The Higgs Boson: Discovery of the Millennium (So Far)

UC Davis HEFTI Frontiers of Physics Symposium
April 6, 2013
Maxwell Chertok, UC Davis

Outline

Particle Physics & Symmetry

A Little History of Charged Particles

The Large Hadron Collider

Machine, CMS and ATLAS

Search for the Higgs

Results (we found it!)

Conclusions

Particle Physics: “Matter & Energy, Space & Time”

We study the microworld ~10^{-19} m to better understand the universe at a fundamental scale

World’s biggest scientific apparatus needed to study smallest phenomena

Accelerators or Cosmic Rays or Reactors

High-energy particle collisions recreate conditions immediately after Big Bang

Symmetry

Study fundamental symmetries of nature

Emmy Noether, 1918

Symmetry $\Longleftrightarrow$

Conserved Quantity

Rotational invariance $\Longleftrightarrow$

Angular momentum conserved

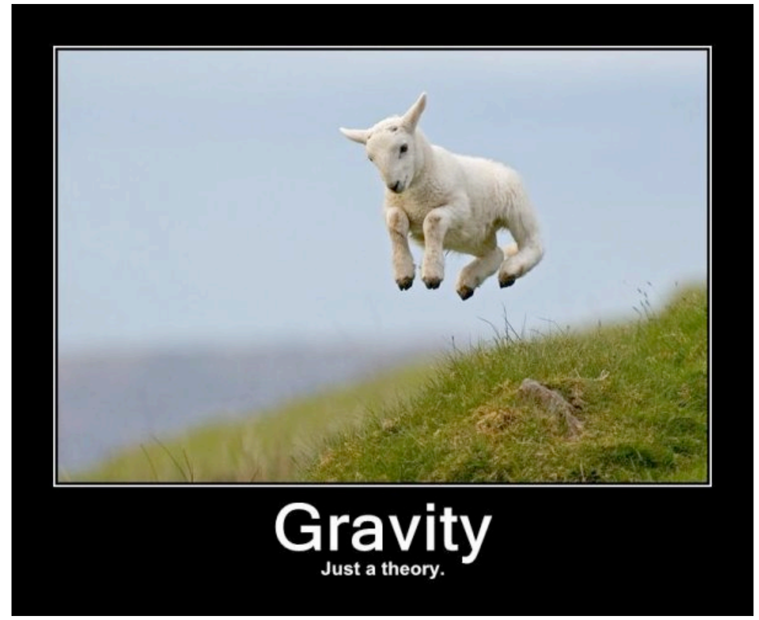
Time translation invariance $\Longleftrightarrow$

Energy conserved

These ideas are cornerstones of physics!

Use symmetry principles to understand fundamental forces of nature

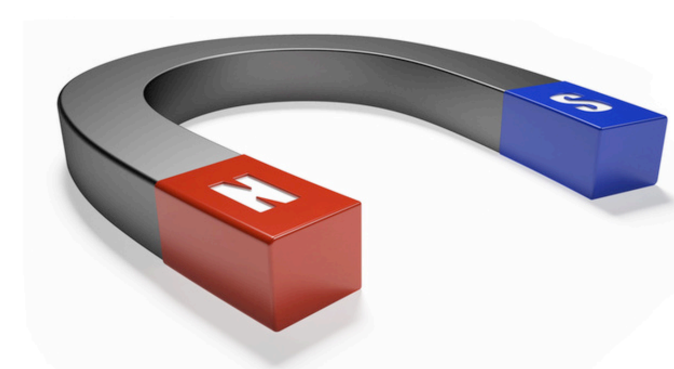
Gravity



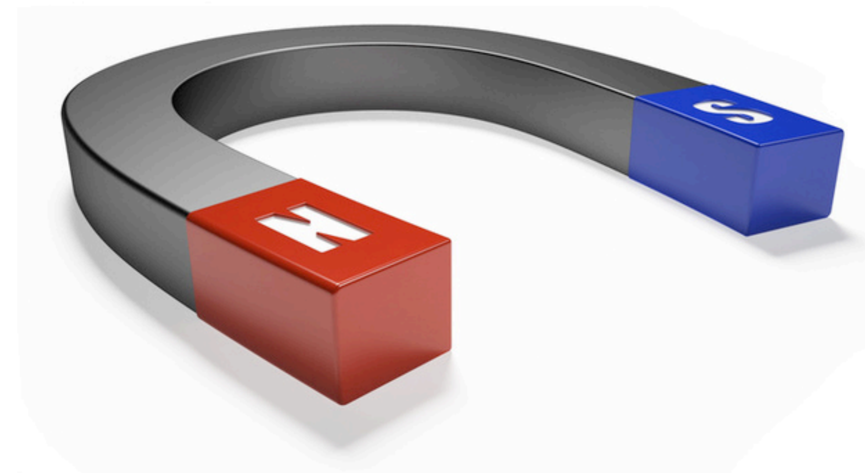
Strong

Weak

Electromagnetic



Electro-Weak Symmetry

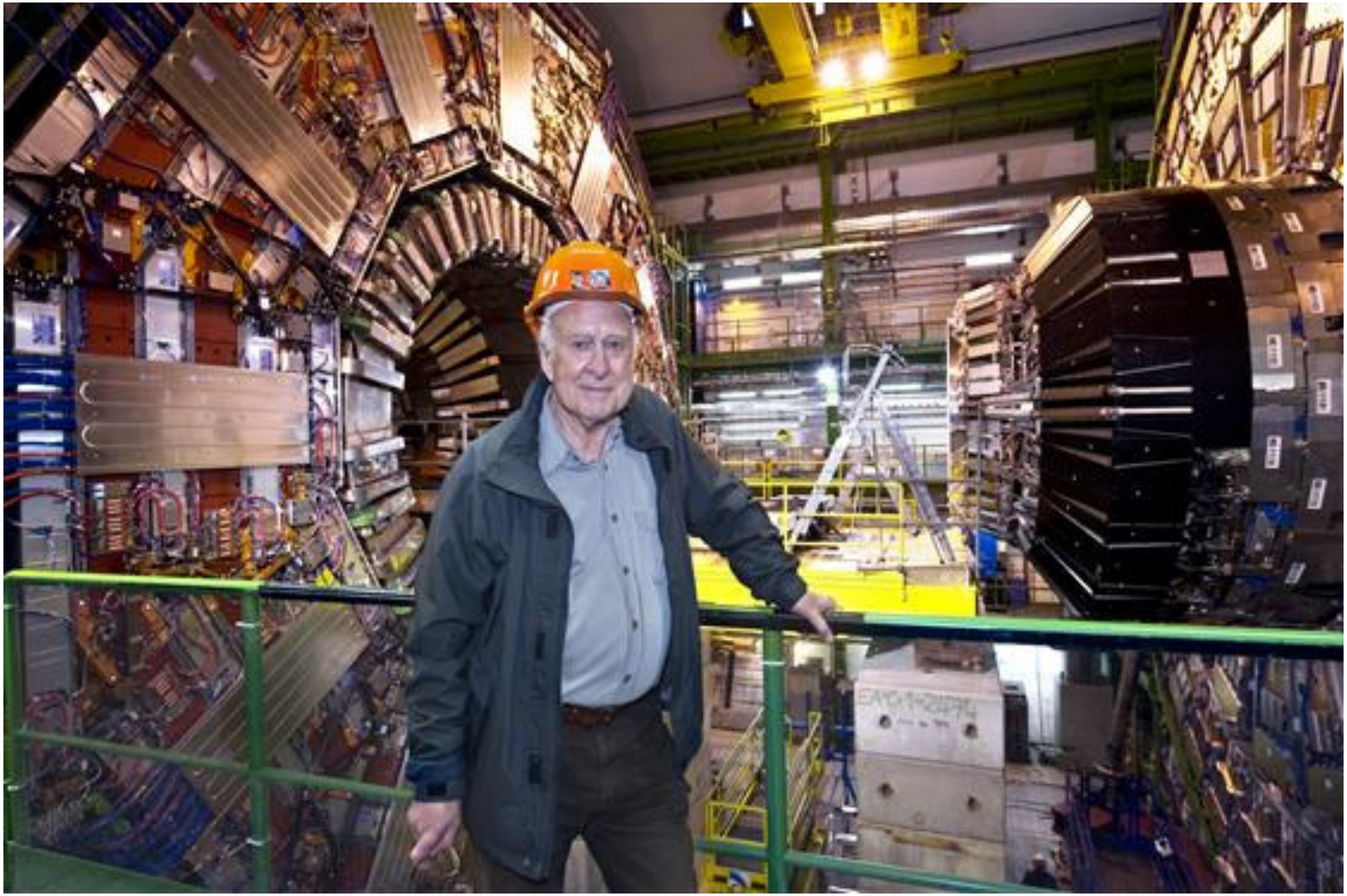


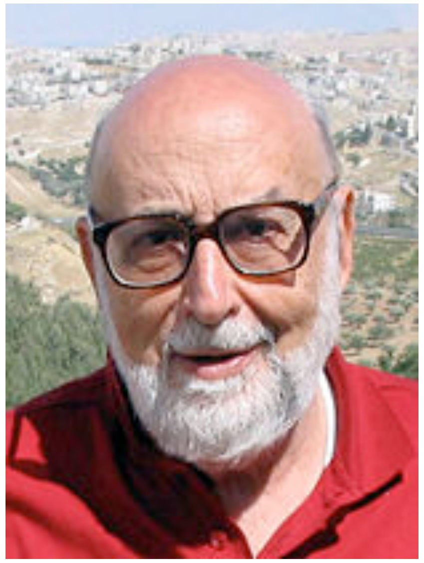
Tho' phenomena seem wildly different, try to unify EM and Weak forces. One gauge theory.

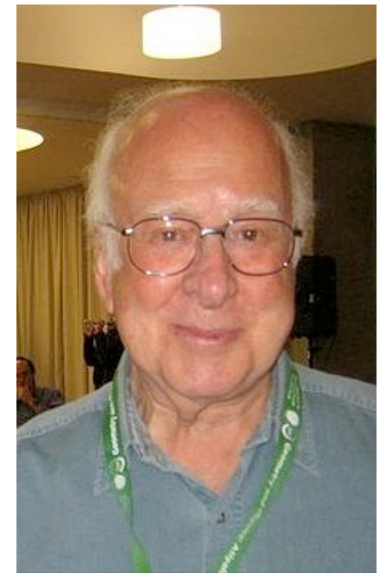
Weak interactions appear weak, not because of some fundamental coupling constant, but because mediated by massive gauge particles. (short-range)

On the other hand, photon is massless. (infinite-range)

Enter Mr. Higgs








Or, should we call it...

The Englert-Brout-Higgs-Guralnik-Hagen-Kibble Boson


?

Generating mass

We can't just add massive particles, but we can introduce a new field, the scalar Higgs field.

Higgs field preserves gauge symmetry

This field permeates all time and space (ether, anyone?) The other particles interact with the Higgs field and thereby acquire an effective mass.

Without the Higgs, all the particles would be massless and travel at the speed of light. The universe would have no structure!

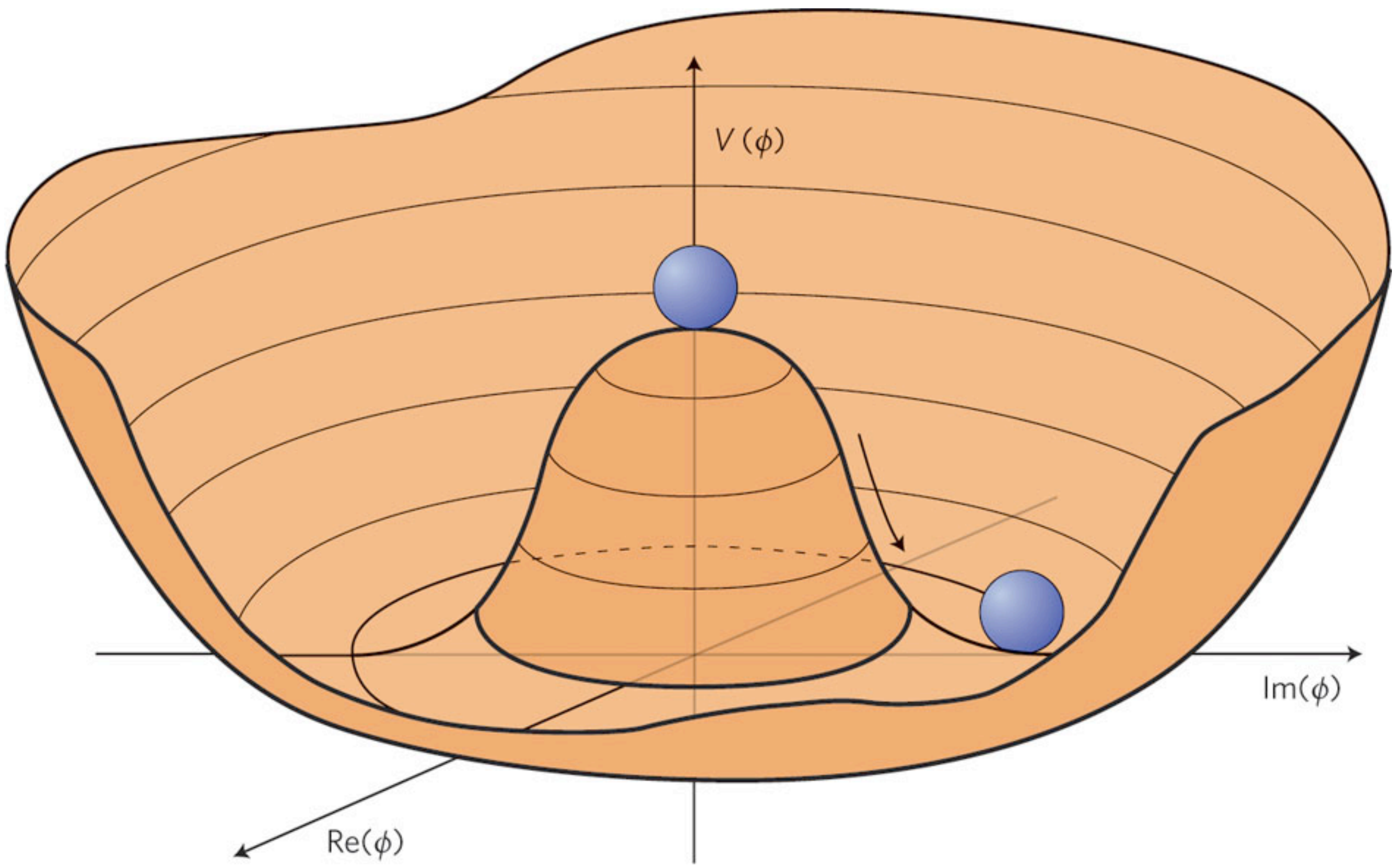
Spontaneous Symmetry Breaking

Higgs field potential designed so that non-zero field values have lowest energy

Must choose a specific place on that circle. This breaks the symmetry.

Rotations about minimum circle lead to massive W,Z

Example from solid state physics: a ferromagnet above Tc has spins randomly oriented (symmetric). At T<Tc, the spins align spontaneously, breaking the symmetry.



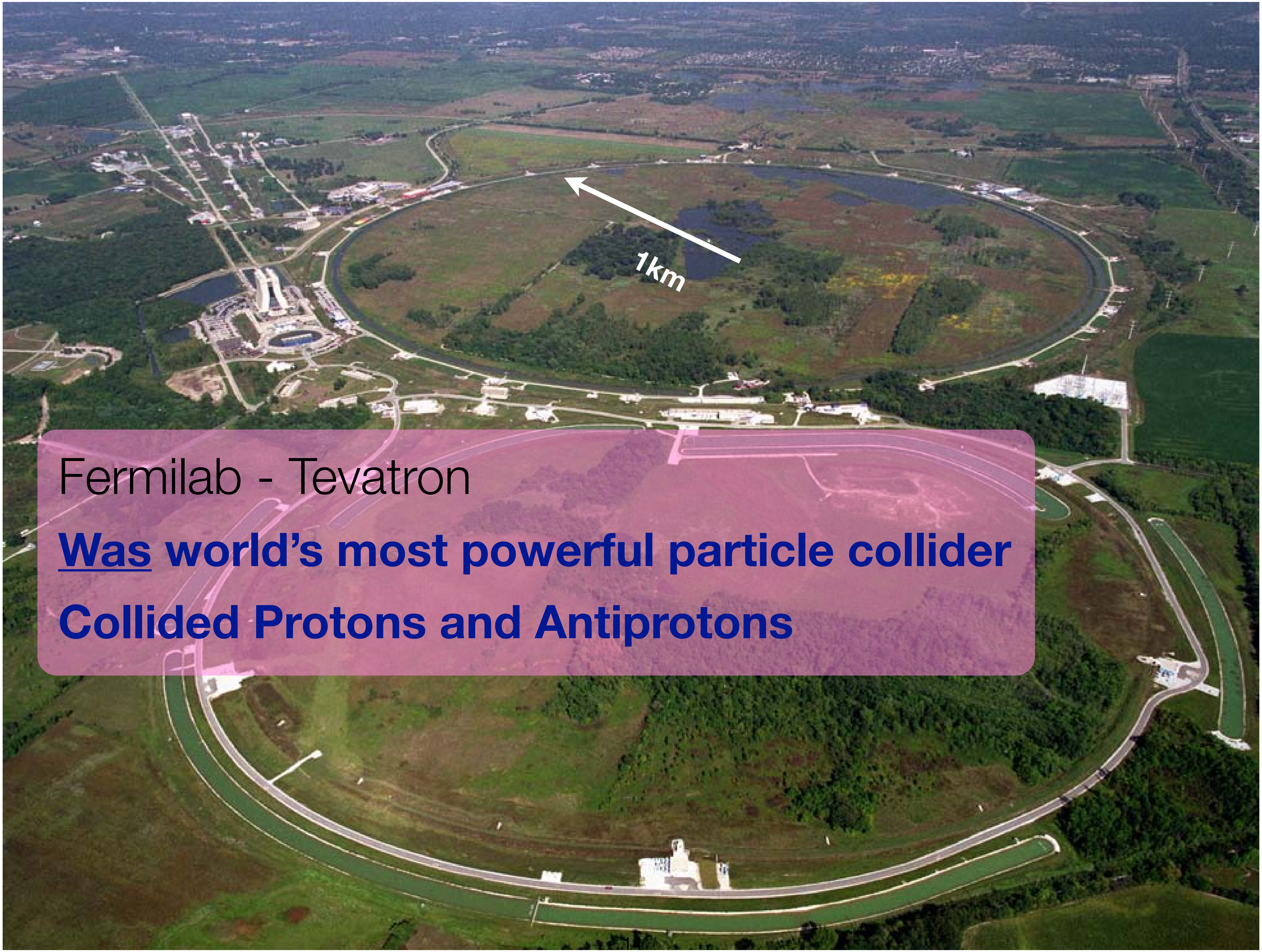
A little history of charged particles

Discovery of the electron, 1897

“Could anything at first sight seem more impractical than a body which is so small that its mass is an insignificant fraction of the mass of an atom of hydrogen?” --J.J. Thomson

The electron has no size

M(electron) = 2.000×10^{-30} lbs

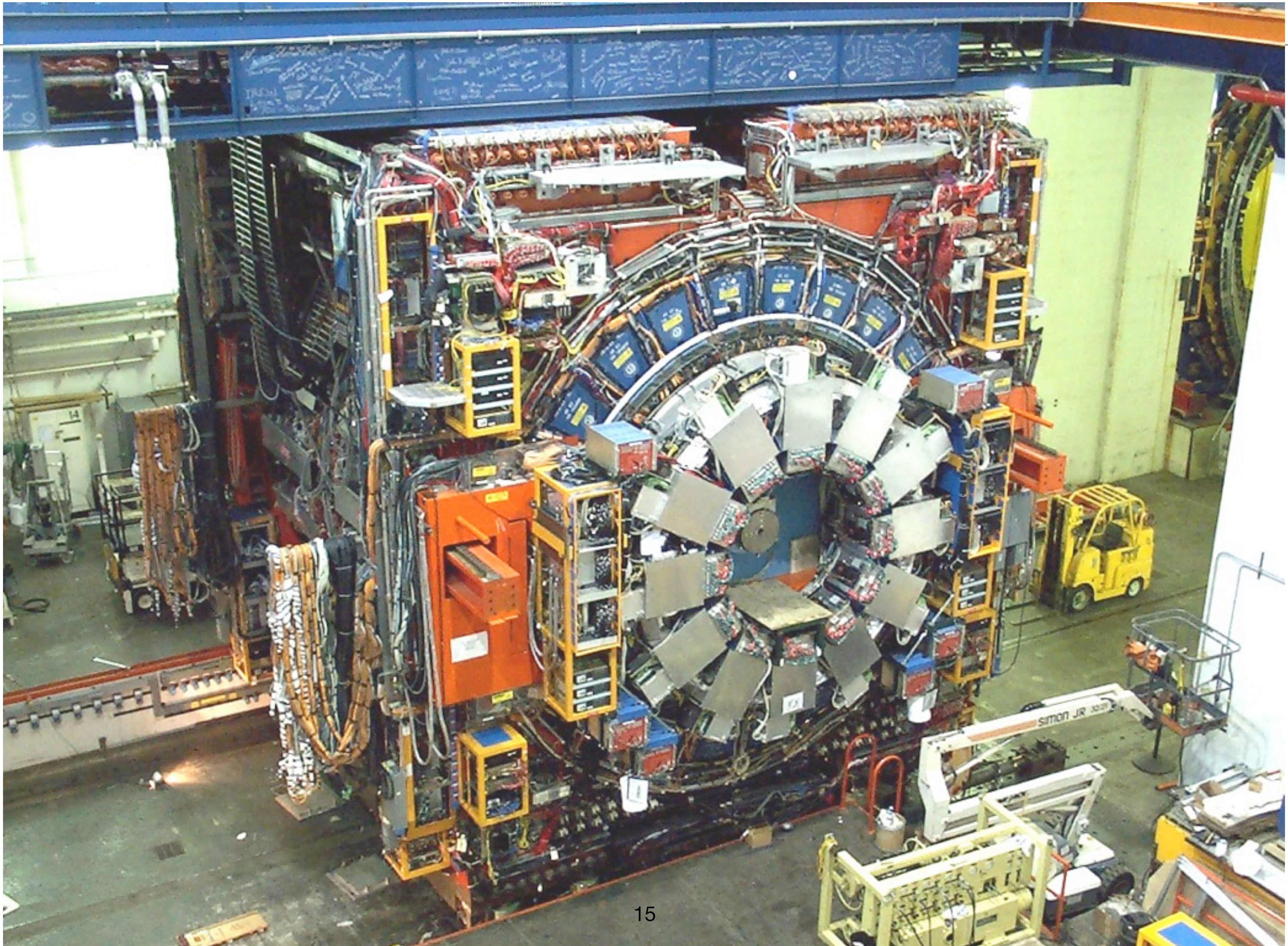


Fermilab - Tevatron

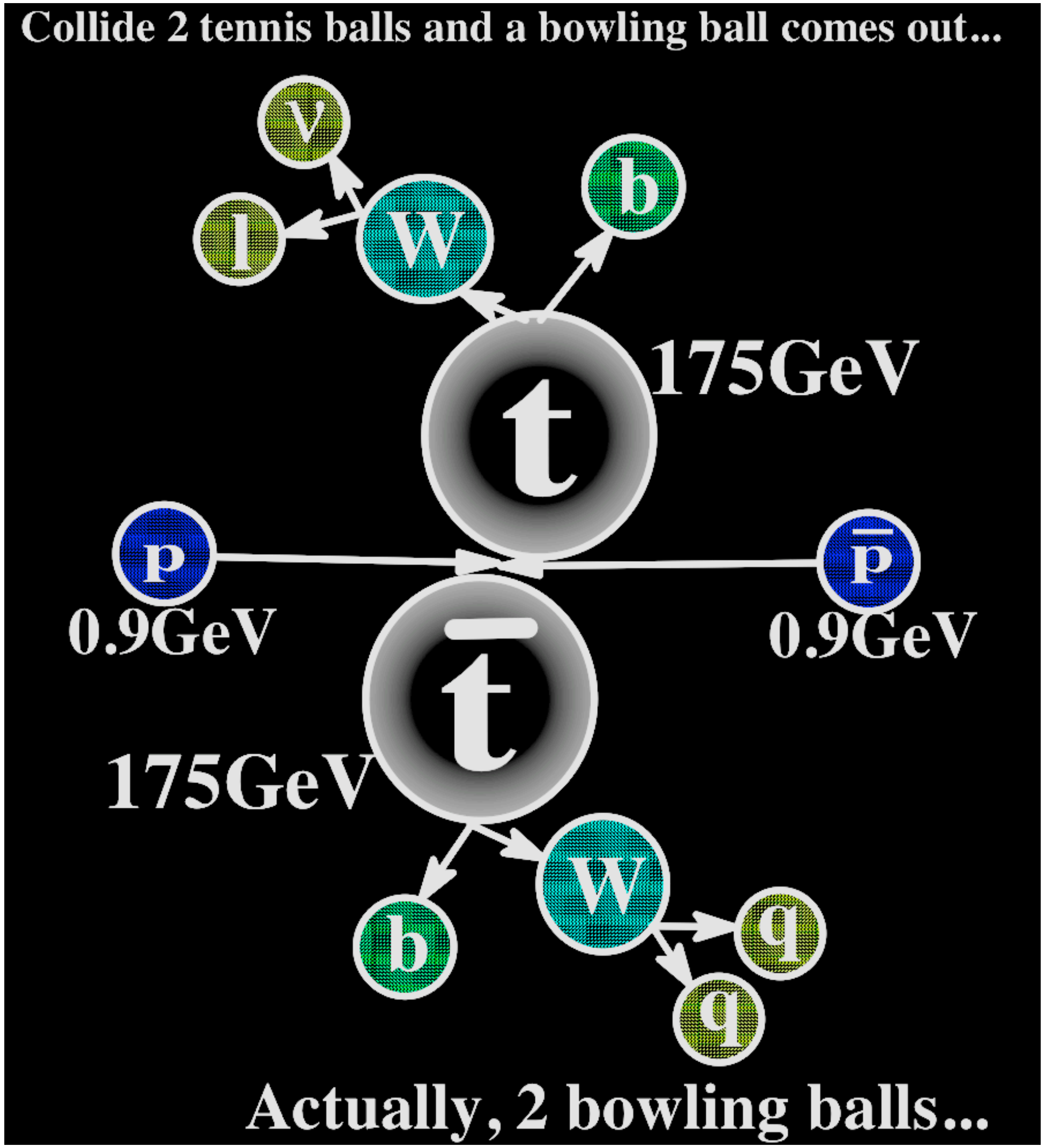
Was world's most powerful particle collider

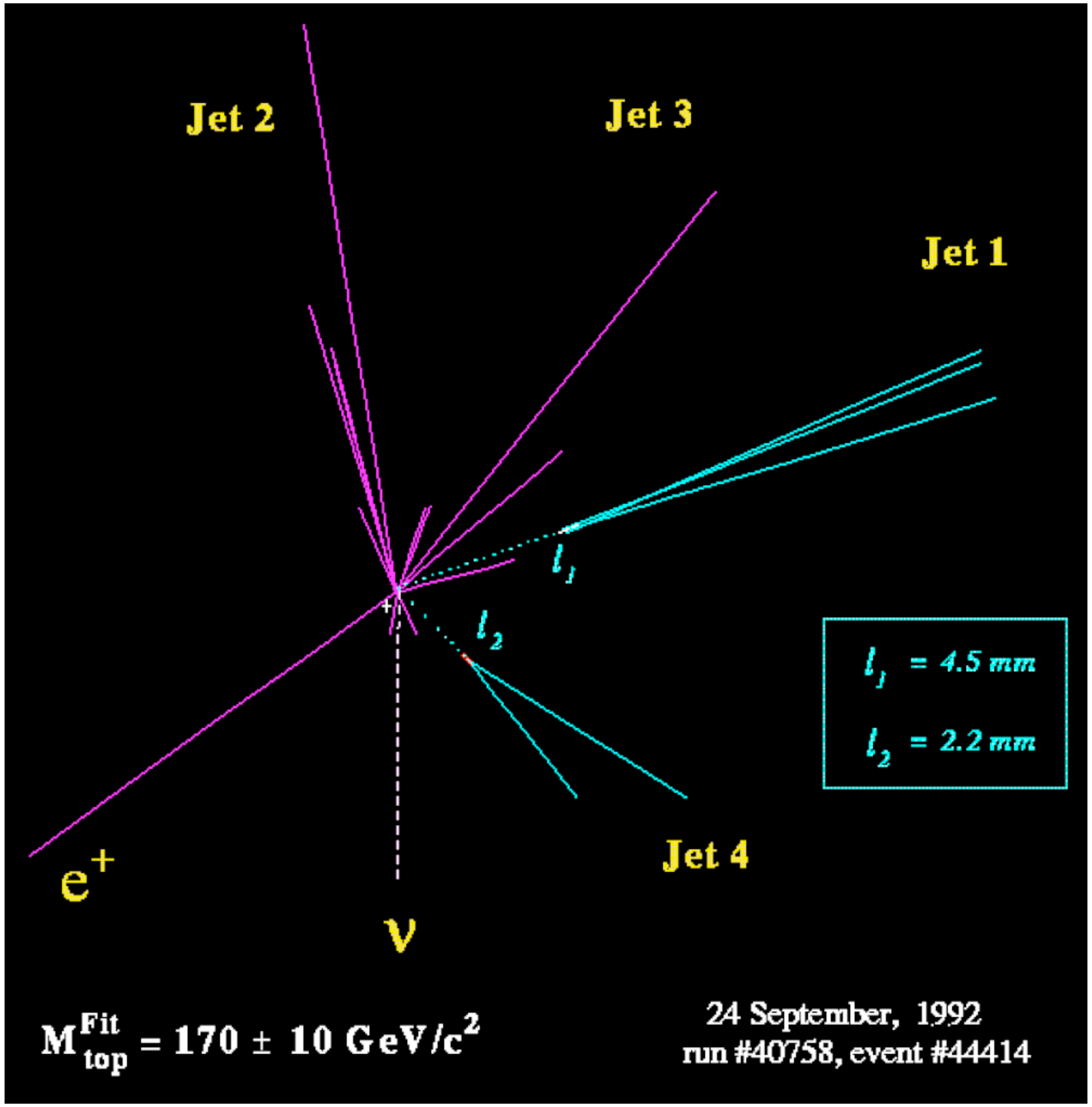
Collided Protons and Antiprotons

Collider Detector at Fermilab



Discovery of Truth (top quark), 1992

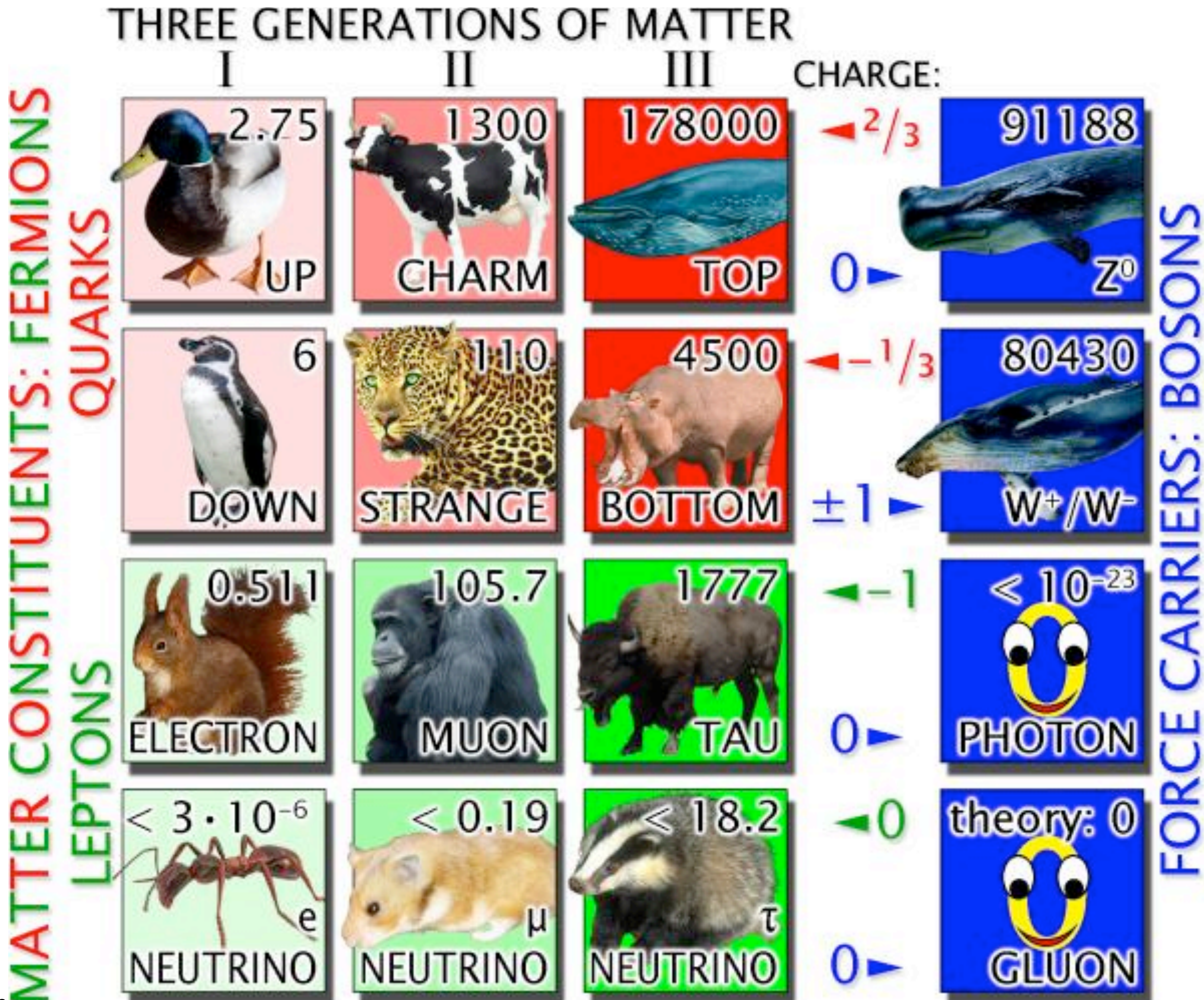




M. Chertok

Top quark as heavy as...

The Standard Model, 1897-2011



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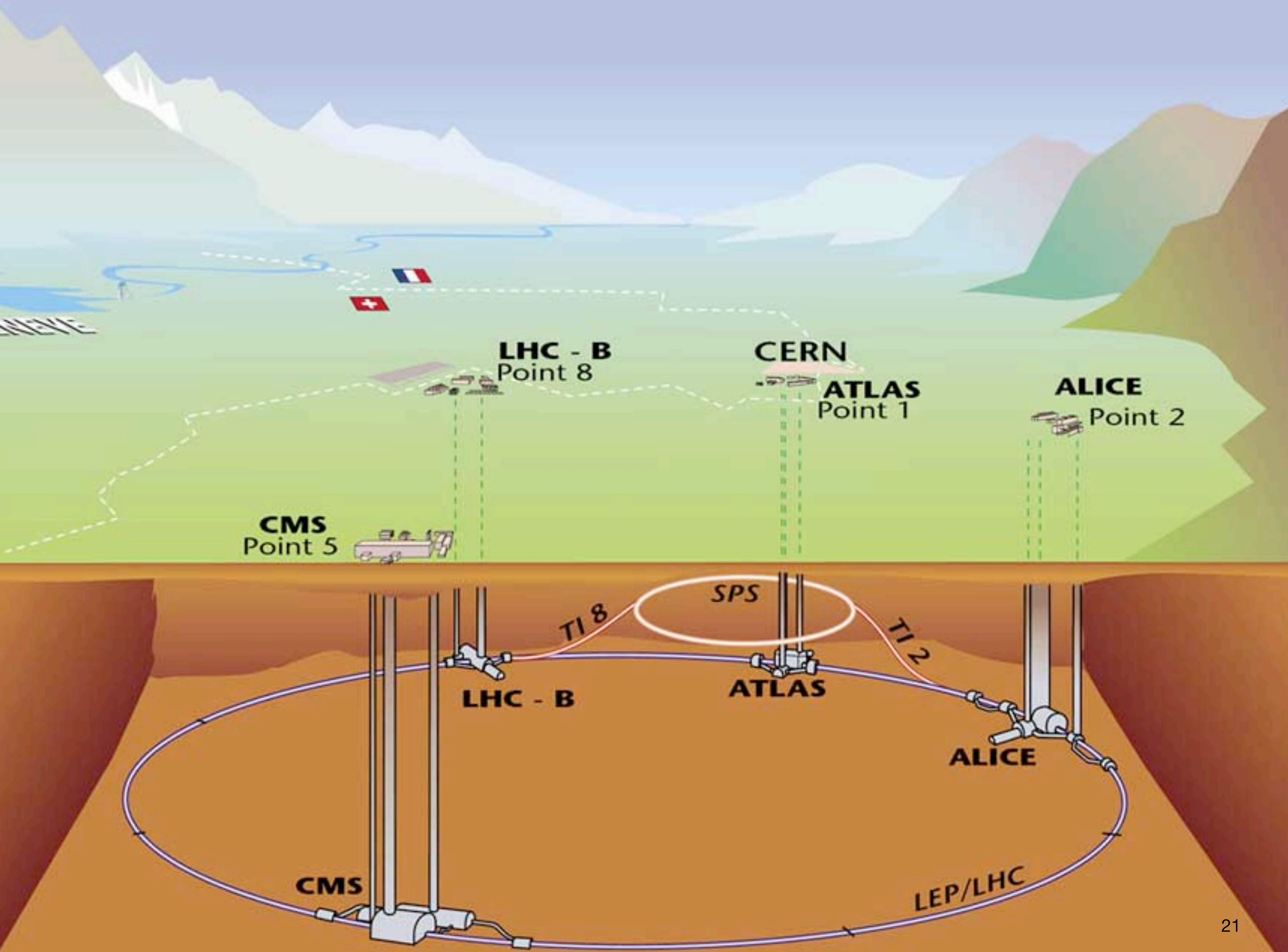
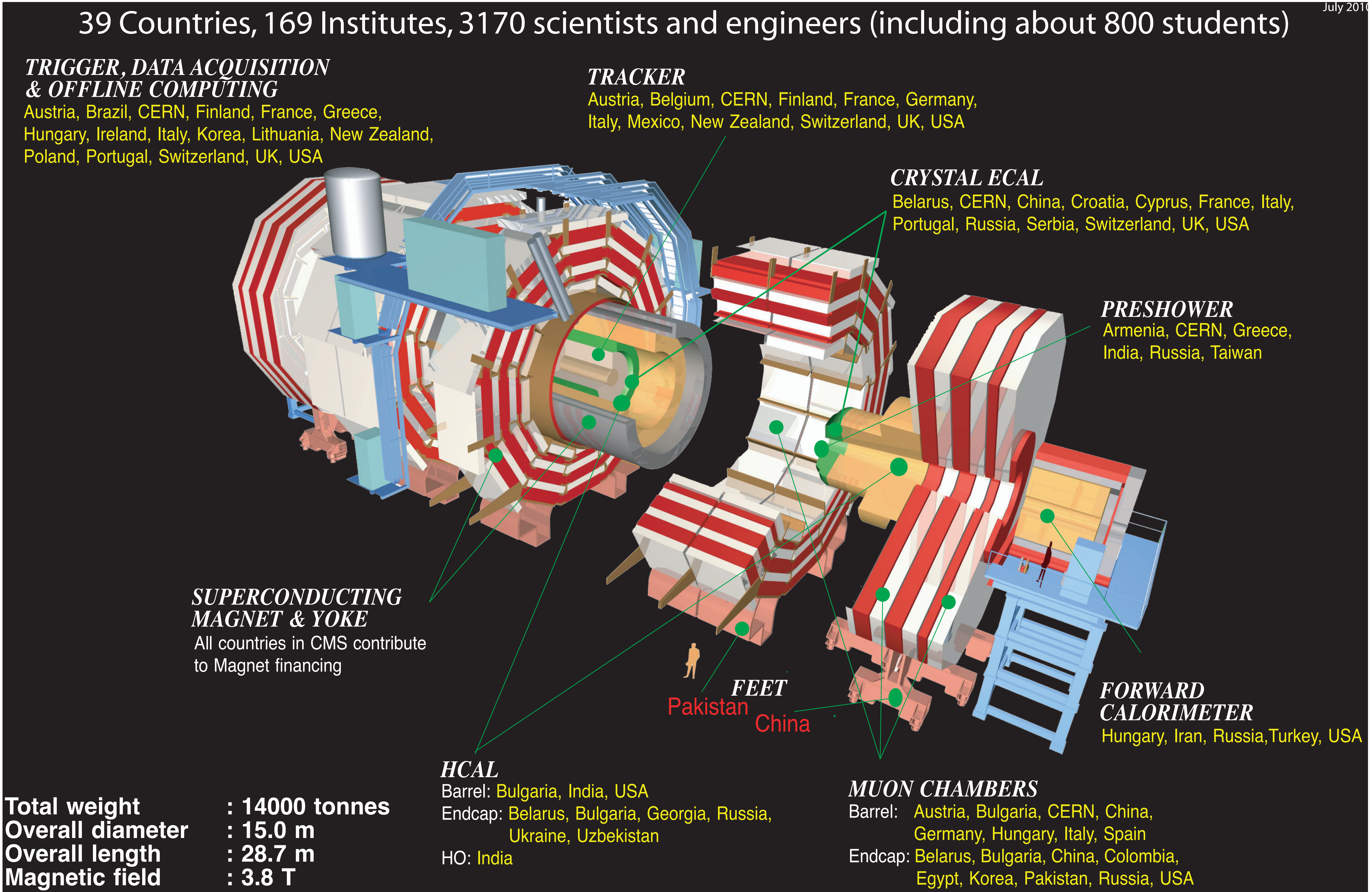
CERN and the Large Hadron Collider

CERN: at the foot of the Jura

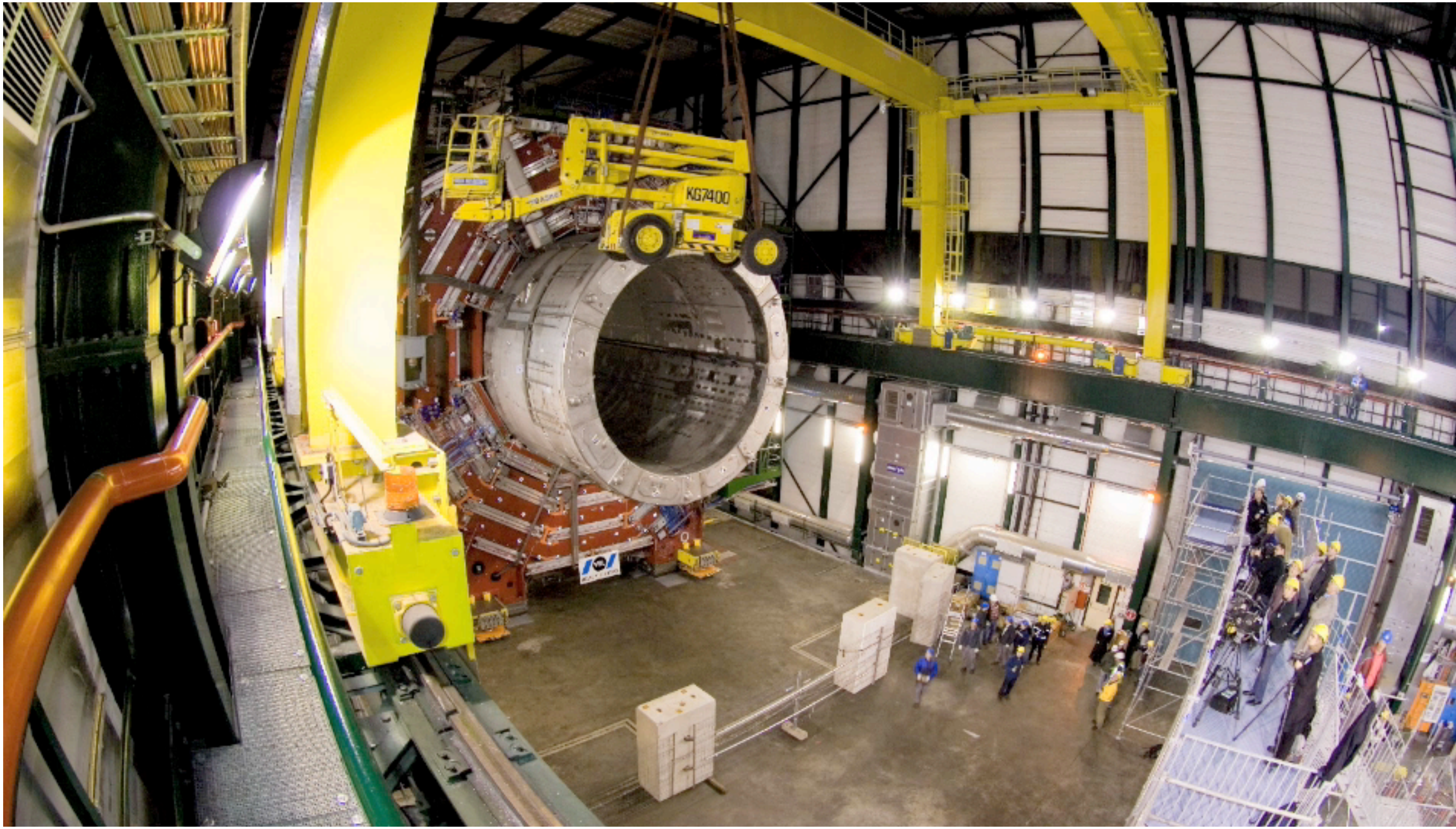


LHC - B
Point 8
CERN
ATLAS
Point 1
ALICE
Point 2
CMS
Point 5
SPS
TI 8
TI 2
LHC - B
ATLAS
ALICE
CMS
LEP/LHC

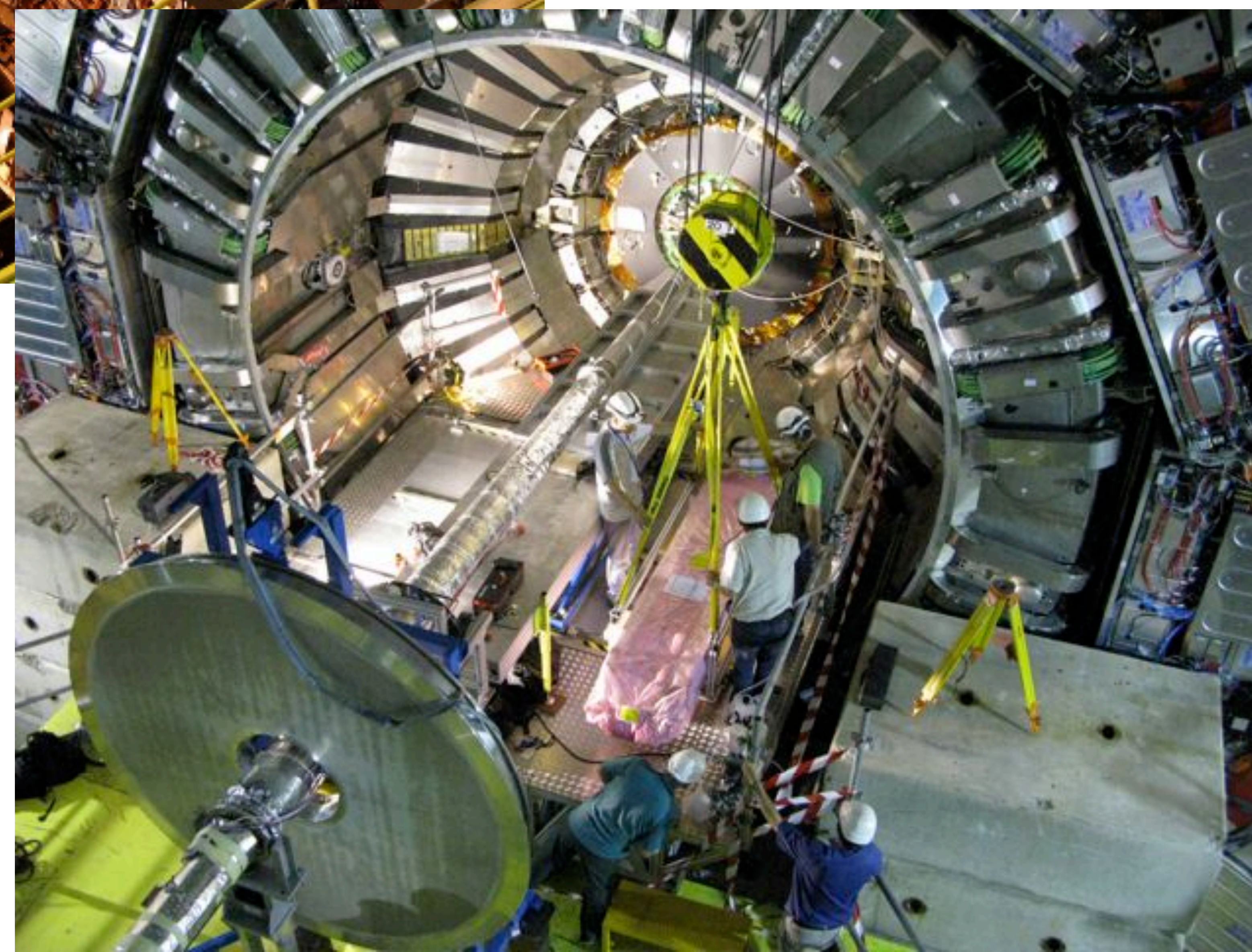
CMS Experiment



CMS: World’s largest solenoid

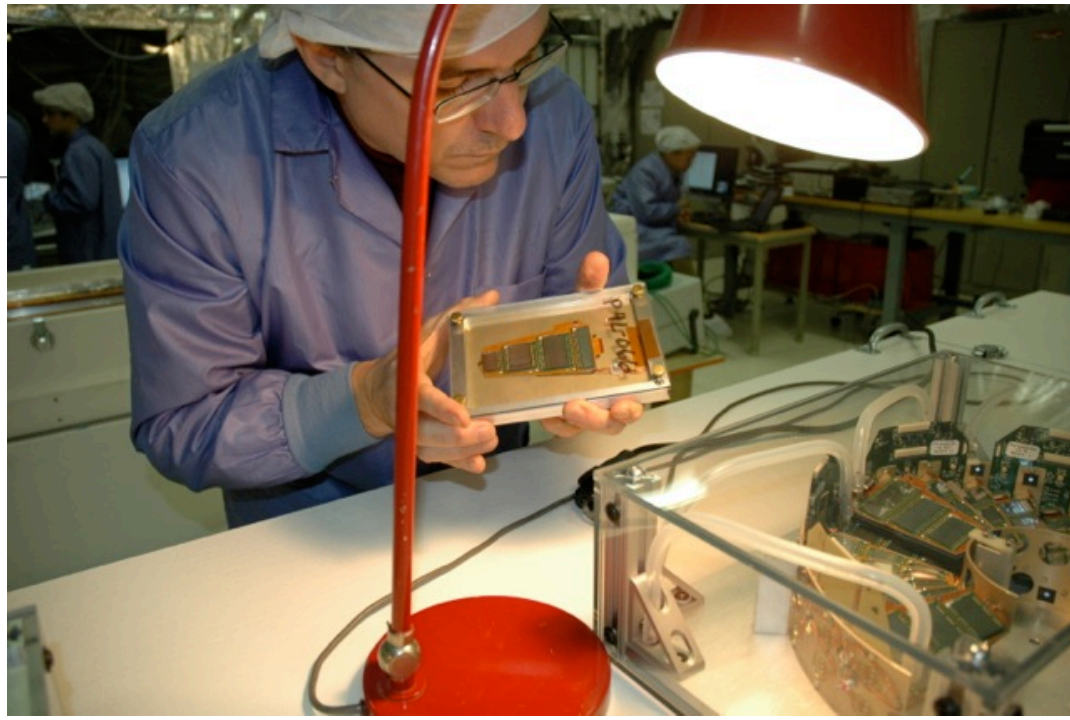

KG7400

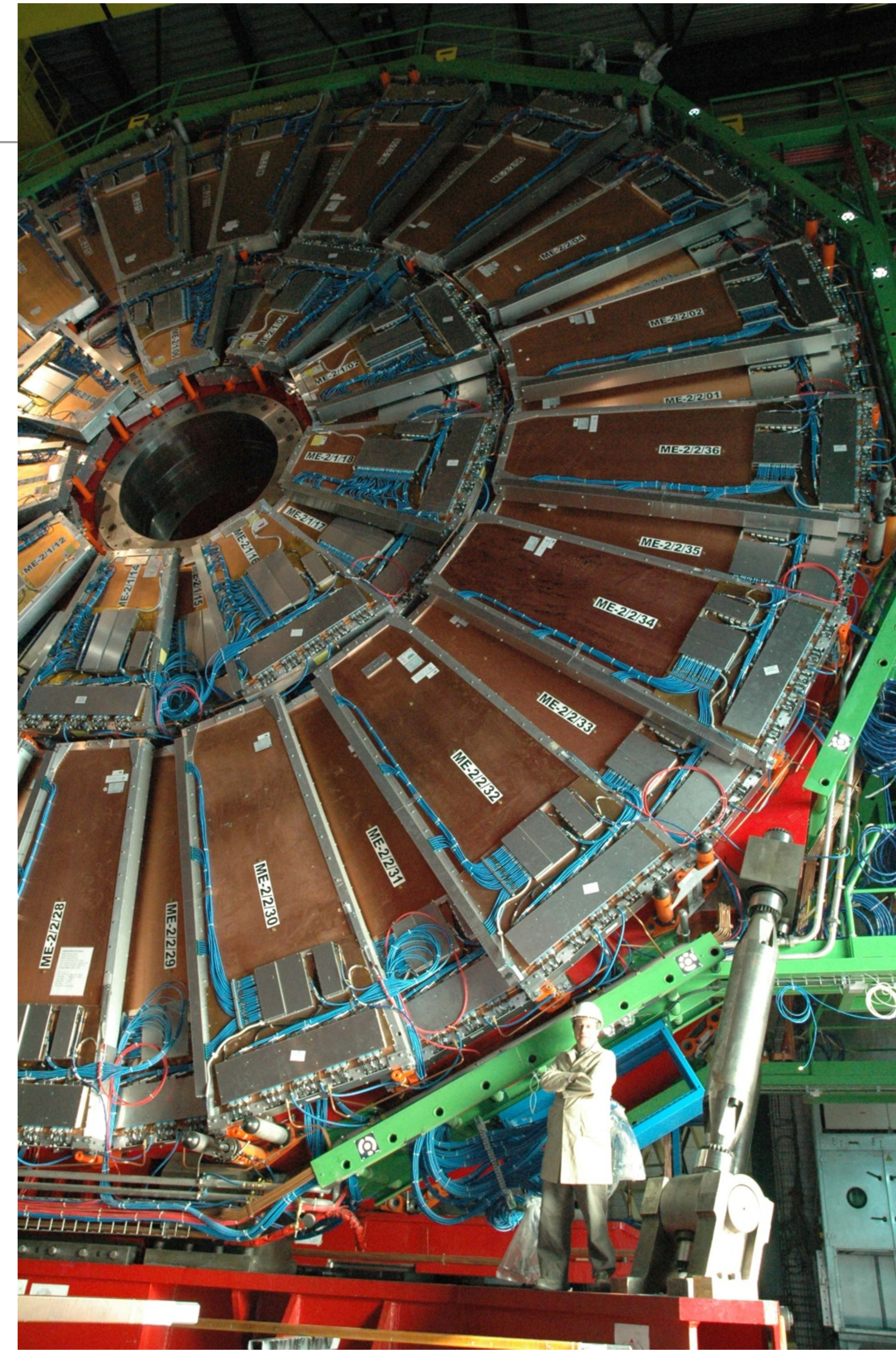
Then we installed the Forward Pixel Detector...

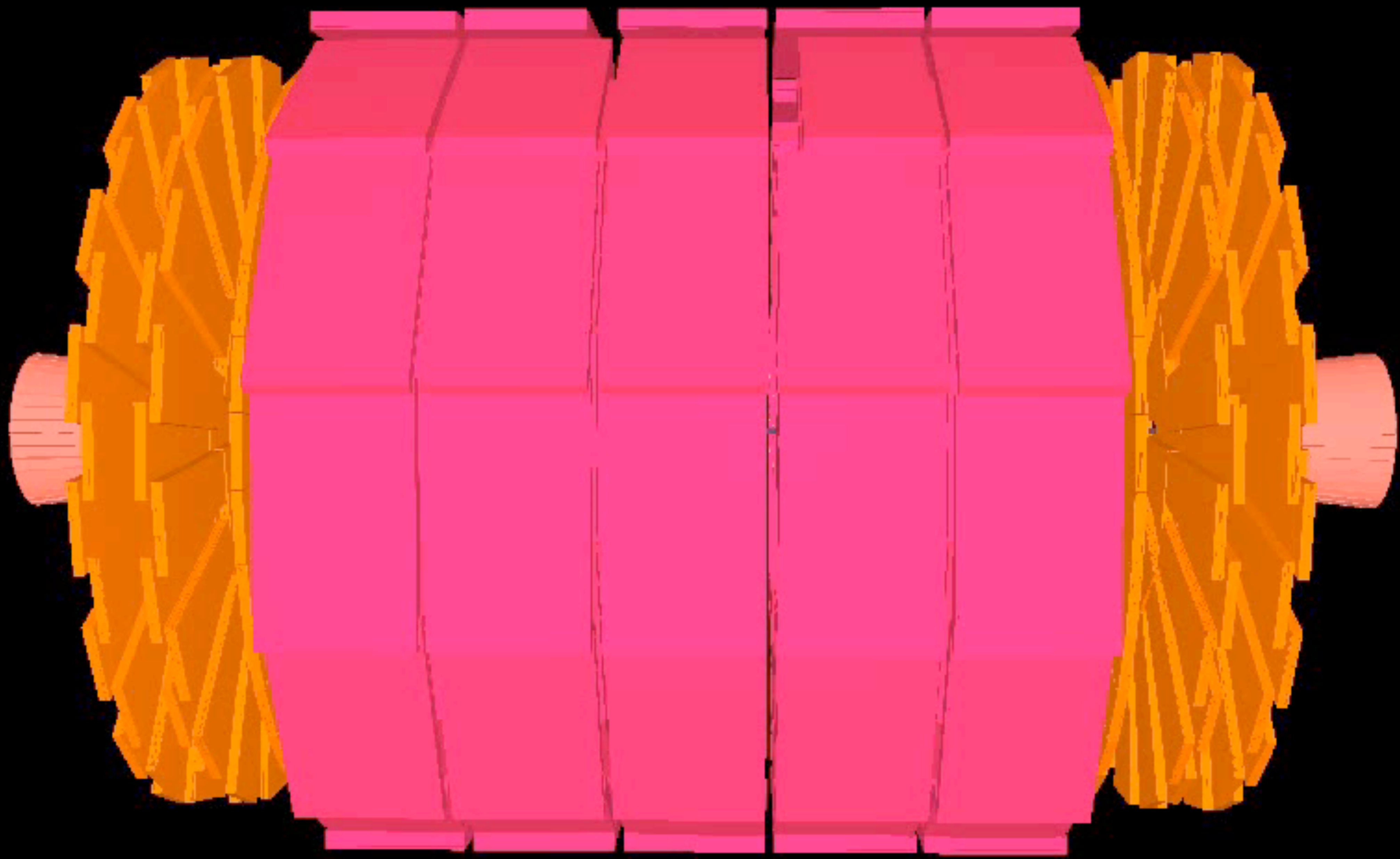

PETZL

UC Davis Signed original CMS Letter of Intent, 1992

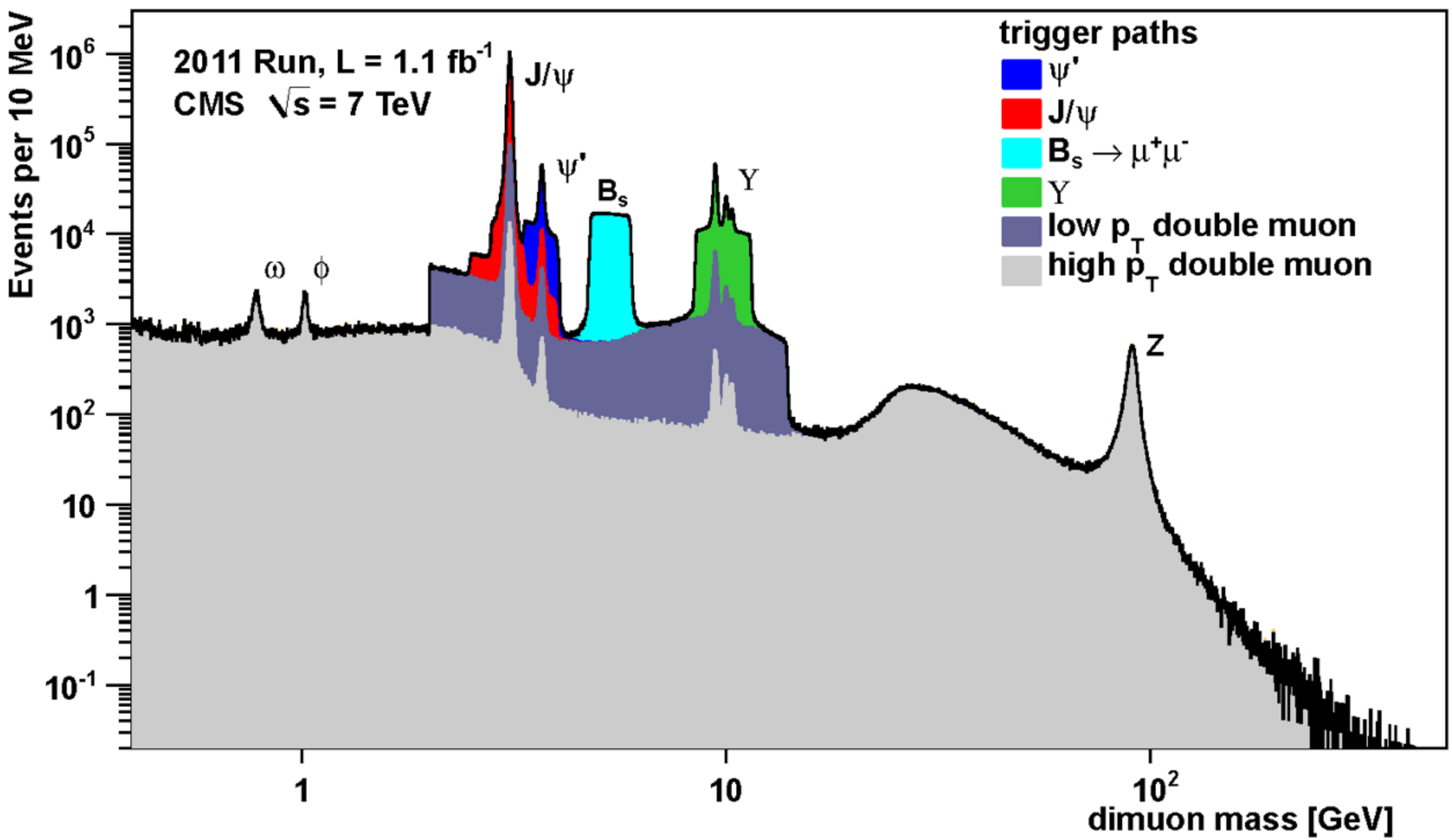




Collision in CMS



dimuon spectrum



A Toroidal LHC Apparatus

Searching for the Higgs

The <u>idea:</u>

Collide protons at high energy at LHC

Repeat 40 million times per second for a year

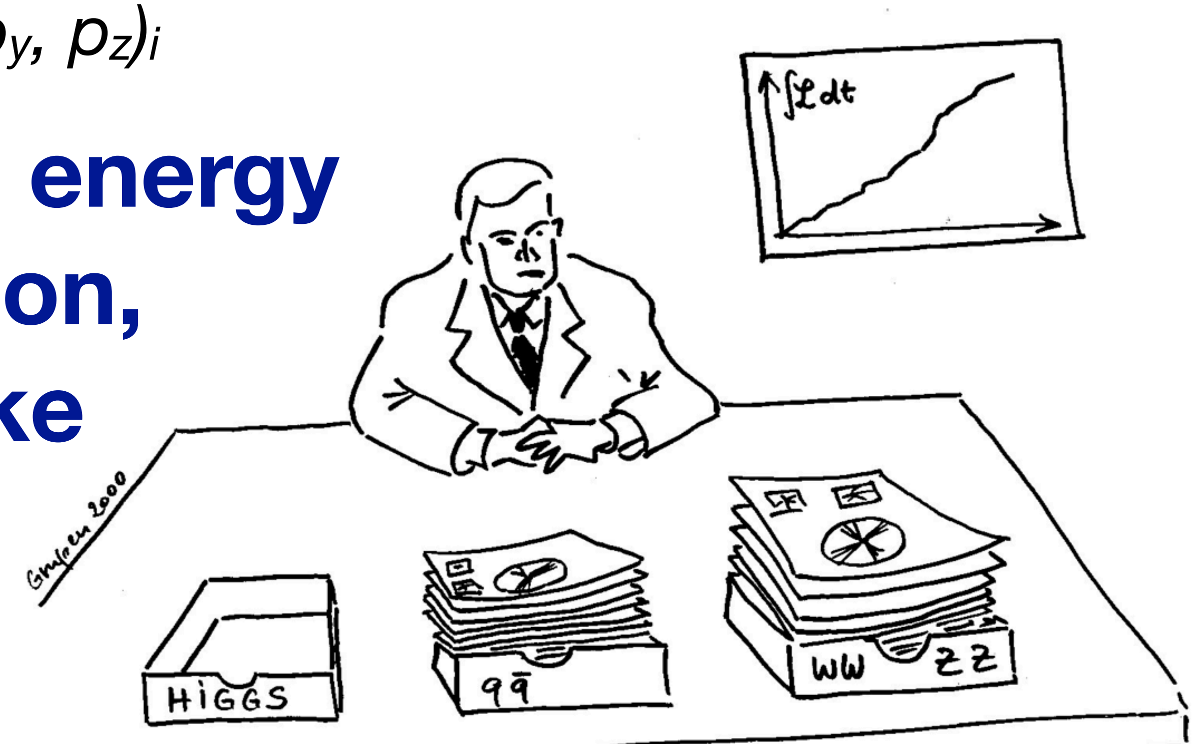
in 1 year = 3×10^{7} s x 4×10^{7} /s = 10^{14} = 100 trillion collisions!

Look for distinctive "signature" in decay products, as recorded with detector

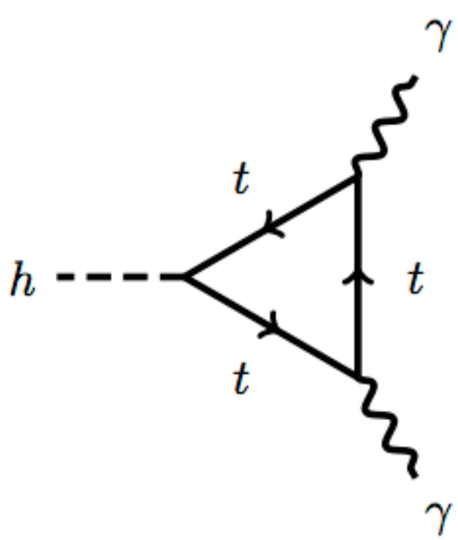
TYPES (electrons, photons, quarks, muons...)

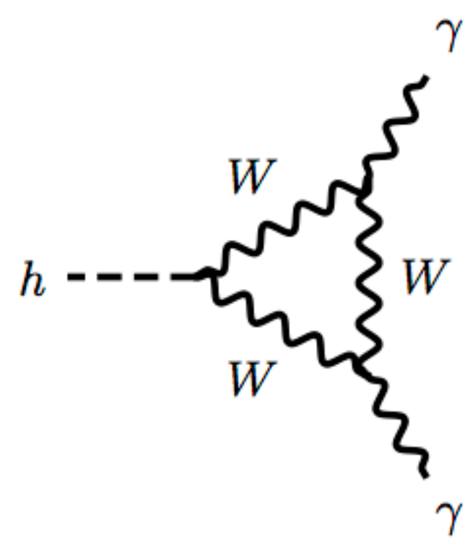
ENERGIES and MOMENTA: $(E, p_x, p_y, p_z)_i$

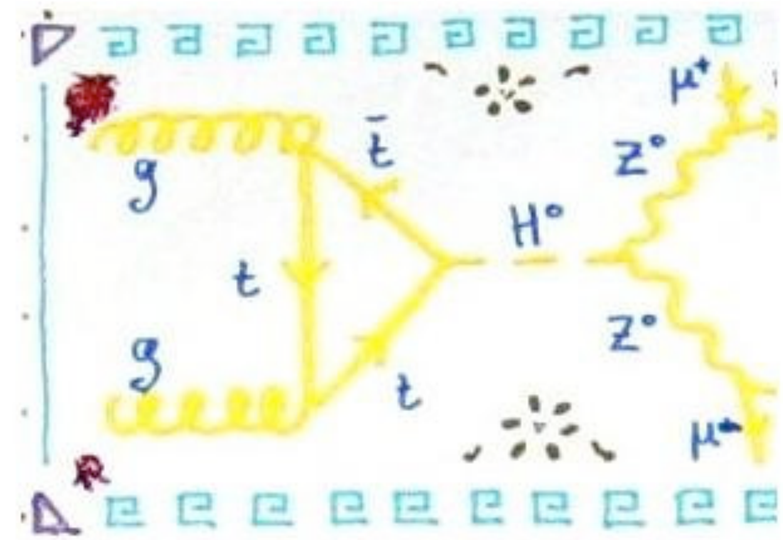
Analyze all the tracks and energy deposits from each collision, create sample of Higgs-like events

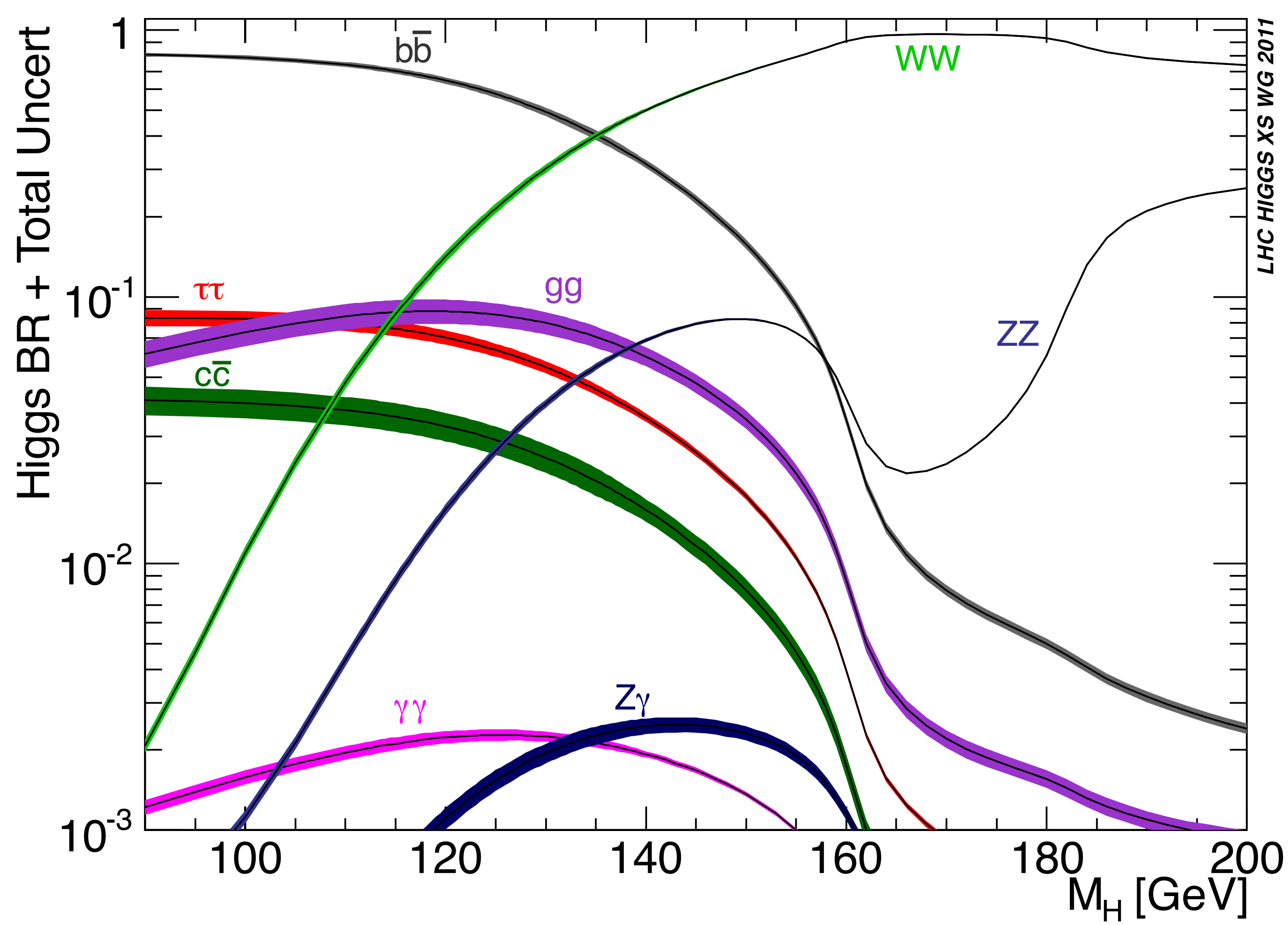


Higgs Decay Signatures

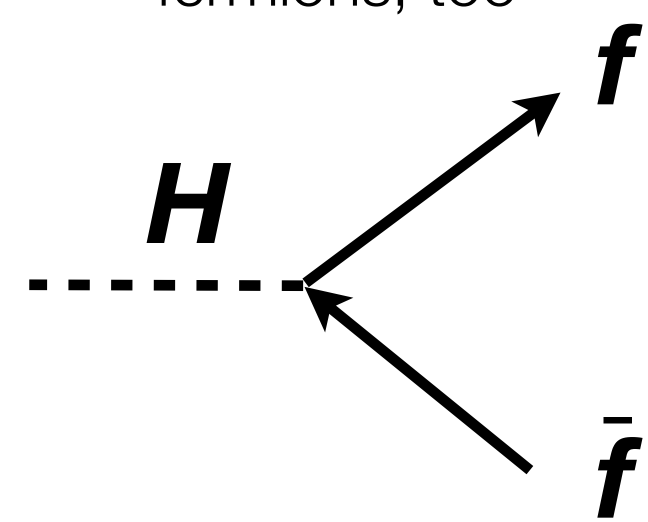




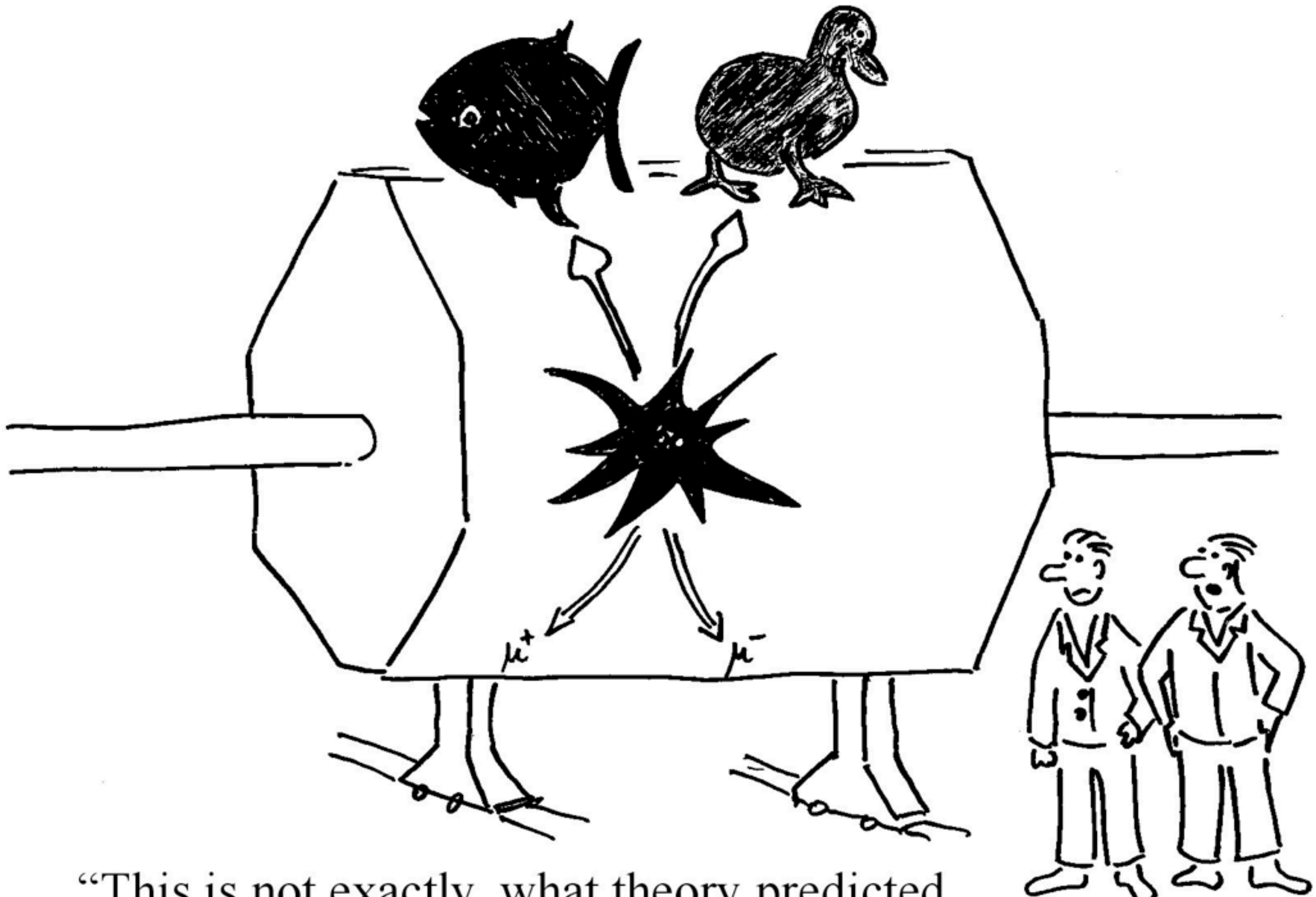




Higgs should couple to fermions, too

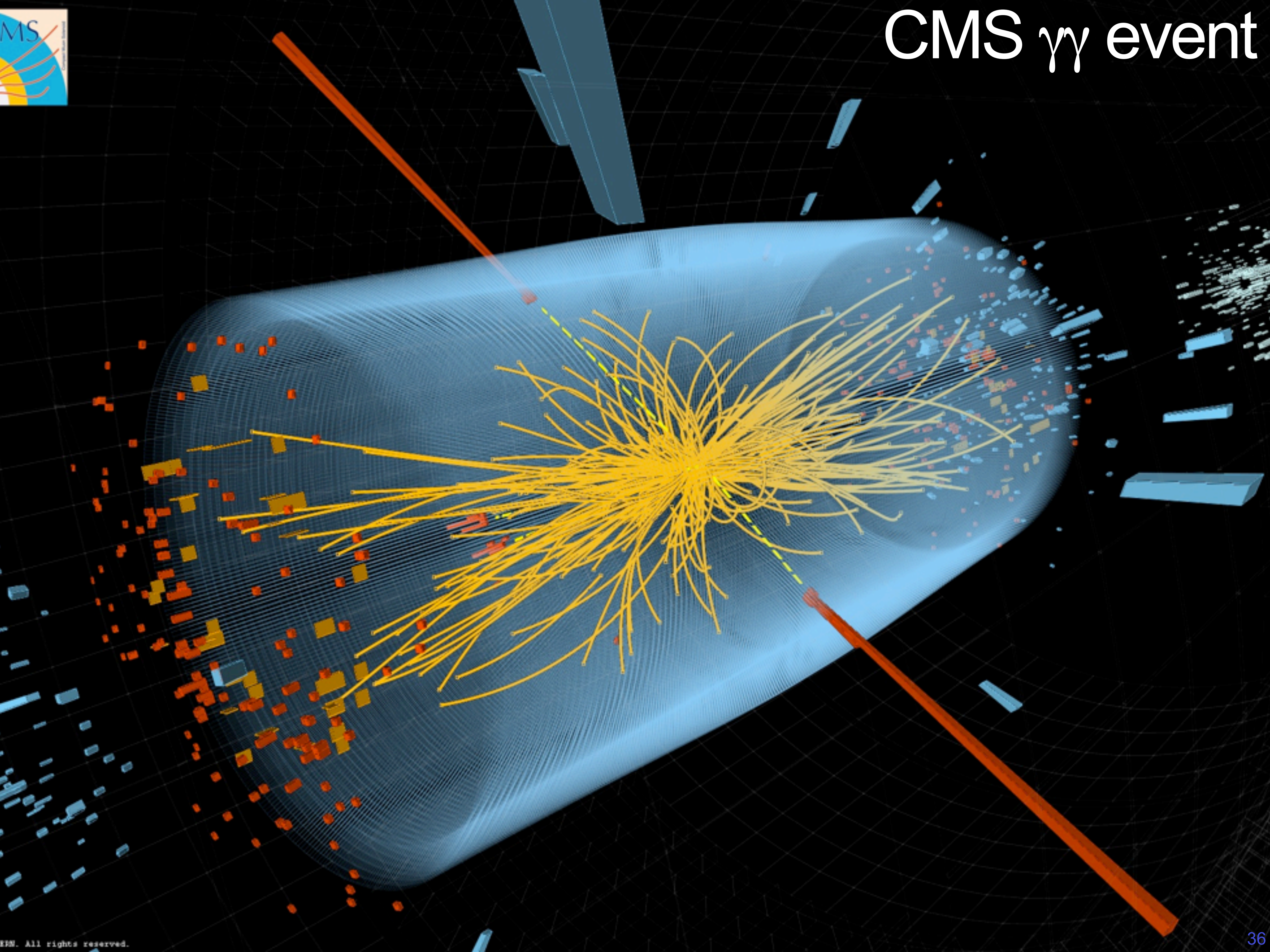


Higgs Decays?

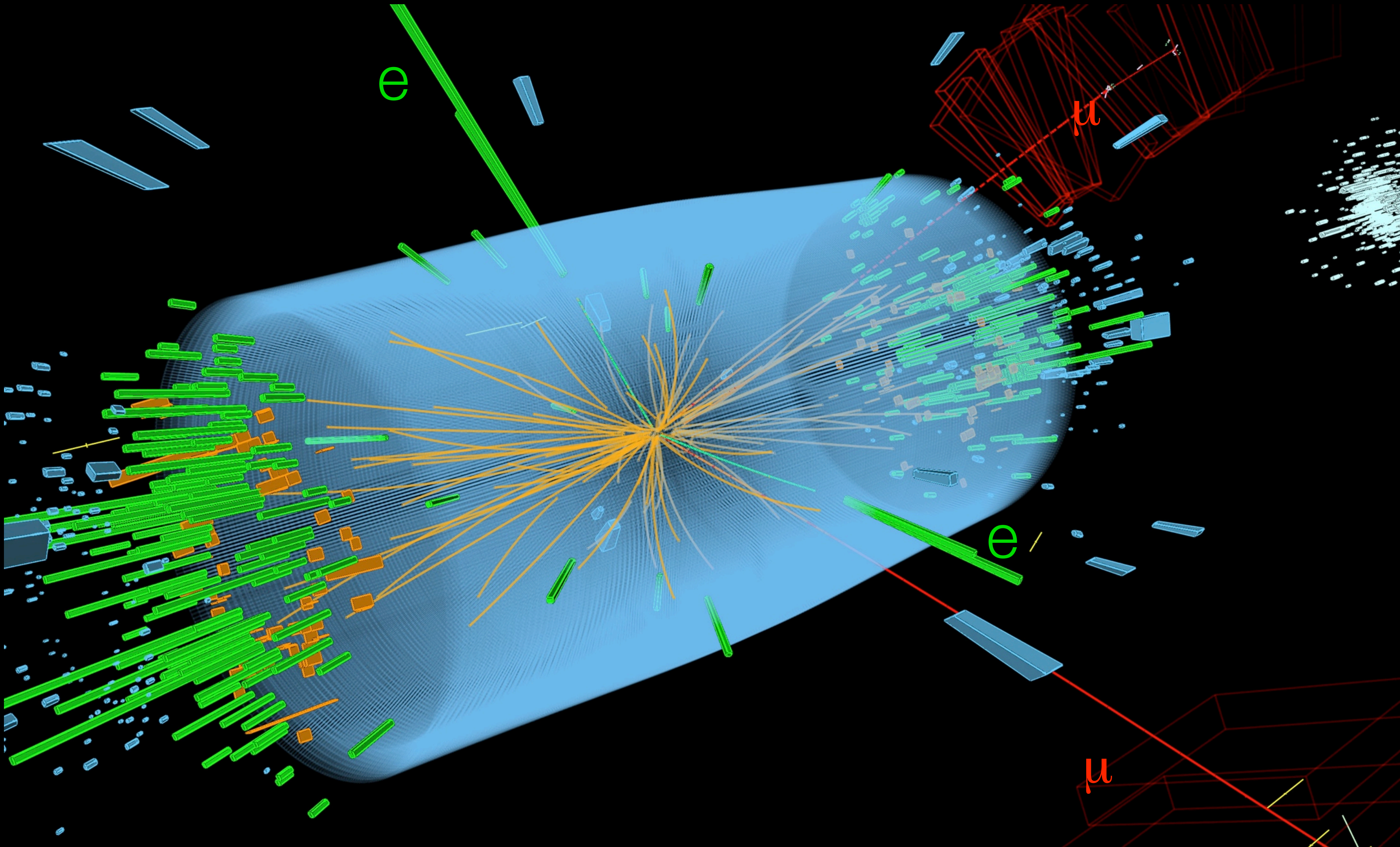


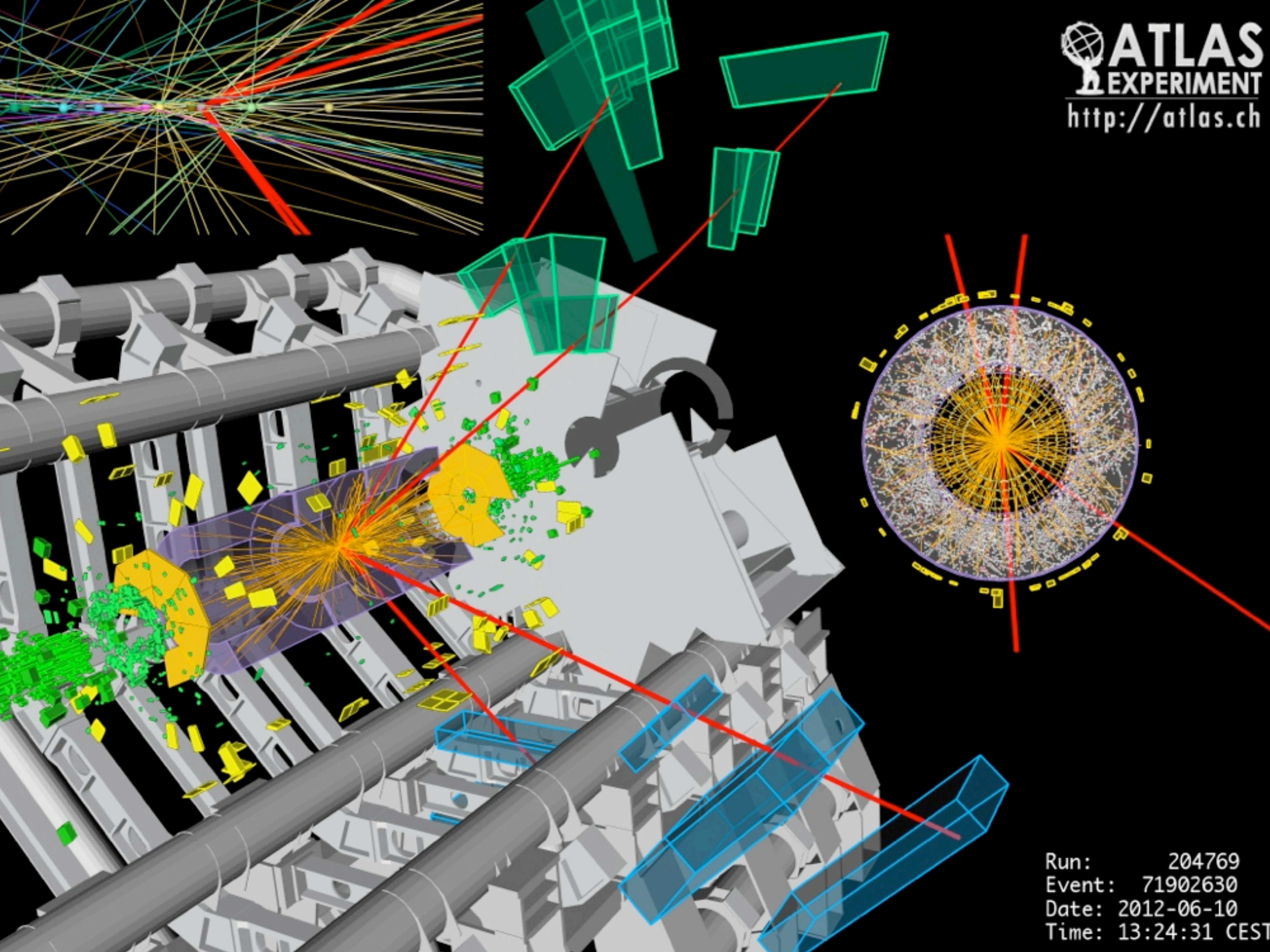
"This is not exactly, what theory predicted for the Higgs decay!"

CMS $\gamma\gamma$ event



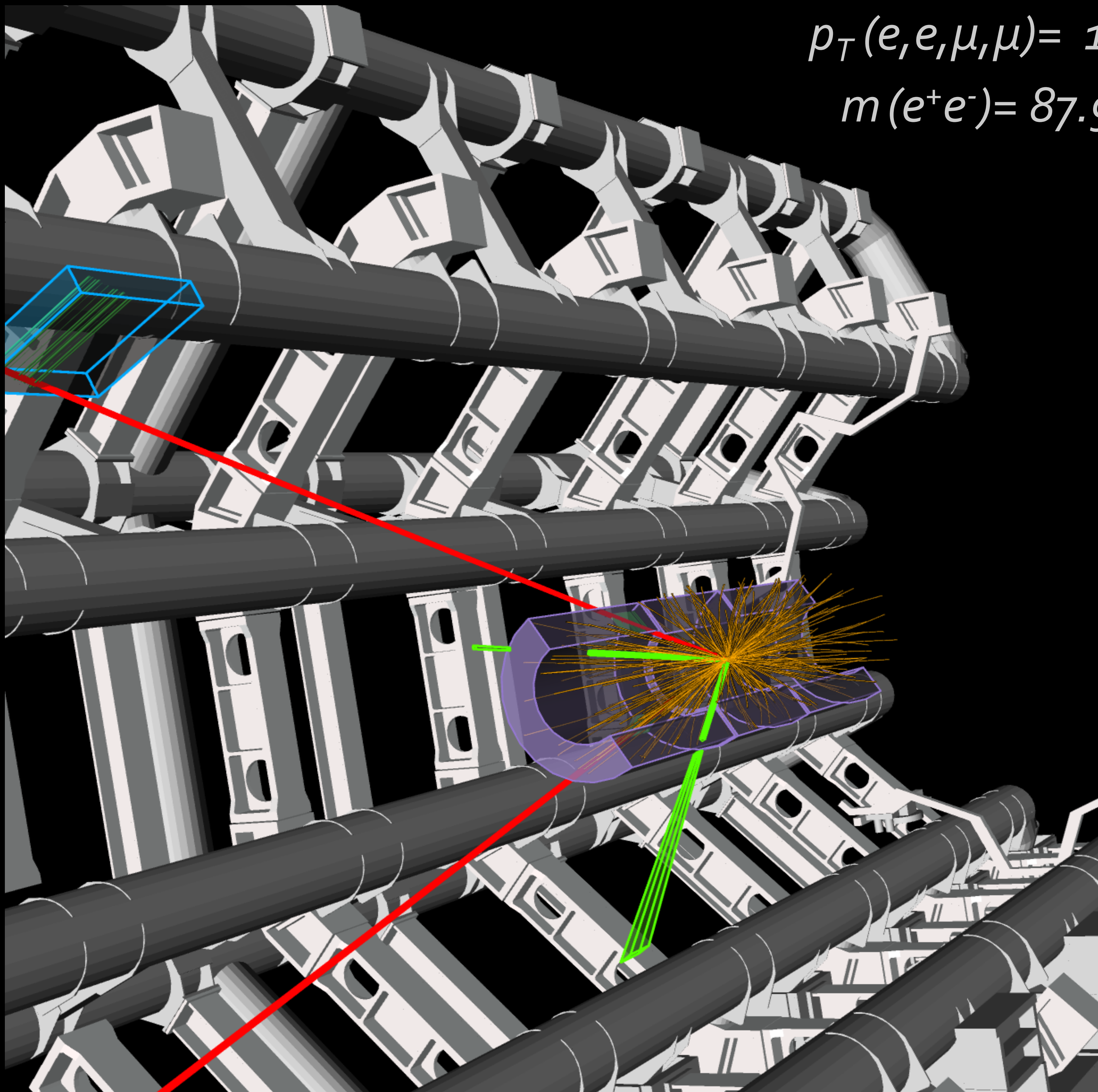
CMS ZZ→eeμμ candidate



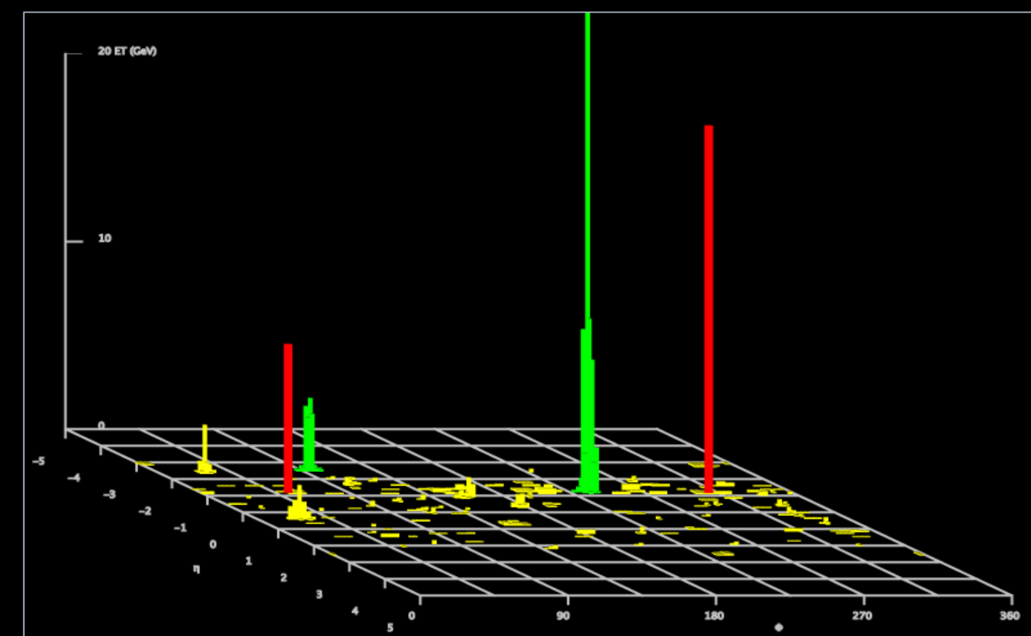

ATLAS
EXPERIMENT
http://atlas.ch
Run: 204769
Event: 71902630
Date: 2012-06-10
Time: 13:24:31 CEST

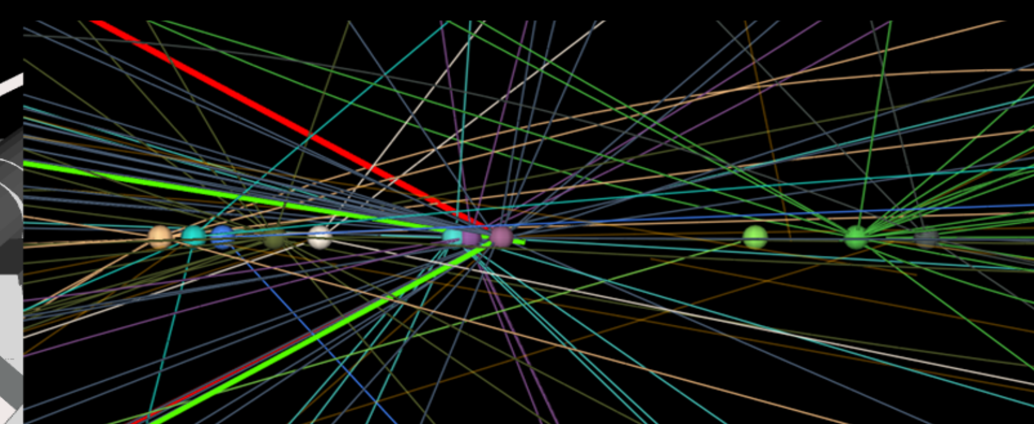
ATLAS: $M_{2e2\mu}$= 123.9 GeV

$p_T\,(e,e,\mu,\mu)$= 18.7, 76, 19.6, 7.9 GeV,
$m\,(e^+e^-)$= 87.9 GeV, $m(\mu^+\mu^-)$ =19.6 GeV



ATLAS EXPERIMENT
http://atlas.ch
Run: 205113
Event: 12611816
Date: 2012-06-18
Time: 11:07:47 CEST



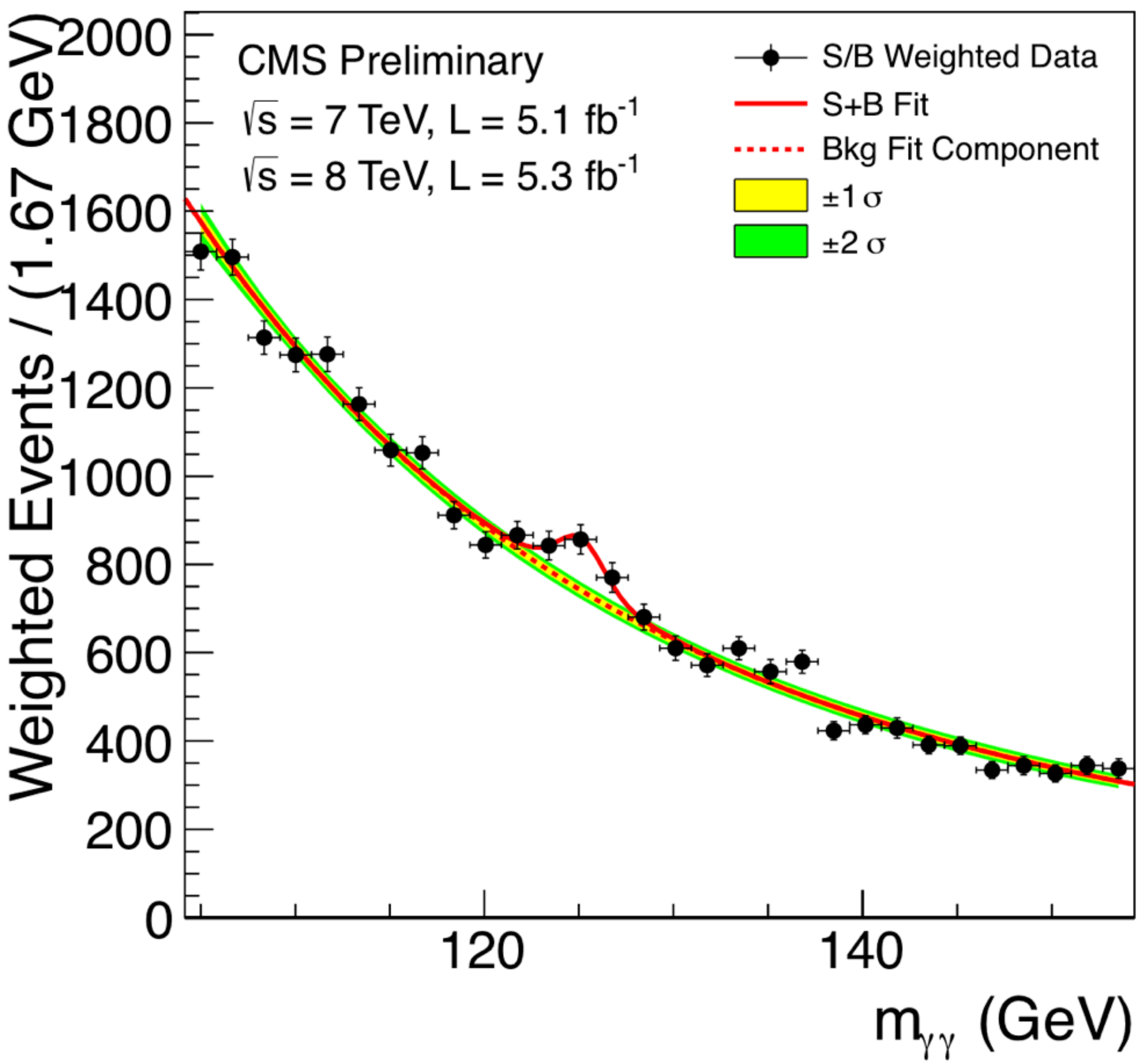


12 reconstructed vertices

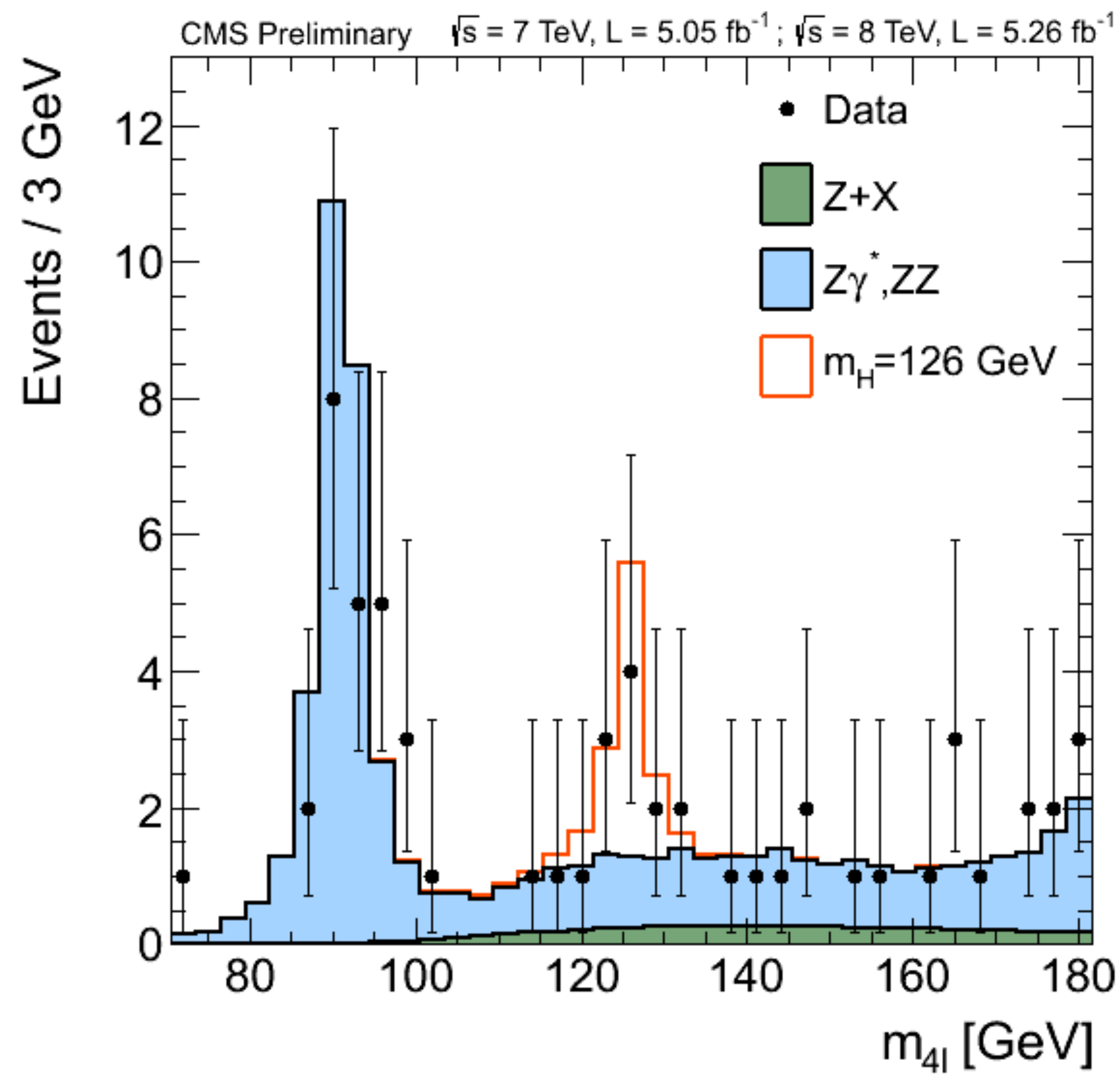
We waited as the data slowly accumulated

CMS Higgs Results: Presented July 4, 2012

H→photon+photon



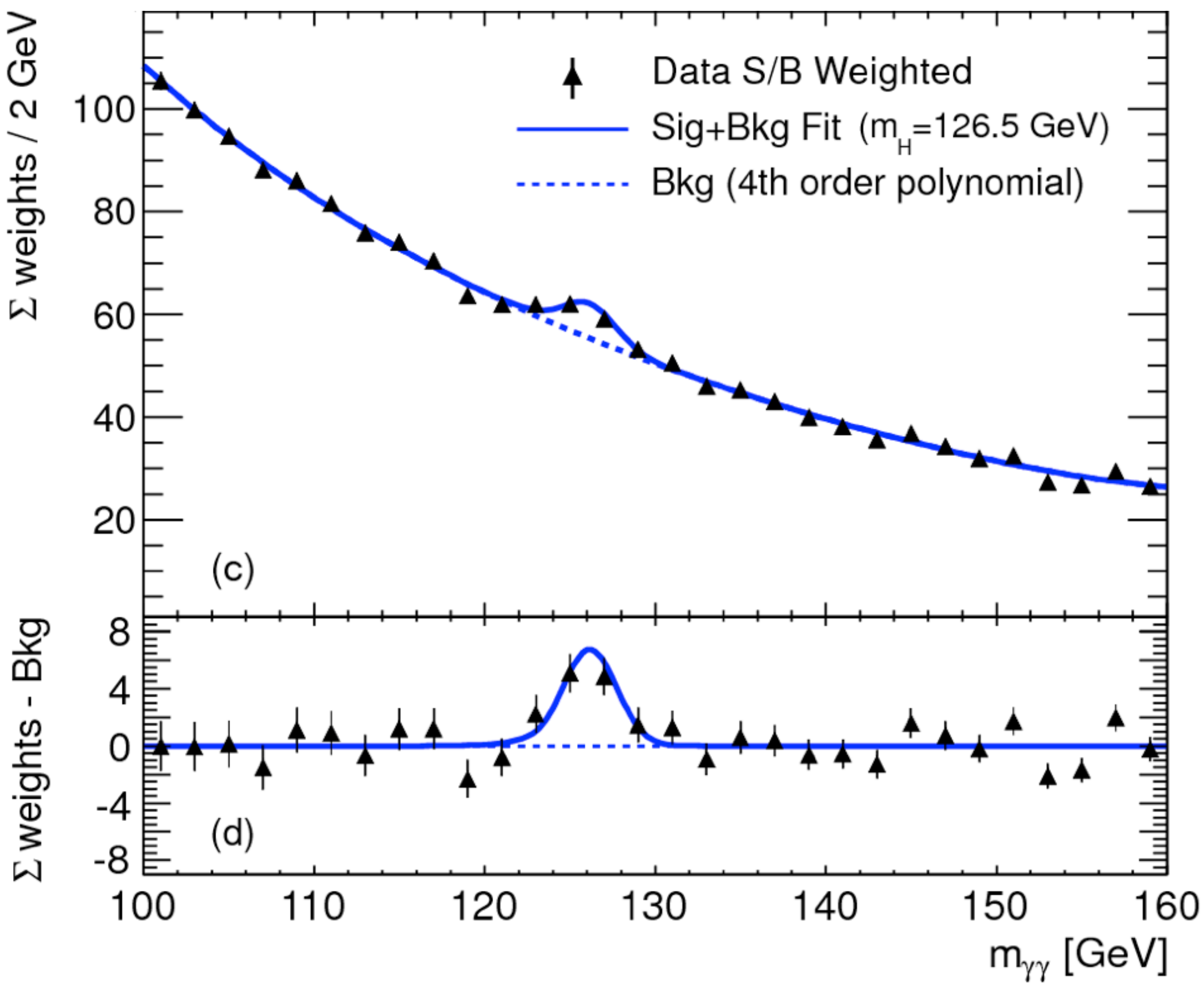
H→Z Z→4 leptons



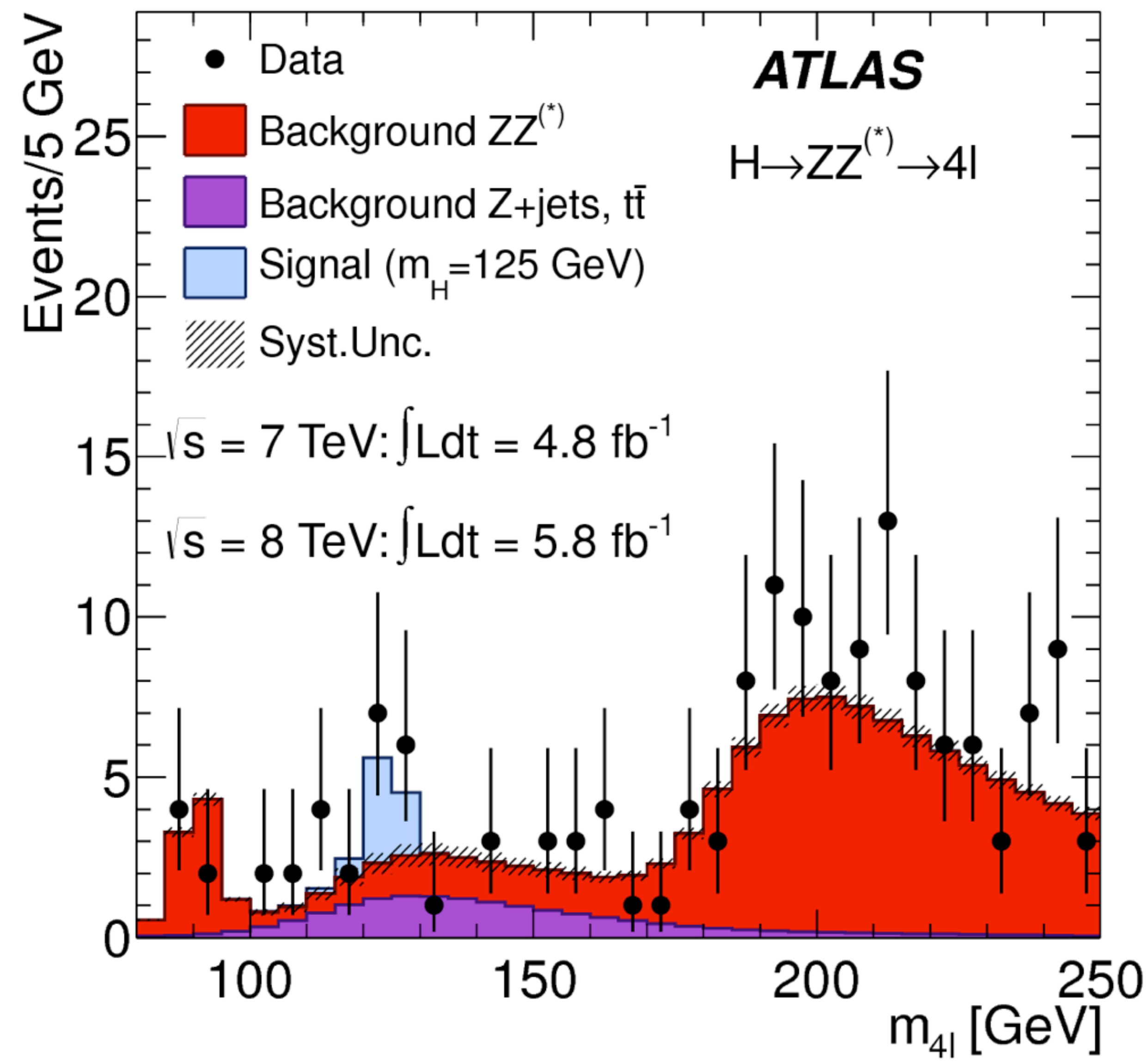

I FOUND A NEW PARTICLE

ATLAS Higgs Results

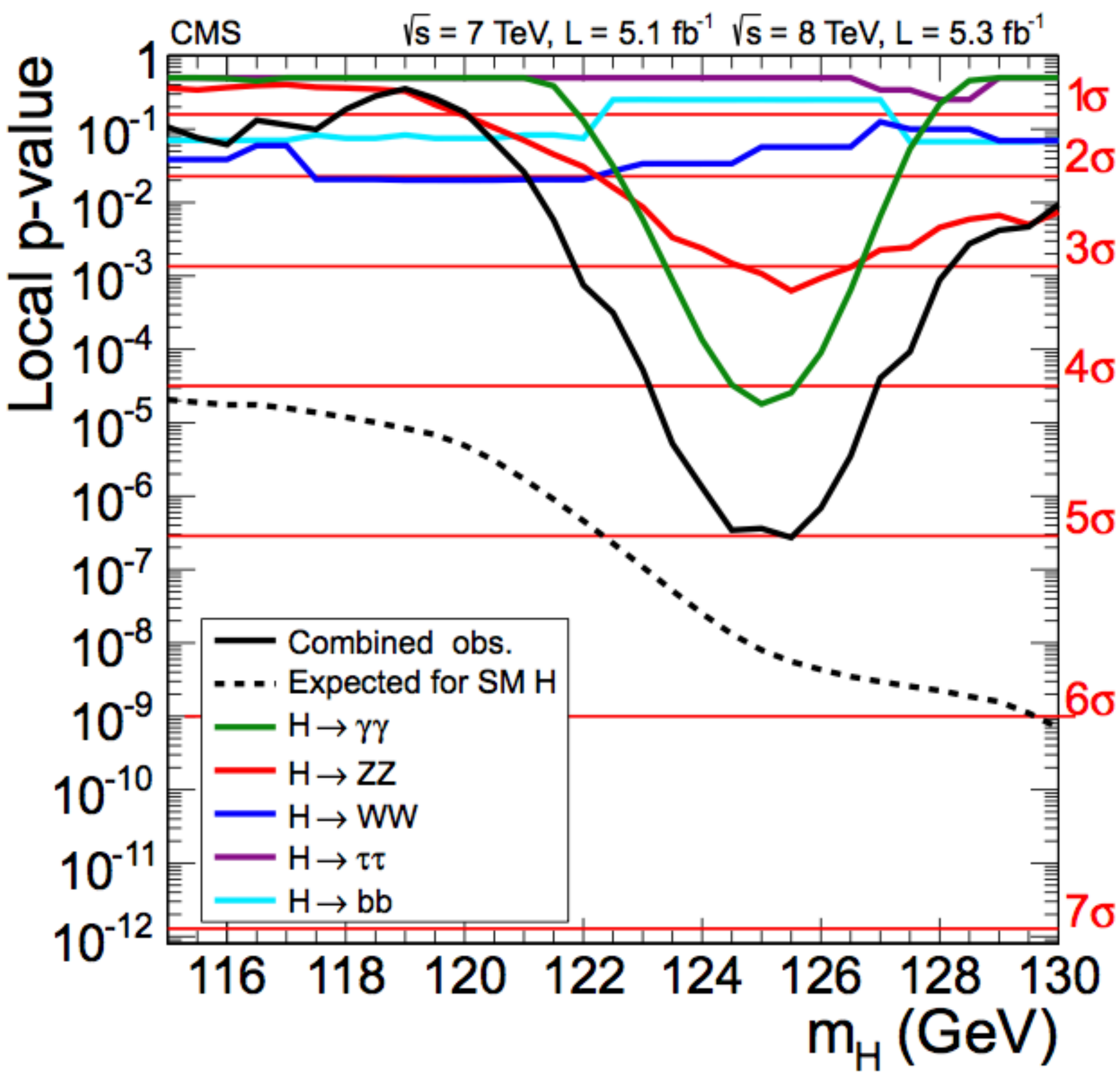
H→photon+photon

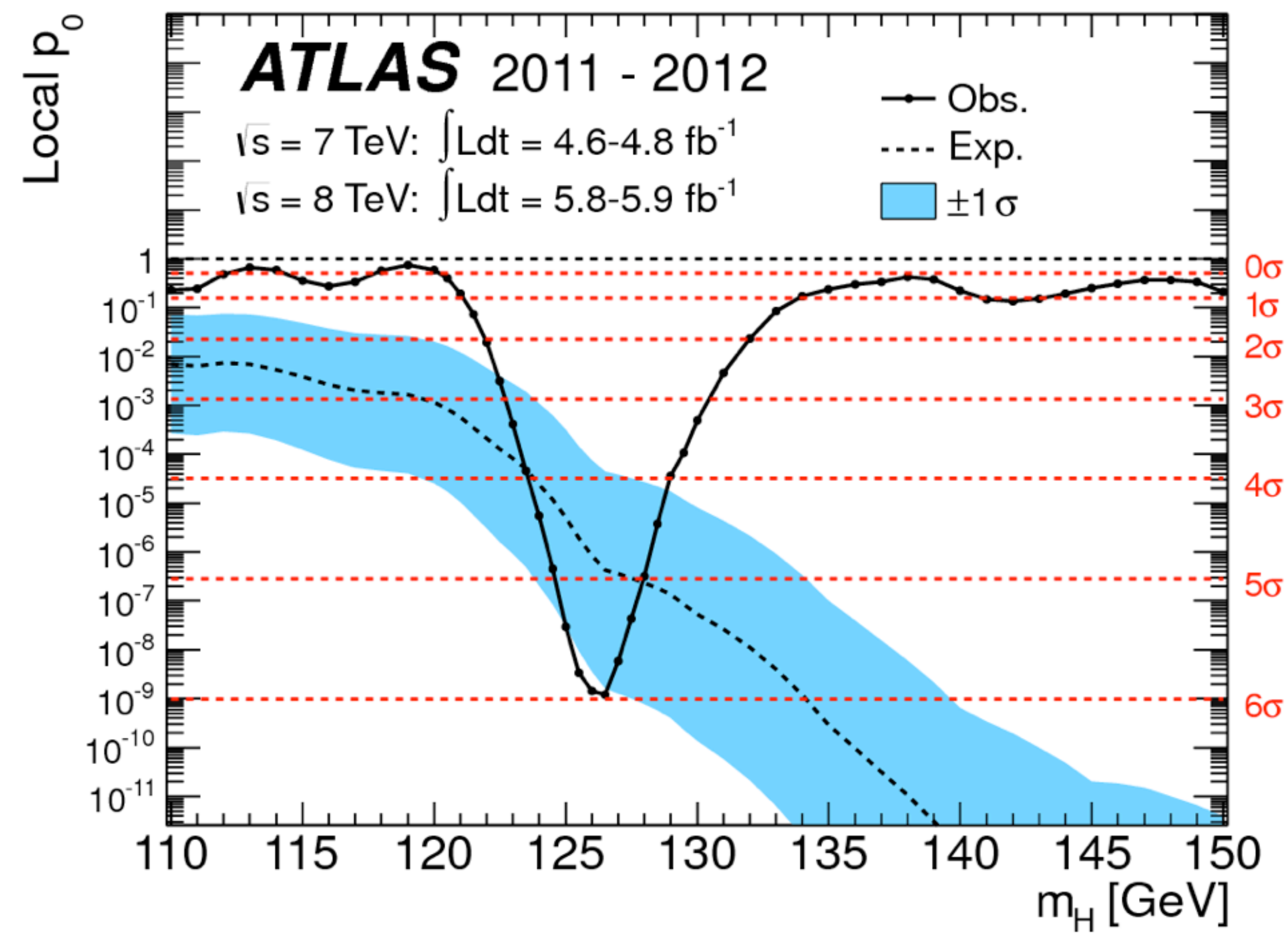


H→Z Z→4 leptons

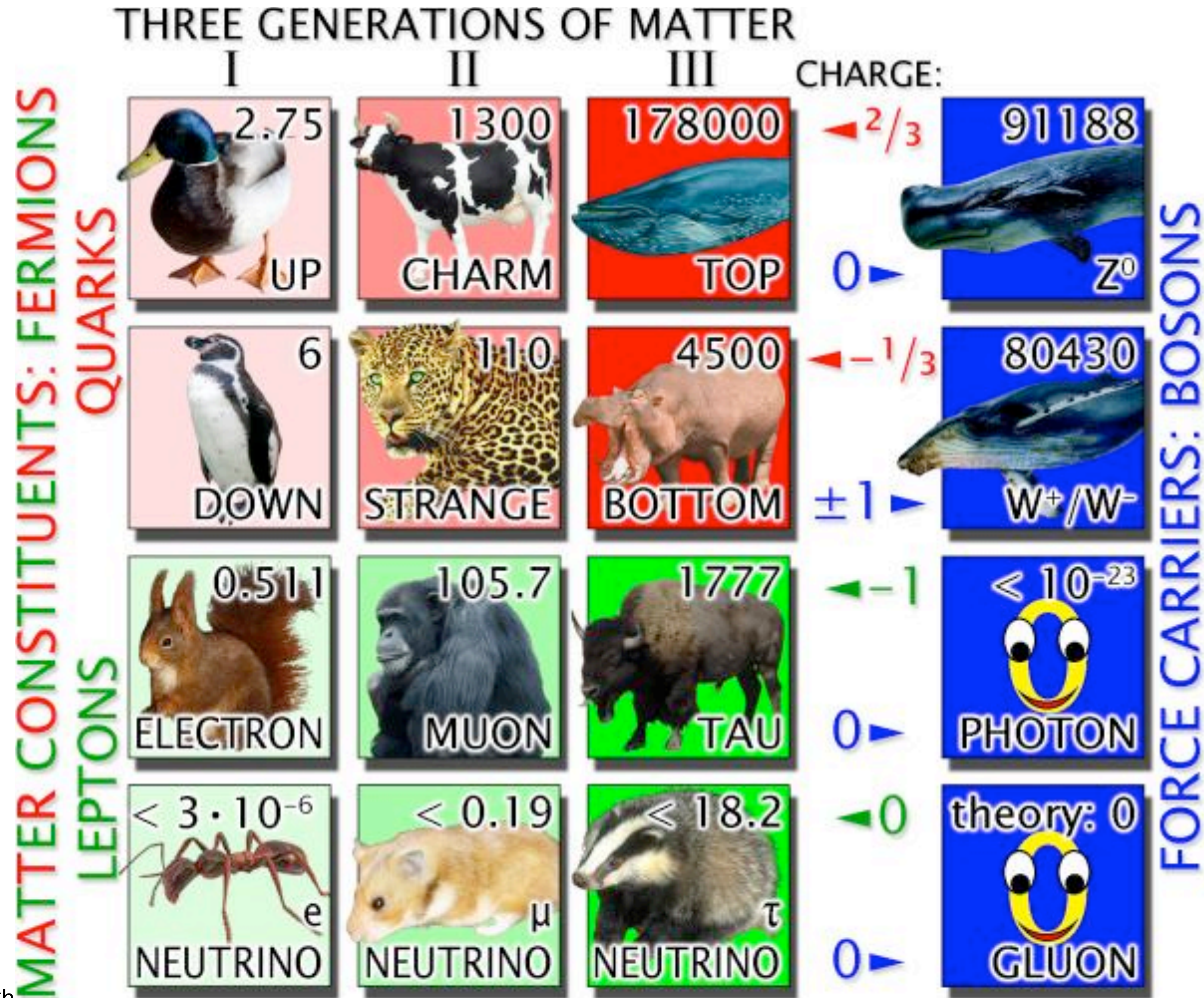


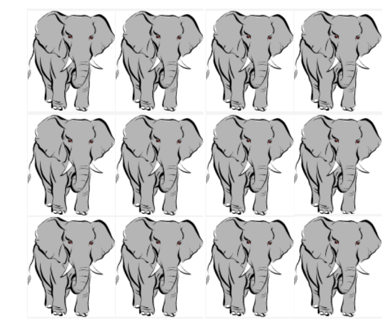
Significance of Results





The Standard Model, July 4, 2012





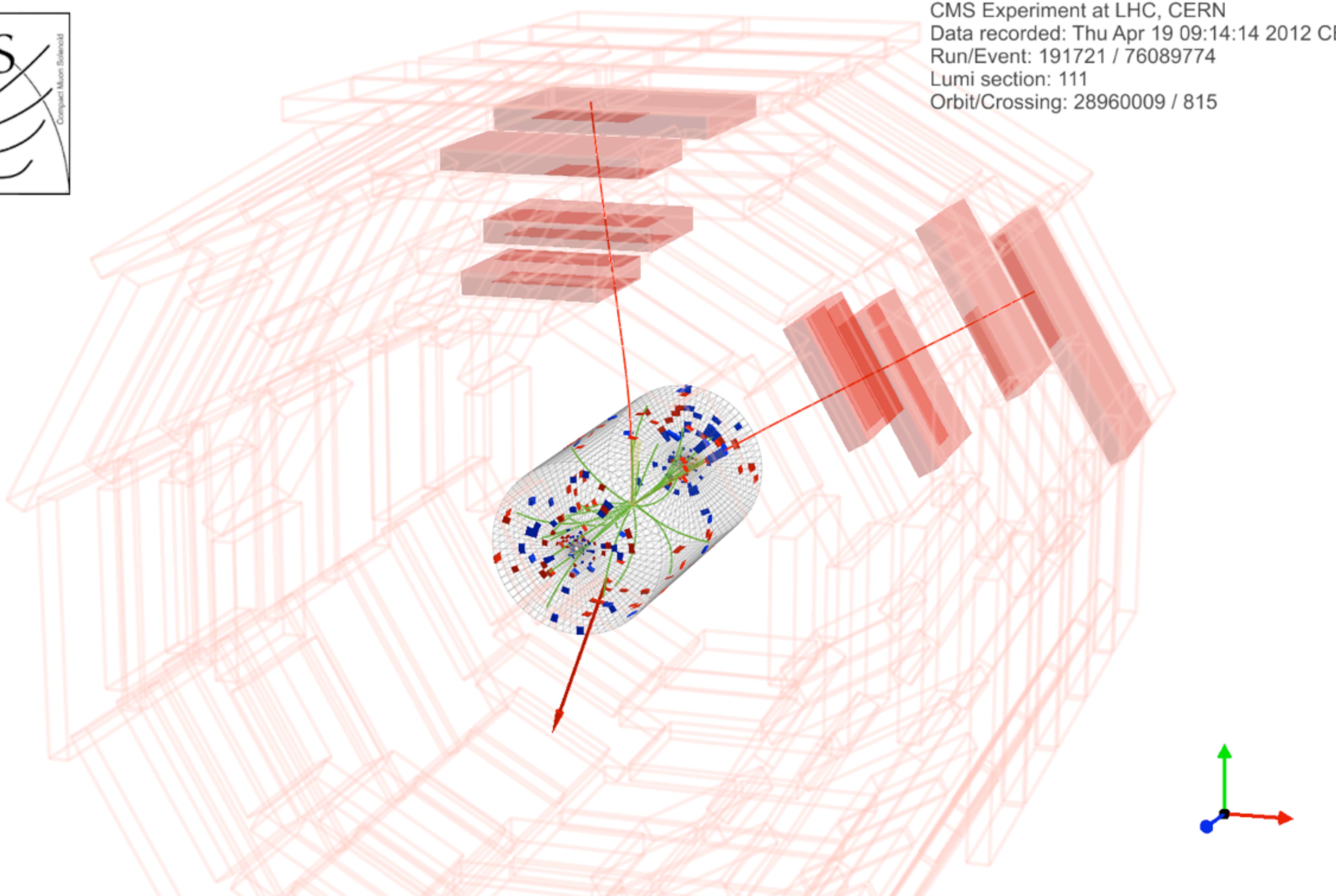
125000

12 elephants

HIGGS-LIKE

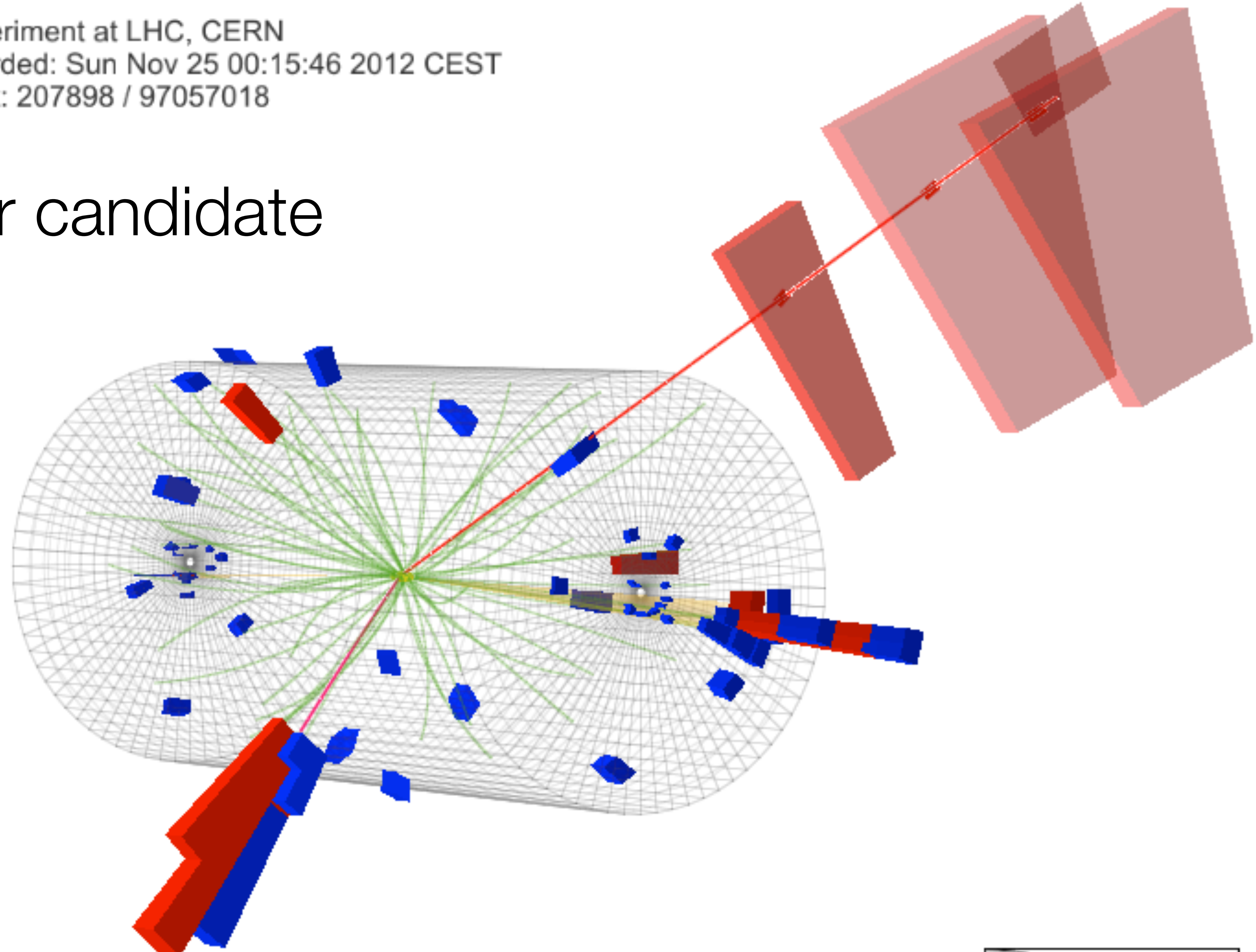
M. Ch

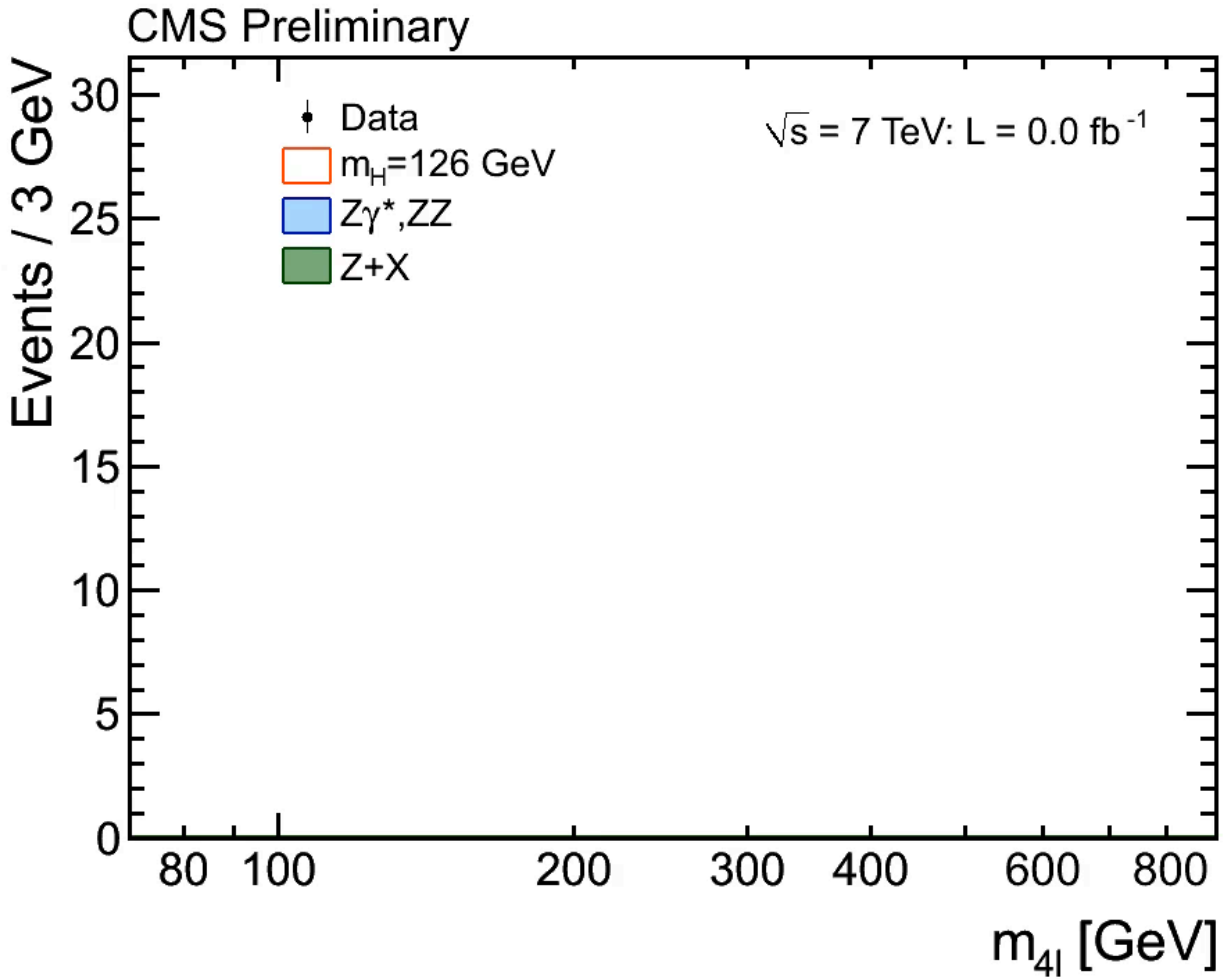
Adding in the newest data from 2012: H→ WW candidate



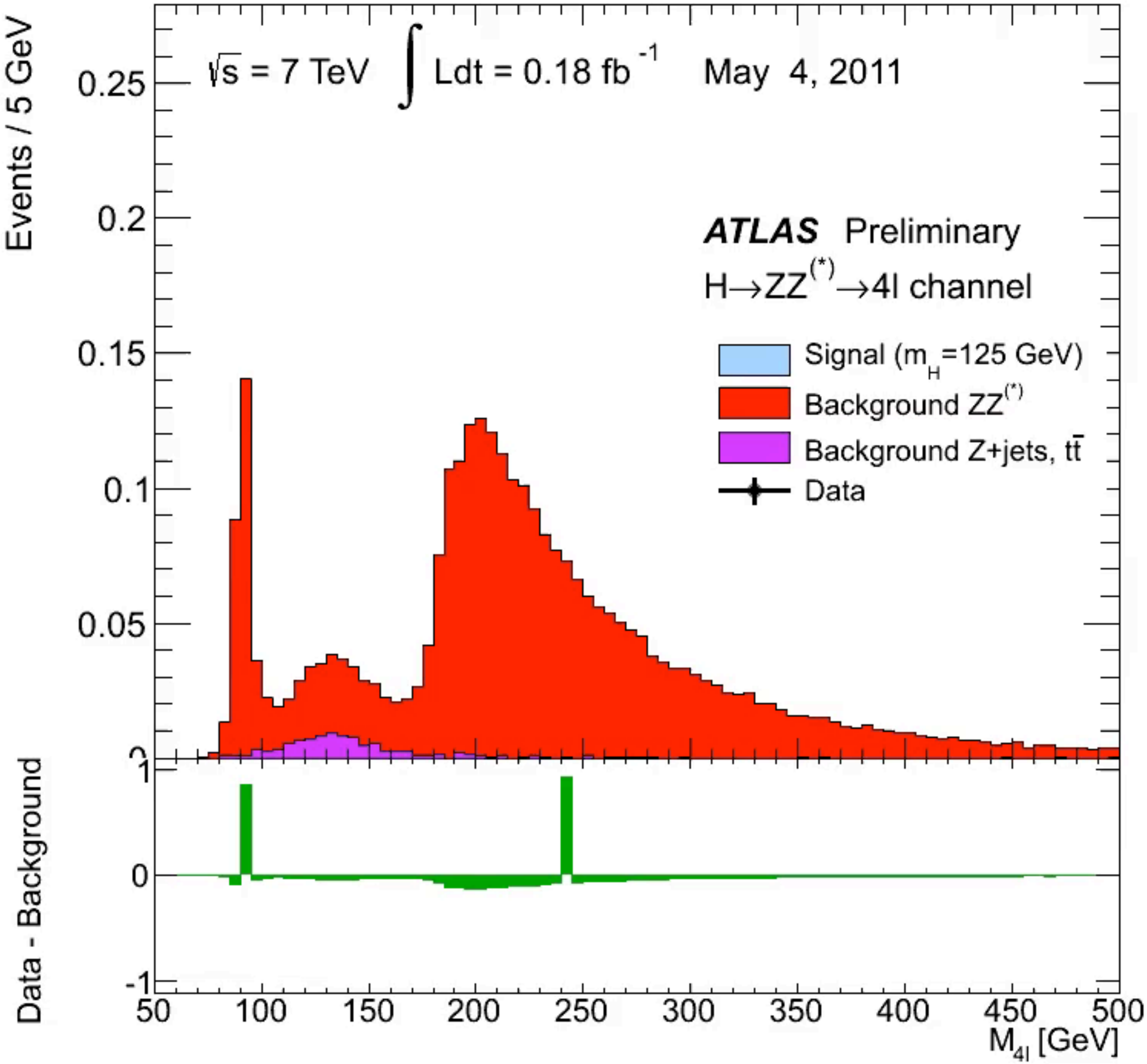
CMS Experiment at LHC, CERN
Data recorded: Sun Nov 25 00:15:46 2012 CEST
Run/Event: 207898 / 97057018

H → tau pair candidate





CMS Preliminary
Data
m_H=126 GeV
Zγ*,ZZ
Z+X
$\sqrt{s}$ = 7 TeV: L = 0.0 fb^{-1}
Events / 3 GeV
0
5
10
15
20
25
30
80
100
200
300
400
600
800
m_{4l} [GeV]



√s = 7 TeV ∫Ldt = 0.18 fb^-1 May 4, 2011
ATLAS Preliminary
H→ZZ(*)→4l channel
Signal (m_H=125 GeV)
Background ZZ(*)
Background Z+jets, tt̄
Data
Events / 5 GeV
0.25
0.2
0.15
0.1
0.05
0
Data - Background
1
0
-1
50
100
150
200
250
300
350
400
450
500
M_4l [GeV]

Press release from CERN

New results indicate that particle discovered at CERN is a Higgs boson -- Geneva, 14 March 2013

Some quotes:

“The preliminary results with the full 2012 data set are magnificent and to me it is clear that we are dealing with a Higgs boson though we still have a long way to go to know what kind of Higgs boson it is.” said CMS spokesperson Joe Incandela.

"The beautiful new results represent a huge effort by many dedicated people. They point to the new particle having the spin-parity of a Higgs boson as in the Standard Model. We are now well started on the measurement programme in the Higgs sector," said ATLAS spokesperson Dave Charlton.

(Notice it says “A Higgs boson” not “THE Higgs boson”)

Why is this theory still incomplete?

Why do these particles have the masses that they do?

Why are there three families?

Do the 4 forces all unify at some scale?

Is gravity special?

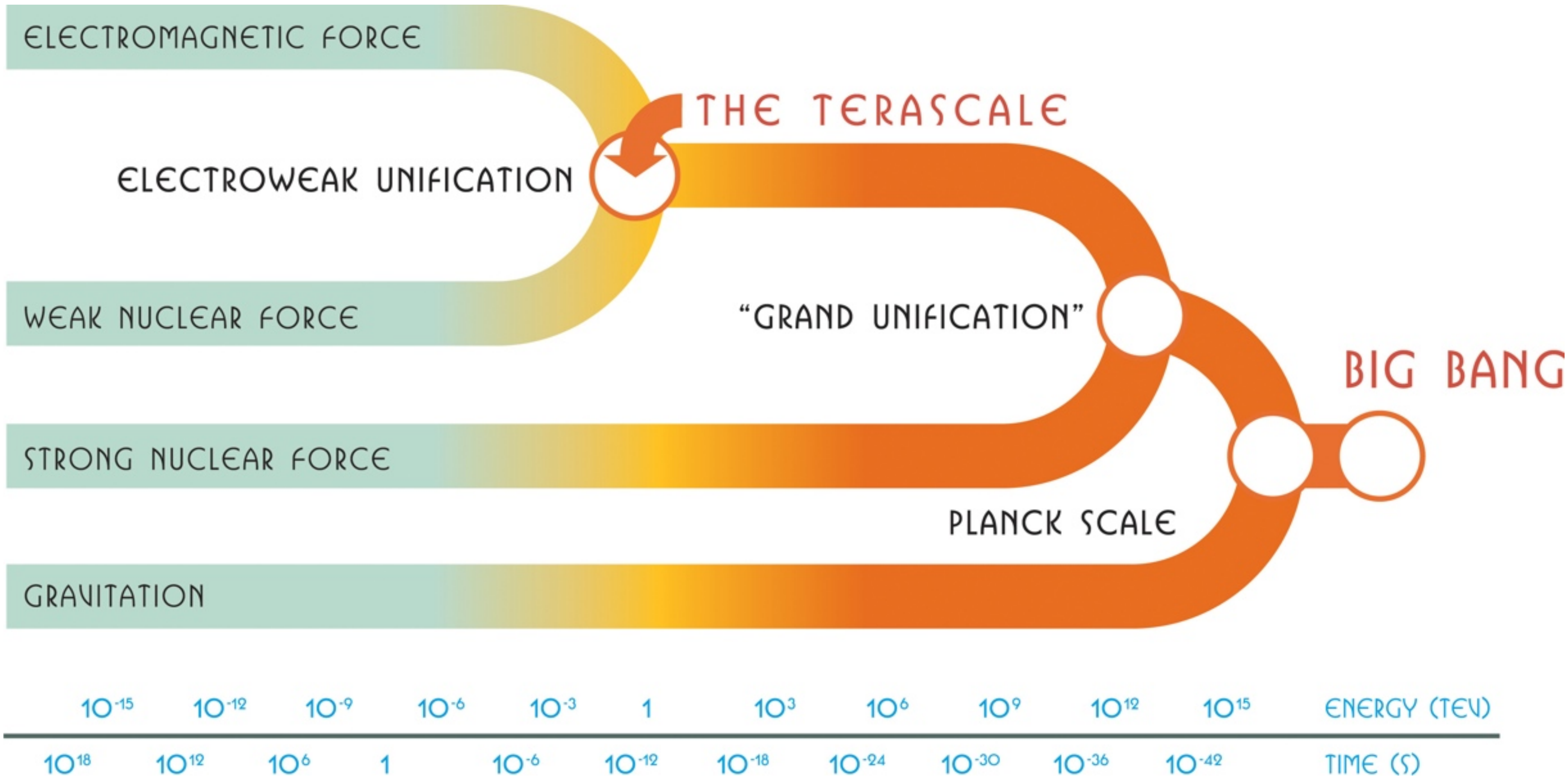
Why is there CP violation?

Where did the universe's antimatter go?

What is the source of dark matter in the universe?

What is the source of dark energy in the universe?

Terascale & Beyond



SUSY to rescue!?

SUPERSYMMETRY is a theory with intriguing features:

Plays nicely with string theory

Resolves the "hierarchy" problem

Unifies force couplings at high energy

Includes dark matter candidate

We need more data

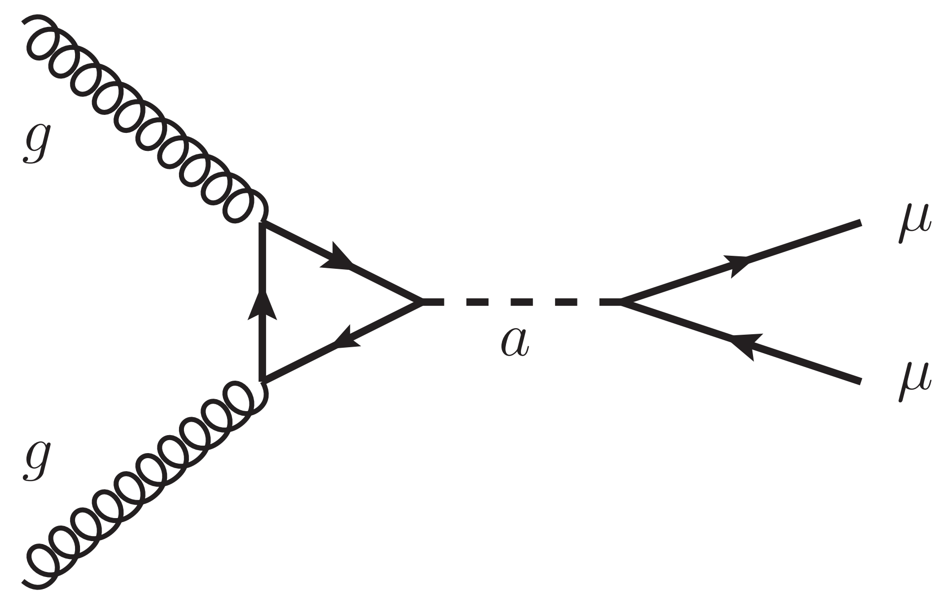
Search for a Light Pseudoscalar Higgs Boson

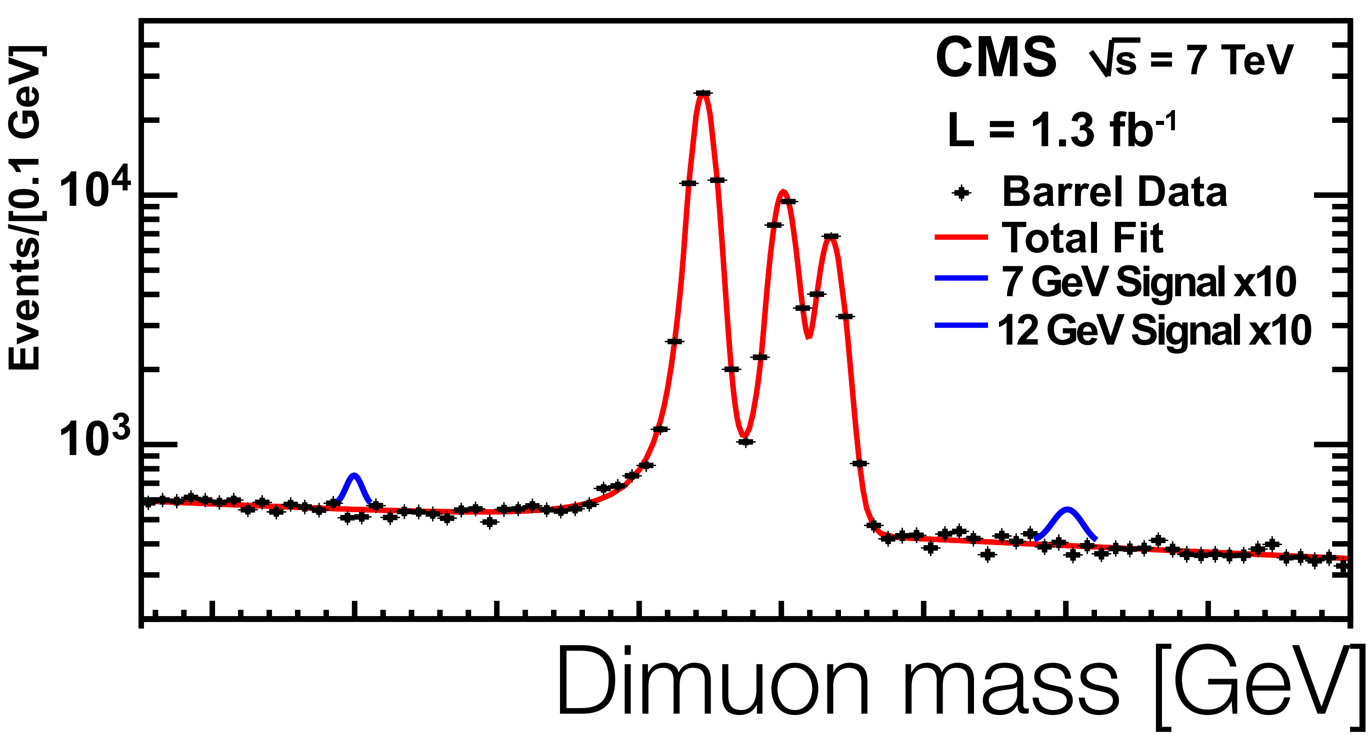
Next-to-minimal SUSY Higgs spectrum:

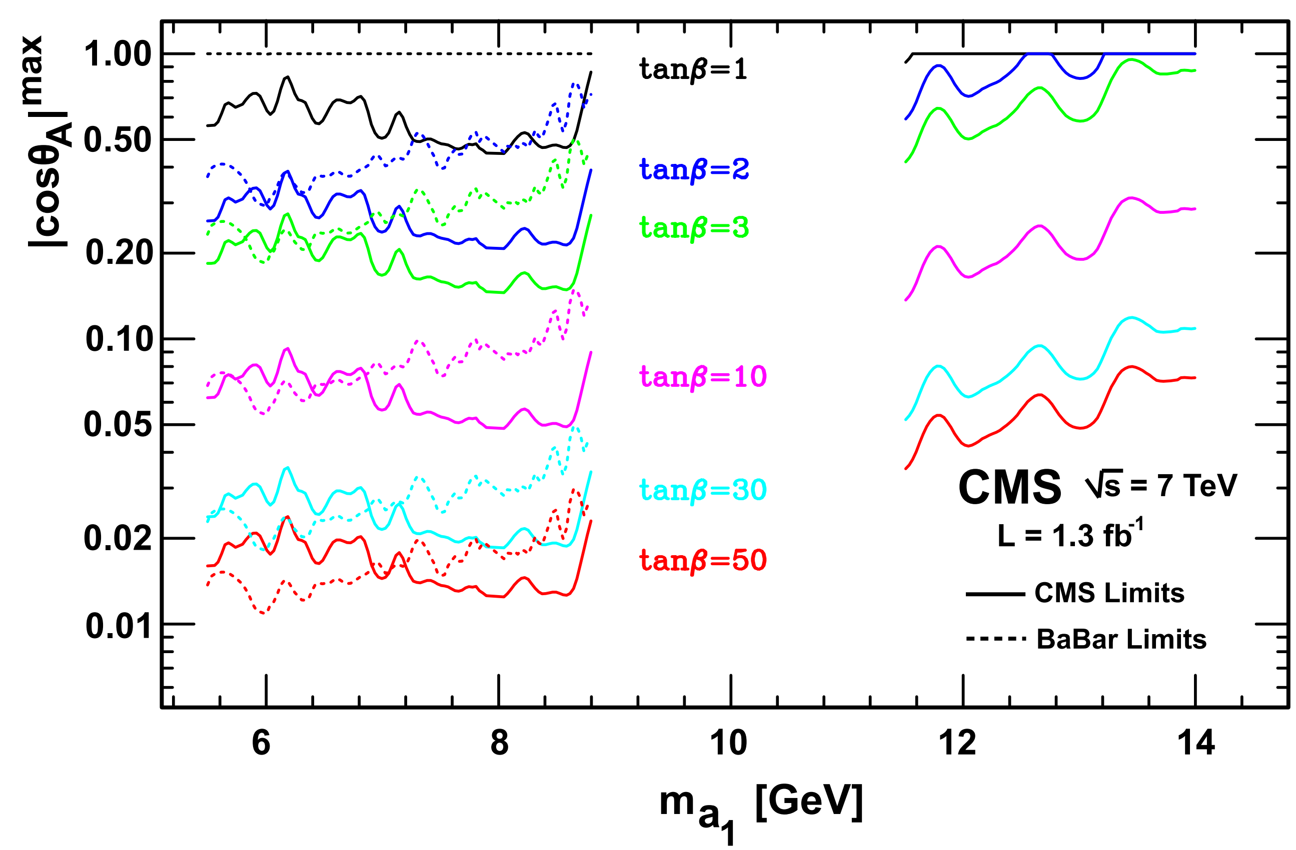
3 CP even scalars (h_1,h_2,h_3)

2 CP odd scalars (a_1,a_2)

2 charged scalars (H^+,H^-)







PRL 109 (2012) 121801 Much more to come!

Conclusions

Particle physics ~century of discoveries

Experimental and theoretical

Electroweak theory → Higgs prediction

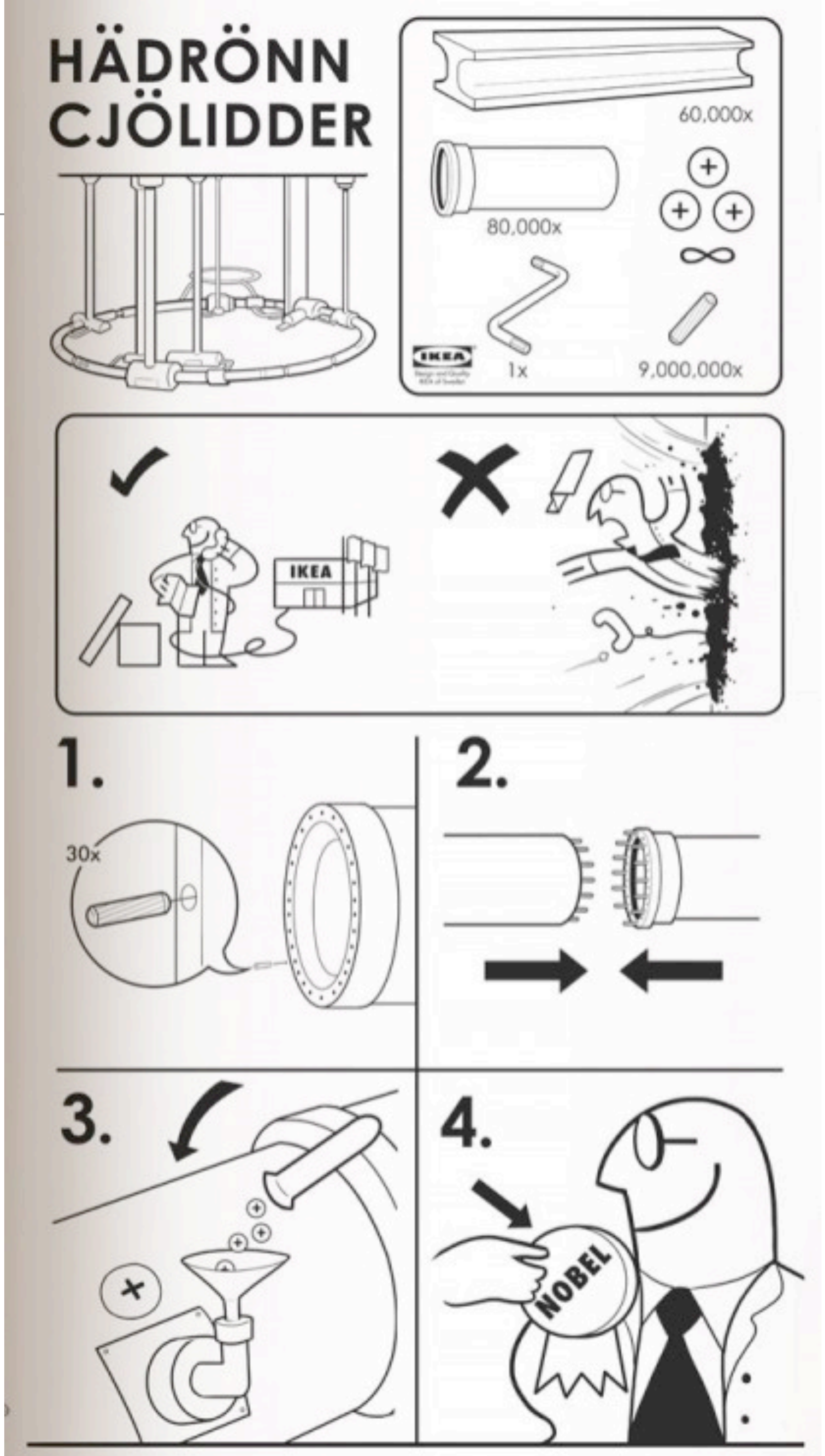
Major Discovery, 2012

Higgs spin, parity, and couplings are SM-like

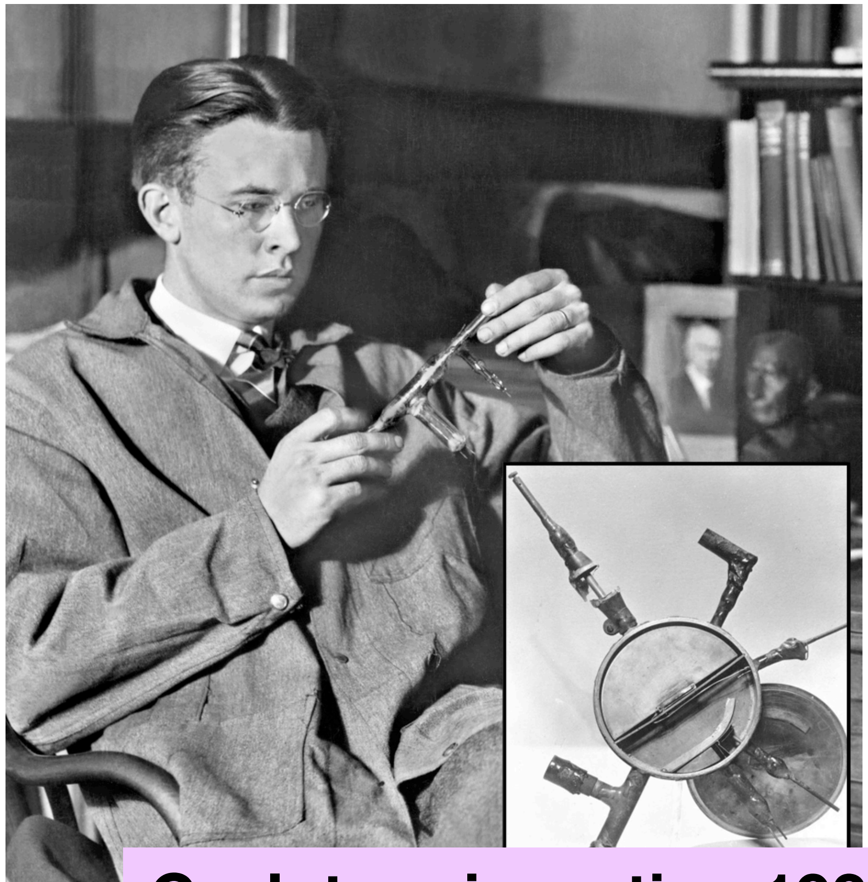
Is the Standard Model all there is?

Or, are there more exotic new particles and forces to be discovered?

LHC: protons 12 MPH faster in 2014!

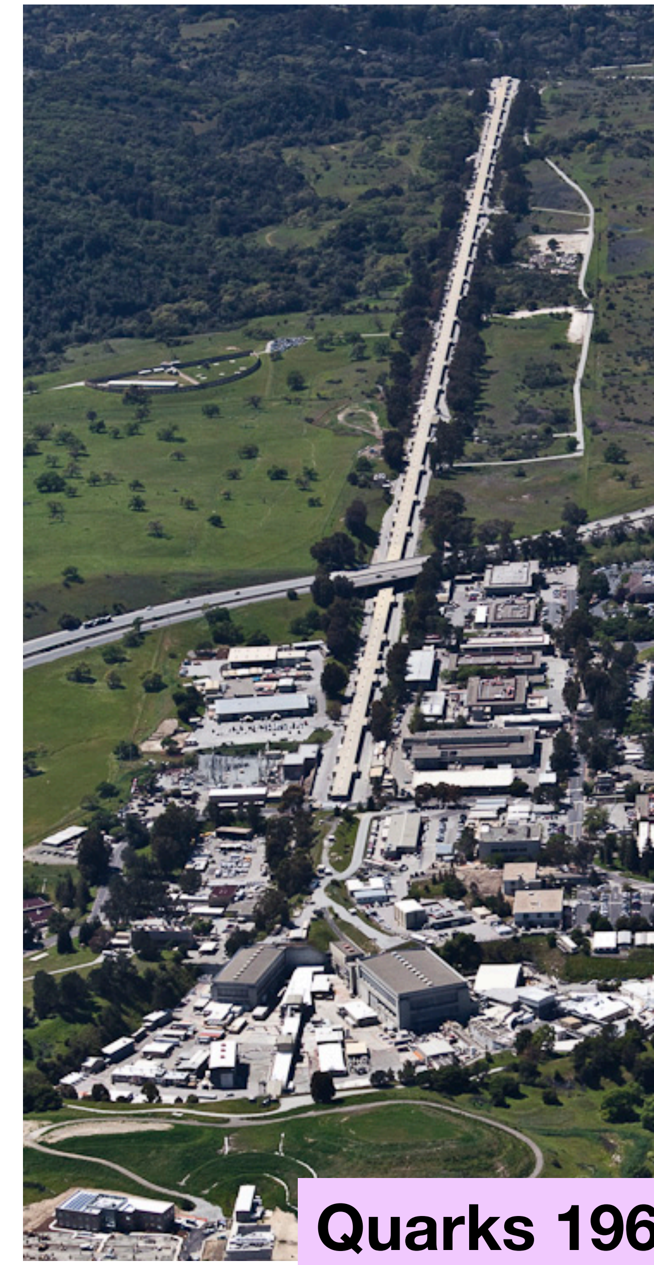


Backup

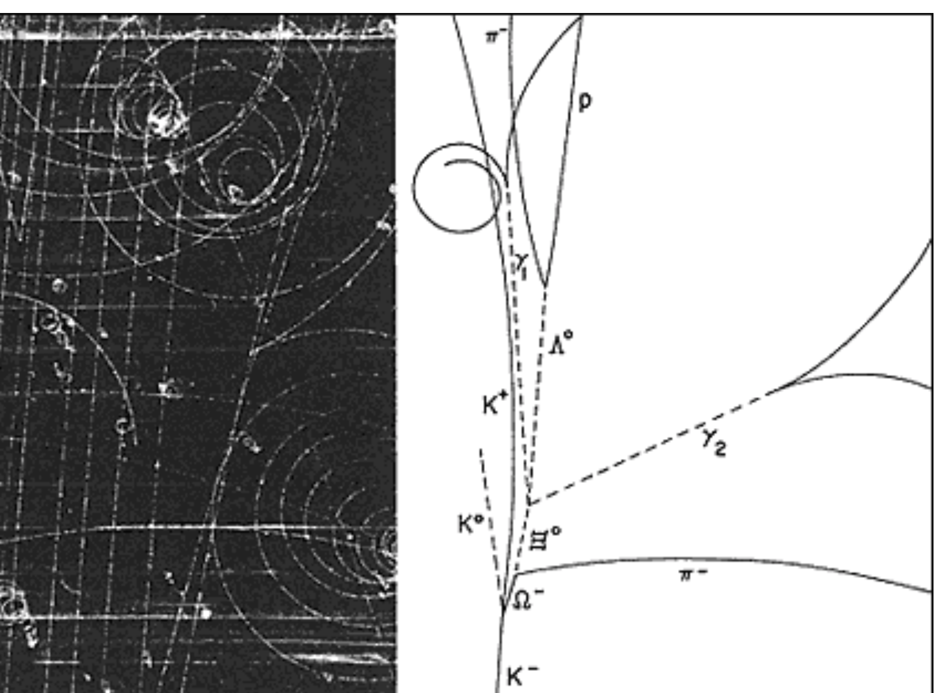


Cyclotron invention 1931

Muon 1936,
Charged Pion 1947

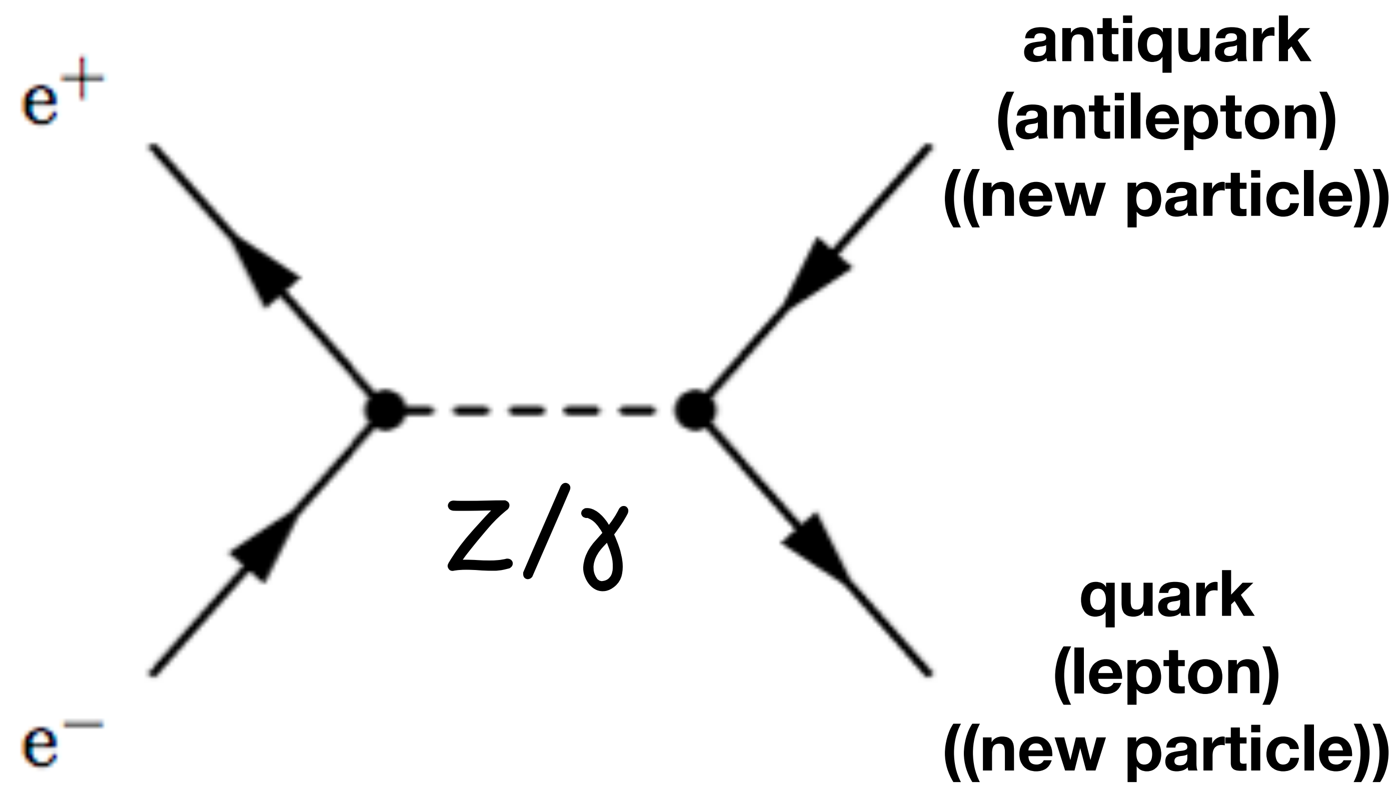


Quarks 1969

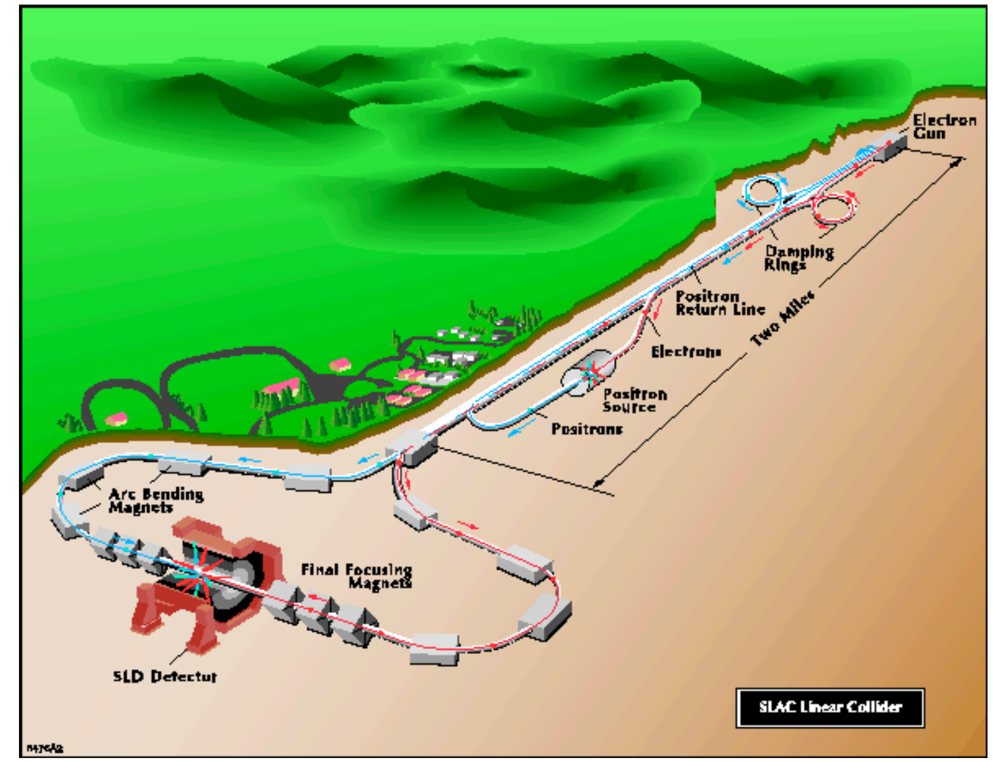


Omega Minus 1964

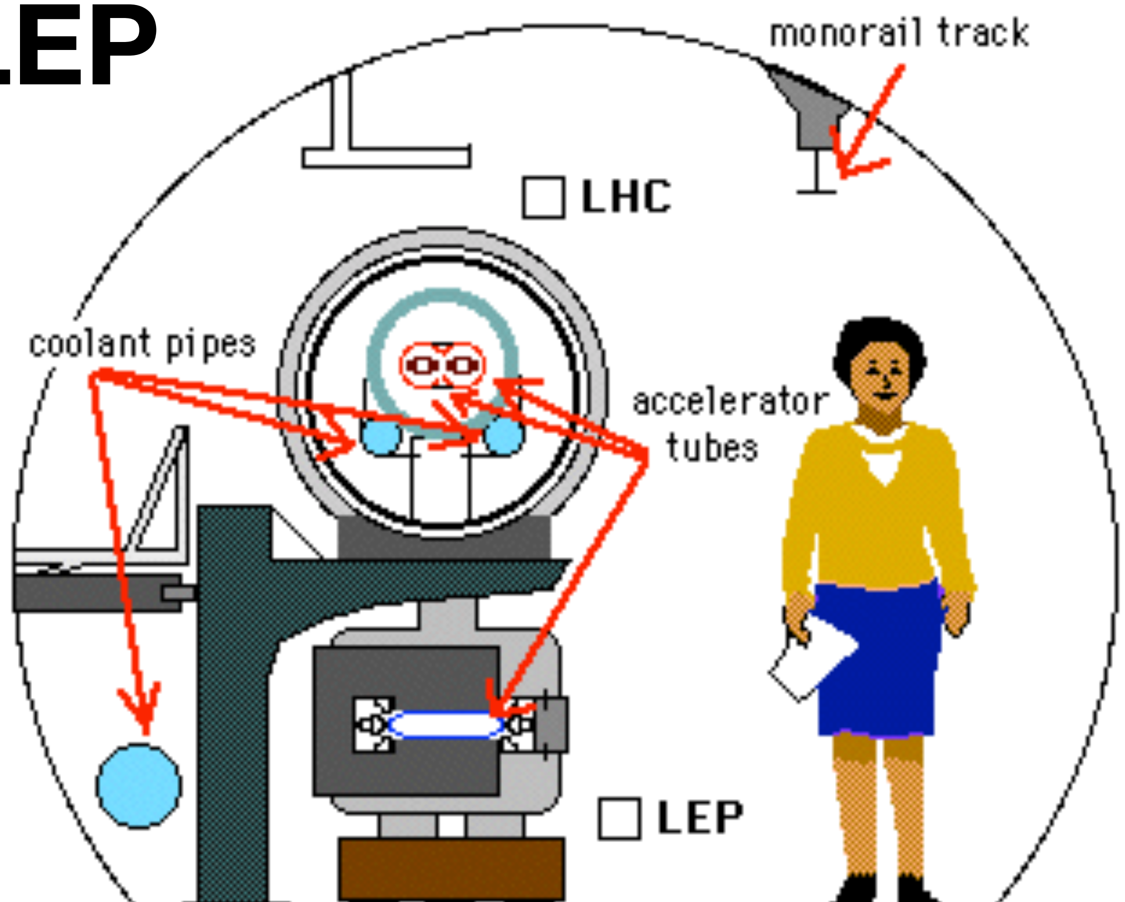
Neutral Current 1973

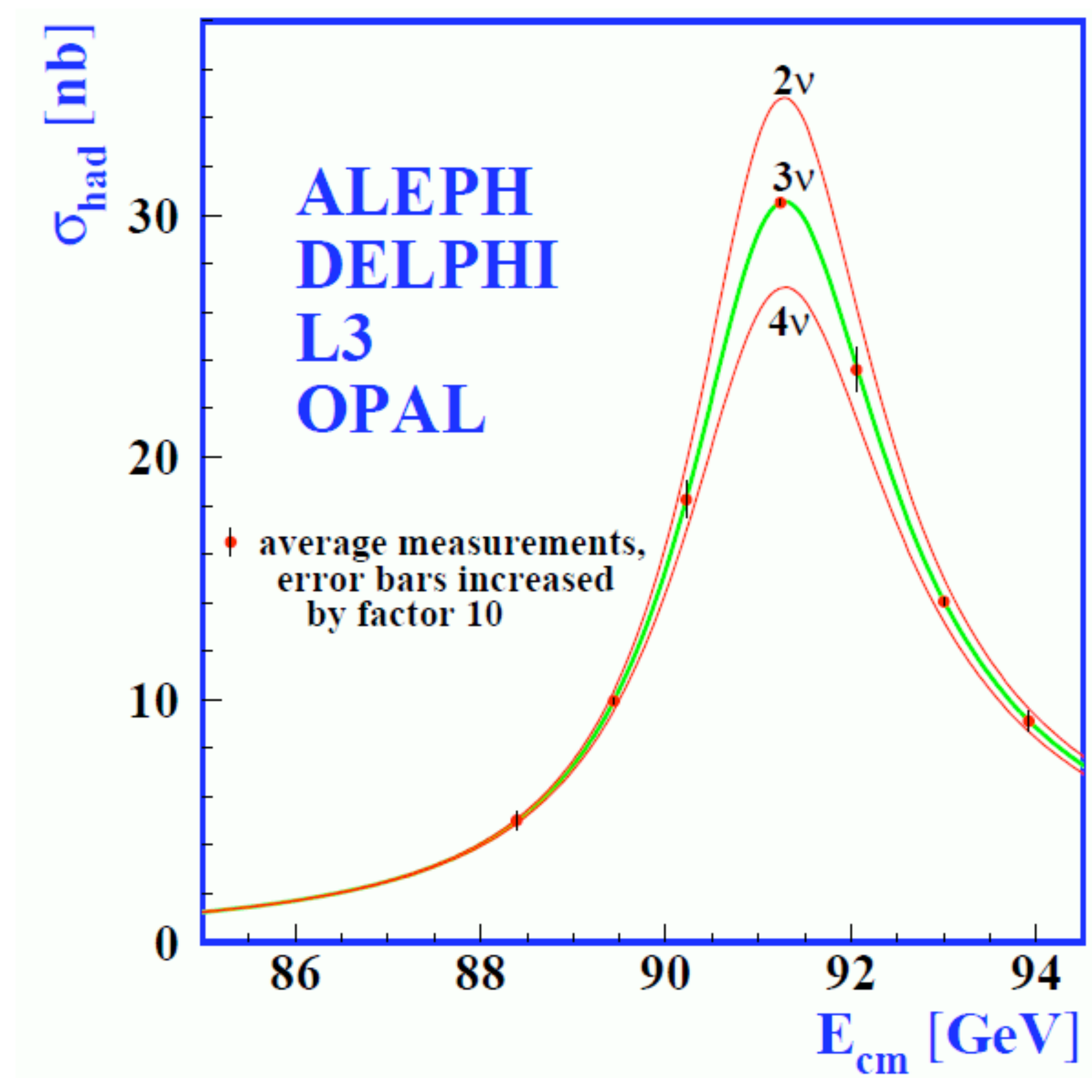


Stanford Linear Collider



LEP





The Photon, W, and Z

Start with 4 massless quantum fields

(W_1,W_2,W_3); a triplet with a certain kind of symmetry

B; a singlet with a different symmetry

These mix to give:

$$W^{\pm} = \frac{1}{\sqrt{2}}(W_1 \pm iW_2)$$

$$Z^0 = W_3 \cos\theta_W - B \sin\theta_W$$

$$A = W_3 \sin\theta_W + B \cos\theta_W$$

The weak mixing angle (measured: $\theta_W \approx 29^0$) relates the two neutral interactions.

Predicting the W and Z masses

Use this "Electroweak" Theory with measurements from EM, weak phenomena: predict W, Z masses!

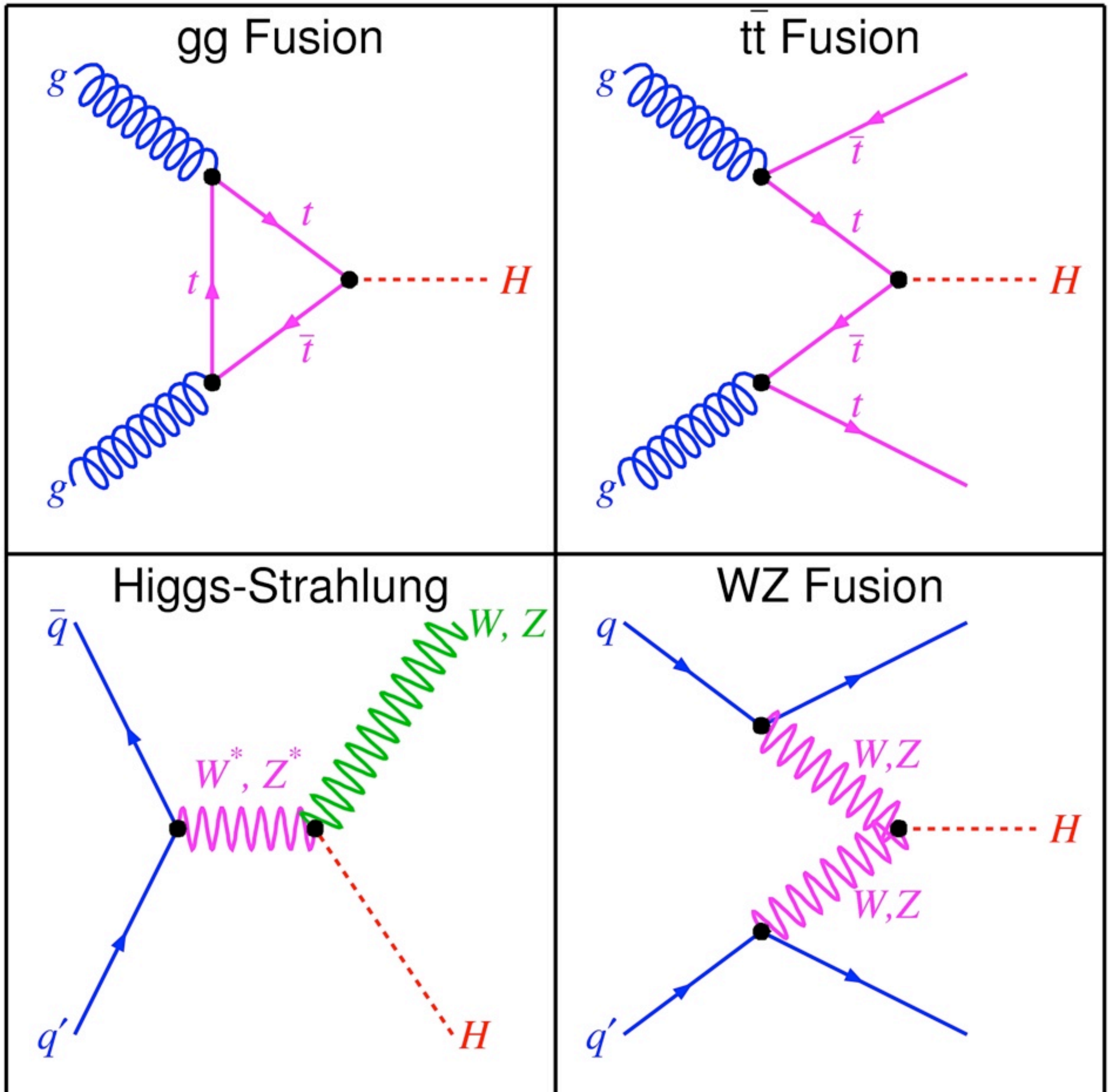
EM charge and weak charge related as: $e = g \sin \theta_W$

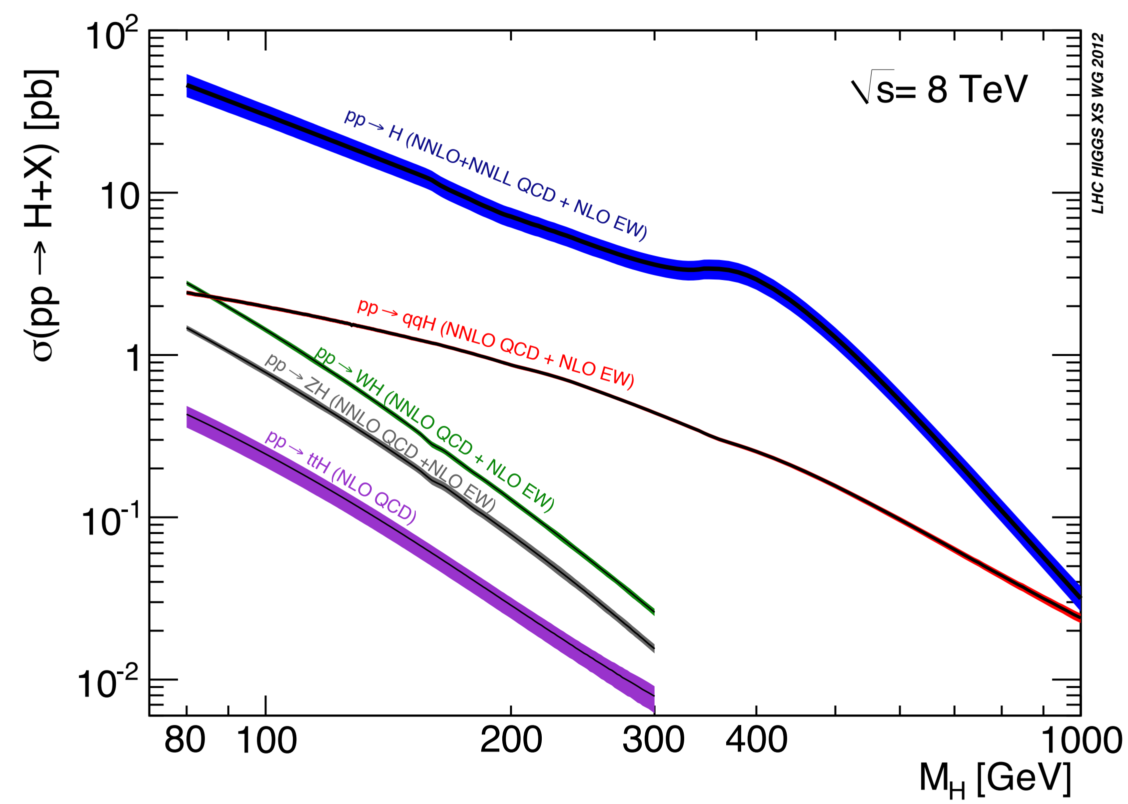
Then,

$$M_W = \frac{\sqrt{\pi\alpha/\sqrt{2}G_F}}{\sin \theta_W} \sim 80 \text{ GeV}$$

$$M_Z = M_W / \cos \theta_W \sim 90 \text{ GeV}$$

Higgs Production





Guinness World Records

LHC: Largest Machine Ever Built

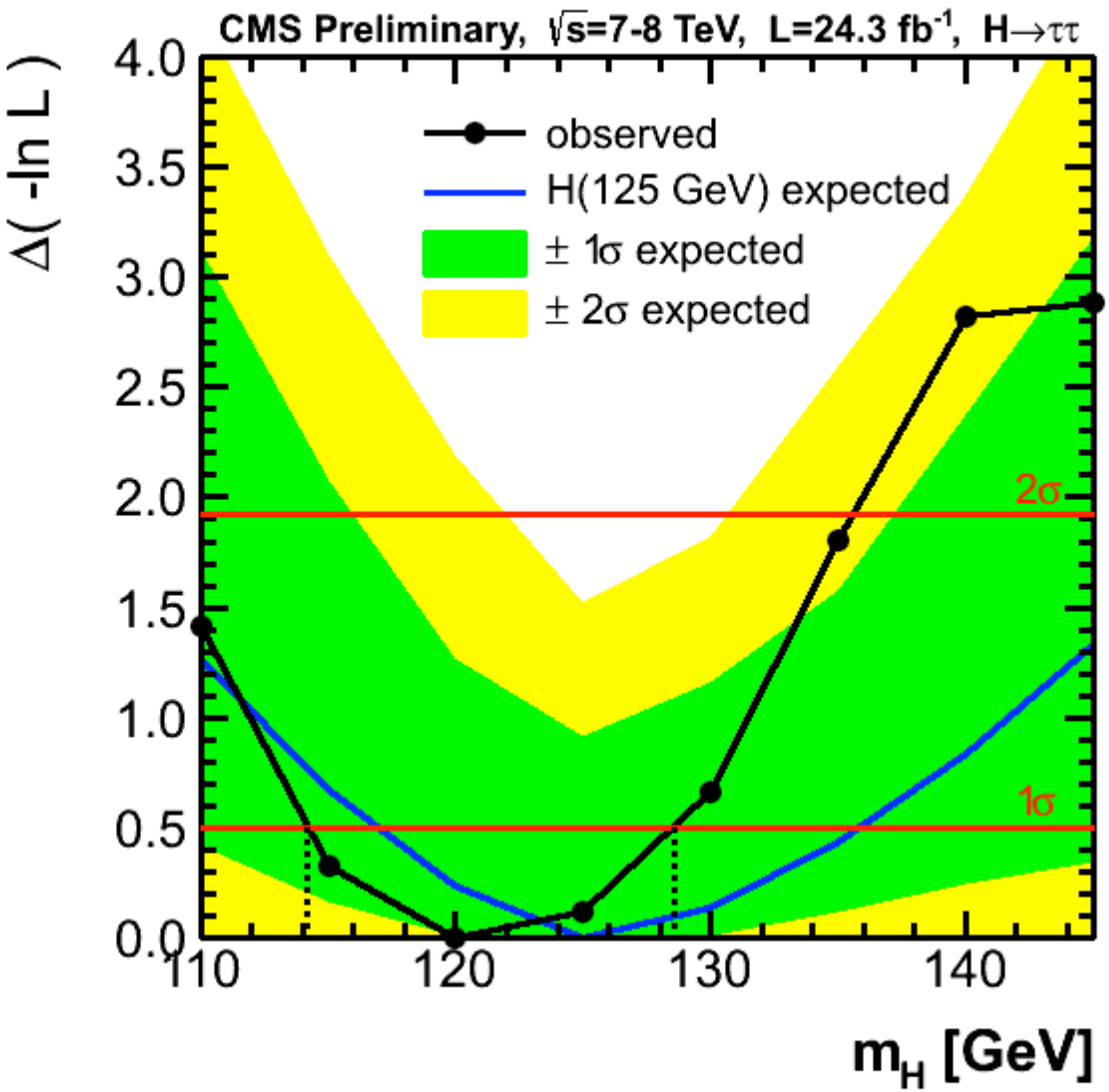
LHC: Largest cryogenic system ever

CMS: Heaviest particle detector ever

CMS: Largest superconducting solenoid ever

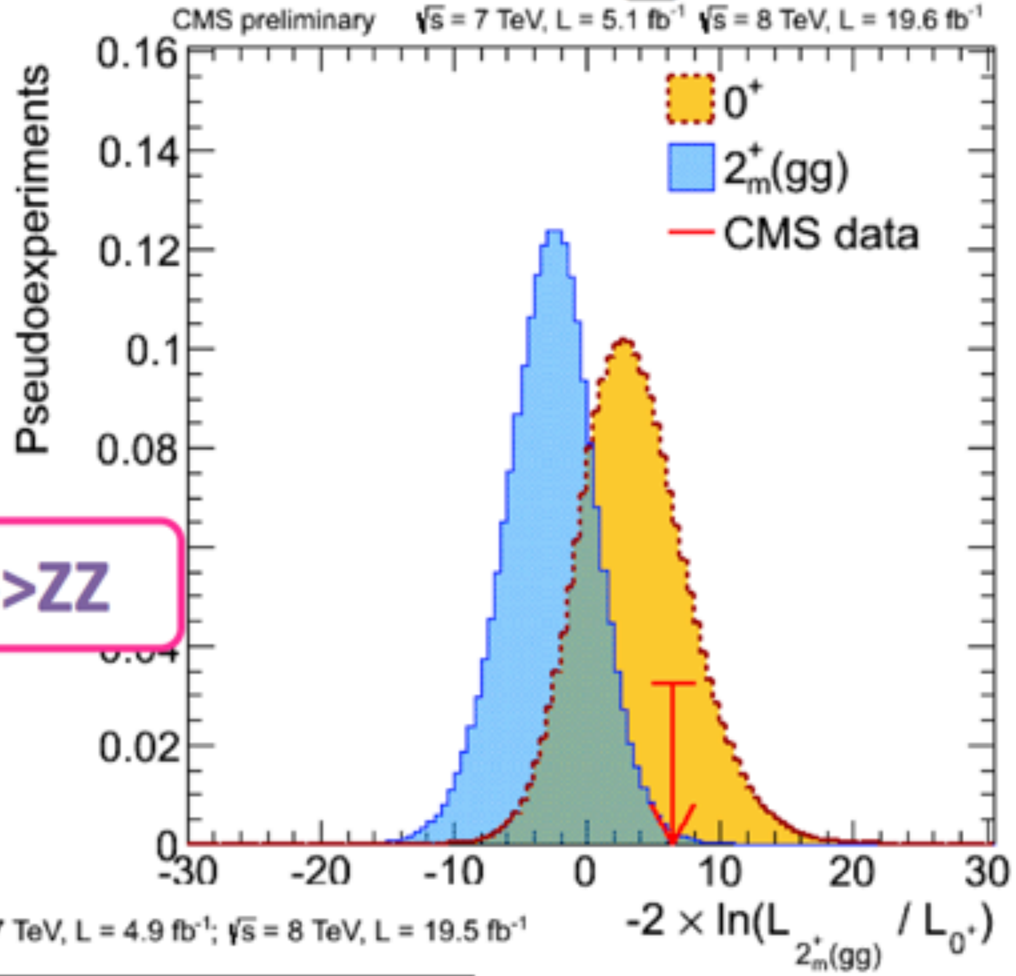
CMS: Largest silicon detector ever

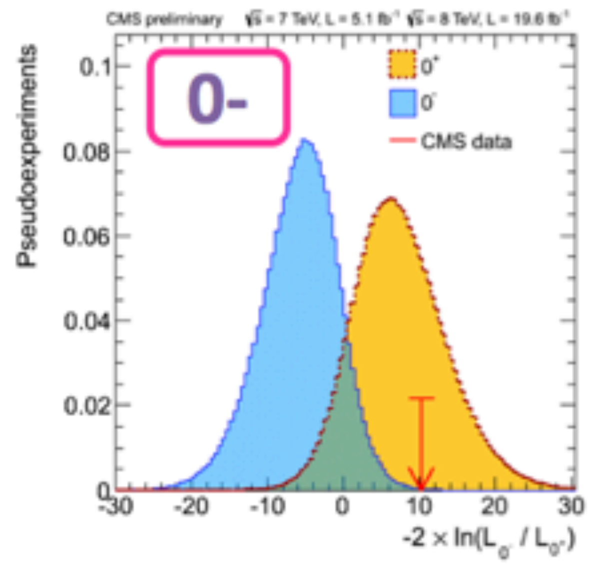
H → tau pair results from Moriond, 2013

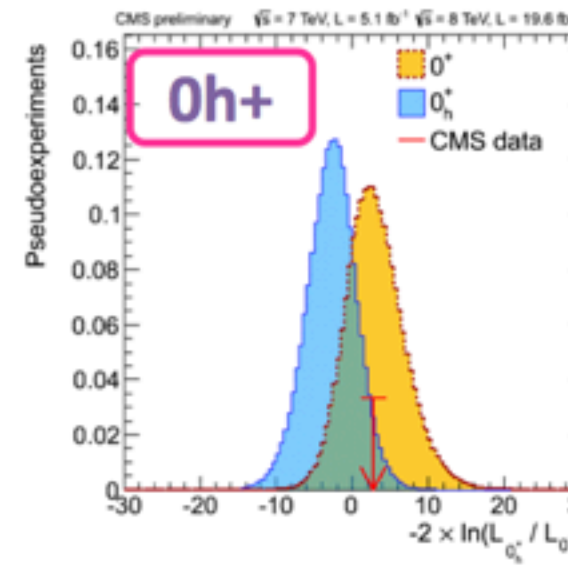


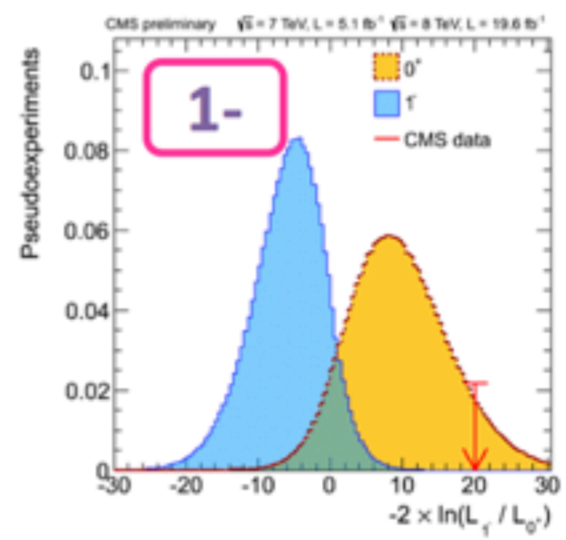
Spin-Parity Results

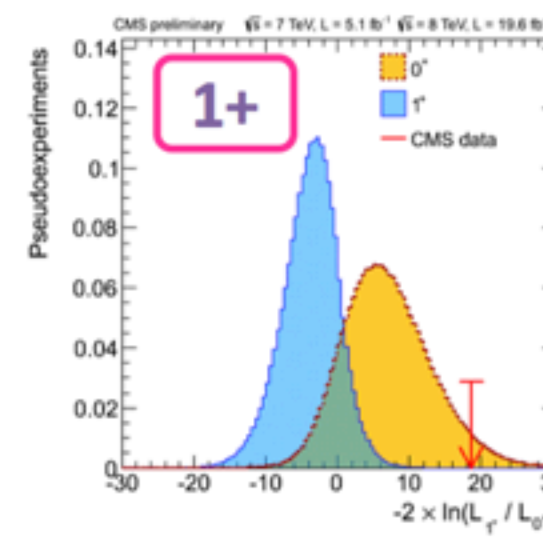
gg->2m+->ZZ

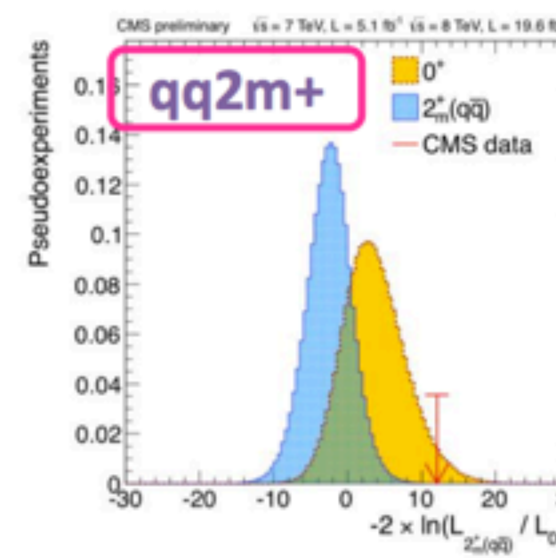




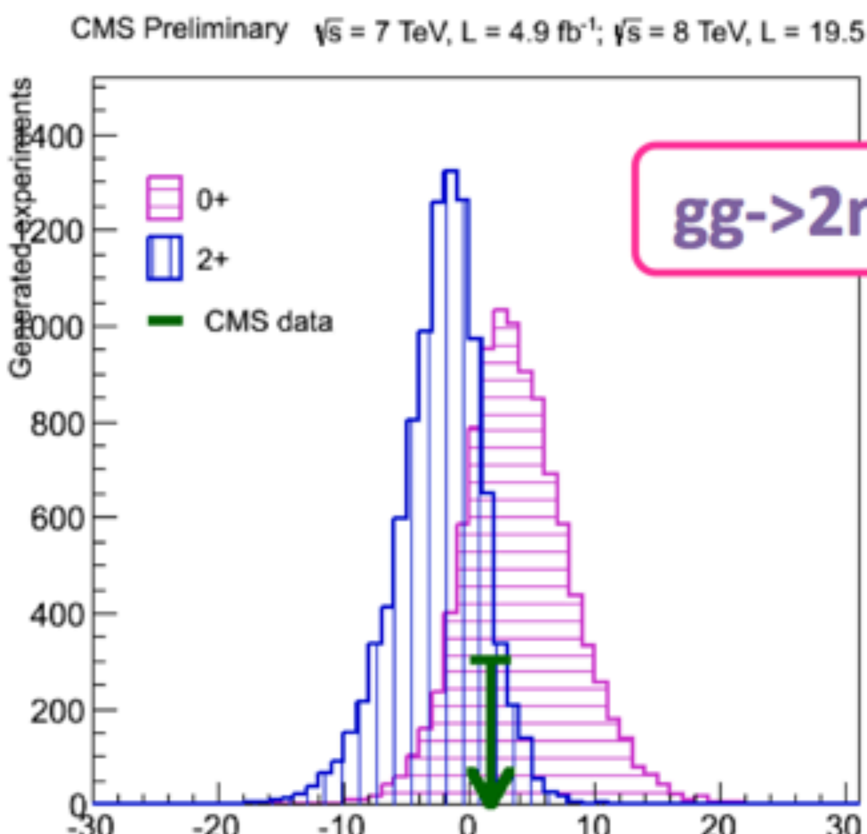






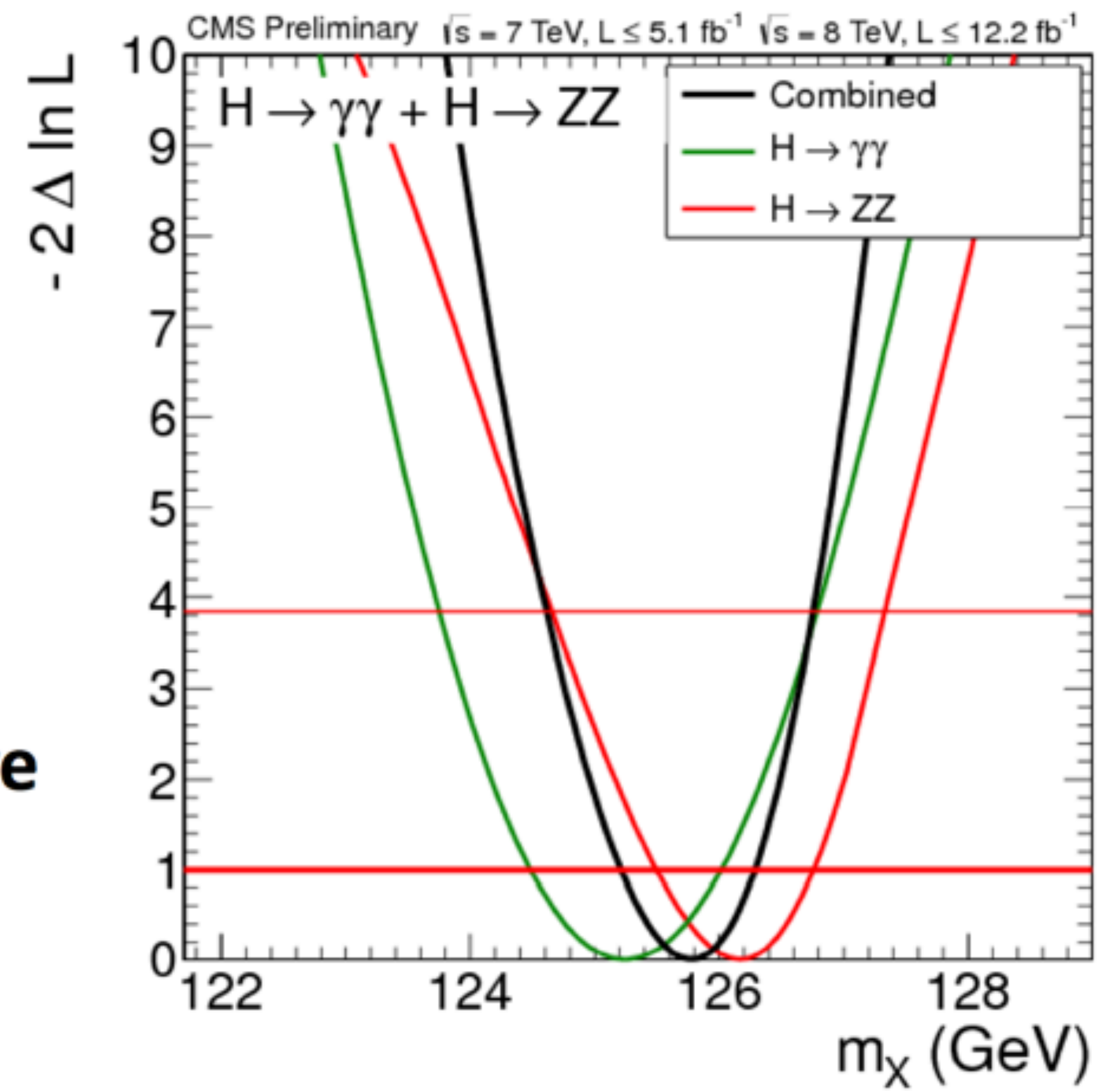


gg->2m+->WW



Mass Measurement

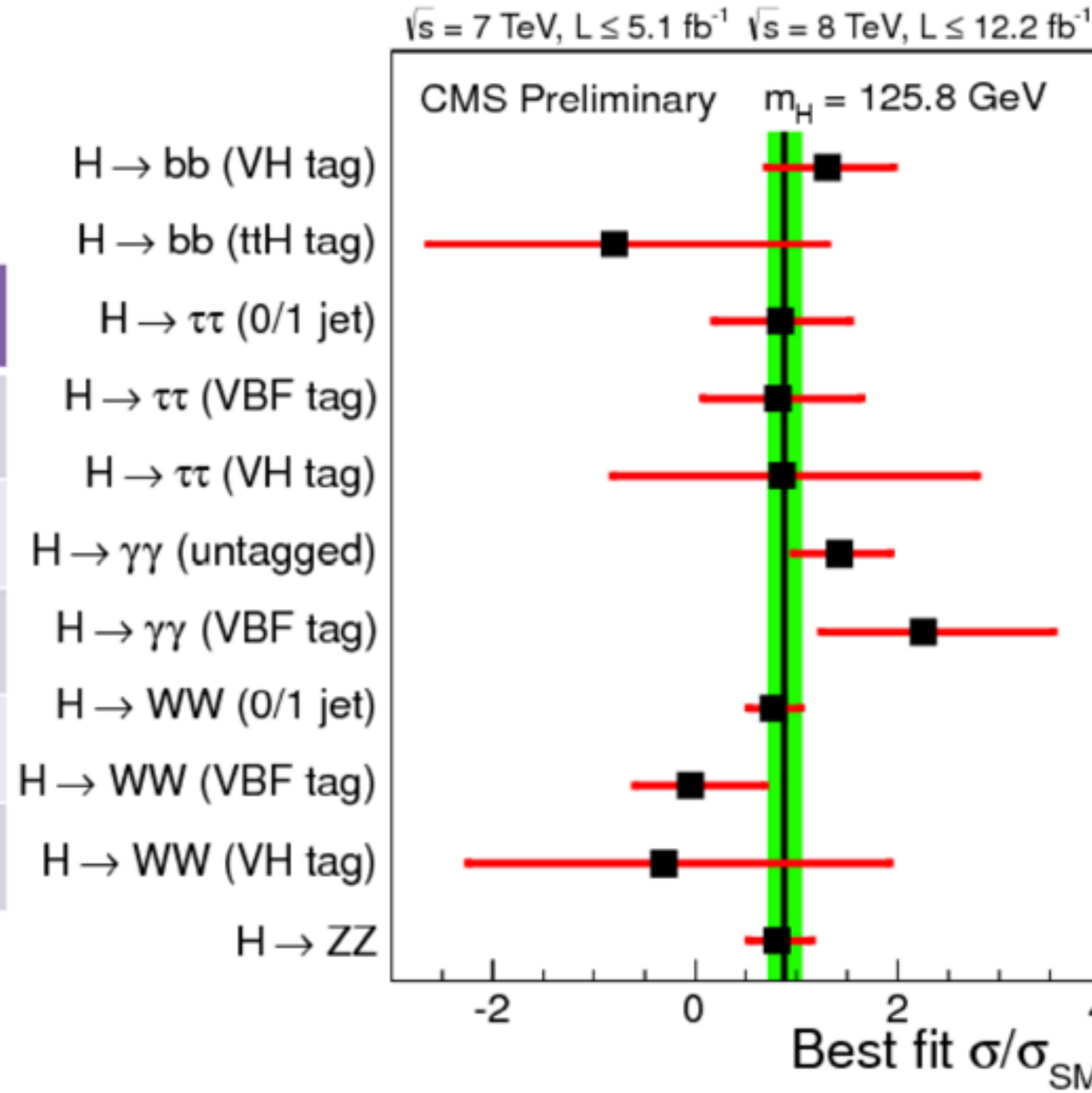
- Combined mass using HZZ and Hγγ
  - Resolutions of 1-2%
- signal strength for Hγγ, Hγγ +2j, and HZZ profiled (model independent)
  - Results consistent when relative yields are fixed to SM



m_H = 125.8 +/- 0.4 (stat) +/- 0.4 (syst) GeV

Signal Strength

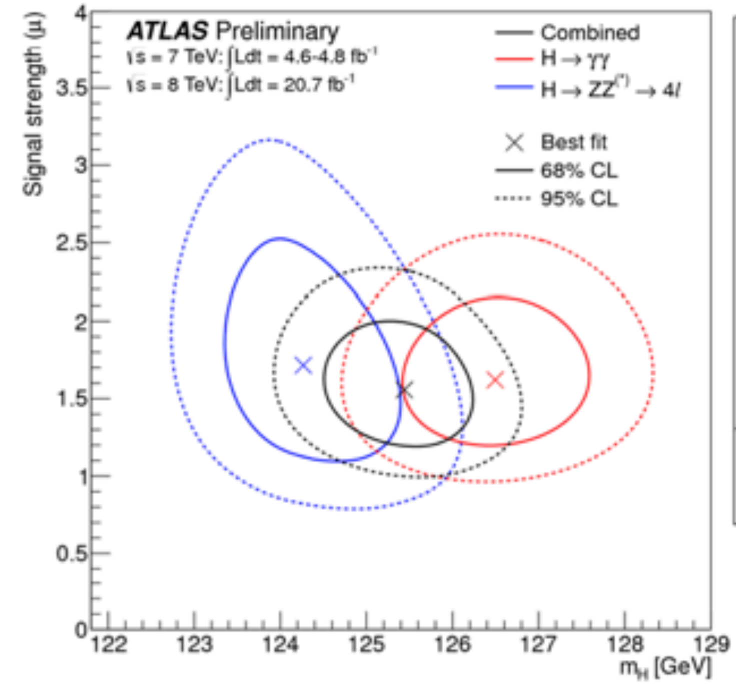
	ggH	VBFH	VH	ttH
H→γγ	✓	✓		
H→ZZ	✓			
H→WW	✓	✓	✓	
H→ττ	✓	✓	✓	
H→bb			✓	✓

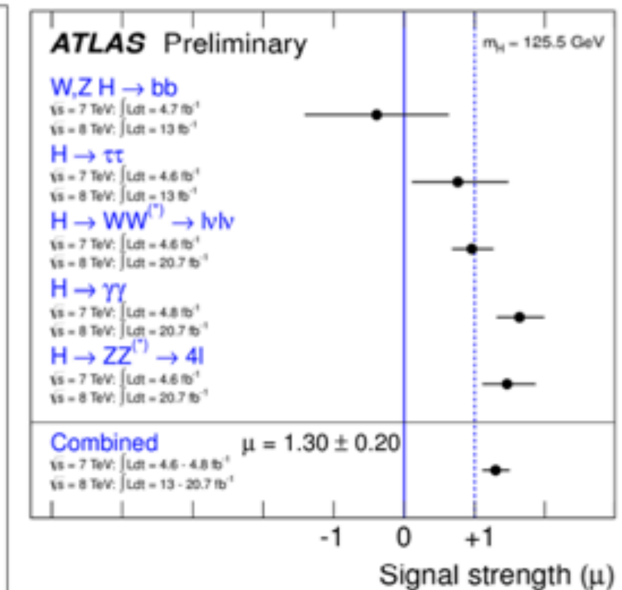


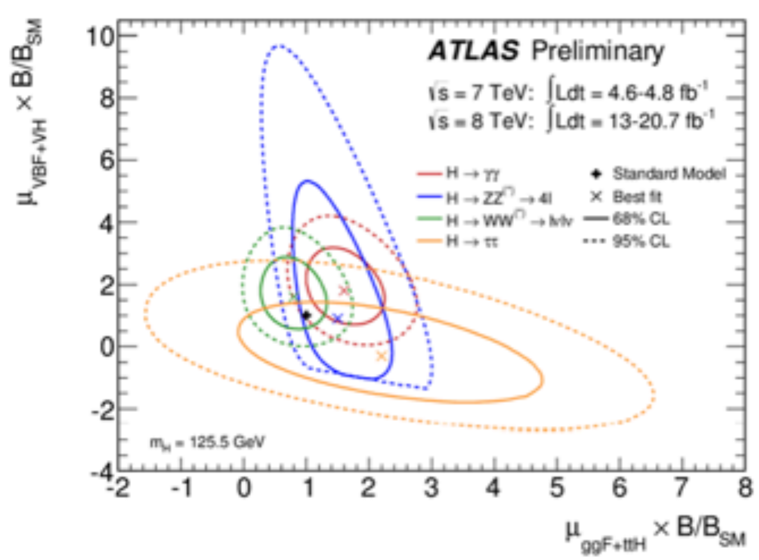
$\sigma/\sigma_{SM} = 0.88 \pm 0.21$

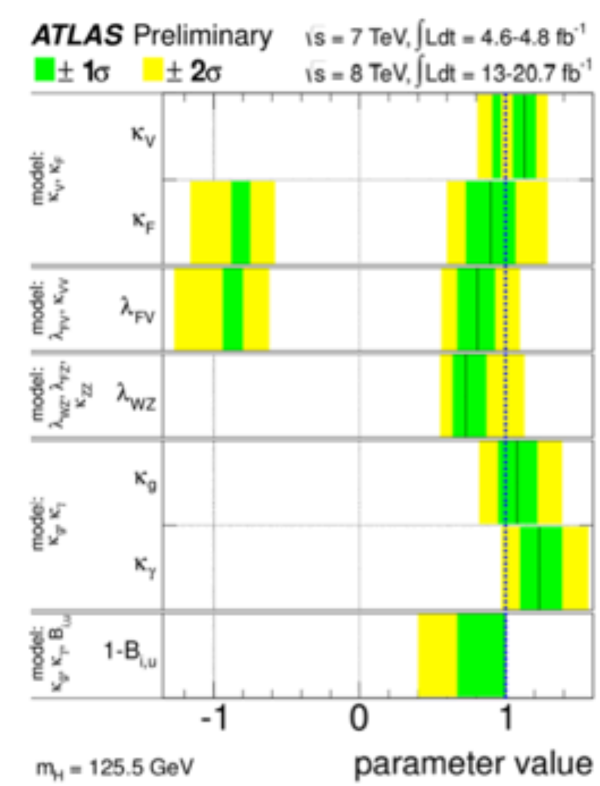
Latest ATLAS Results on Higgs Properties

- $m_H = 125.5 \pm 0.2\,(\text{stat})\,^{+0.5}_{-0.6}\,(\text{sys})\,\text{GeV}$
- $\mu = 1.30 \pm 0.13\,(\text{stat}) \pm 0.14\,(\text{sys})$
- $\mu_{VBF+VH} / \mu_{ggF+ttH} = 1.2^{+0.7}_{-0.5}$
- 3.1σ evidence for VBF production
- Higgs couplings consistent with SM
- Spin and parity (from Eleni's talk):
    - compatible with 0^+
    - start to exclude 2^+_m in γγ and WW, and 0^-, 1^+ in ZZ









Higgs searches have guided conception, design and technological choices of ATLAS and CMS:

- one of the primary LHC goals
- among the most challenging processes → have set some of the most stringent performance (hence technical) requirements: lepton identification and energy/momentum resolution, b-tagging, E_T^{miss} measurement, forward-jet tagging, etc.

	ATLAS	CMS
MAGNET (S)	Air-core toroids + solenoid 4 magnets Calorimeters in field-free region	Solenoid 1 magnet Calorimeters inside field
TRACKER	Si pixels+ strips TRT → particle identification B=2T $\sigma/p_T \sim 5\text{x}10^{-4}\ p_T \oplus 0.01$	Si pixels + strips No particle identification B=4T $\sigma/p_T \sim 1.5\text{x}10^{-4}\ p_T \oplus 0.005$
EM CALO	Pb-liquid argon $\sigma/E \sim 10\%/\sqrt{E}$ longitudinal segmentation	$PbWO_4$ crystals $\sigma/E \sim 2\text{-}5\%/\sqrt{E}$ no longitudinal segmentation
HAD CALO	Fe-scint. + Cu-liquid argon (10 λ) $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$	Cu-scint. (> 5.8 λ +catcher) $\sigma/E \sim 100\%/\sqrt{E} \oplus 0.05$
MUON	Air → $\sigma/p_T \sim 7$ % at 1 TeVstandalone	Fe → $\sigma/p_T \sim 5\%$ at 1 TeV combining with tracker

CMS: excellent μ momentum resolution (H→ 4μ !) but B=4T solenoid constrains HCAL radius

H→ γγ:
CMS: E-resolution
ATLAS: γ “pointing” and γ/jet separation

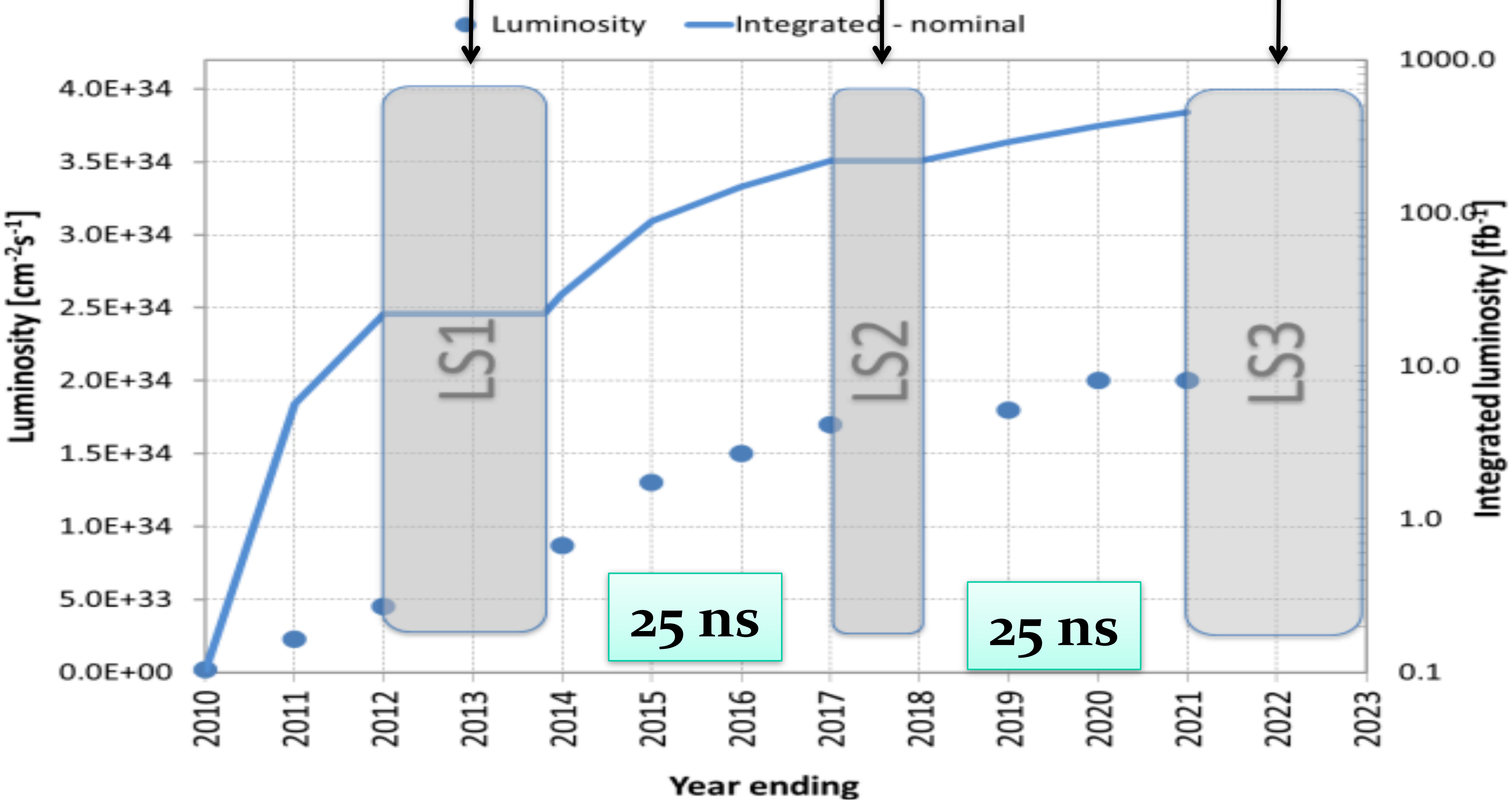
ATLAS: excellent HCAL → jets and E_T^{miss} (H→ lνlν)

LHC performance projection

Energy increase
7 TeV → 13/14 TeV

Injection upgrade

Interaction region upgrade

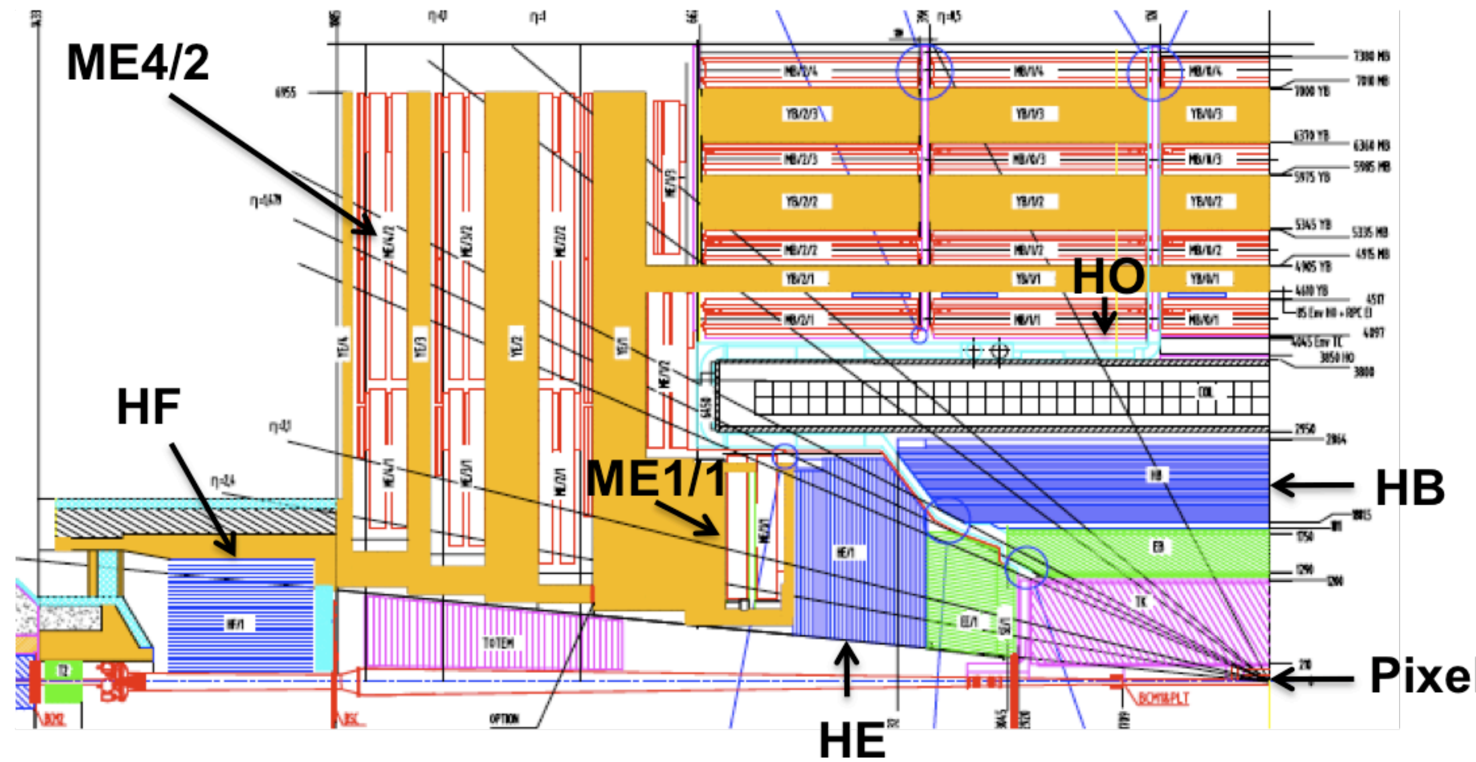


LHC - European Strategy Aug. 12

Phase 2:
HL-LHC
5×10^{34} Hz/cm^2 3000 fb^{-1}

Phase 1: 2×10^{34} Hz/cm^2 500 fb^{-1}

CMS Upgrade program



LS1 Projects: in production

- Complete muon coverage (ME4)
- Improve muon operation (ME1), DT electronics
- Replace HCAL photo-detectors in HF (new PMTs) and HO (HPD→SiPM)

LS1 LS2 LS3

Phase 1 Upgrades (TDRs)

- Pixel detector replacement
- HCAL electronics upgrade
- L1-Trigger upgrade
- Preparatory work during LS1
  - New beam pipe for pixel upgrade
  - Install test slices of pixel, HCAL, L1-trigger
  - Install ECAL optical splitters for L1-trigger upgrade and oon to operations

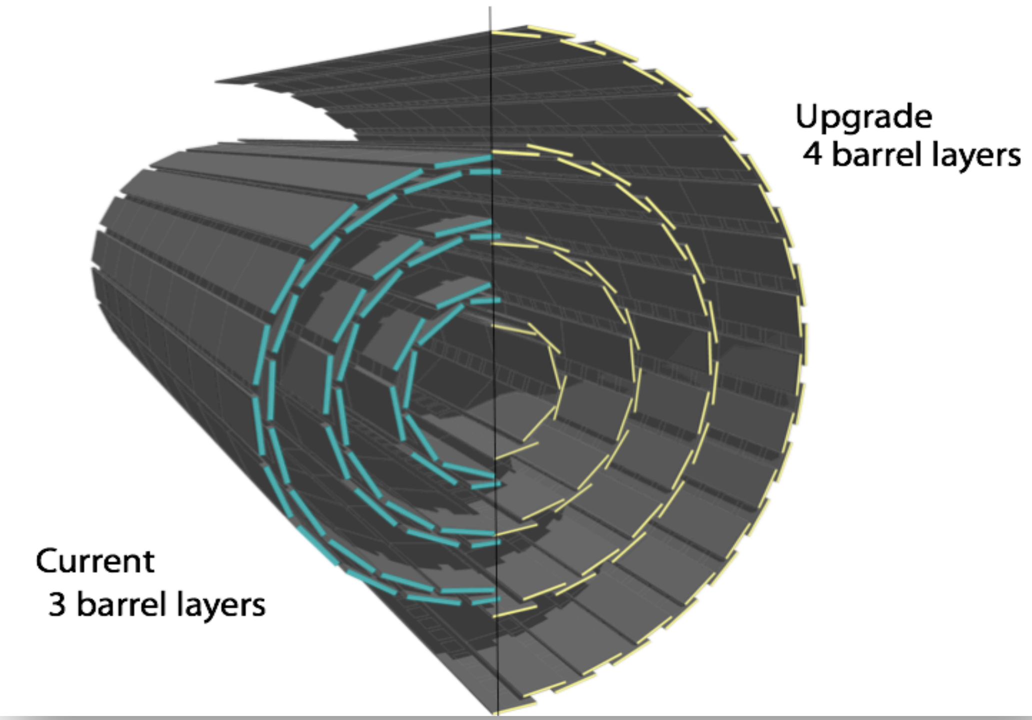
Phase 2: Now being defined

- Tracker Replacement, Track Trigger
- Forward : Calorimetry and Muons and tracking
- Further Trigger upgrade

CMS Pixel and HCAL Upgrades

- Both CMS and ATLAS will upgrade their detectors.

- CMS Plans
- Upgraded Pixel Detector
  - Less material, better radial distribution
- Upgraded HCAL
  - Improve background rejection
  - Improve MET resolution
  - Improve Particle Flow
    - *via improved S/N photodetectors*
  - Identify depth of shower max
    - *via longitudinal segmentation, timing*



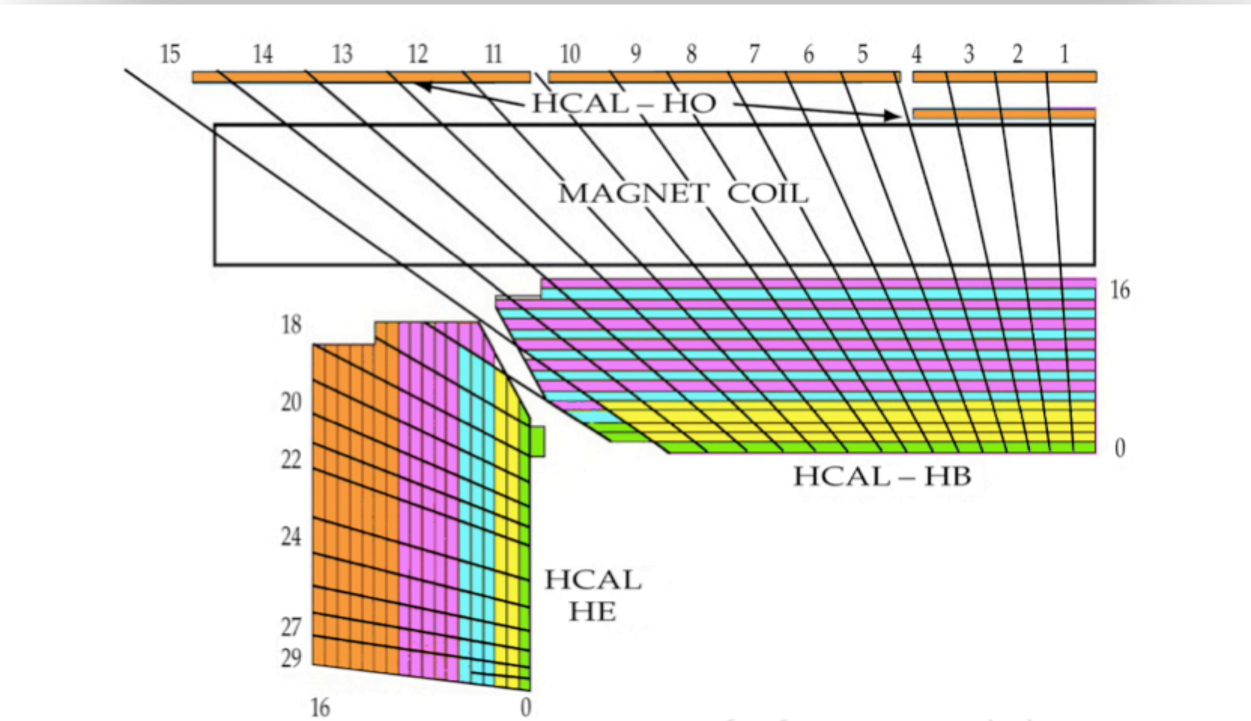


Figure 3.1: Current proposed depth segmentation structure for the HB and HE calorimeters, made possible by the use of SiPM photodetectors.

Upgrades: Impact on Higgs Physics

Improved signal yield (relative to current detector): shaded regions indicate cuts with biggest gains expected

$H \rightarrow ZZ \rightarrow 4l$

- *Key channel very sensitive to efficiency*
  - *50% improved*

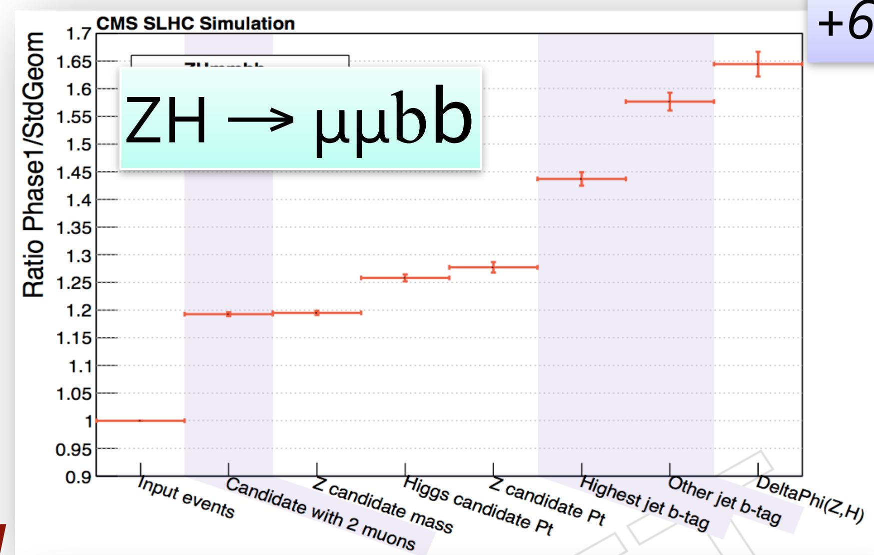
$ZH \rightarrow \mu\mu bb$

- *High muon ID efficiency high b-tagging efficiency good dijet mass resolution.*
  - *65% improved*

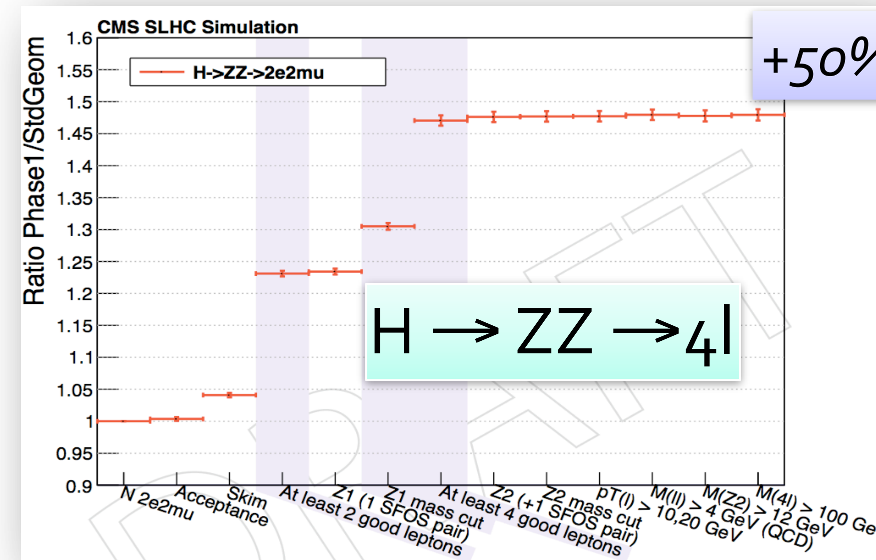
$H \rightarrow \tau\tau$ (VBF)

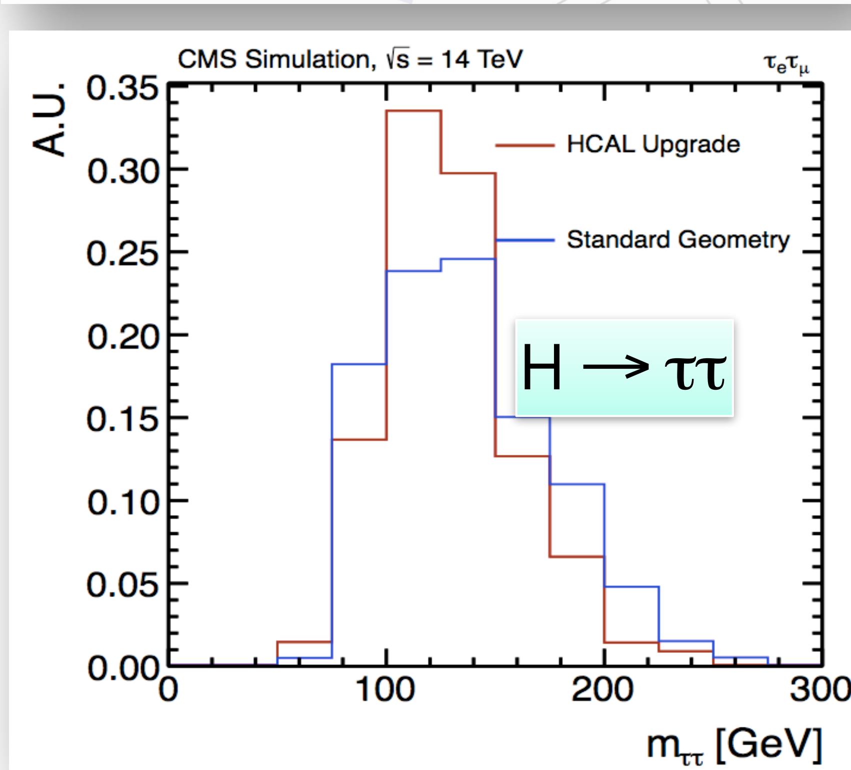
- *MET resolution, forward jet tagging, τ Identification*
  - *Better mass resolution*

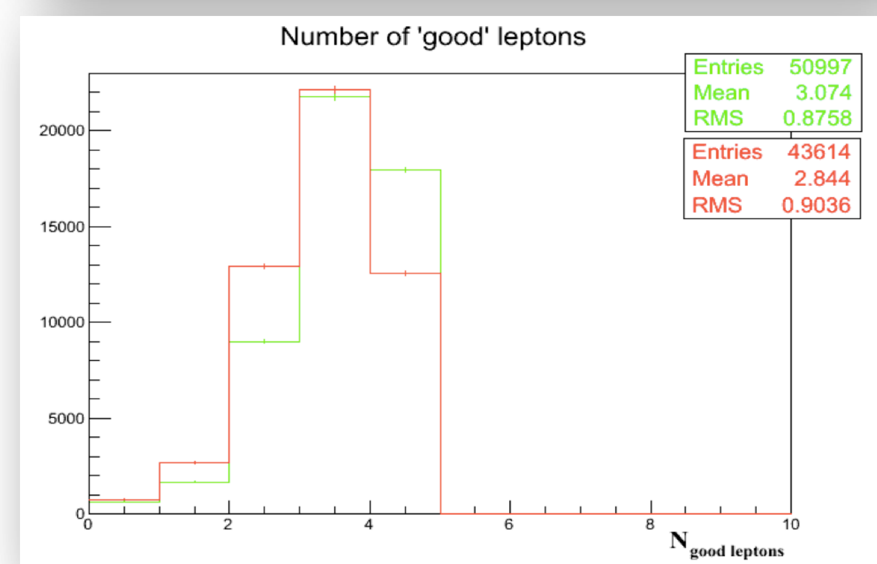
+65%



+50%



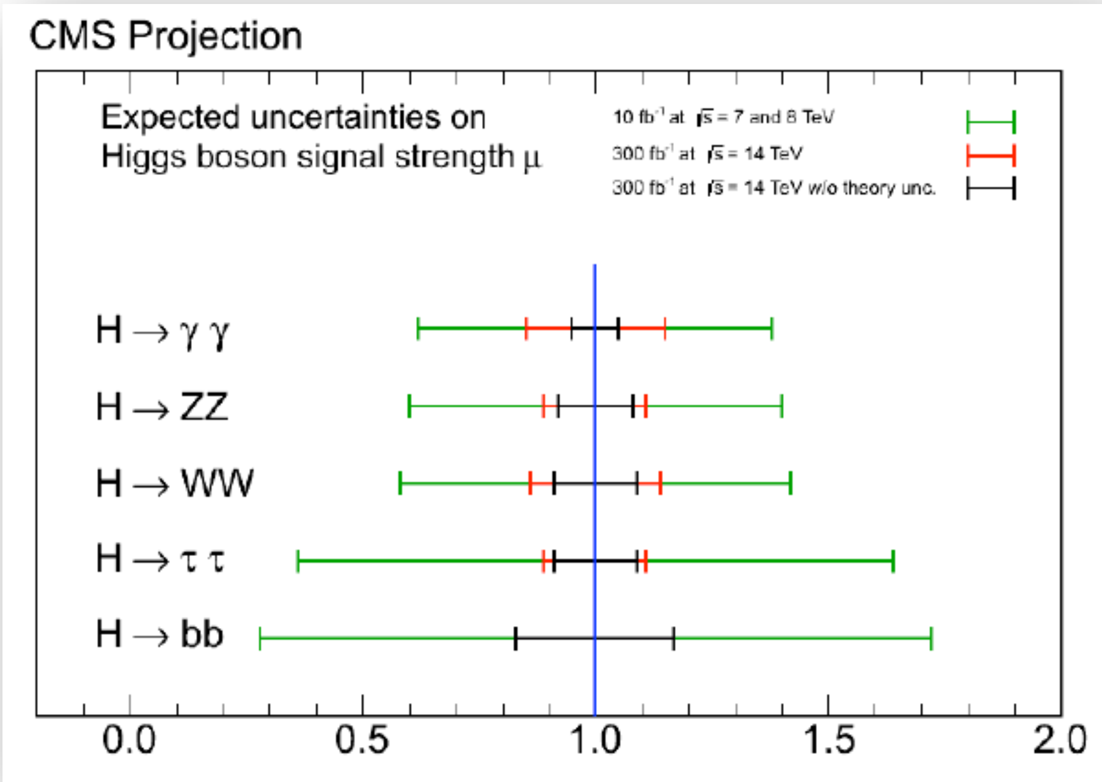


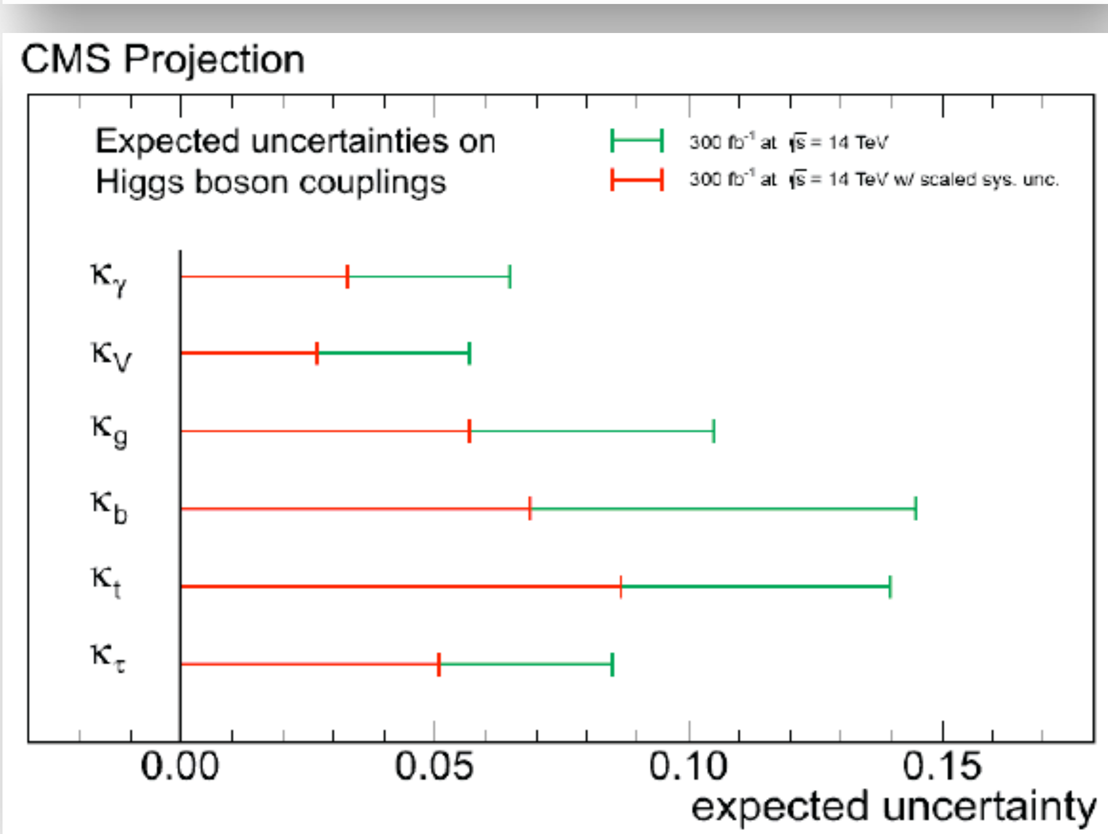


- Improved $m_{\tau\tau}$ resolution

- More good leptons
  better tracking & isolation

Signal strengths, couplings: 300,3000 fb^{-1}





- Signal Strengths: ~10-15%
  - Present (Green). Present systematics at 300 /fb 14 TeV (Red). Setting theoretical uncertainties to zero (Black).

	Uncertainty (%)			
Coupling	300 fb^{-1}		3000 fb^{-1}	
κ_γ	6.5	5.1	5.4	1.5
κ_V	5.7	2.7	4.5	1.0
κ_g	11	5.7	7.5	2.7
κ_b	15	6.9	11	2.7
κ_t	14	8.7	8.0	3.9
κ_τ	8.5	5.1	5.4	2.0

Simple scenarios for couplings

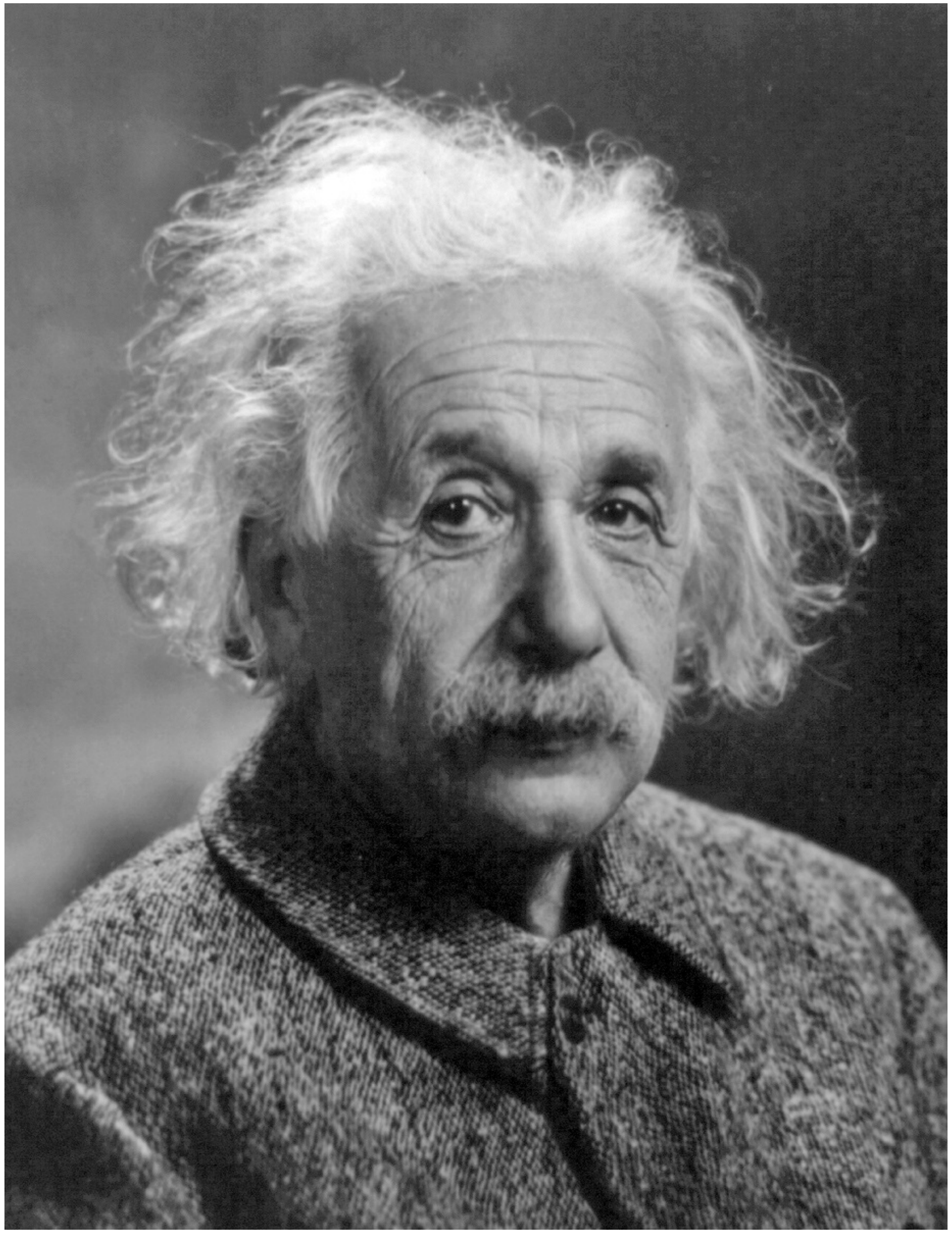
1. Systematics unchanged
2. Theory uncertainties reduced ½, all other systematics ~ $1/\sqrt{(\int L dt)}$

Phase 2 HL-LHC Projects

- Study longevity of detectors through phase 1 and phase 2
- Study constraints at experimental area
- Develop scope for phase 2 detector :
  - Motivation and requirements on detector performance
  - Trigger Performance and Strategy
    - Develop requirements (rates) and architecture
  - Forward Detector
    - Develop detector concept including tracking, calorimetry and muons
  - Tracker project
    - Develop concept with hardware trigger capability
  - Simulation and reconstruction
    - Develop tools for new geometries and high pile-up
- Target R&D programs

- Technical Proposal in 2014

Theorists vs Experimentalists



Einstein

Newton Fermi Ting