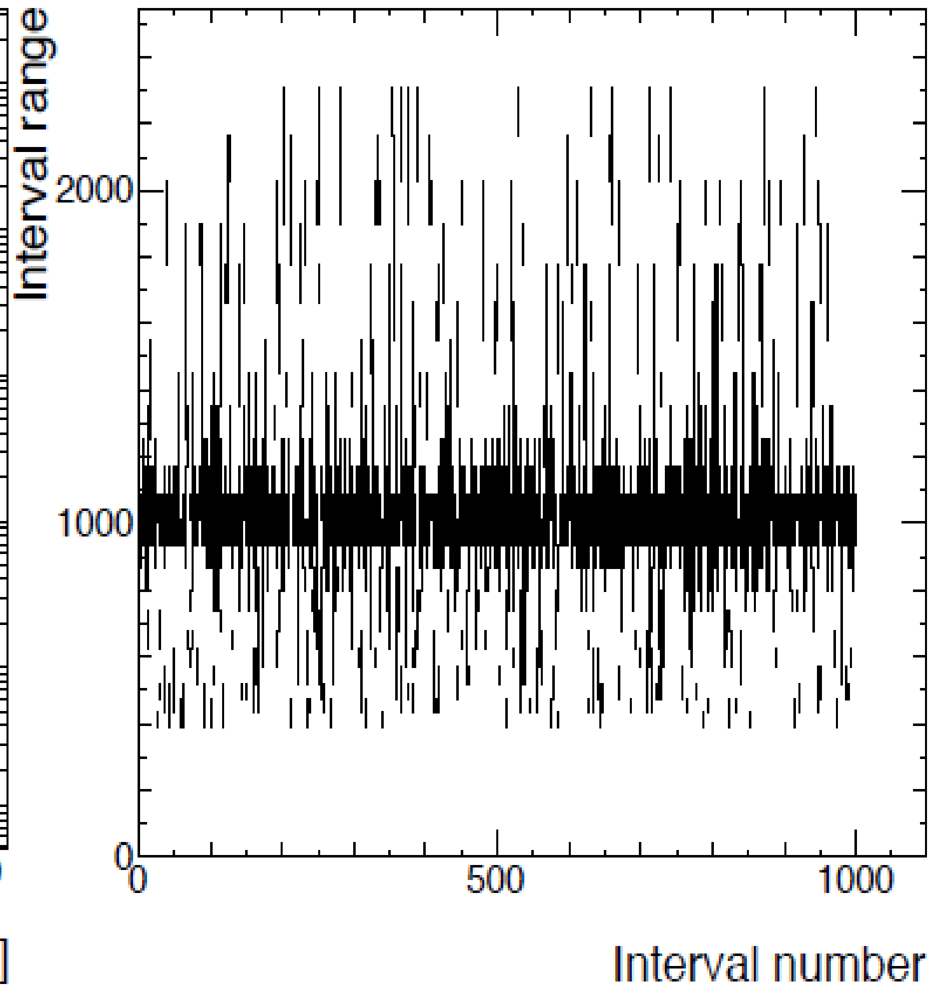
BumpHunter Demo





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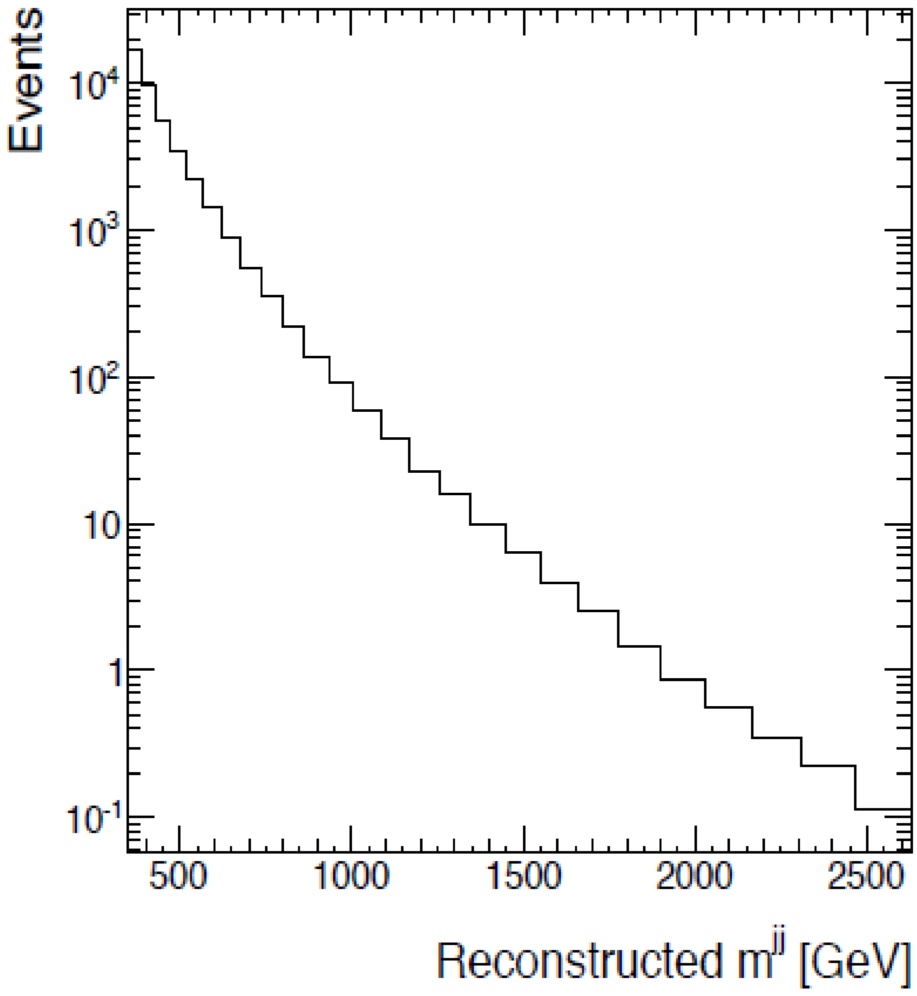
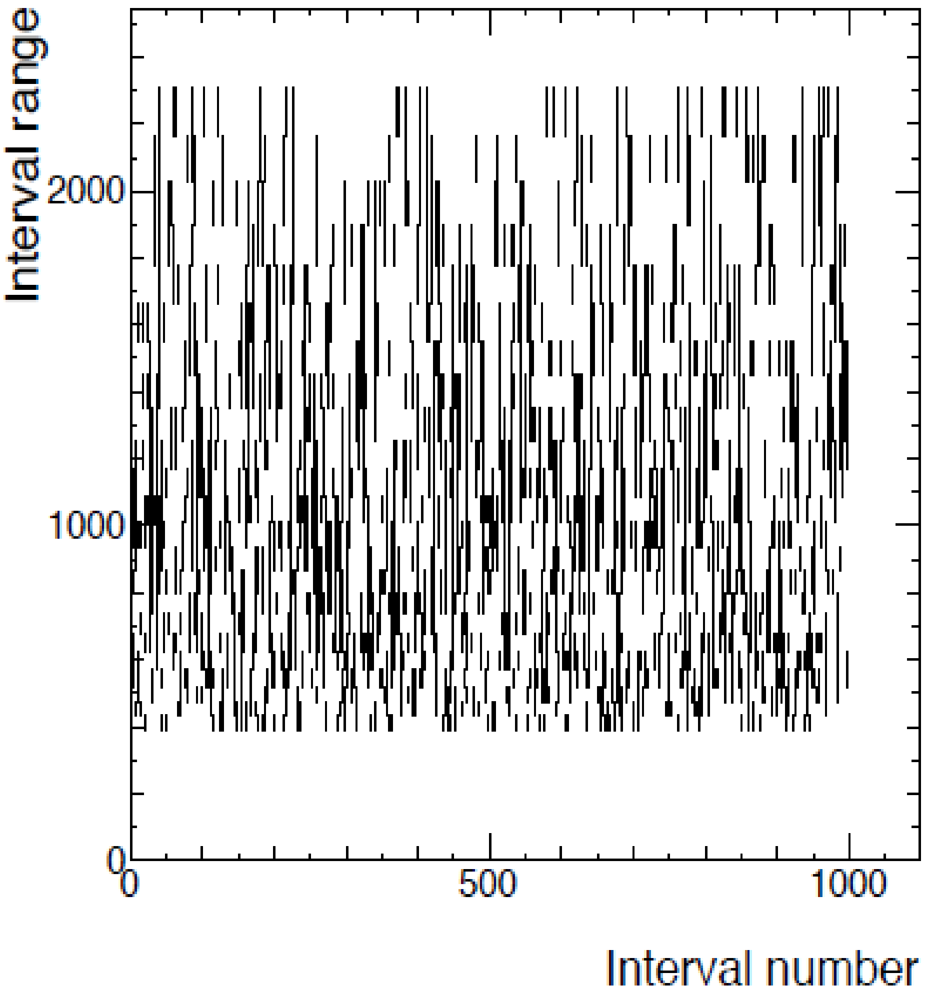
BumpHunter Demo





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Results

- 6 tests, independently, indicated that the data are consistent with the background-only hypothesis.

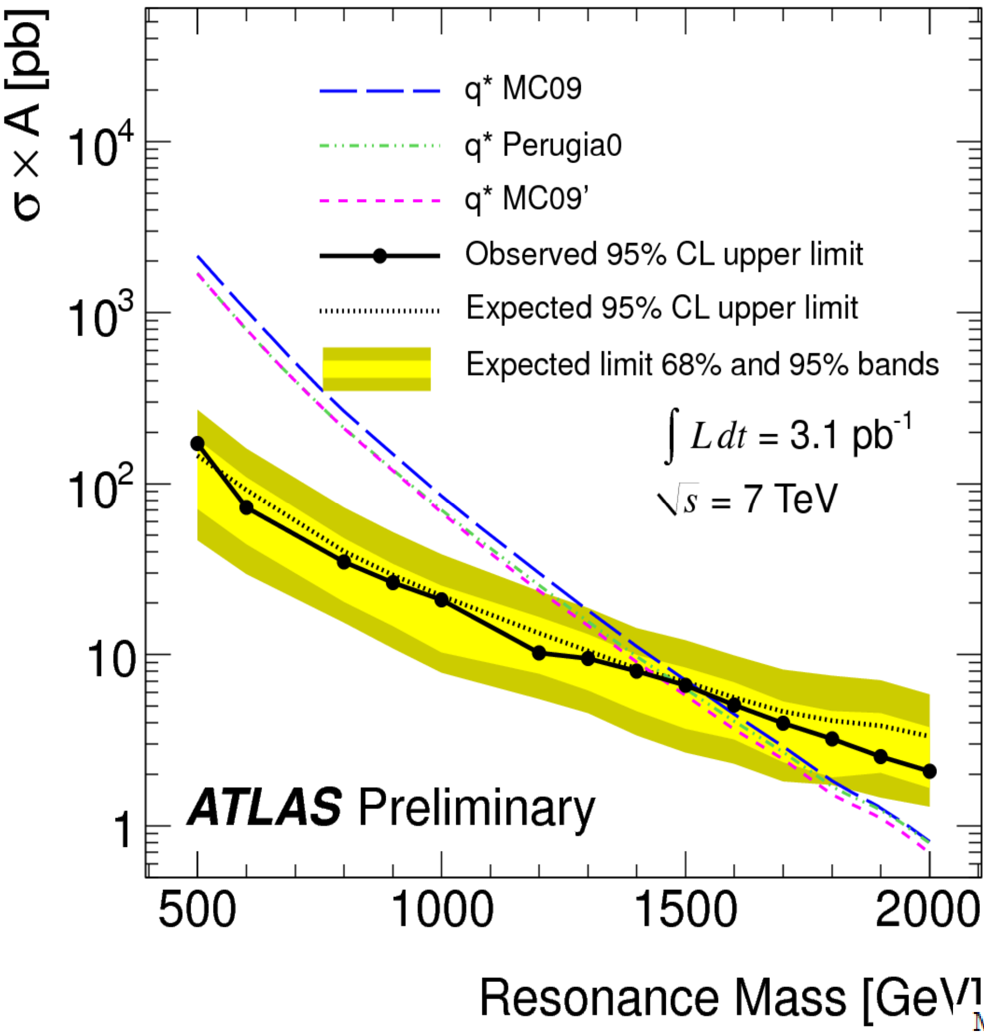
- Data were so well-fitted that the p-values were ~ 99%.
  - → *Perfectly consistent.*
  - Multiple tests agreed that this was just a coincidence.

NOTHING FOUND

Back to setting limits...

Georgios Choudalakis

Limits on excited Quarks



	Observed Limit	Expected Limit
MRST2007	1.53 TeV	1.51 TeV
CTEQ6L1	1.45 TeV	1.43 TeV

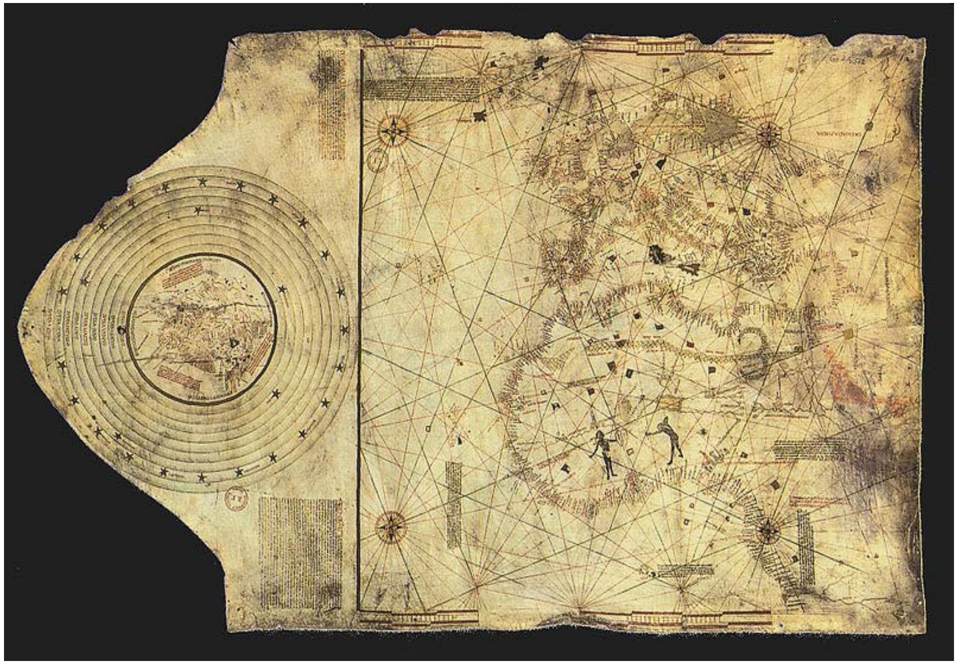
Observed ~ Expected

MC Tune	PDF Set	Stat. ⊕ Syst.	Stat. only	Stat. ⊕ Syst.
MC09 [3]	MRST2007 [4]	1.53	1.64	1.51
MC09′	CTEQ6L1 [5]	1.45	1.56	1.43
Perugia0 [6]	CTEQ5L [7]	1.49	1.60	1.46

ATLAS-CONF-2010-093

Why set limits and publish?

- Mapping of our knowledge



- Quantifying search with help of bench mark models
  - Comparison with other models via bench mark models

Credits

- Some slides taken from
  - Alan Barr
  - Beate Heinemann
  - Georgios Choudalakis
  - Chris Llewellyn Smith
  - Tom Lecompte
  - Phil Burrows
  - Tara Shears
  - John Ellis
  - David Britton
  - Steven Worm
- Theory friends: Glenn Starkman, Dejan Stojkovic and Dechang Dai
- Wikipedia and CERN public web pages