The Search for the Higgs Boson: Discovery in Sight!

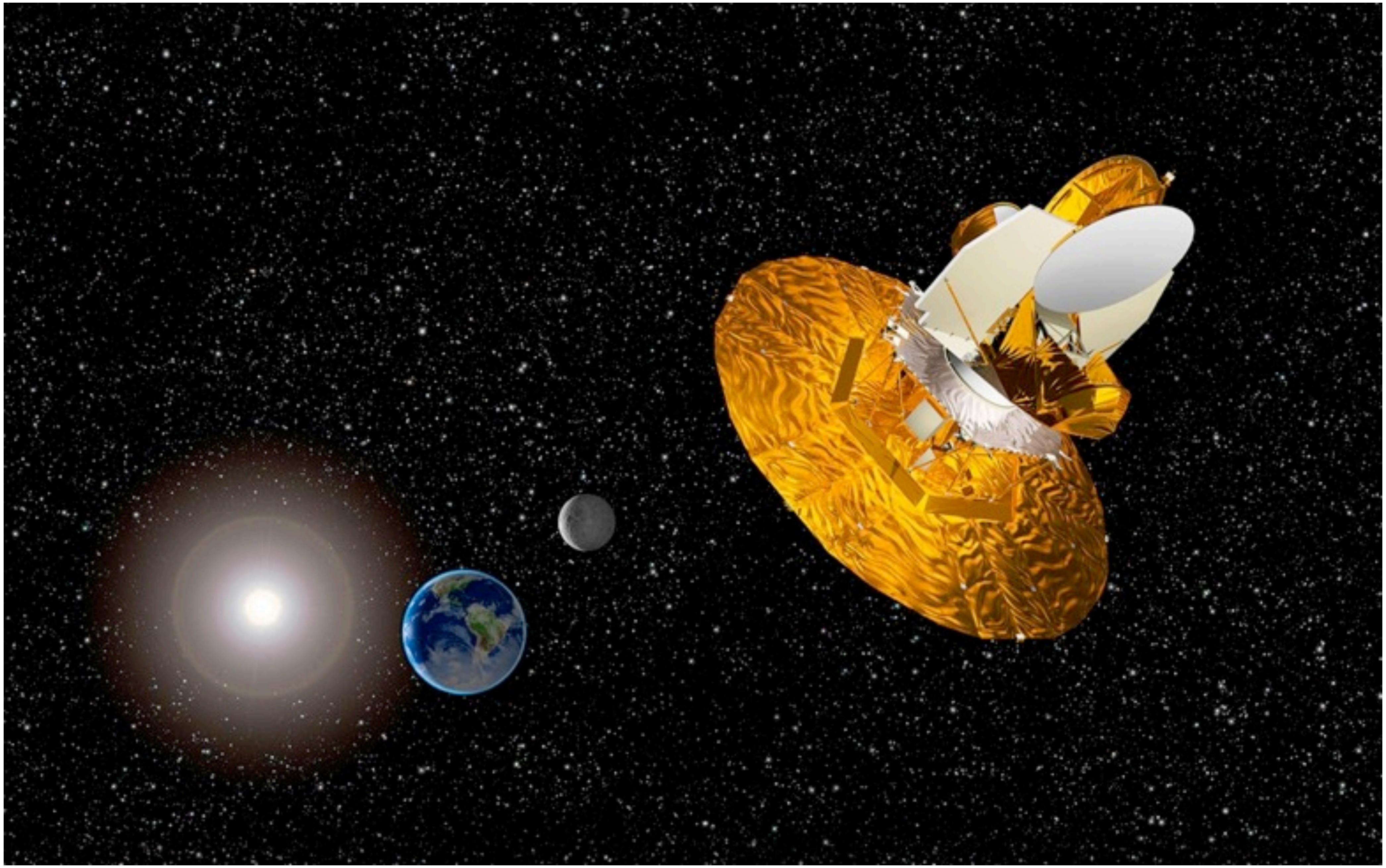
Frank Filthaut
Radboud Universiteit Nijmegen / Nikhef

- Particle physics: general picture
- The Higgs boson
- Higgs hunting at the LHC

Particle Physics: the General Picture

Rotational Symmetry

The Universe at large is isotropic and homogeneous!



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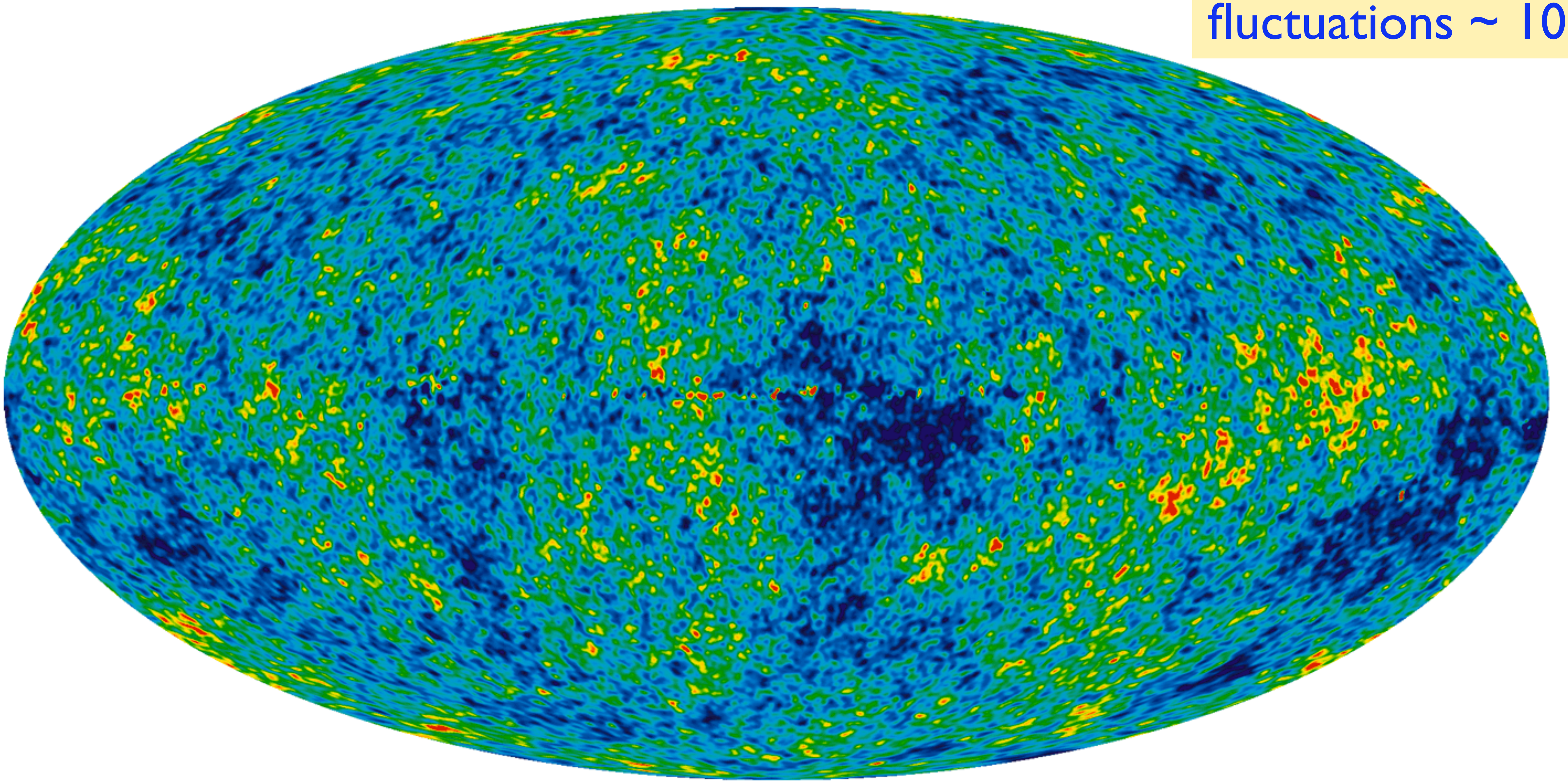
CMWB: temperature fluctuations ~ 10^{-5} K



WMAP 7-year results, full sky

Symmetries and Conserved Quantities

Rotational symmetry: laws of physics do not depend on any direction.
Symmetries are important in many areas of physics

- e.g. conserved quantities like angular momentum in the case of rotational symmetry

Particle physics extends these concepts to internal symmetries, preserved even under arbitrary space-time dependent (gauge) transformations

Allows for extraordinarily successful description of electromagnetism: QED

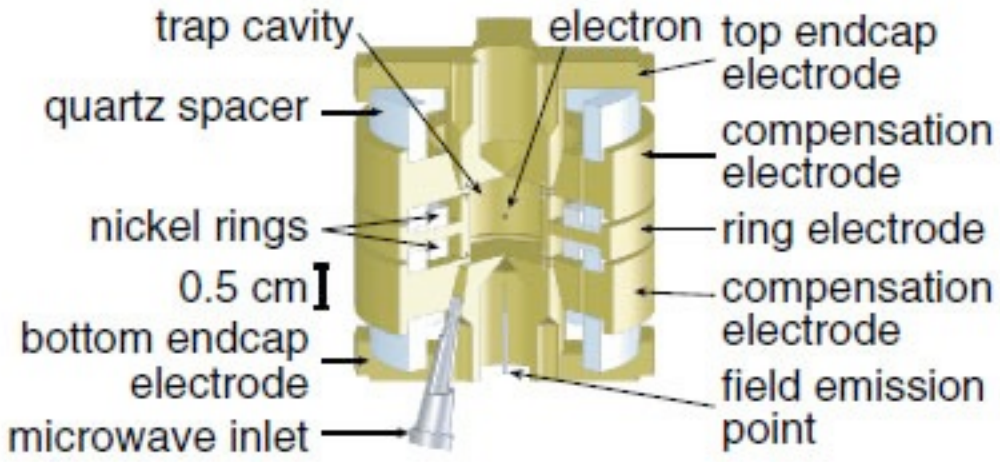
- interaction of magnetic dipole moment with external magnetic field:

$$H = -\vec{\mu} \cdot \vec{B}, \quad \vec{\mu} = \gamma \vec{S} \equiv g \left(\frac{q}{2m} \right) \vec{S}$$

In contrast to "ordinary" QM, g can be computed from first principles! Only input:

$$\alpha \equiv \frac{e^2}{4\pi}$$

Observe trapped single electron for months



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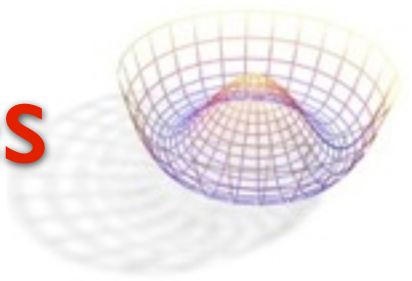

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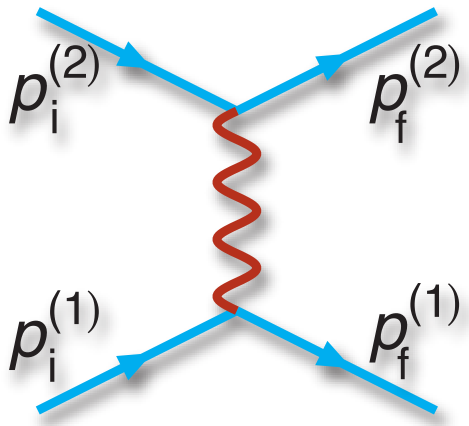
$$g/2 = \begin{cases} 1.001\,159\,652\,180\,73(28) & \text{(experiment)} \\ 1.001\,159\,652\,180\,85(76) & \text{(theory)} \end{cases}$$

Particle Paradigm

QED implements EM interaction as exchange of (massless) photon

- same for (massless) gluons as force carriers of strong interaction



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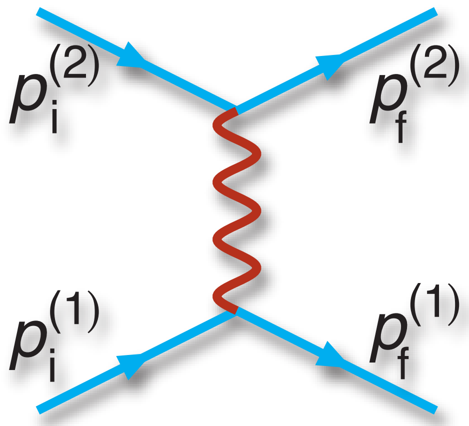
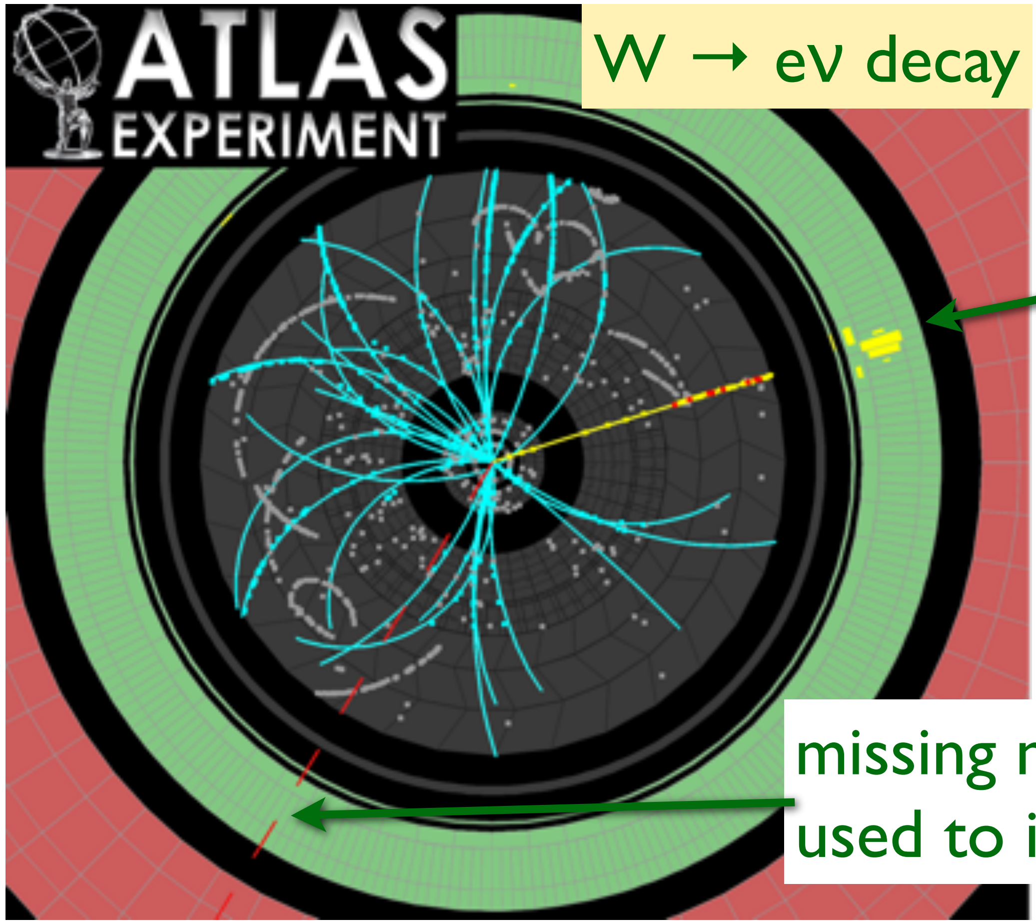


The same paradigm also applies to the weak interaction, but the W and Z bosons are heavy!

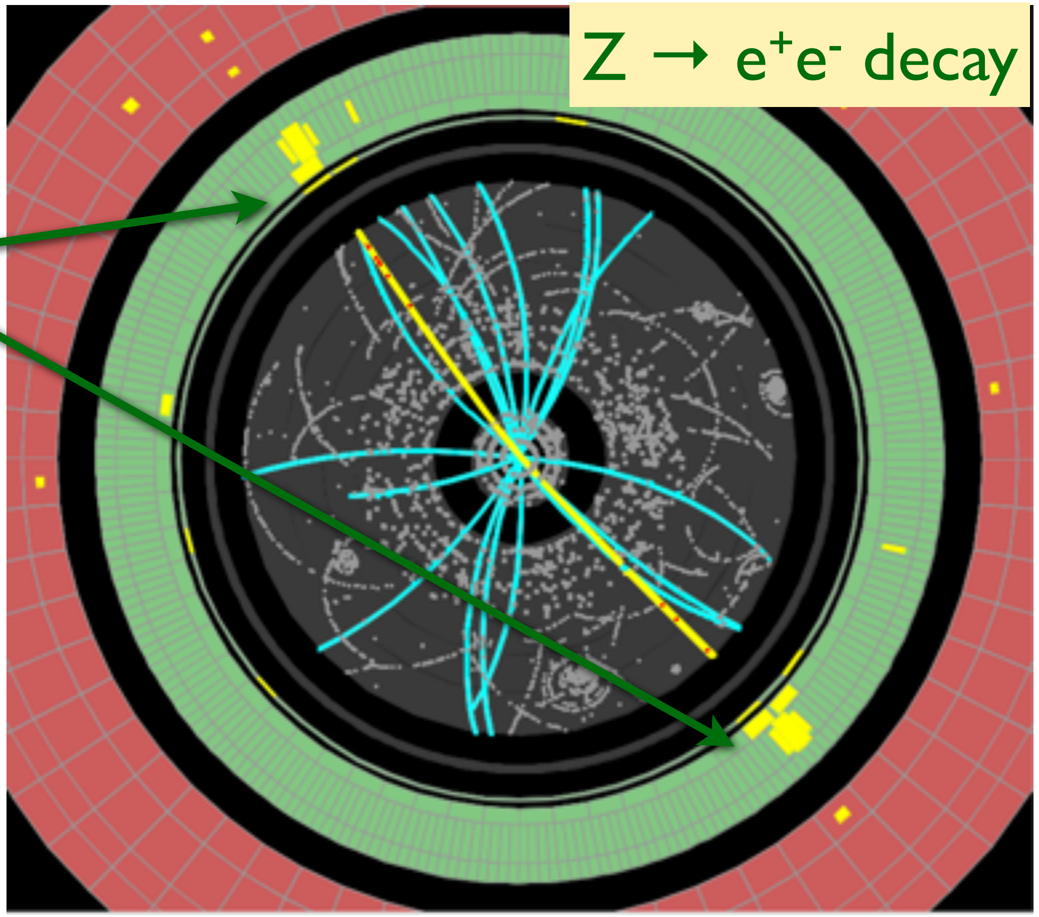
- $M_W = 80.387 \pm 0.017$ GeV
- $M_Z = 91.188 \pm 0.002$ GeV



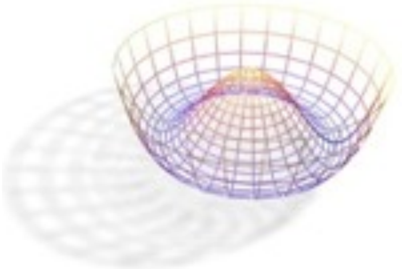
W → eν decay

e±

missing momentum used to infer ν



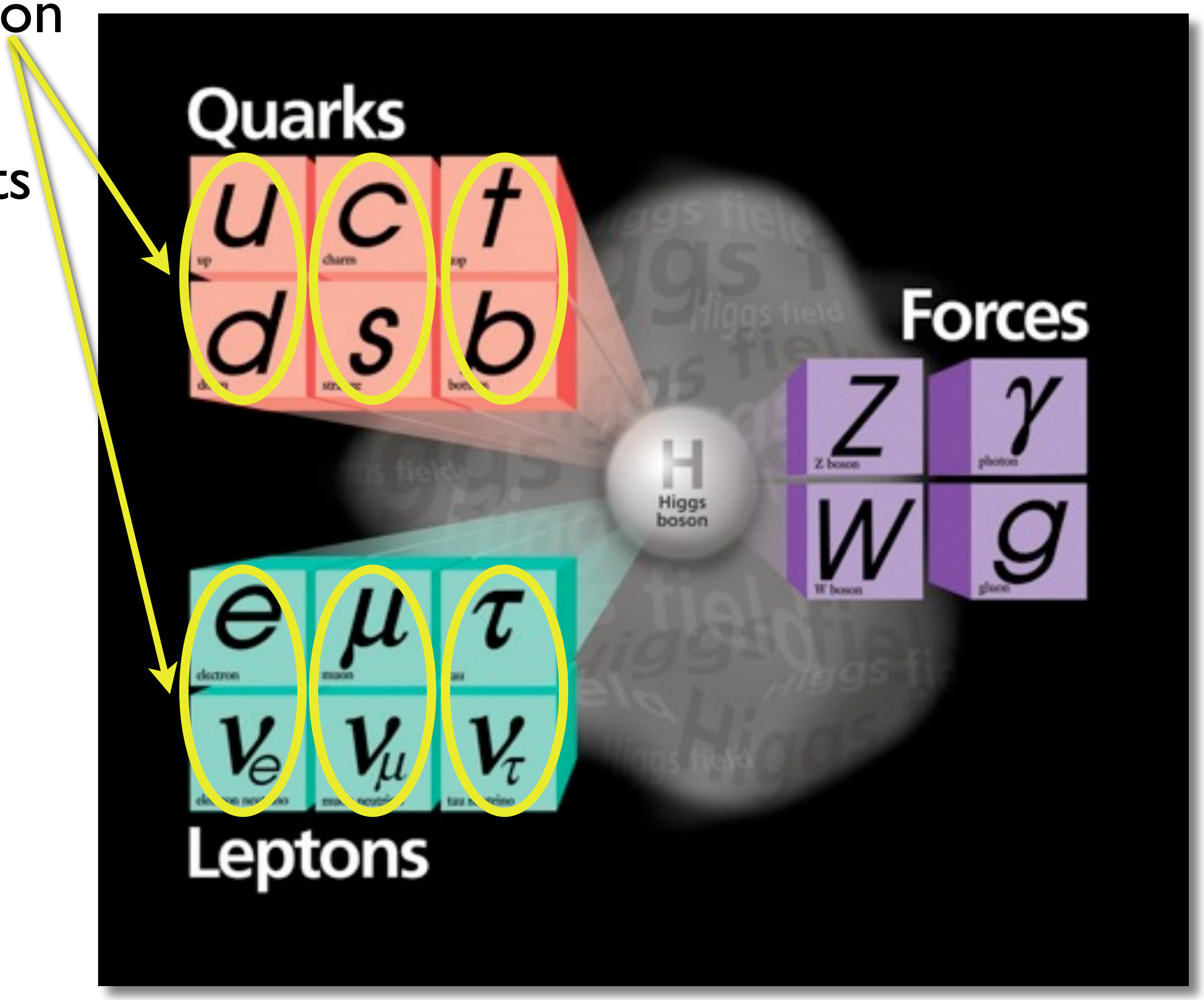
Z → e⁺e⁻ decay



Particle Summary

Internal symmetries can turn particles into one another

- most clearly visible for weak interaction
- but this symmetry must be broken!
  For the masses of partners in doublets of the weak symmetry are different
- force carriers mediating interactions should be massless: clearly invalidated by heavy W and Z particles



Consequence of introducing the Higgs field:

- interactions obey symmetry
  ➠ theory remains meaningful
- ground state does not:
  spontaneous symmetry breaking

The Standard Model is invalid without the Higgs boson!

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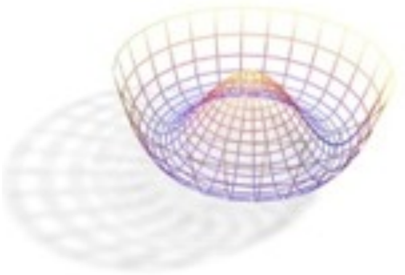

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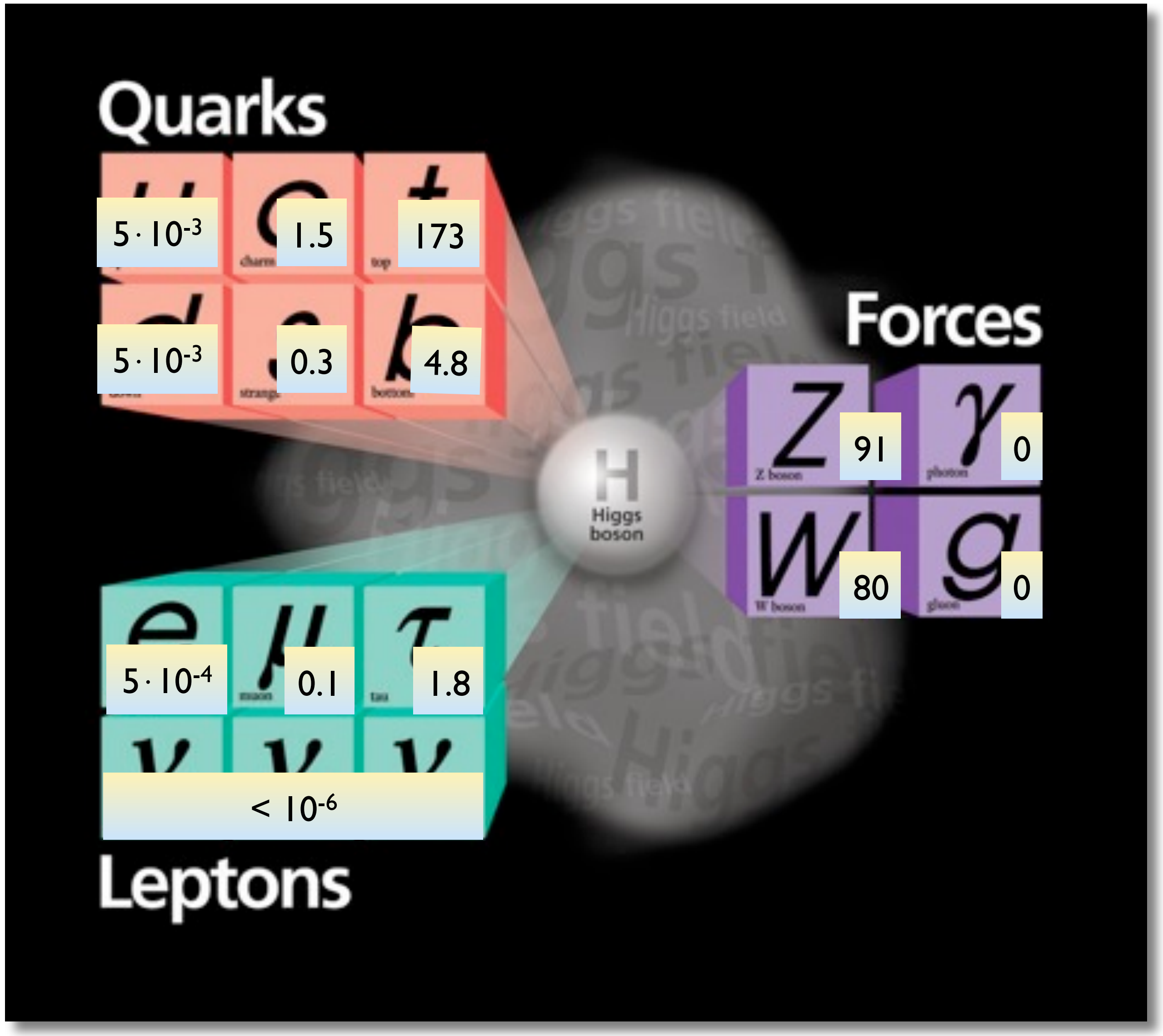
(masses in GeV)



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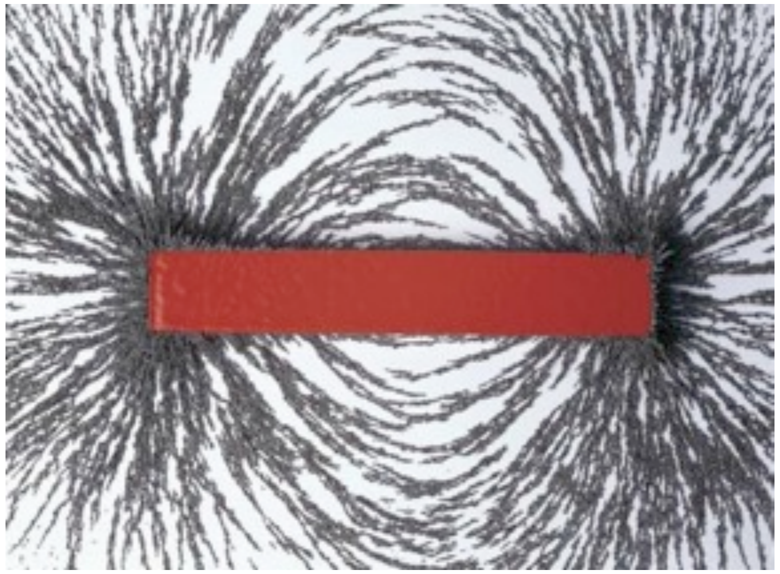
The Higgs Boson

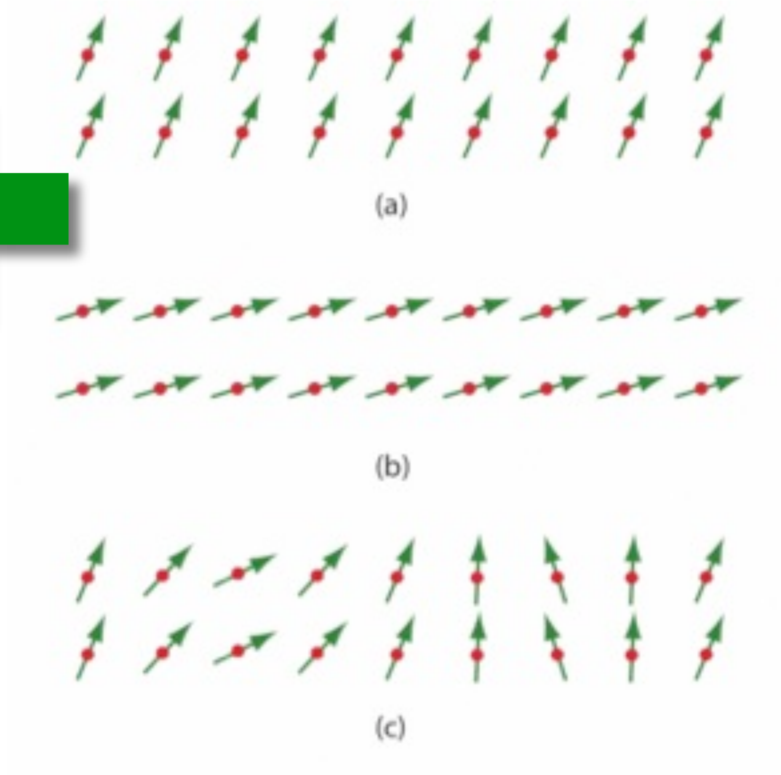
Magnetic Analogues

Spontaneous symmetry breaking



equivalent
ground states

excitation



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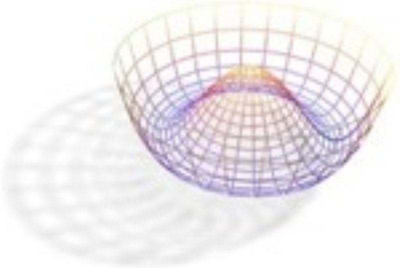
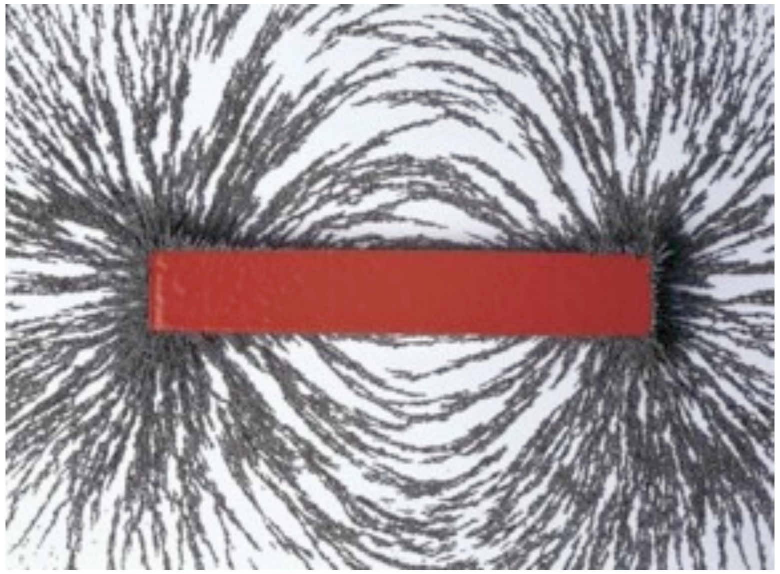
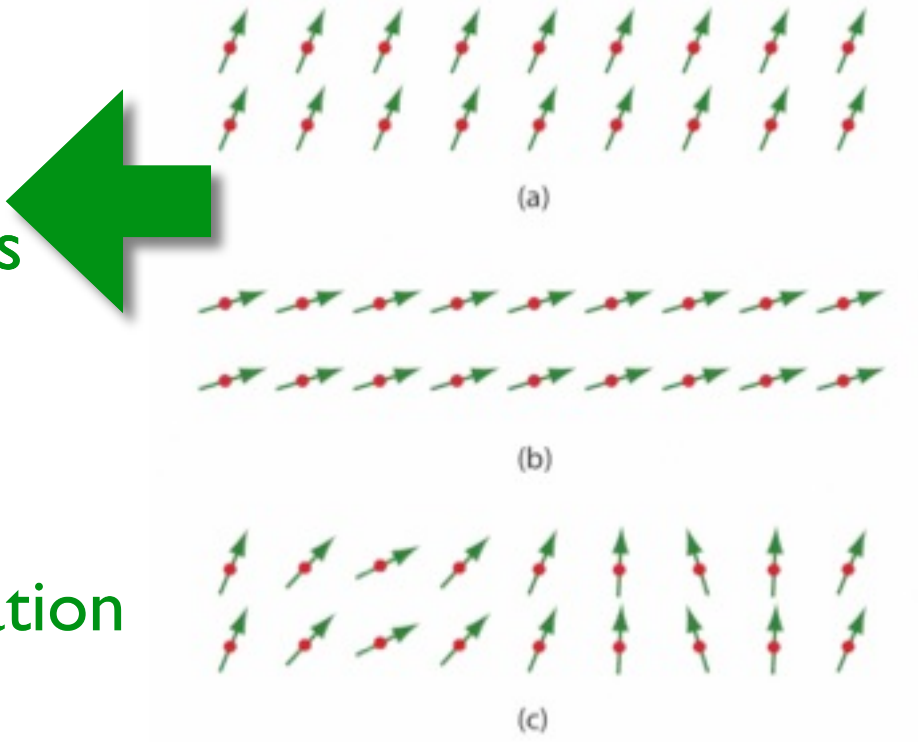


Spontaneous symmetry breaking





equivalent ground states

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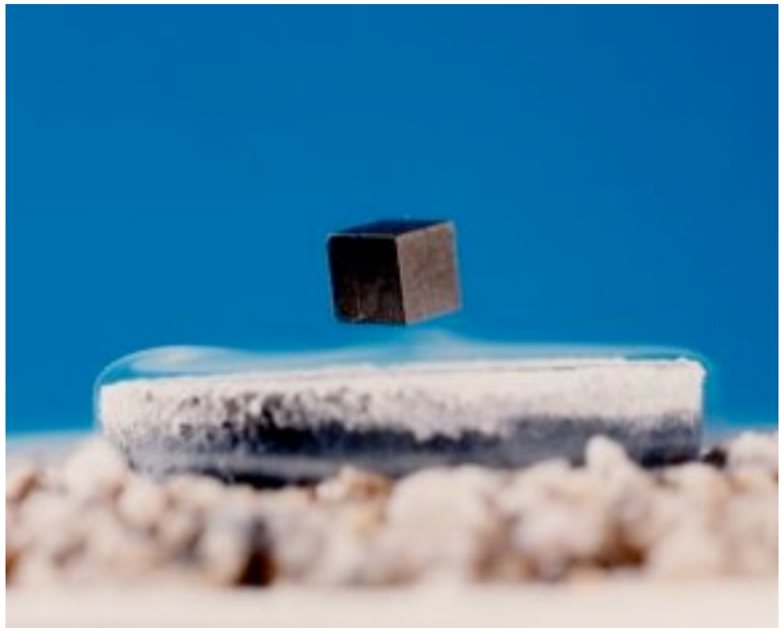
Massive photons



Meißner effect: superconductor repels magnetic field lines

- massive photons
- but needs a medium (e^- pair condensate)!

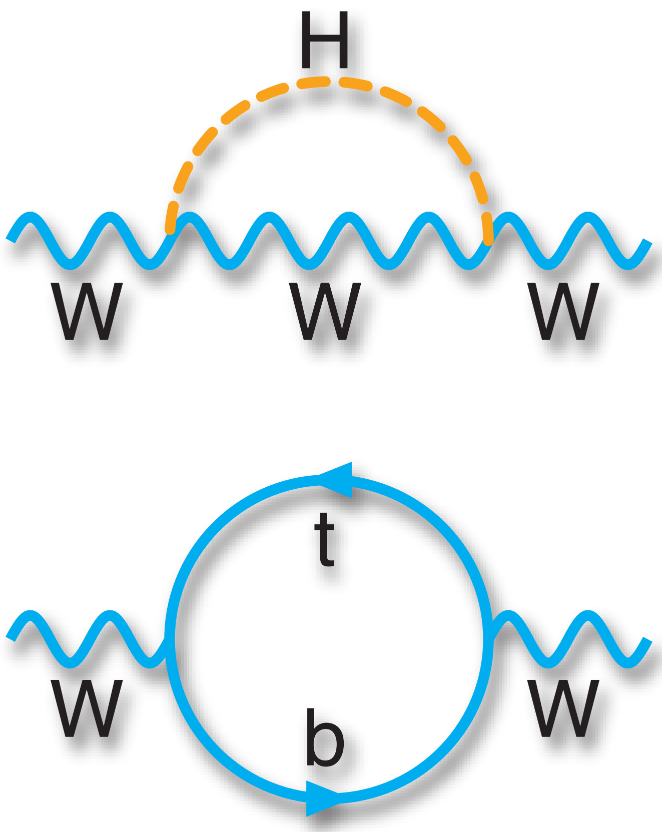
In the particle physics case, the "medium" is the vacuum!

Electroweak Constraints

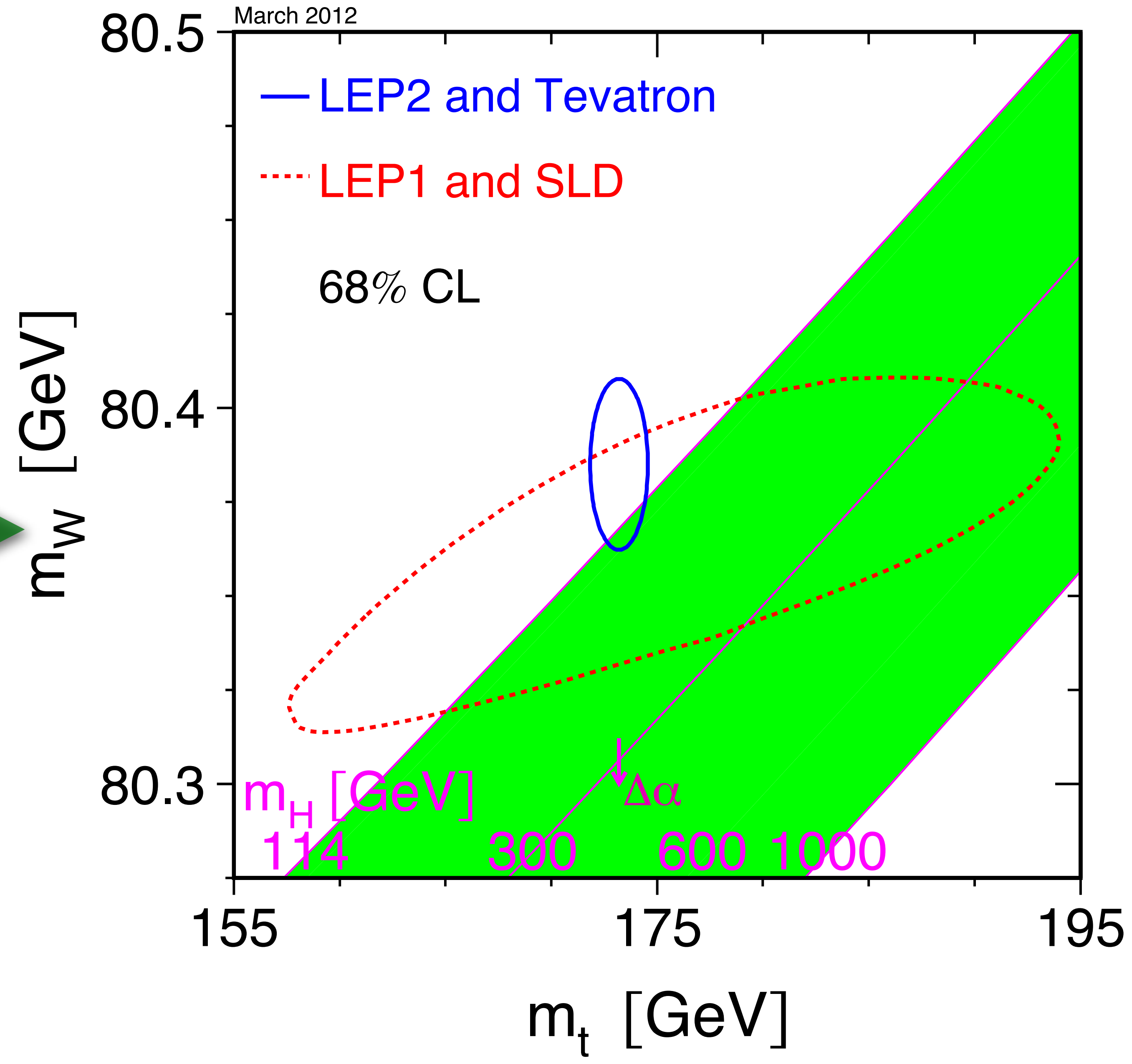
M_H unknown, but for given M_H all Higgs boson properties are fixed

➟ know “exactly” what to look for

- many constraints! Most important: masses of W boson and top quark



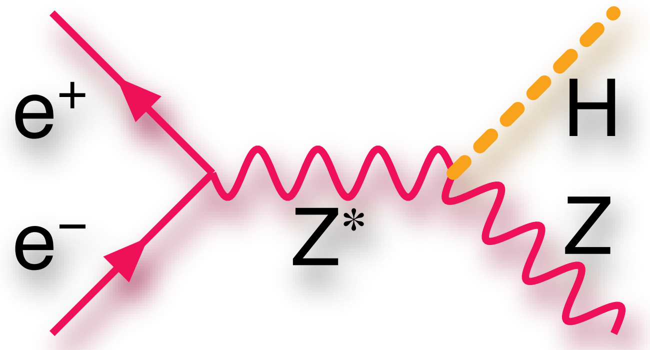
small modifications to M_W from radiative corrections

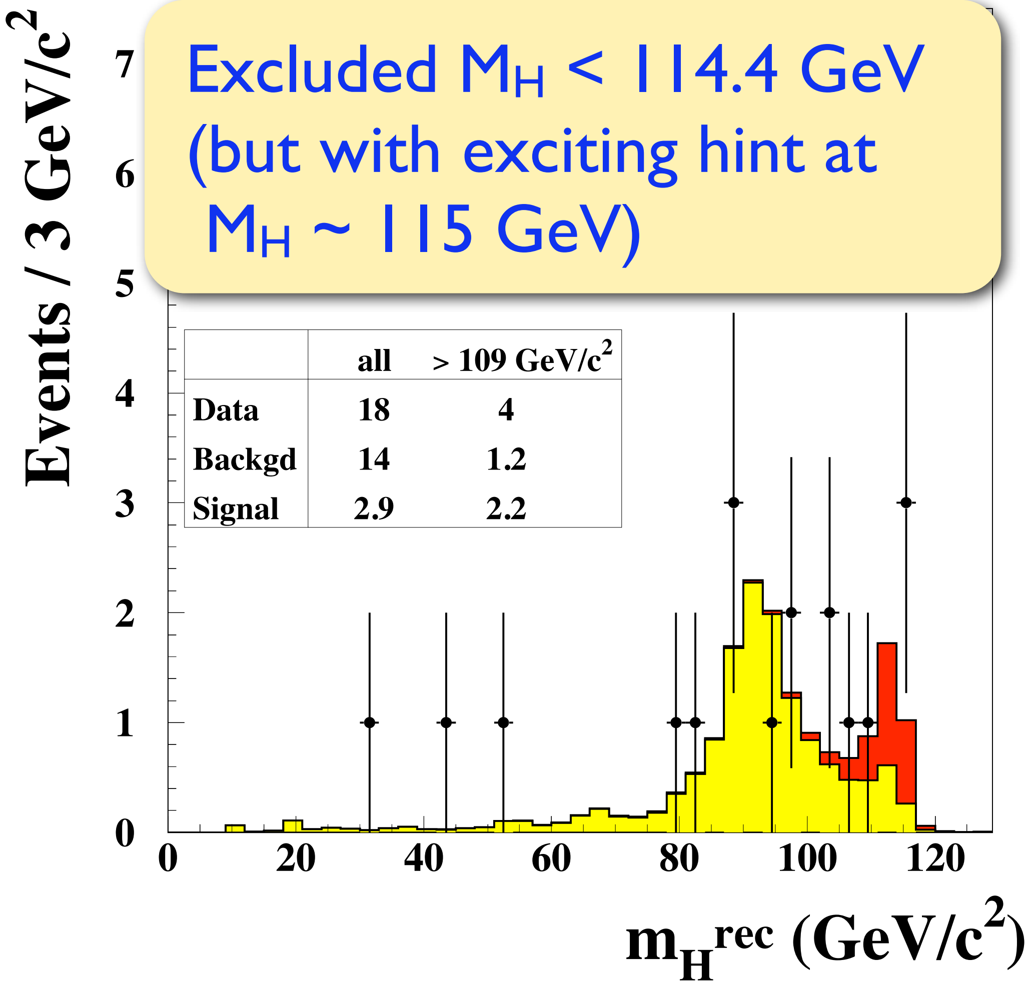


Preference for a “light” Higgs boson!

Previous Higgs Boson Searches

LEP: e^+e^-, E_{CM} < 210 GeV





	all	> 109 GeV/c^2
Data	18	4
Backgd	14	1.2
Signal	2.9	2.2

Excluded M_H < 114.4 GeV
(but with exciting hint at
M_H ~ 115 GeV)

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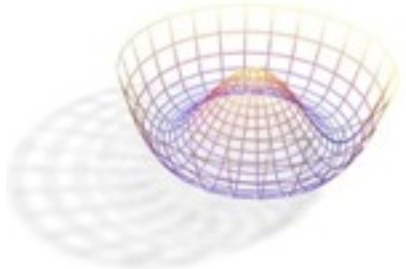

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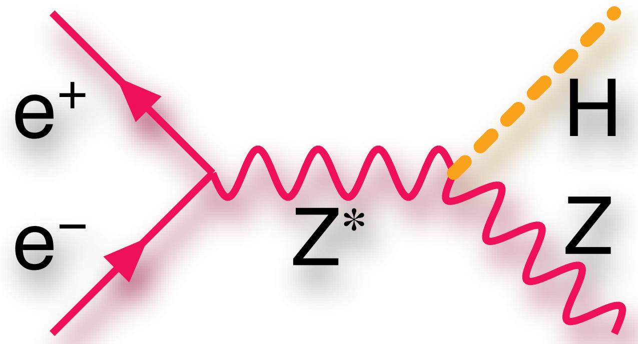
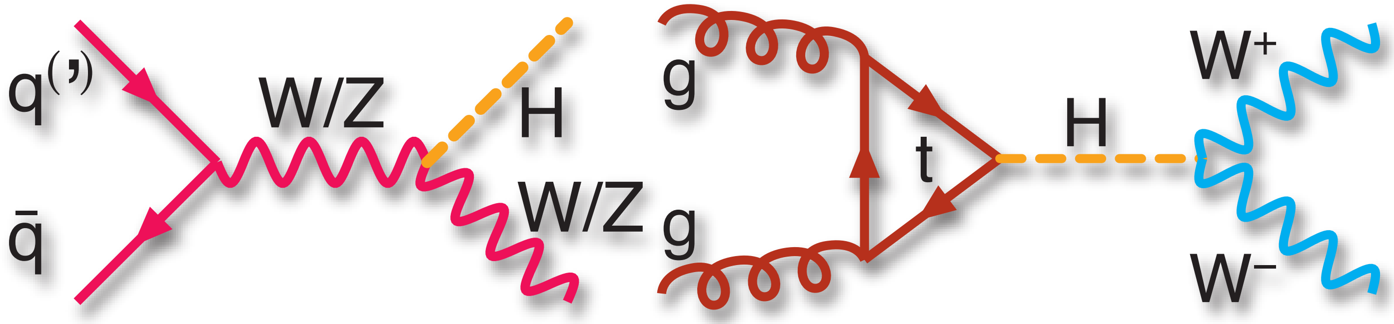


Tevatron: $p\bar{p}$, E_{CM} = 1.96 TeV

- but much lower E_{CM} of colliding partons!



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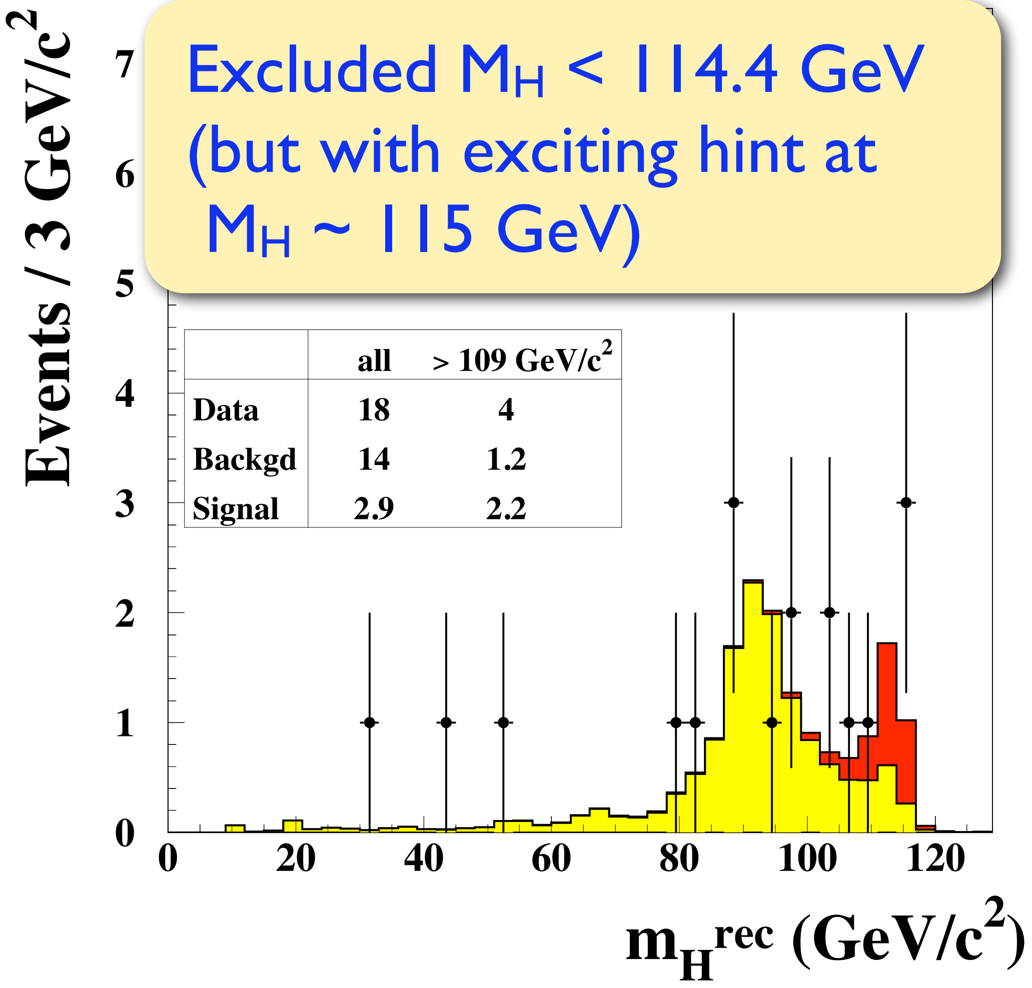

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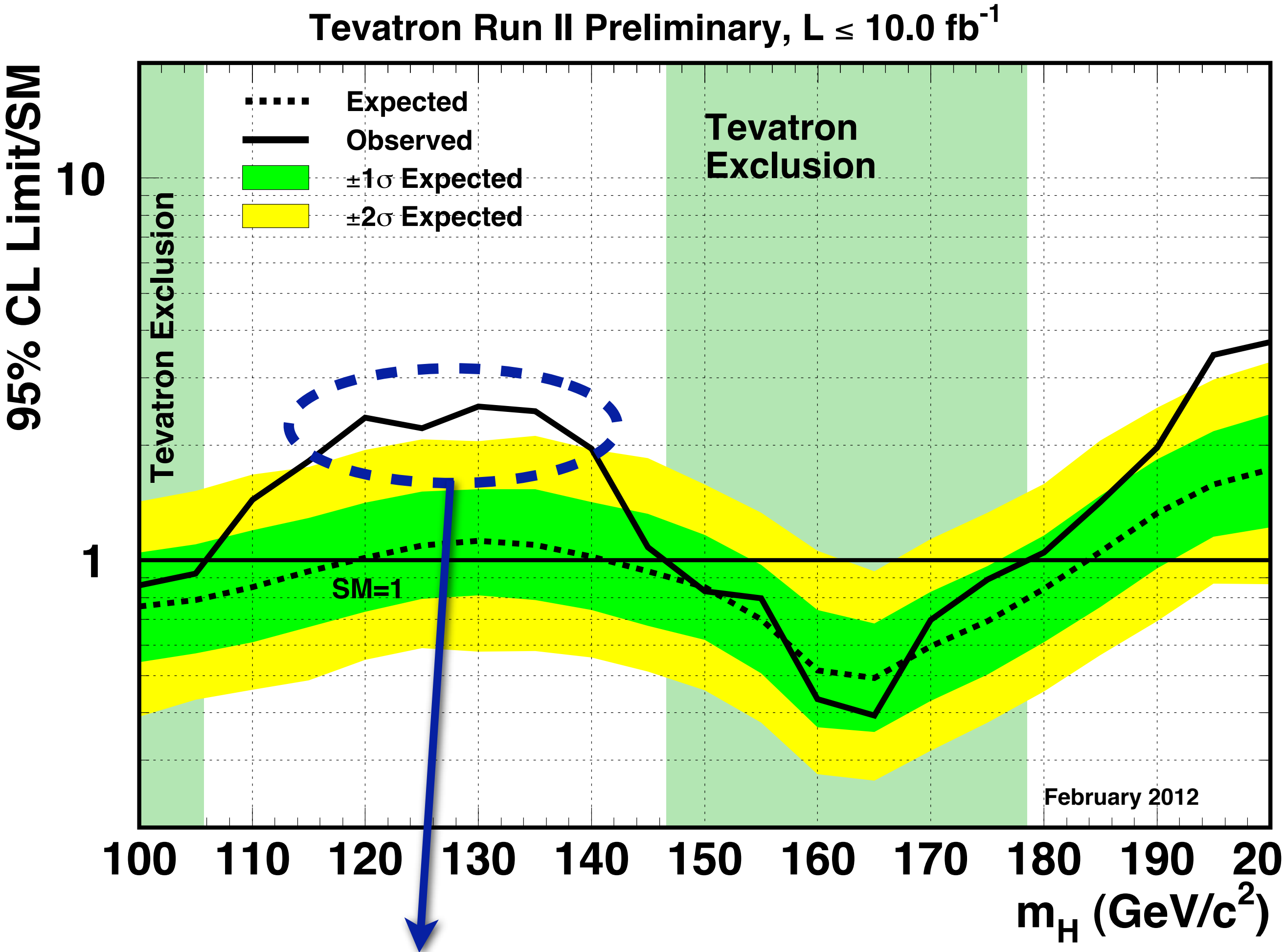
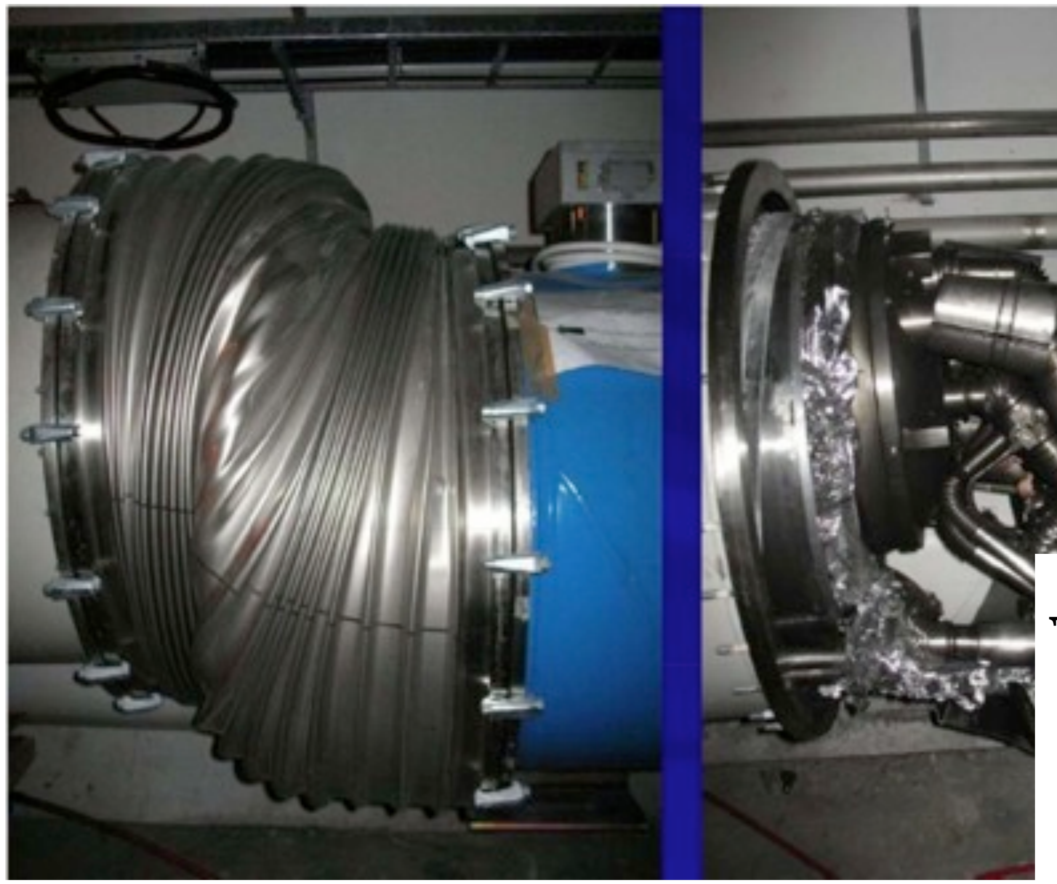


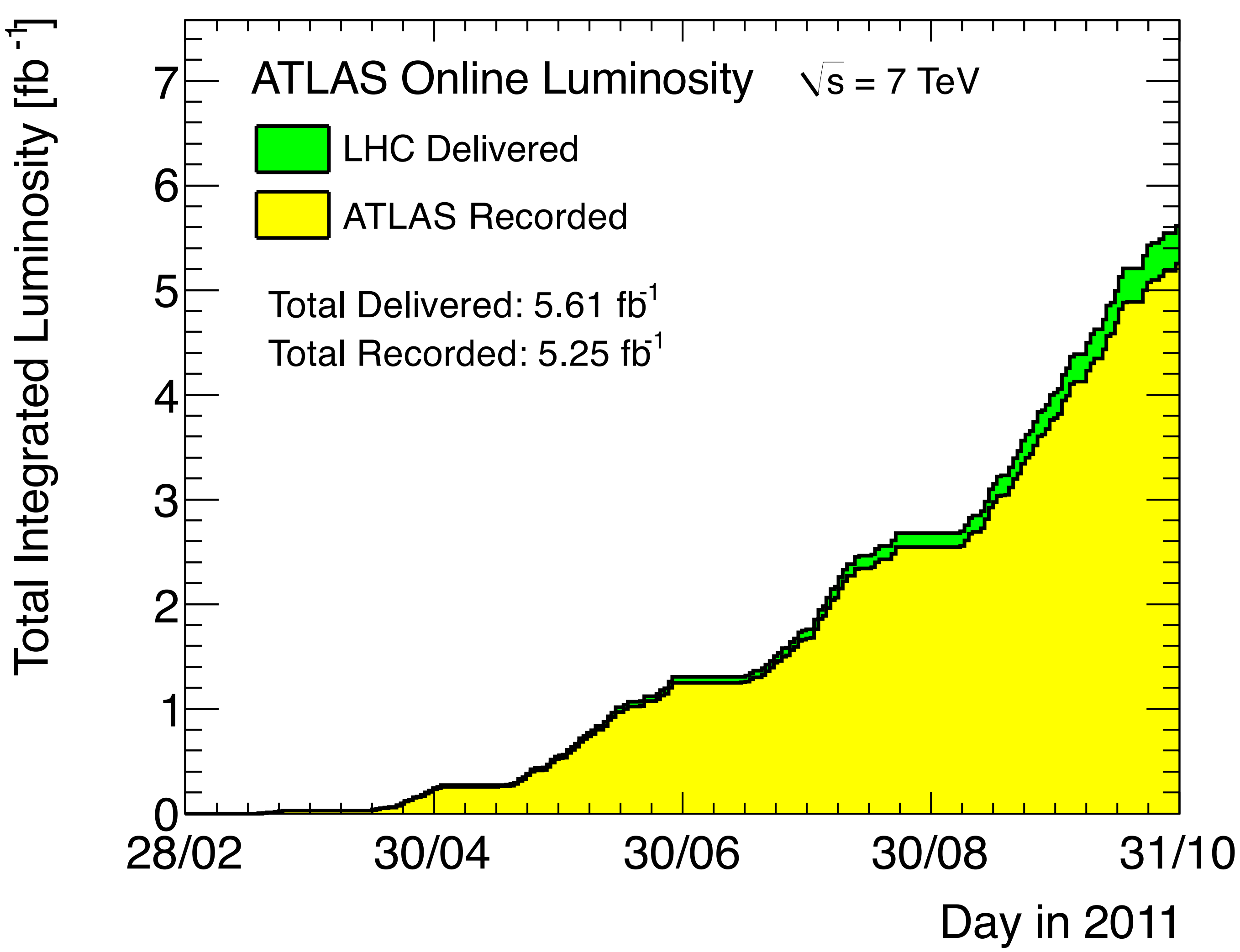
(inconclusive) hint for a signal...

Higgs Hunting at the LHC

The LHC: a Success Story!



$\underline{1\ fb^{-1}}$: integrated "intensity" needed to produce 1 interaction for a process with a production cross section of 1 fb = 10^{-43} m^2



Expectations for 2011 exceeded by a factor 5

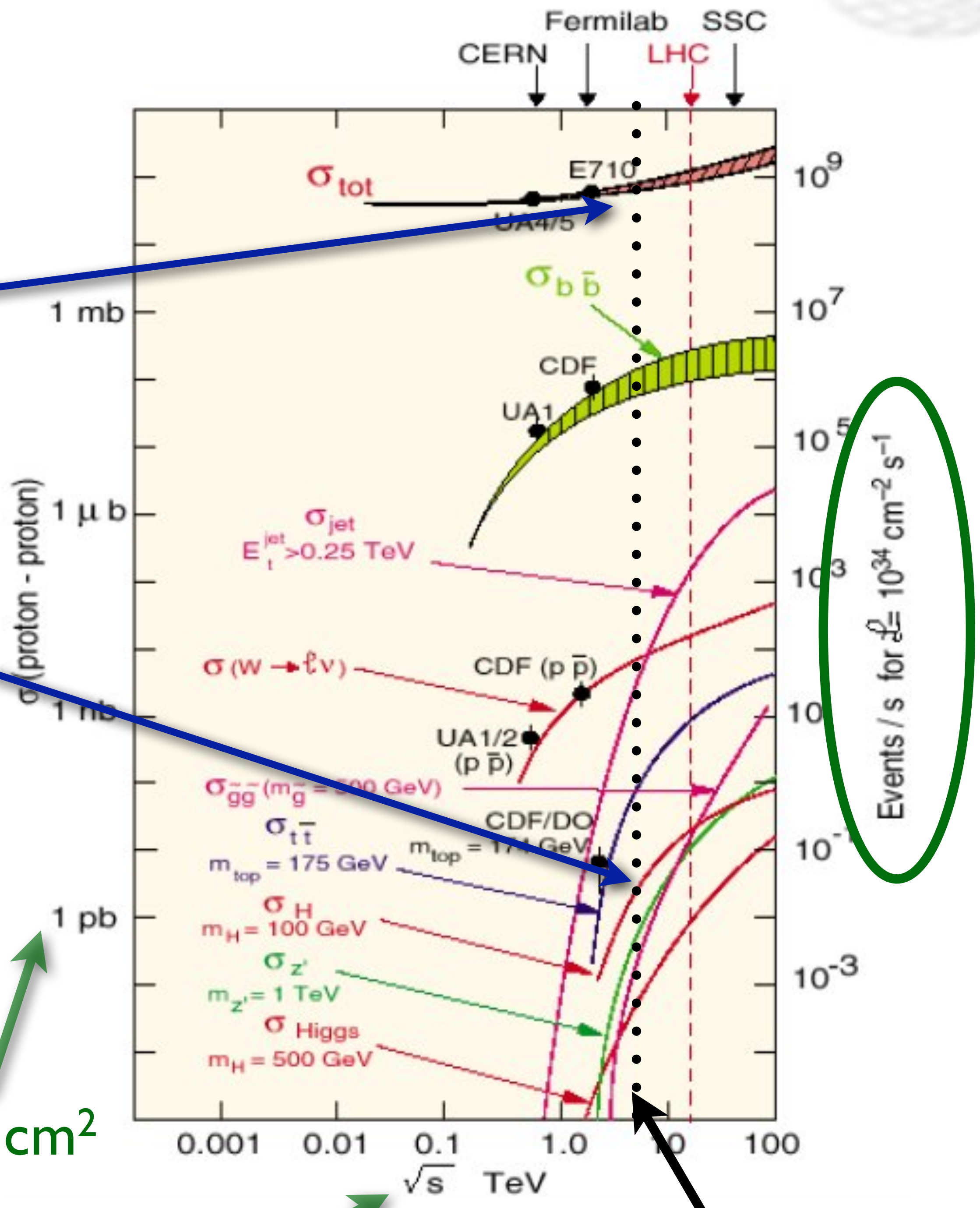
- even if at half the CM energy initially foreseen

Experimental conditions

We need this performance!

- interactions at hadron colliders dominated by strong interaction
- when searching for Higgs boson production, need to suppress backgrounds by ~ 10^{10}

Look for striking signatures setting the Higgs boson apart from more ubiquitous "background" processes



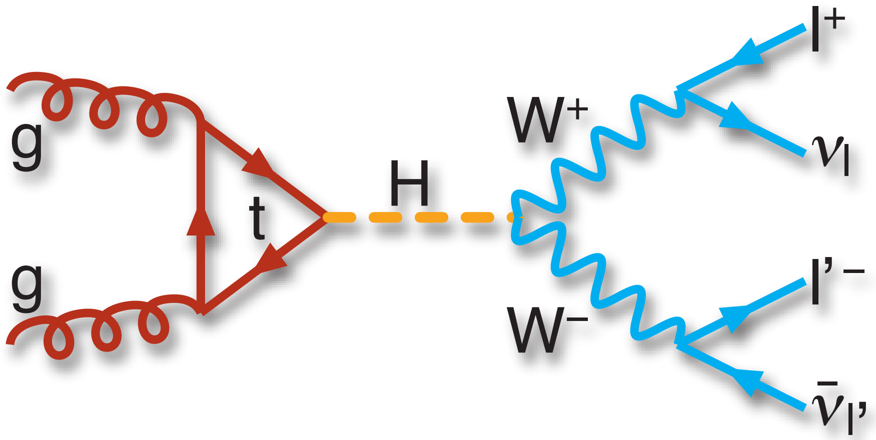
1 pb = 10^{-36} cm^2

$\sqrt{s} \equiv E_{CM}$

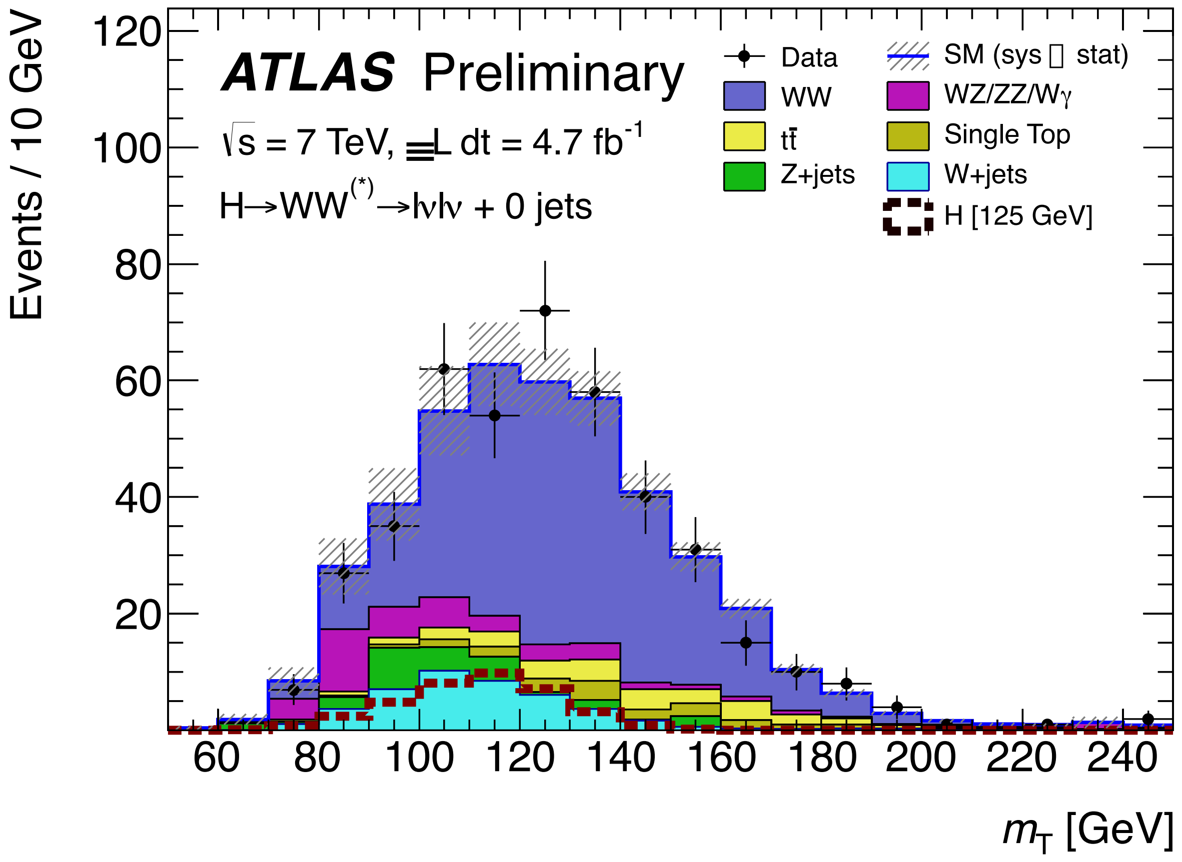
now

Higgs Boson Searches

Many possible production and decay modes! Here, focus on channels relevant in the most "interesting" mass range:



- $H \rightarrow WW^{(*)} \rightarrow l\nu l\nu$: relatively large event rate but cannot reconstruct mass of event candidates due to escaping neutrinos
  - rely on shapes of kinematic variables
  - also substantial backgrounds



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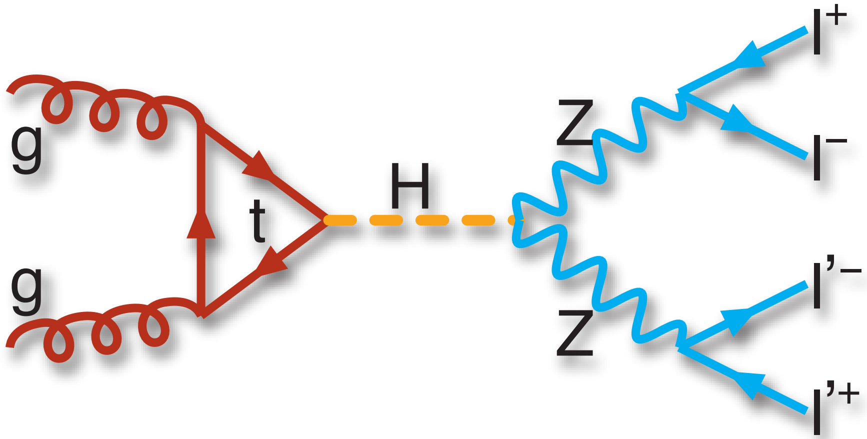

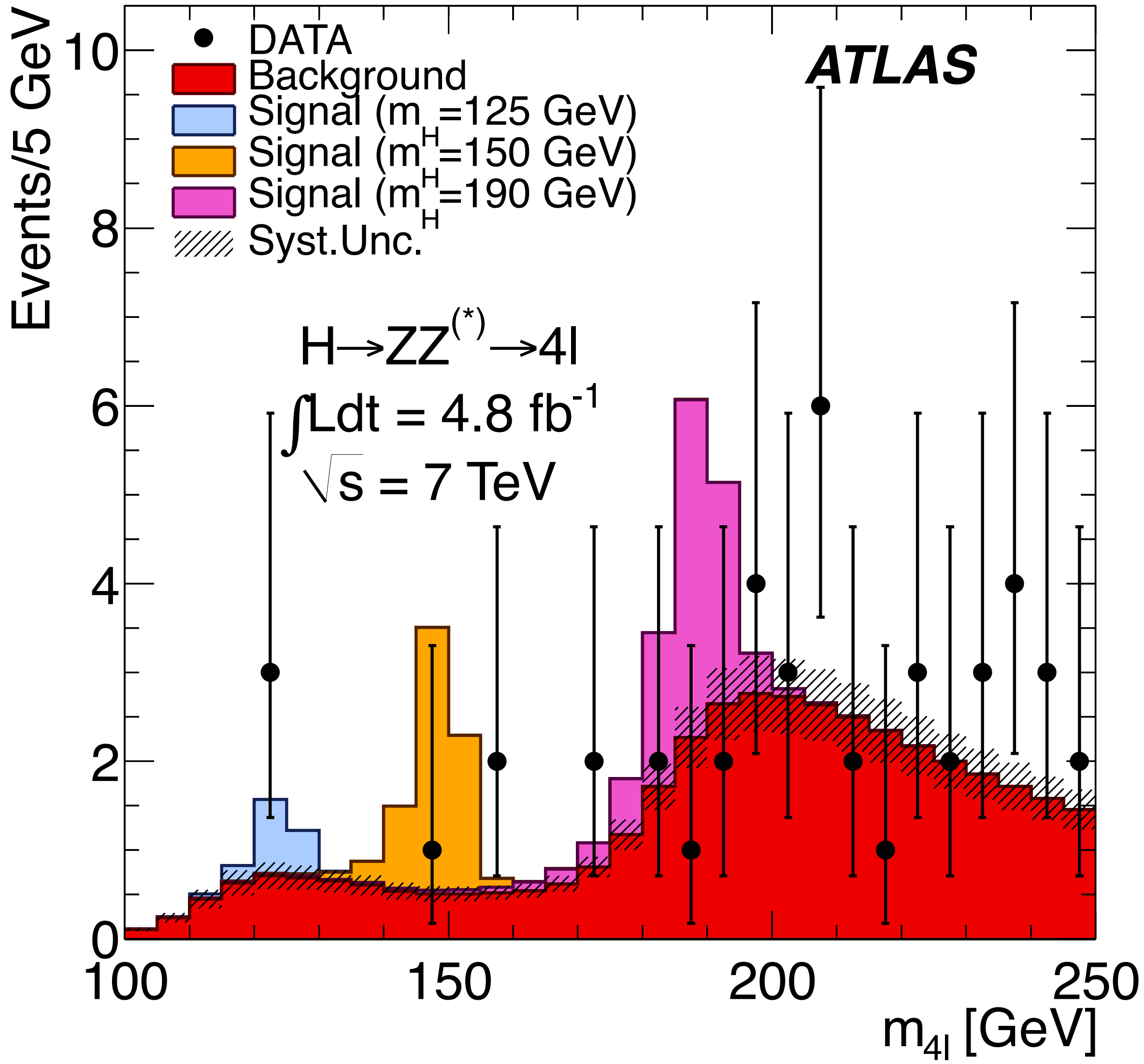

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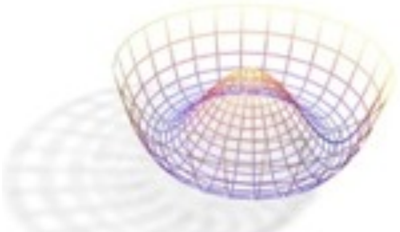

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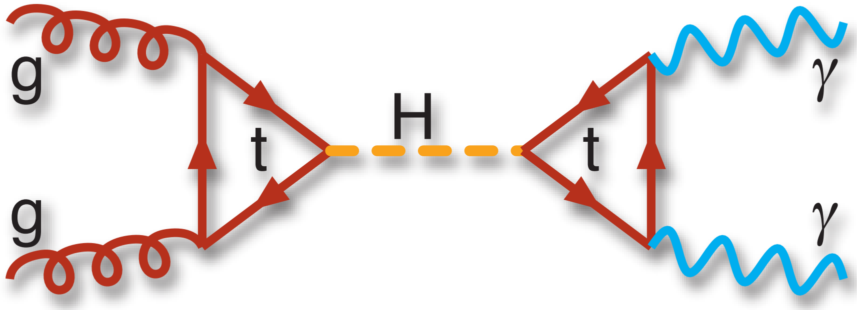

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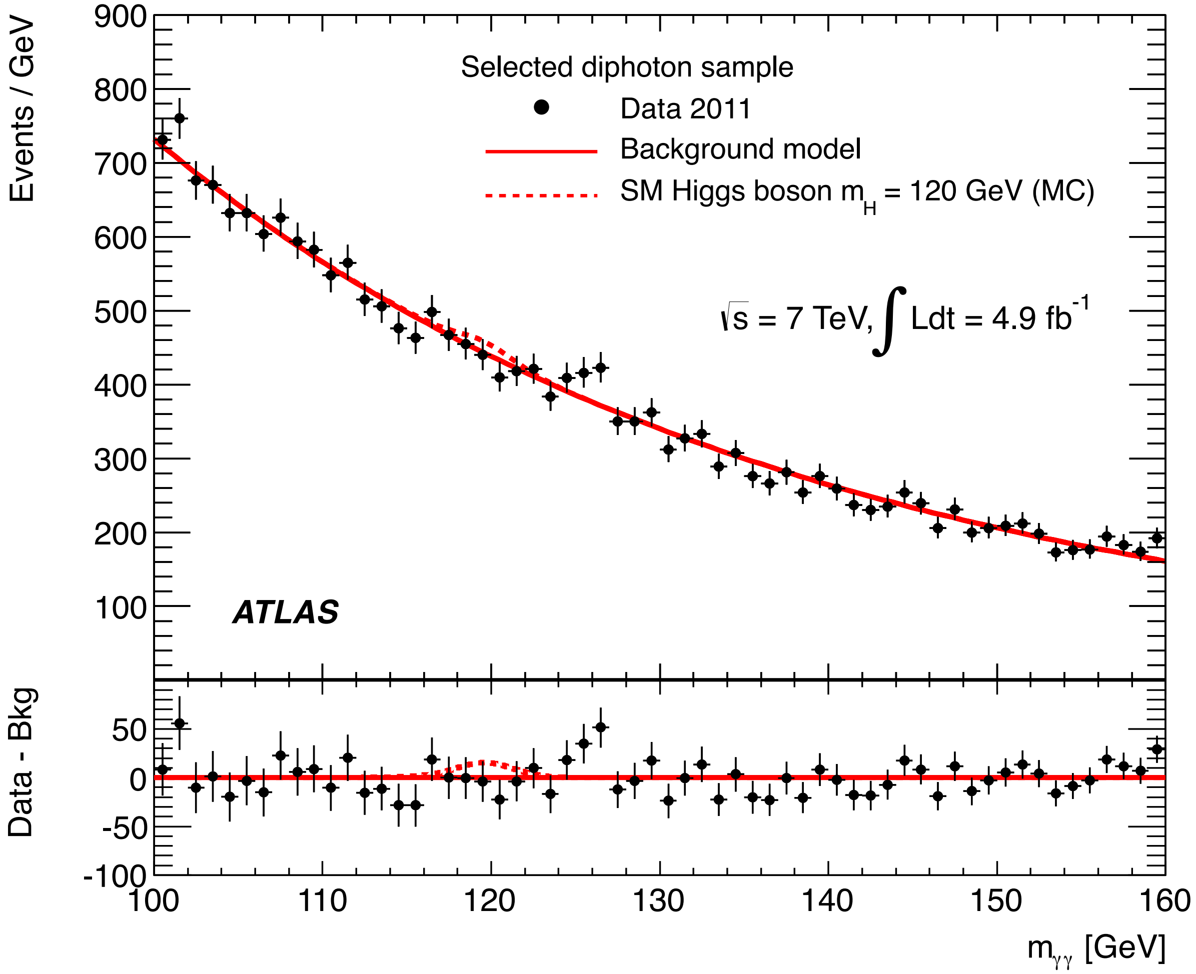

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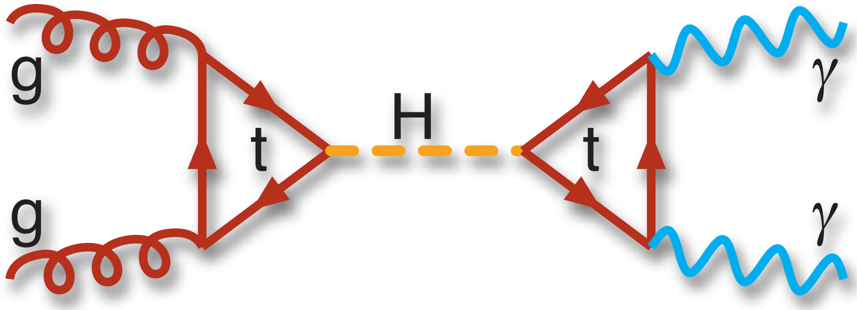

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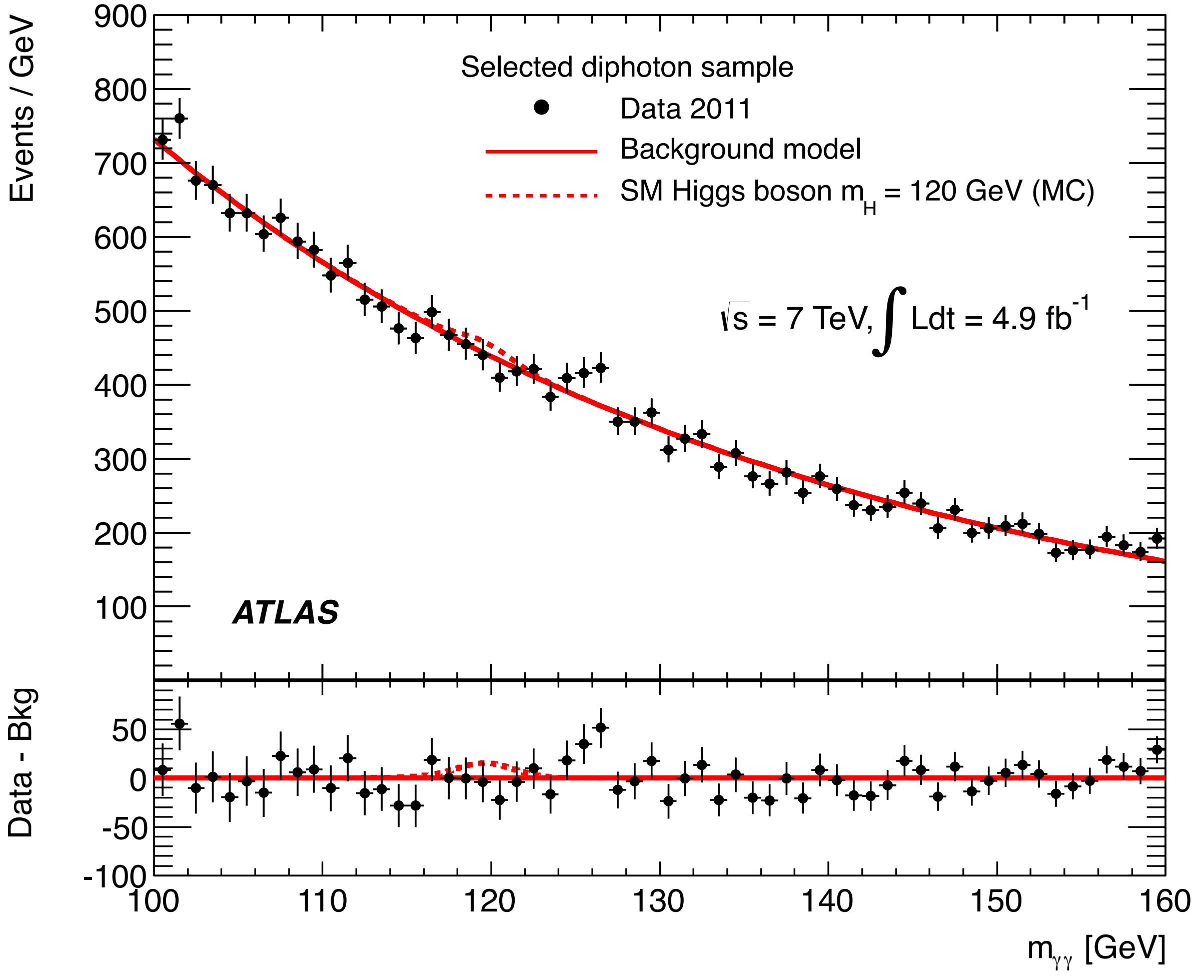
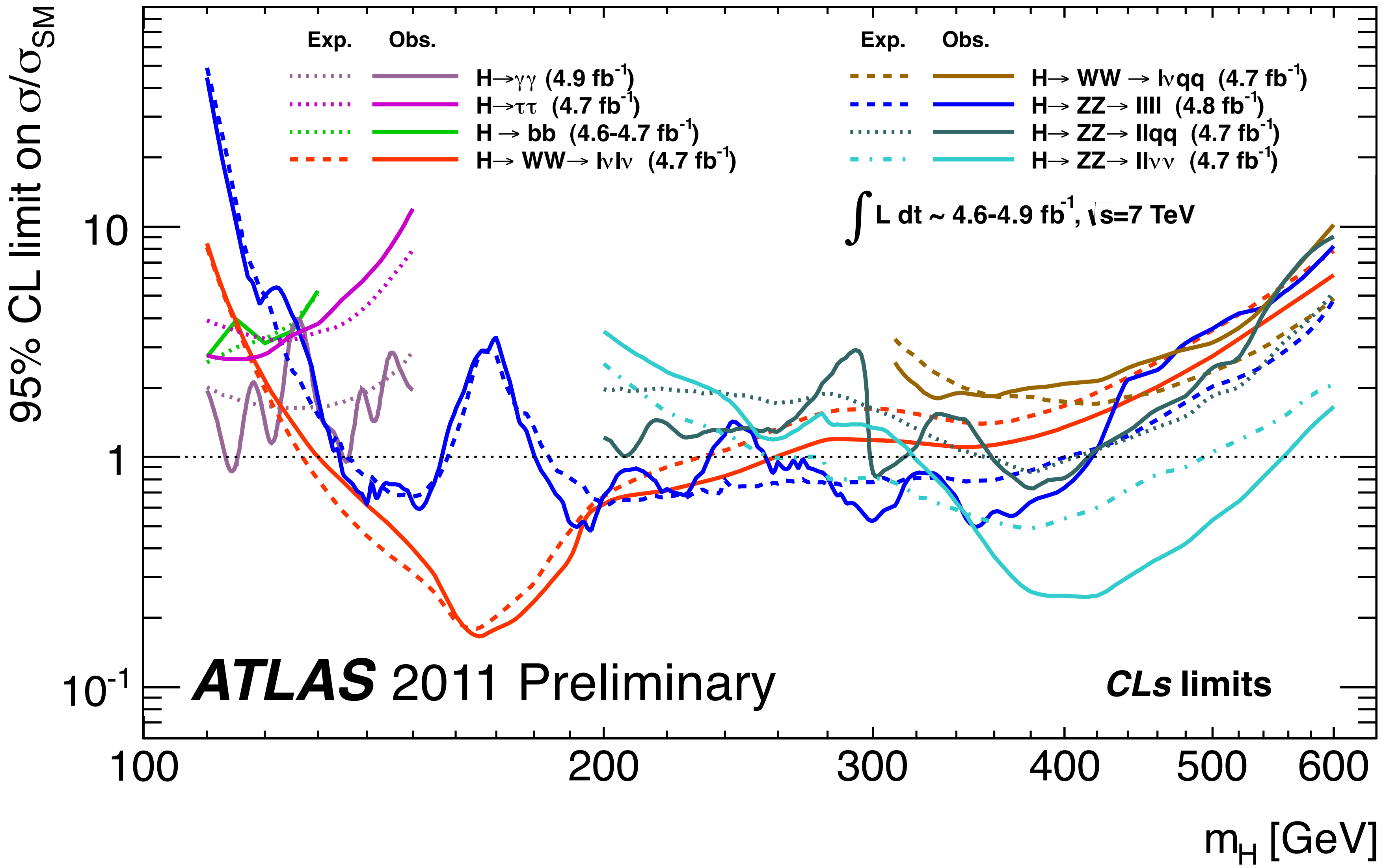


Note: Higgs boson couples to mass but most promising production modes involve massless gluons...

Combining It All



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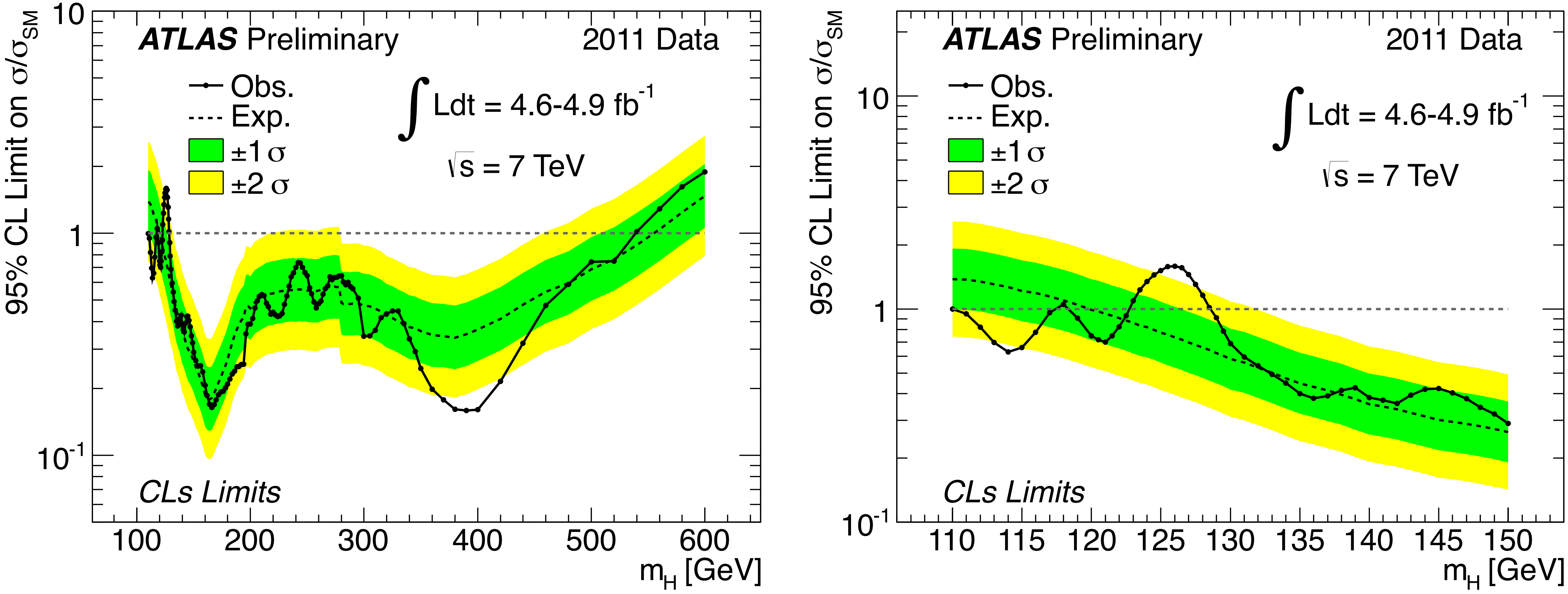
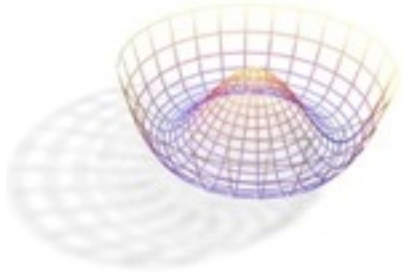


Very similar results by the CMS collaboration!

- exclude 127 GeV < M_H < 600 GeV; see excess around 124 GeV (ATLAS excess is around 126 GeV)

Prospects



With full 2012 dataset, expect to multiply statistics by factor > 4

- even if we have to cope with more difficult data taking conditions (learning...)

Should be able either to discover a $M_H \sim 125$ GeV Higgs signal, or rule it out altogether!

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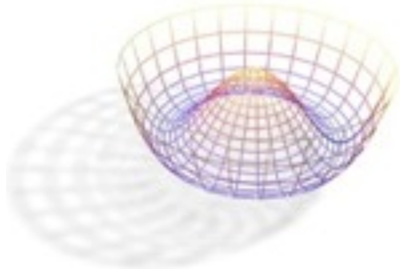

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- this (essentially) means ruling out the Standard Model!
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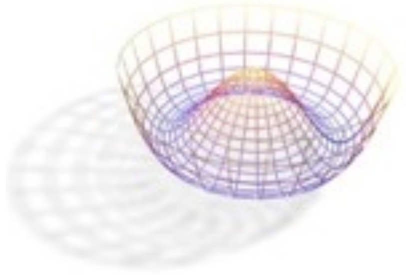
  - study vector boson scattering at high energy; look for direct signs of new physics

↑

See talk by
P. de Jong

Prospects



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- lacking direct signs of supersymmetry, the best way to distinguish the Standard Model from this alternative!

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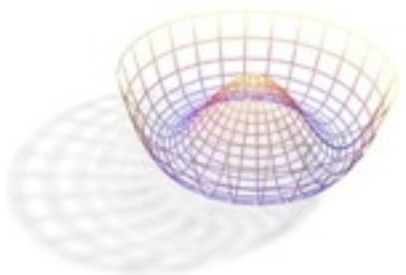

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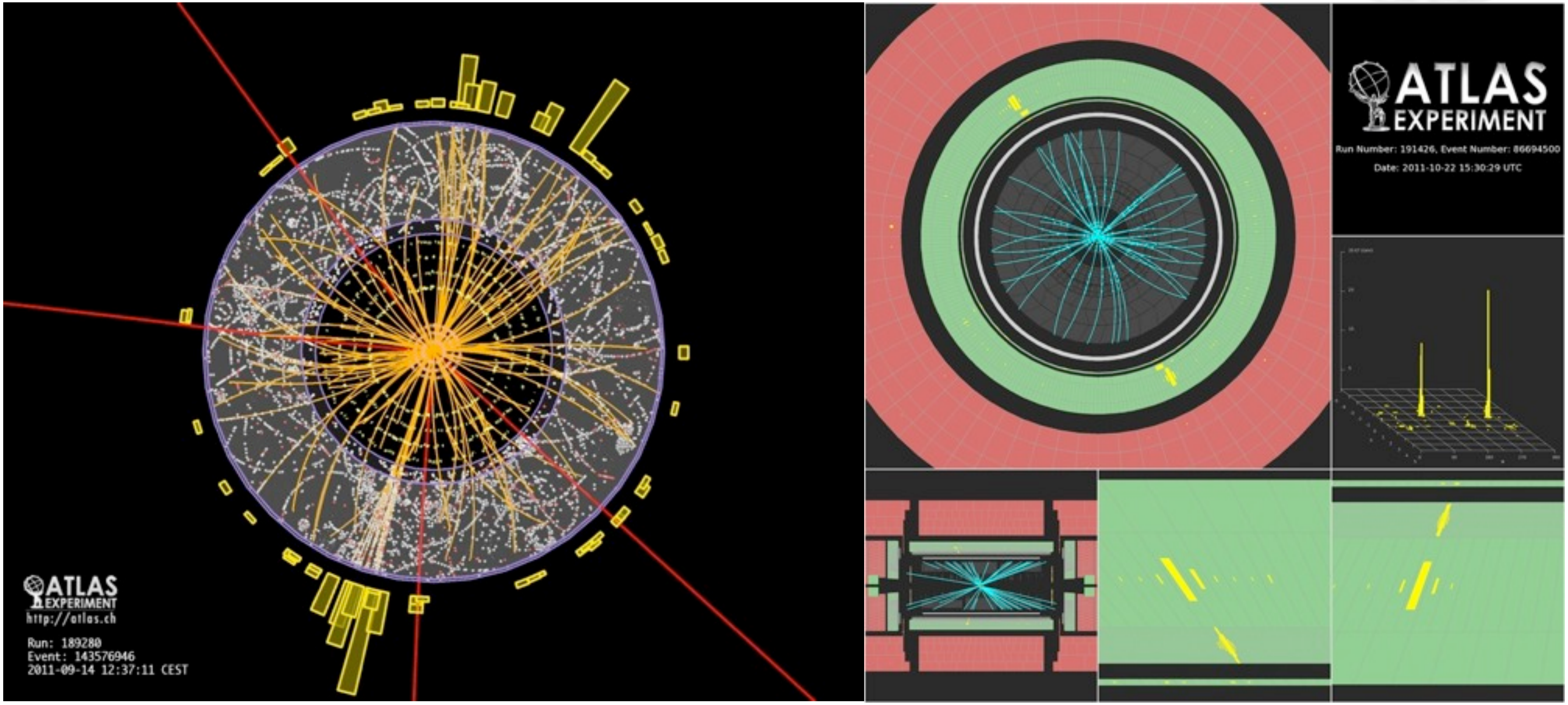
Particle physics has an exciting time ahead!

Thank you!



ATLAS H → ZZ(*) → μ+μ-μ+μ- and H →γγ candidates

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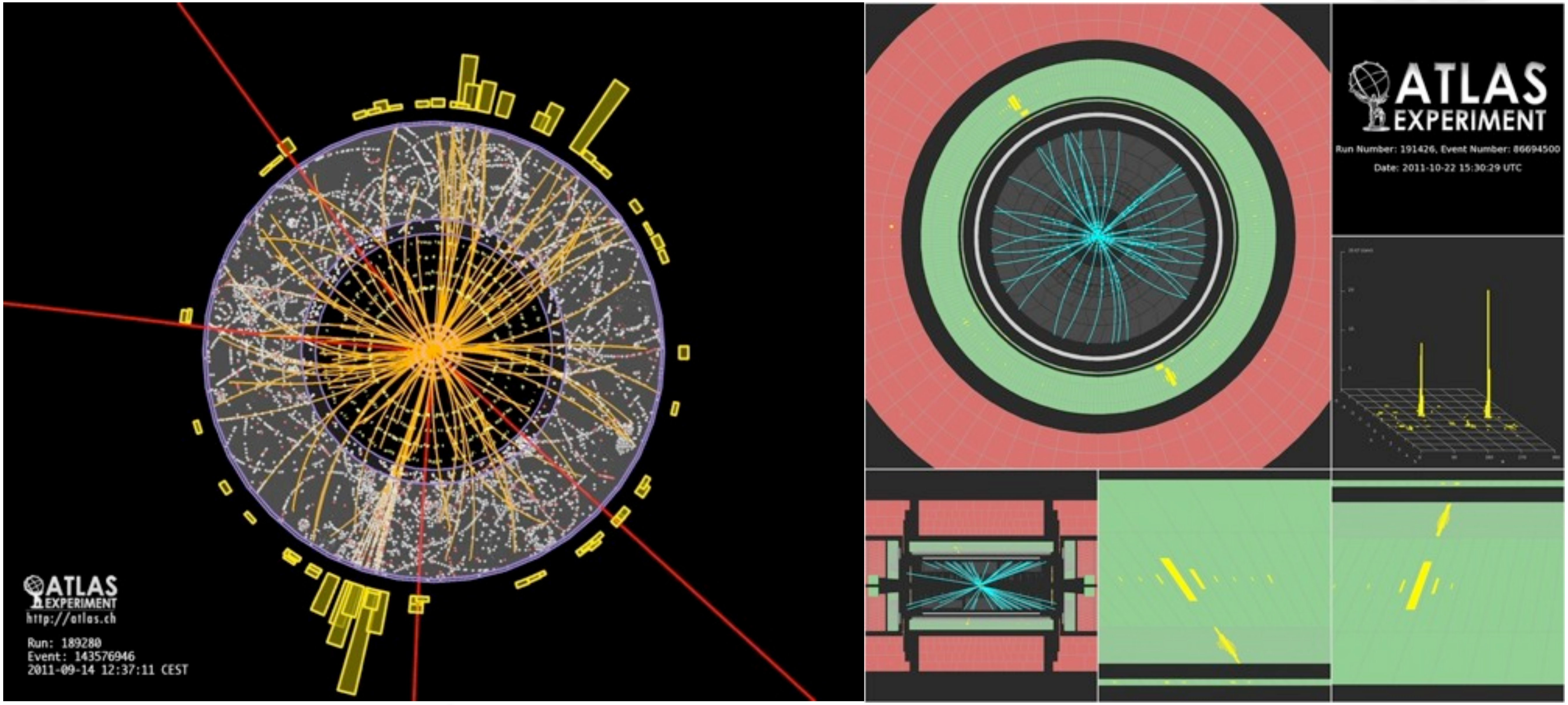

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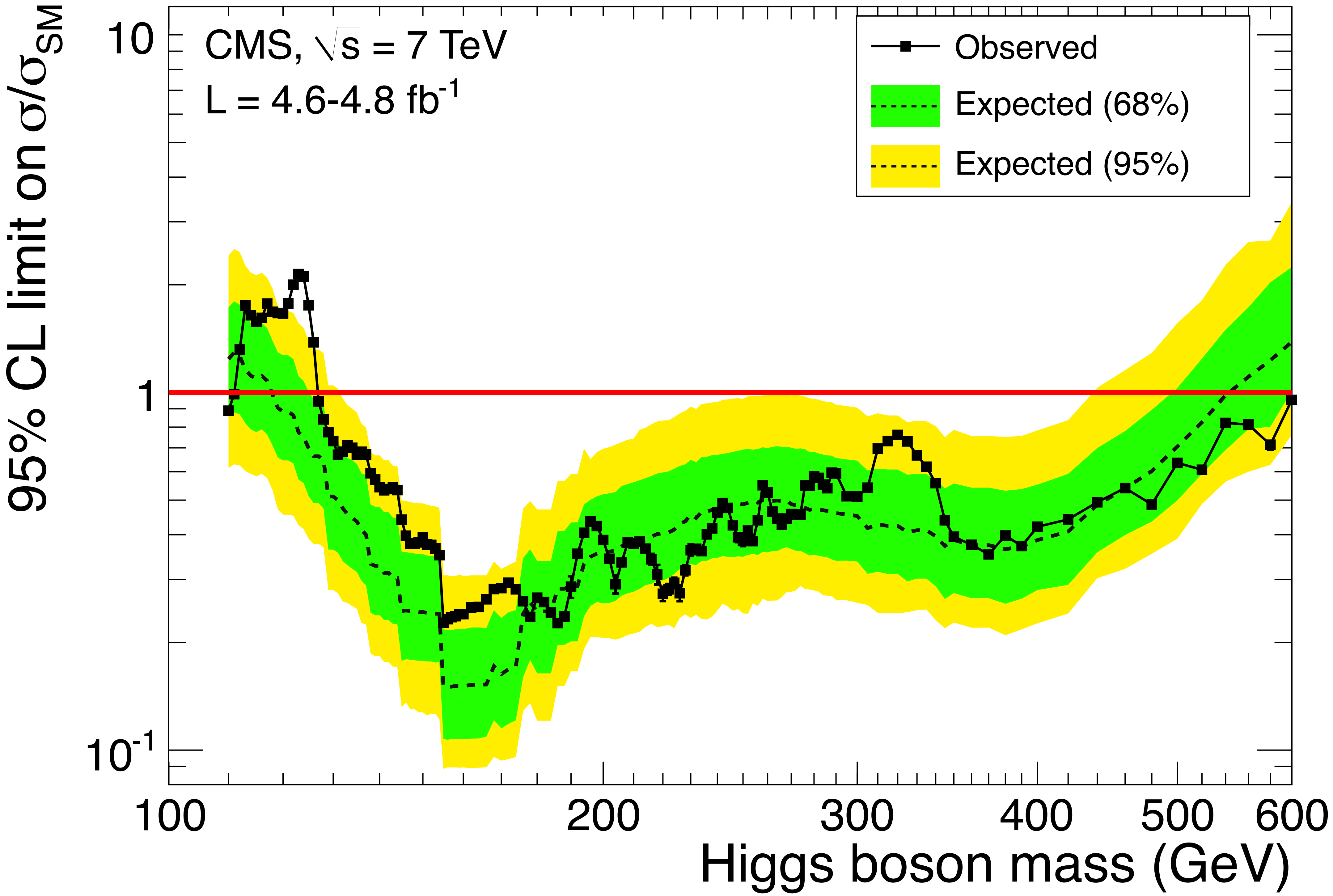
Results by the CMS Experiment



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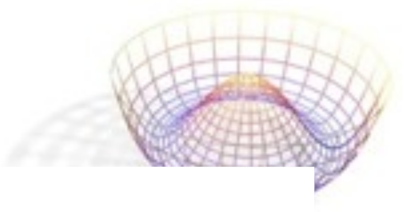
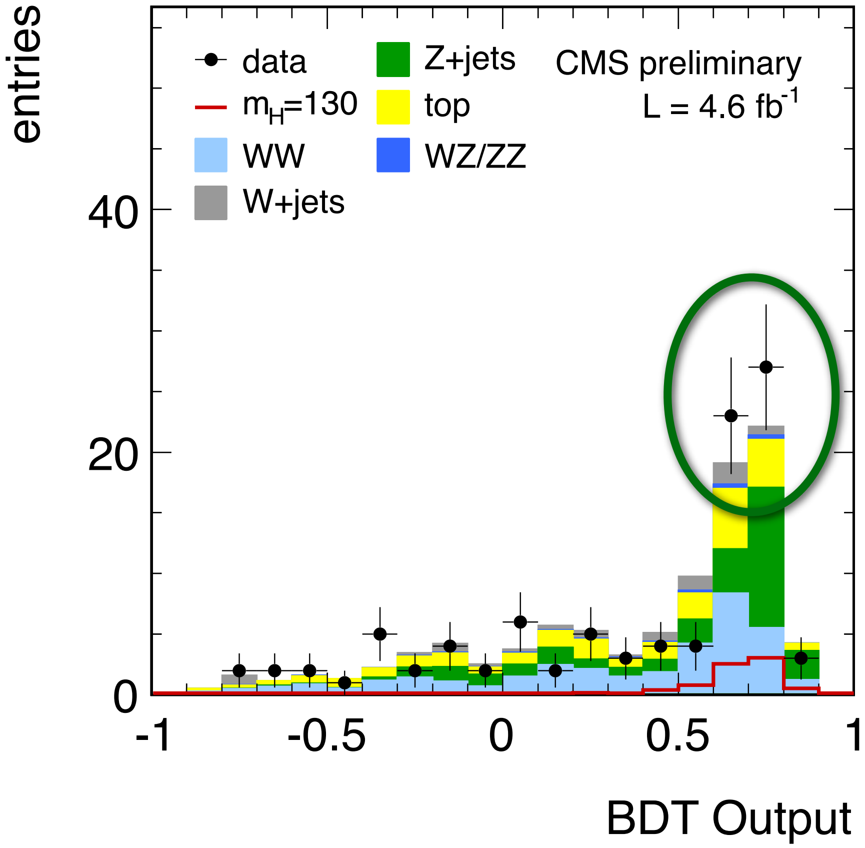
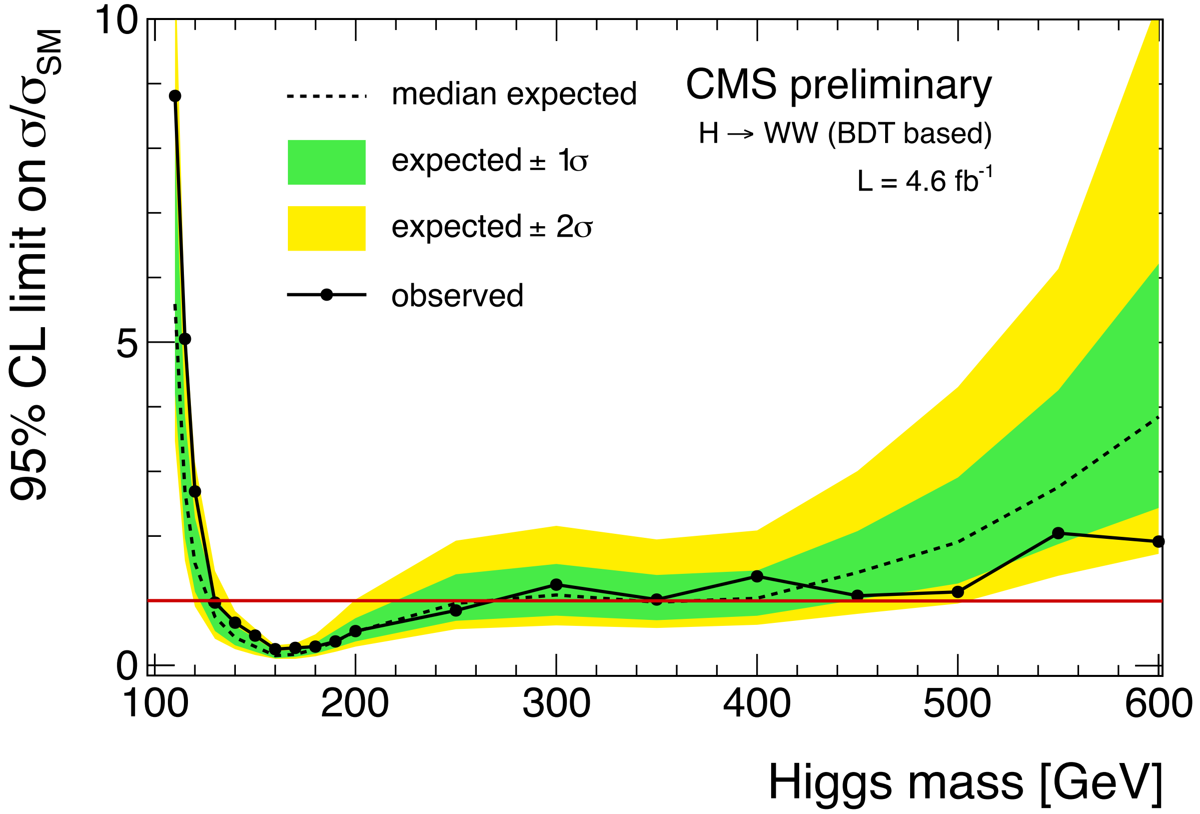
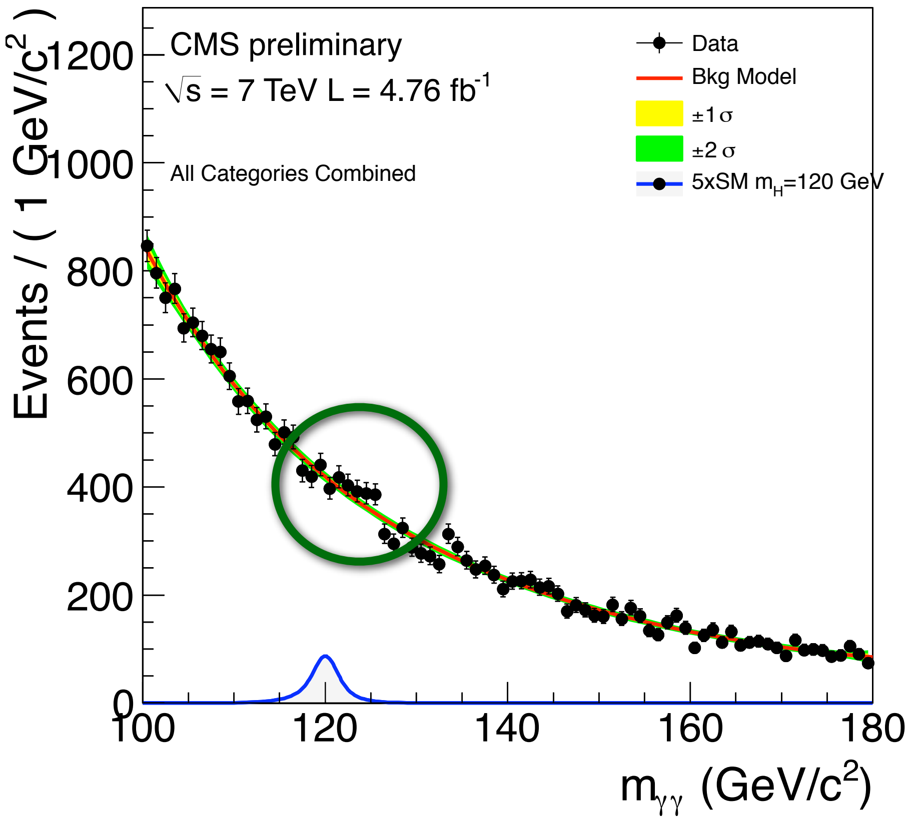


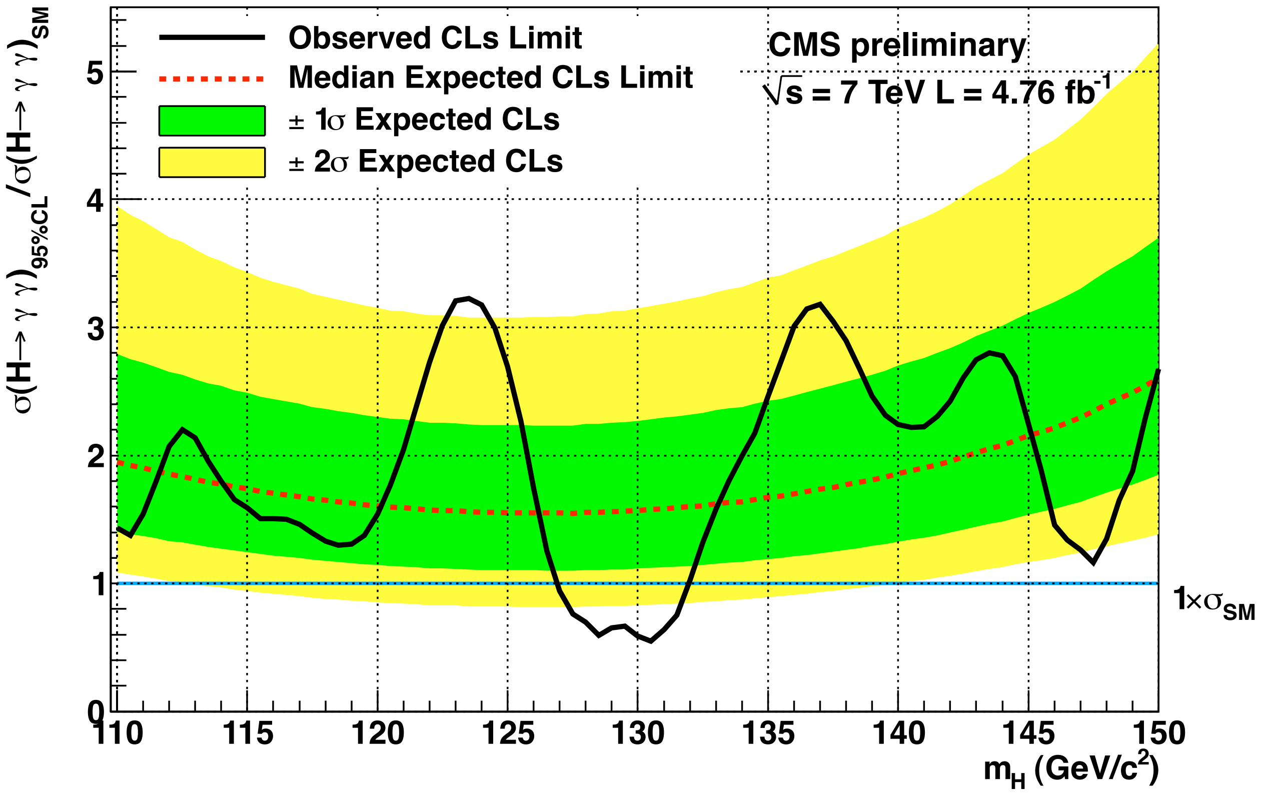


H→W⁺W⁻

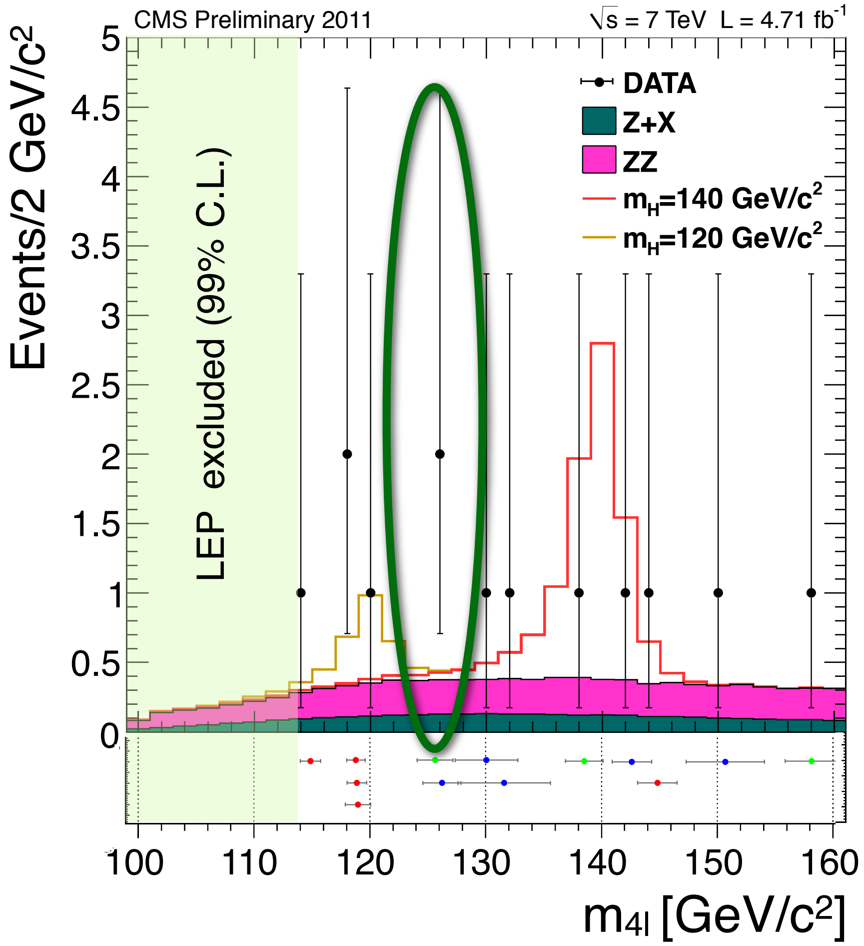




H→γγ



Results by the CMS Experiment

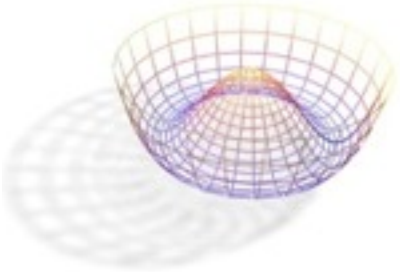


H→ZZ

Found 2 candidate events near 126 GeV

- 1 in $e^+e^-e^+e^-$
- 1 in $e^+e^-\mu^+\mu^-$

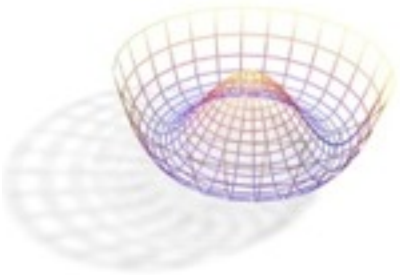
Comparison



ATLAS:

- excess in W^+W^- final states: broad but compatible with low-mass Higgs boson
- excess in ZZ final state (124 GeV)
- excess in $\gamma\gamma$ final state (126 GeV)

Comparison



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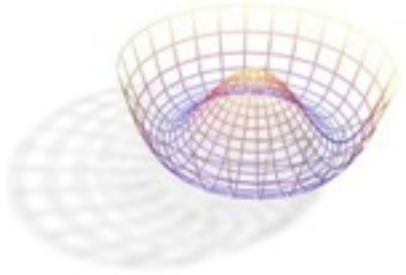
CMS:

- excess in W^+W^- final states: broad but compatible with low-mass Higgs boson
- excess in ZZ final state (126 GeV)
- excess in γγ final state (123 GeV)

Comparison



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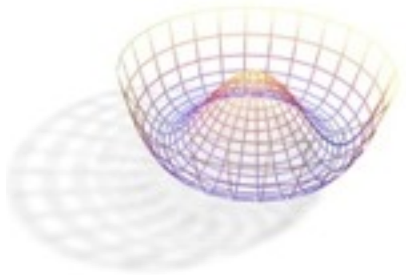
Caveat emptor!

- each individual excess not statistically significant
- masses in γγ, ZZ are close but do not match ➠ questions:
  - are the energy calibrations as well understood as we think?
  - is this just a statistical fluctuation after all?

Time (and additional investigation) will tell

But one way or the other, we expect to make a much more definite statement within a year

Comparison



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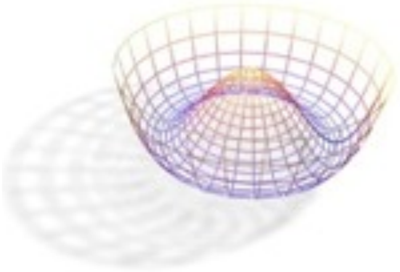
- masses in $\gamma\gamma$, ZZ are close but do not match ➠ questions:
  - are the energy calibrations as well understood as we think?
  - is this just a statistical fluctuation after all?

Time (and additional investigation) will tell

Either we find the Higgs particle or we rule out the Standard Model!

Finally...

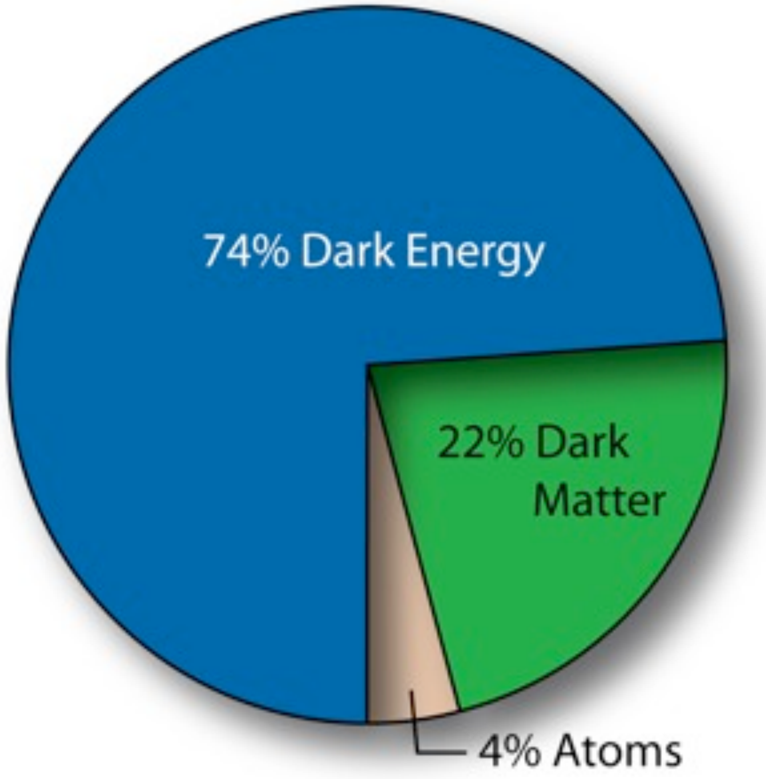


Finding the Higgs boson does not mean particle physics is finished!

The Standard Model cannot incorporate gravity in a consistent way

The Higgs boson's mass is not stable against radiative corrections

The Standard Model does not explain Dark Matter / Dark Energy

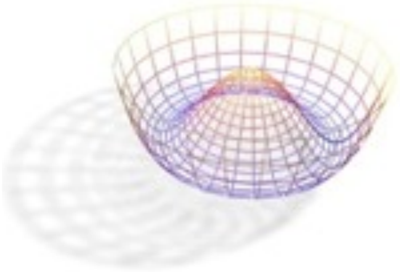


Outlook


gaspirtz.com

The ghost you're trying to reach is currently unavailable.
Please leave a message after the beep.

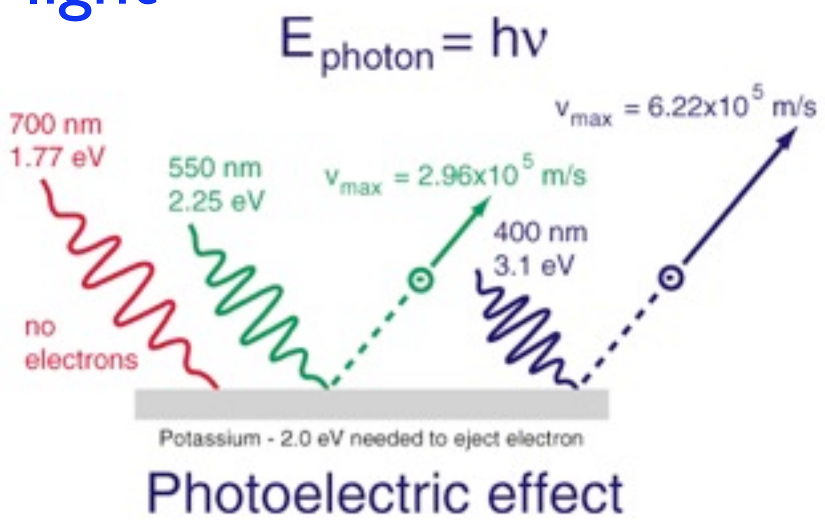
Outlook

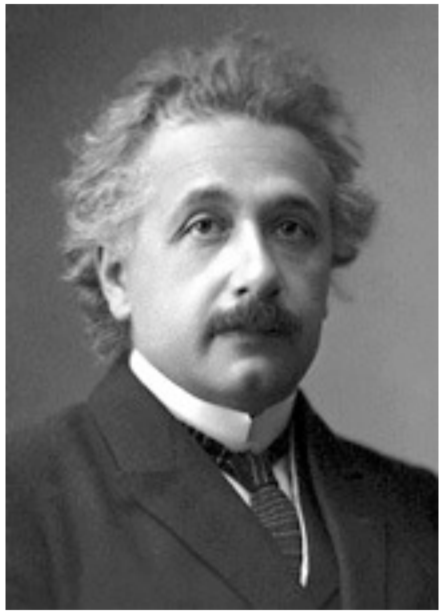


Quantum Electrodynamics

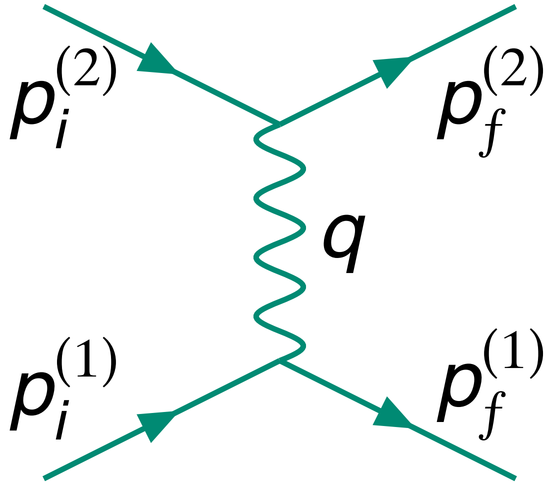
Einstein (1905): photo-electric effect

➠ particle nature of light





Paradigm change! Electromagnetic interaction described as photon exchange



Graphical representation: Feynman diagrams (intuitive way to compute outcome of scattering processes in QM)

Going beyond the naked eye

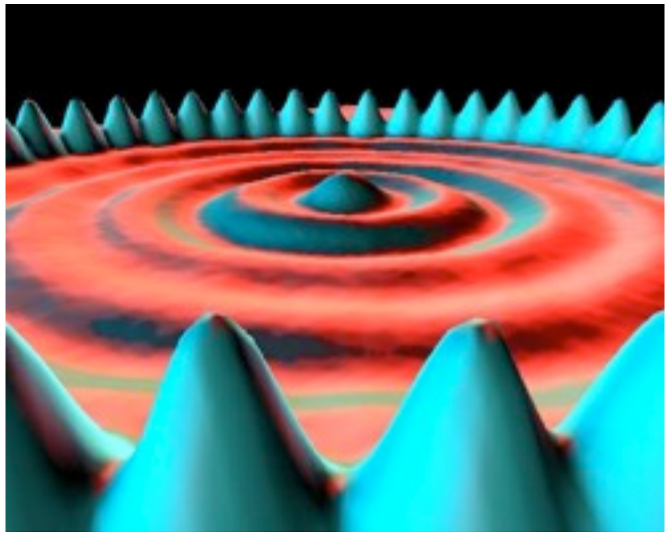
Antoni van Leeuwenhoek, 1632-1723:

- invention of the microscope
- discovery first bacteria ("kleine beestjes"), 0.5 - 500 μm

E. coli (size ~ 1 μm)

Minimum discernible dimensions ~ λ

- limit when using visible light: 0.5 μm
- improvement to ~ 1Å possible using STM, AFM

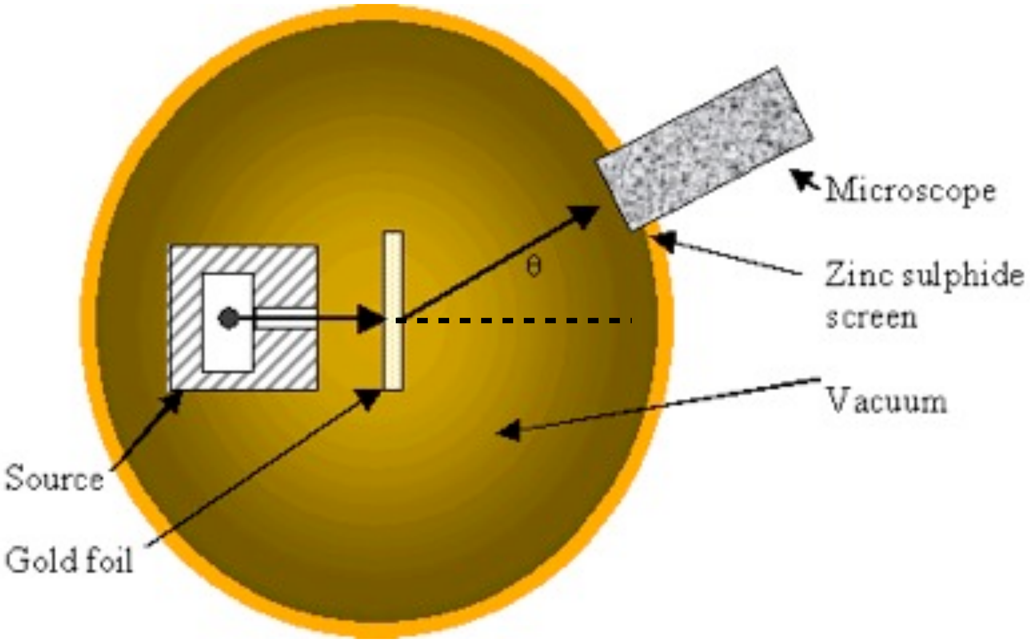


The atom “cracked”

Idea: use particles to “see” smaller structures

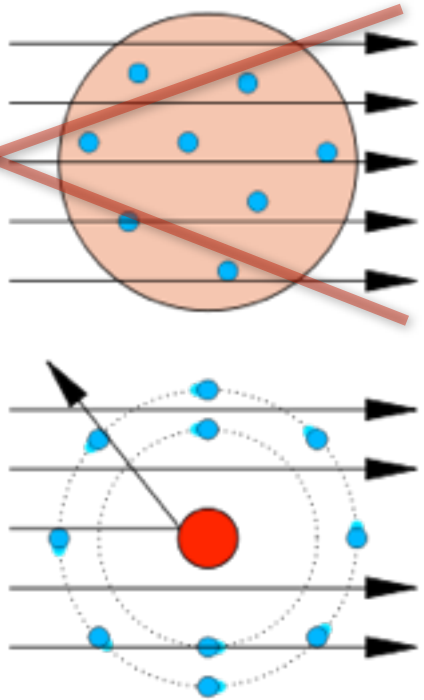
- **Rutherford**: scattering of α-particles (^{4}He nuclei, $E_\alpha \approx 3$ MeV) off a gold foil
- Quantum mechanical translation: de Broglie wavelength $\lambda \sim h/p$

Planck’s constant projectile momentum



~~diffuse charge distribution (Thomson)~~

charge distribution with nucleus (Rutherford)



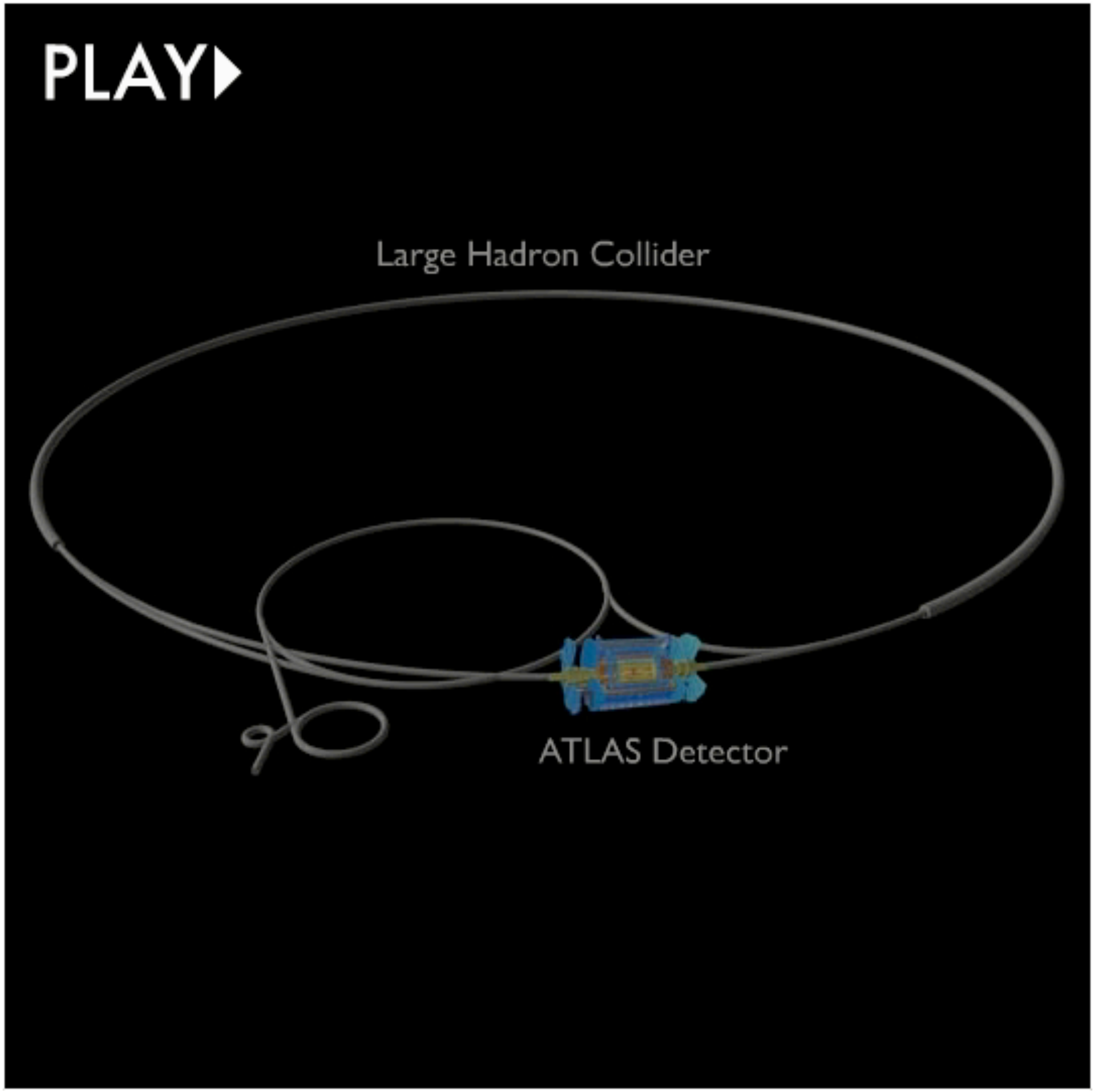
Repeated in the 60’s with scattering of 180 MeV electrons on protons

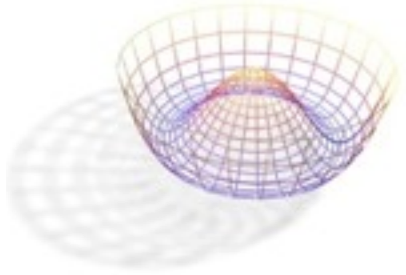
➠ the proton (r ~ 1 fm) contains further sub-structure (quarks)!

State of the art

Present scheme in CERN’s Large Hadron Collider:

- accelerate proton beams to energies of 3.5 TeV per proton
    - v/c ≈ 0.99999996 (energy to be doubled in 2014: 6→8)
    - in both directions!
- make them collide in the centres of the detectors
- experiments analyze outcome of collisions and select “interesting” events
    - stochastic process, no control over outcome of individual collision
      ➠ can only select after the fact

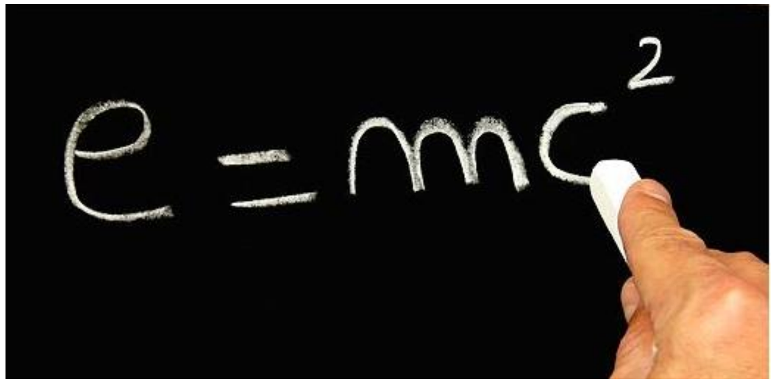


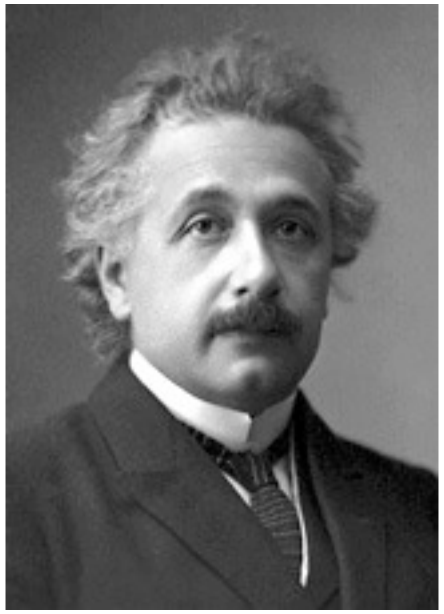


Techniques

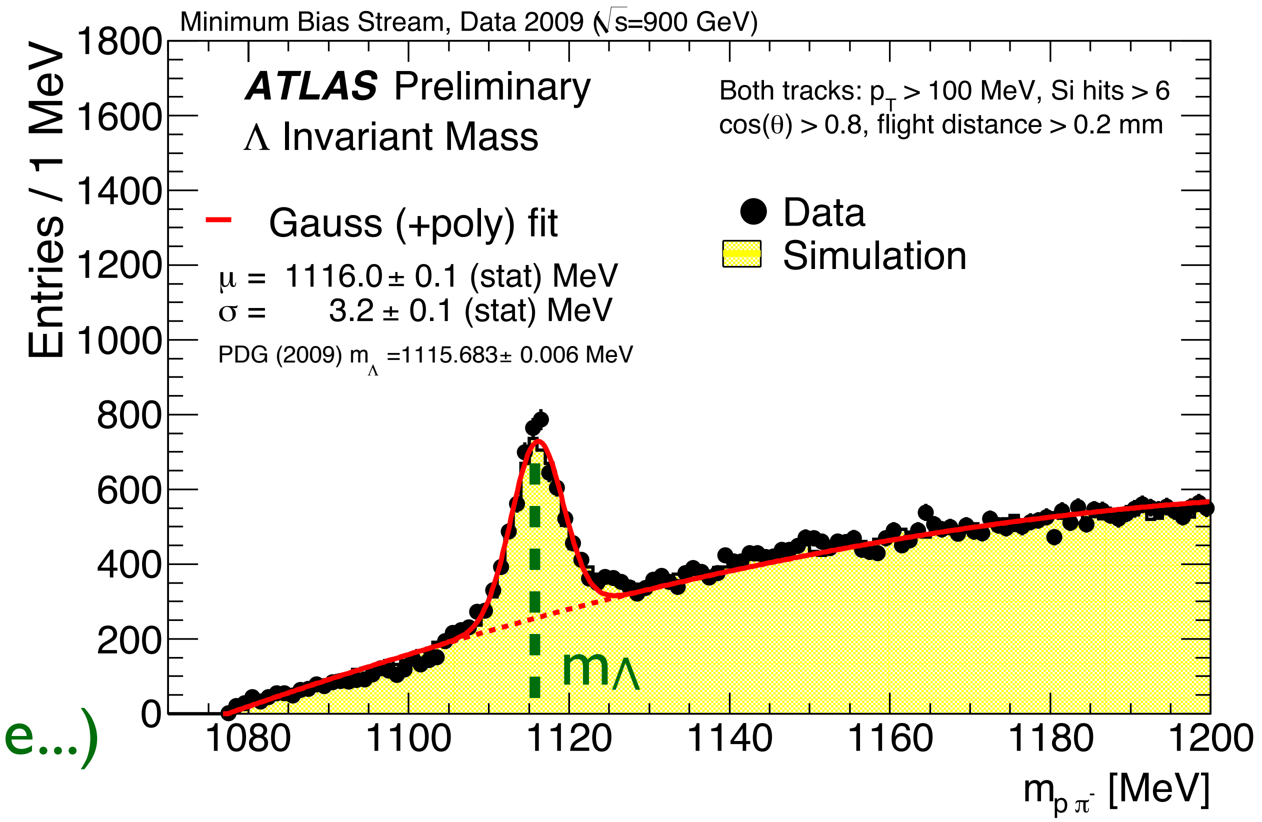
High energy allows for the creation of other, usually short-lived particles

- $\tau < 10^{-22}$ s for "interesting" particles





- in collisions: convert kinetic energy into mass
- in decay processes: reconstruct mass of the decaying particle (if all decay products are measured)



(not the Higgs particle...)

The Electron’s Magnetic Dipole Moment

Well-known system: interaction of magnetic dipole moments with external magnetic field

$$H = -\vec{\mu} \cdot \vec{B}, \quad \vec{\mu} = \gamma \vec{S} \equiv g \left(\frac{q}{2m} \right) \vec{S}$$

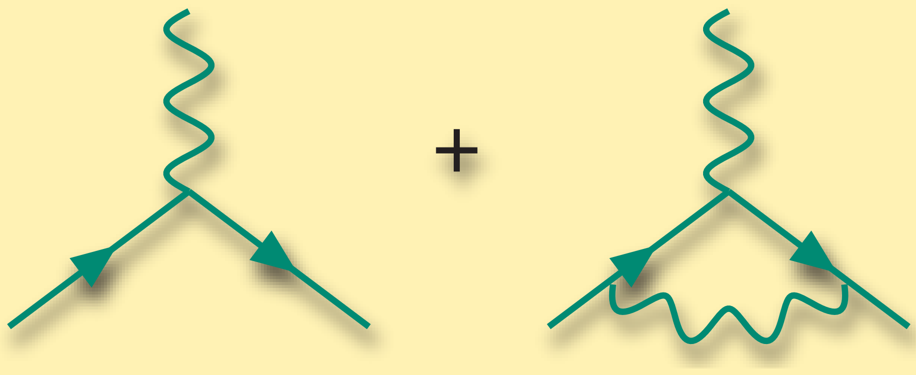
- Zeeman splitting of (atomic) energy levels
- Spin precession around B-field axis, Larmor frequency $\omega = \gamma B$

Unlike regular QM, QED provides a prediction for g!

- Applying the gauge principle to the Dirac equation (relativistic equation of motion for spin-1/2 particles): g=2
- Computing quantum corrections: expansion in powers (up to fifth power) of fine structure constant

$$\alpha \equiv \frac{e^2}{4\pi}$$

contributions at lowest orders



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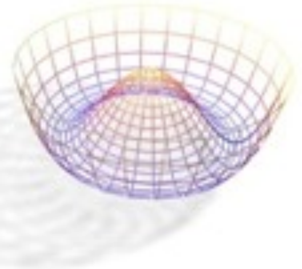

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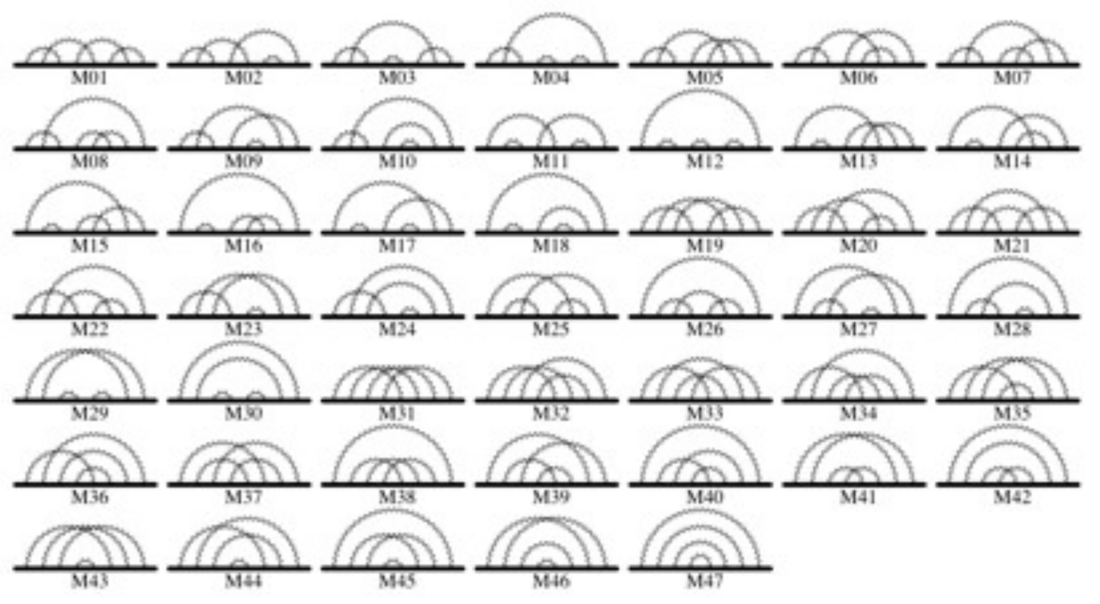
subset of contributions at 5th order



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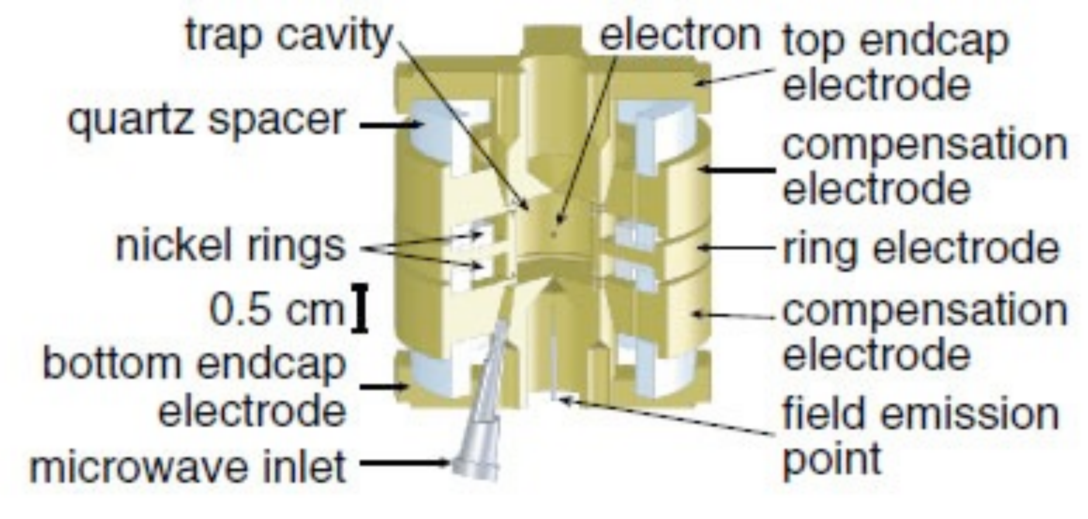
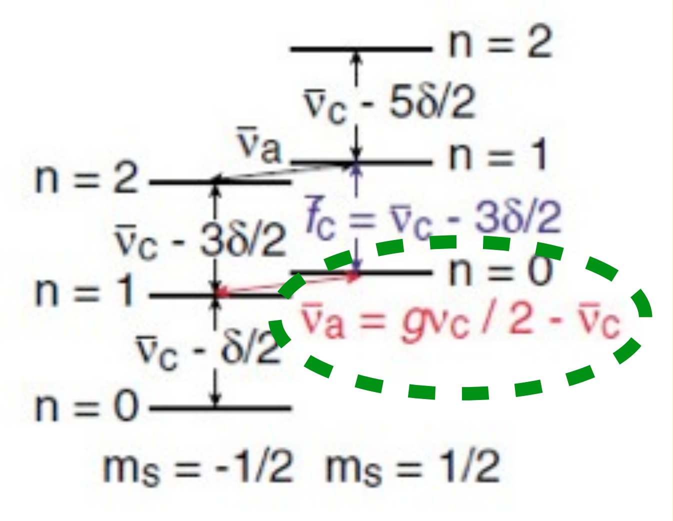
G. Gabrielse et al., 2008
Cylindrical Penning trap



Observe a single electron for months



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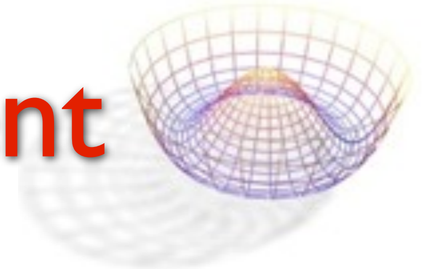
The comparison:

The Electron’s Magnetic Dipole Moment



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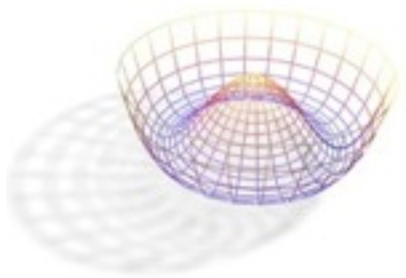
Unlike regular QM, QED provides a prediction for g!

The comparison:

$$g/2 = \begin{cases} 1.001\,159\,652\,180\,73(28) & \text{(experiment)} \\ 1.001\,159\,652\,180\,85(76) & \text{(theory)} \end{cases}$$

A triumph for QED!

A Colourful Interaction



Three quarks forming baryons (and quark-antiquark pairs forming mesons): a new symmetry (and interaction), colour

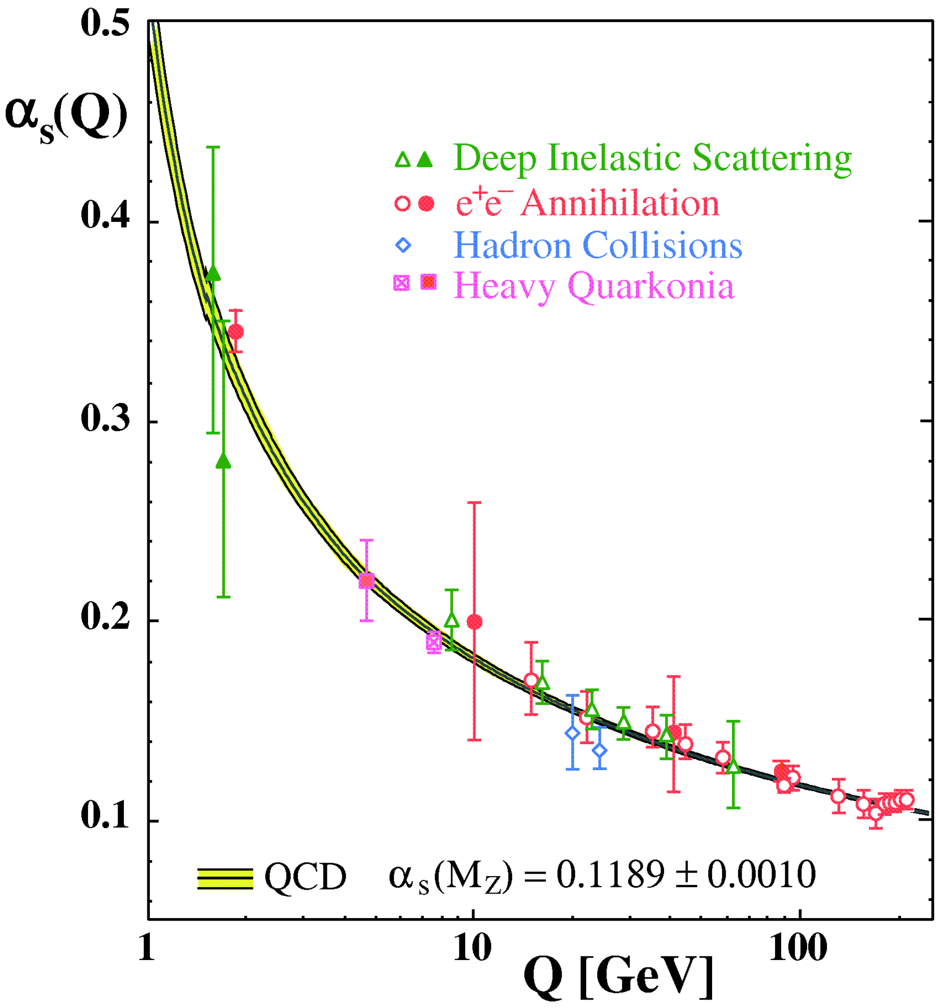
- “gauge principle” interaction with gluons:

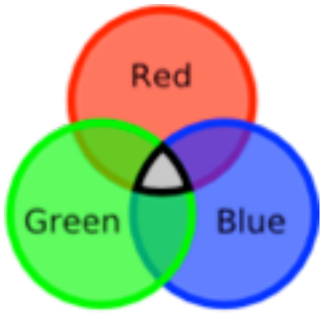
$$q \to \begin{pmatrix} q_r \\ q_g \\ q_b \end{pmatrix}$$

- quarks change identity (colour) under exchange of a gluon!

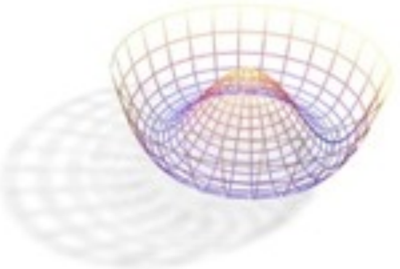
$$p \to p + \frac{g_s}{2} \sum_a T_a G_a$$

$$\alpha_s = \frac{g_s^2}{4\pi}$$





Quark confinement at low energy



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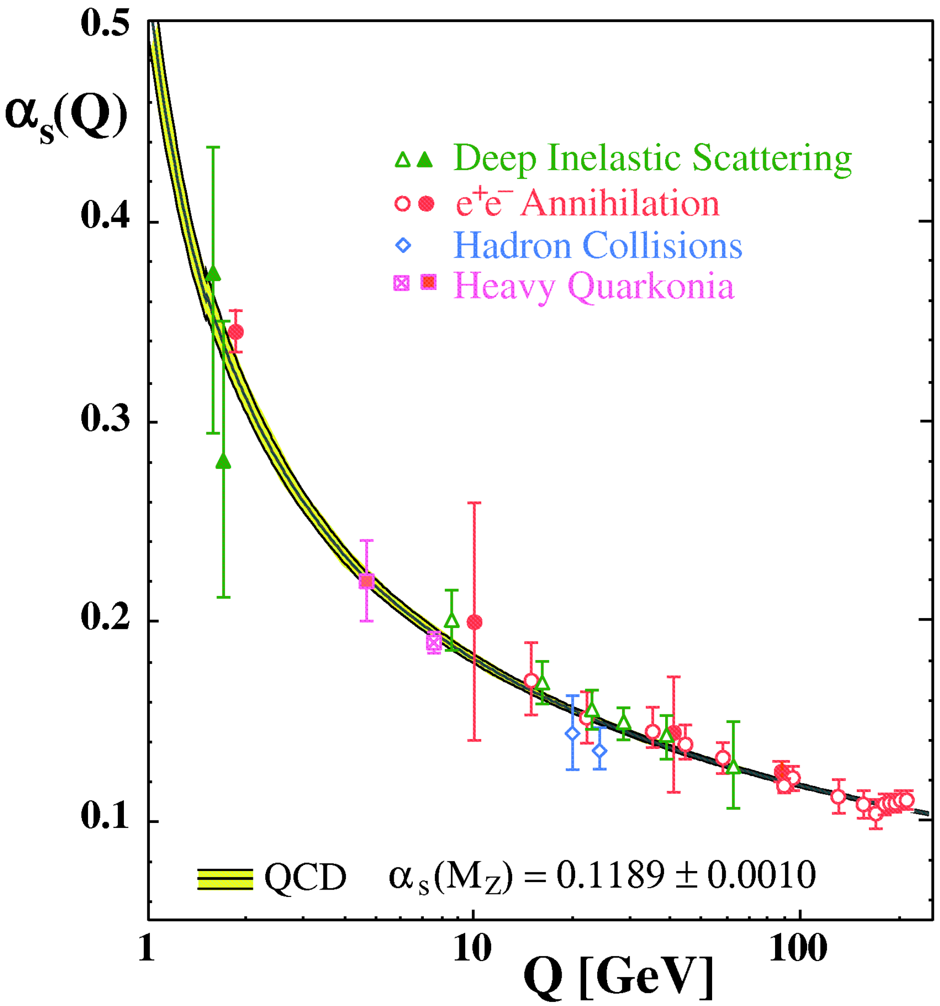
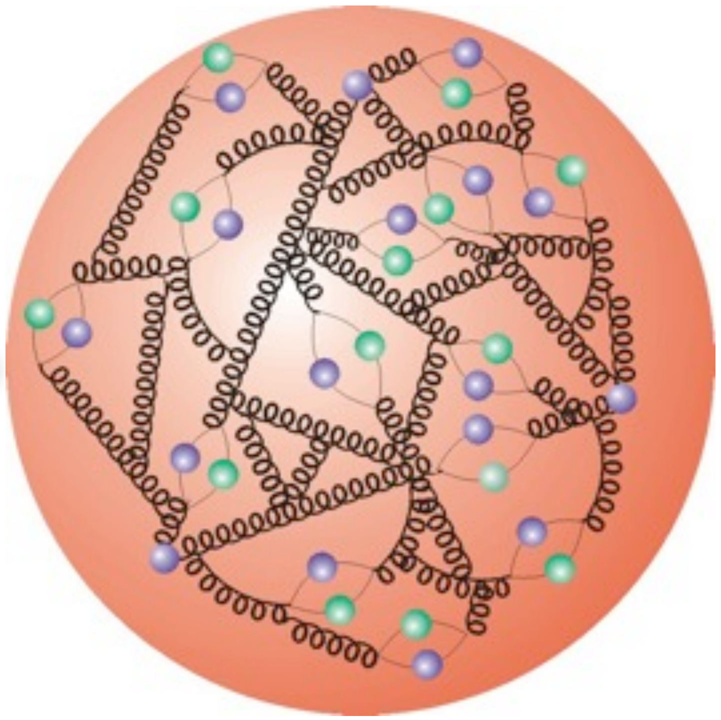
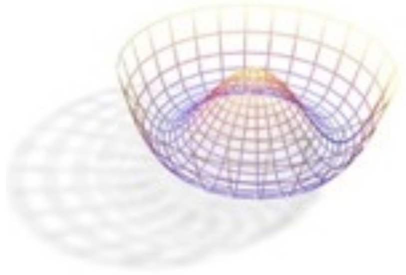




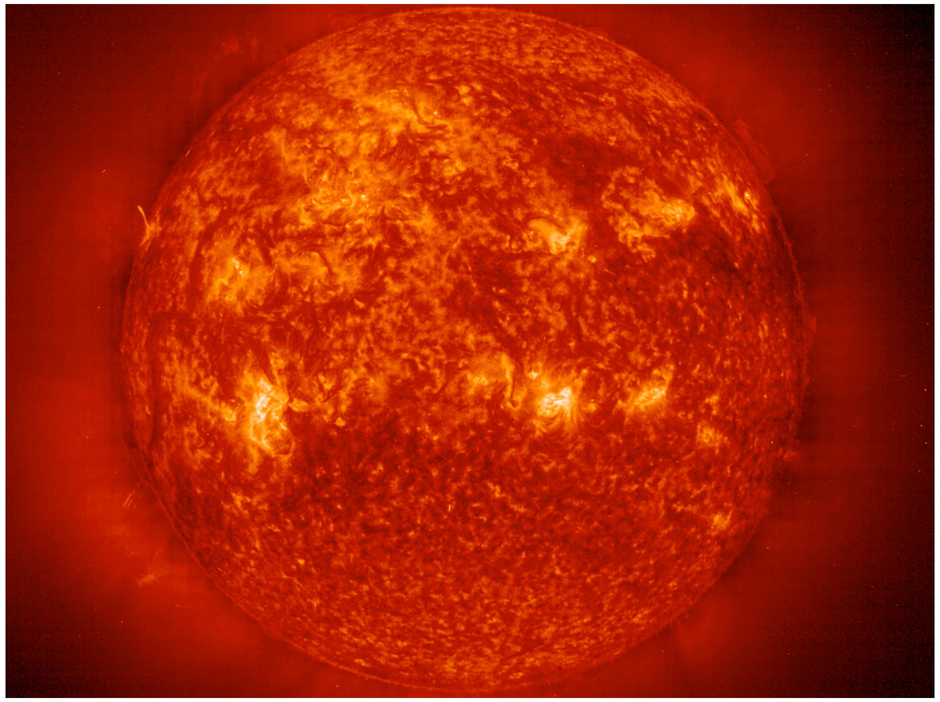
Quark confinement at low energy

The Weak Interaction

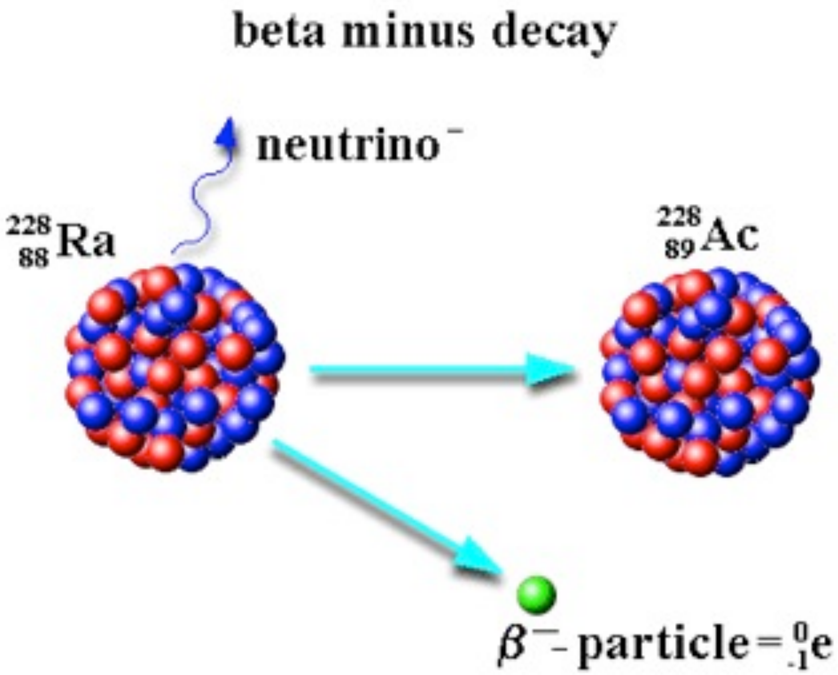


Responsible for all nucleonic transmutations

fusion



radioactivity (β decay)



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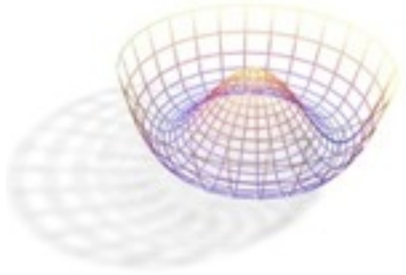
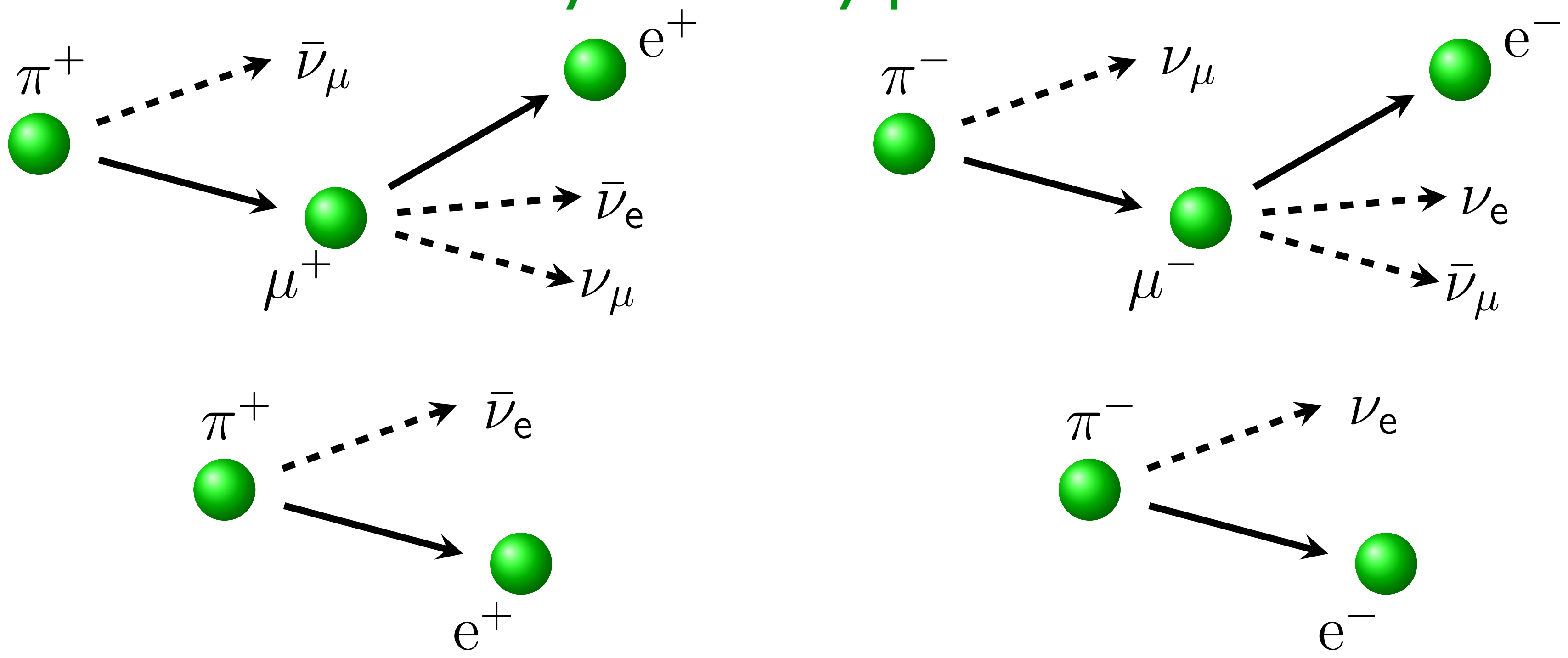


Responsible for all nucleonic transmutations

and particle decays

Decays of heavy particles



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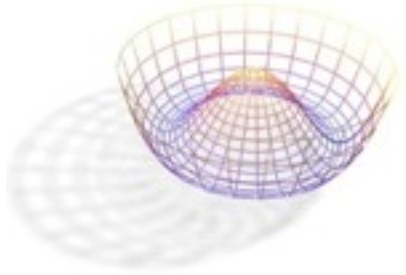

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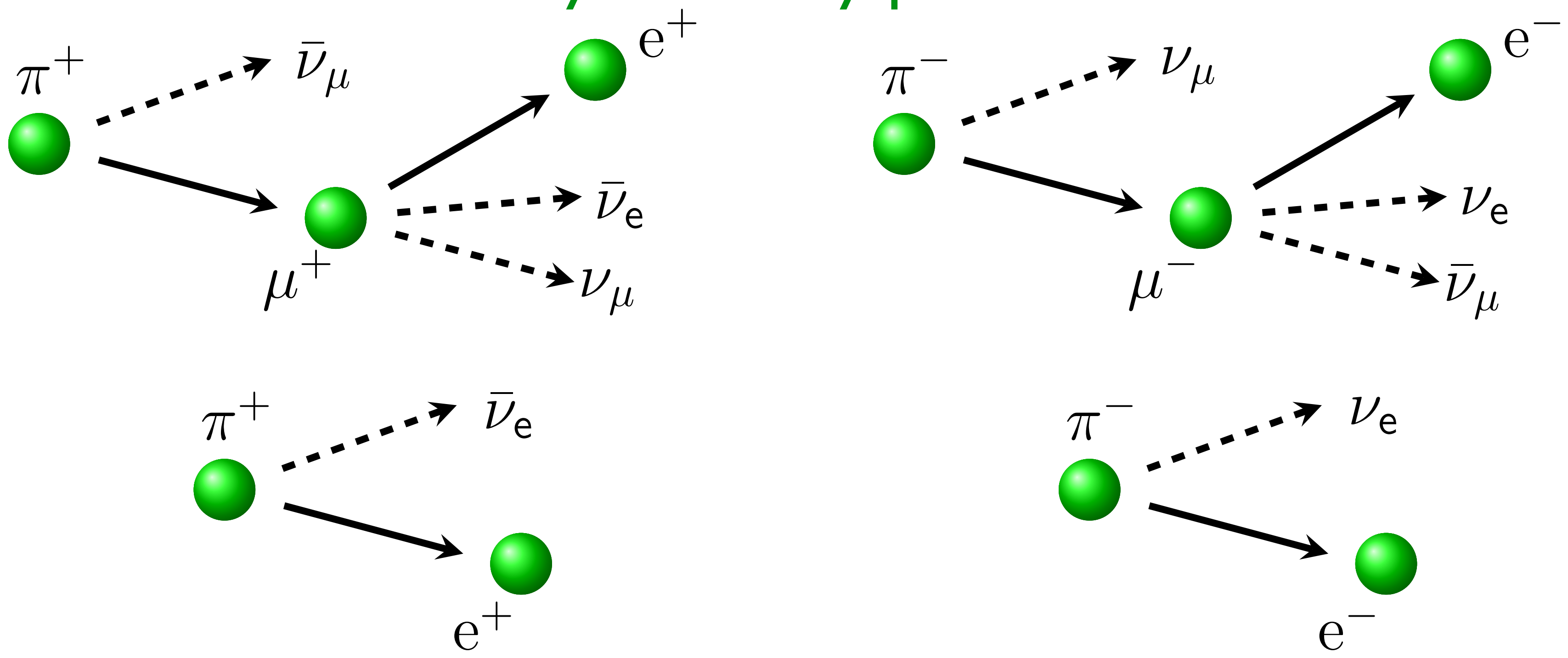
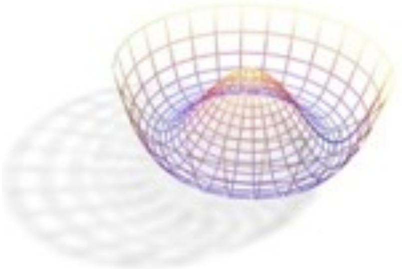


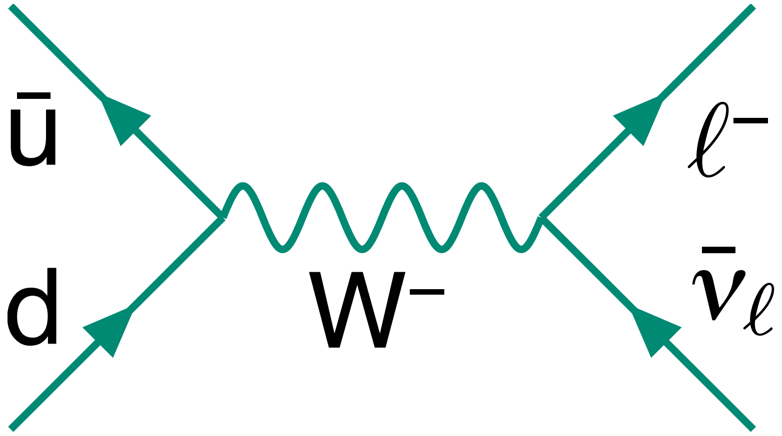
- Truly a weak interaction:
  - solar ν flux on Earth: ~ $6 \cdot 10^{14}$ m^{-2} s^{-1}
  - during your lifetime, at most a few will interact with your body at all!

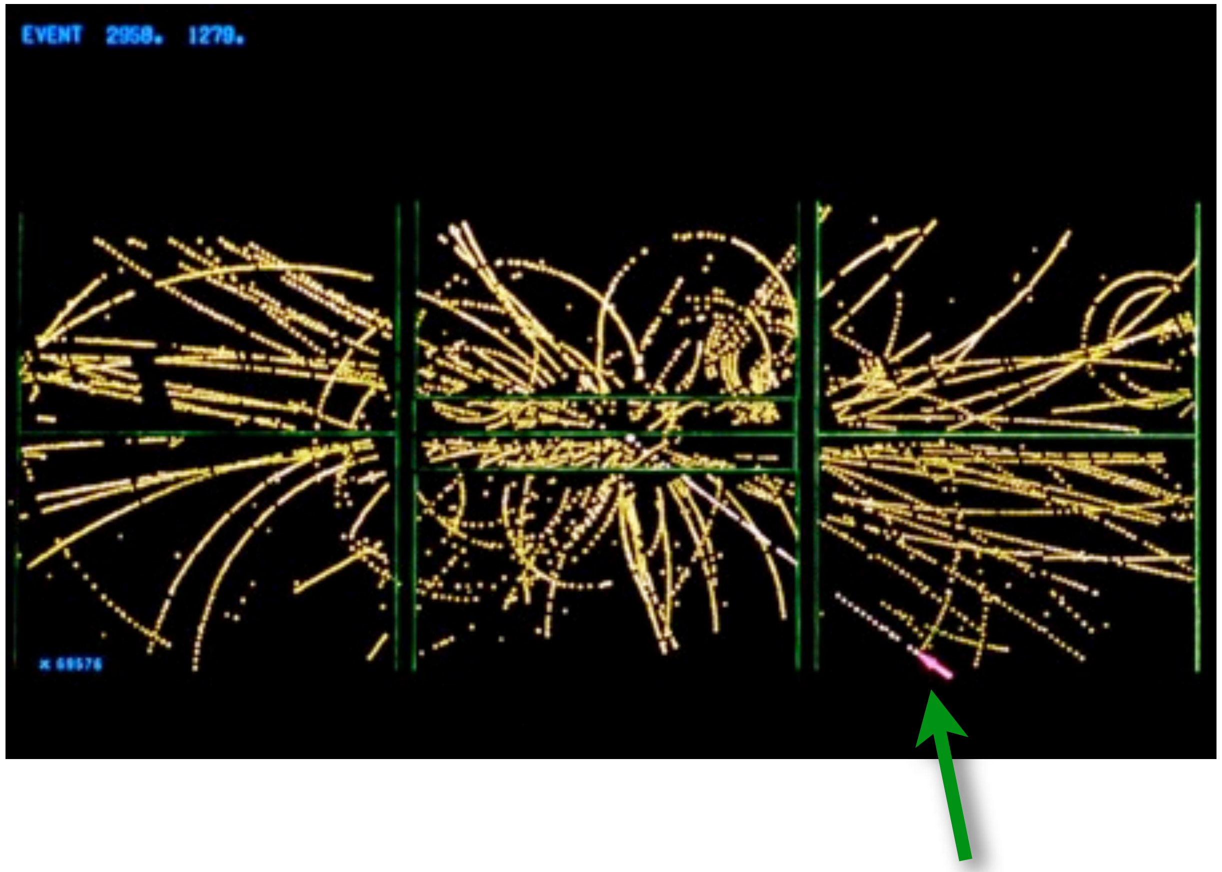
The Weak Interaction



Exchange / production of heavy particles!

W-boson production (and decay)





$e^\pm$

W and Z particles are heavy!

- M_W = 80.398(25) GeV (~ Sr, Kr)
- M_Z = 92.188(2) GeV (~ Ru)

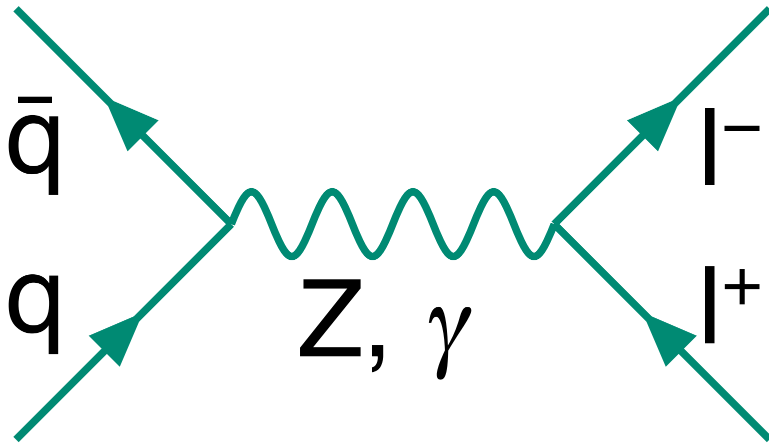
Discovered in p-$\bar{p}$ collisions, E_{CM} = 630 GeV

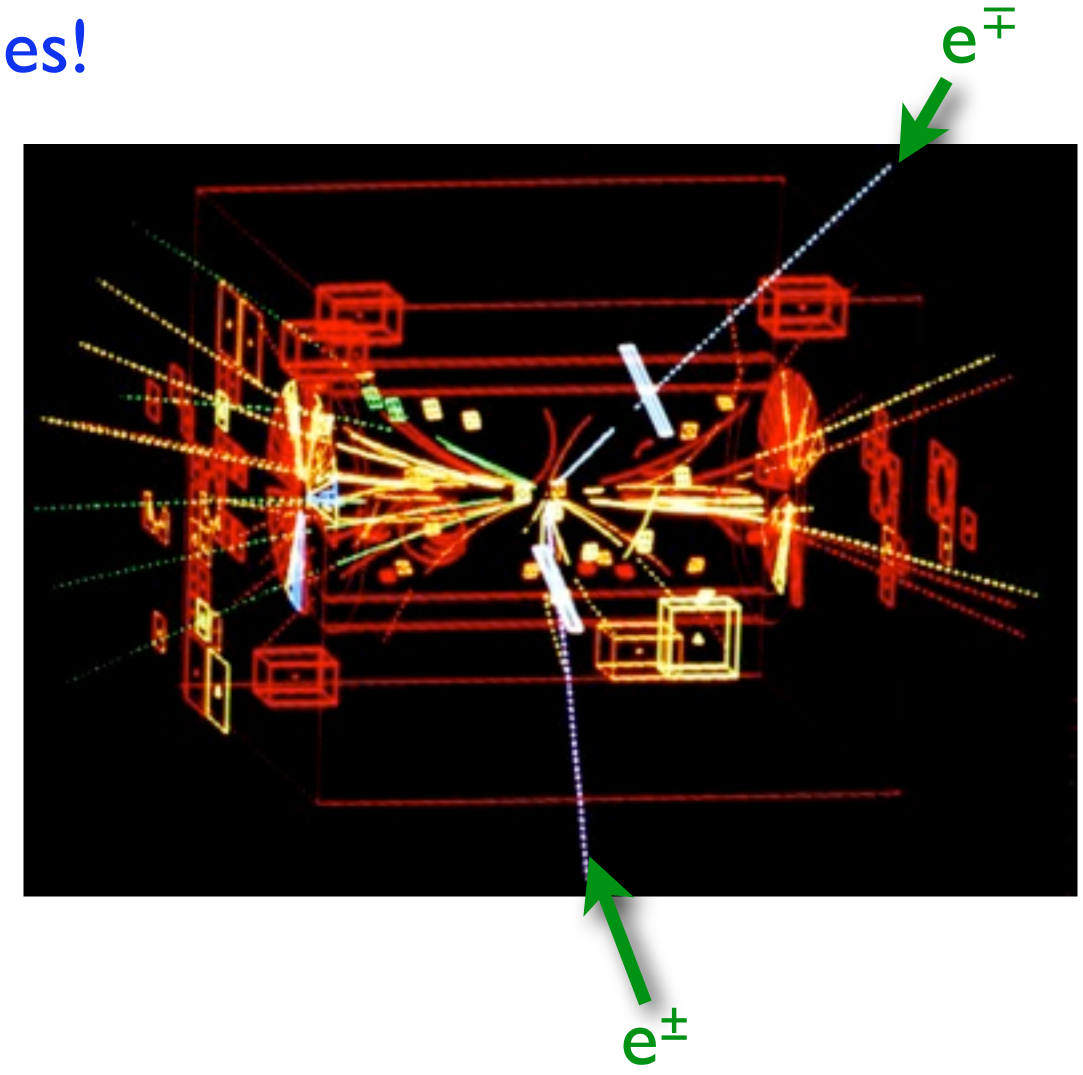
Most collisions between protons involve the strong interaction ➡ look for leptons (only EM and weak interactions)

The Weak Interaction

Exchange / production of heavy particles!

Z-boson production and decay





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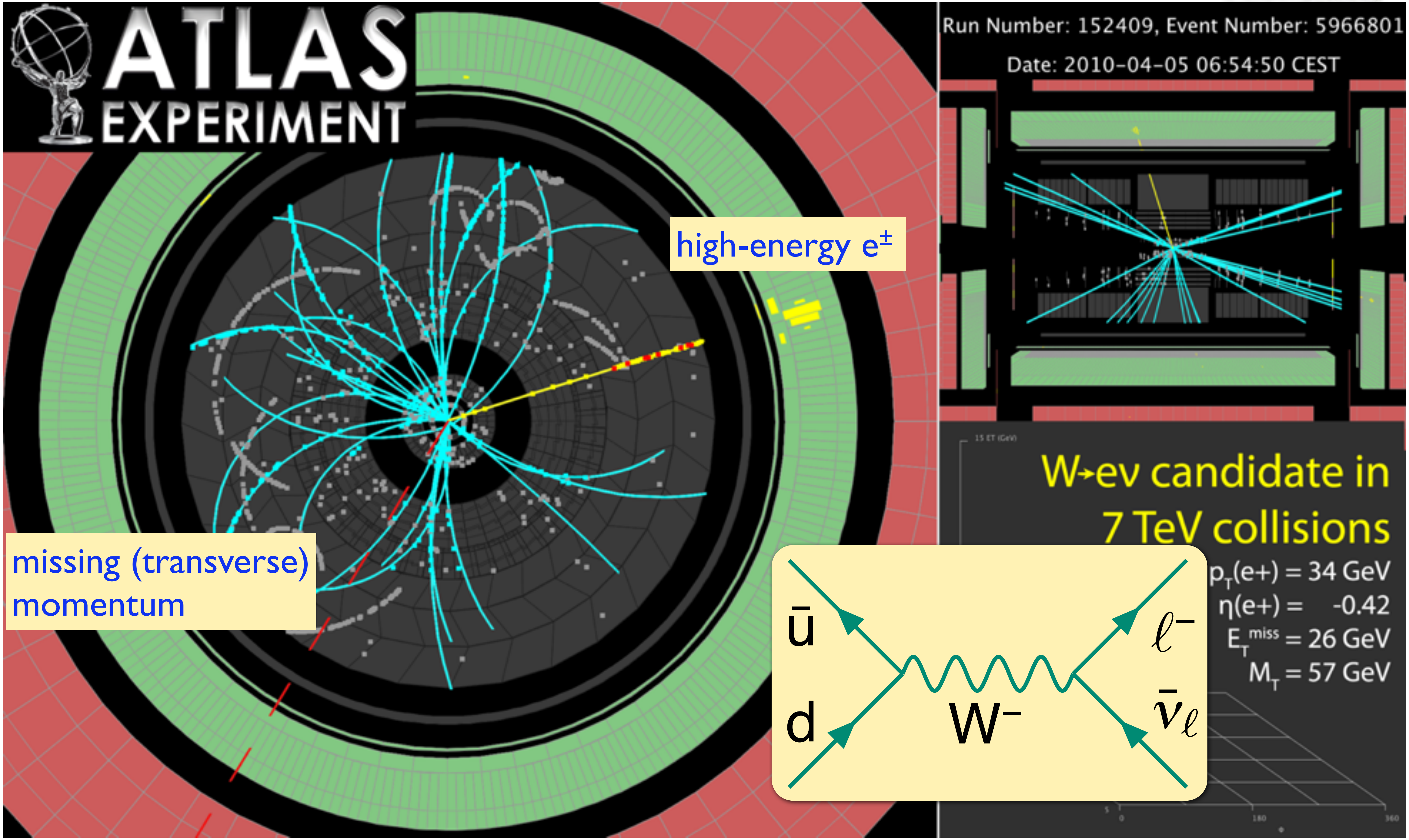
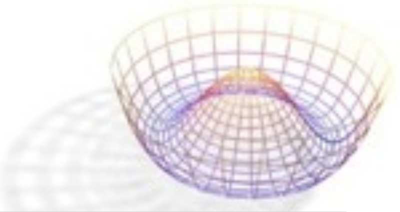
The Weak Interaction: W Boson



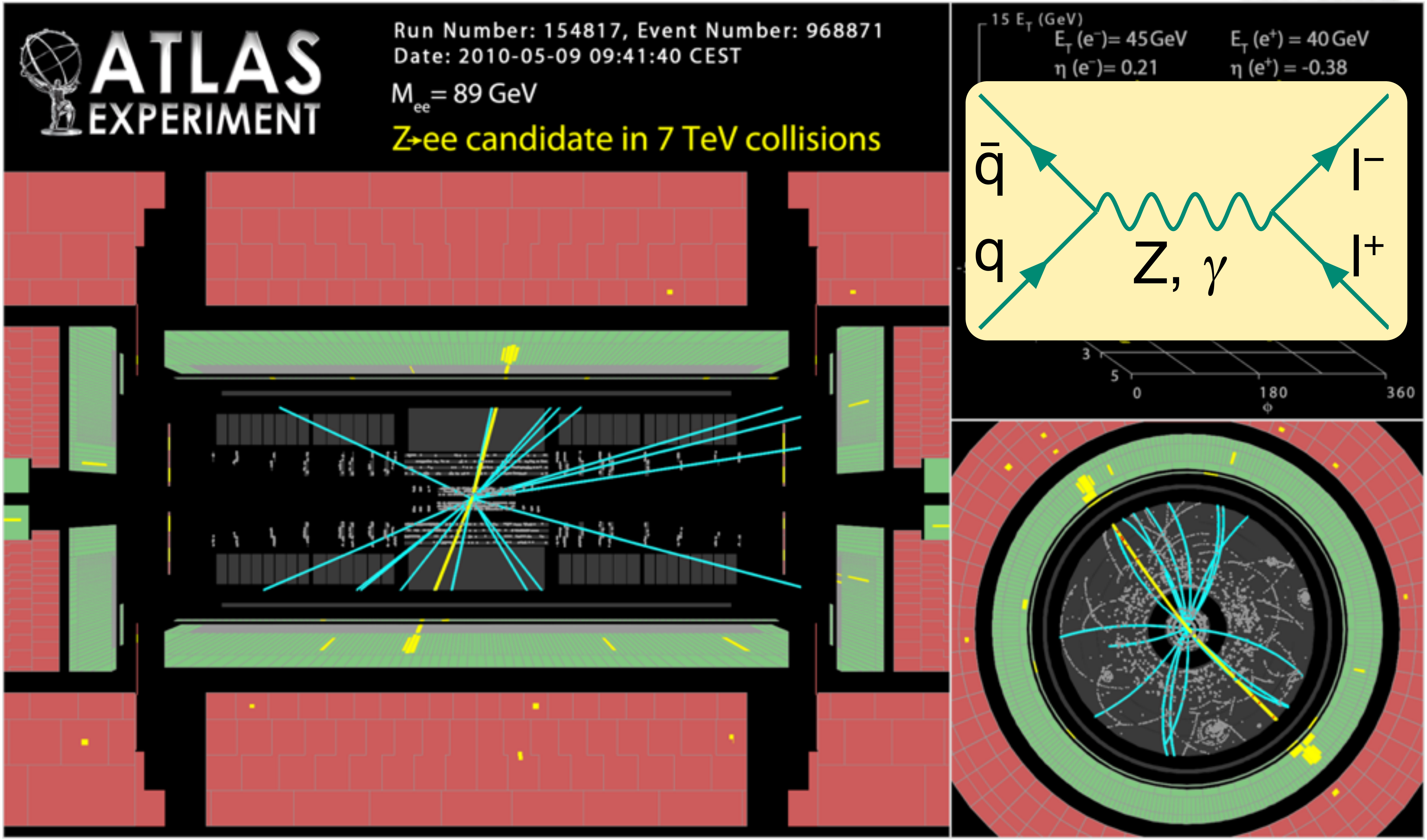
high-energy e±

missing (transverse) momentum

$M_W = 80.387 \pm 0.017$ GeV (~ krypton)

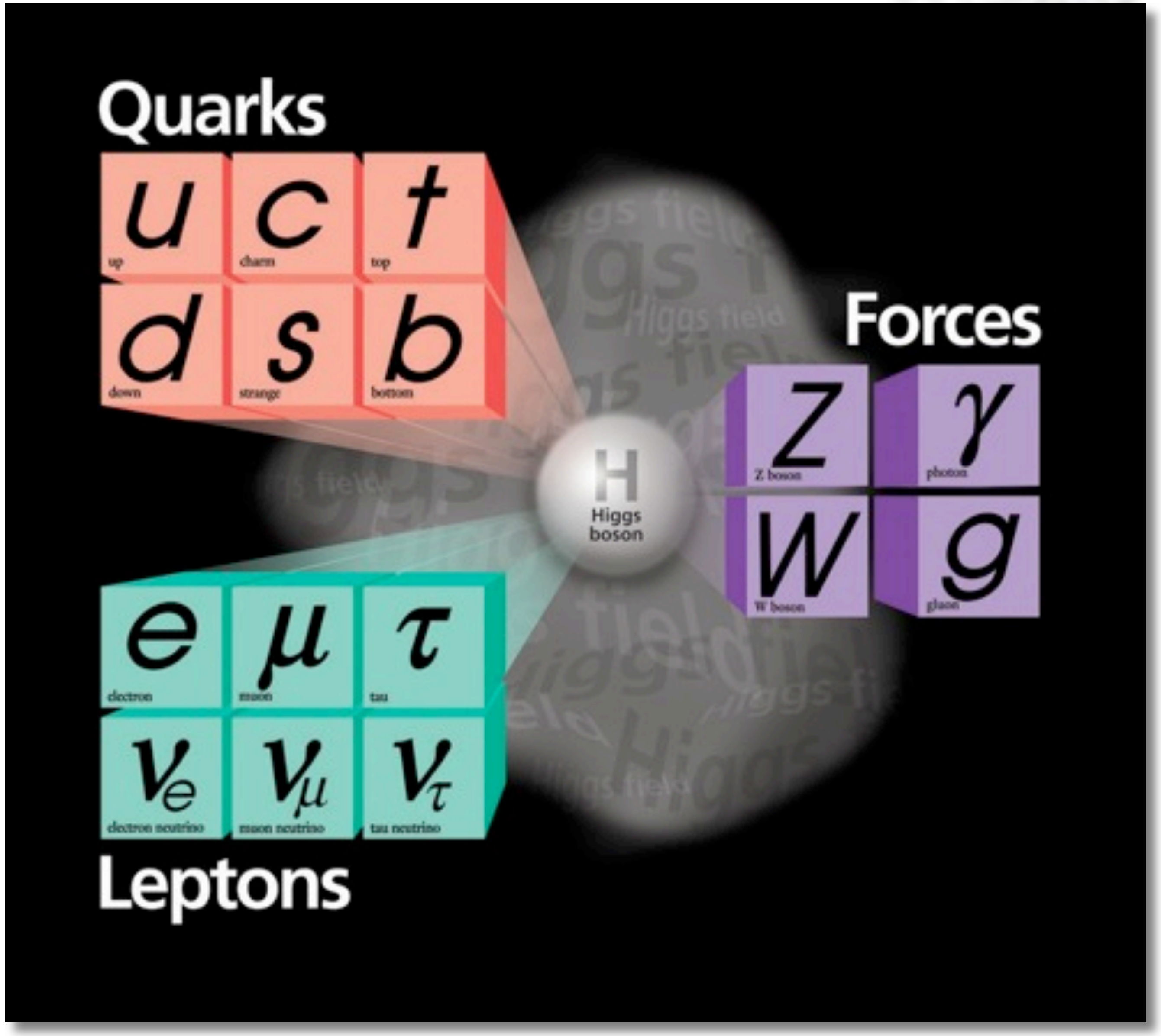


The Weak Interaction: Z Boson



M_Z = 91.188 ± 0.002 GeV (~ rubidium)

The Particle Family



“Leptons”??

- particles not involved in the strong interaction (only weak, EM)
- also heavier counterparts of the electron and its neutral partner, ν_e

Quarks:

- particles also susceptible to the strong interaction
- again, 3 “generations” involving heavier partners than the u, d that are constituents of the proton

Force carriers:

- photon (EM), W/Z (weak interaction), gluon(s) (strong interaction)

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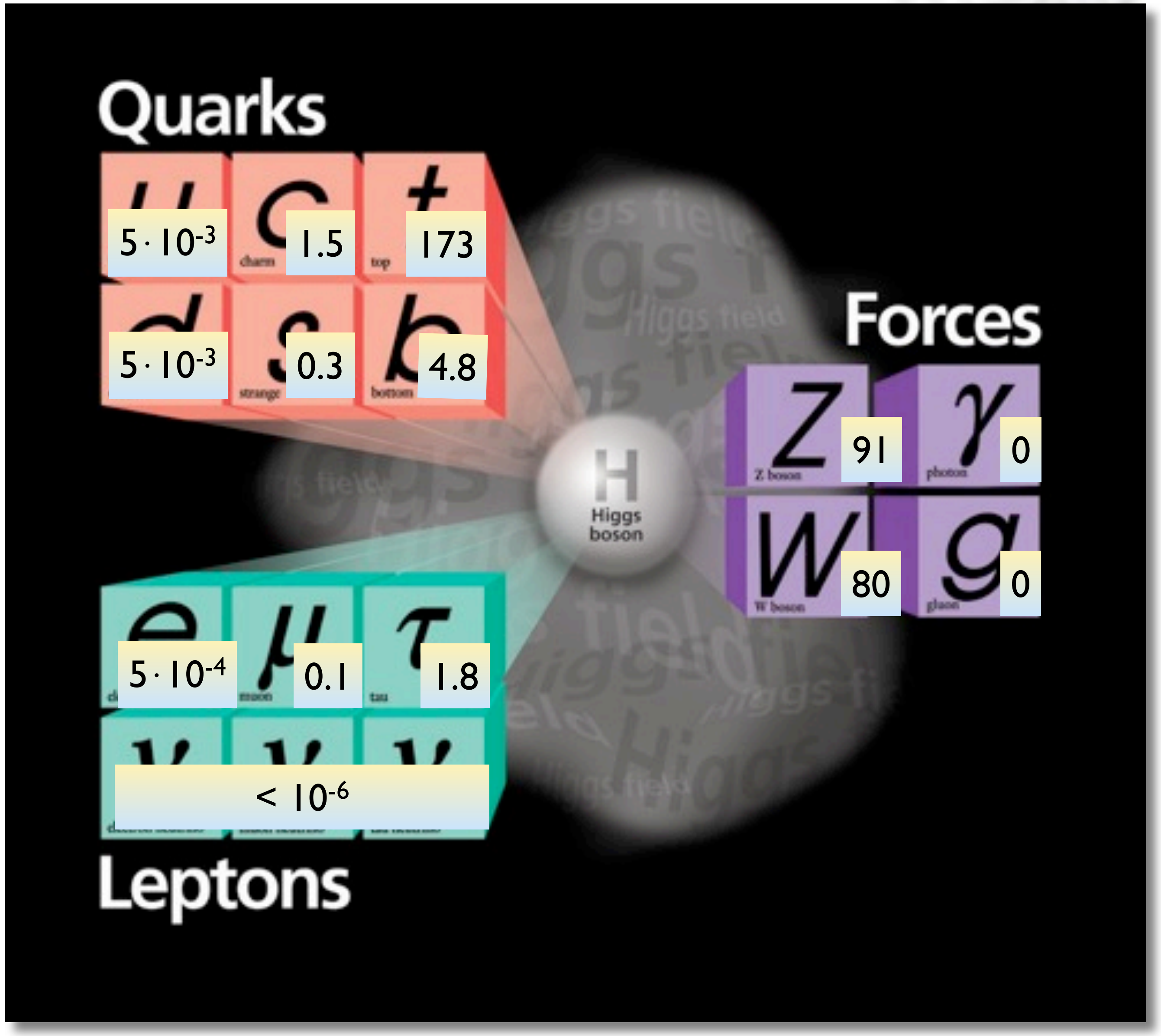

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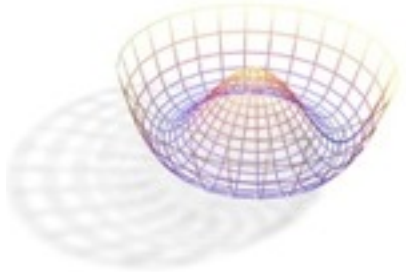
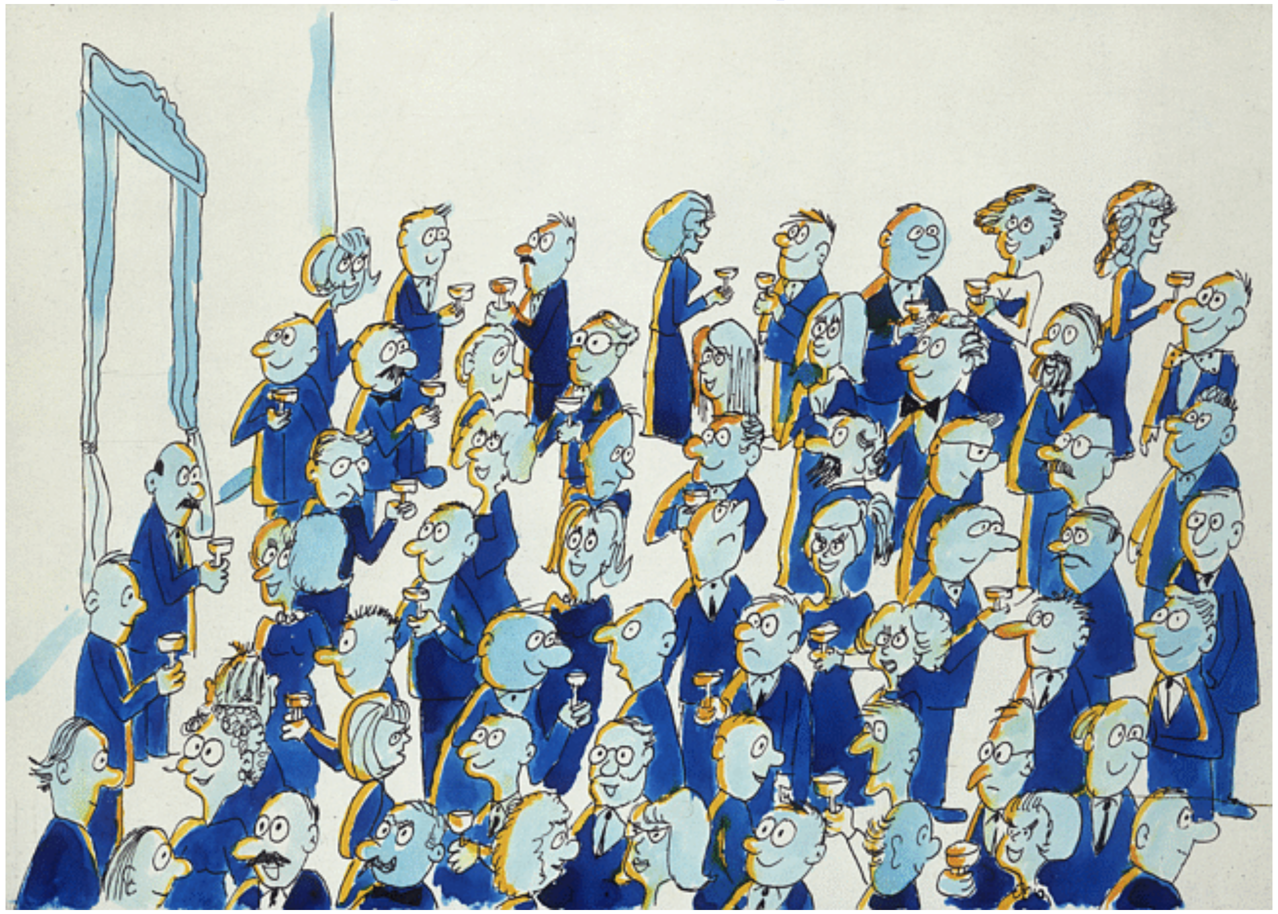
The Higgs Mechanism



Particles become "effectively" massive by means of their interaction with the Higgs field!



More physical analogy: refractive index

- caused by different speed of light in medium
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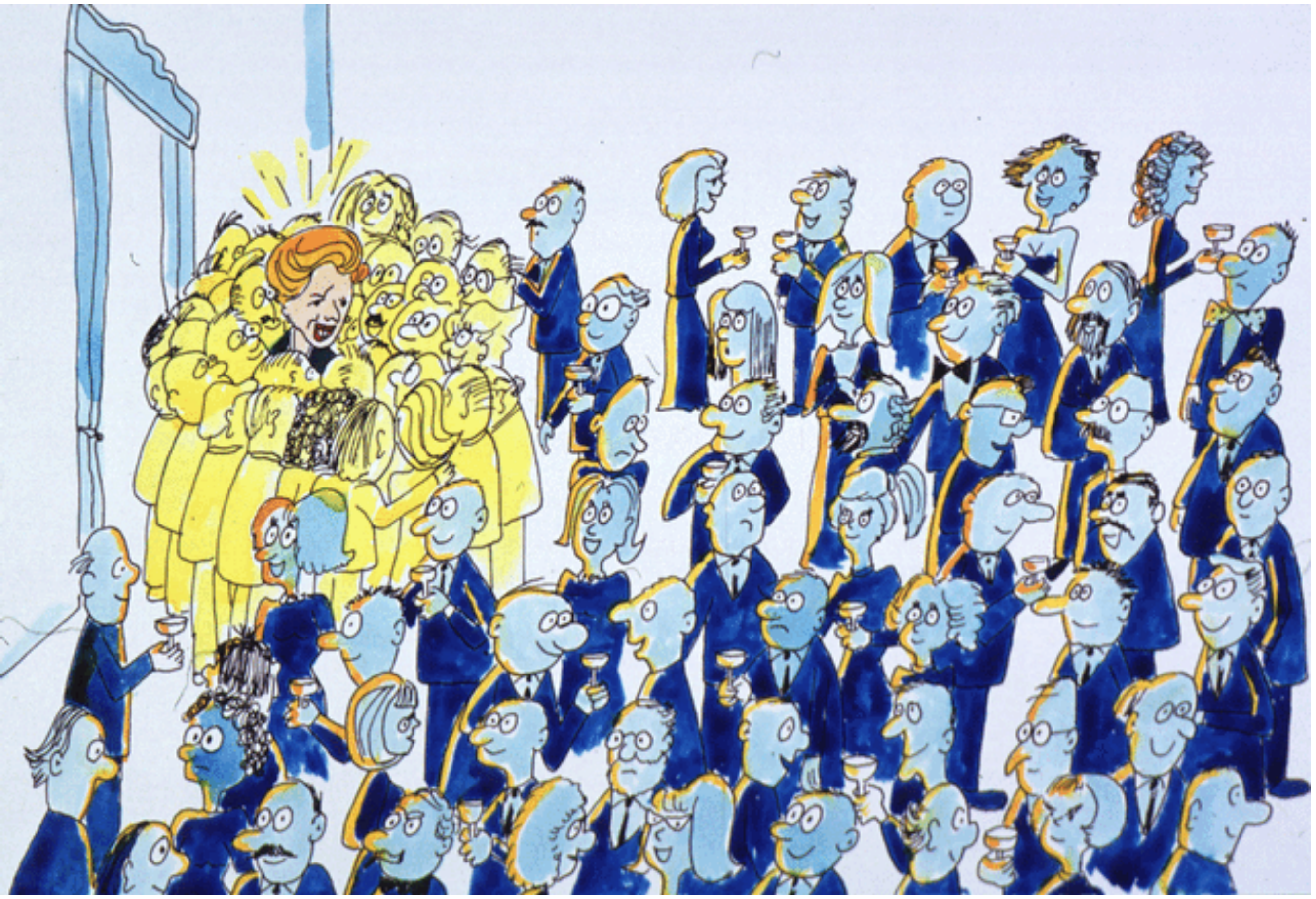

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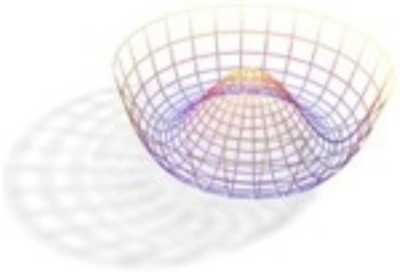

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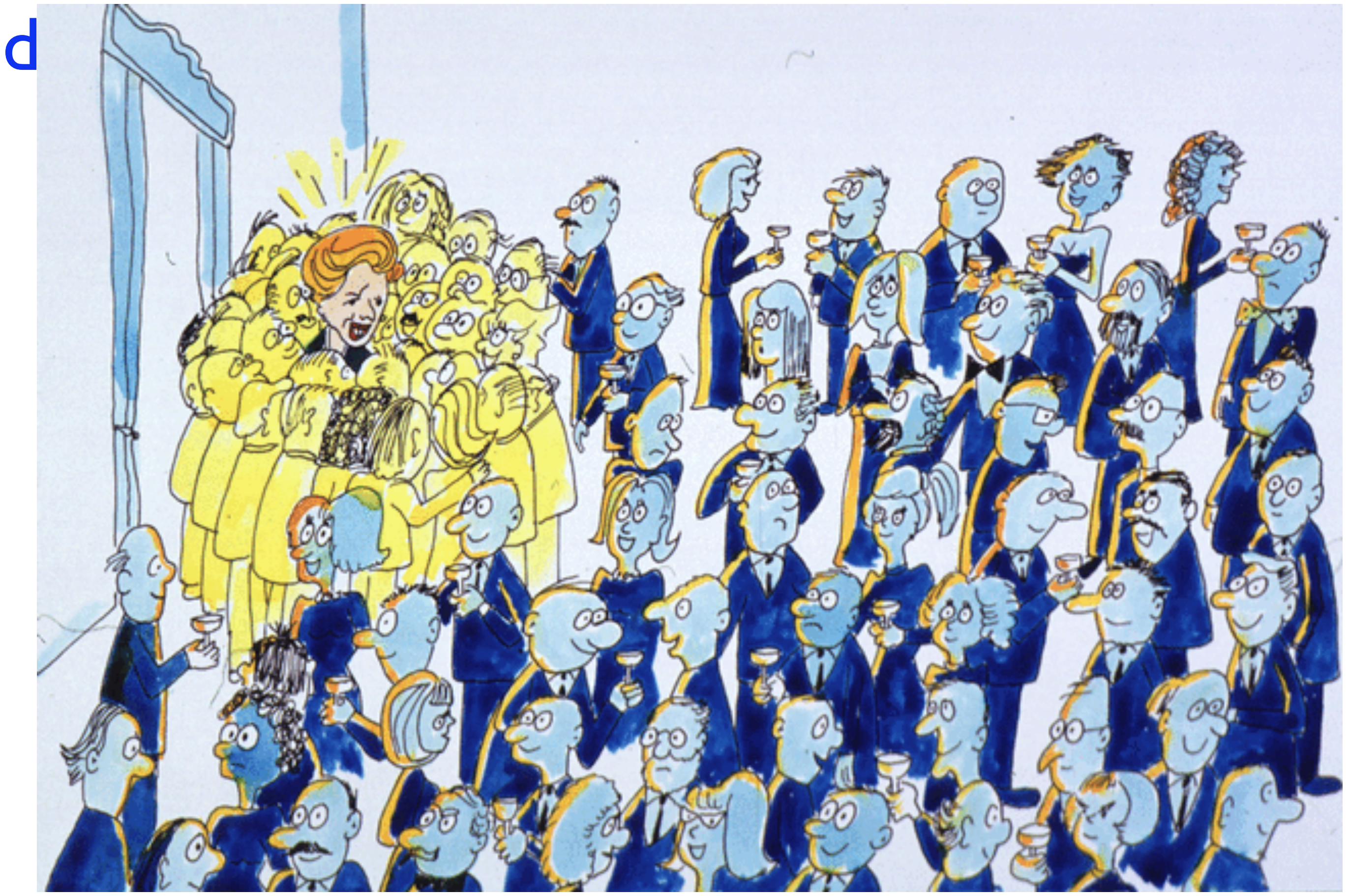

More physical analogy: refractive index

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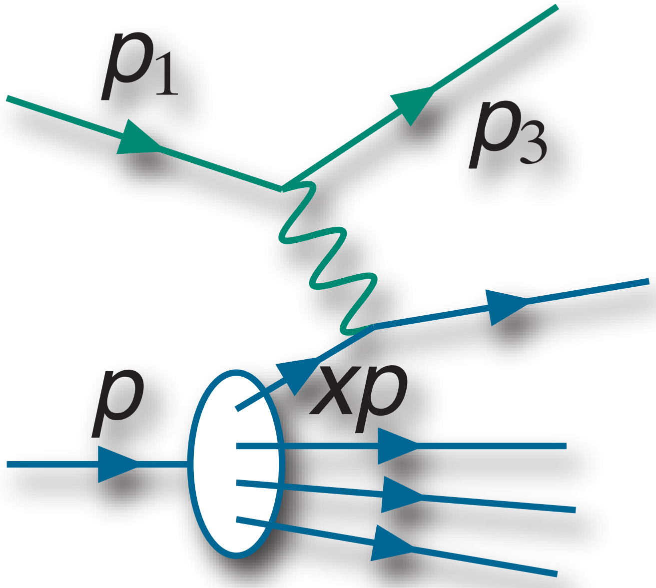
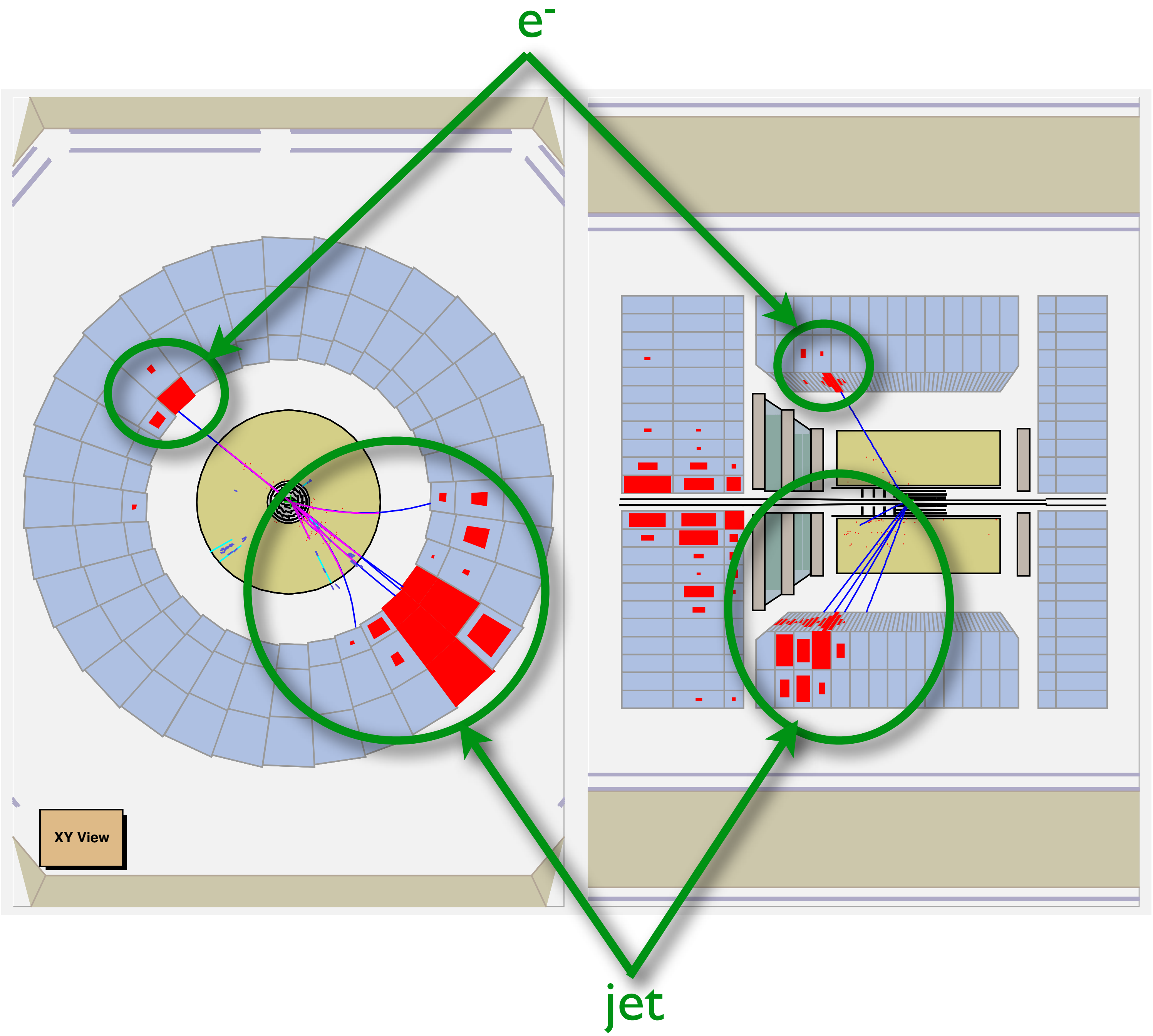
Photons in the medium are effectively massive

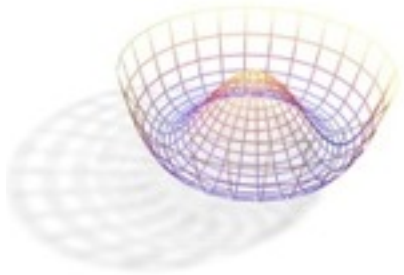
QCD at High Energies

At high energies, quarks and gluons do manifest themselves as “free” particles → hadron jets



electron-proton scattering:
27.5 GeV + 920 GeV





A Weighty Issue...

QED, QCD: photon & gluons are strictly massless

Weak interaction:

- massive W and Z bosons
- fermion masses: $m_\ell \neq m_{\nu_\ell}$ (and similarly for quarks)

A Weighty Issue...

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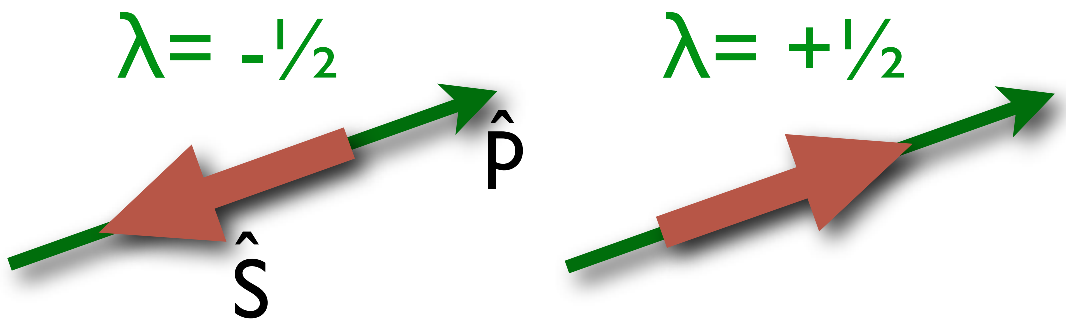
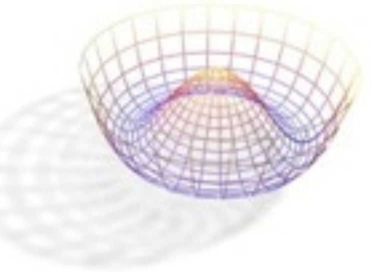
And worse!

- W-boson deals with left-handed fermions (right-handed anti-fermions) only



- left- and right-handed fermions should be different particles
- this requires them to be strictly massless

The Higgs Mechanism to the Rescue



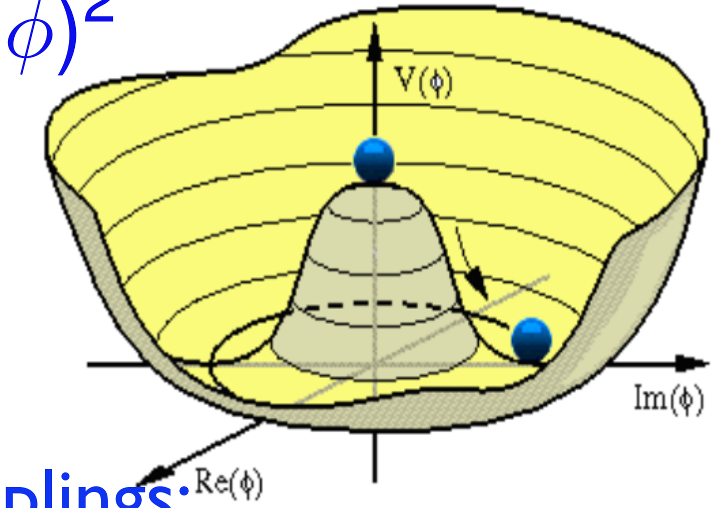
Required: a mechanism to break the EW symmetry spontaneously

- Lagrangian maintains full EW symmetry $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$
- but the ground state does not!

Achieved through the introduction of the (complex scalar) Higgs field

$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \qquad V_\phi = \mu(\phi^\dagger \phi) + \lambda(\phi^\dagger \phi)^2$$

- With $\mu < 0$: minimum at $\phi \neq 0$

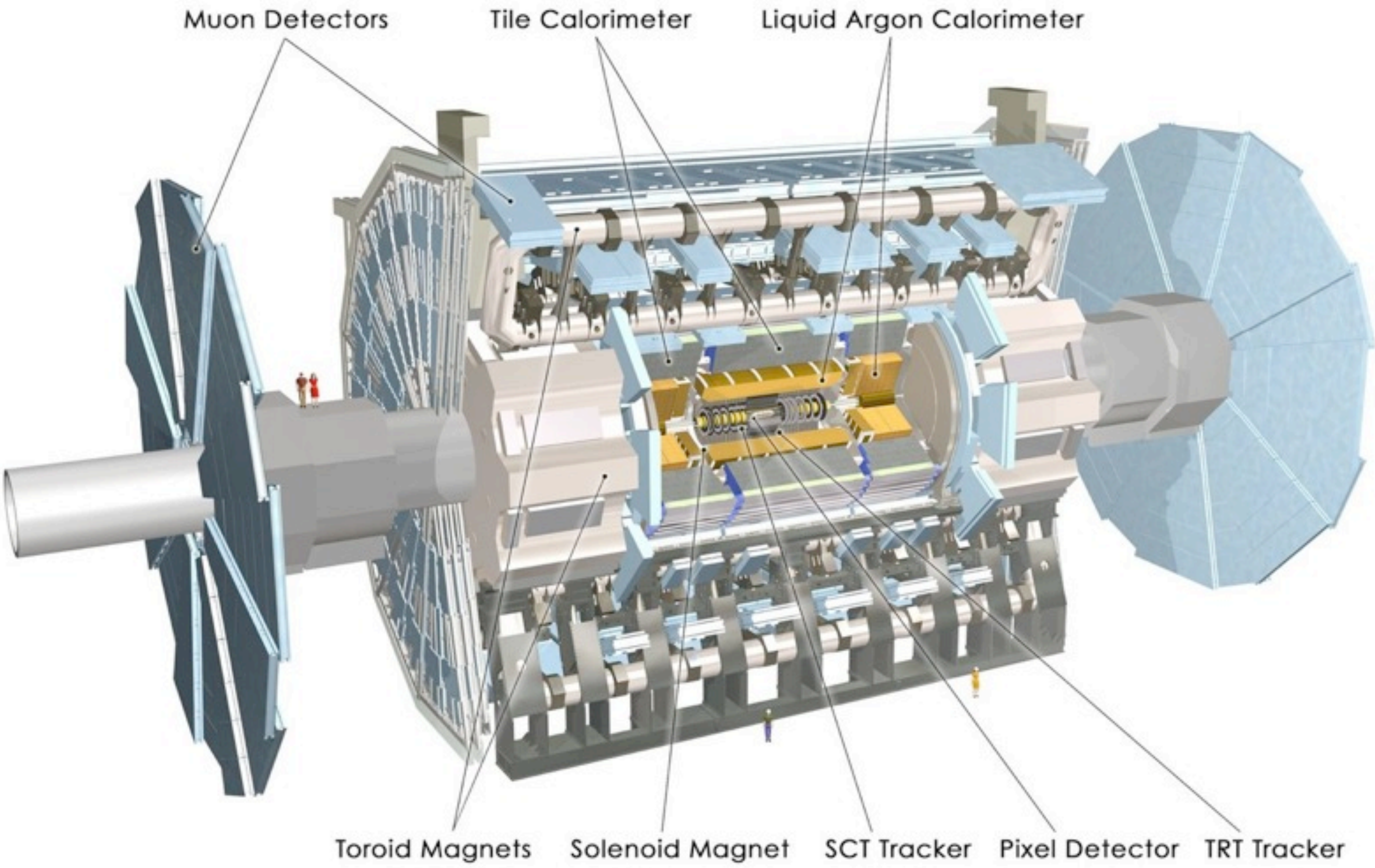


Generation of fermion masses through "Yukawa" couplings:

$$\begin{aligned} \mathcal{L}_Y &= -g_e \left(\overline{e_R} \phi^\dagger \psi_L + \overline{\psi_L} \phi e_R \right) \\ \left(\langle \phi \rangle = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix} \right) &\rightarrow -\frac{g_e v}{\sqrt{2}} \left(\overline{e_R} e_L + \overline{e_L} e_R \right) = -\frac{g_e v}{\sqrt{2}} \overline{e} e \end{aligned}$$

The Higgs Hunters

ATLAS... and CMS

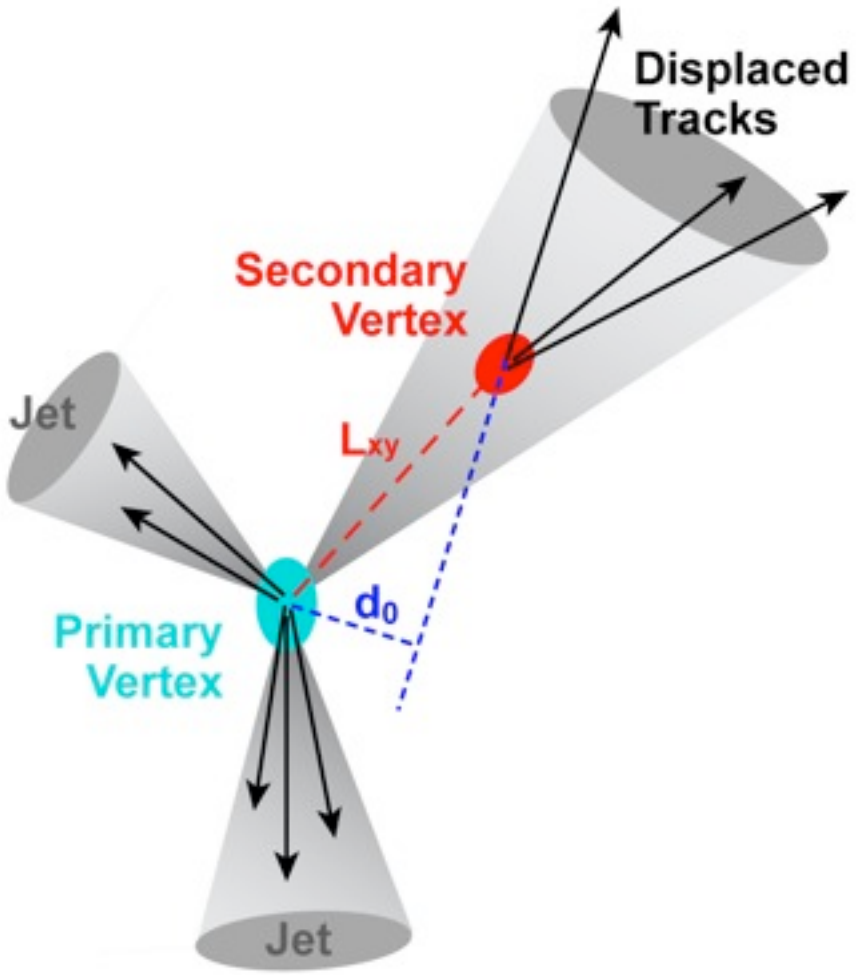


Particle Detection

Particle Detection

In addition to individually observable particles:

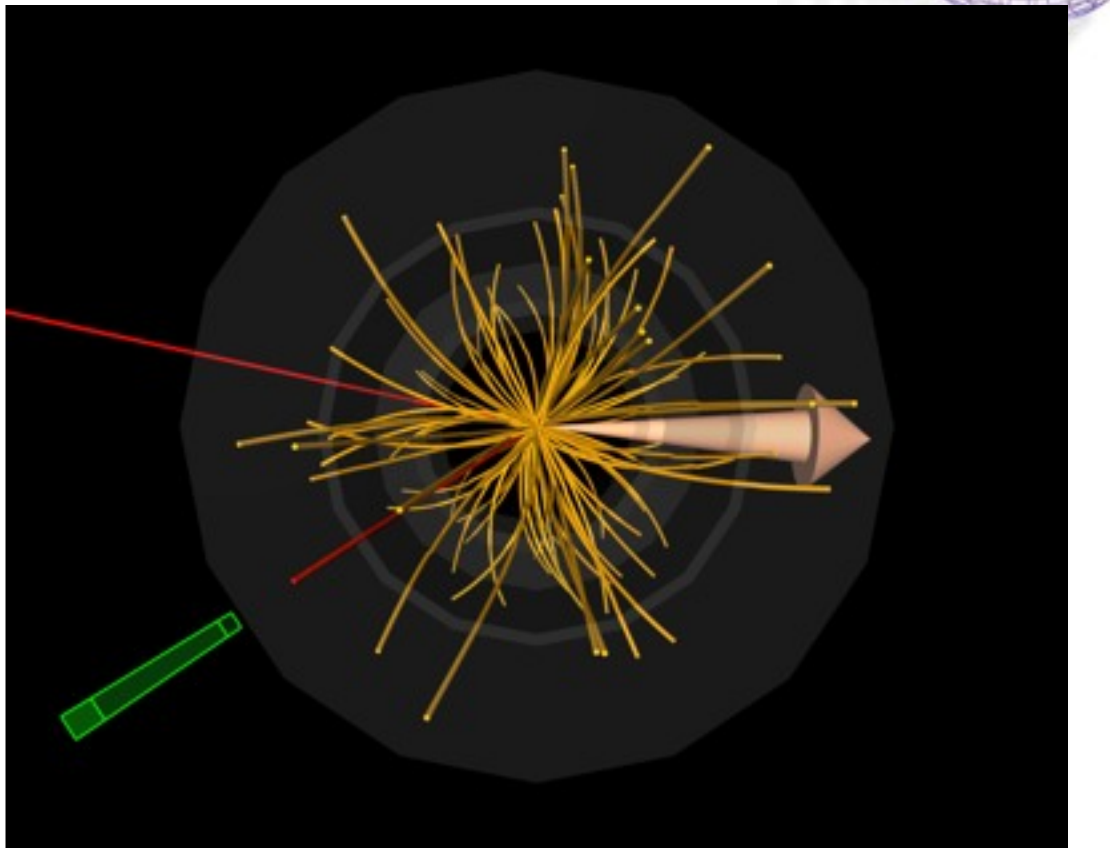
- neutrinos (from apparent lack of momentum conservation)
- hadron jets (from calorimeter energy deposits/tracks)
- τ leptons (very narrow “hadronic jet”)
- b-jets (from hadronisation of b-quarks: “long” lifetime of B-hadrons, $\tau_B \approx 1.5$ ps)

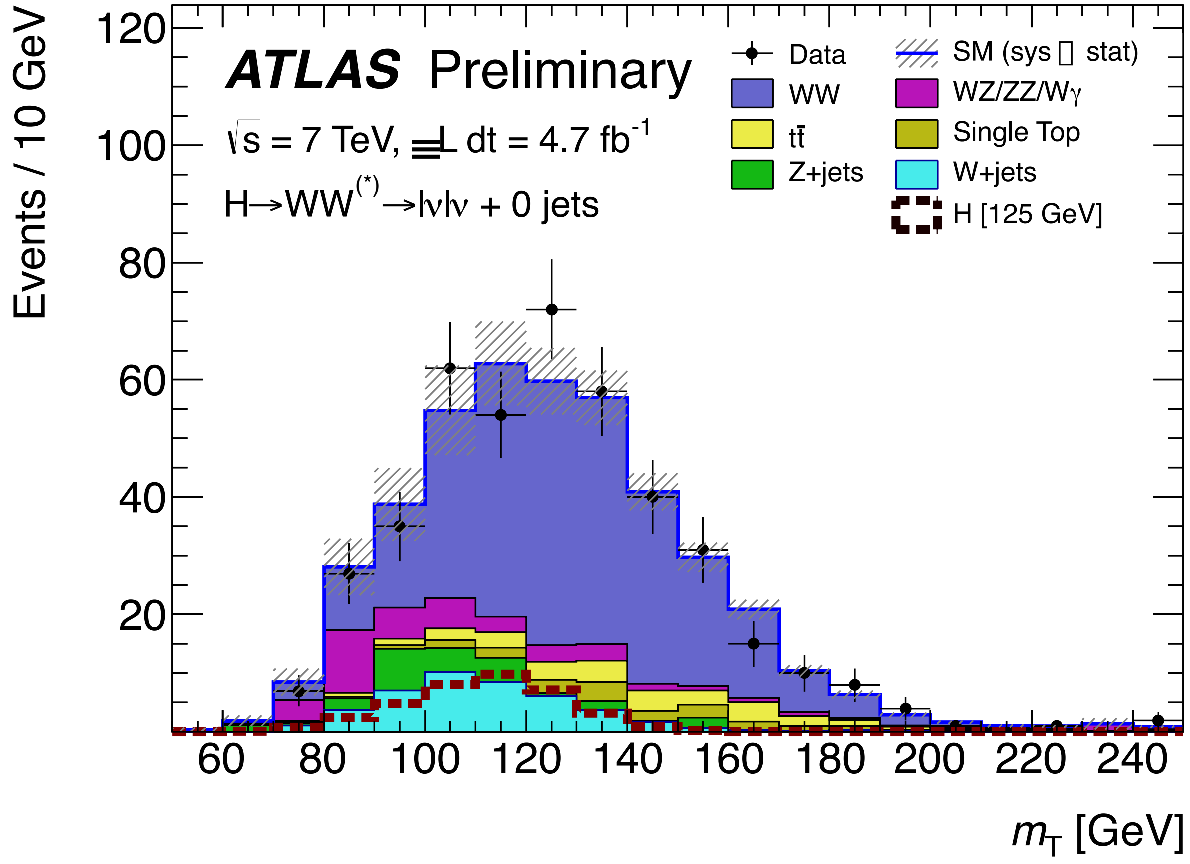


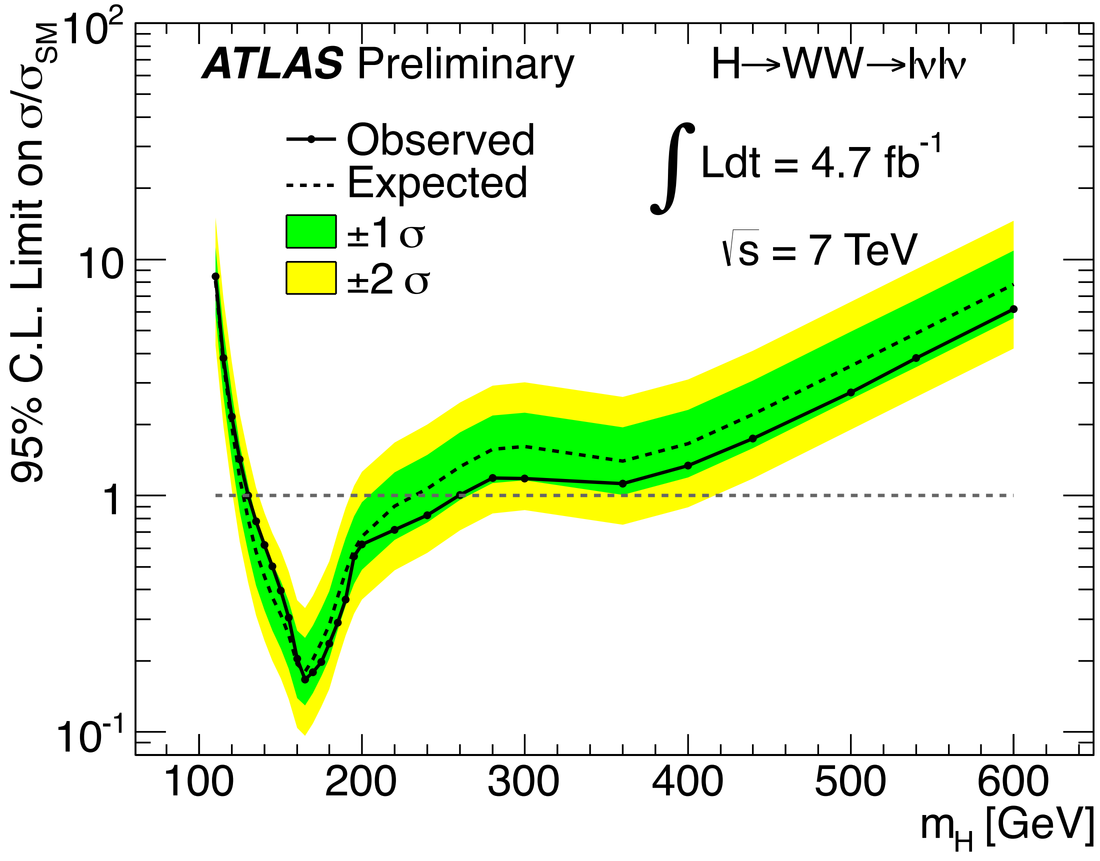
$H \to W^+W^-$

Relatively large event rate, but leptonic W boson decays lead to unobserved neutrinos

- cannot reconstruct mass of a system decaying to W^+W^-
- consider distribution of kinematic variables







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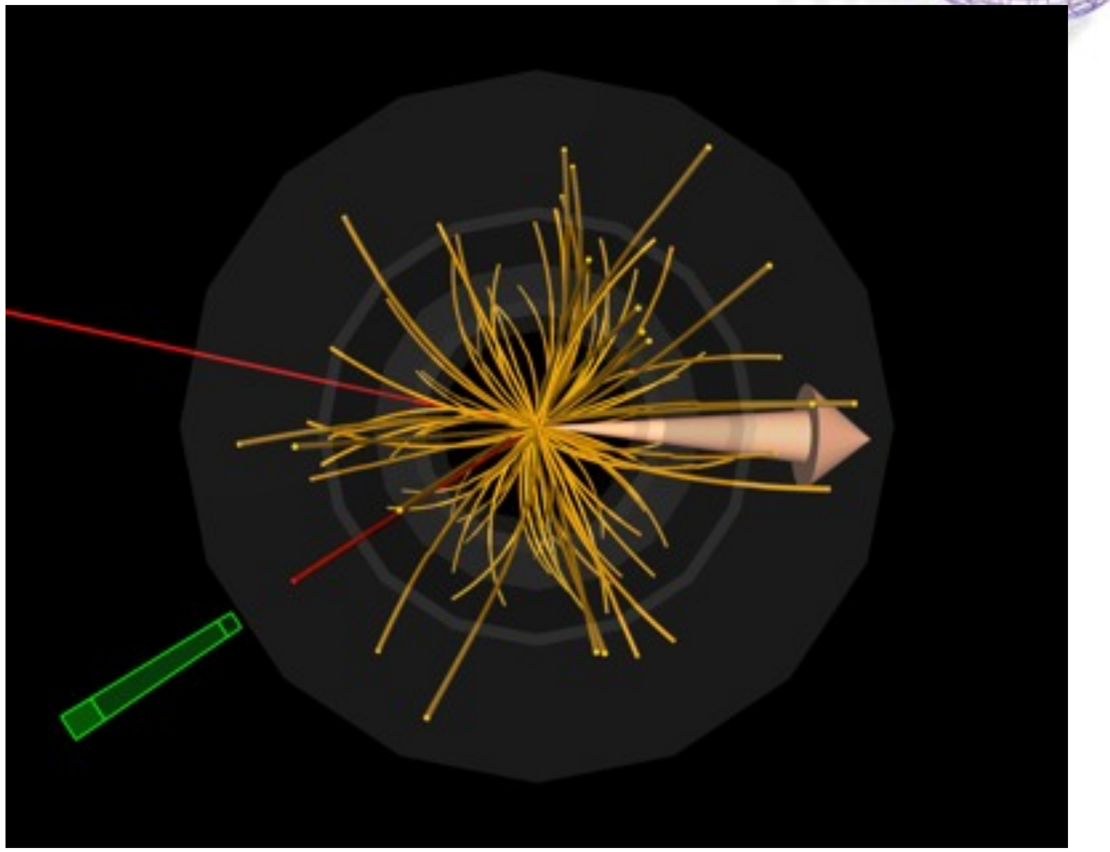
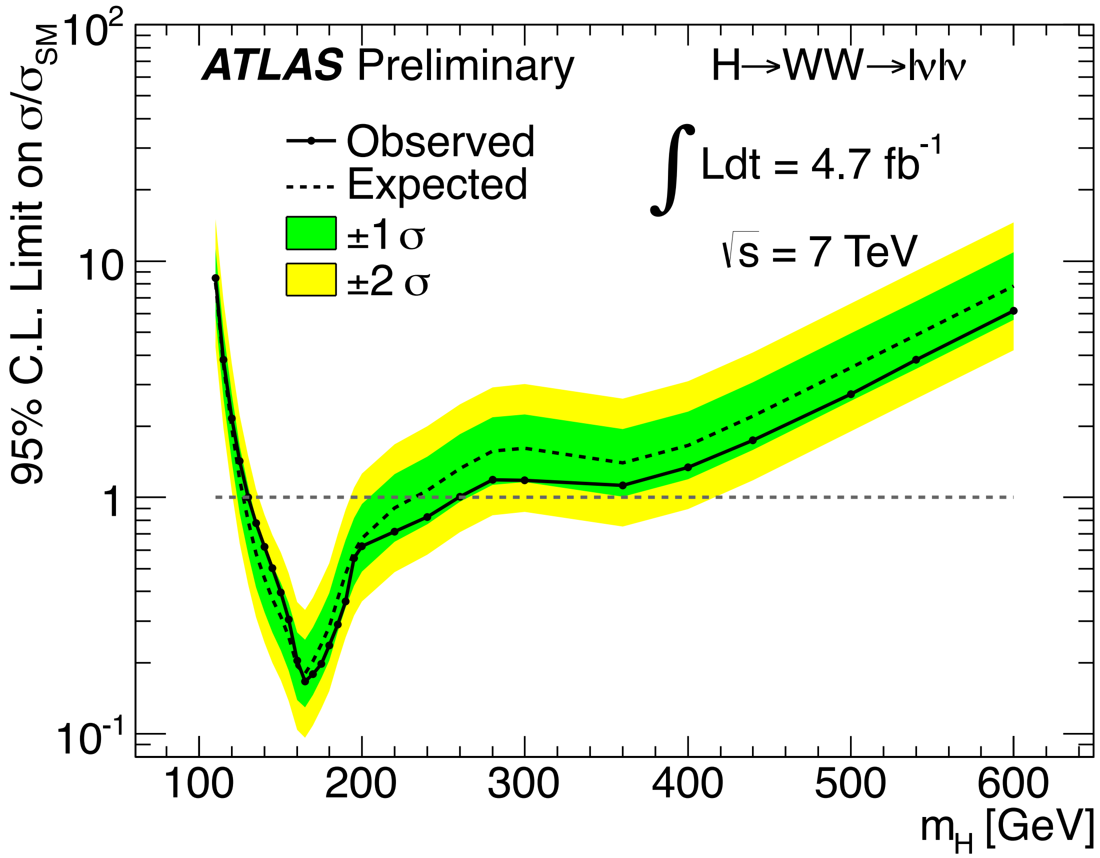
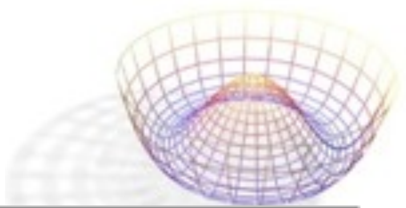


Exclude (at 95% confidence level) the Standard Model Higgs boson if 130 GeV < M_H < 260 GeV

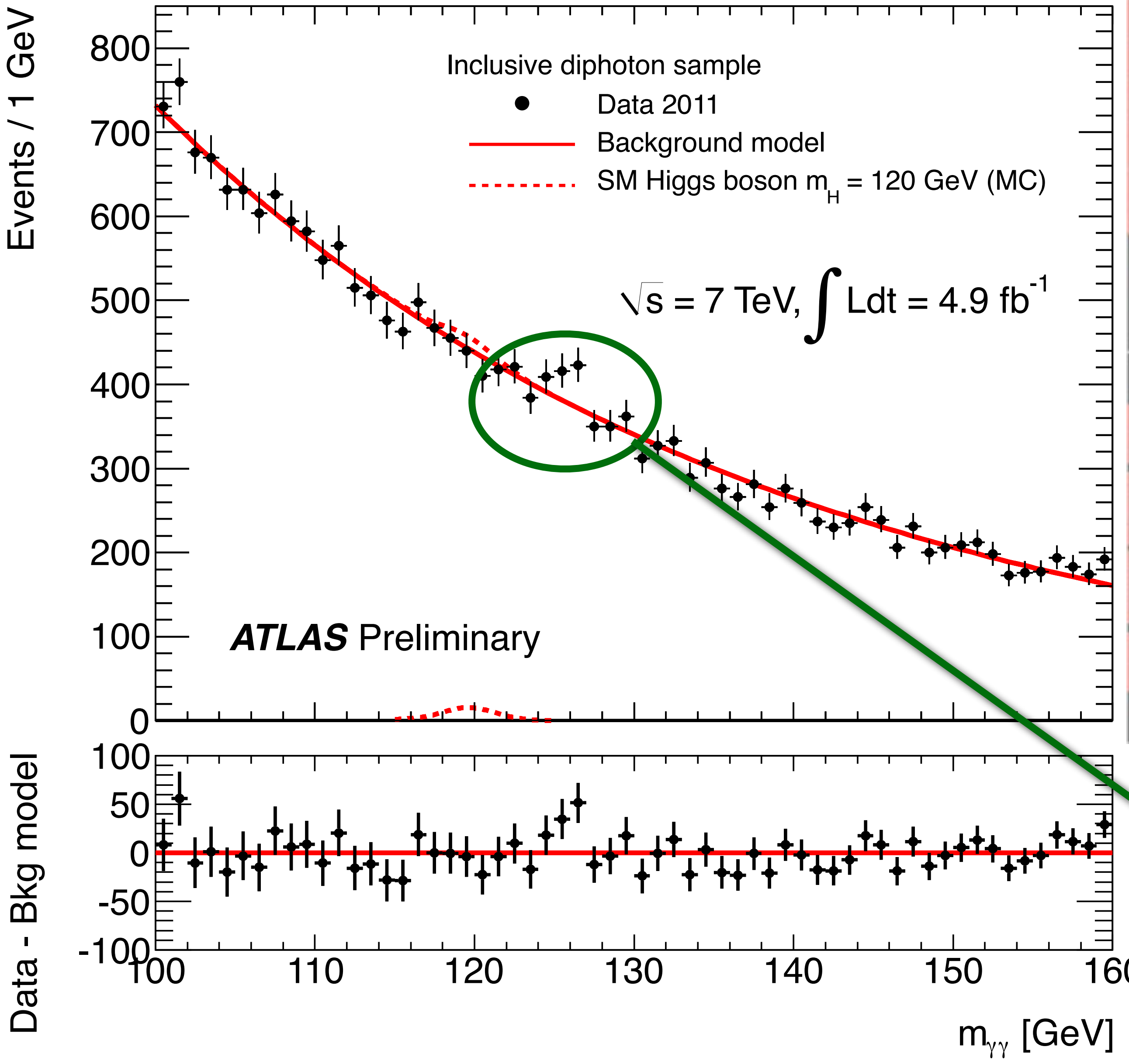


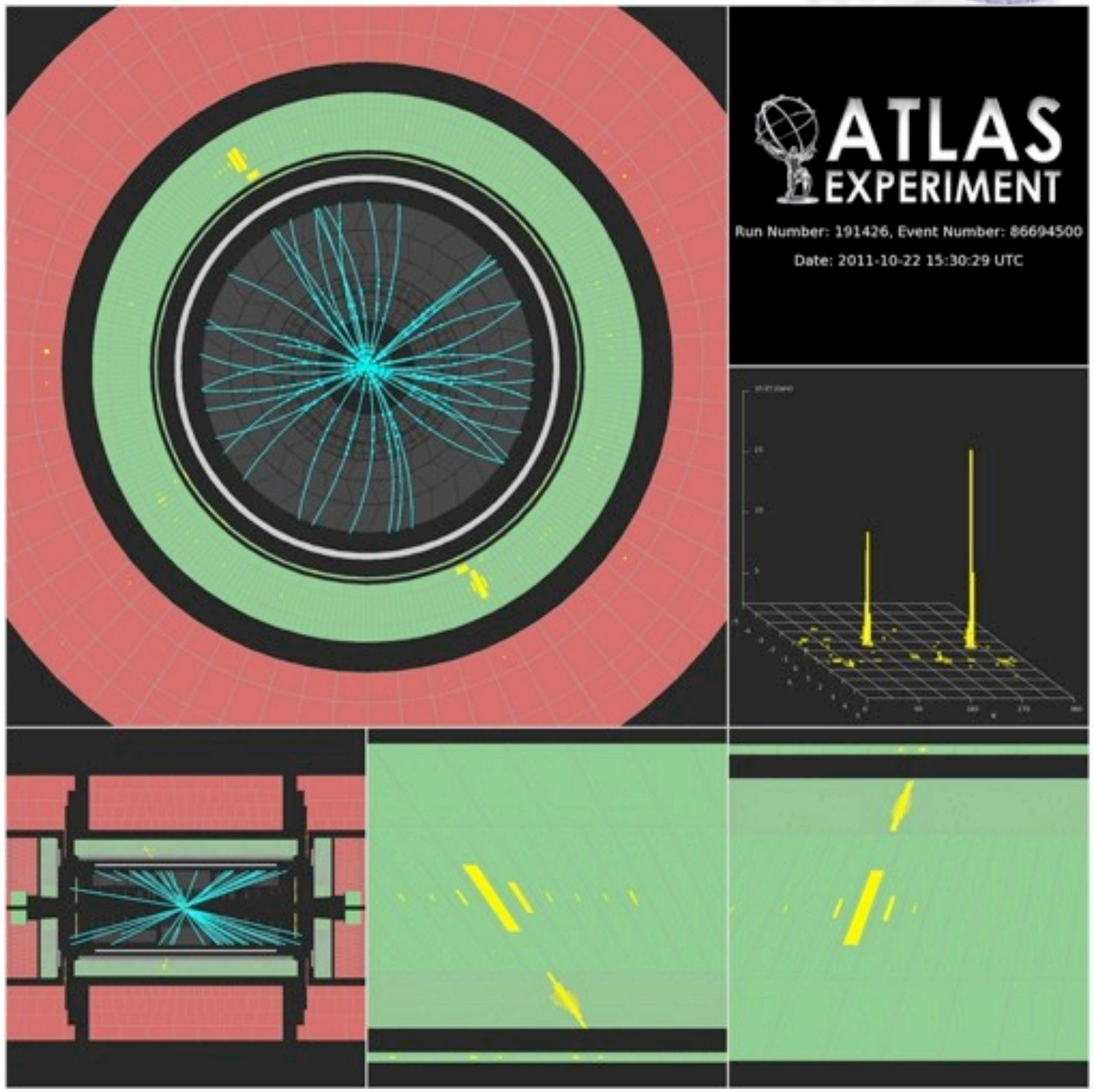


H → γγ

Requires excellent discrimination between single high-energy photons from hadrons

- but offers good energy resolution





Looking for small excess on top of large (but smooth) background

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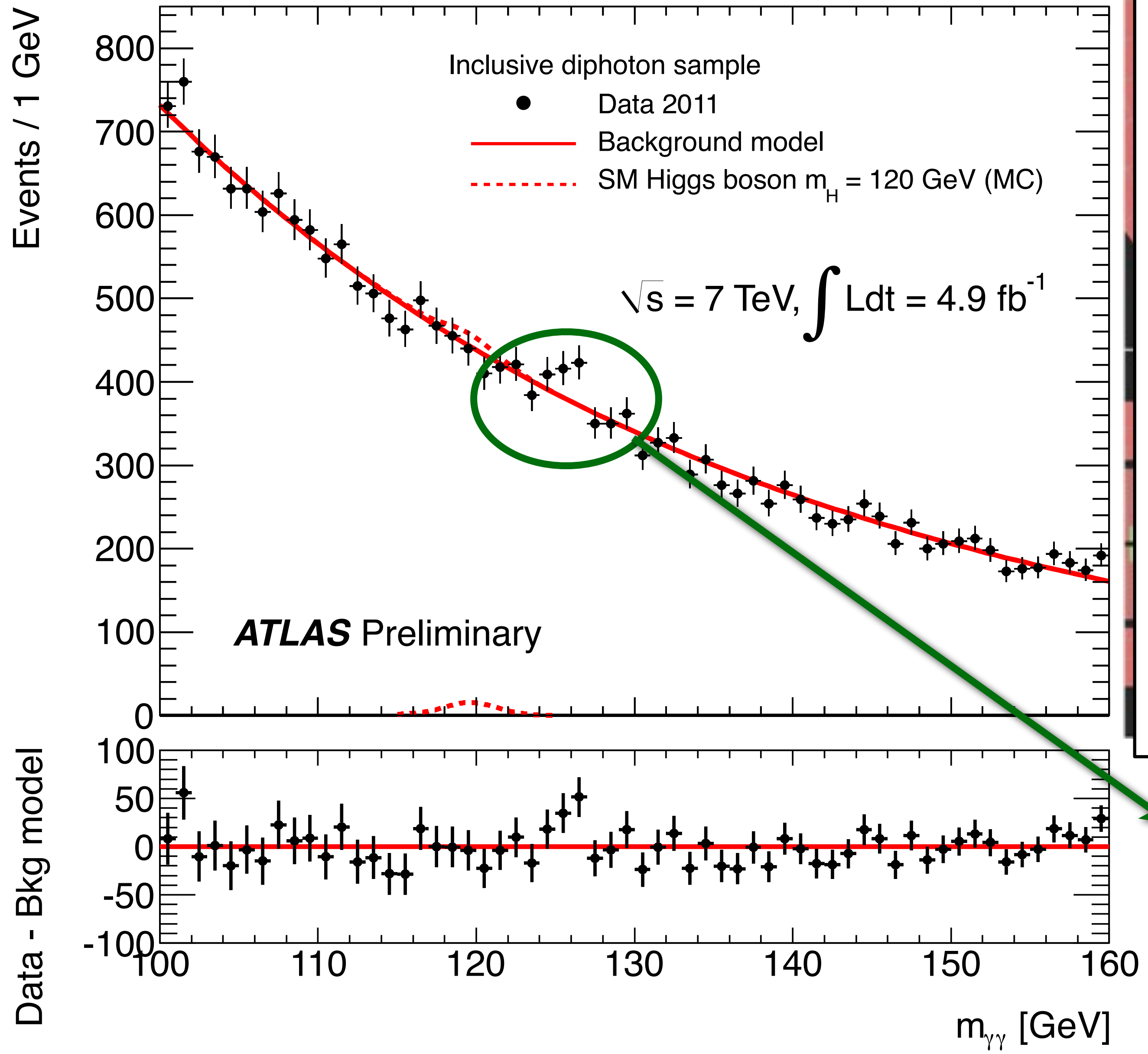
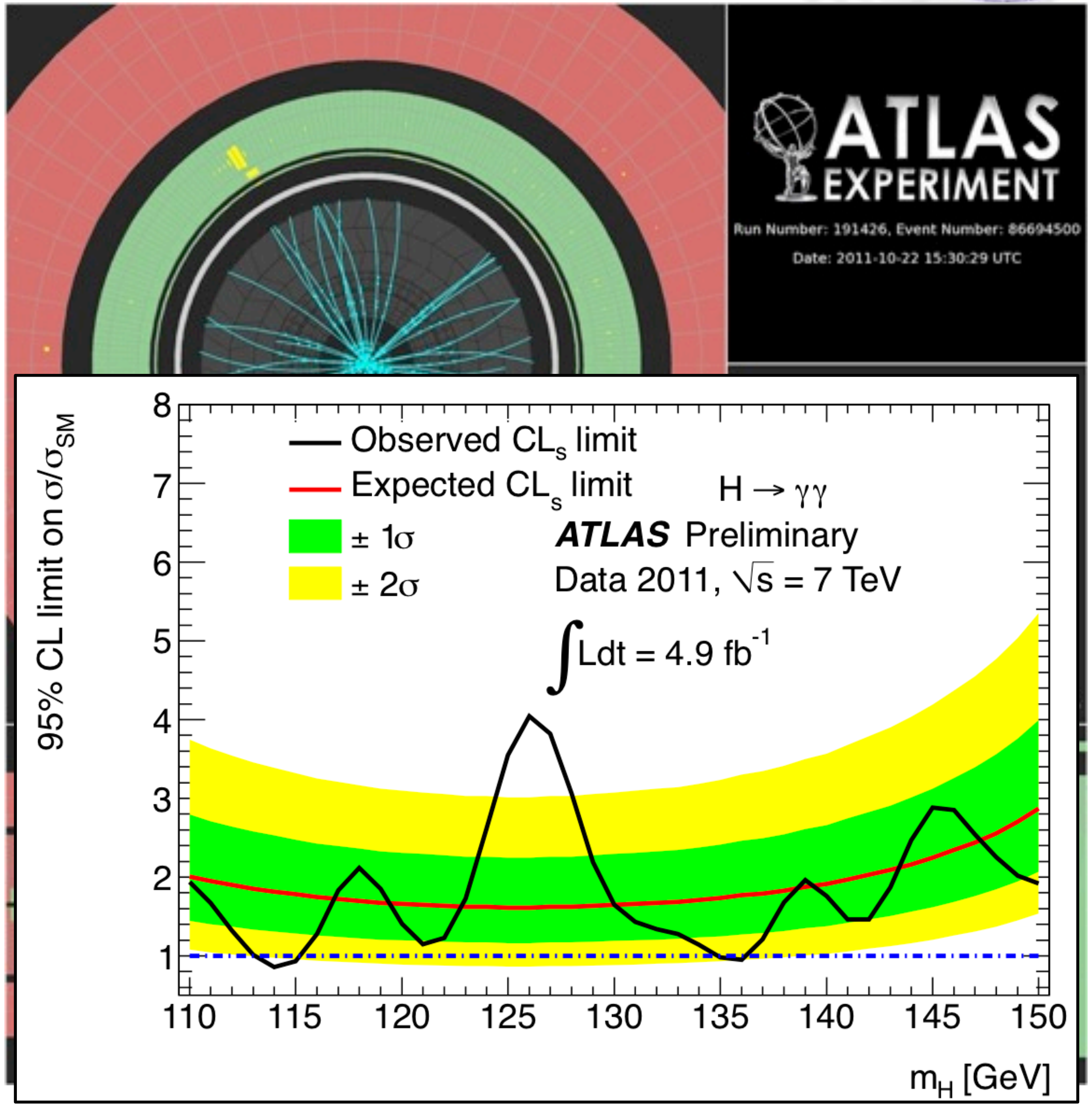


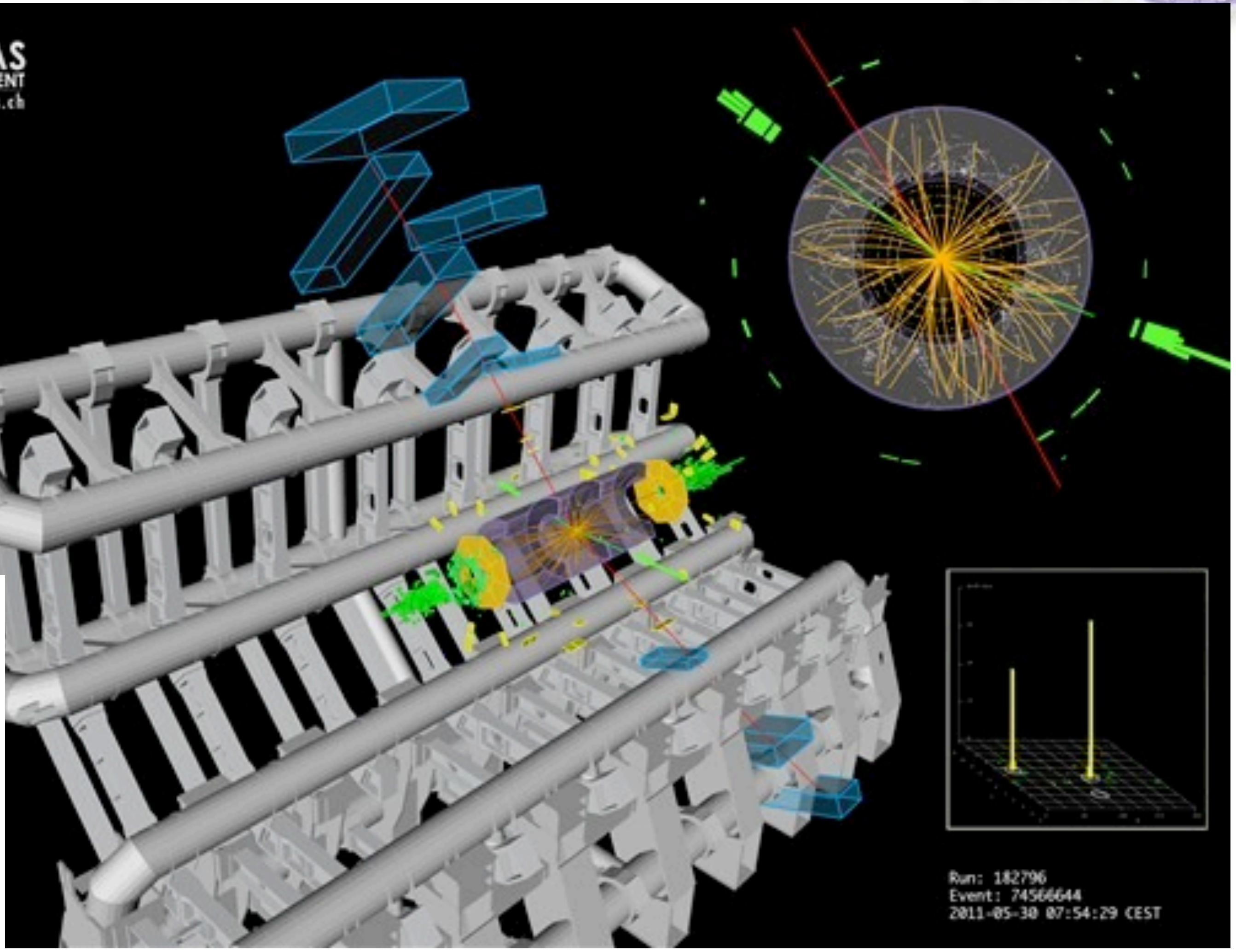


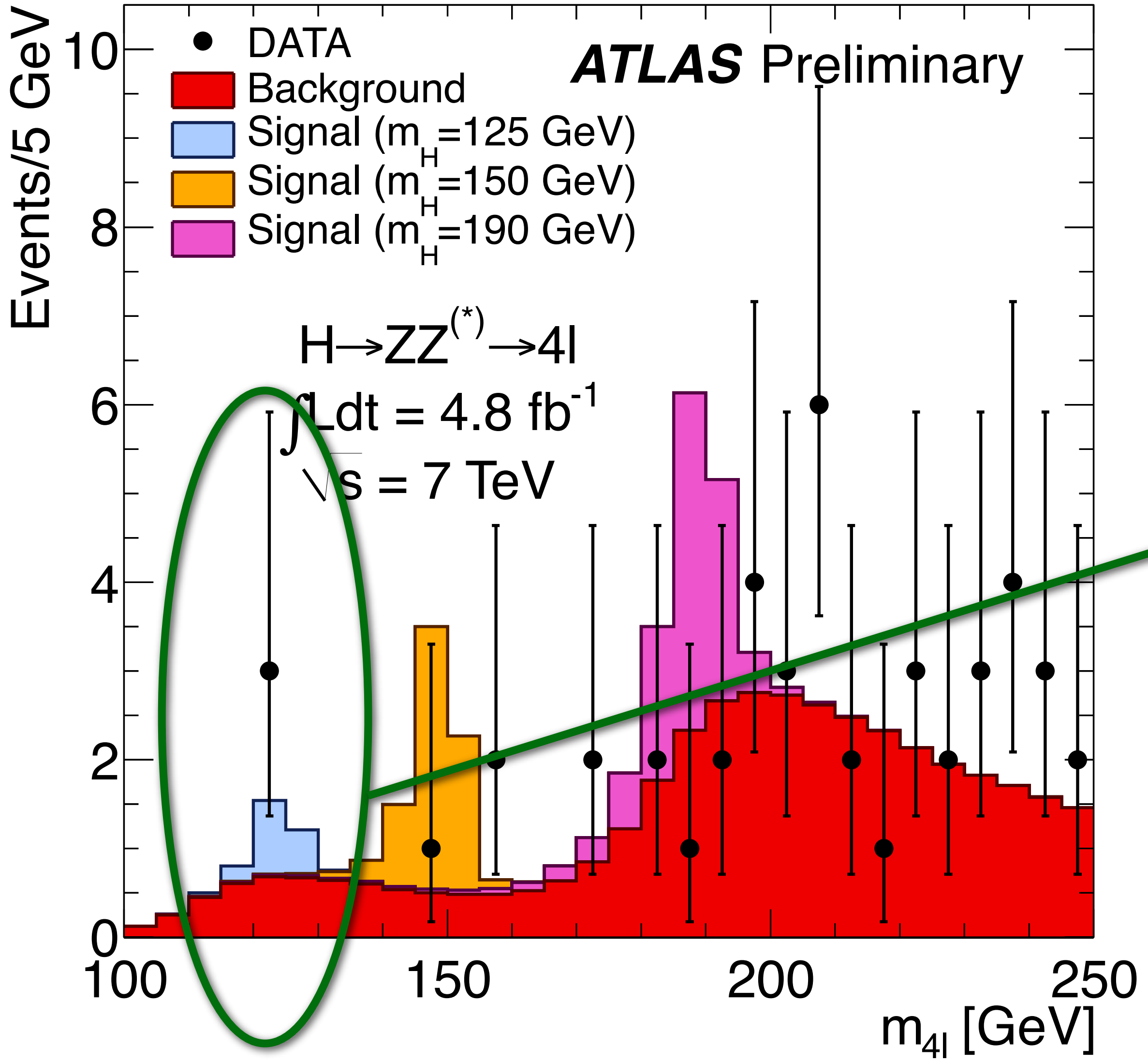
Looking for small excess on top of large (but smooth) background

H → ZZ

Very rare process, especially with both Z particles decaying to leptons

- but very clean, and with good mass resolution

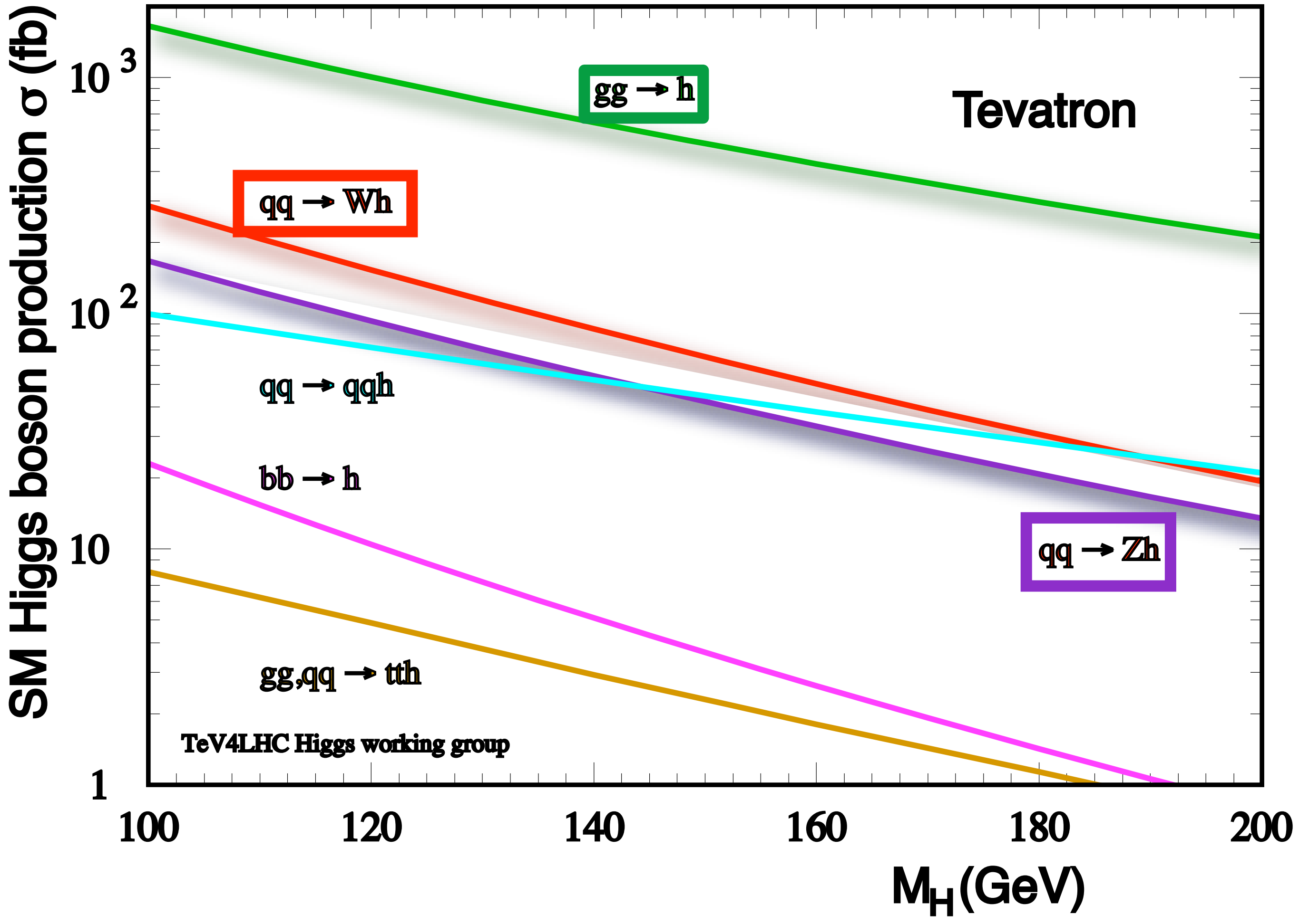




Found 3 candidate events at low mass:

- 2 in $e^+e^-\mu^+\mu^-$ final state (124.3 GeV, 123.6 GeV)
- 1 in $\mu^+\mu^-\mu^+\mu^-$ final state (124.6 GeV)

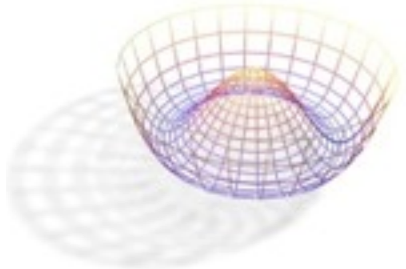
Higgs Boson Production and Decay

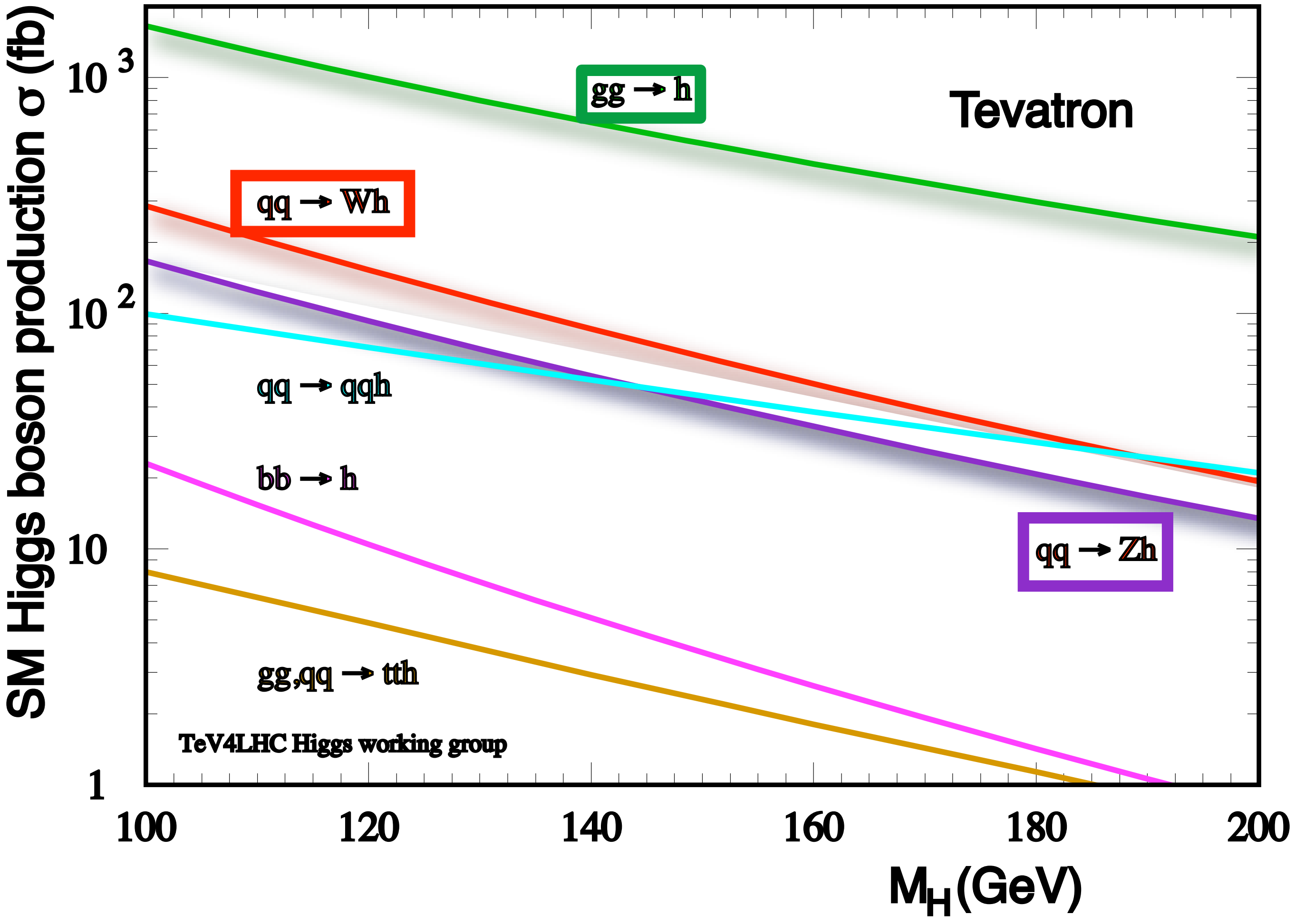


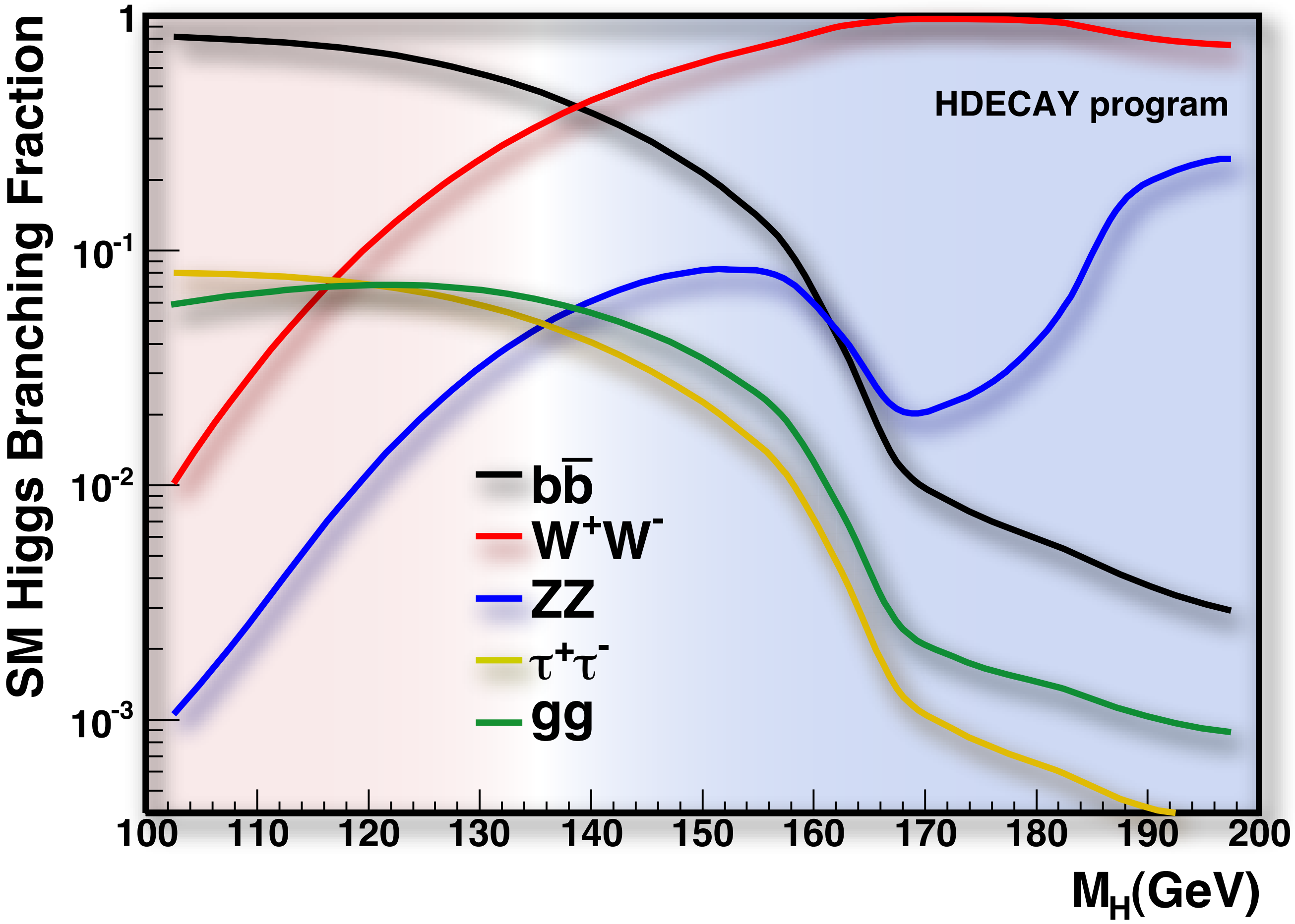
Total inelastic scattering cross section (strong interaction) ~ 60 mb:

- background suppression by 10-11 orders of magnitude required
- use signatures not overwhelmed by the strong interaction

Higgs Boson Production and Decay







Strategy: use leptons!

- low M_H (≲ 135 GeV): VH associated production, leptonic V decay (V=W,Z)
- high M_H (≳ 135 GeV): H→ W^+W^-, both W bosons decaying leptonically

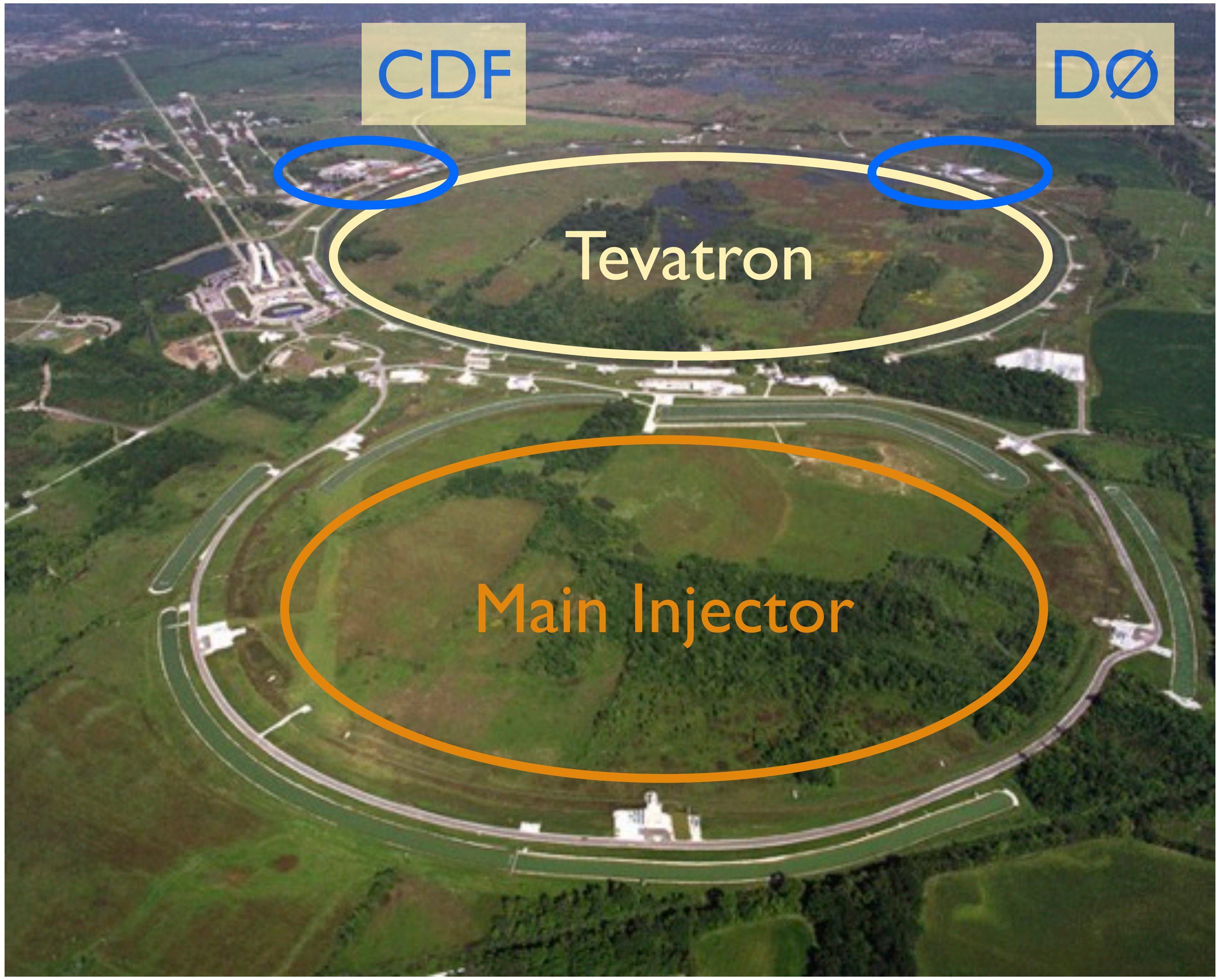
A straightforward strategy, but leading to a large number of final states

The Tevatron Collider

$p\bar{p}$ collisions, $\sqrt{s}$ = 1.96 TeV

mature collider and experiments

- running since 2001



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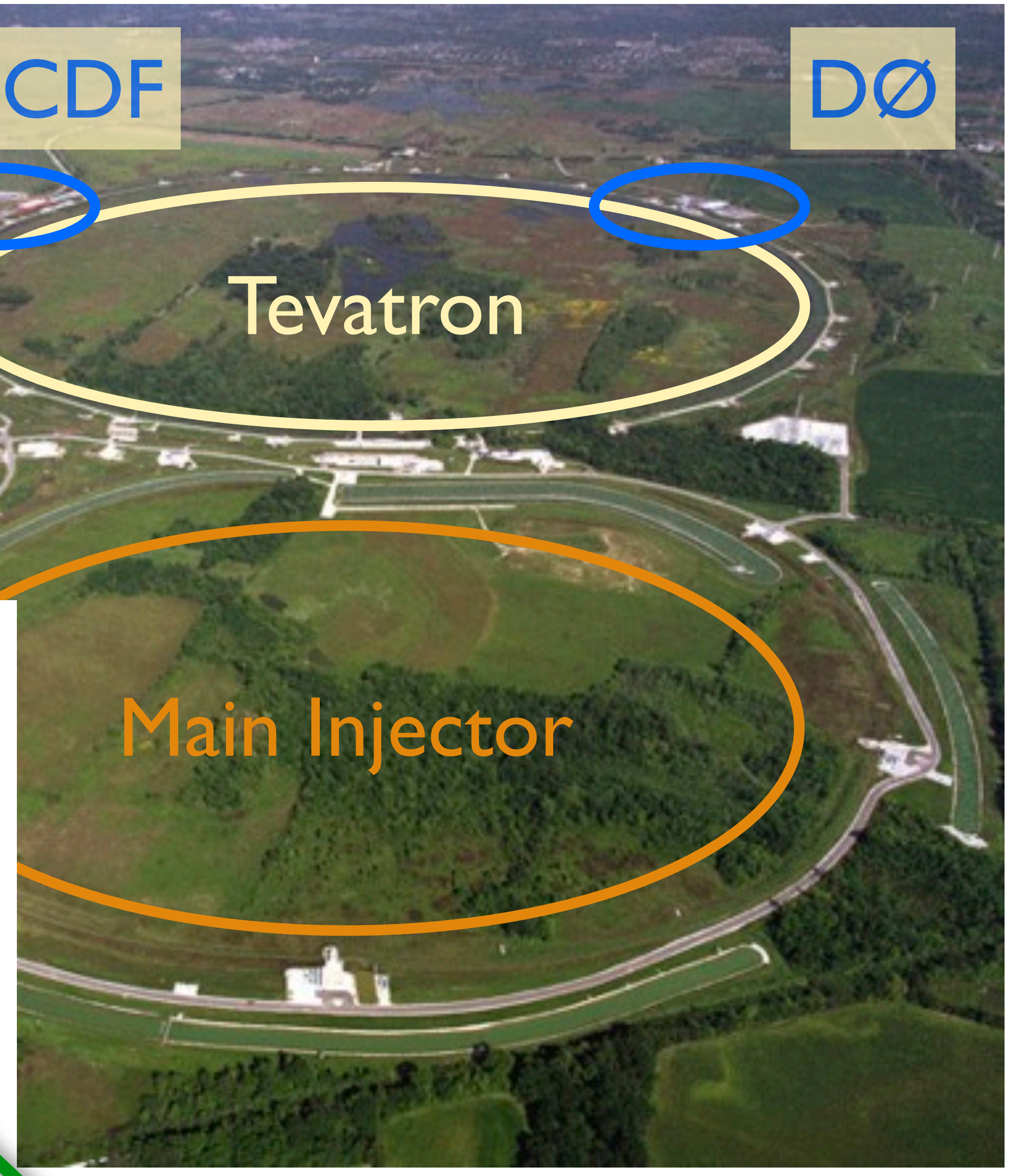
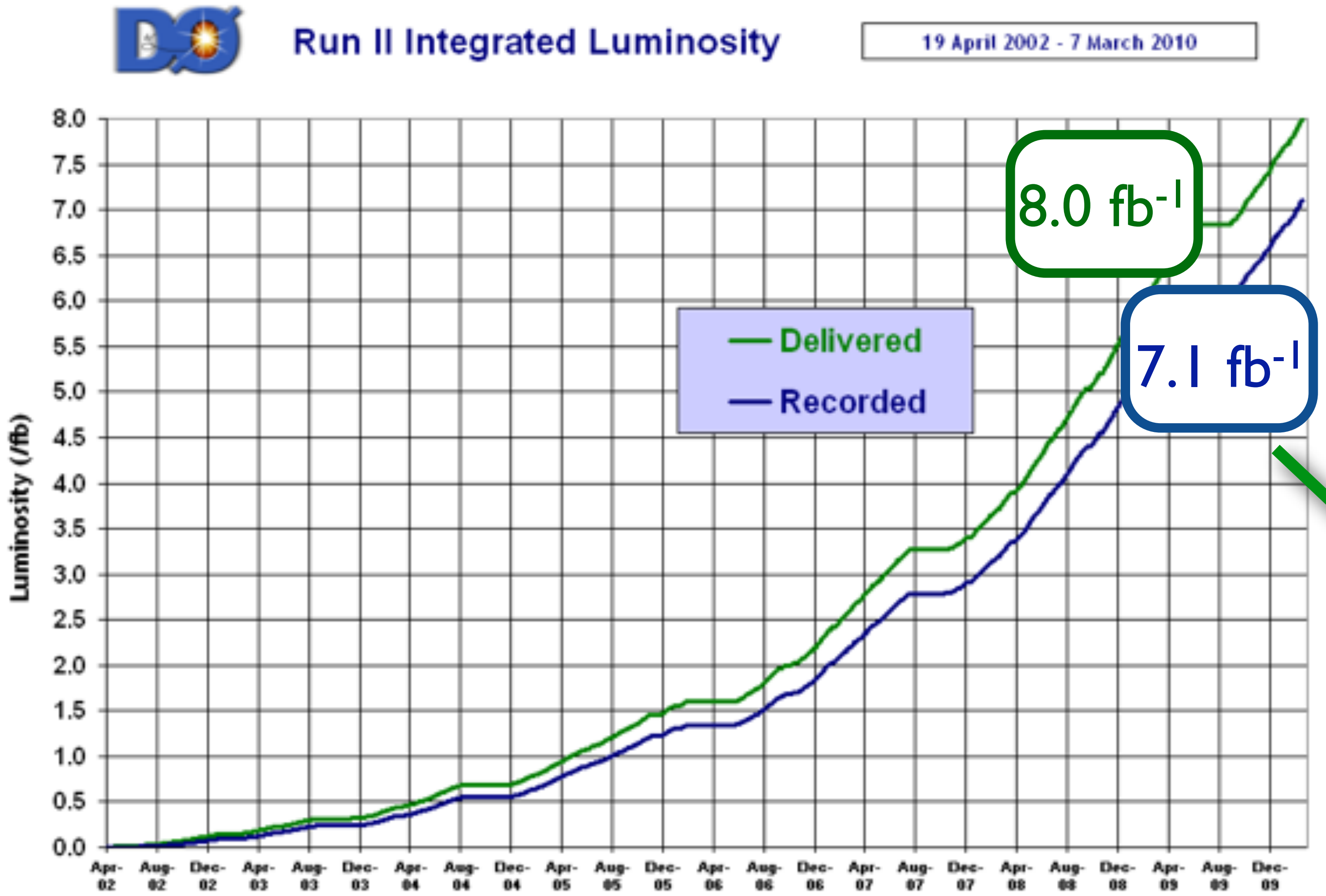
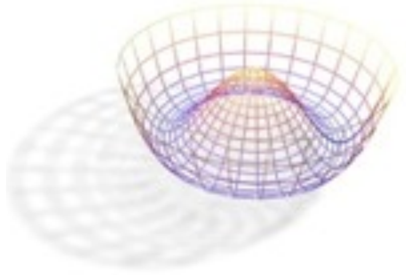




- 1 fb = 10^{-43} cm^2
- if σ =1 fb: need L=1 fb^{-1} to produce one event
- many interesting processes have σ ~ 100-1000 fb



Limits

No significant signal-like excess observed... ➡ set limits

Procedure:

- Compare data compatibility with s+b / b-only hypotheses (each M_H)

$$Q = \frac{\mathcal{L}(s+b|m_H)}{\mathcal{L}(b)} = \prod_{i \in \text{bins}} \frac{e^{-(s_i+b_i)}(s_i+b_i)^{n_i}}{n_i!} \Big/ \frac{e^{-b_i} b_i^{n_i}}{n_i!}$$

- Calibrate outcome with toy experiments

  - Compare resulting distributions with observed Q

$CL_{b/s+b}$ ≡ fraction of background-only/signal+bg experiments less signal-like than data

Reject s+b hypothesis if $CL_{s+b} < 0.05$