Higgs Searches in ATLAS

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Particle Physics and Nature

Particle physics is the modern name for the centuries-old effort to understand the laws of nature.

E. Witten

Aims to answer the two following questions:

What are the elementary constituents of matter ?

What are the forces that control their behavior at the most basic level?

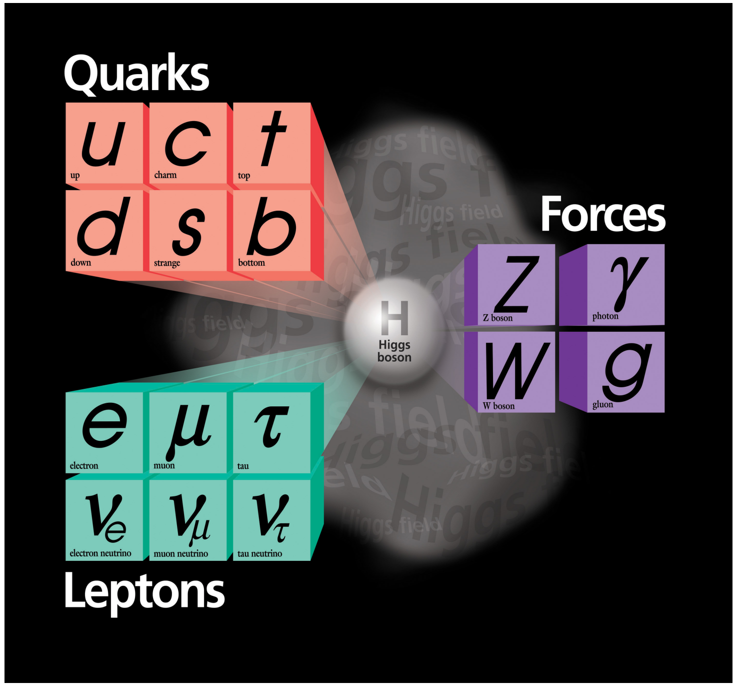
Experimentally:

- **Make particles interact and study the products and properties of the result of the interaction**
- **Measure the energy, direction, momentum and type of the products as accurately as possible**
- **Reconstruct what happened during the collision**

The Standard Model

Last 100 years: combination of **Quantum Mechanics and Special Theory of relativity** along with all new particles discovered has led to the **Standard Model of Particle Physics. With the new (final?) "Periodic Table" of fundamental elements**

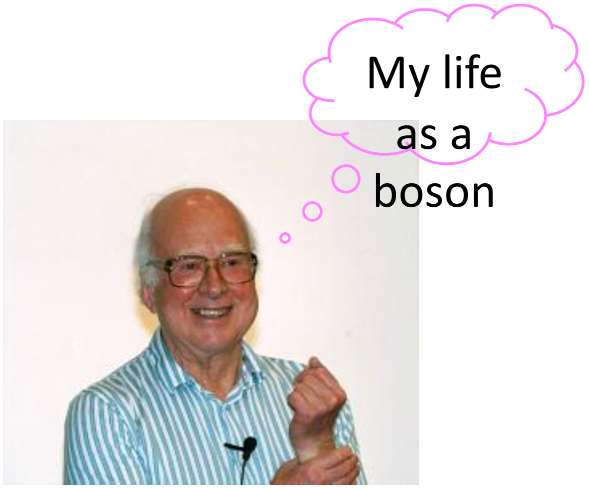
Matter particles



Force particles

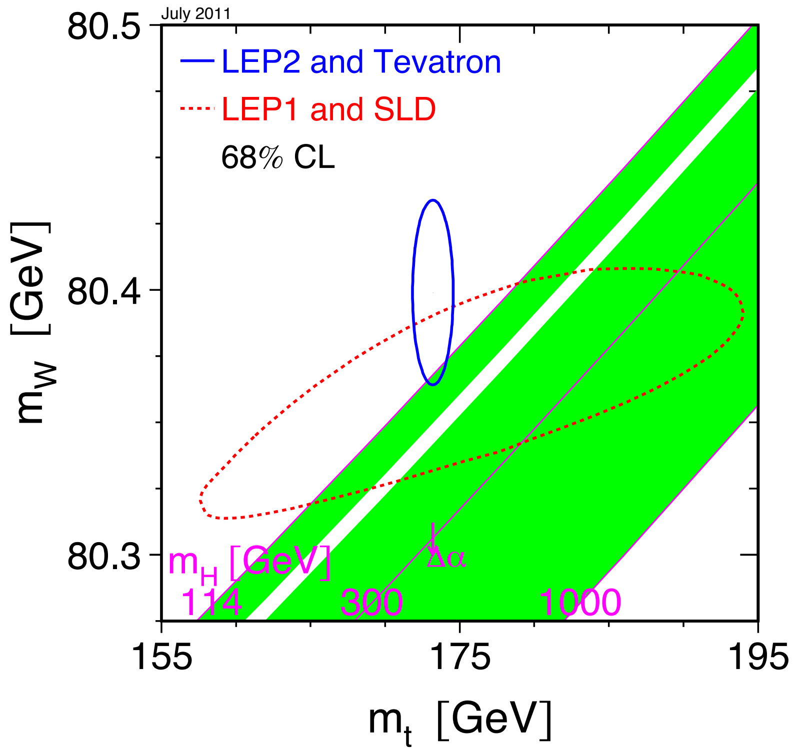
The SM has been tested thousands of times, to excellent precision.
Yet, its most basic mechanism, that of granting mass to particles, the Higgs mechanism, is still missing!

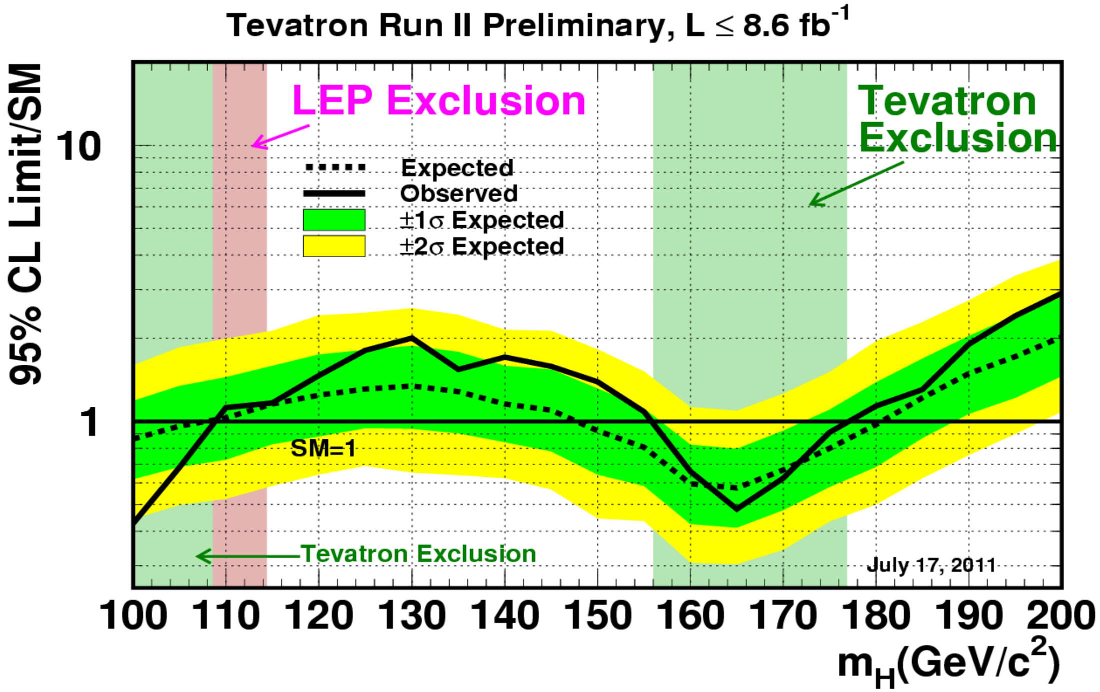
The Higgs Mechanism



- Imagine a vacuum that is not empty, one that is permeated by a field
  - This field has no characteristics other than itself – no spin, no charge. Potentially, only mass
- If true, then every particle moving “in the vacuum” is actually “swimming” in this “field sea”
- Therefore, particles feel a resistance to their motion. An inertia. They have mass!
- FAQ:
  - What makes one particle more massive than another?
    - The resistance it feels, i.e. its “coupling” to the field!
  - And what about the field that permeates everything? Its quantum excitation is a particle – like all others. The “Higgs boson”!
- We thus say that “the Higgs gives mass” (i.e. provides “inertia”!) to all the particles in nature. Surprisingly, this idea works extremely well.

What do we know about the SM Higgs from outside the LHC?





From theory: $m_H < 1$ TeV

Lower mass bound from direct searches at LEP: 114.4 GeV @ 95%CL

From direct searches at Tevatron:
$156 < m_H < 177$ GeV excluded @ 95%CL

Indirect constraints on the Higgs boson mass from global EW fits:

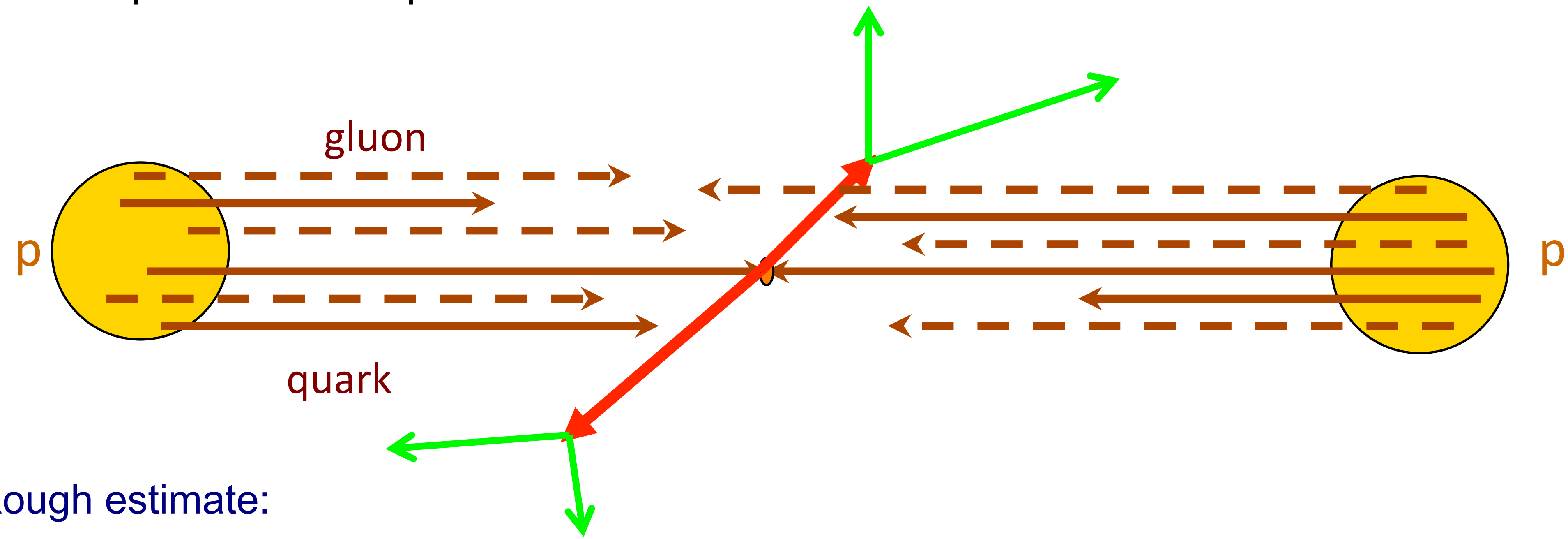
$m_H < 186$ GeV @ 95%CL

(including the direct limit from LEP)

EW data (interpreted in SM) prefer a rather "light" Higgs boson

Proton-Proton Collisions

- To search for the Higgs boson (and potentially other new heavier particles):
  - → production of particles with a few TeV needed



Rough estimate:

- In a collision, one of the constituents of the proton (~3 quarks+3 gluons) collides
  - → To produce a new particle with m > 1 TeV: $E_{constituent}$ > 0.5 TeV
  - → Proton needs at least 6×0.5 TeV = 3 TeV of energy

In practice gluons/quarks do not share energy equally so eventually the proton needs at least 5TeV of energy

Choice for our experiments: a discovery (p) machine
= LHC (Large Hadron Collider) with 7 TeV beam energy

Proton-Proton Collisions

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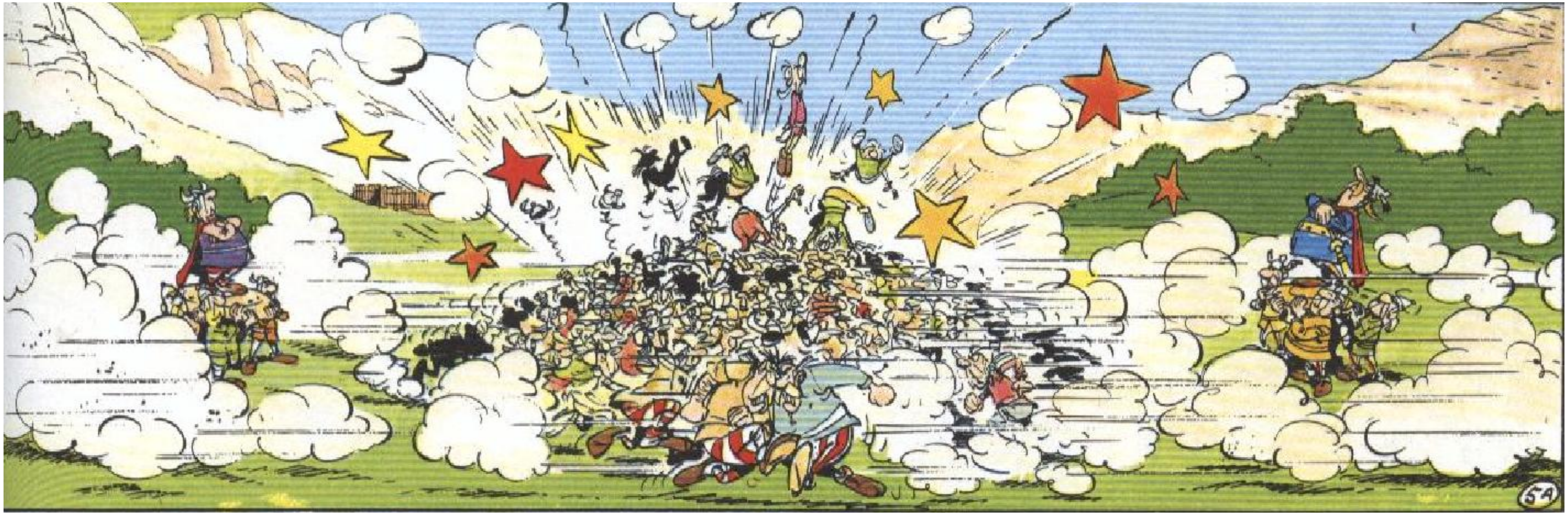

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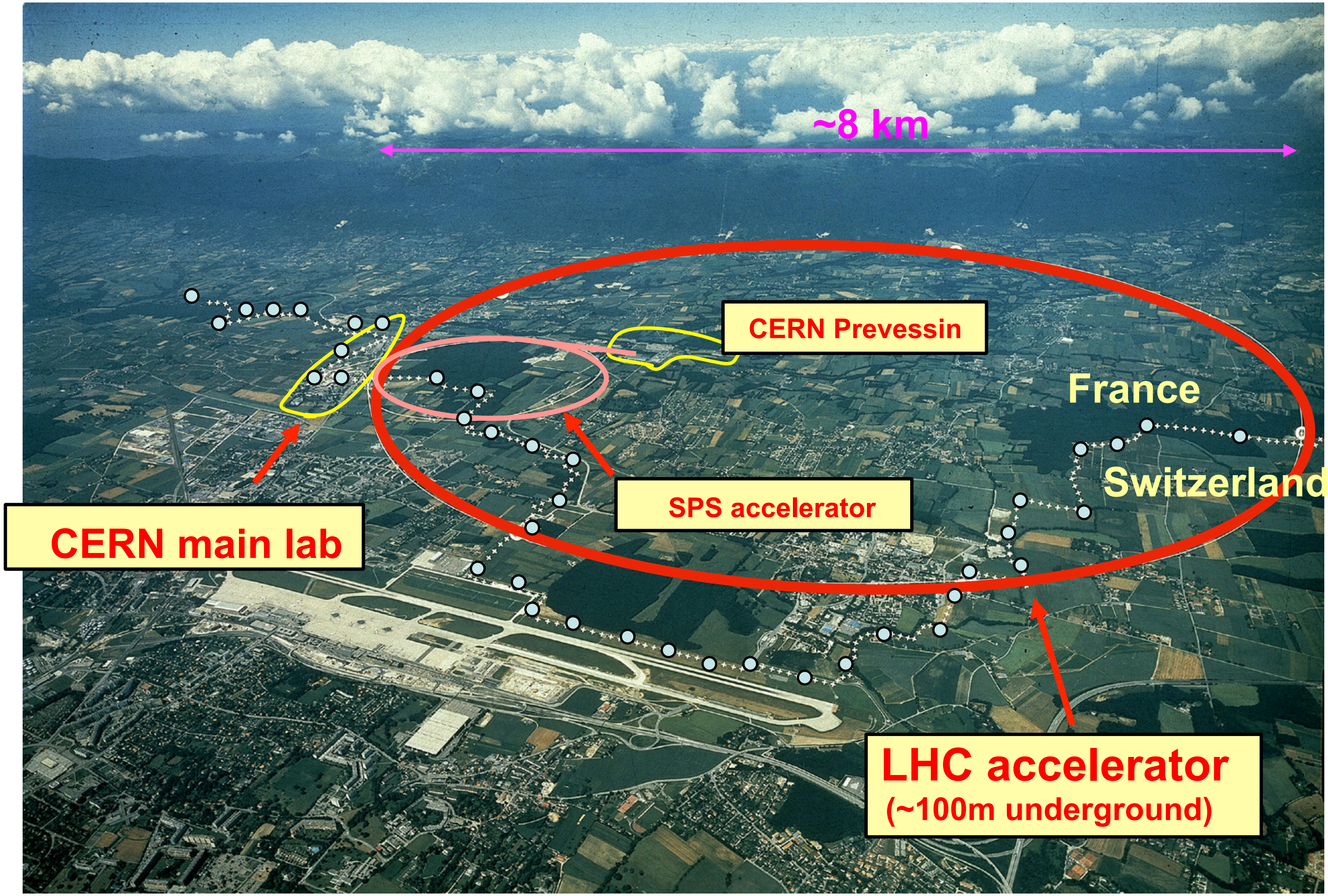
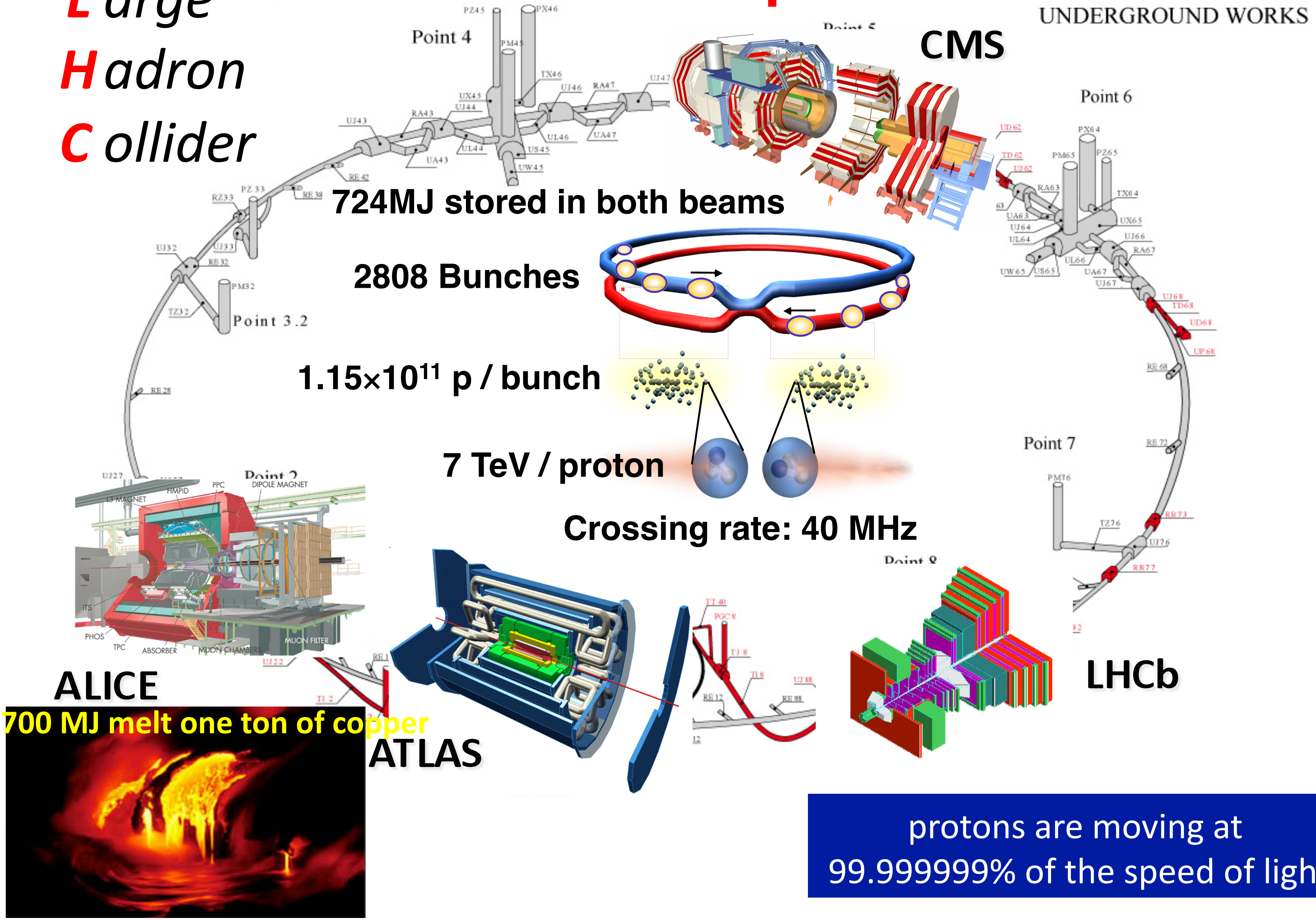
Large Hadron Collider at CERN



The Four LHC Experiments

*L*arge
*H*adron
*C*ollider



protons are moving at
99.999999% of the speed of light

Key parameter: magnetic field of (beam-bending) dipoles

$$p\,(\text{TeV}) = 0.3\, B(\text{T})\, R(\text{km})$$

For p = 7 TeV and R = 4.3 km

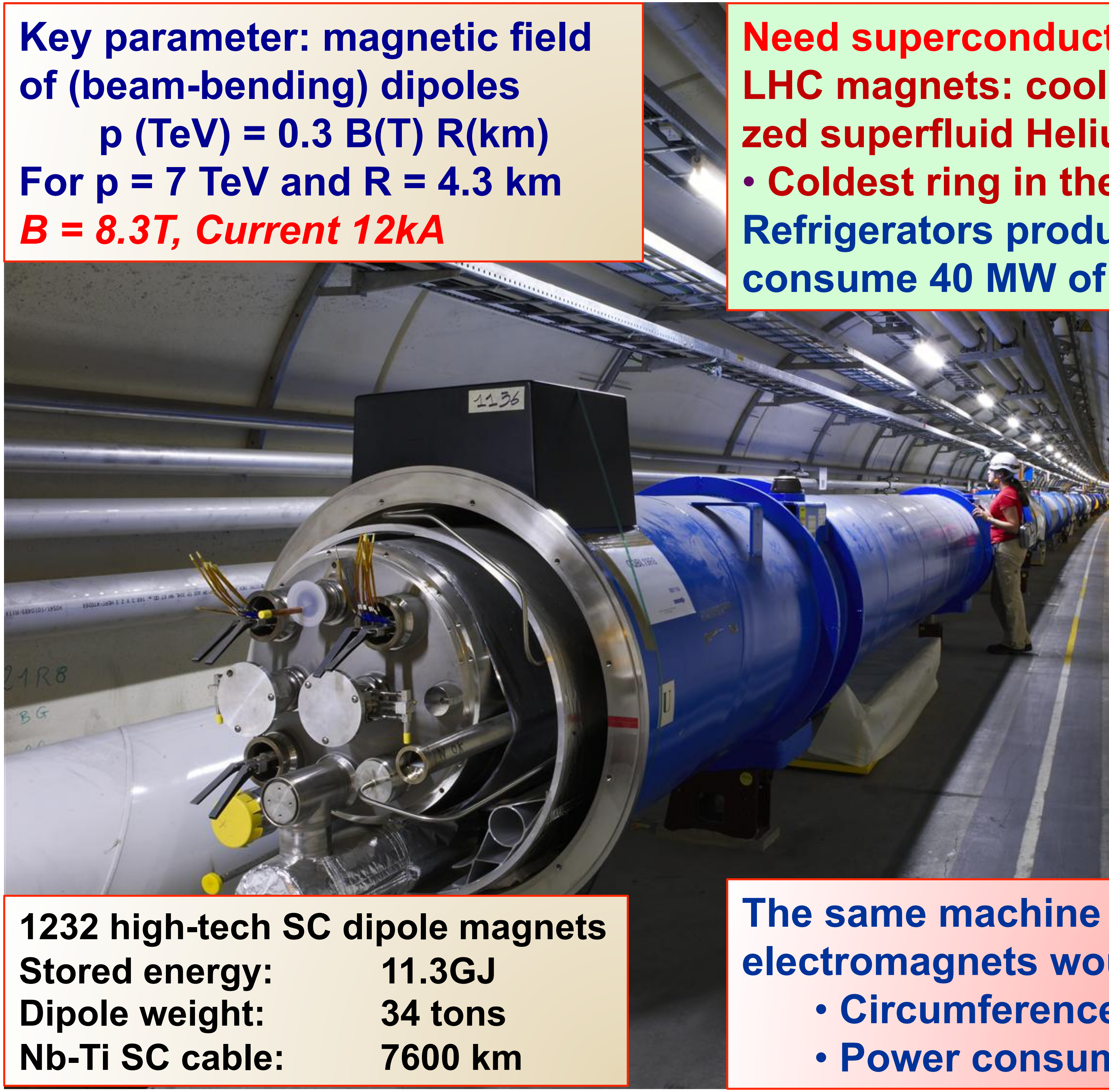
B = 8.3T, Current 12kA

Need superconducting magnets

LHC magnets: cooled with pressurized superfluid Helium (1.9K)

- **Coldest ring in the universe (?)**

Refrigerators producing liquid He consume 40 MW of power.



1232 high-tech SC dipole magnets

Stored energy:	**11.3GJ**
Dipole weight:	**34 tons**
Nb-Ti SC cable:	**7600 km**

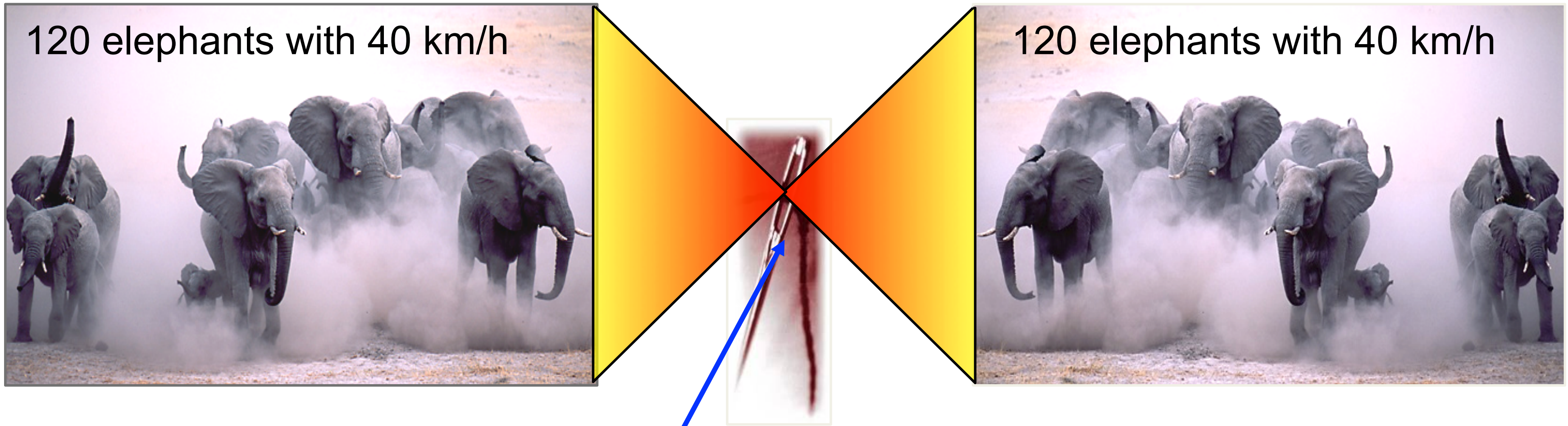
The same machine with classical electromagnets would have:

- **Circumference: 100 km**
- **Power consumption: 1000 MW**

Beam Energy at the LHC

2808 “wagons” with 10^{11} protons, each of 7 TeV energy
➡ 360 MJ stored energy in each beam

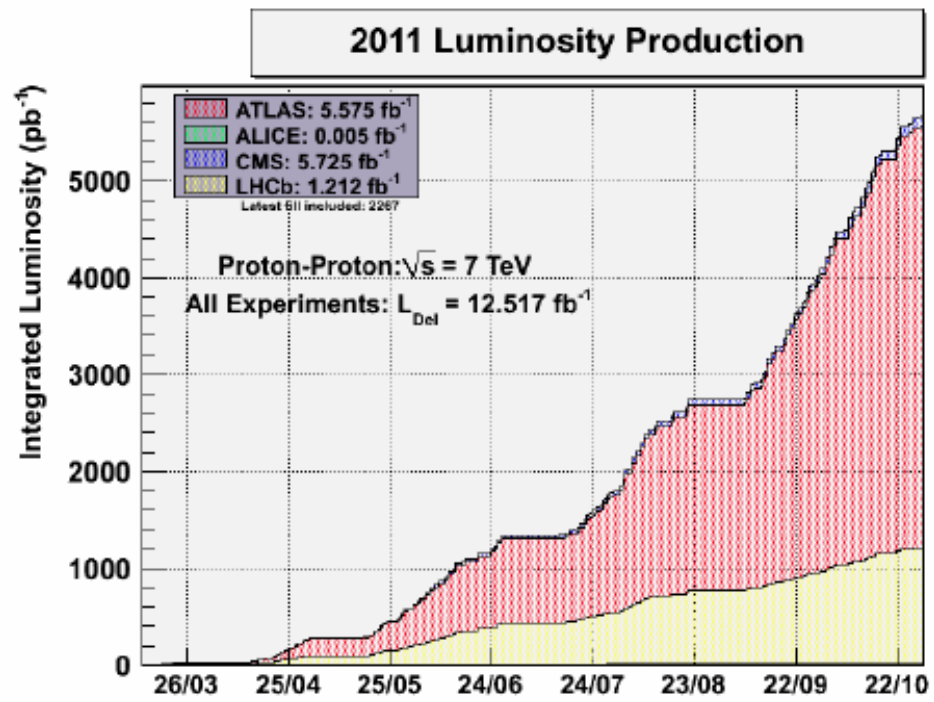
Corresponds to collision of 2×120 elephants



Needle head: diameter 0.3 mm. The proton beams at collision point are ~20 times smaller: diameter 16 μm

LHC Performance in 2011

5.6 fb^{-1} delivered to ATLAS and CMS! Outstanding achievement!

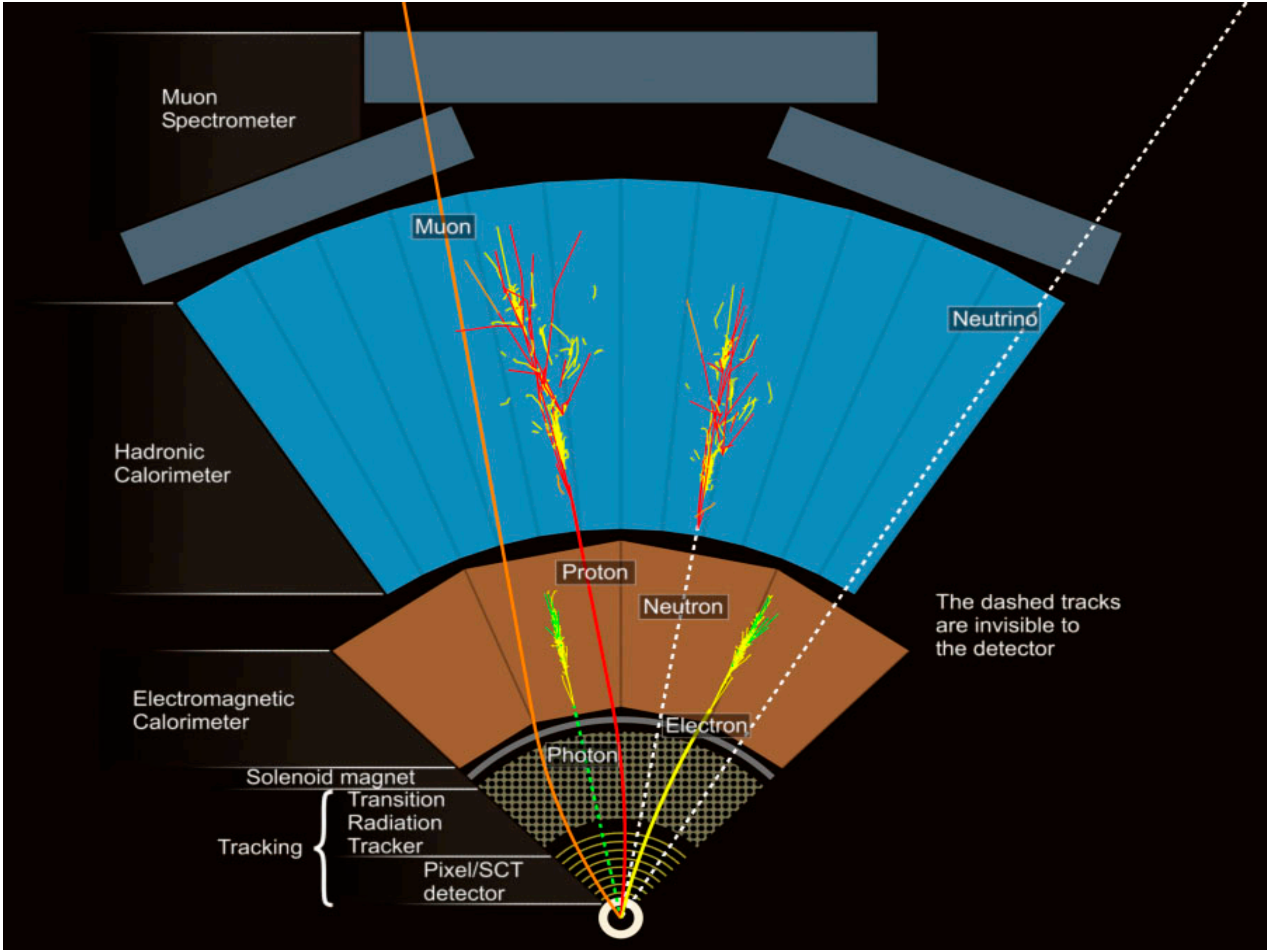


Parameter	2010	2011	Nominal
N (10^{11} p/b)	1.2	1.5	1.15
k (n bunches)	368	1380	2808
B. spacing	150	50	25
ε (µm rad)	2.4-4	1.9-2.3	3.75
β* (m)	3.5	1	0.55
L ($cm^{-2}s^{-1}$)	2 10^{32}	3.6 10^{33}	10^{34}
Stored Energy(MJ)	28	110	360

Factor of ~20 in delivered peak luminosity compared to 2010

Pile-up is becoming a real issue and will be a major concern in 2012

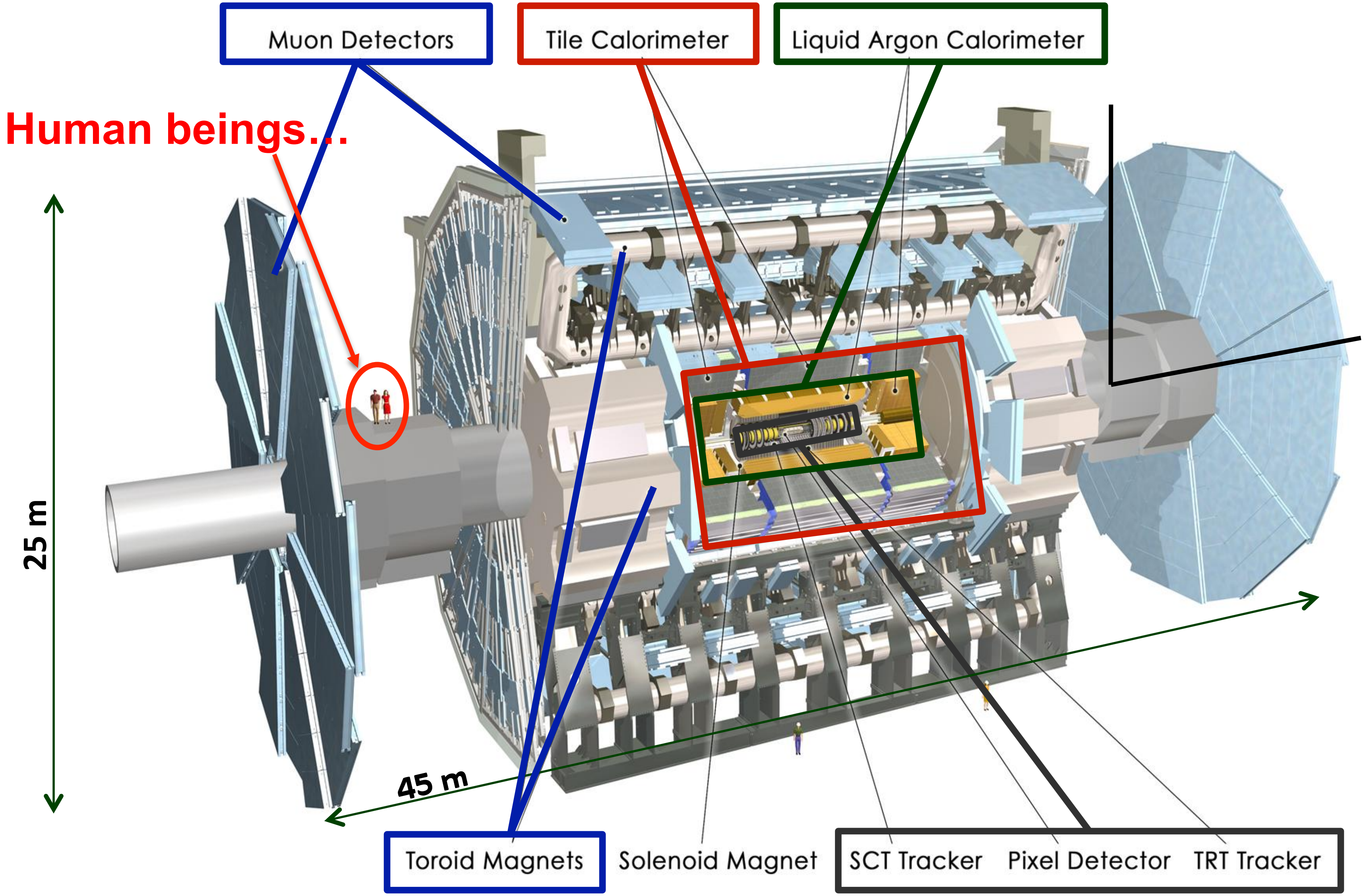
Detector Layers- Different “Camera” Types



Perspective: Operation of an LHC Detector

- Analogy: 3D digital camera with 100 Mpix
- 40 million pictures per sec (which correspond to the happenings during the first ~1/10 of a billionth of a second after the Big Bang)
  - Information: 10,000 encyclopedias per second
- First selection of photographs: 100,000 / sec
  - Each is up to ~ 1MB
- Gets analyzed on a process farm with ~ 50000 CPU cores
- Every second, store the best 200-300 of these pictures
- ~ 10 million GB/year (3 million DVDs/year)
- Good camera allows one to see details
  - When taking many pictures "rare" events can be studied

A Toroidal LHC ApparatuS



To get our bearings:

- Use cylindrical coordinates (φ,η), where $\eta = -\ln[\tan(\theta/2)]$

LHC Higgs Production

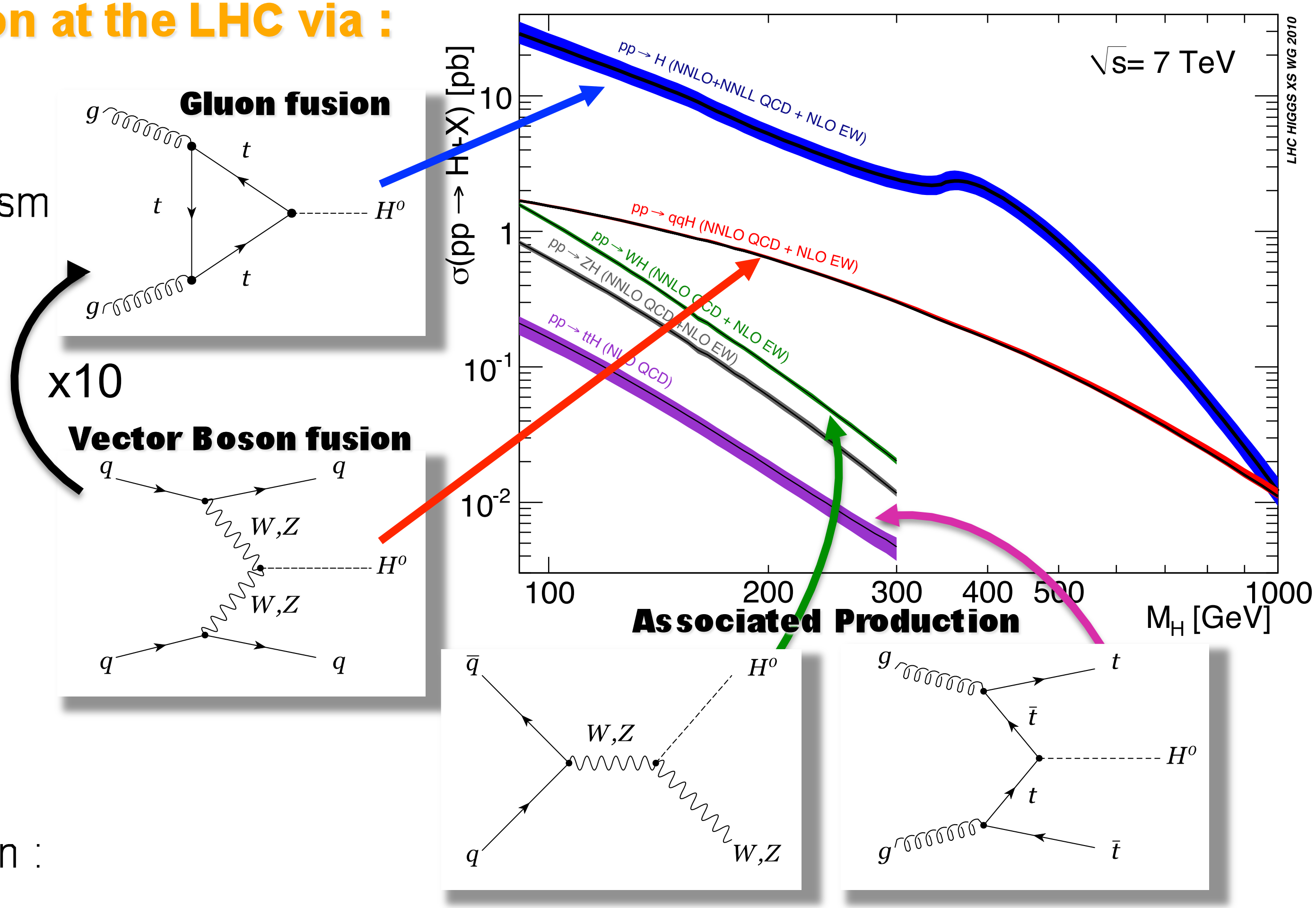
CERN-2011-002: arXiv:1101.0593

Higgs Boson production at the LHC via :

- Gluon fusion :
  - gg → H
  - dominant mechanism
  - channels :
    H → WW ,ZZ, γγ

- Vector Boson fusion :
  - qq → qqH
  - smaller but distinct
  - channels :
    H → ττ

- Associated Production :
  - qq → WH,ZH, ttH
  - the smallest
  - difficult
  - channels :
    H → bb



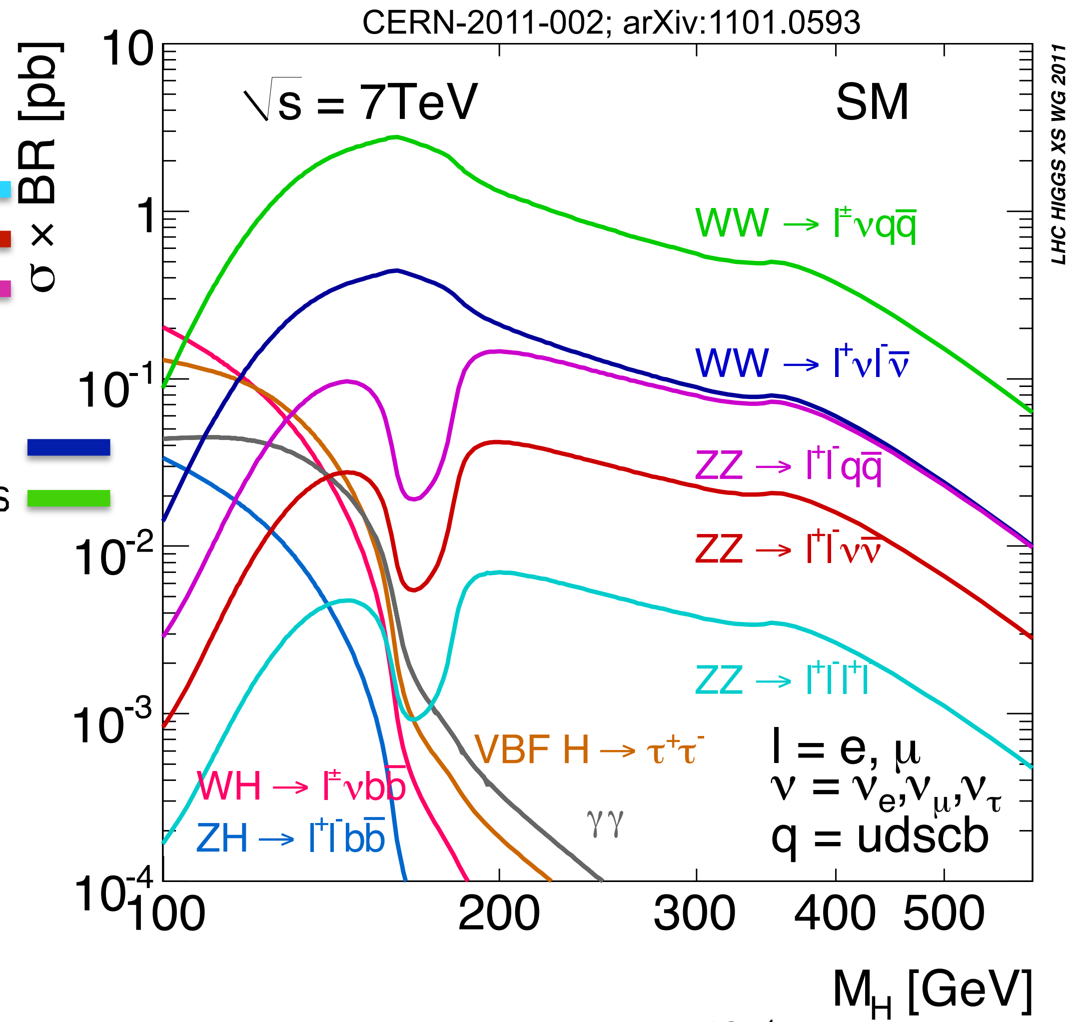
Typical uncertainties on total cross-sections

gg	15-20 %	NNLO + NNLL + NLO EW
VBF	5 %	NNLO + NLO EW
WH, ZH	5 %	NNLO + NLO EW
$t\bar{t}$H	15 %	NNLO

Higgs Boson Cross-Section

Most important channels :

- $H \to ZZ^{(*)}$:
  - $ZZ \to llll$: "golden" mode
  - $ZZ \to llnn$: good for high mass
  - $ZZ \to llqq$: good at high mass
- $H \to WW^{(*)}$:
  - $WW \to lnln$: most sensitive
  - $WW \to lnqq$: important at high mass
- $H \to \gamma\gamma$:
  - rare channel
  - best for low mass
- $H \to \tau\tau$:
  - good s/b
  - low mass
  - rare
- $H \to bb$:
  - with associated production
  - useful but difficult

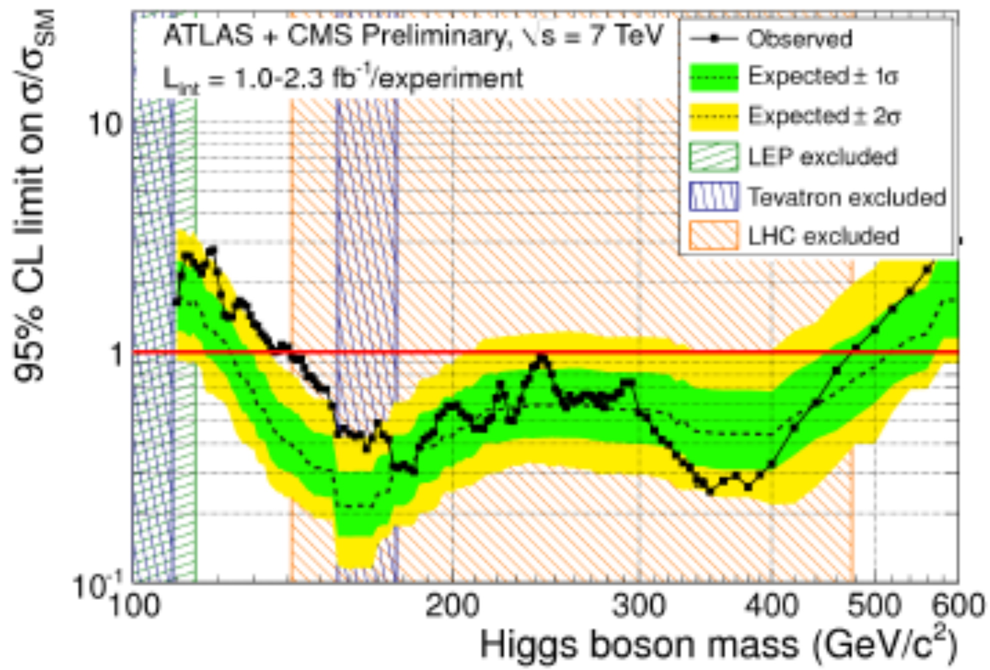


Events expected to be produced with $L = 1 fb^{-1}$

m_H, GeV	$WW \to l\nu l\nu$	$ZZ \to 4l$	$\gamma\gamma$
120	127	1.5	43
150	390	4.6	16
300	89	3.8	0.04

Higgs Searches at the LHC: Summer 2011

The most recent ATLAS-CMS combined Higgs searches (using the LHC data collected up to the end of summer 2011, have excluded a SM Higgs in the mass range 141-476 GeV with 95% CL. By now the most probable scenario for a SM Higgs is for a mass in the 115-140 GeV (perhaps even 115-130 GeV) range.



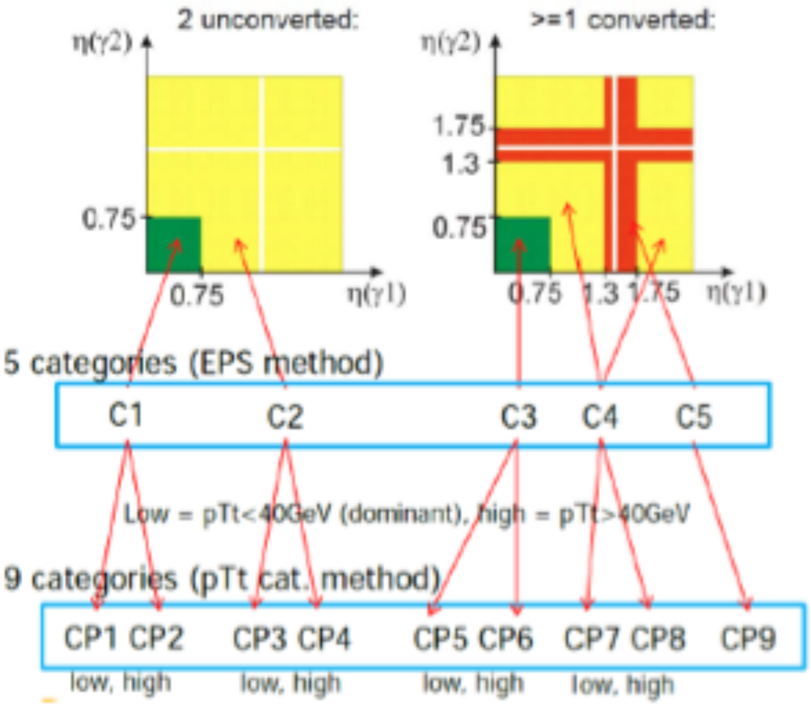
Two Higgs decay channels are well placed to look for the Higgs in that range:

- H->γγ looking for a peak on top of a continuous background
- H->ZZ*->4l with excellent mass resolution capability and fairly low background.

Carleton has been heavily involved in both of these two channels

Higgs Decay to Two Photons

Signal consists of two converted/unconverted almost back-to-back isolated photons. Signal-like events are further classified in samples with different S/B and mass resolution to optimize the sensitivity.

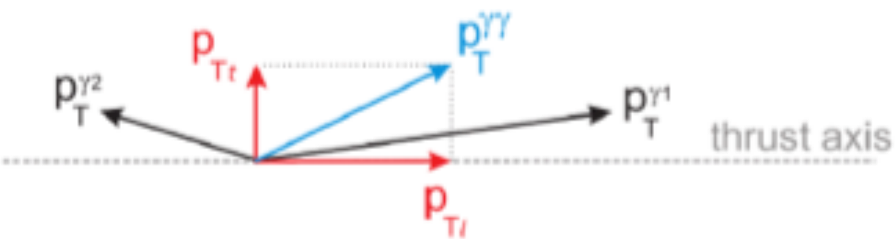


Conversion-eta categories:

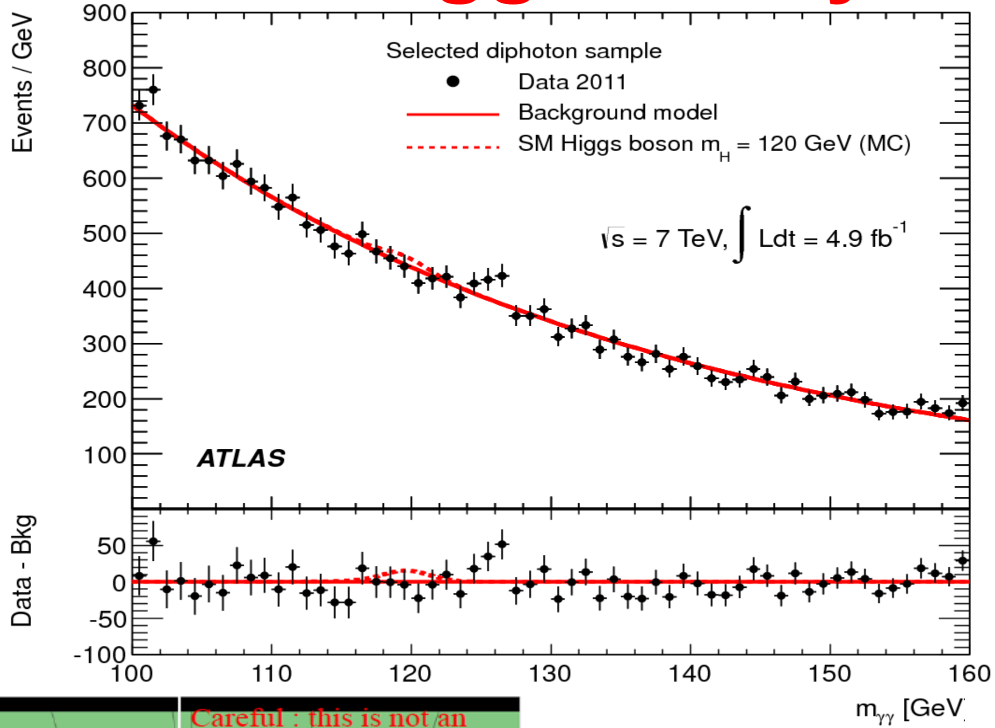
- Unconverted: both γ's are unconverted
- Converted: at least one γ is converted
- Eta central: both photons $|\eta|<0.75$
- Eta transition: at least one γ with $1.3<|\eta|<1.75$
- Eta rest: all other cases

p_{Tt} categories:

- Low $p_{Tt}<40$ GeV
- High $p_{Tt}>40$ GeV



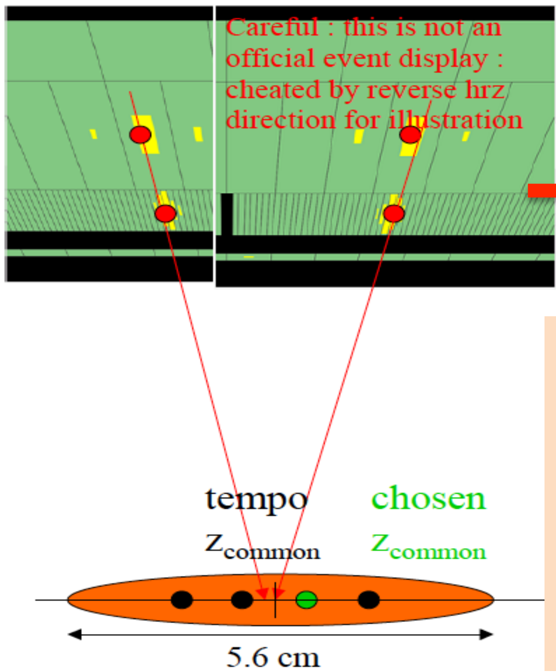
Higgs Decay to Two Photons



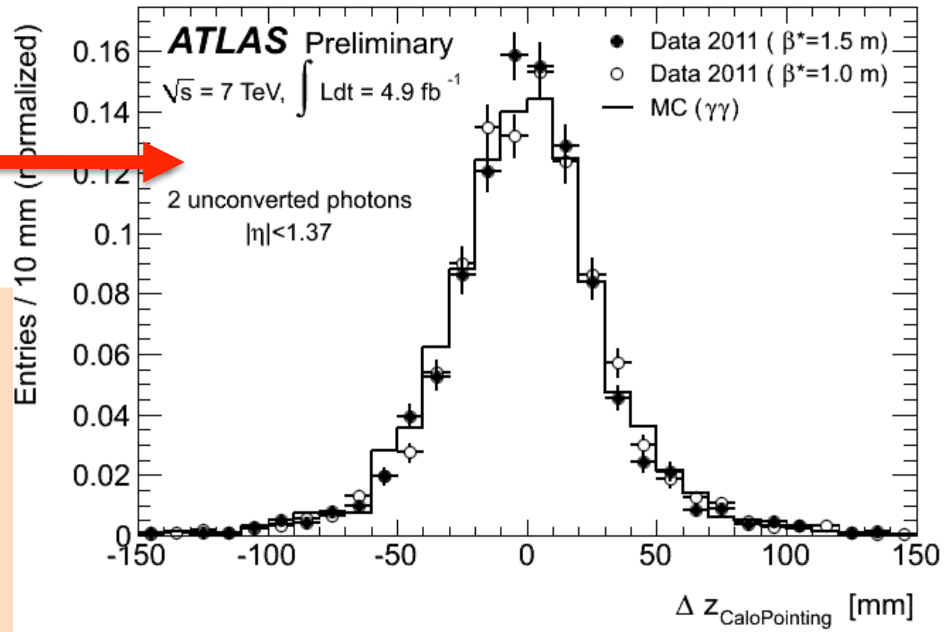
Energy spectrum of the diphoton selected events. Smooth background due to:

- SM diphoton events (irreducible)
- One or two jets mimicking photons (reducible)

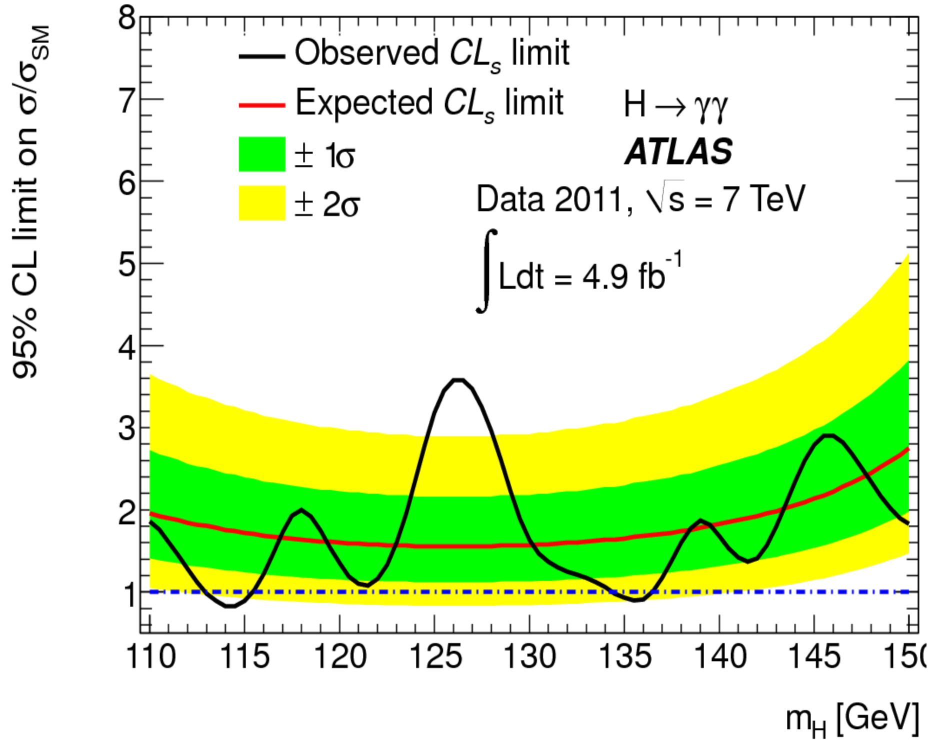
Signal should look like a "bump" on top of the background continuum.

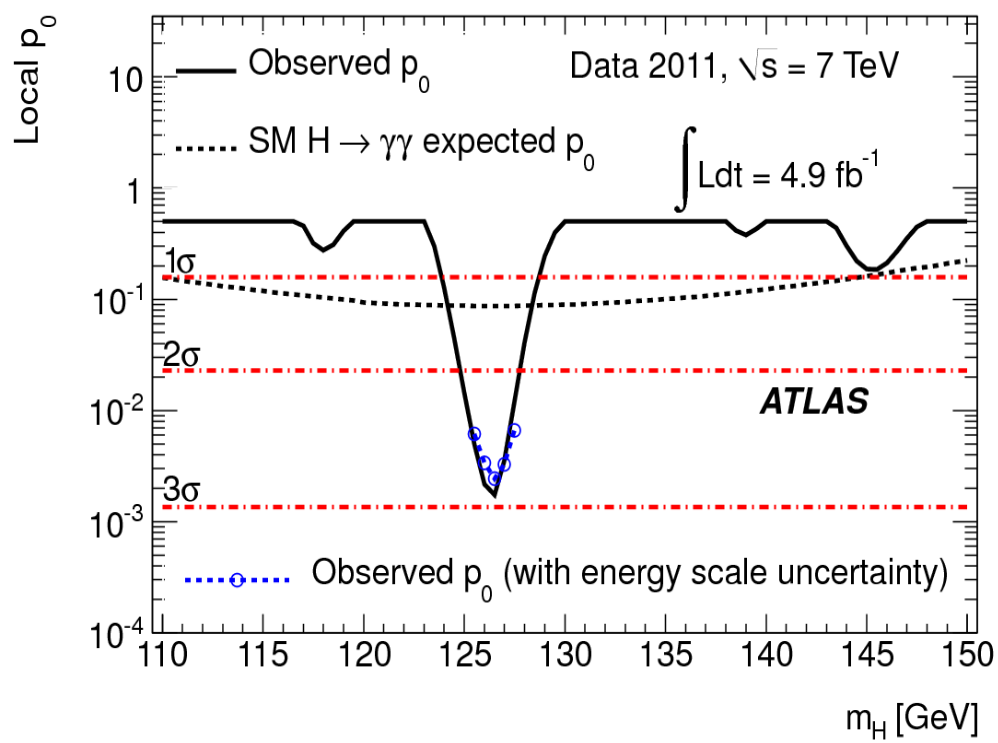


Photon Pointing: Fundamental in improving the reconstructed Higgs invariant mass



Higgs Decay to Two Photons





The expected limit varies between 1.6 and 2.7× SM cross-section for the full mass range of 110 GeV<m_H<150 GeV and the observed between 0.83 and 3.6 × SM cross-section. A SM Higgs boson with a mass in the range of 113 GeV-115 GeV, or in the range 134.5 GeV-136 GeV is excluded at 95% CL.

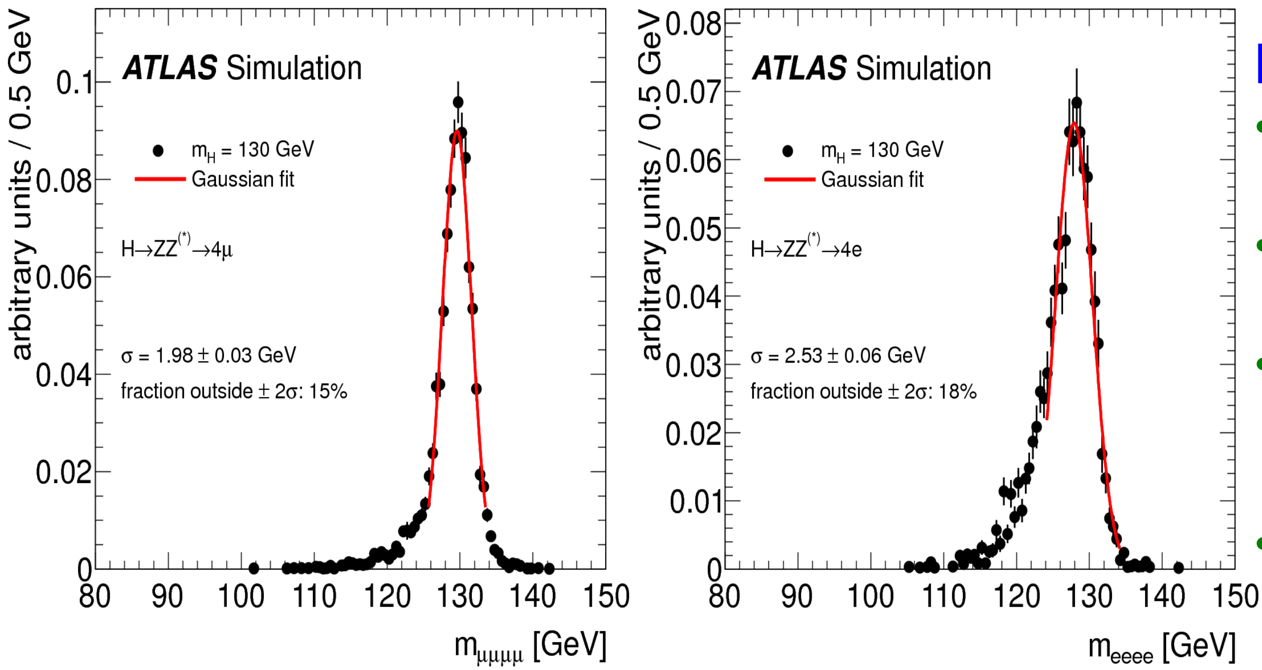
The largest excess is found to be at 126.5 GeV and corresponds to a ~2.9σ local significance. This reduces to 2.8 σ when the uncertainty in the photon energy scale is taken into account. Its global significance is reduced to 1.5σ.

Higgs Decay to Four Leptons

Signal consists of 2 pairs of isolated leptons (4μ or 2μ2e or 4e) where at least one of them corresponds to the Z-boson invariant mass.

For the case of "low" mass Higgs (m_H<150 GeV) at least one of the leptons is rather "soft" (p_T<15 GeV). In the case of electrons this can be particularly problematic, since the effects of the energy loss due to bremsstrahlung become significant:

- Major overhaul of the electron reconstruction and identification
- New electrons (known as "GSF electrons") are used in this analysis

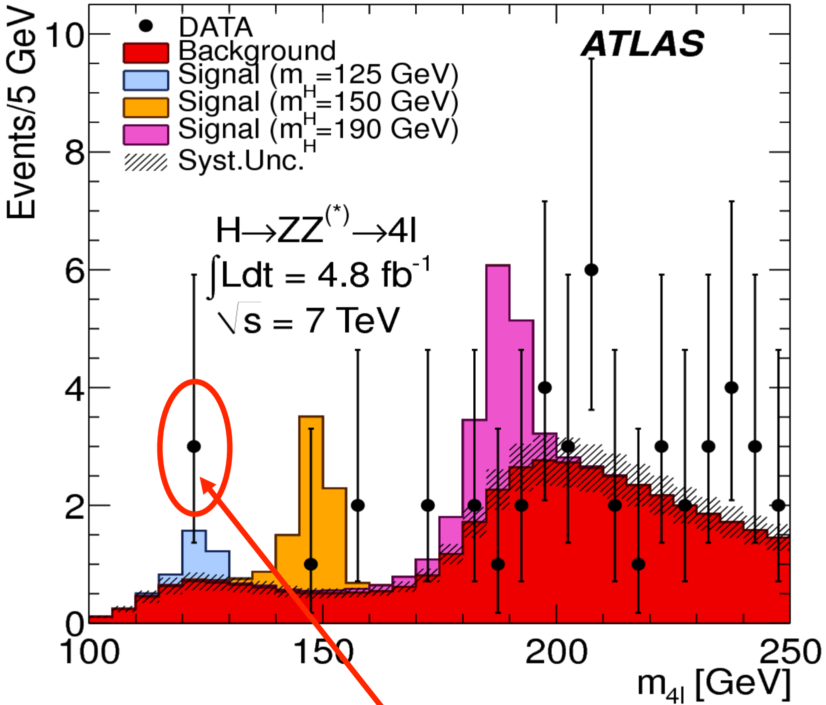


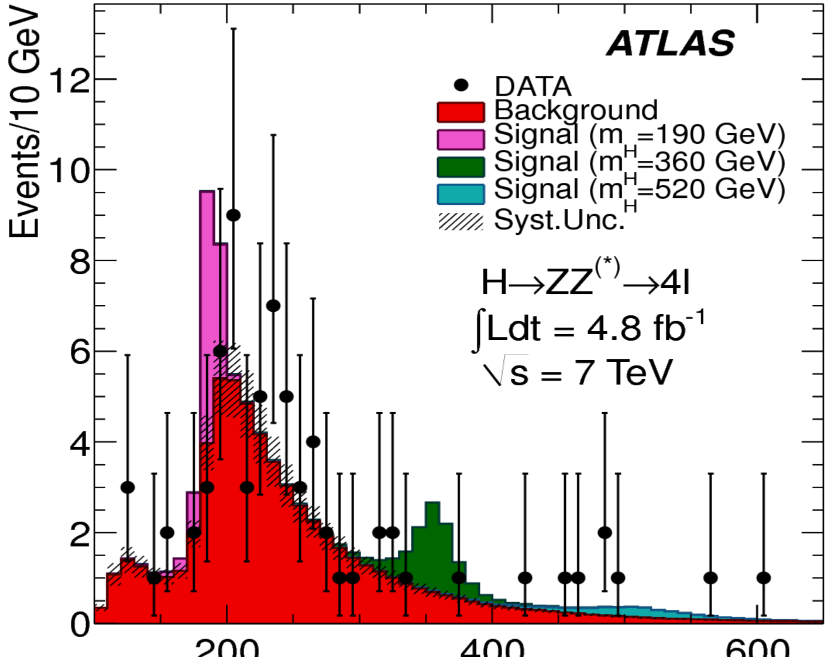
Main backgrounds:

- SM ZZ production decaying to four leptons
- SM inclusive Z+jets where jets decay into leptons
- QCD background with jets decaying or misidentified as leptons.
- tt-bar, but rather insignificant

Electrons are more comparable to muons now…

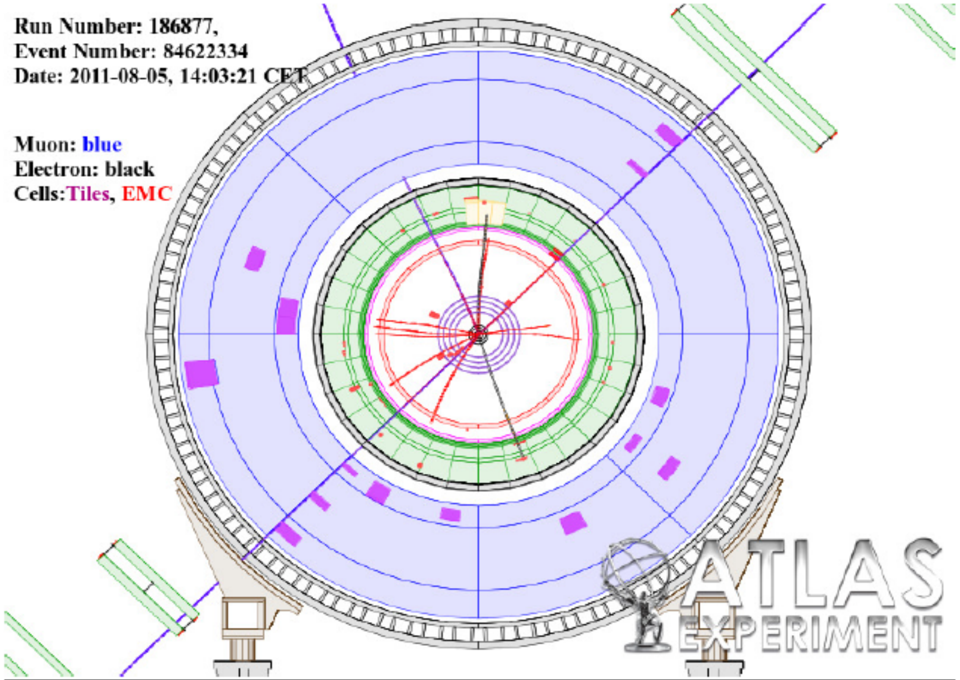
Higgs Decay to Four Leptons



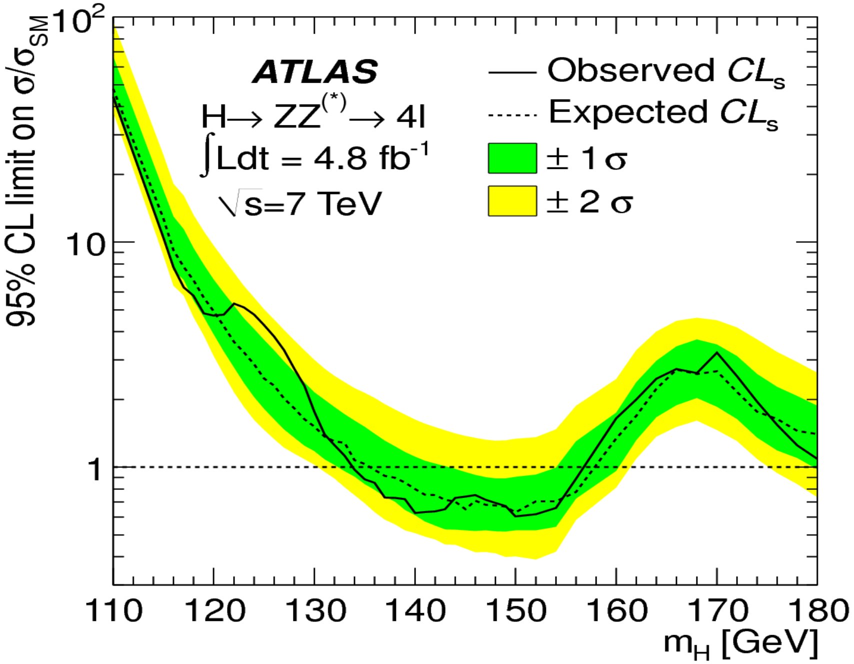


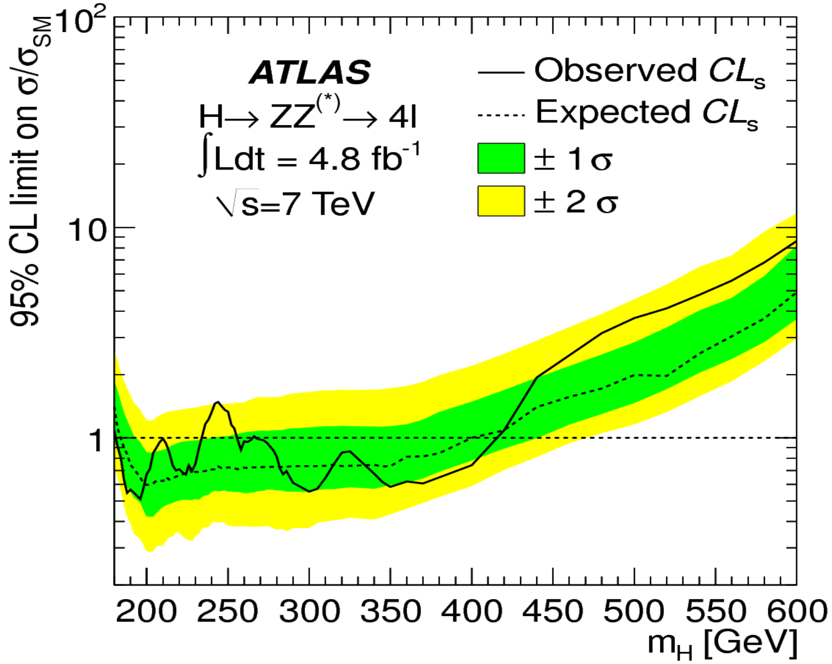
The most direct Carleton contribution…

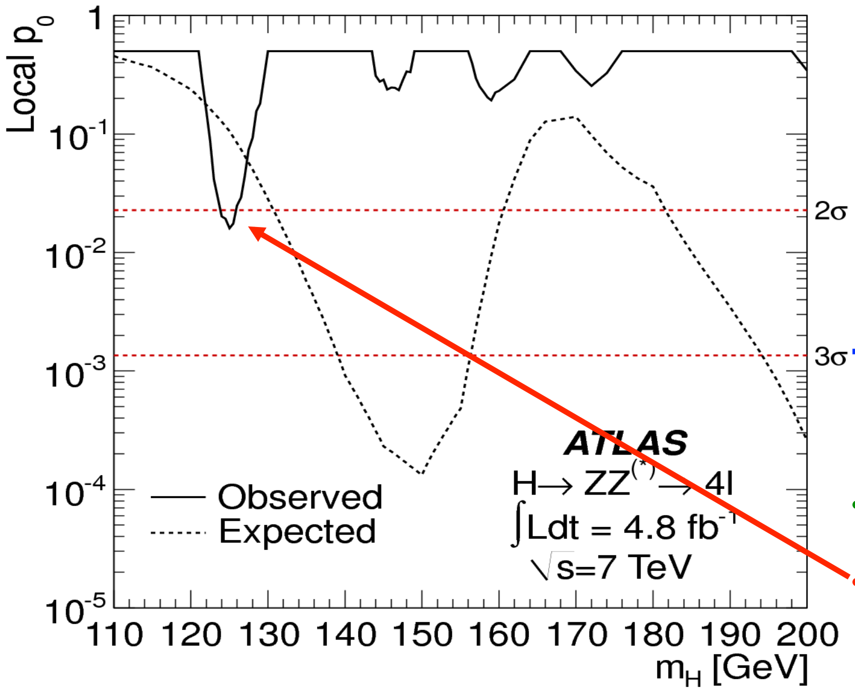
A new event has been added in the area ~125 GeV, due to the GSF electrons. An event display is shown on the left. This is an electron that lost >50% of its energy due to bremsstrahlung inside the tracker and was recovered by the new electron reconstruction.



Higgs Decay to Four Leptons







Exclusion (observed) 95% CL :

-[134.0−156.0] GeV

-[182.0−233.0] GeV

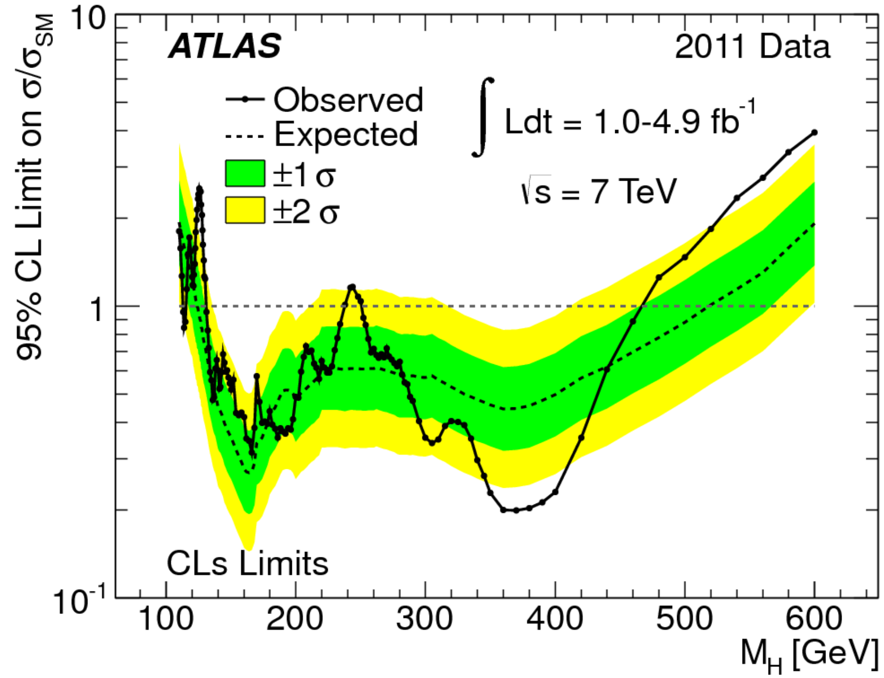
- [256.0-265.0] GeV

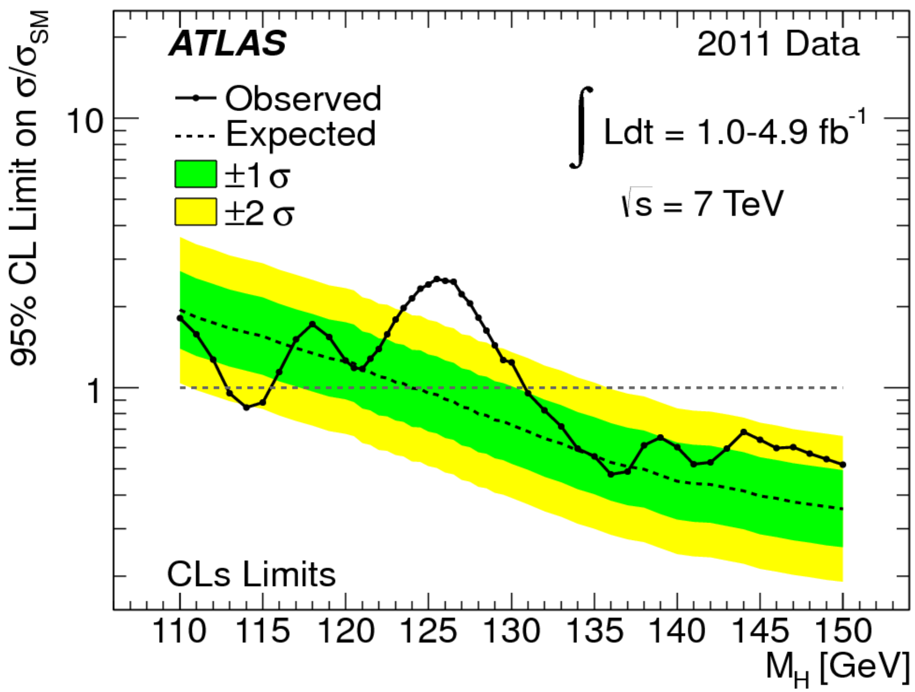
-[266.0−415.0] GeV

The most significant deviations from the background-only hypothesis are observed for:

- m_{Higgs} = 244 GeV with 2.1σ significance
- m_{Higgs} = 125 GeV with 2.2σ significance
- m_{Higgs} = 500 GeV with 2.1σ significance

ATLAS Combined Higgs Searches





Higgs Decay Modes	Mass Range (GeV) (arrows are for illustration only)	Luminosity (fb-1)
$WW \to l\nu qq$	240-600	1.04 (since EPS11)
$ZZ \to llqq$	200-600	2.05 NEW
$ZZ \to ll\nu\nu$	200-600	2.05 NEW
$WW \to l\nu l\nu$	110-300	2.05 NEW
$ZZ \to llll$	110-600	4.8 NEW
$\gamma\gamma$	110-150	4.9 NEW

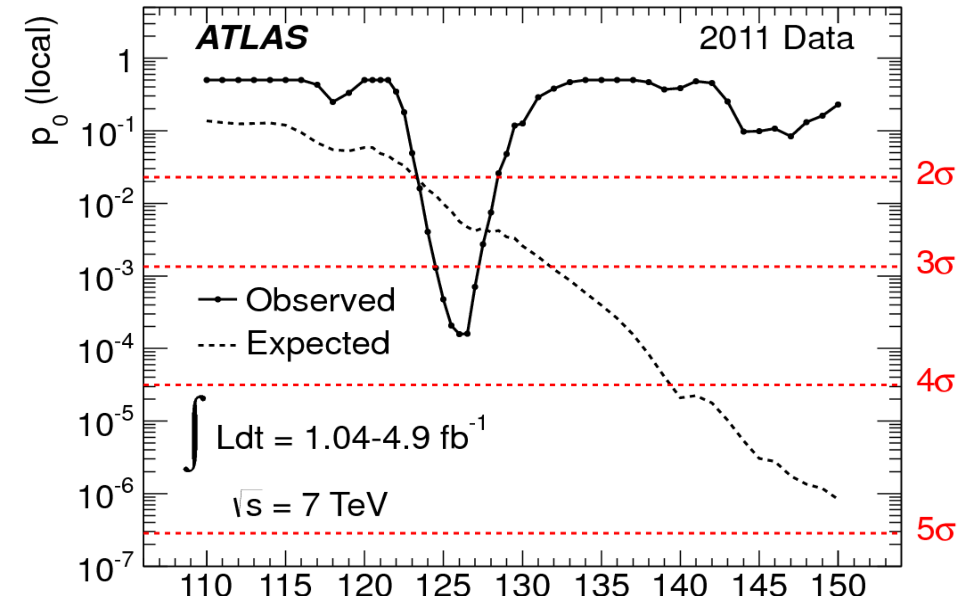
Observed exclusions @ 95% CL:

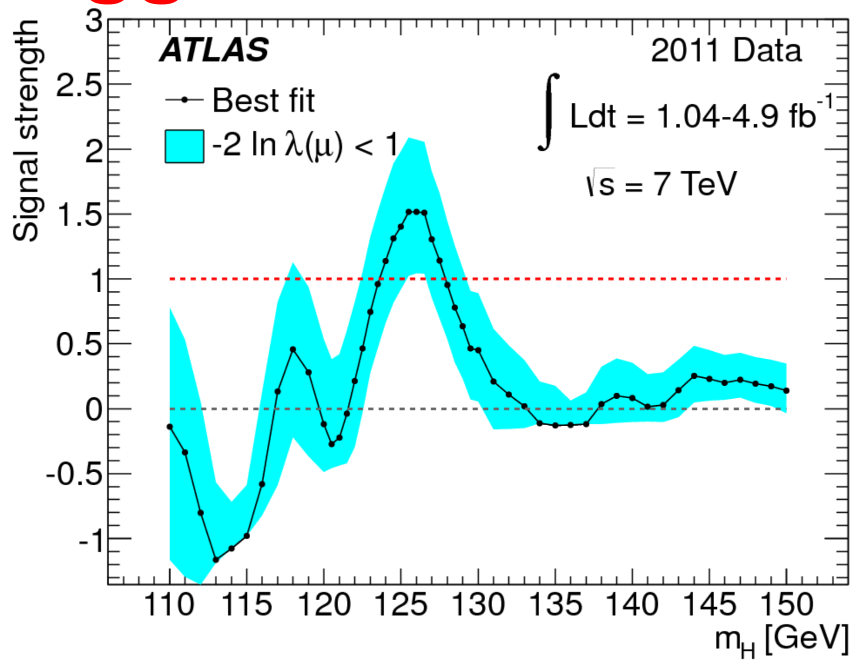
- 112.9 GeV – 115.5 GeV
- 131.0 GeV – 238.0 GeV
- 251.0 GeV – 466.0 GeV

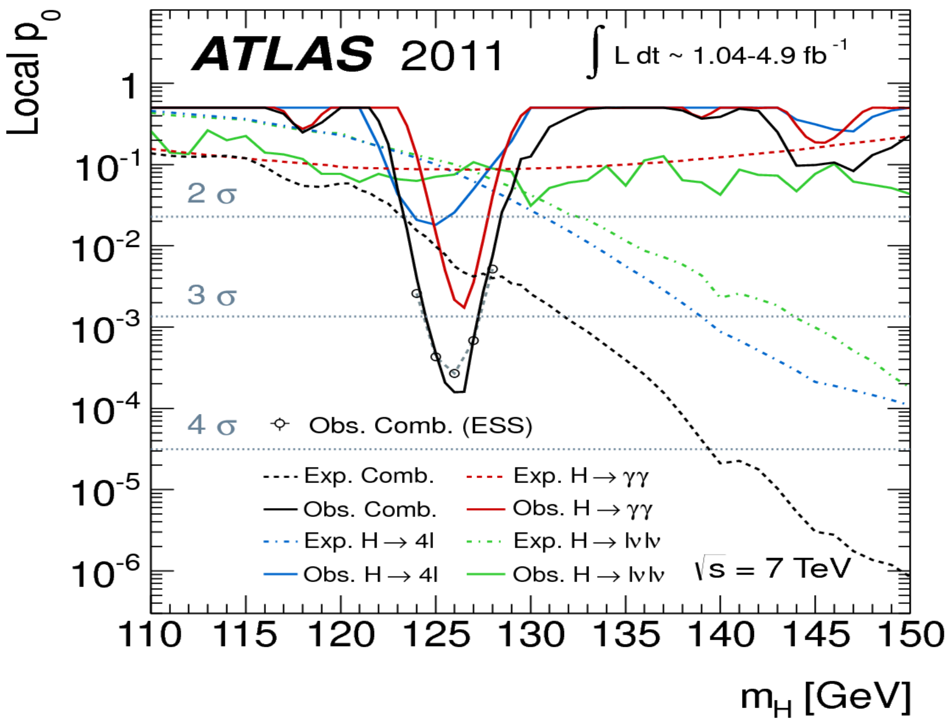
Areas not excluded @ 95% CL:

- 115.5 GeV – 131.0 GeV
- 238.0 GeV – 251.0 GeV
- > 466.0 GeV

ATLAS Combined Higgs Searches







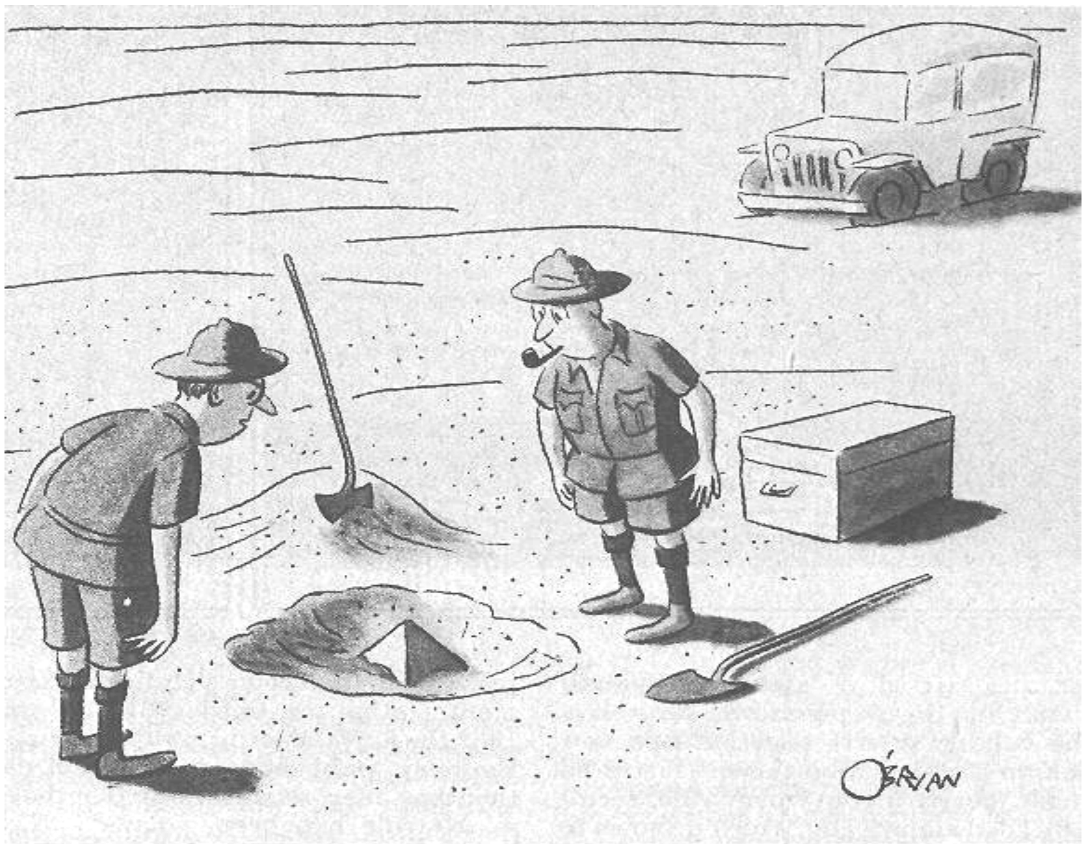
Background hypothesis test: the smaller the number the less likely for it to be a background fluctuation…

Signal strength of ~1.5 at ~126 GeV is not incompatible with the SM Higgs expectation of 1.

Main contribution to the excess seen by the two "resonance" channels. This is where the Carleton ATLAS group is strongly involved…

Conclusion

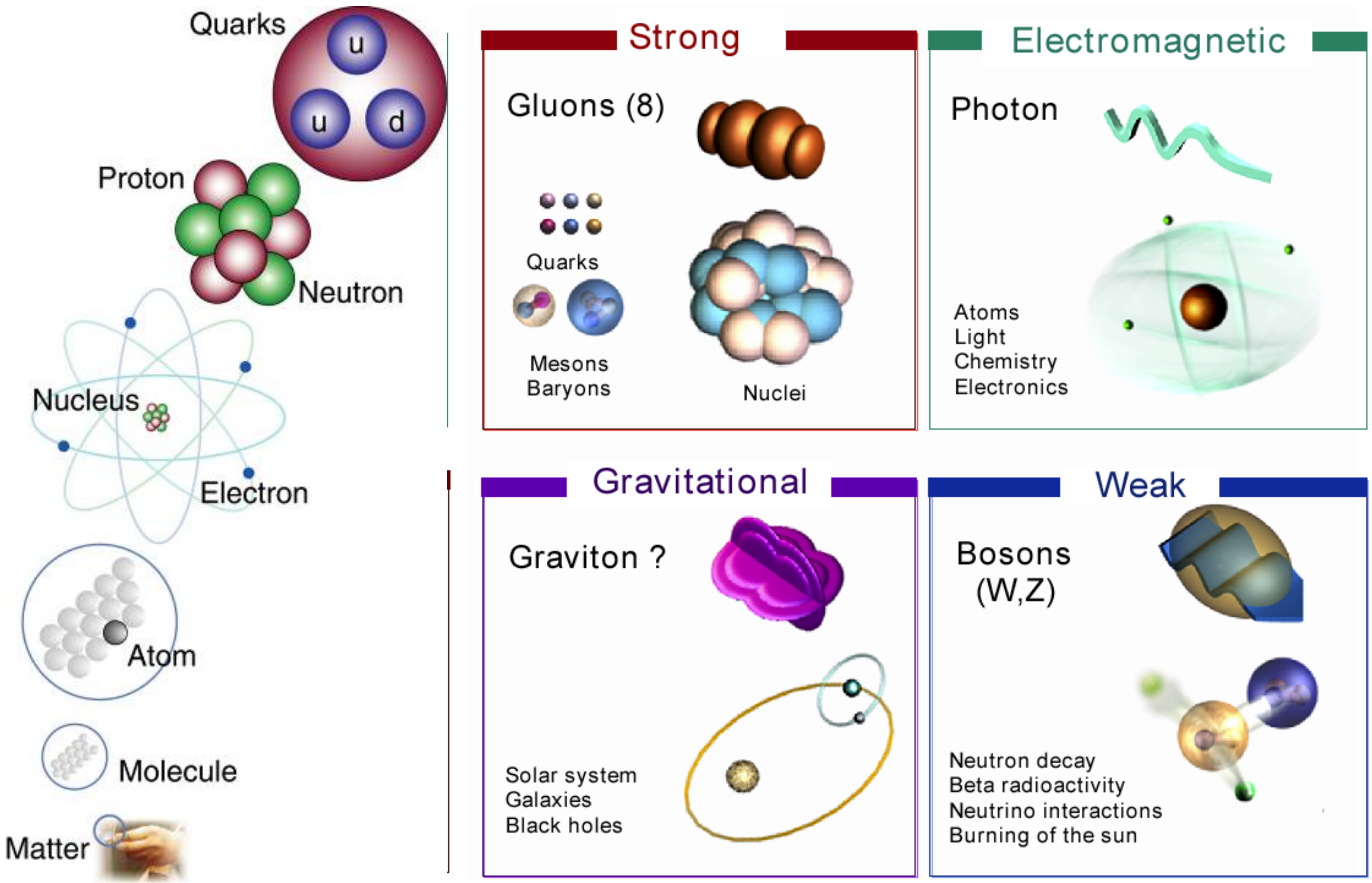
- The LHC has worked beautifully over 2011 delivering large quantities of data
- With the 2011 statistics the region of interest for the SM Higgs search has been significantly narrowed down.
- The "low" Higgs mass region (<131 GeV) will be the most "hot" search endeavor in 2012.
- We may have had a glimpse of what is going to be. Perhaps by next summer we'll know for sure…



"This could be the discovery of the century. Depending, of course, on how far down it goes."

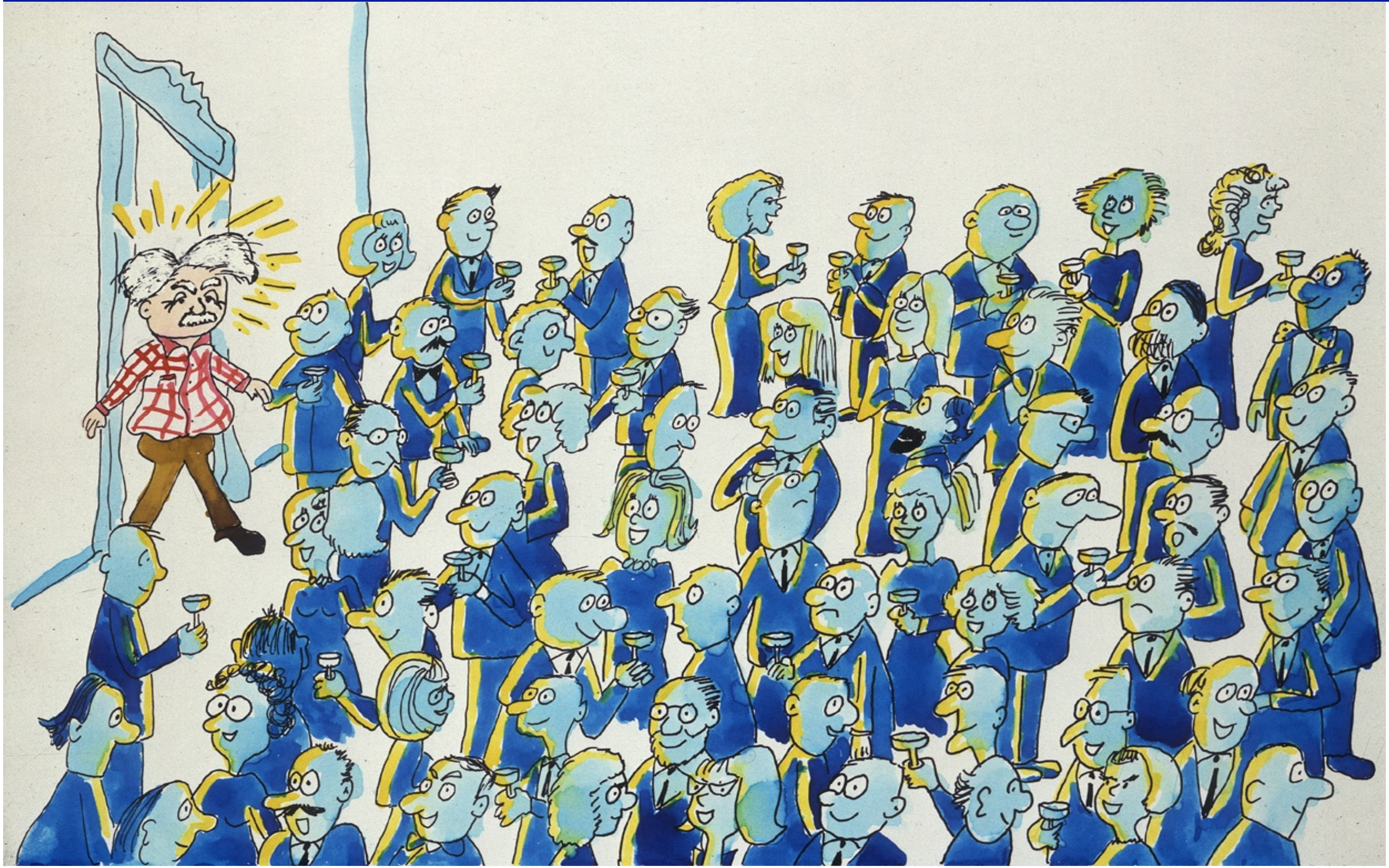
BACKUP

Known Particles and Forces

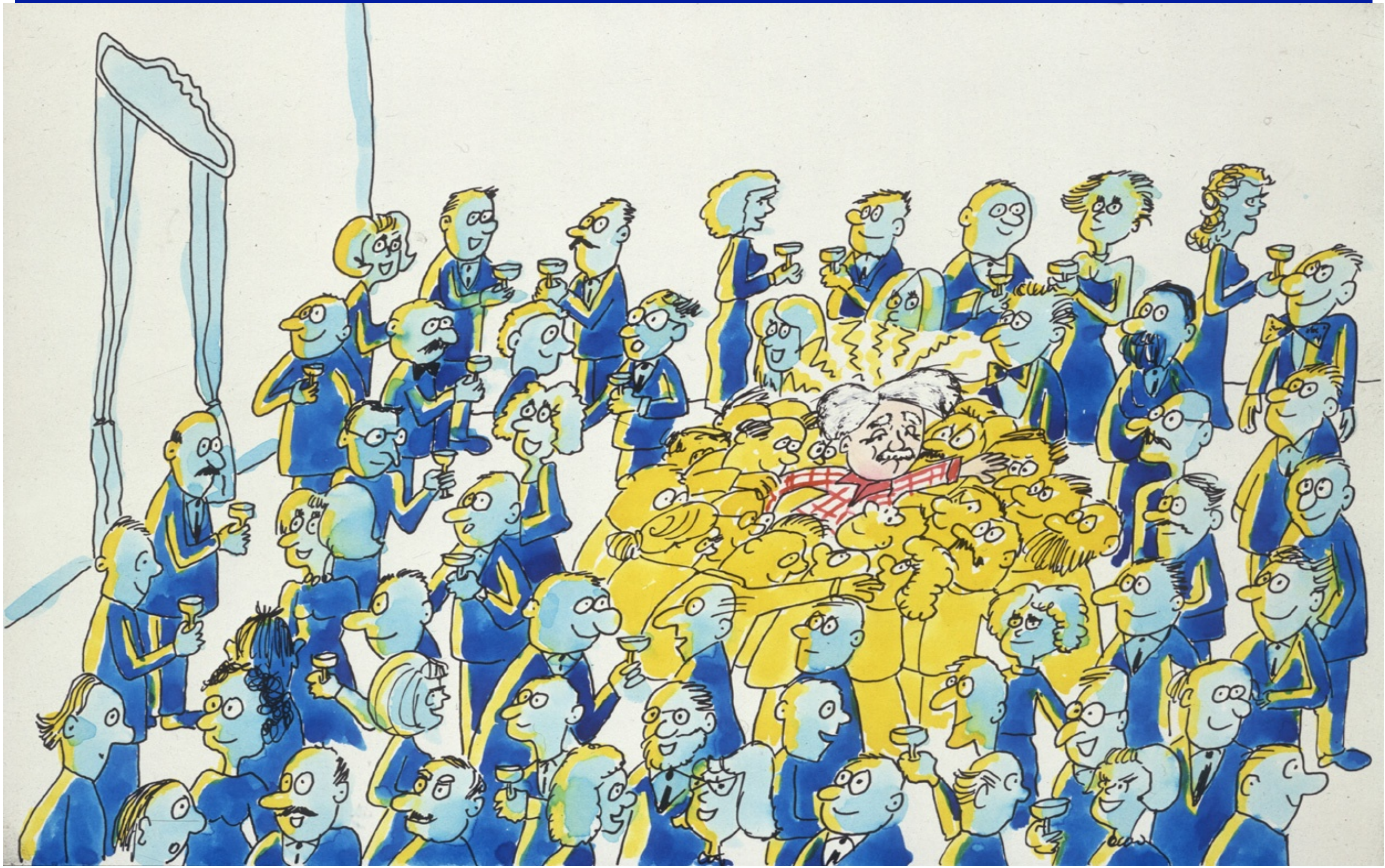


Higgs Mechanism I: A room full of physicists quietly chattering is like space filled only with the Higgs field…

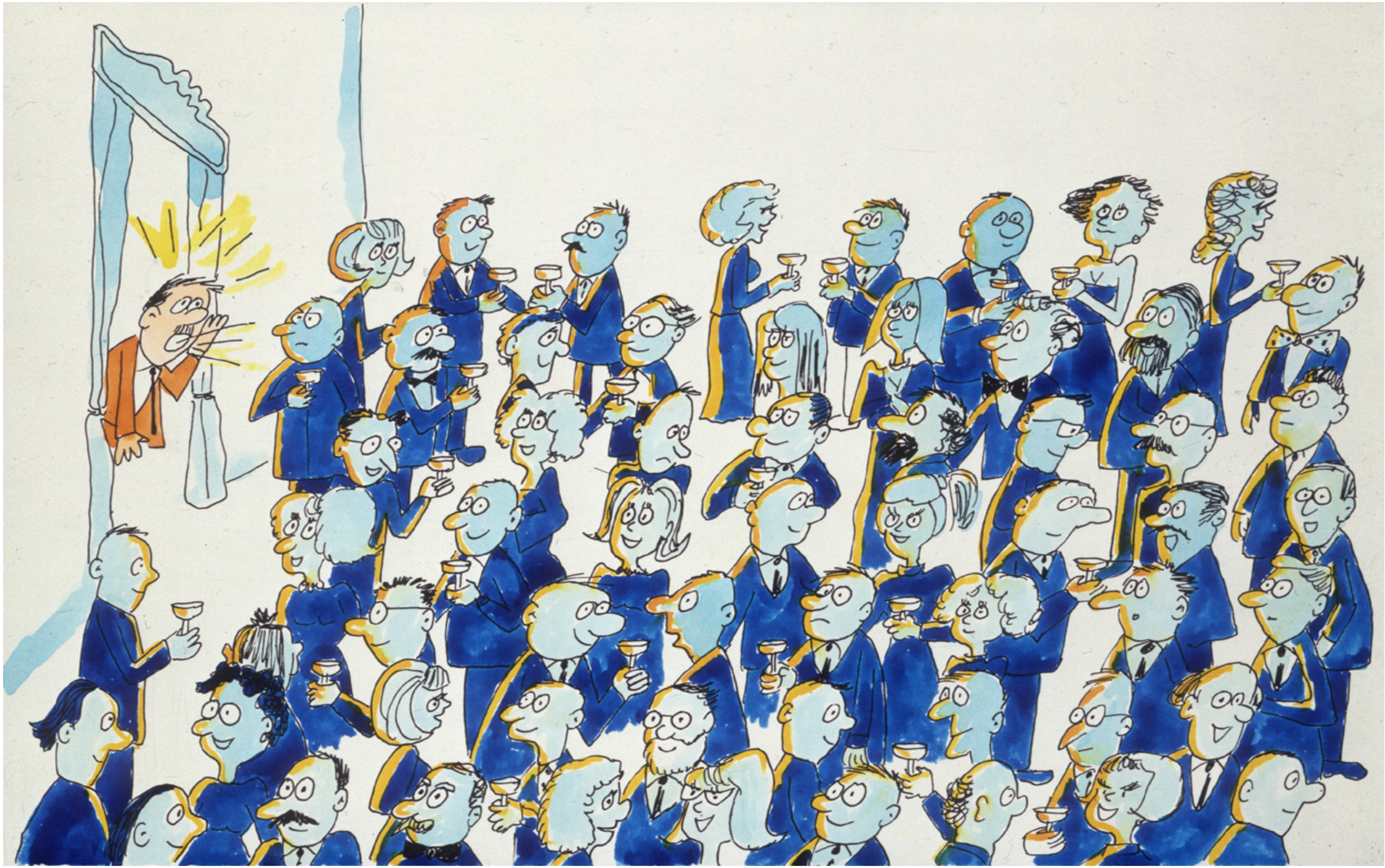
Higgs Mechanism II: A famous scientist walks in, creating a stir as he moves across the room, attracting a cluster of admirers…



Higgs Mechanism III: His resistance to movement increases, i.e. he acquires mass, like a particle moving through the Higgs field…



Higgs Mechanism IV: If a rumor crosses the room…



Higgs Mechanism V: …it creates the same kind of clustering only this time among the scientists themselves. These clusters are the Higgs particles.

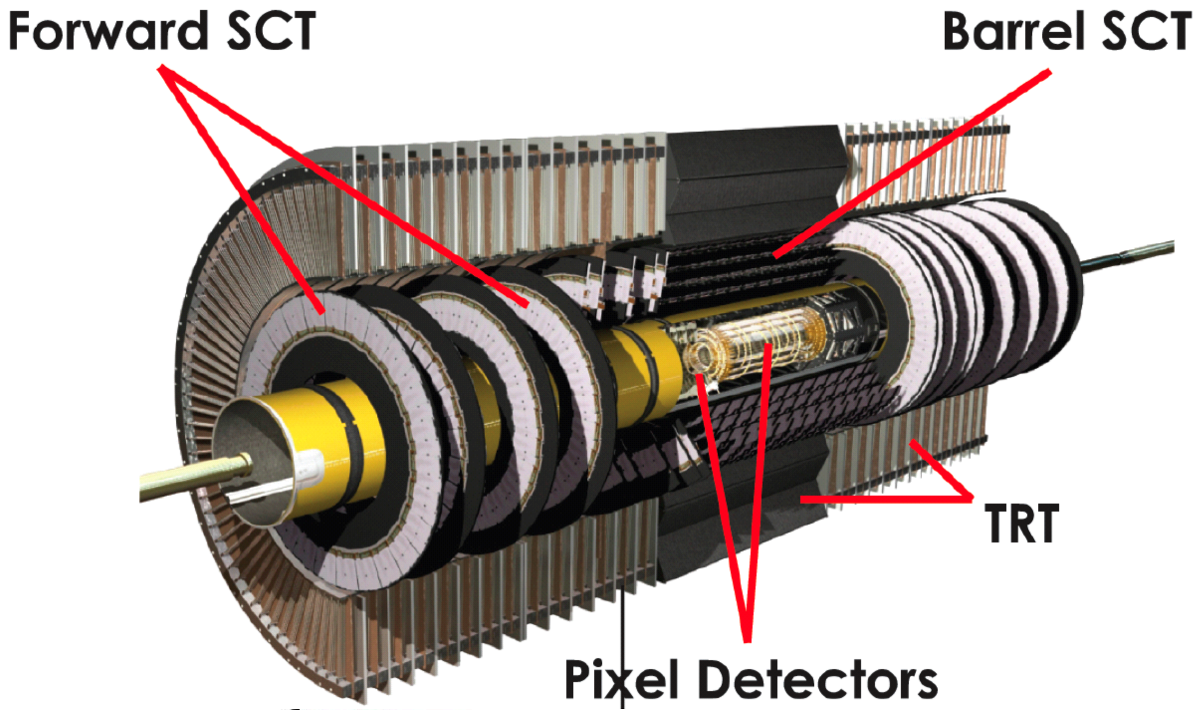
The ATLAS Tracker

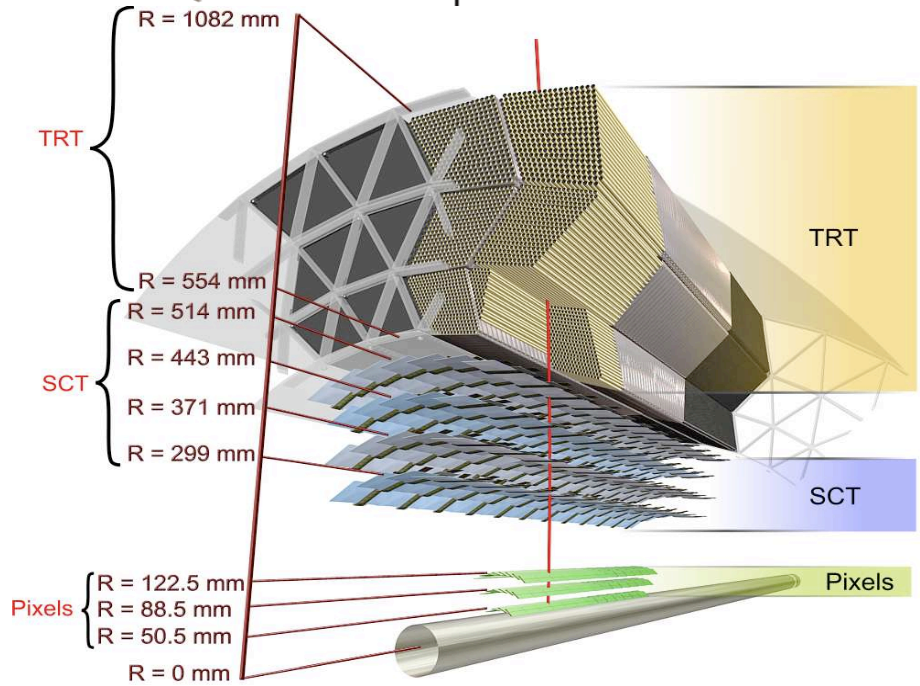
The Inner Detector (ID) is organized into three sub-systems:

Pixels
- high resolution space points
- 1 removable barrel layer
- 2 barrel layers
- 4 end-cap disks on each side
- (0.8 10^8 channels)

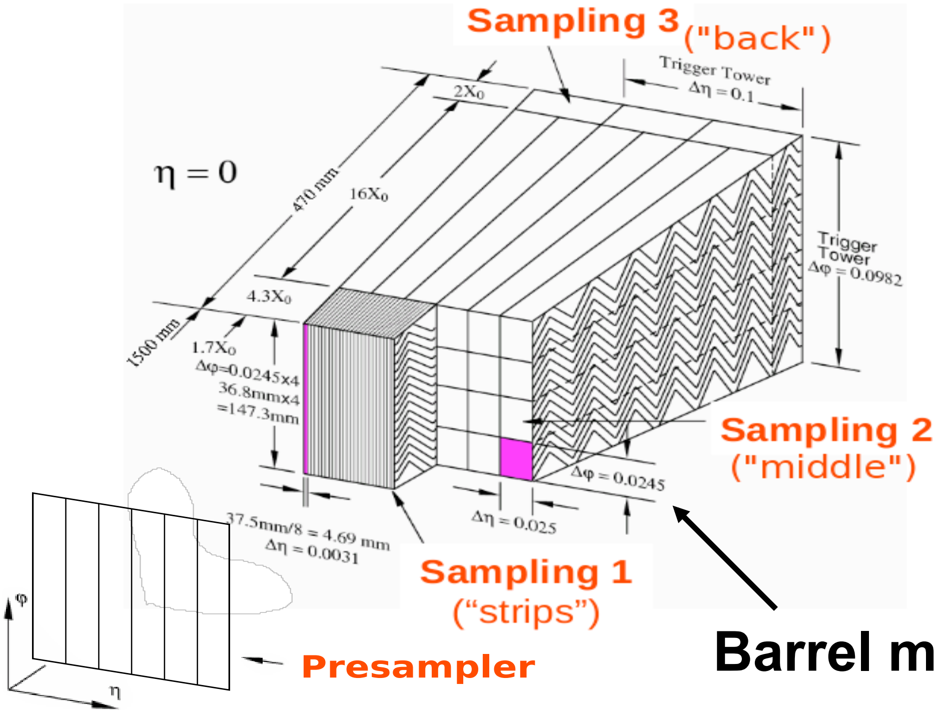
Silicon Tracker (SCT)
- silicon microstrips
- 4 barrel layers
- 9 end-cap wheels on each side
- (6 10^6 channels)

Transition Radiation Tracker (TRT)
- Axial barrel straws
- Radial end-cap straws
- Interleaved with polypropylene radiator
- ~35 straws per track
- (4 10^5 channels)
- electron PID capability

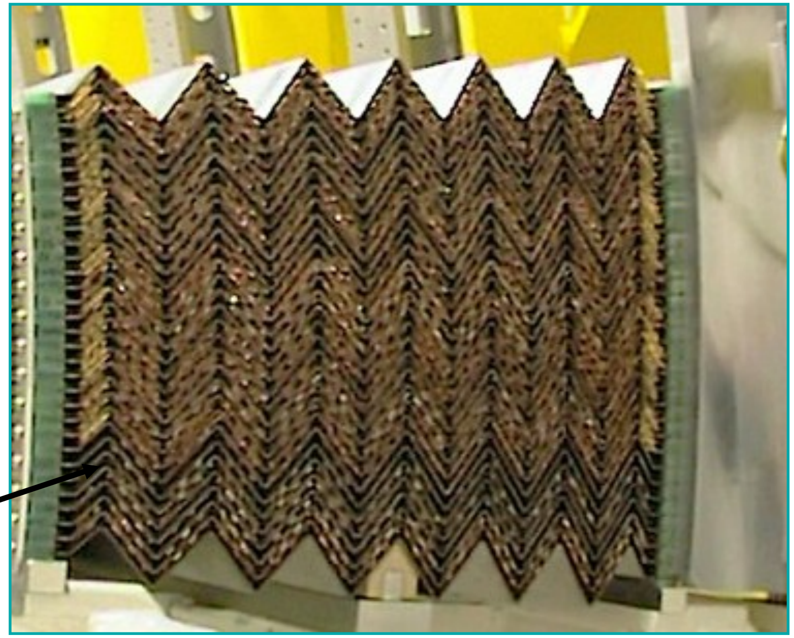




LAr EM Calorimeter description



Barrel module

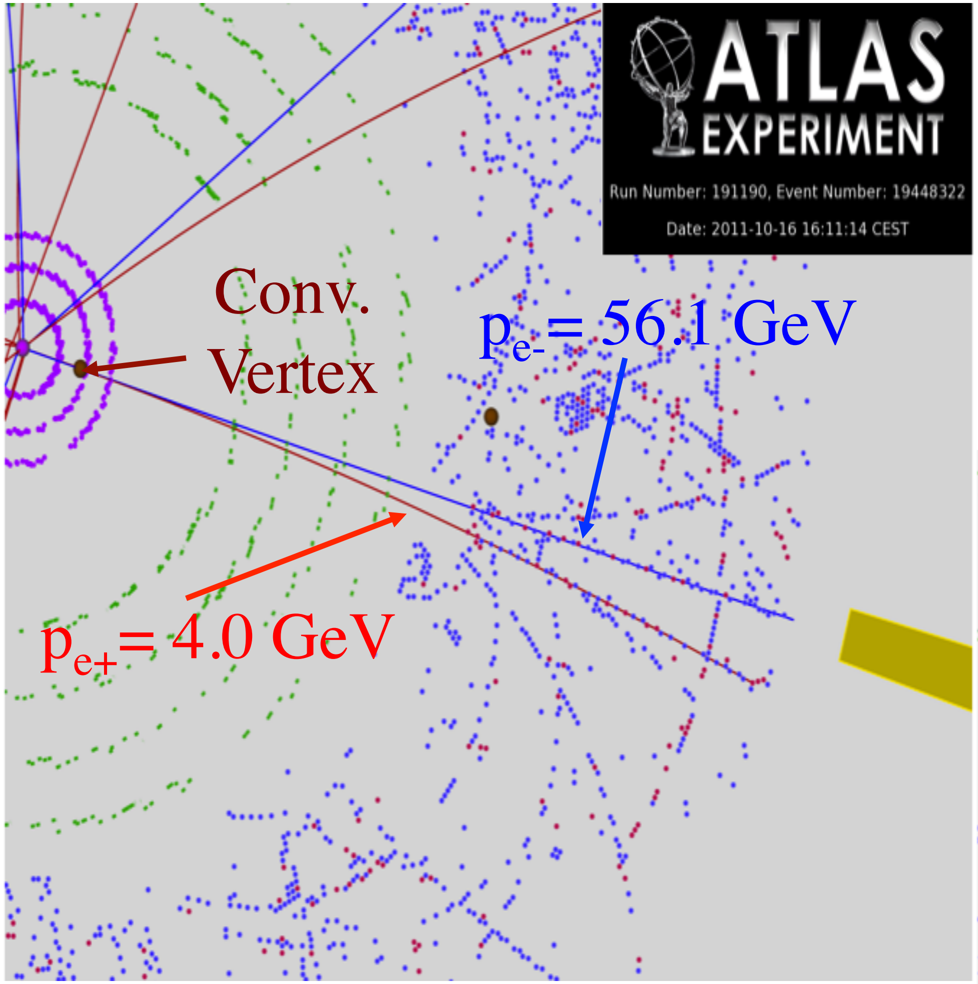


EM Calo (Presampler + 3 layers):

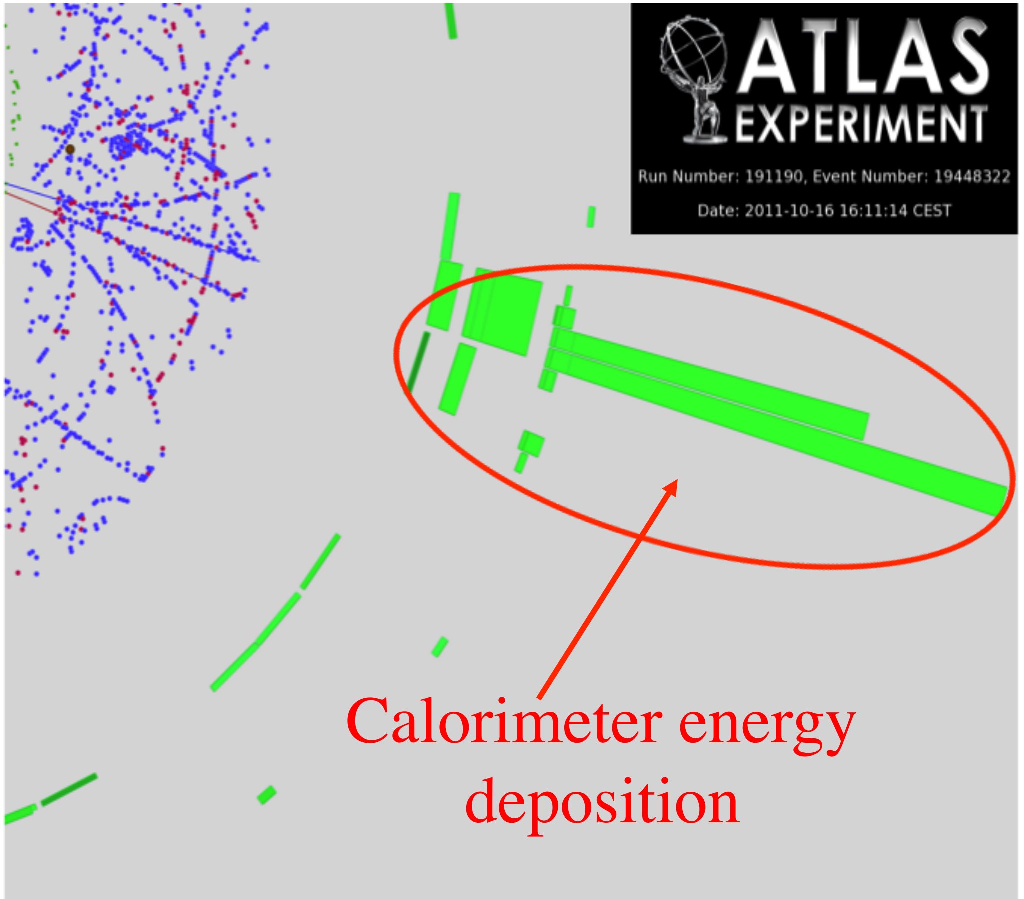
- Presampler 0.025×0.1 (η×φ)
  ⇒ Energy lost in upstream material
- Strips 0.003×0.1 (η×φ)
  ⇒ optimal separation of showers in non-bending plane, pointing
- Middle 0.025×0.025 (η×φ)
  ⇒ Cluster seeds
- Back 0.05×0.025 (η×φ)
  ⇒ Longitudinal leakage

- LAr-Pb sampling calorimeter
- Accordion shaped electrodes
- Fine longitudinal and transverse segmentation
- EM showers (for $e^{\pm}$ and photons) are reconstructed using calorimeter cell-clustering

Higgs Decay to Two Photons



Event display of a Higgs to two photons event where one of the photons has converted inside the ATLAS tracker.



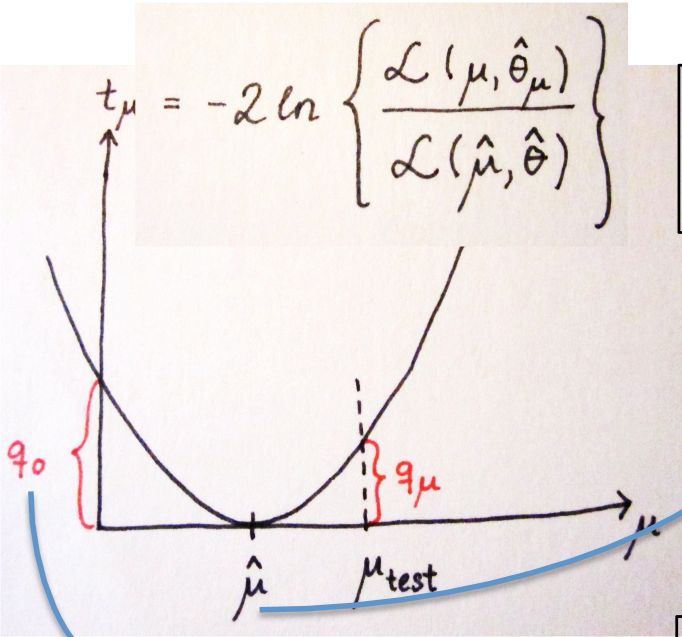
Higgs Decay to Two Photons

List of the sources of the main systematic uncertainties in the H->γγ searches:

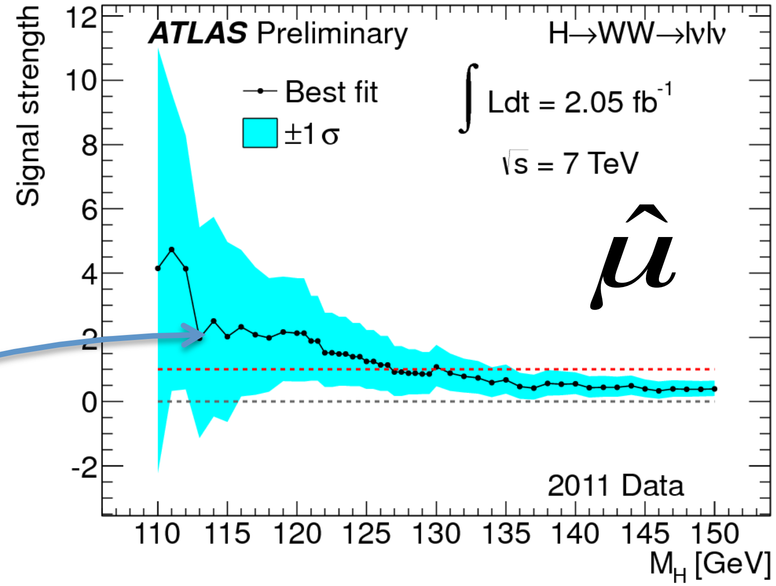
Signal event yield	
Photon reconstruction and identification	±11%
Effect of pileup on photon identification	±4%
Isolation cut efficiency	±5%
Trigger efficiency	±1%
Higgs boson cross section (scales)	$^{+12}_{-8}\%$
Higgs boson cross section (PDF+α_s)	±8%
Higgs boson p_{T} modeling	±1%
Luminosity	±3.9%
Signal mass resolution	
Calorimeter energy resolution	±12%
Photon energy calibration	±6%
Effect of pileup on energy resolution	±3%
Photon angular resolution	±1%
Signal mass position	
Photon energy scale	±0.7 GeV
Signal category migration	
Higgs boson p_{T} modeling	±8%
Conversion rate	±4.5%
Background model	±(0.1 – 7.9) events

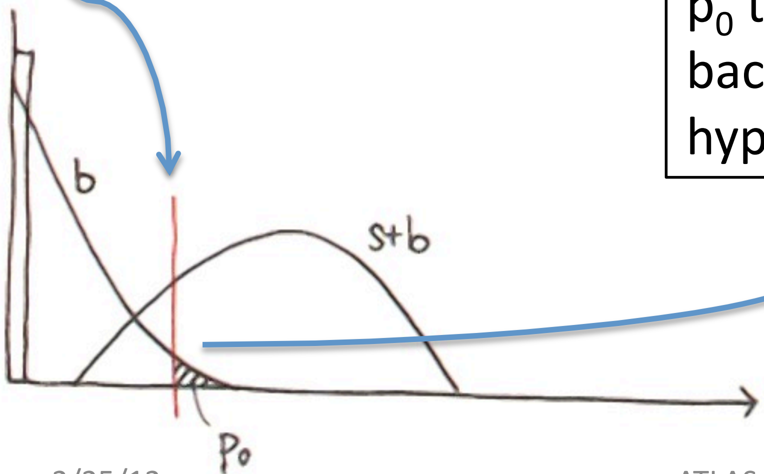
Profile likelihood ratio: p_0 and $\hat{\mu}$

LHCHCG Combination Procedures

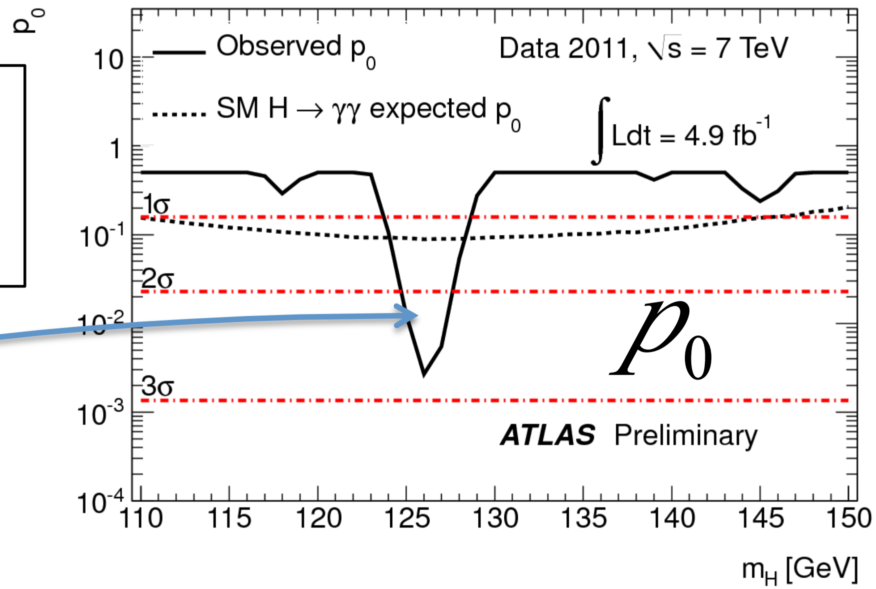


$\hat{\mu}$ to estimate signal strength

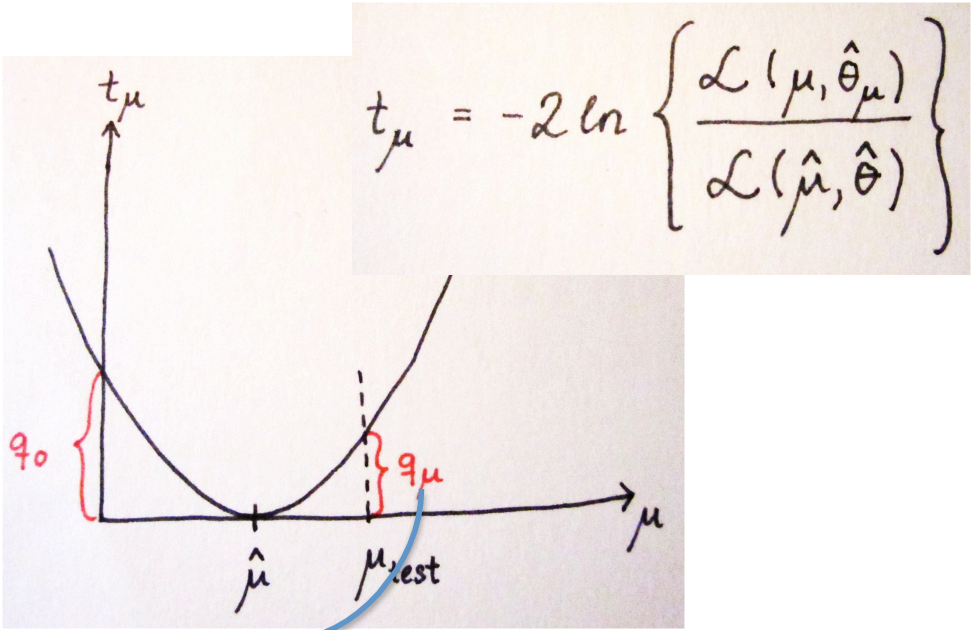


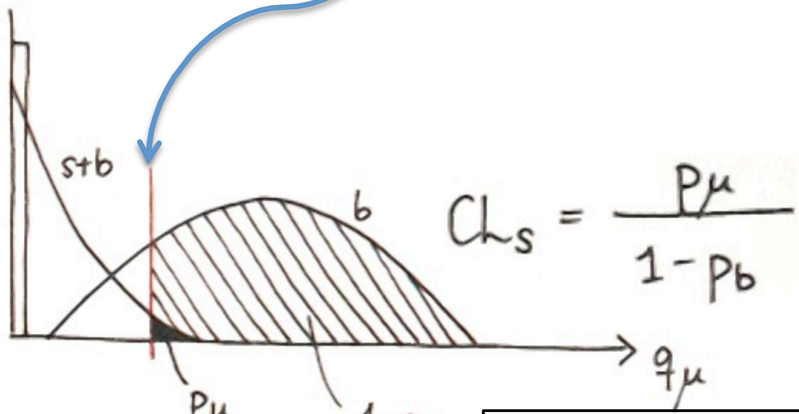


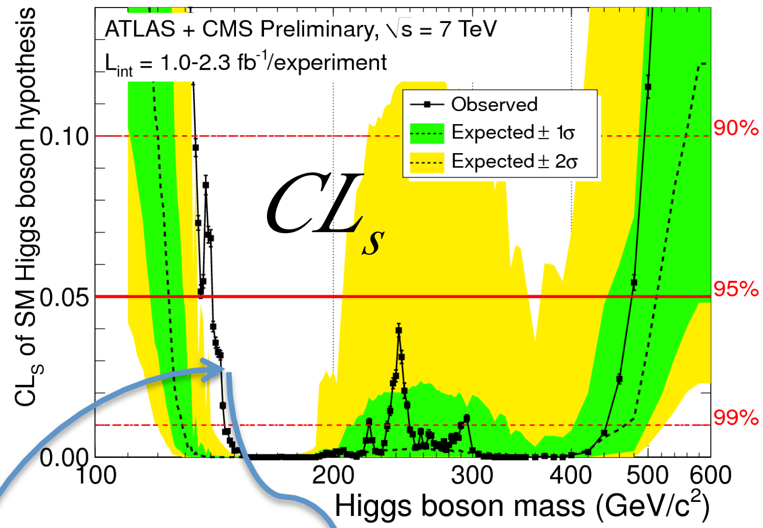
p_0 to test background hypothesis



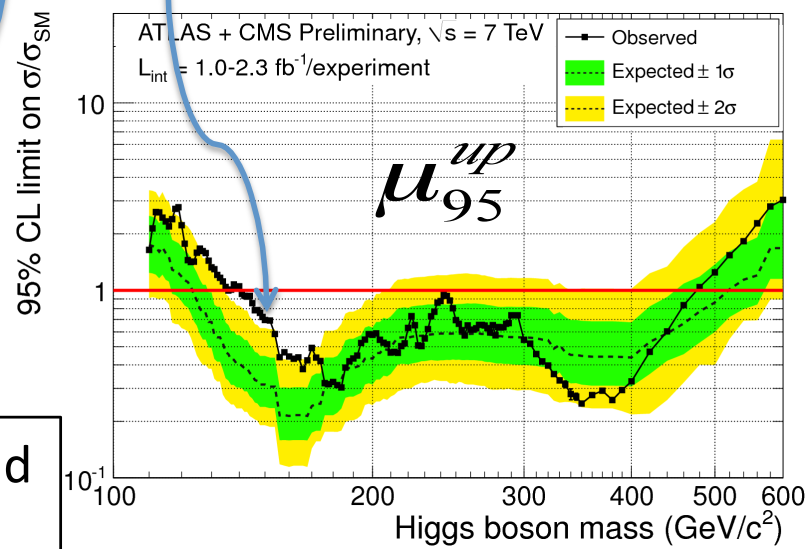
Profile likelihood ratio: CL_s and μ_{95}^{up}





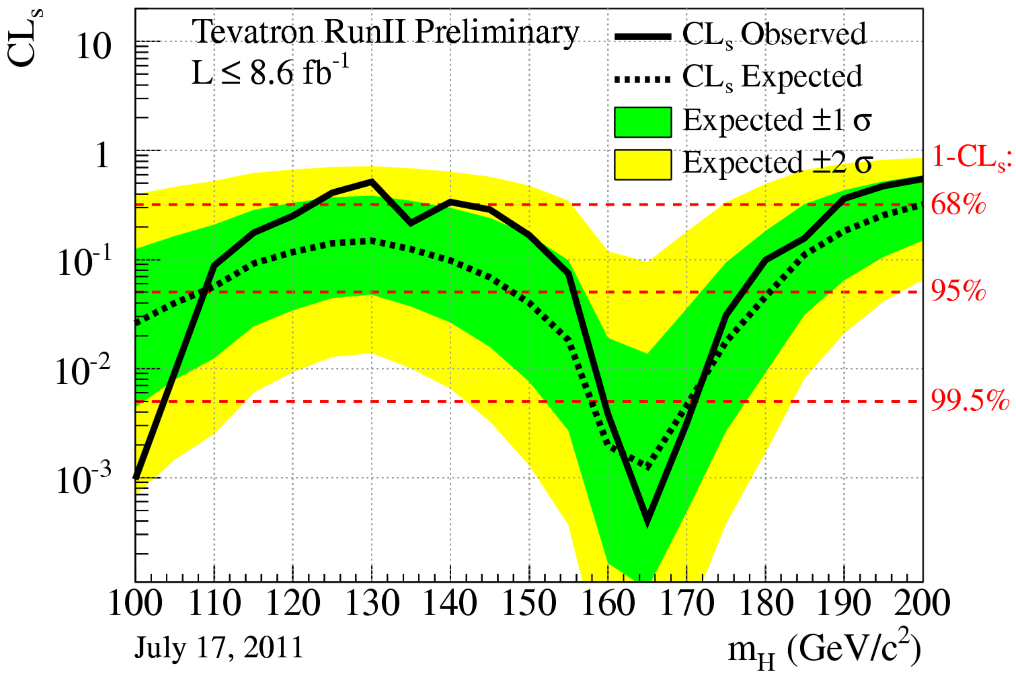


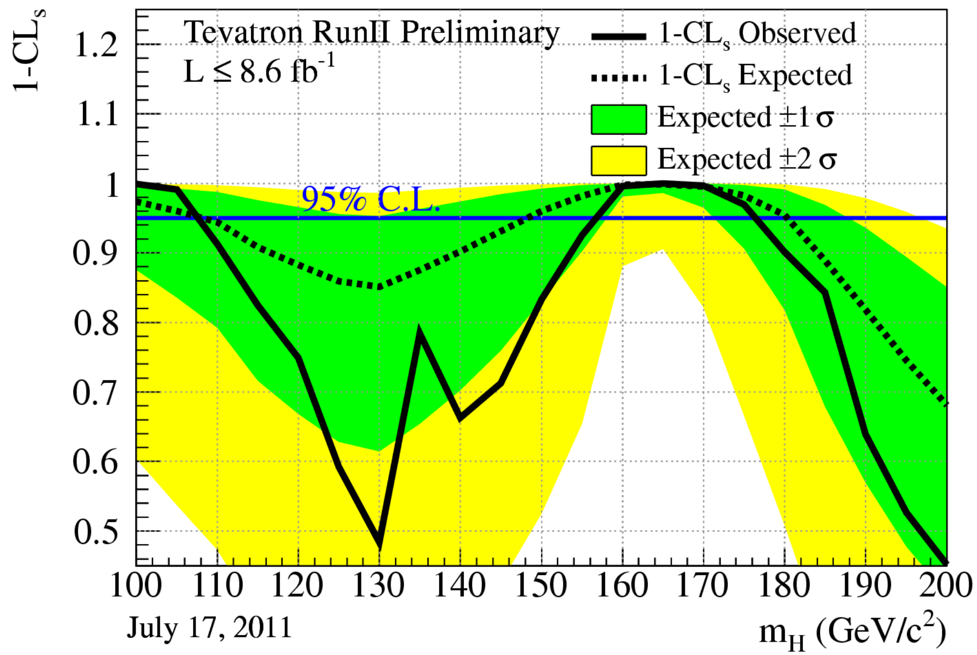
$$\mu_{95}^{up} = \mu(CL_s = 0.05)$$



p_μ : test signal+background
CL_s : ~test signal

Tevatron Higgs Exclusion: Statistics





CL_s is a metric used in order to quantify the strength of an exclusion limit. It is particularly suited to avoid excluding a region where there is insufficient sensitivity. It is defined as:

$$CL_s = \frac{CL_{s+b}}{CL_b}$$

where $1\text{-}CL_b$ is an estimate of the probability for an upward background fluctuation without a signal and CL_{s+b} the probability of a downward fluctuation of the sum of the background and the signal in the data. If $CL_s<0.05$ for a specific mass hypothesis, this means that this mass hypothesis can be excluded at the 95% confidence level.

Statistical Procedure

Used for individual channels and SM Higgs combination at ATLAS :

- Common parameters of interest is a cross-section scale factor :
  $\mu=\sigma/\sigma^{SM}$ $\mu=0$ is the background only model
  $\mu=1$ correspond to the nominal signal model
- Combined probability model is formed by identifying nuisance parameters ν associated to common systematic effects

- The profile likelihood ratio is used as a test statistic :

$$\lambda(\mu) = L_{s+b}(\mu, \hat{\hat{\nu}})/L_{s+b}(\hat{\mu}, \hat{\nu})$$

  one-sided variants of the test statistic are used for the upper-limits and discovery

- Nuisance parameters are "profiles" based on the data

- The distribution of the test statistic is obtained in two ways :
  - ensemble tests with Toy Monte Carlo using a fully frequentist procedure
  - using asymptotic distribution of likelihood ratio (improved χ^2 method)

- Primary results based on CLs
  - more relevant to protect against downward fluctuations
  - additional comparison with Bayesian procedure with a uniform prior on $\mu=\sigma/\sigma^{SM}$

- Use RooFit/RooStats

Understanding the Band

Understanding of the Yellow and Green bands :

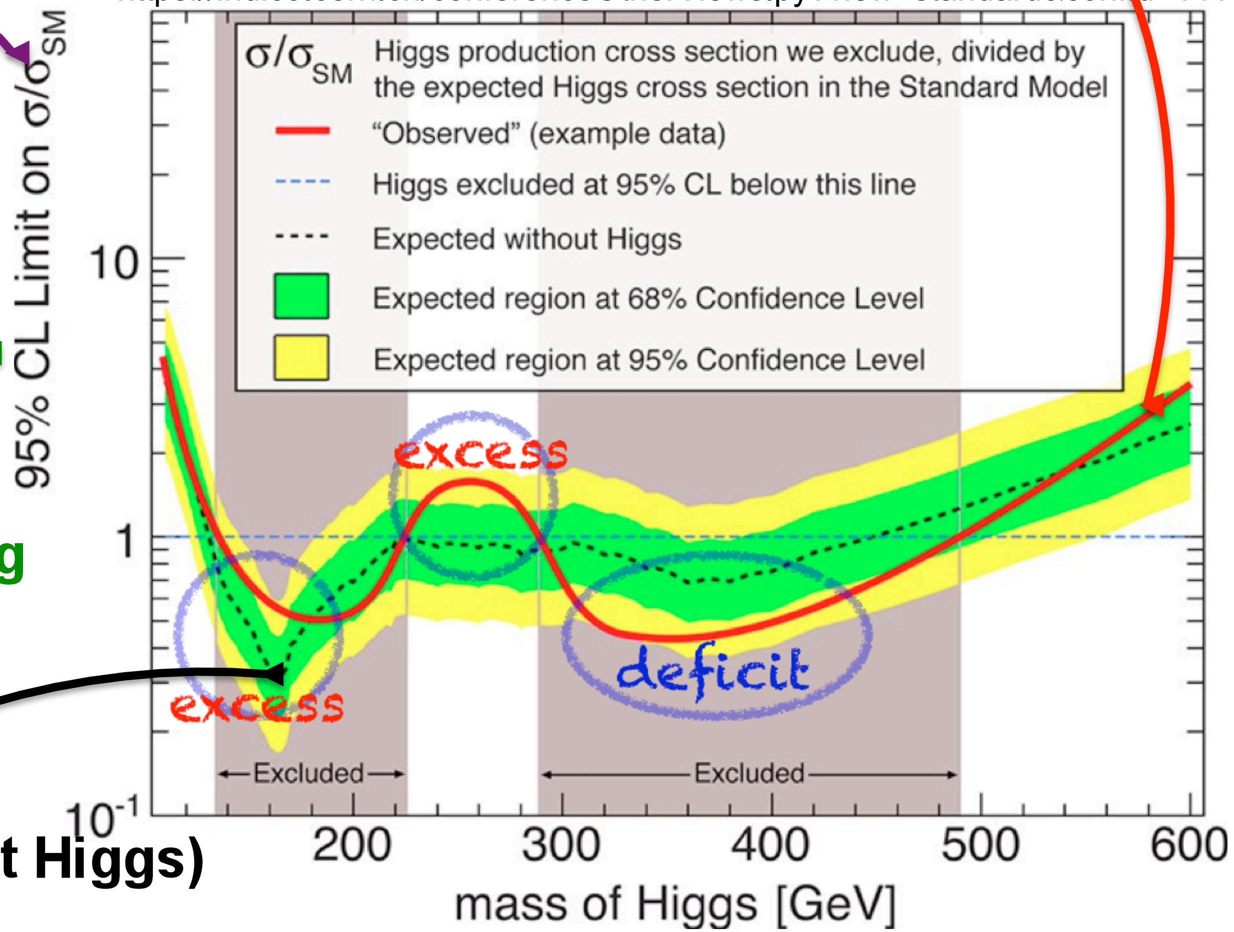
- Upper limit on the Standard Model (SM) Higgs Boson production cross section divided by the Standard Model expectation as a function of m_{Higgs}

observed limit (data)

Eilam Gross
https://indico.cern.ch/conferenceOtherViews.py?view=standard&confId=141983

$\mu=\sigma/\sigma^{SM}$

this is a 95% limit using the CLs method



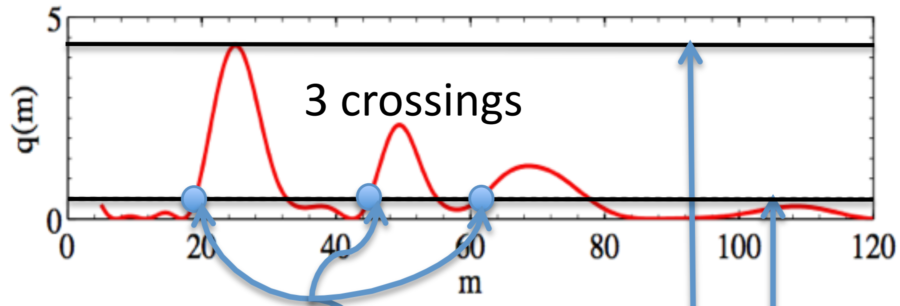
expected limit (without Higgs)

Look-elsewhere effect (LEE)

- Ex: 10^7 searches with 10^{-7} background
  - Expect on the average 1 event with local p-value of 10^{-7}, but this is NOT a 5.2σ discovery!
  - Probability to make a false discovery is

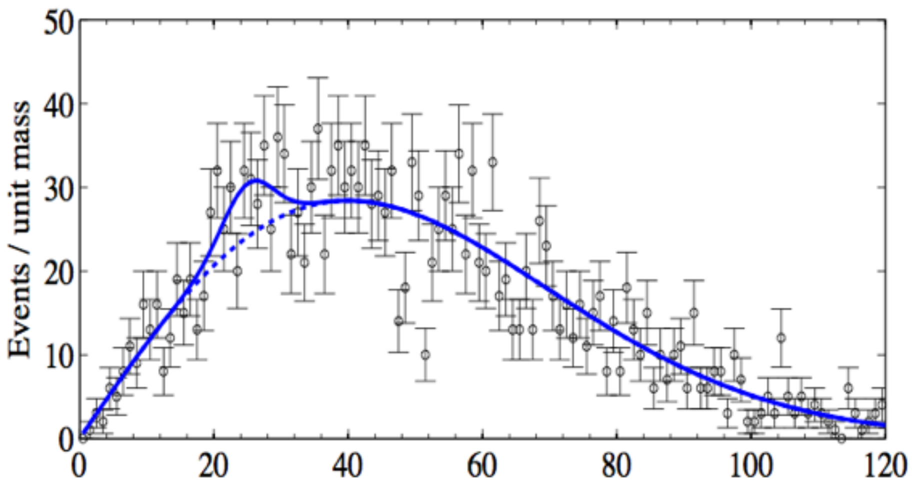
$$P(n \geq 1 \mid b=1) = 1 - e^{-1}(-1)^0/1! = 63\%$$

  - Trials factor p_0^{global}/p_0^{local} from LEE is 0.63×10^7
- Gross&Vitels: LEE in LLR-based search.



$$q_{test} = 2 \cdot \log(L(m))$$

$$p_0^{global} \cong p_0^{local} + \langle N(q_{ref}) \rangle \, e^{-(q_{test}-q_{ref})/2}$$



- Note: Approximation best above 3σ
- Example:
  - q_{test}= 4.5 (2.1σ)
  - 3 crossings at 0.5σ
  - *Local significance* of 2.1σ reduced to *global significance* of about 0.3σ
  - trials factor $p_0^{global}/p_0^{local} \cong 22$

CMS Combined Higgs Search