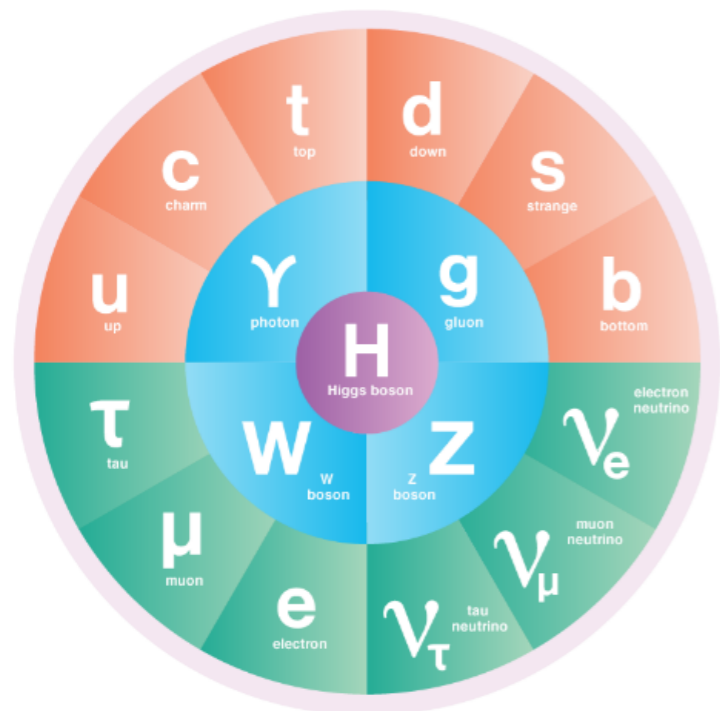
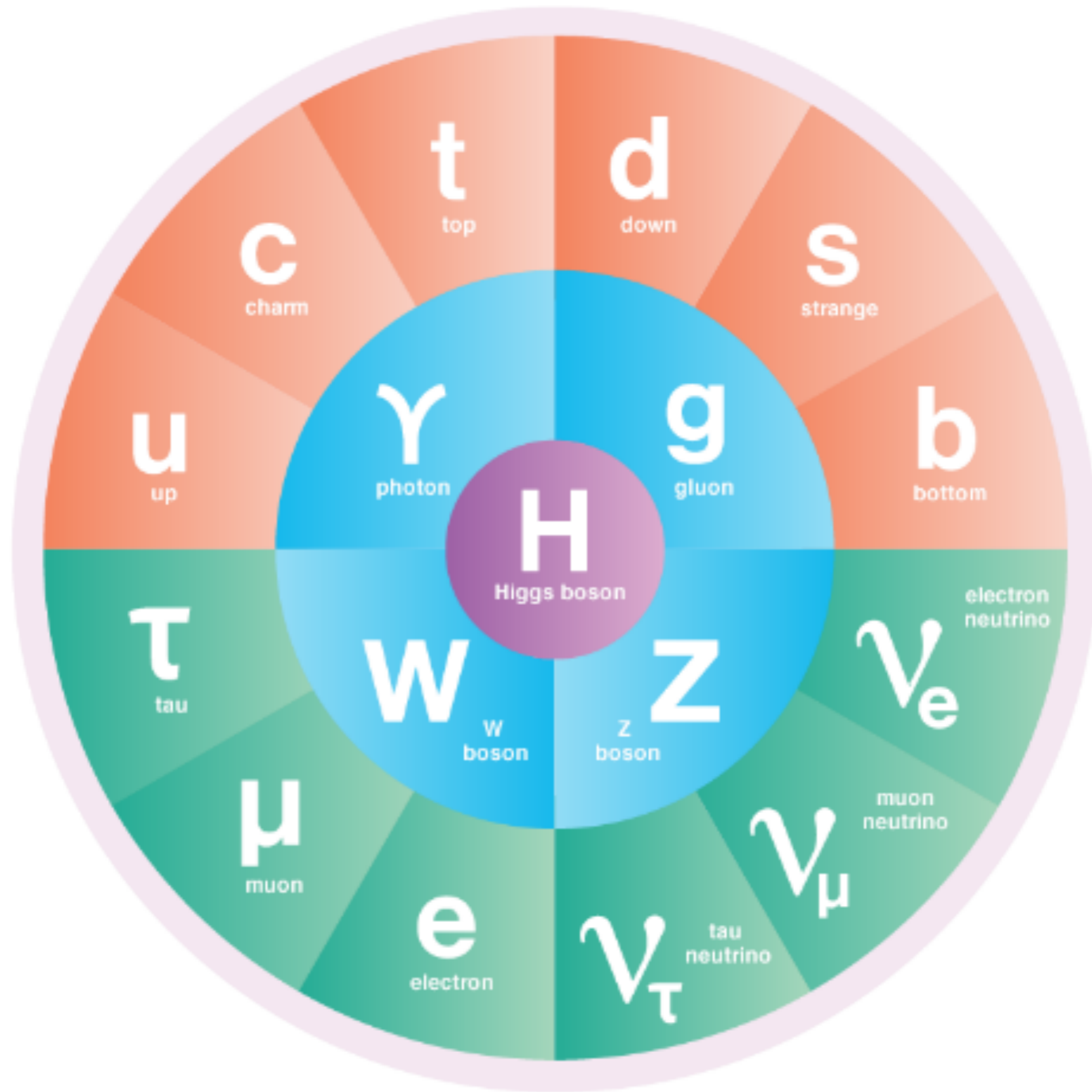


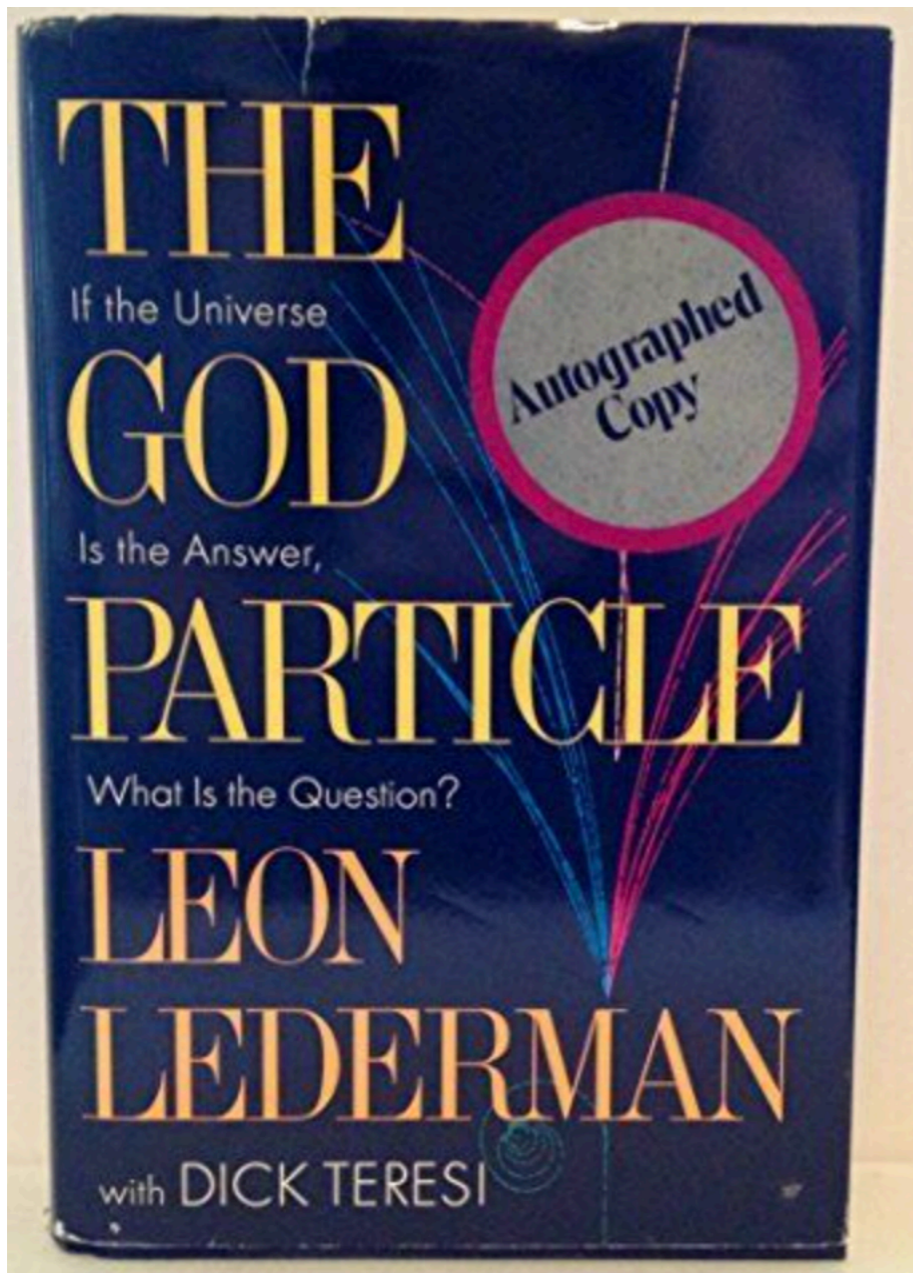
Higgs Boson: the god particle takes a human face



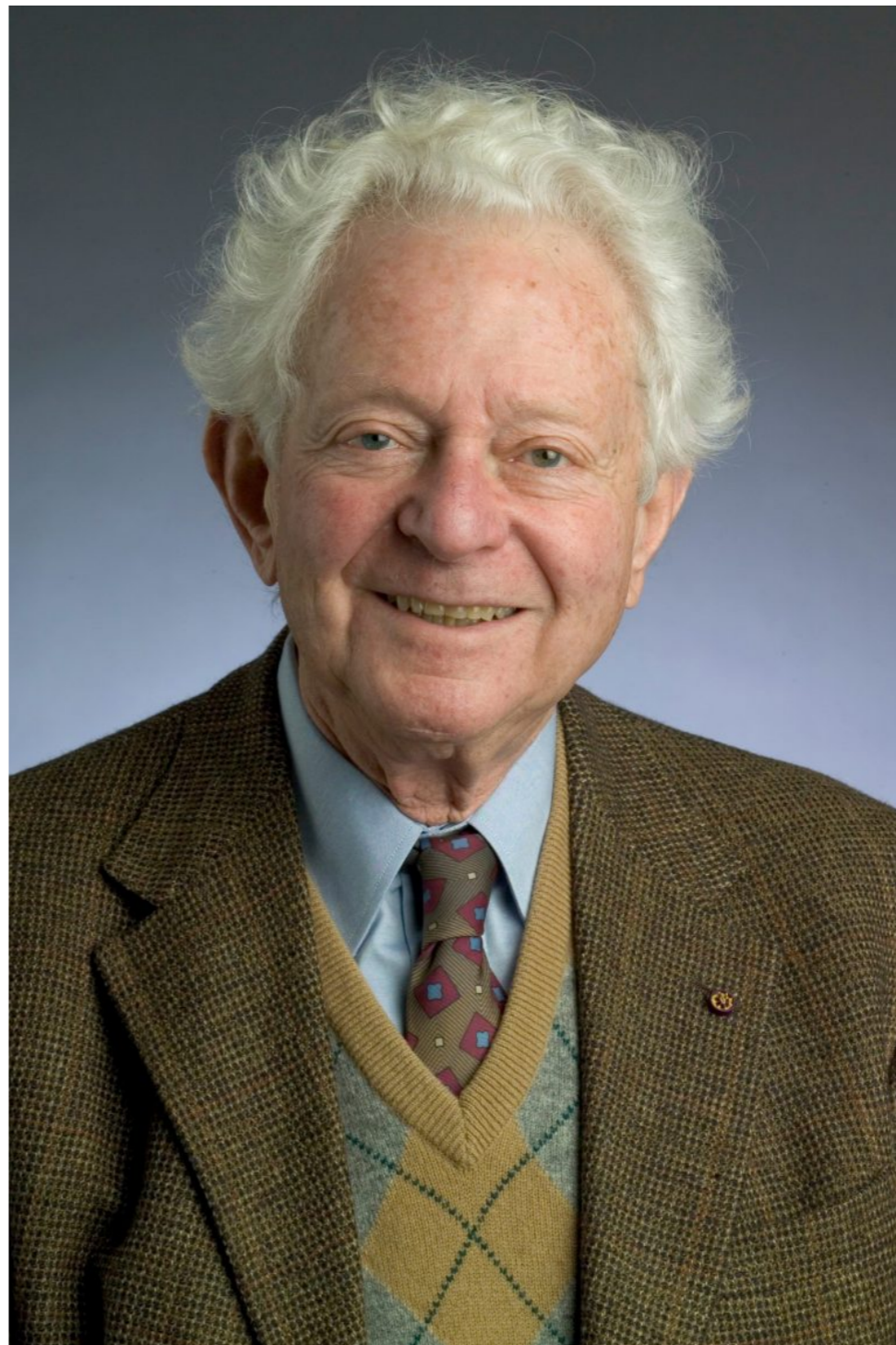
Michael E. Peskin
Moti Lal Rustgi Lecture
April 2023



● **QUARKS**
 ● **LEPTONS**
 ● **BOSONS**
 ● **HIGGS BOSON**



Houghton Mifflin 1993



**Leon
Lederman**

Fermilab

Auguries of Innocence

by William Blake

...

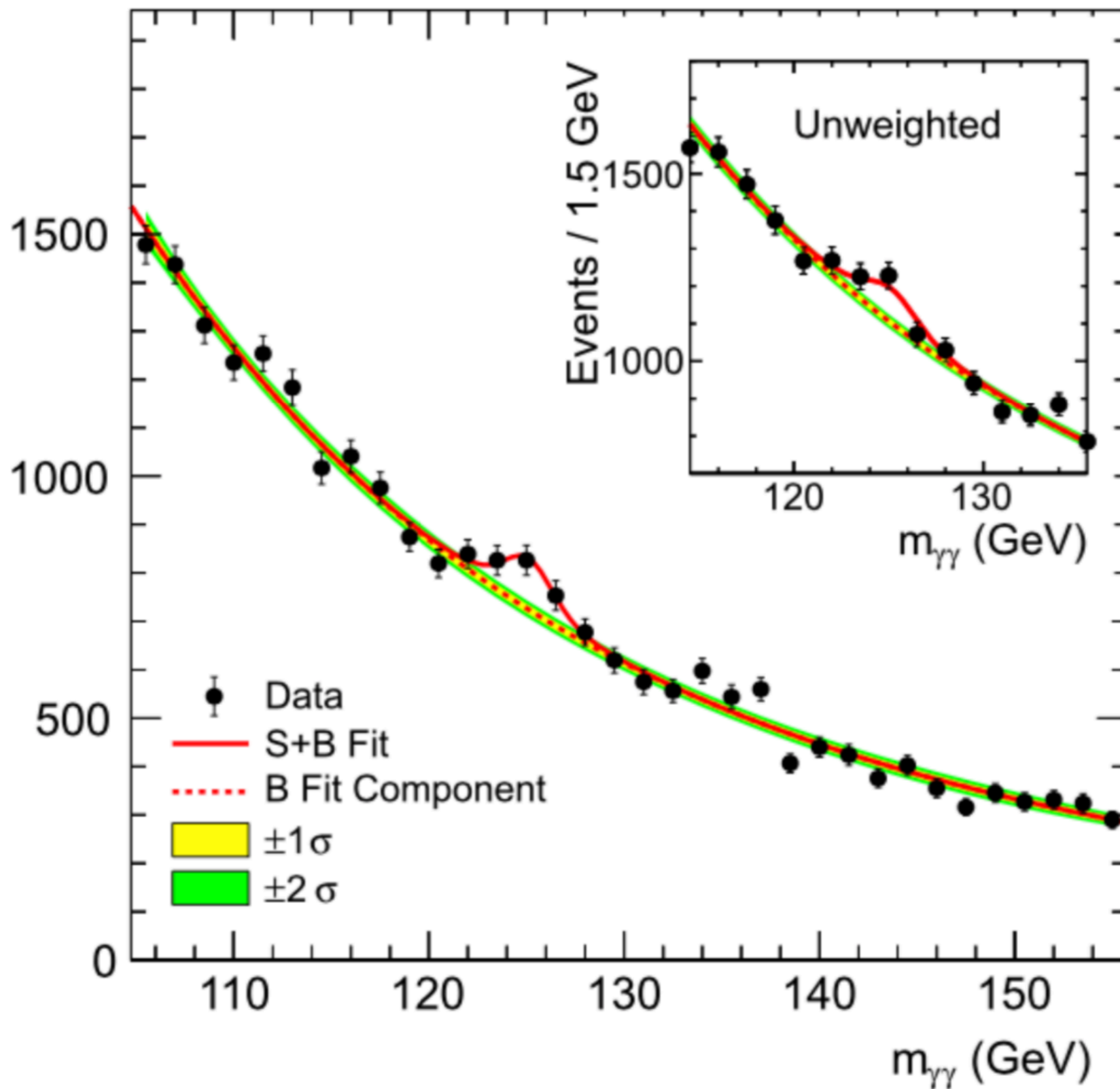
God appears & God is Light
To those poor Souls who dwell in Night
But does a Human Form Display
To those who Dwell in Realms of day.



CERN July 4, 2012

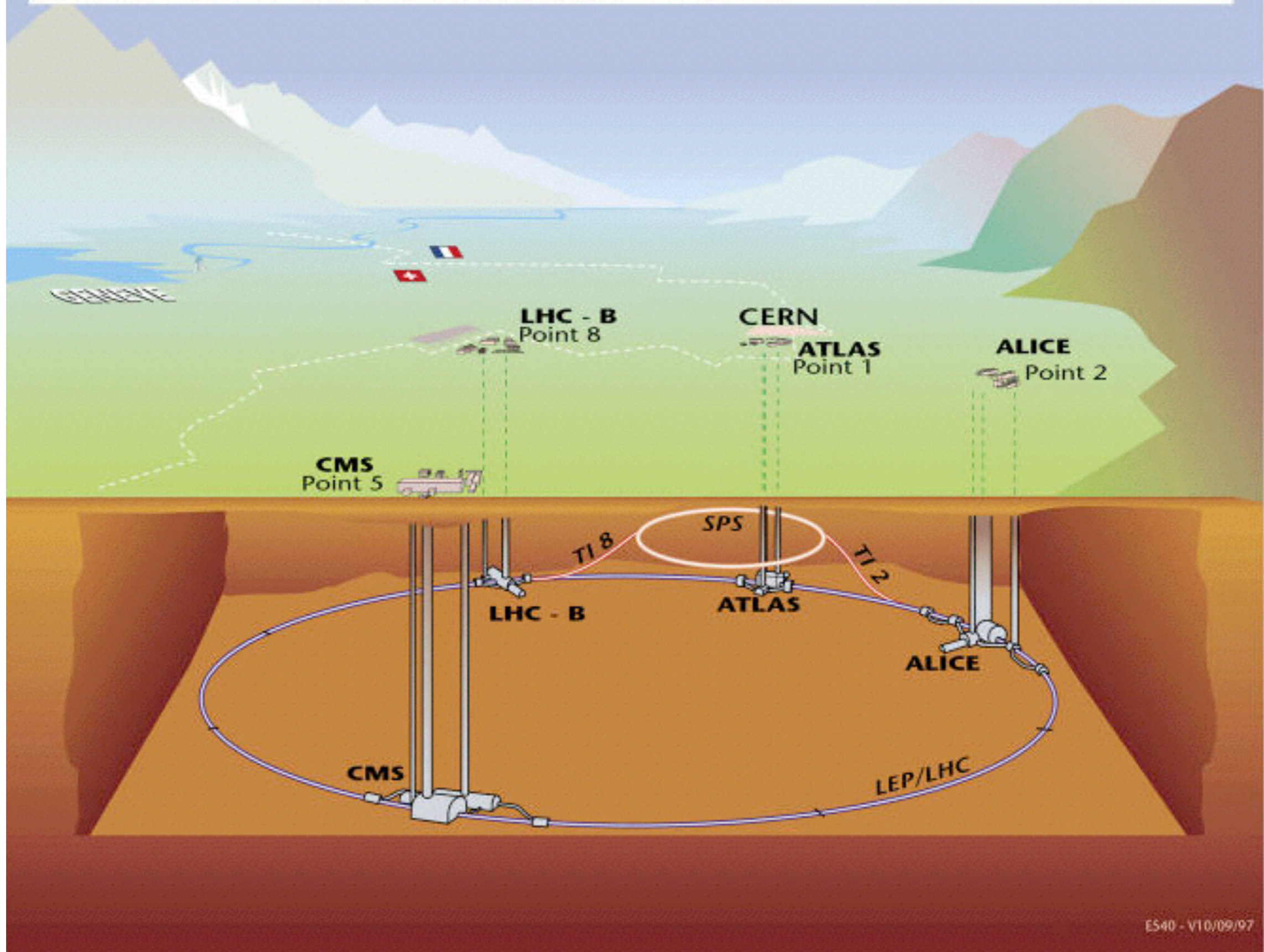
CMS $\sqrt{s} = 7 \text{ TeV}, L = 5.1 \text{ fb}^{-1}$ $\sqrt{s} = 8 \text{ TeV}, L = 5.3 \text{ fb}^{-1}$

S/(S+B) Weighted Events / 1.5 GeV

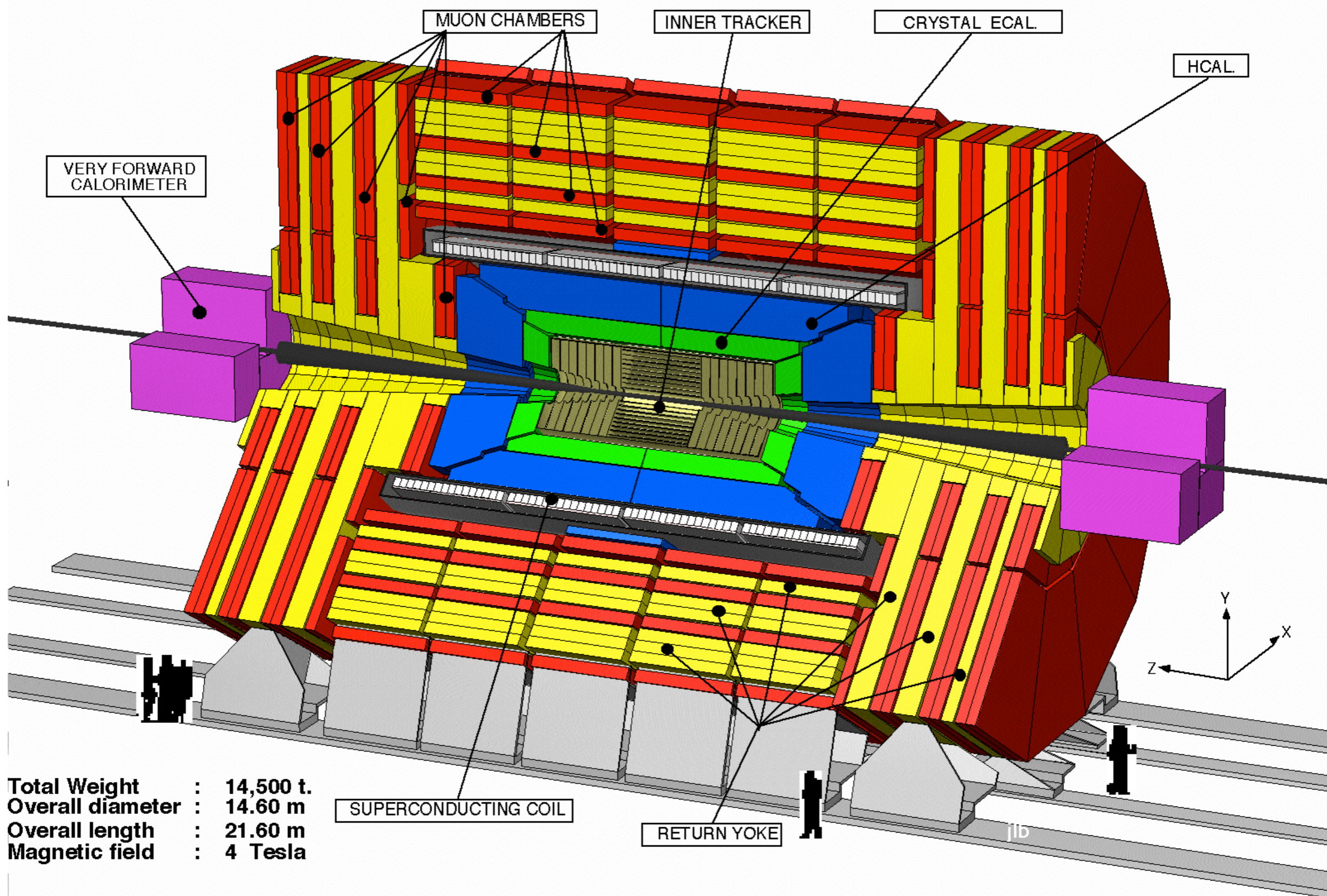


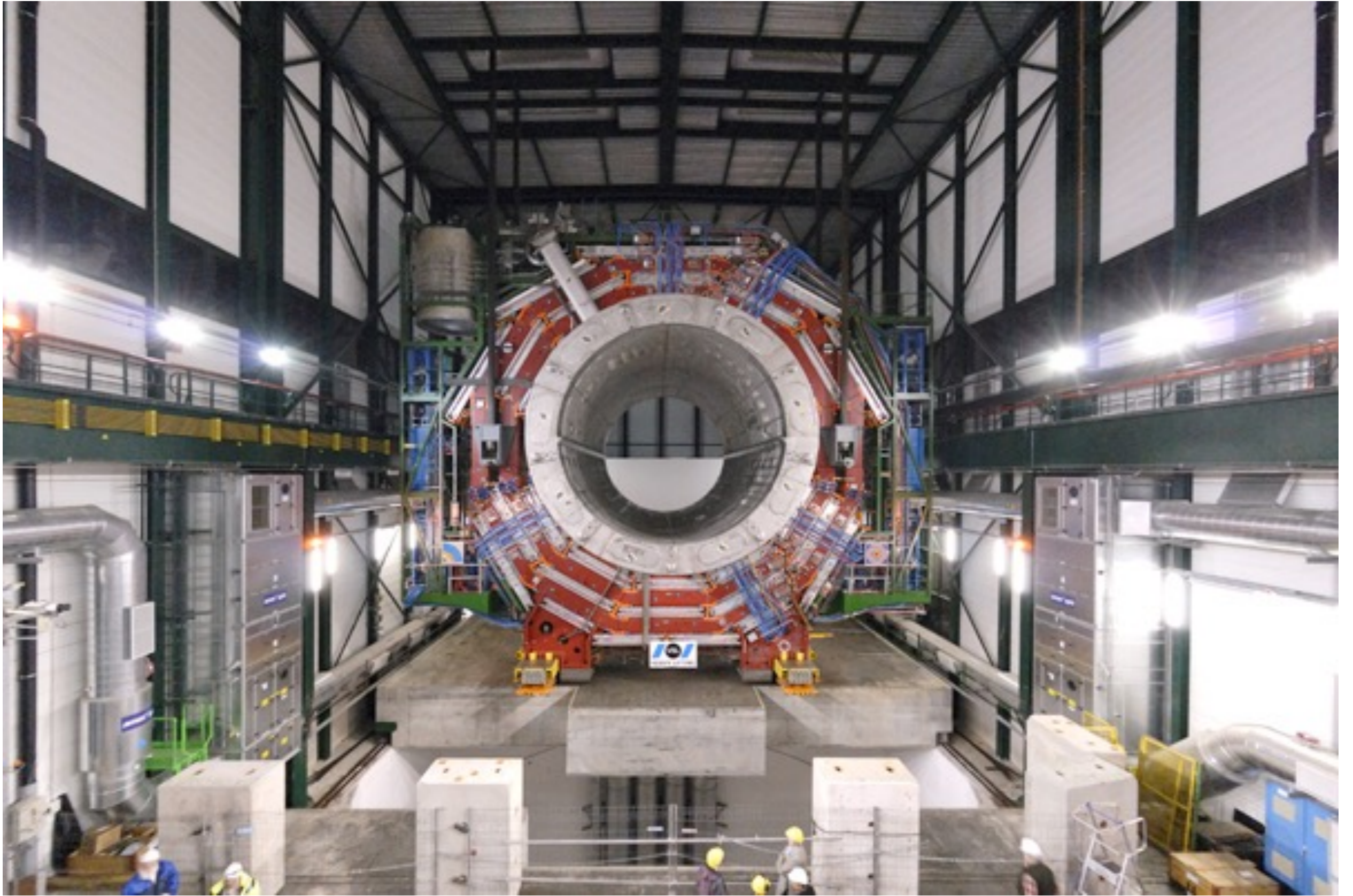


Overall view of the LHC experiments.

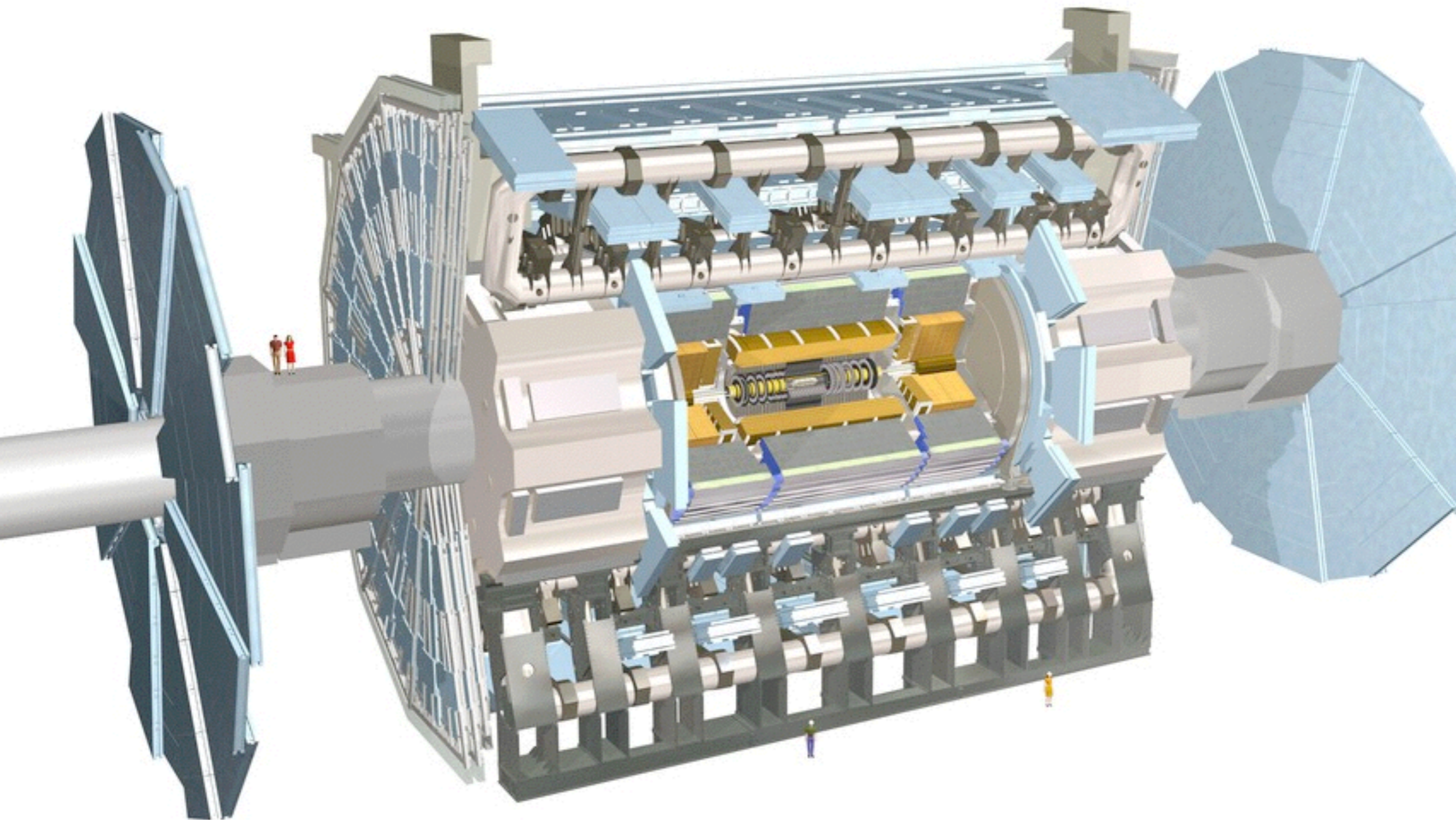


A Compact Solenoidal Detector for LHC





CERN

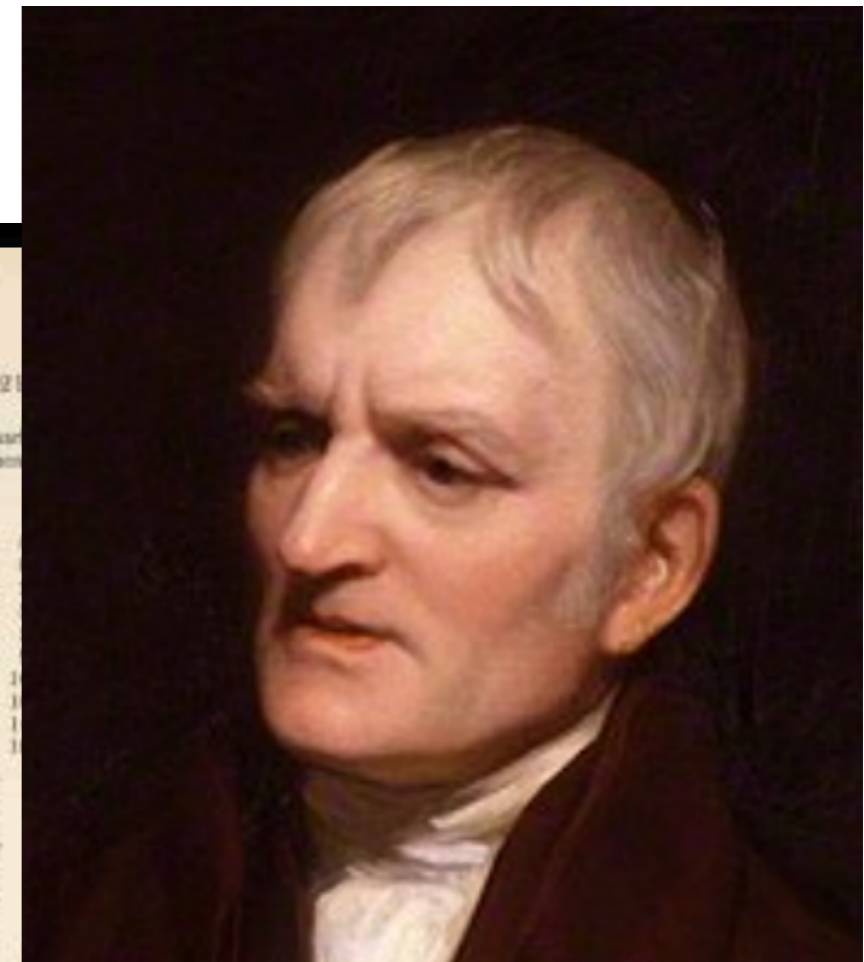
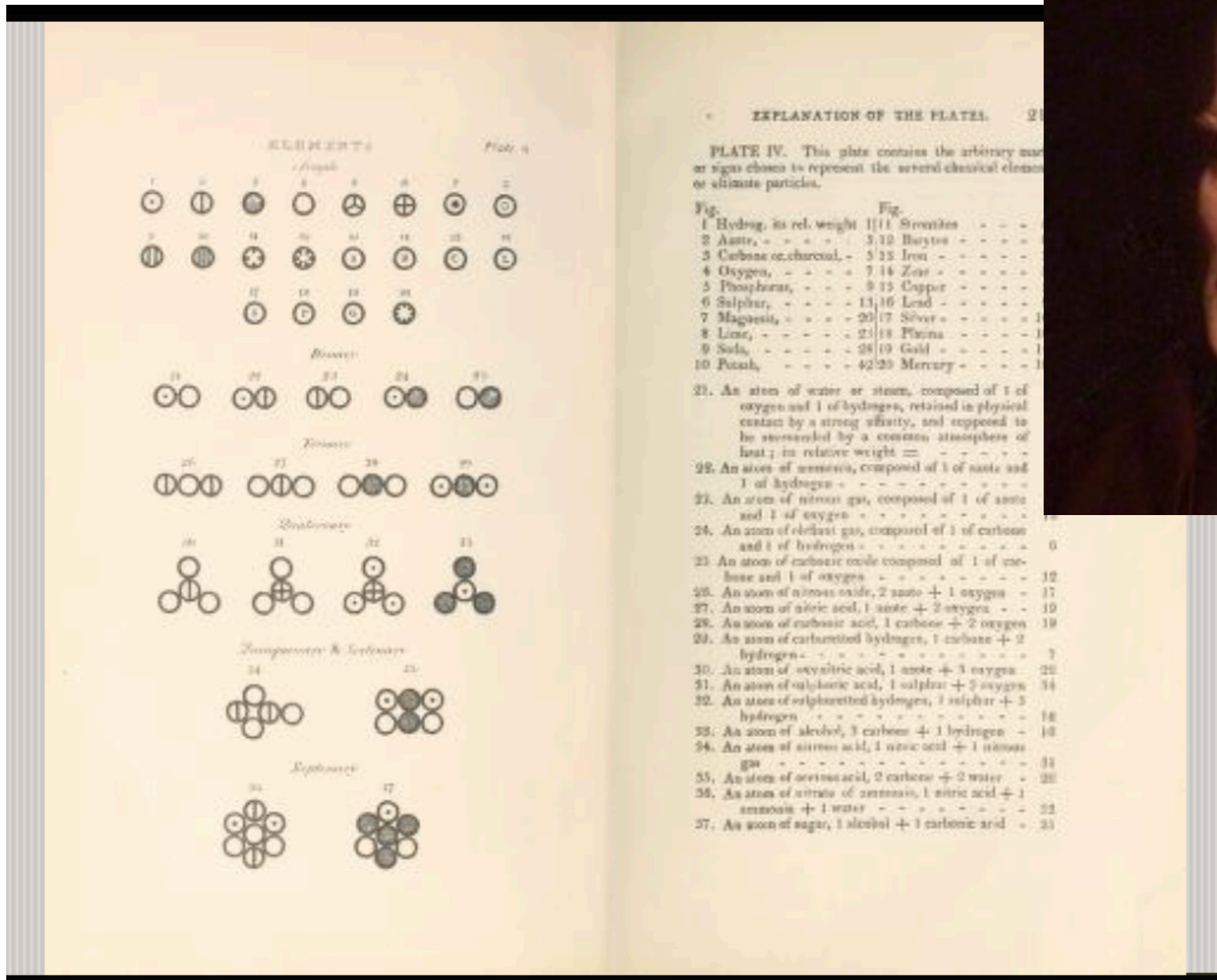


the ATLAS experiment



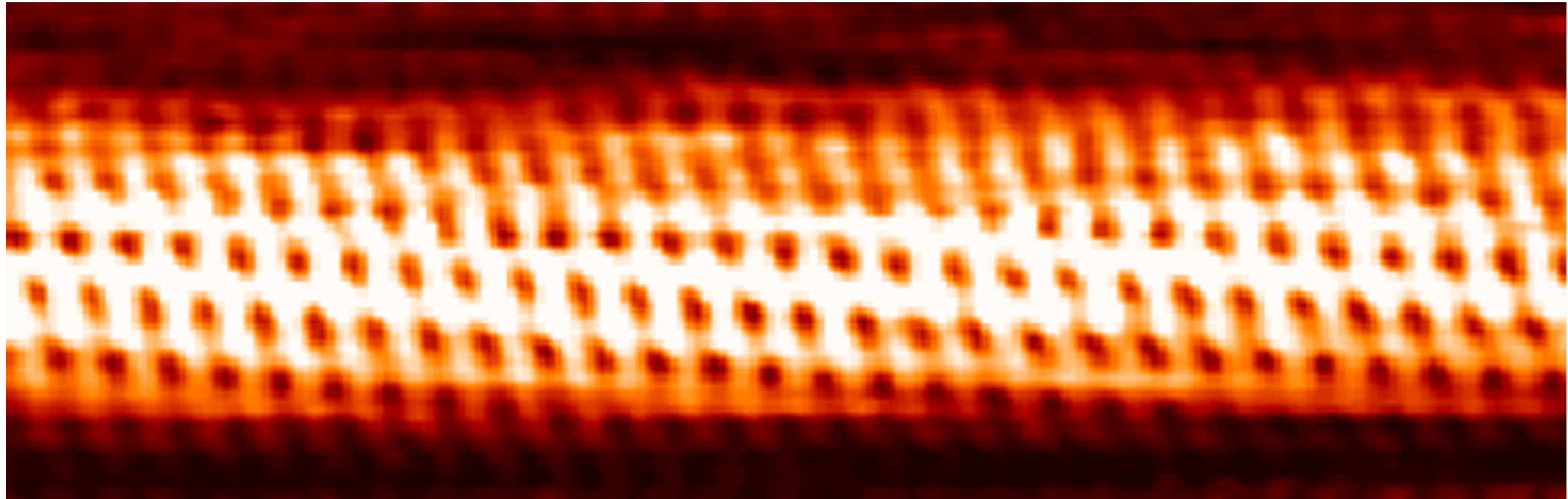
arrival of an ATLAS magnet component at CERN

Paula Collins, CERN



John Dalton

A New System of Chemical Philosophy 1808

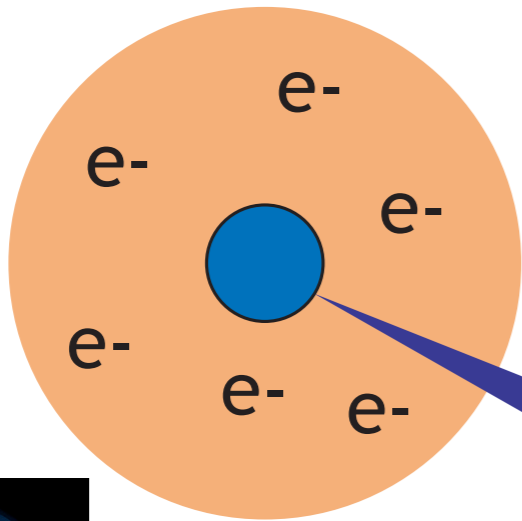


scanning tunneling microscope image
of a carbon nanotube

Taner Yildirim (NIST)

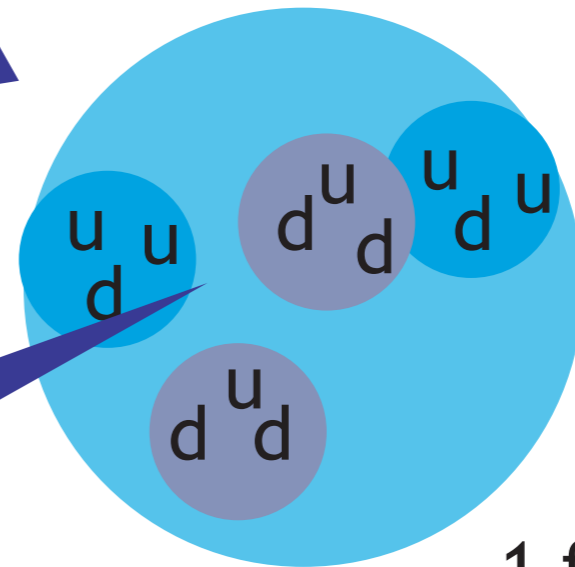
If you can see it ...

... then you are not actually on the frontier.



1/10 nm

x 100,000



1 fm

x 100,000



What is mass,

and how does the Higgs field provide it ?

SMALL
PEQUENA

J's
Purses

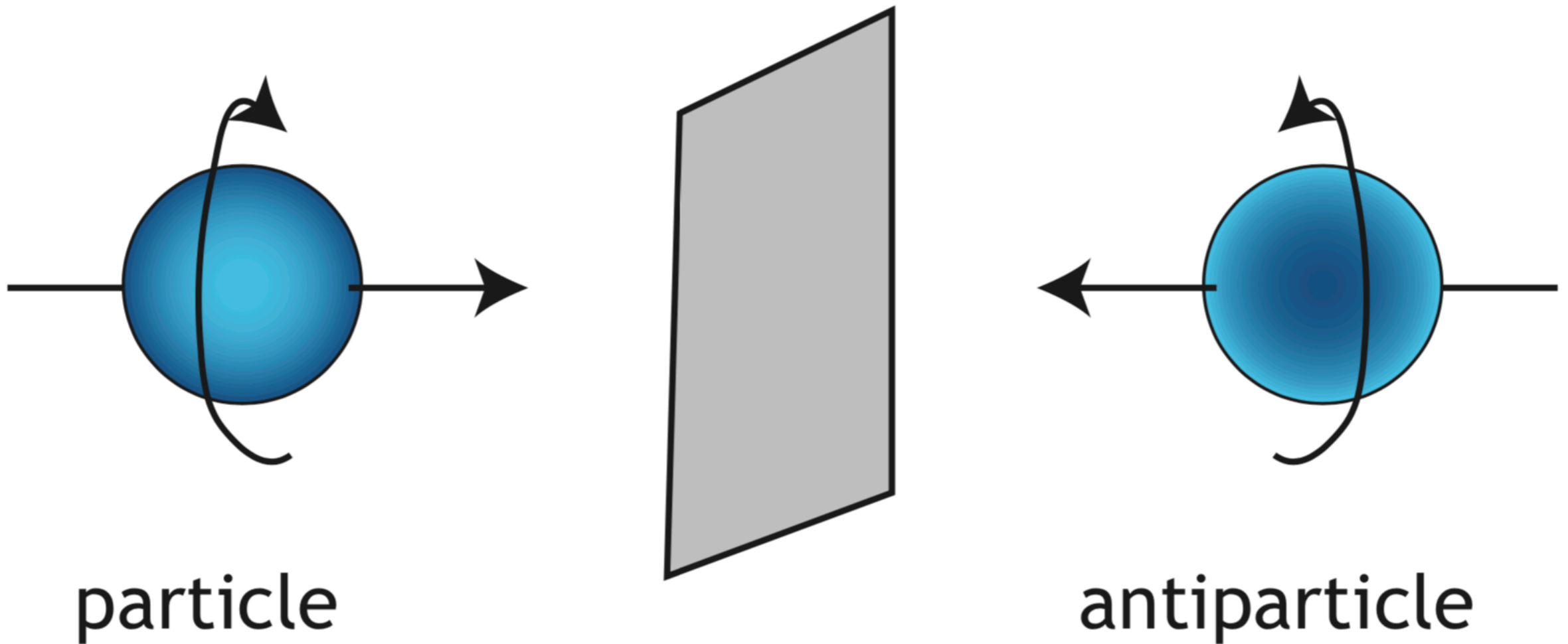


This Green

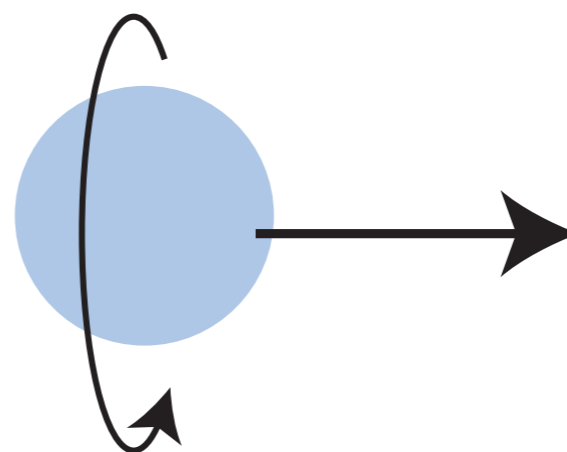
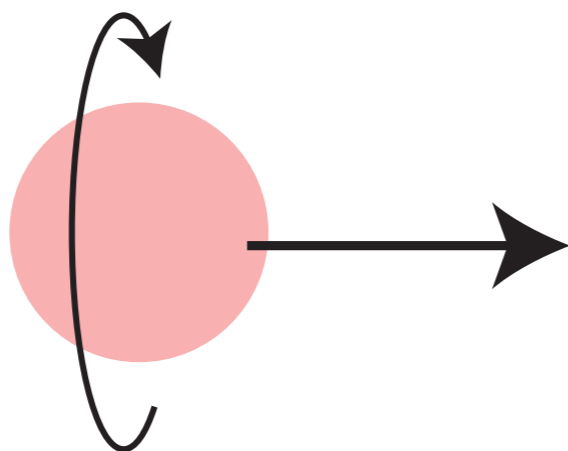


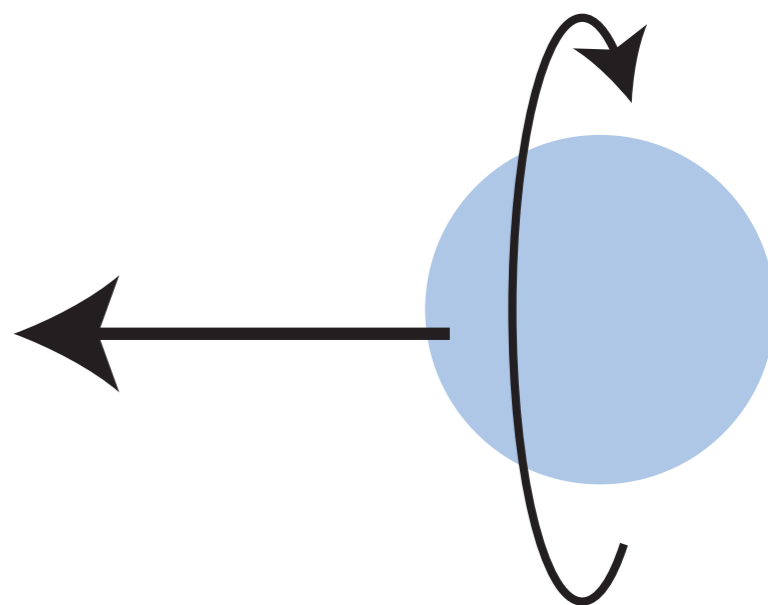
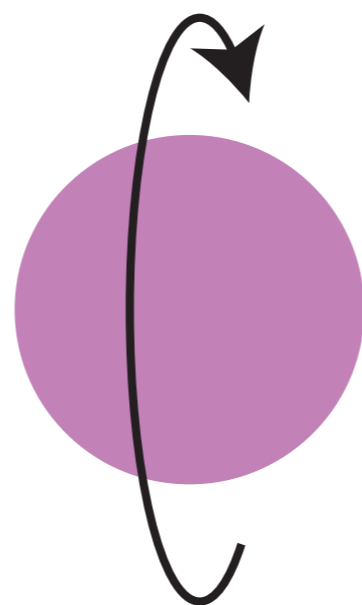
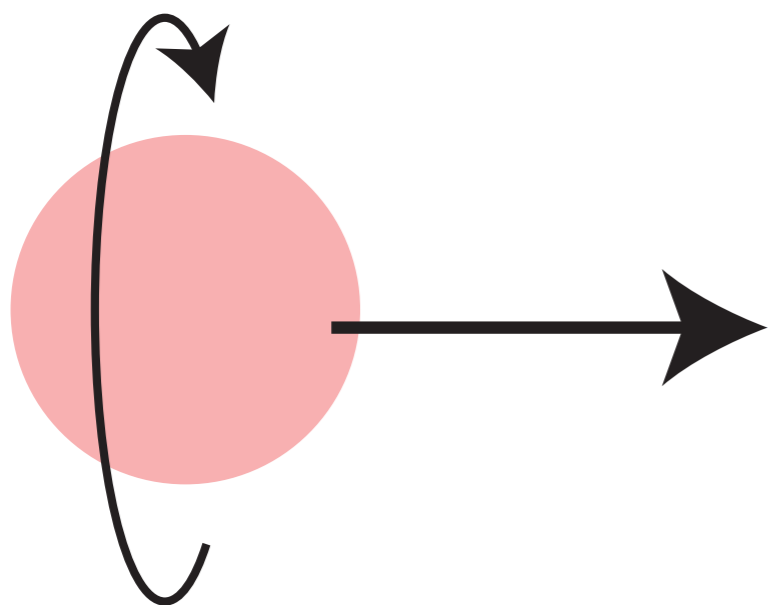
In the theory of relativity,

the simplest kind of particle moves at the speed of light.



“spin 1/2”





A massive particle is an **assemblage of different pieces.**

Do the pieces fit together ?



Radioactivity:

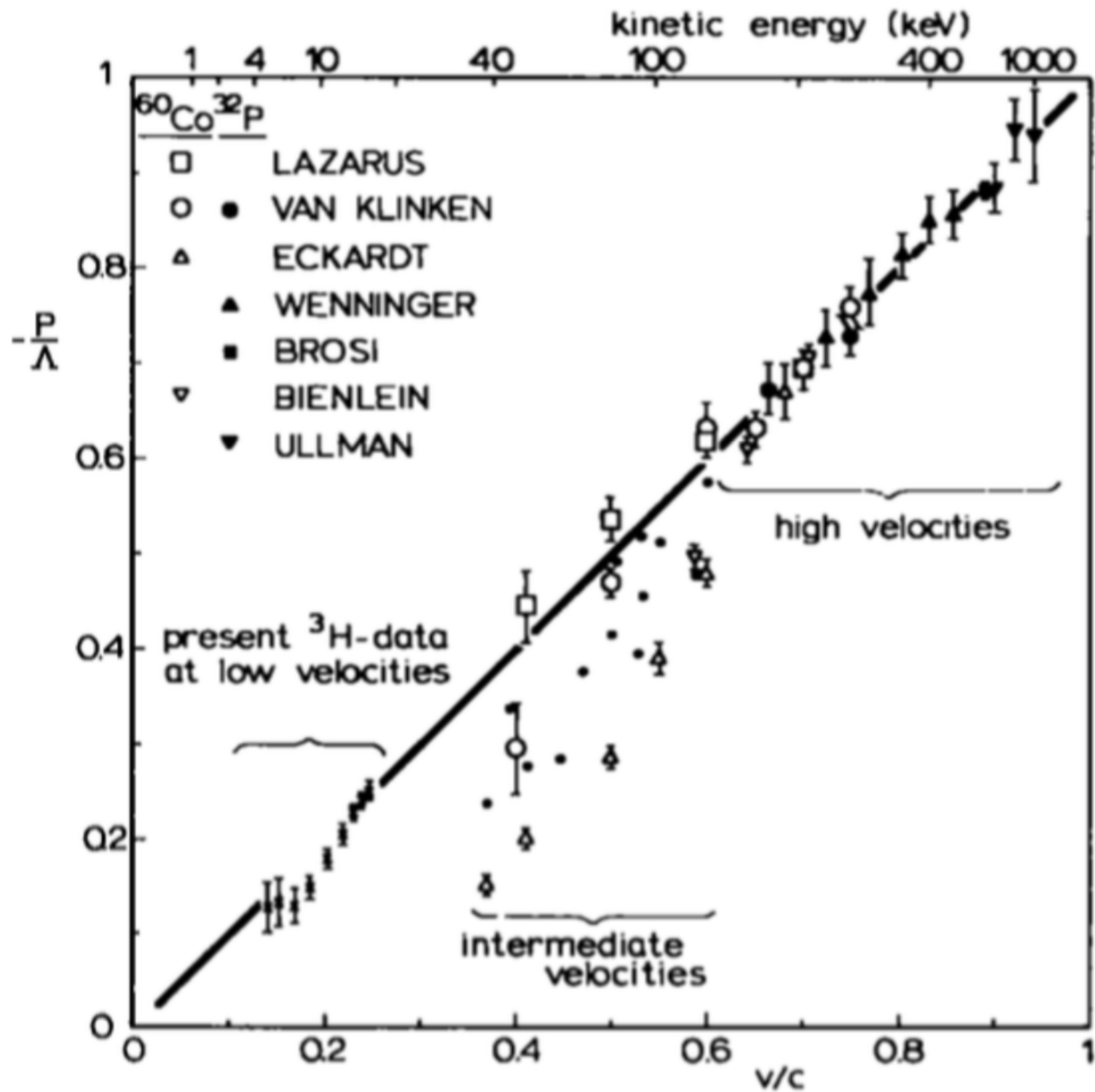
inside a nucleus:

$$n \rightarrow p + e^{-} + \bar{\nu}$$

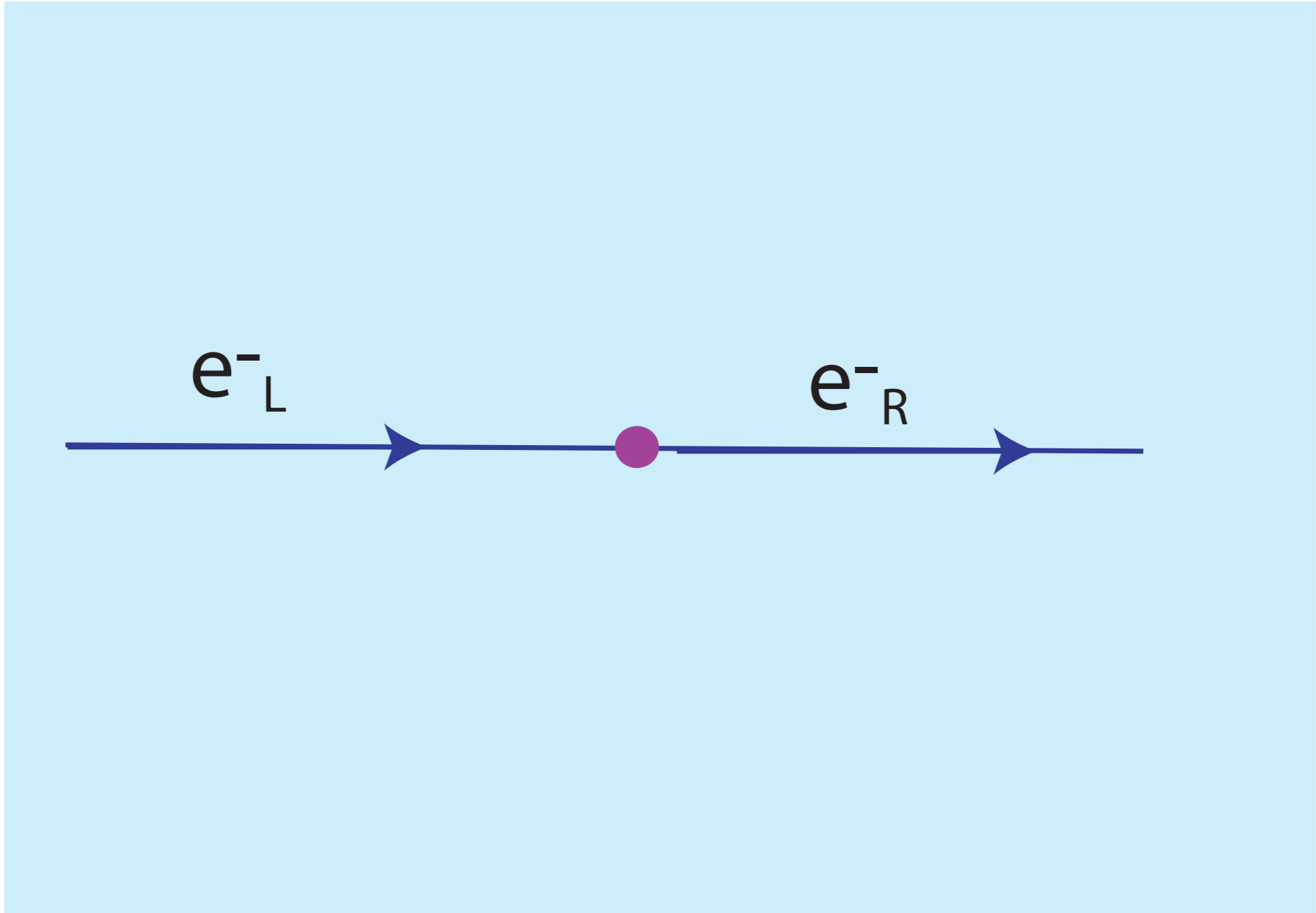
inside a neutron:

$$n = (d d u)$$

$$d \rightarrow u + e^{-} + \bar{\nu}$$



Koks and van Klinken



Fundamental particles, and their masses (MeV)

<i>u</i>	<i>d</i>	<i>s</i>	<i>c</i>	<i>b</i>	<i>t</i>
1.5	3	60	700	2800	164,000
<hr/>					
<i>e</i>	<i>μ</i>	<i>τ</i>			
0.51	105.7	1777			

Can we test this hypothesis ?

1. Find LHC events containing Higgs bosons.
2. Find Higgs bosons in a large number of decay modes.
3. Measure the various rates, and compare them.

Problem #1:

rate for all proton-proton collisions

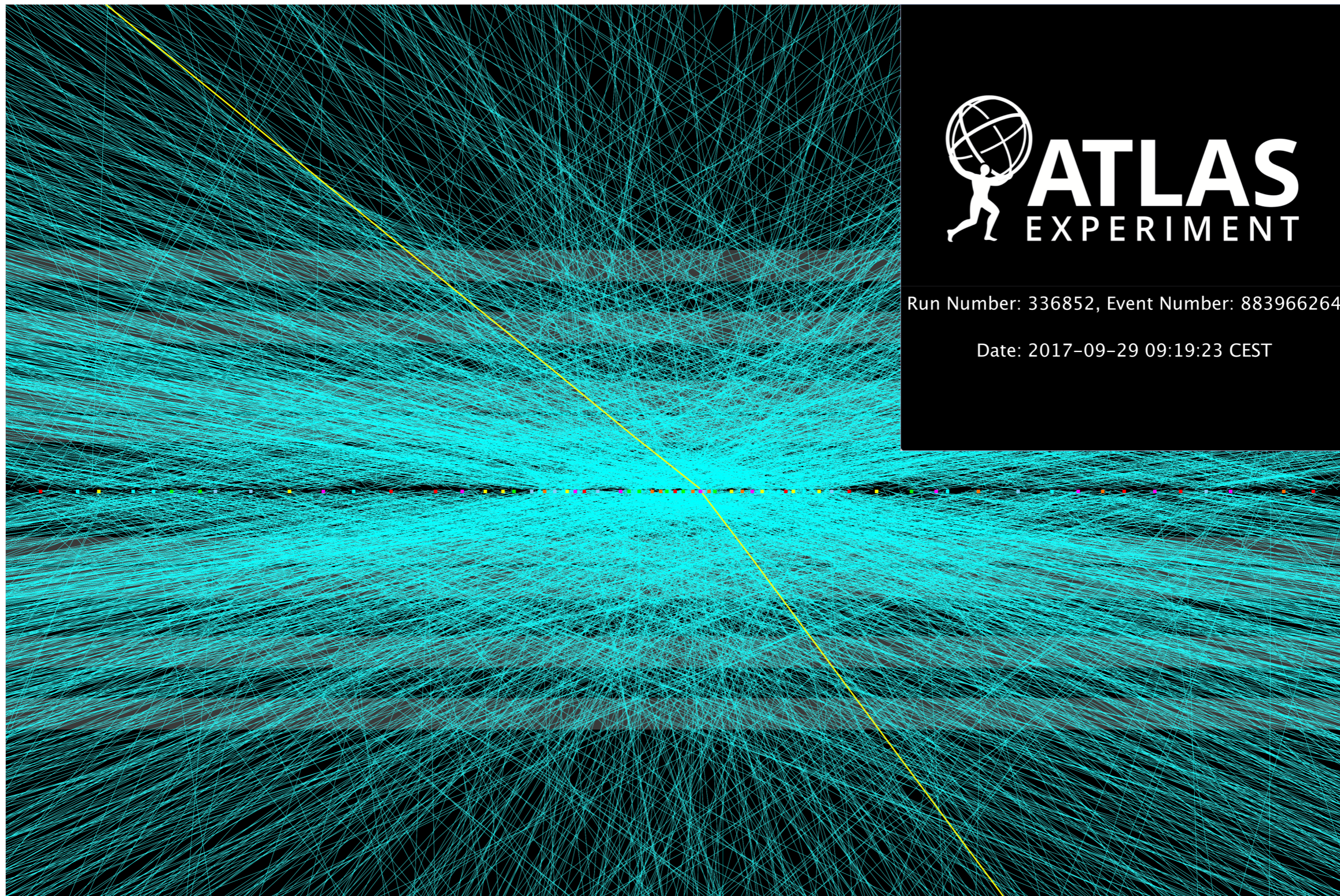
0.1 barn

rate for Higgs boson events

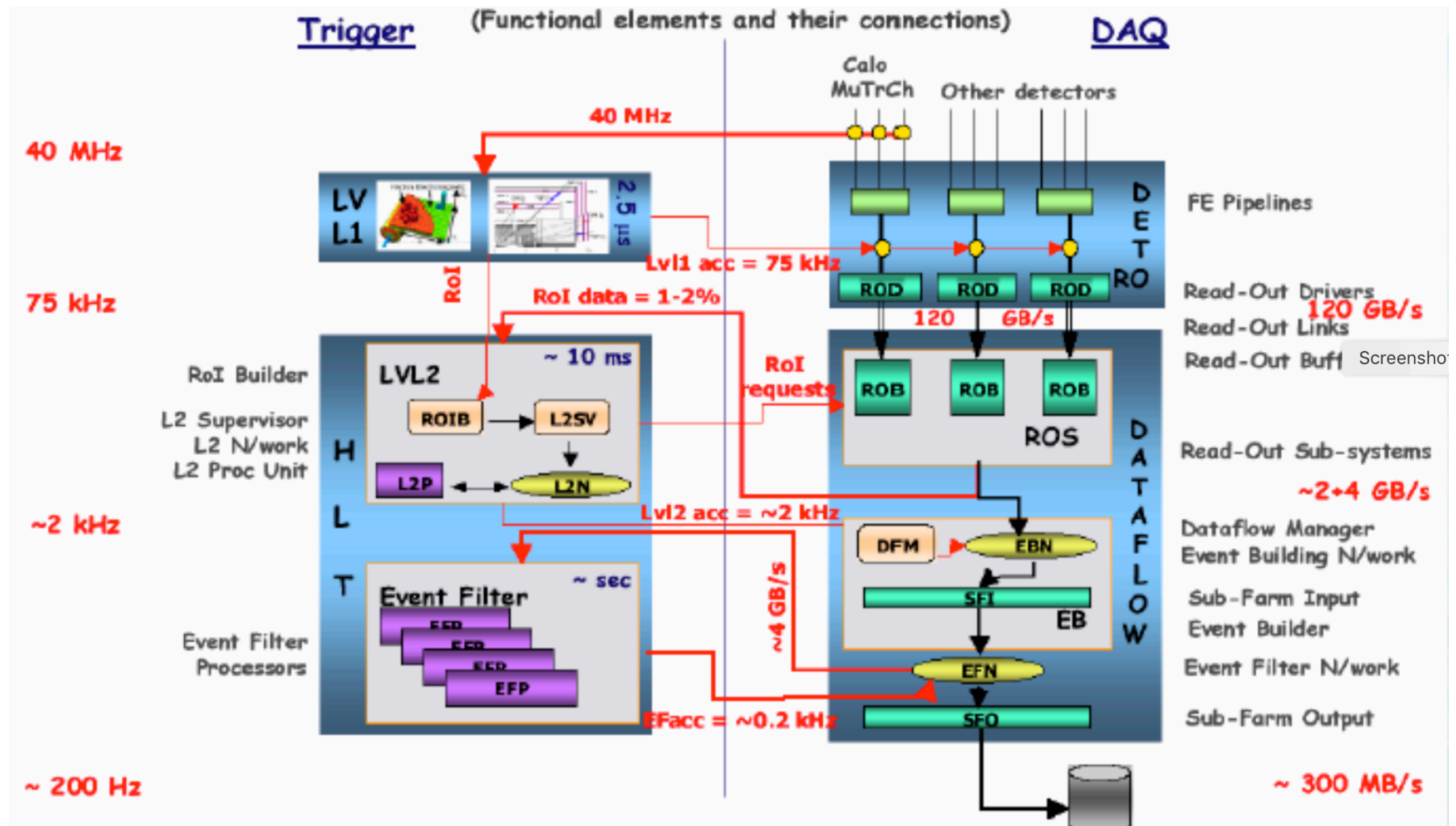
50 pico-barn

rate for Higgs decay to $\gamma\gamma$

120 femto-barn

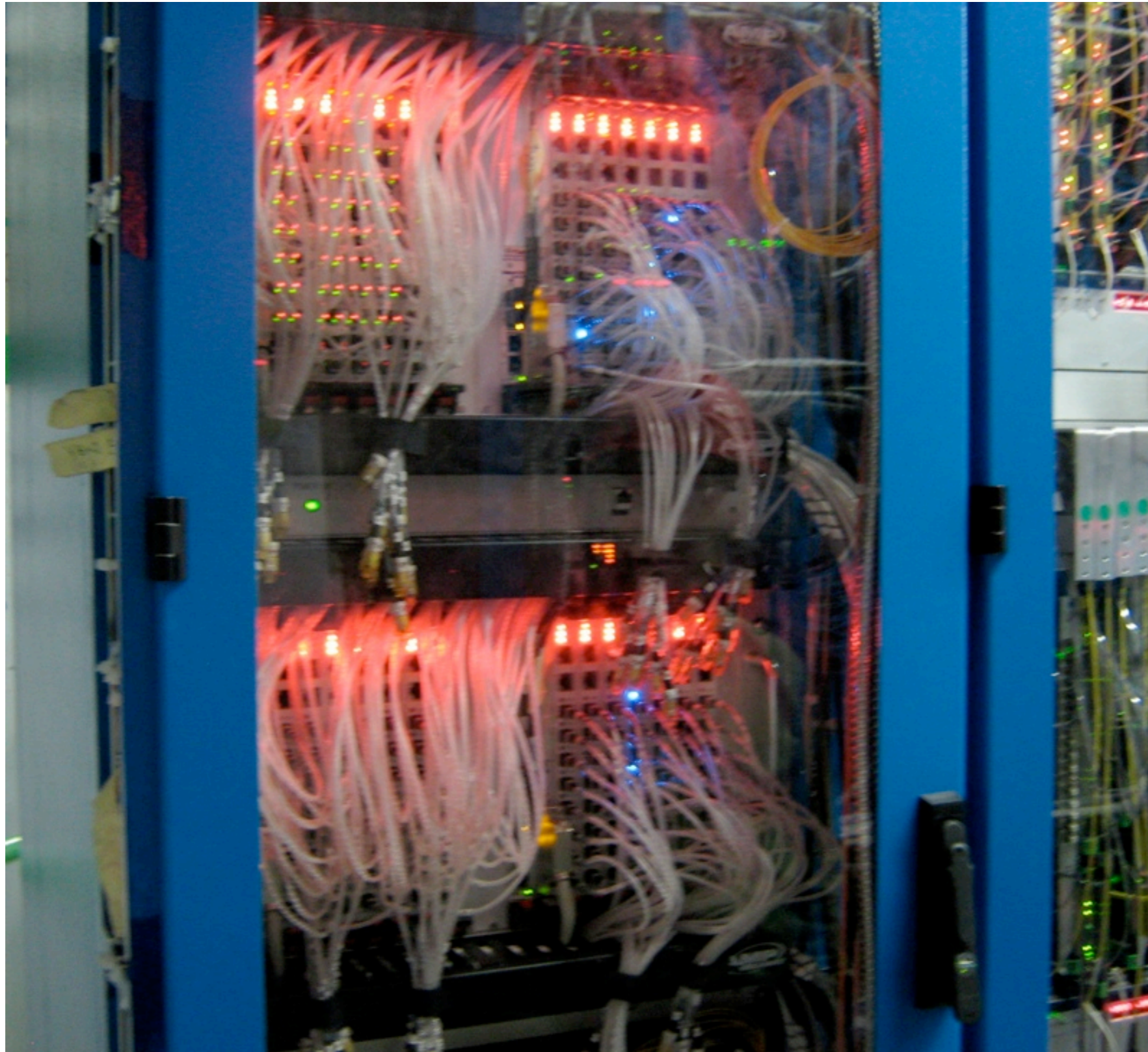


ATLAS event with 65 pileup vertices



ATLAS trigger, c. 2012

N. Ellis, ATLAS



the CMS level 1 trigger, in action !

Major decay modes of the Higgs boson:

predicted fraction

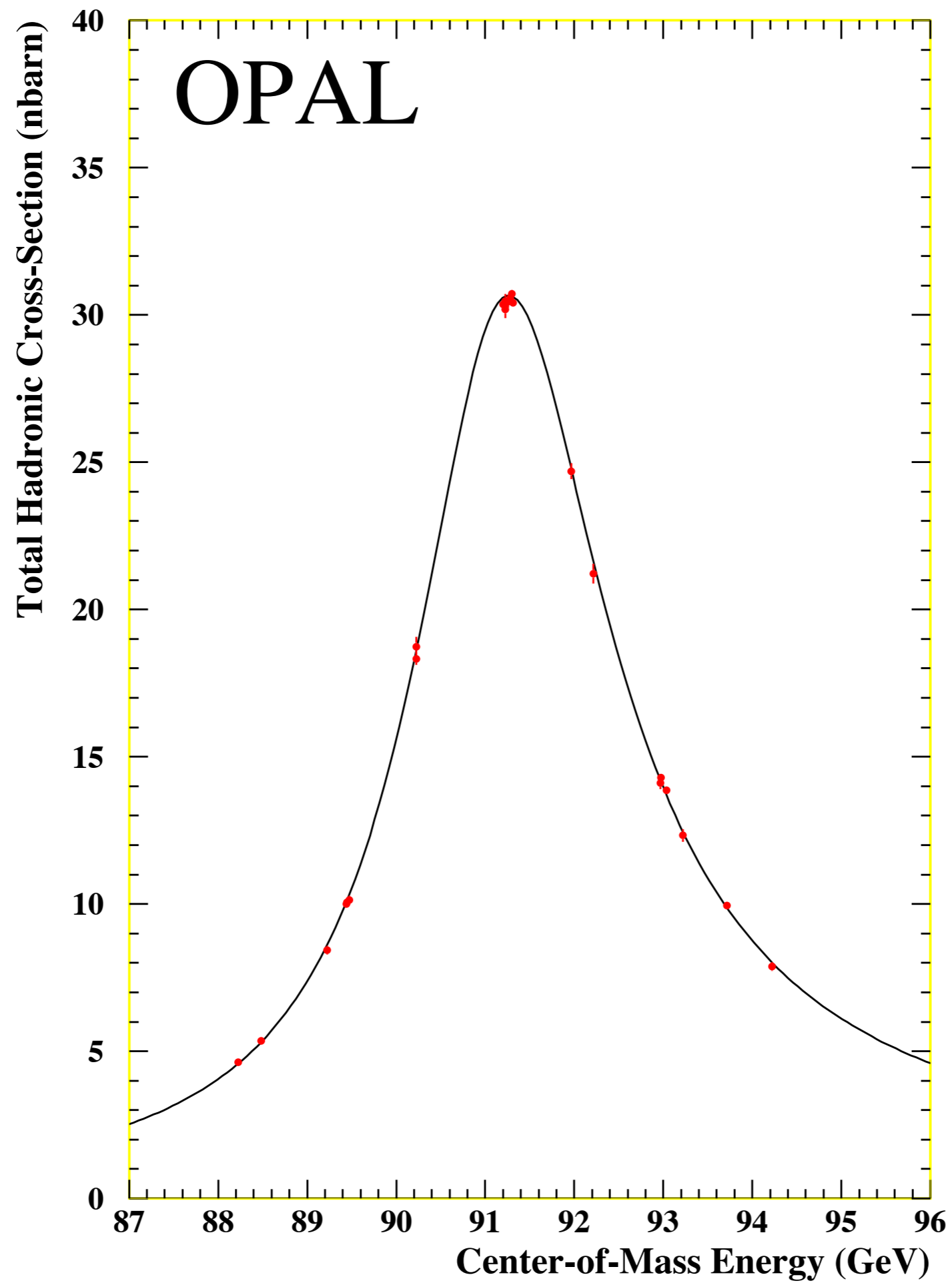
$$h \rightarrow b\bar{b} \quad 56 \%$$

$$h \rightarrow W^+W^- \quad 23 \%$$

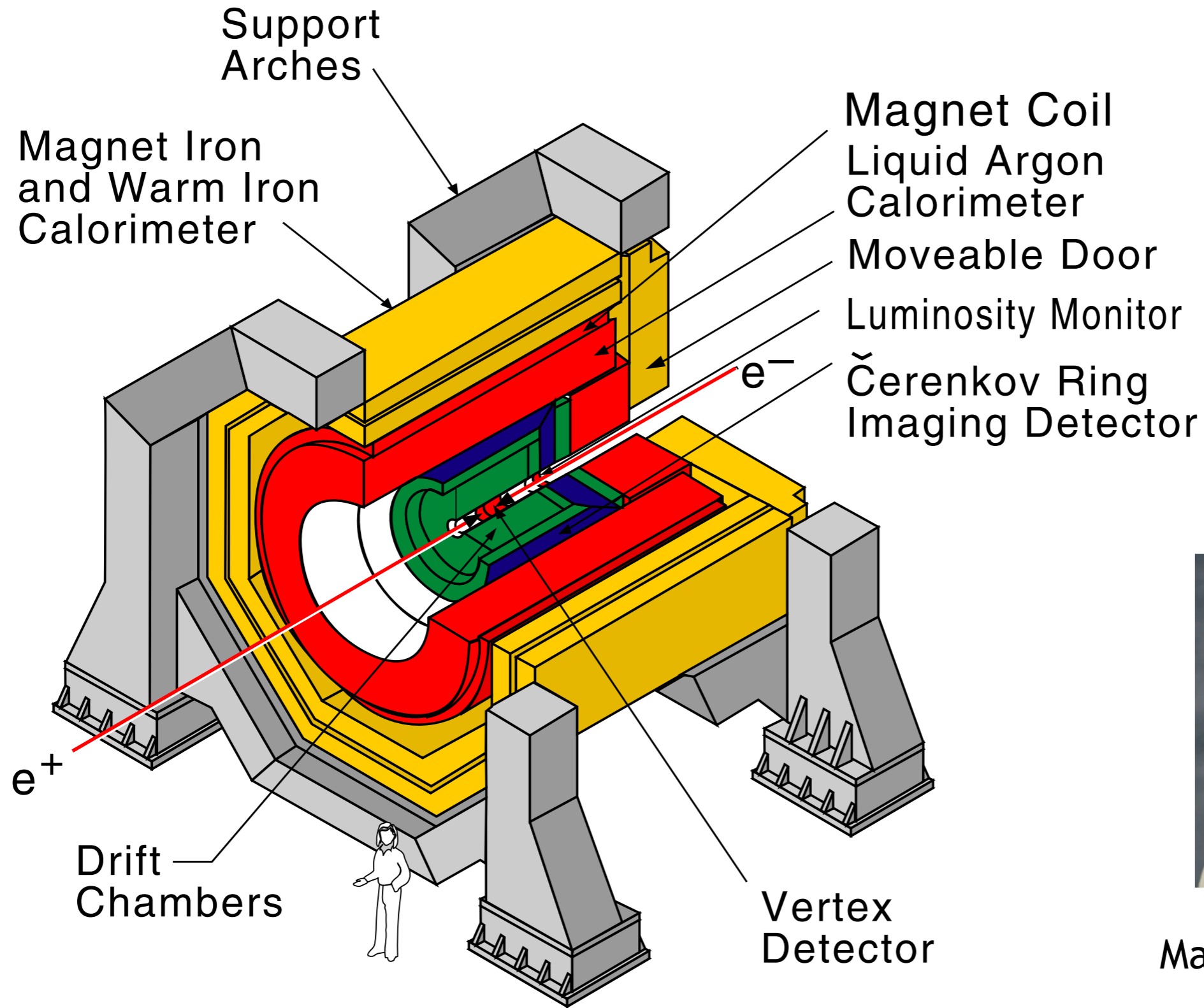
$$h \rightarrow \tau^+\tau^- \quad 6.2 \%$$

$$h \rightarrow Z^0Z^0 \quad 2.9 \% \quad (0.013 \% \text{ 4l})$$

$$h \rightarrow \gamma\gamma \quad 0.23 \%$$

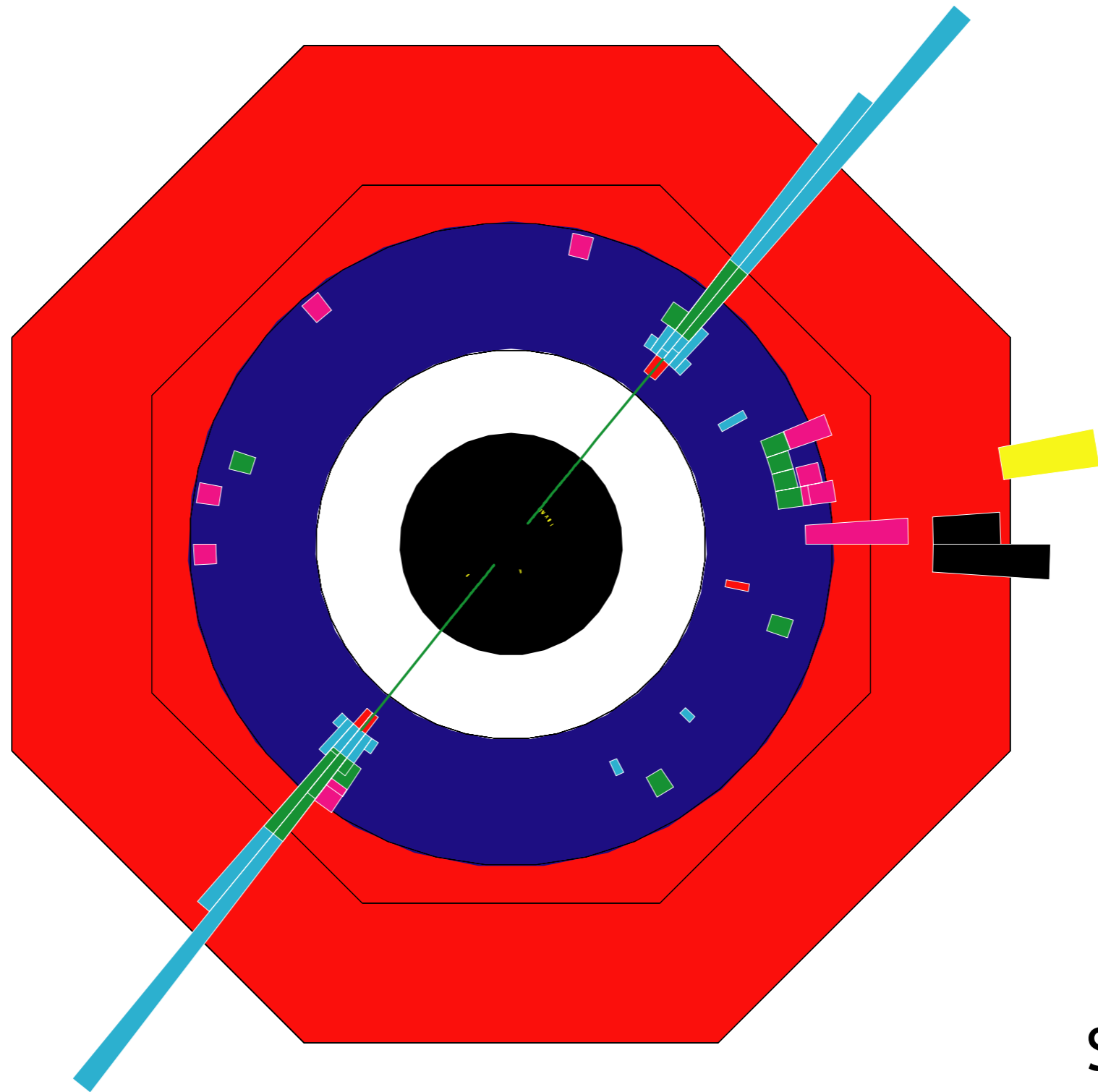


SLD



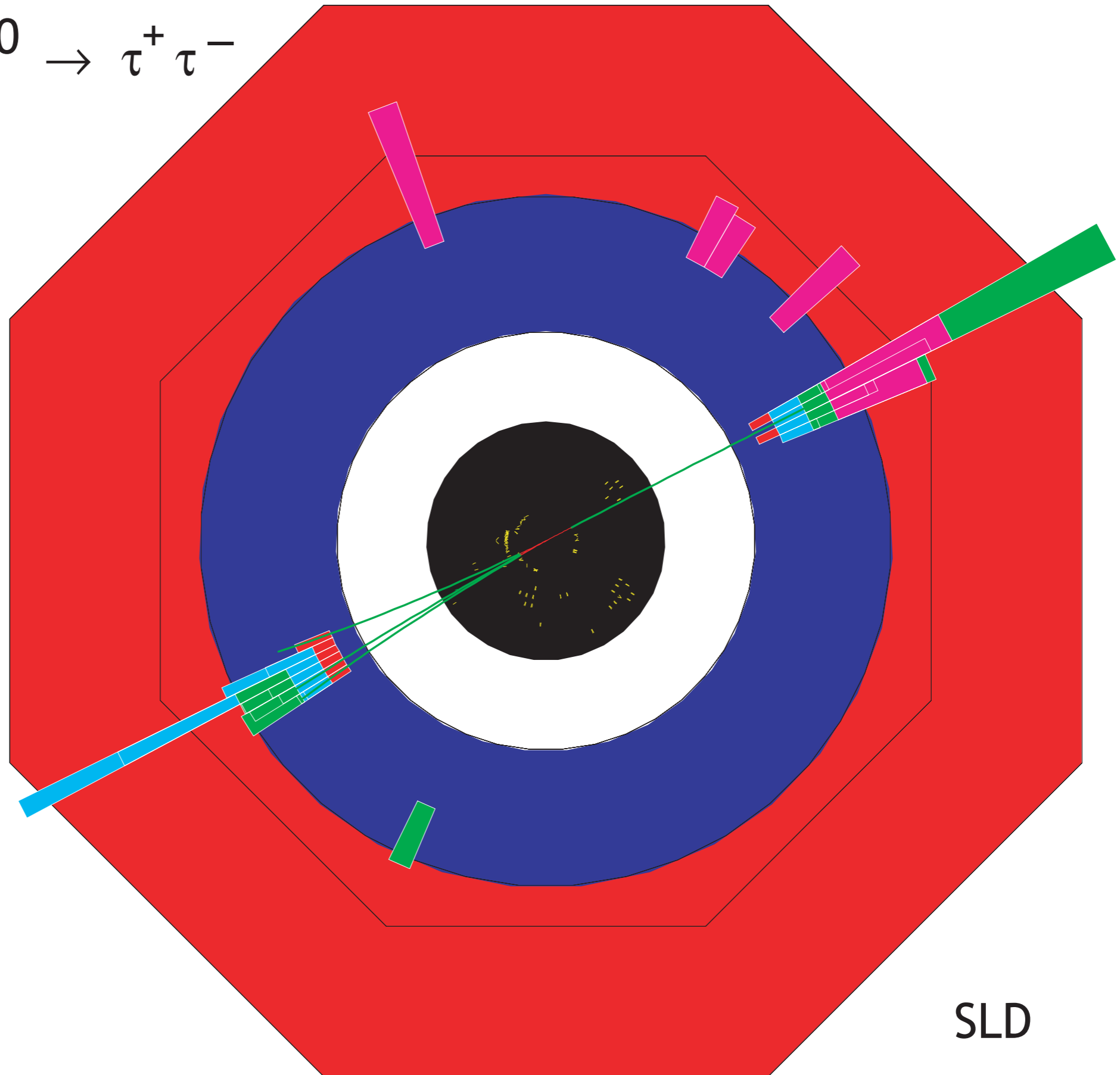
Marty Breidenbach

$$e^+e^- \rightarrow Z^0 \rightarrow e^+e^-$$

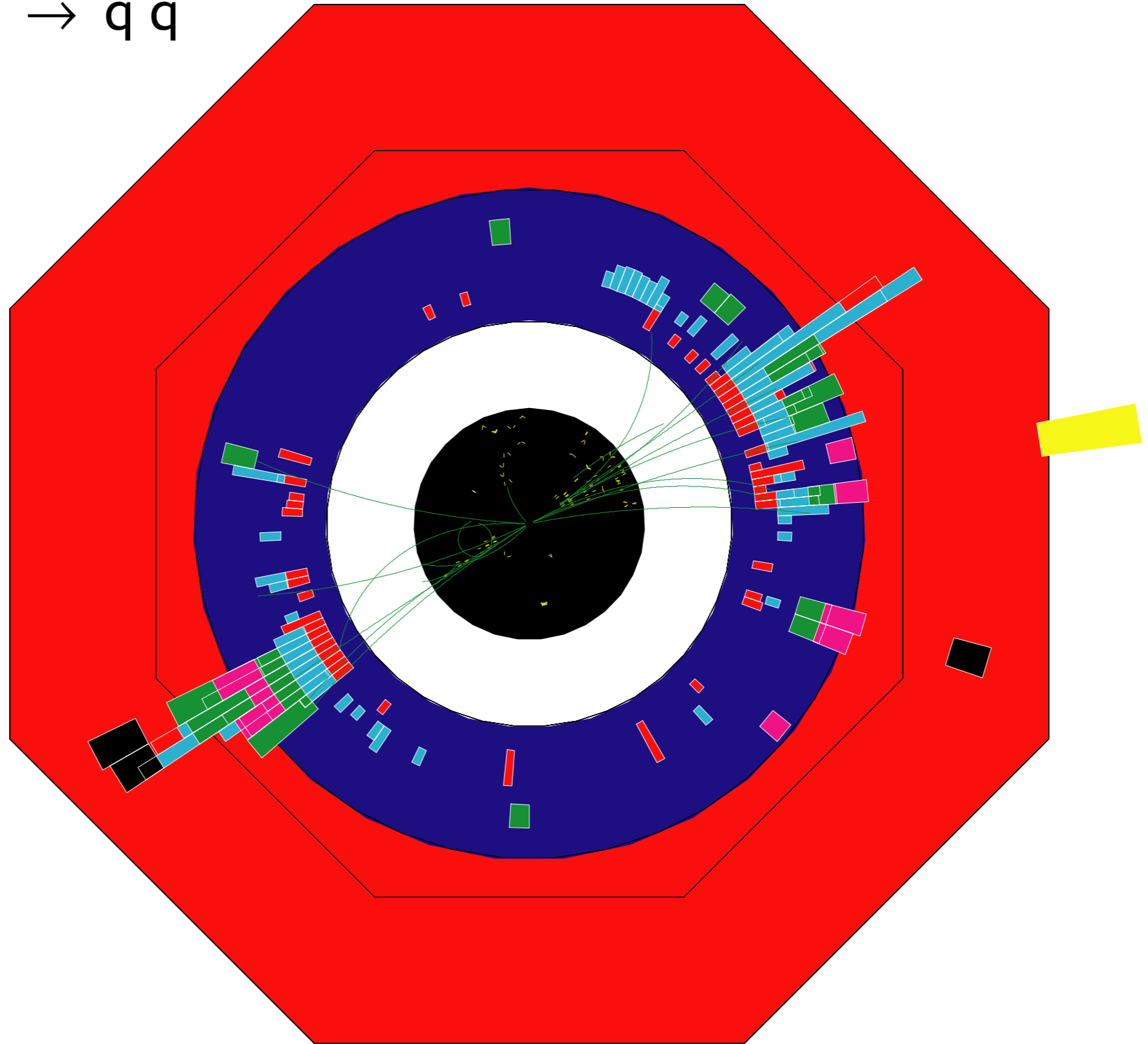


SLD

$$e^+e^- \rightarrow Z^0 \rightarrow \tau^+\tau^-$$

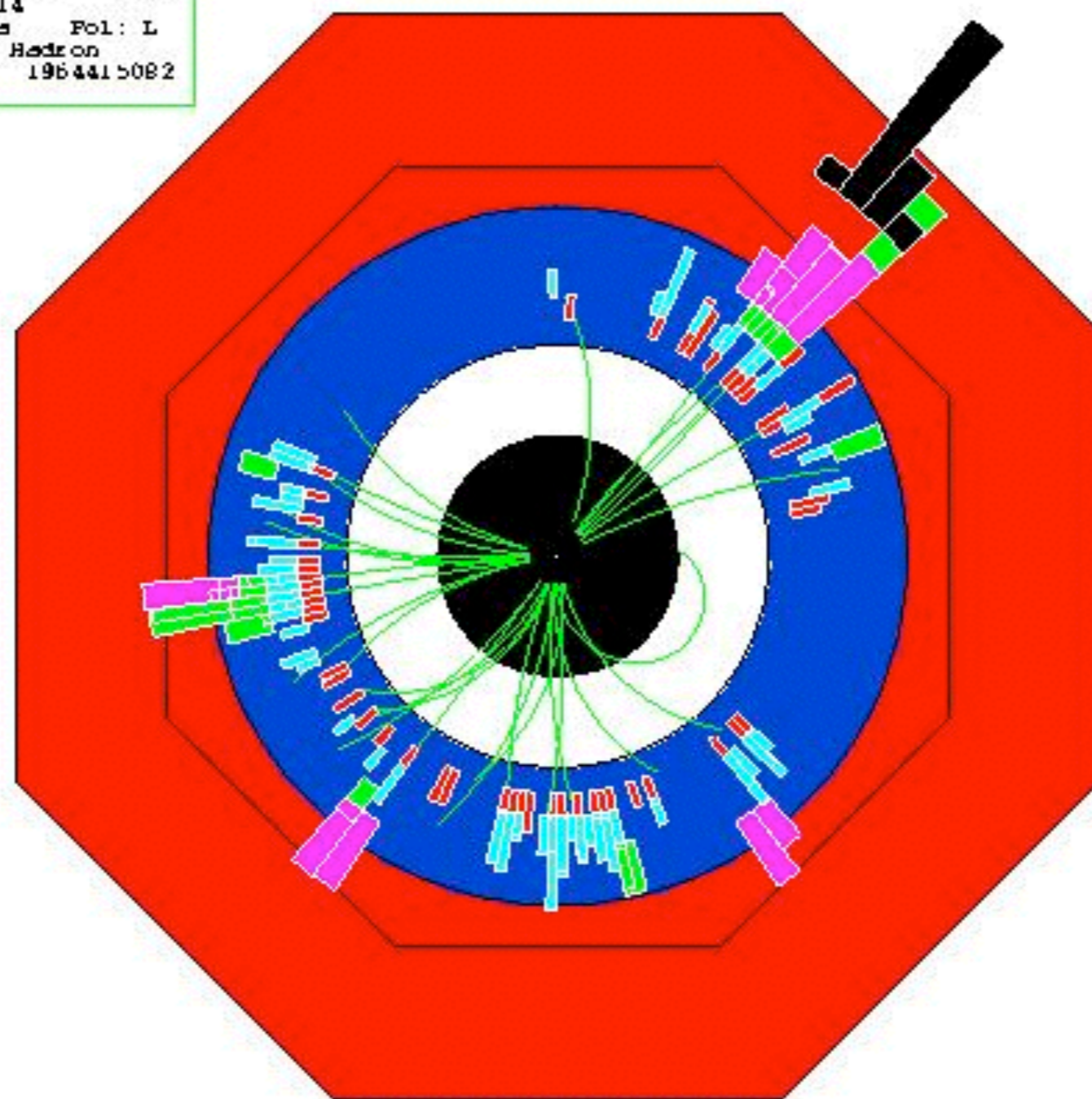


$$e^+ e^- \rightarrow z^0 \rightarrow q \bar{q}$$

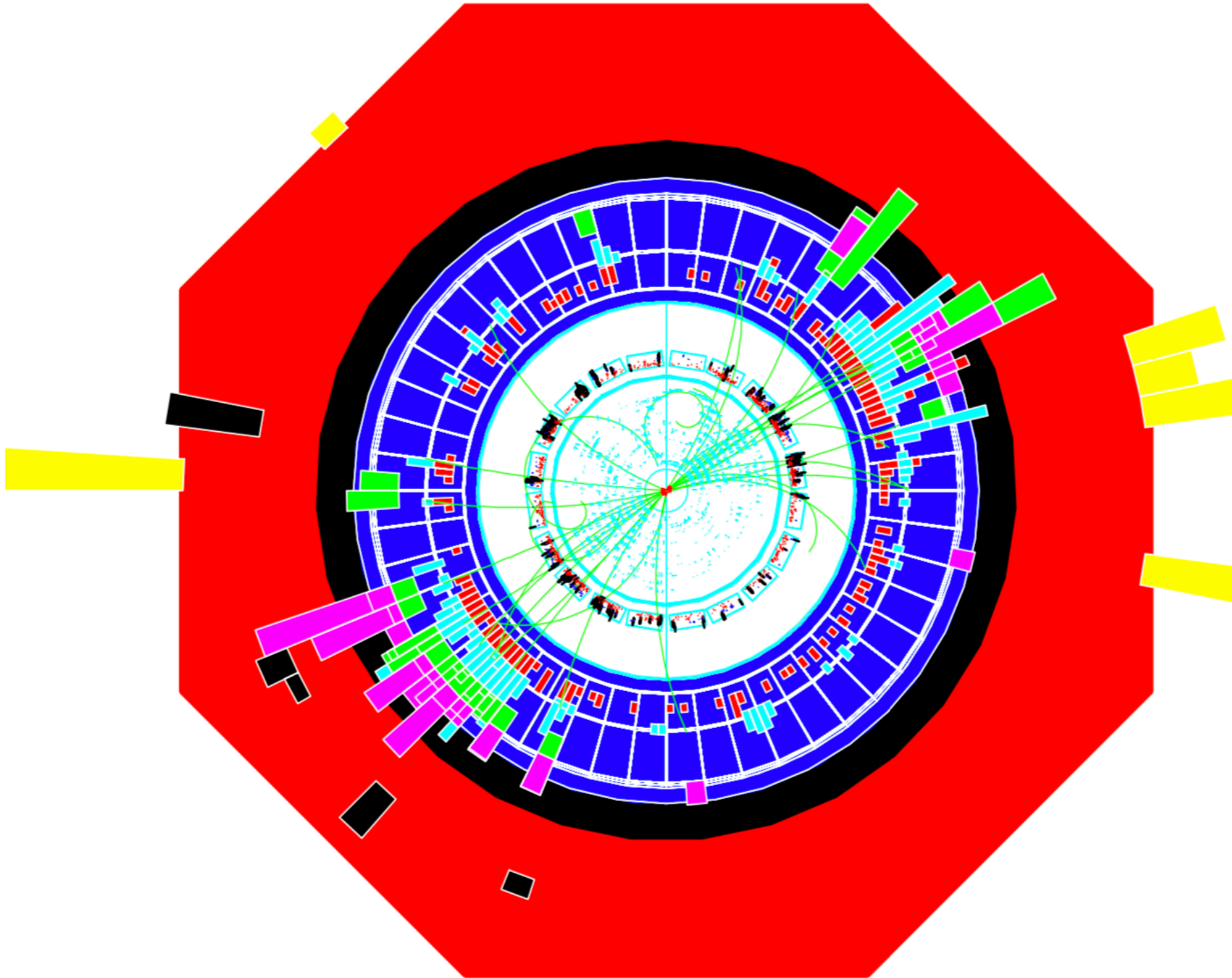


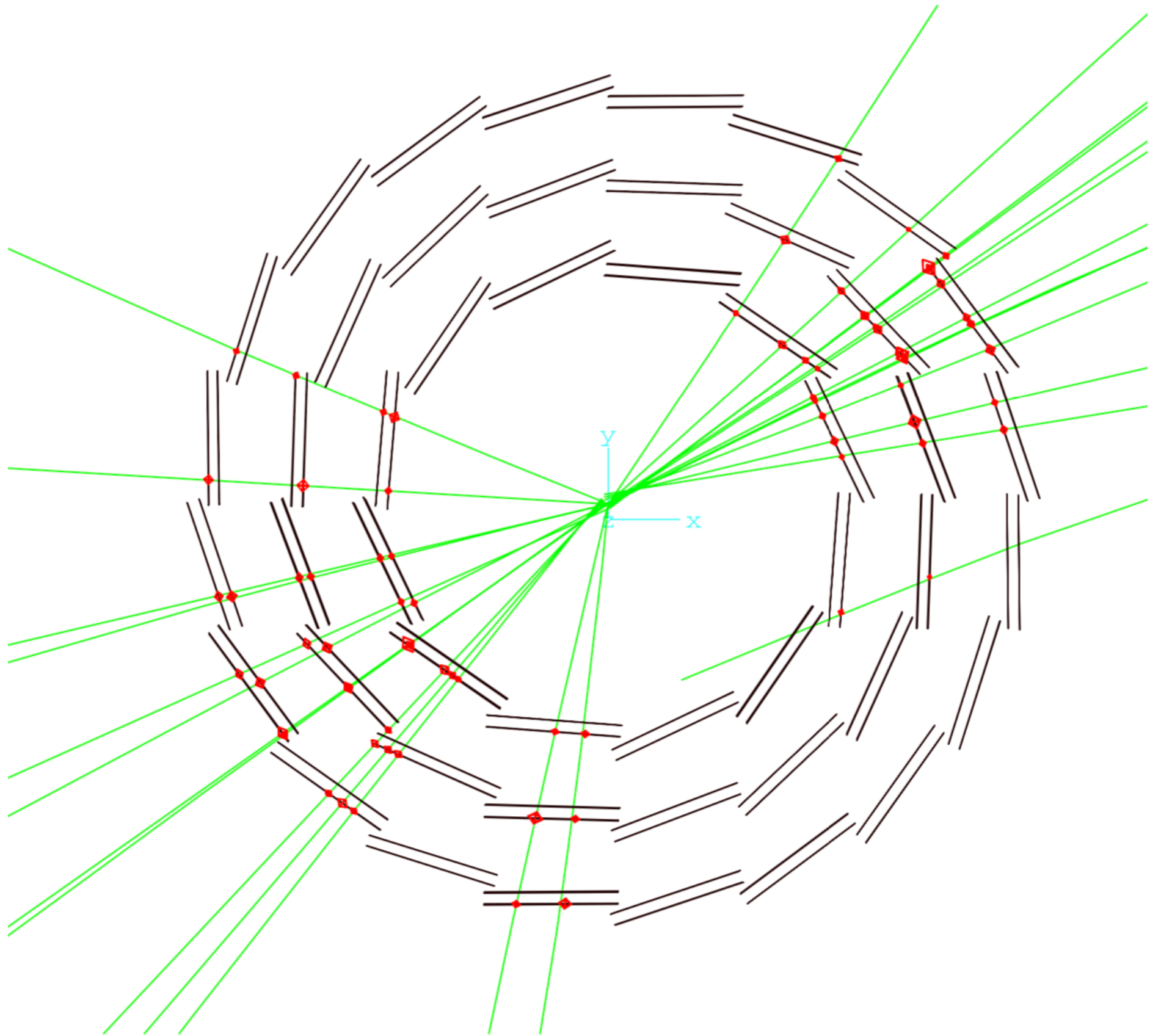
SLD

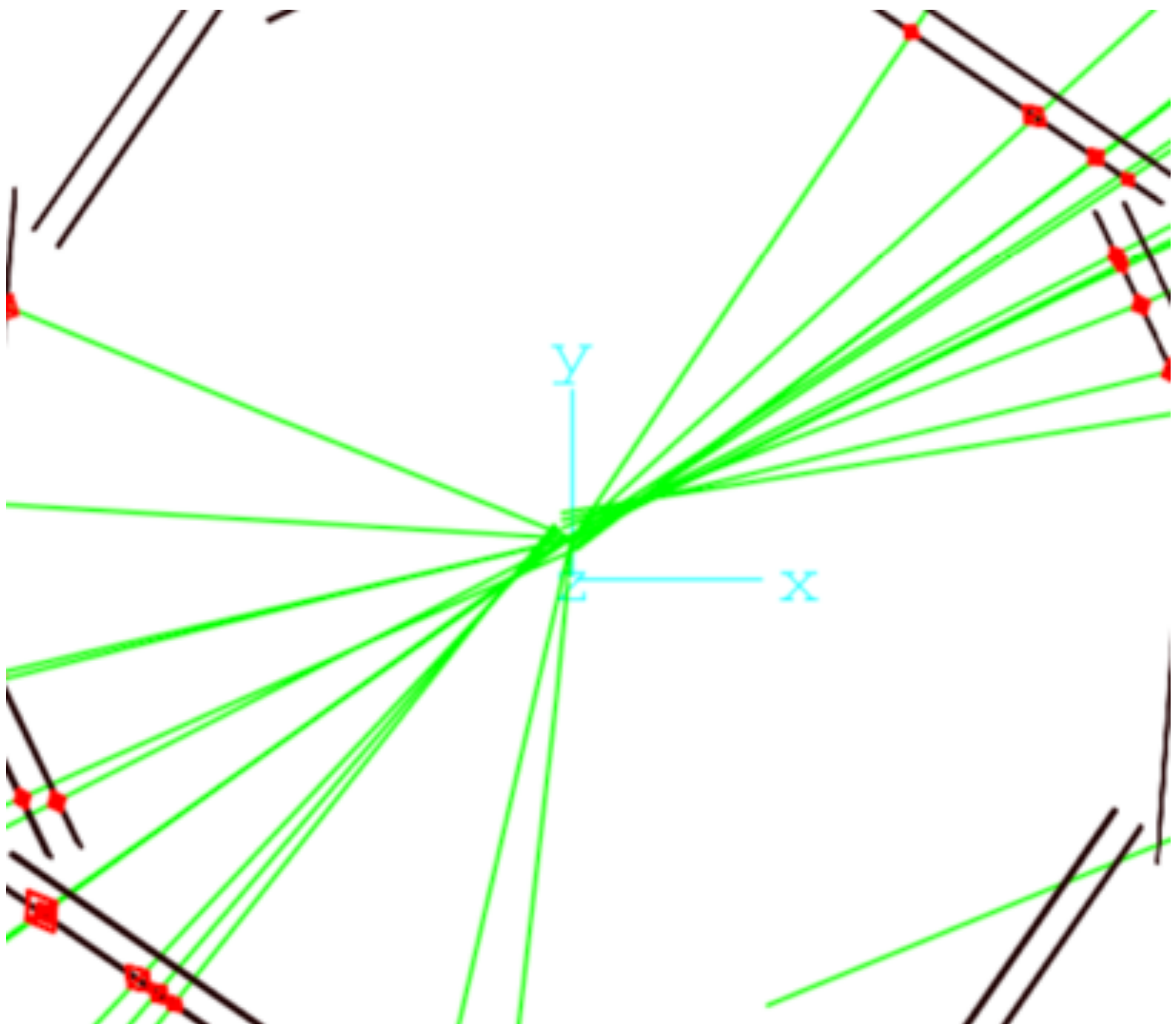
Run 12637, EVENT 6353
8-JUL-1992 10:14
Source: Run Data Pol: L
Trigger: Energy Hadron
Beam Crossing 1964415082



$$e^+ e^- \rightarrow z^0 \rightarrow b \bar{b}$$

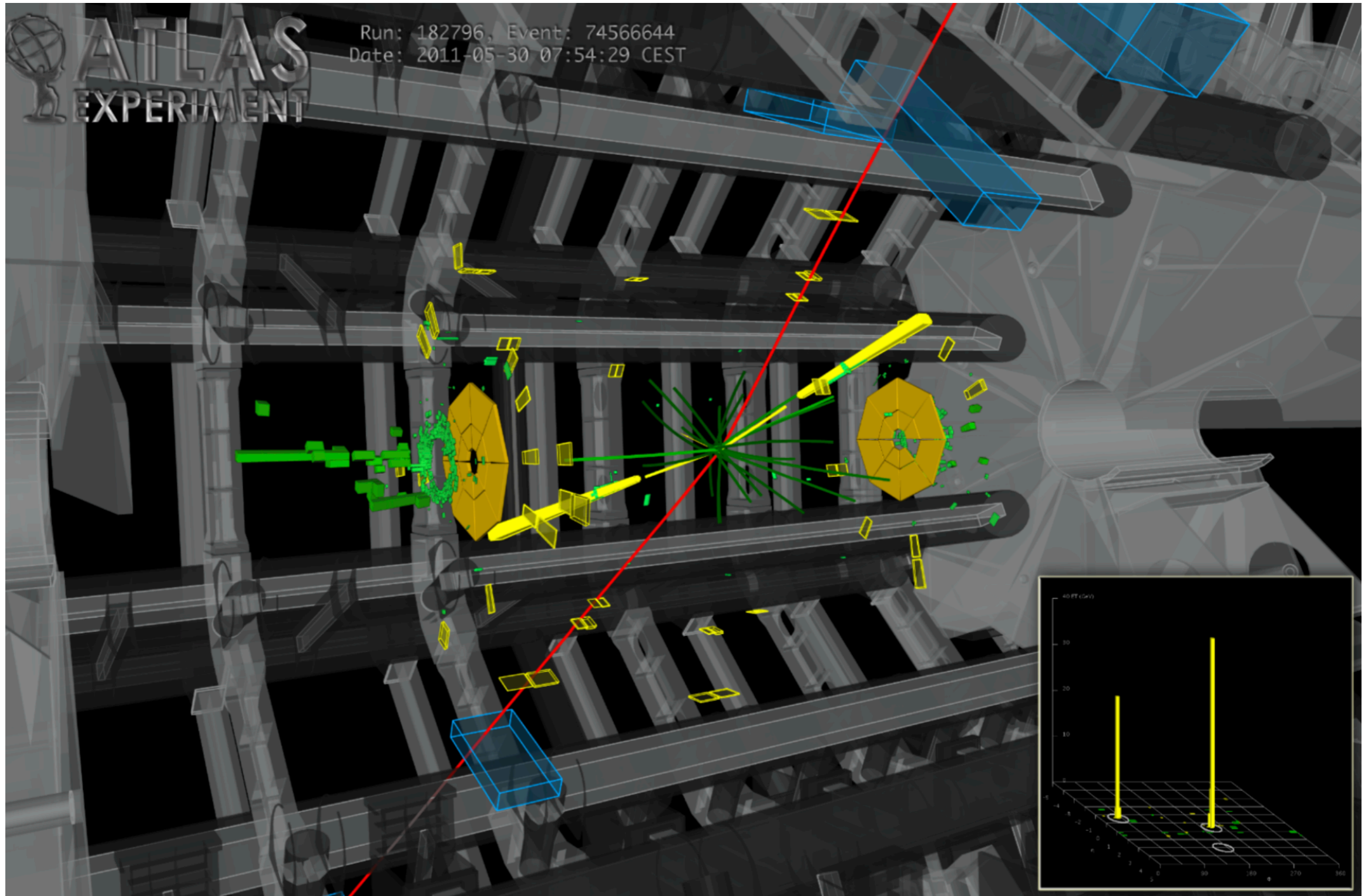


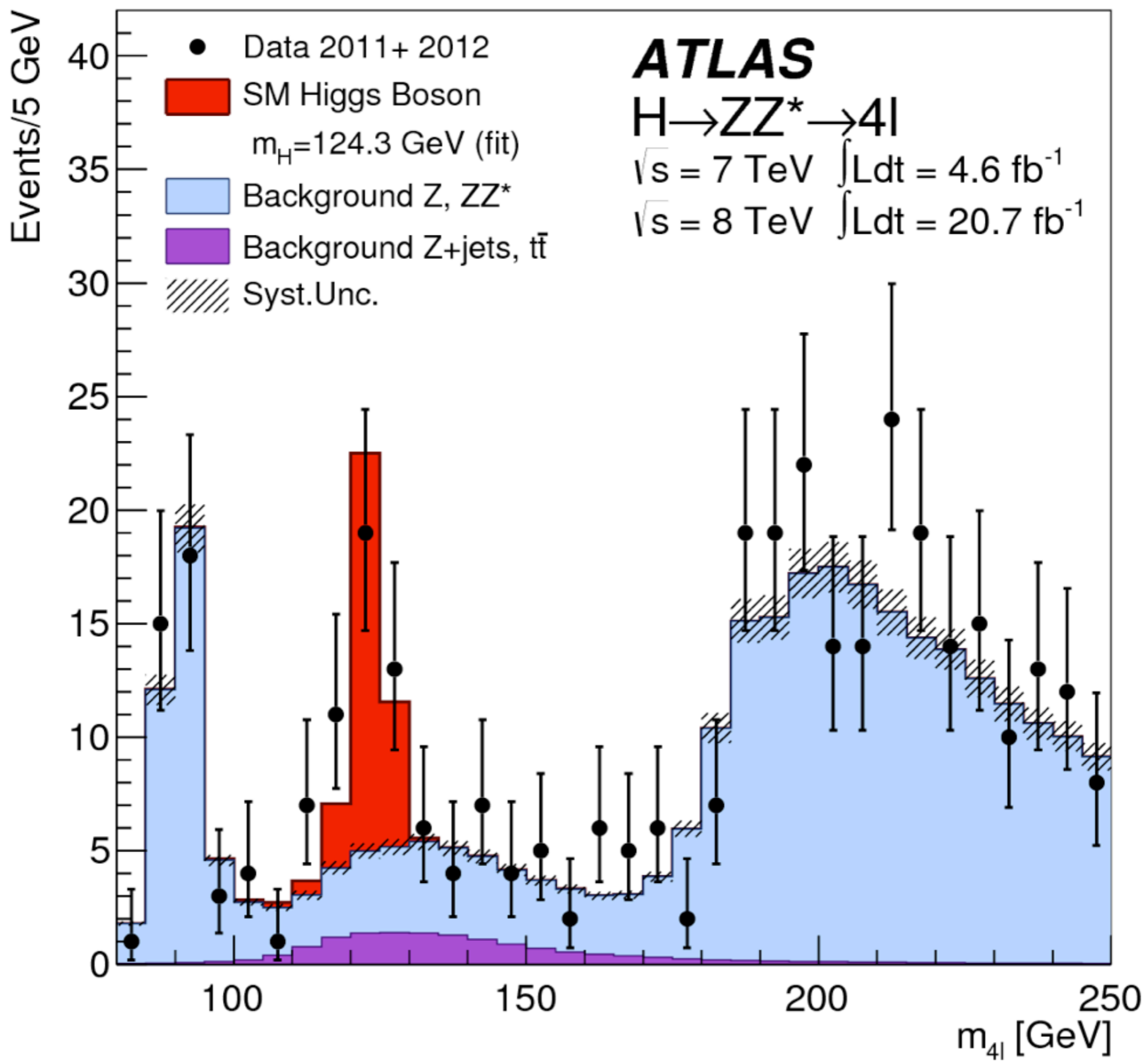




Now let's look at some LHC data.

$h \rightarrow ZZ \rightarrow e^+e^- \mu^+ \mu^-$ candidate





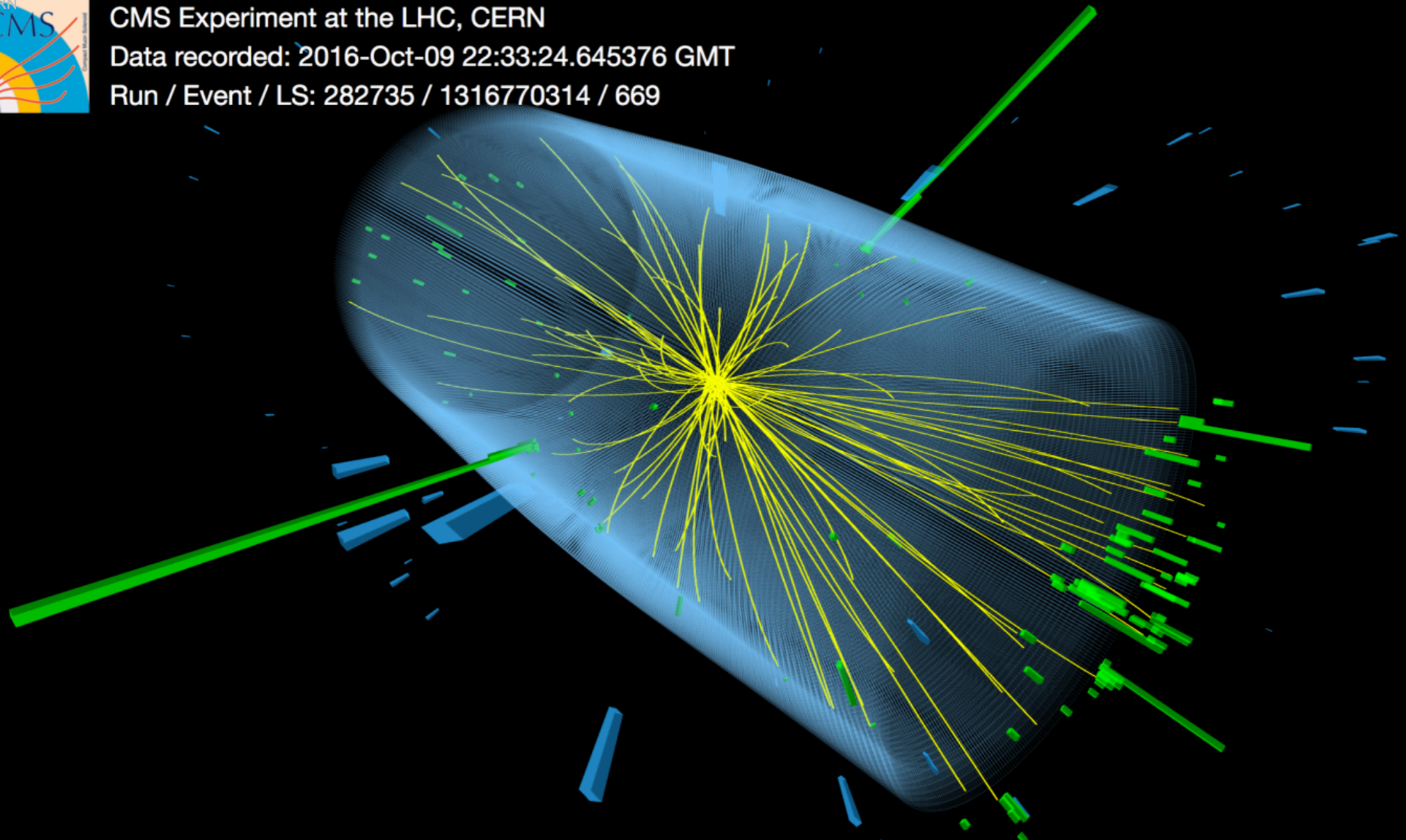
$h \rightarrow \gamma\gamma$ candidate

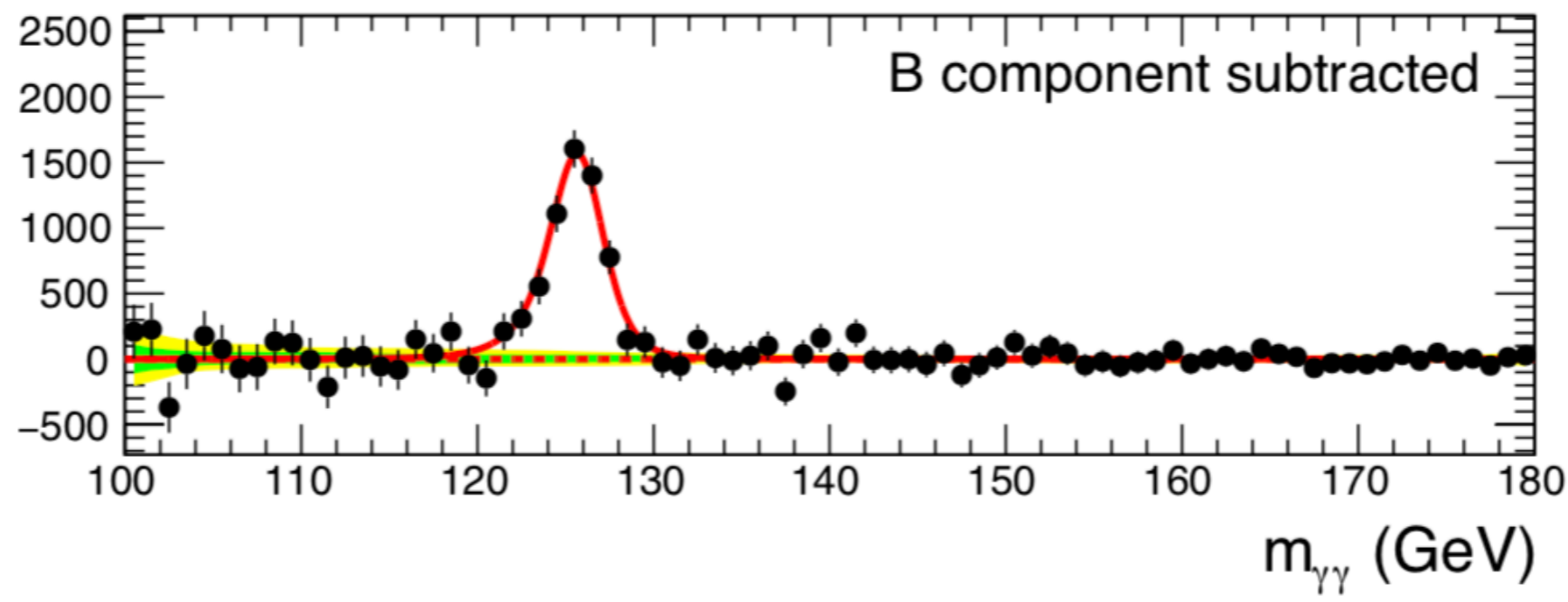
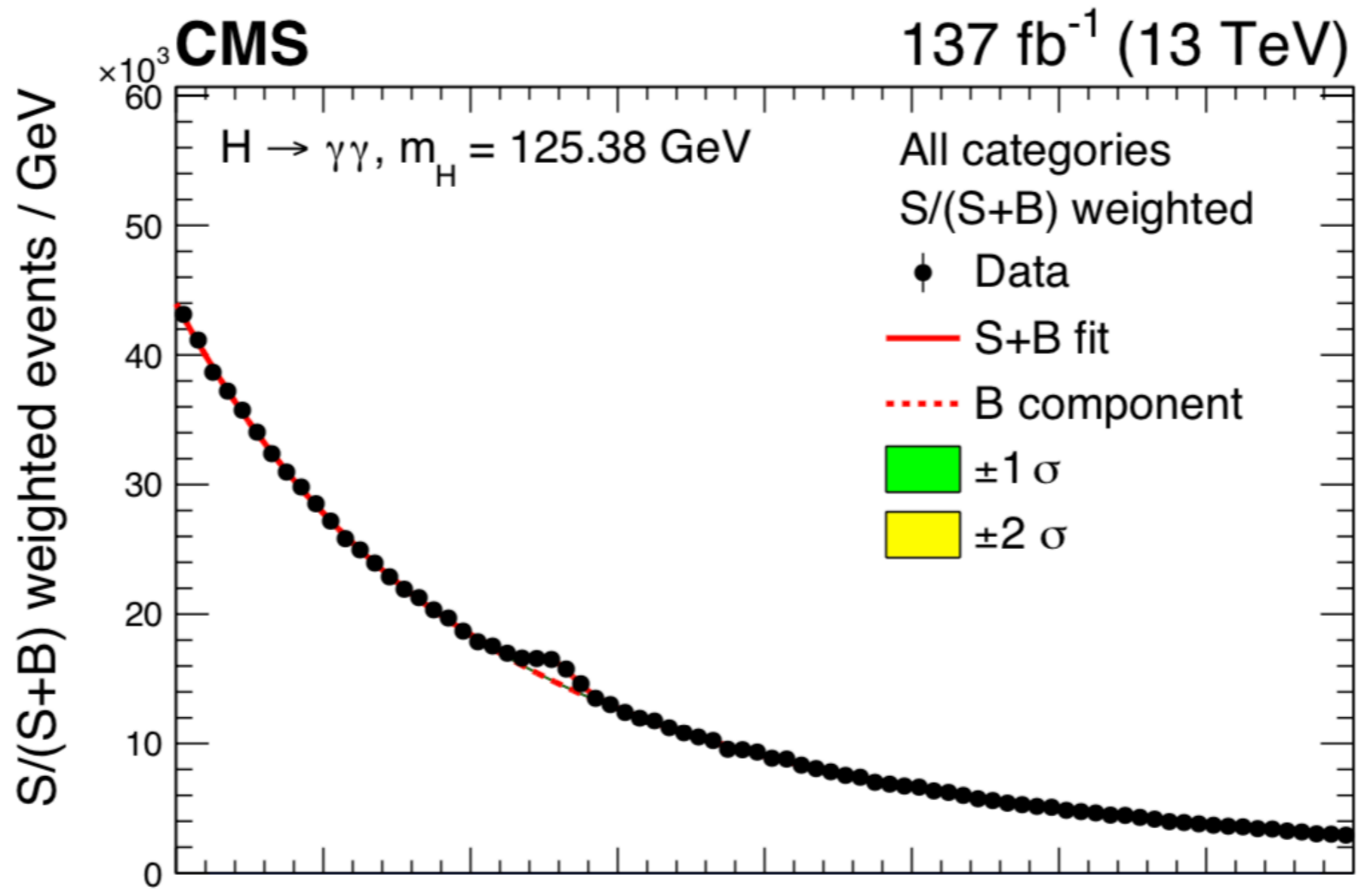


CMS Experiment at the LHC, CERN

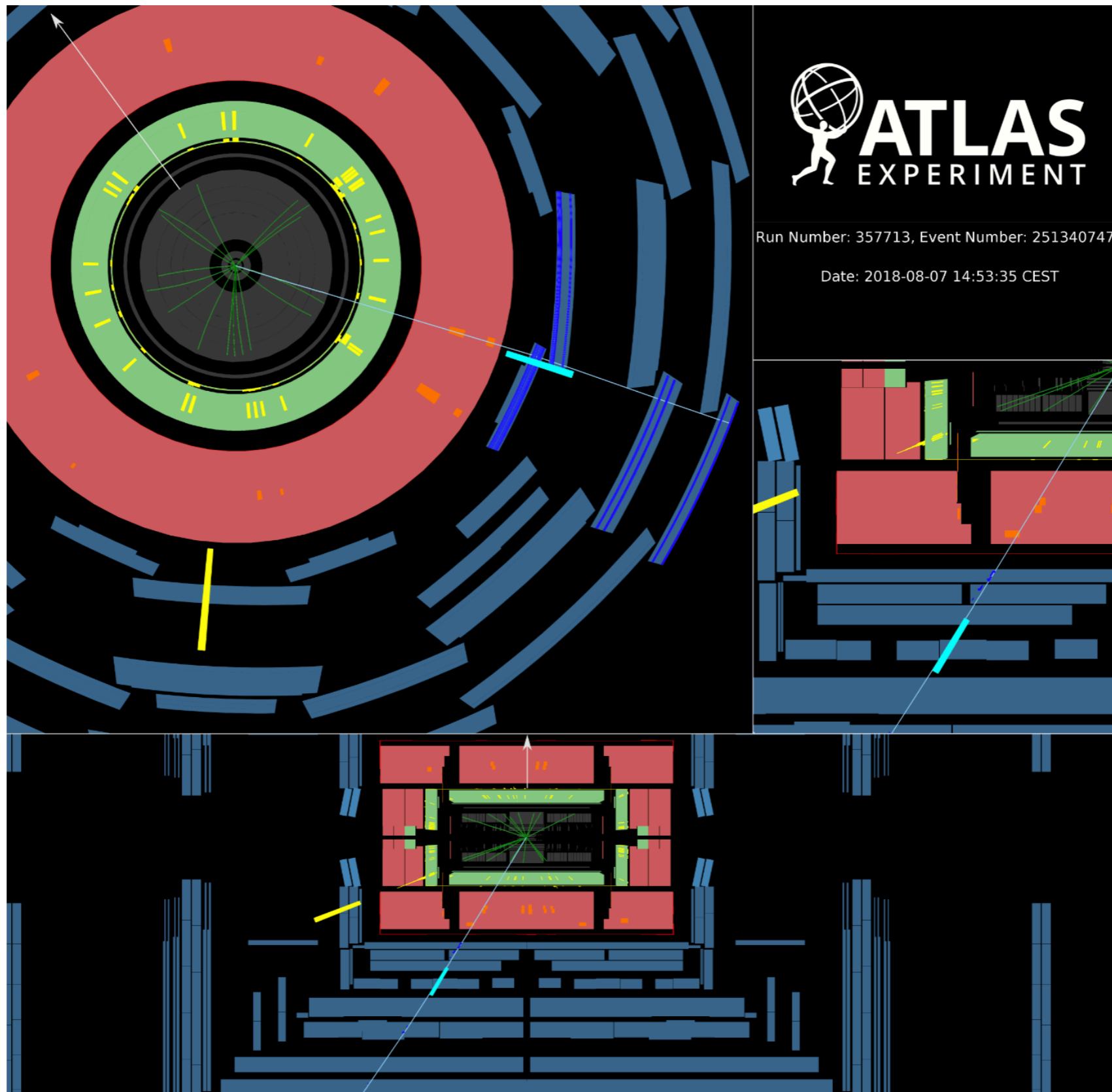
Data recorded: 2016-Oct-09 22:33:24.645376 GMT

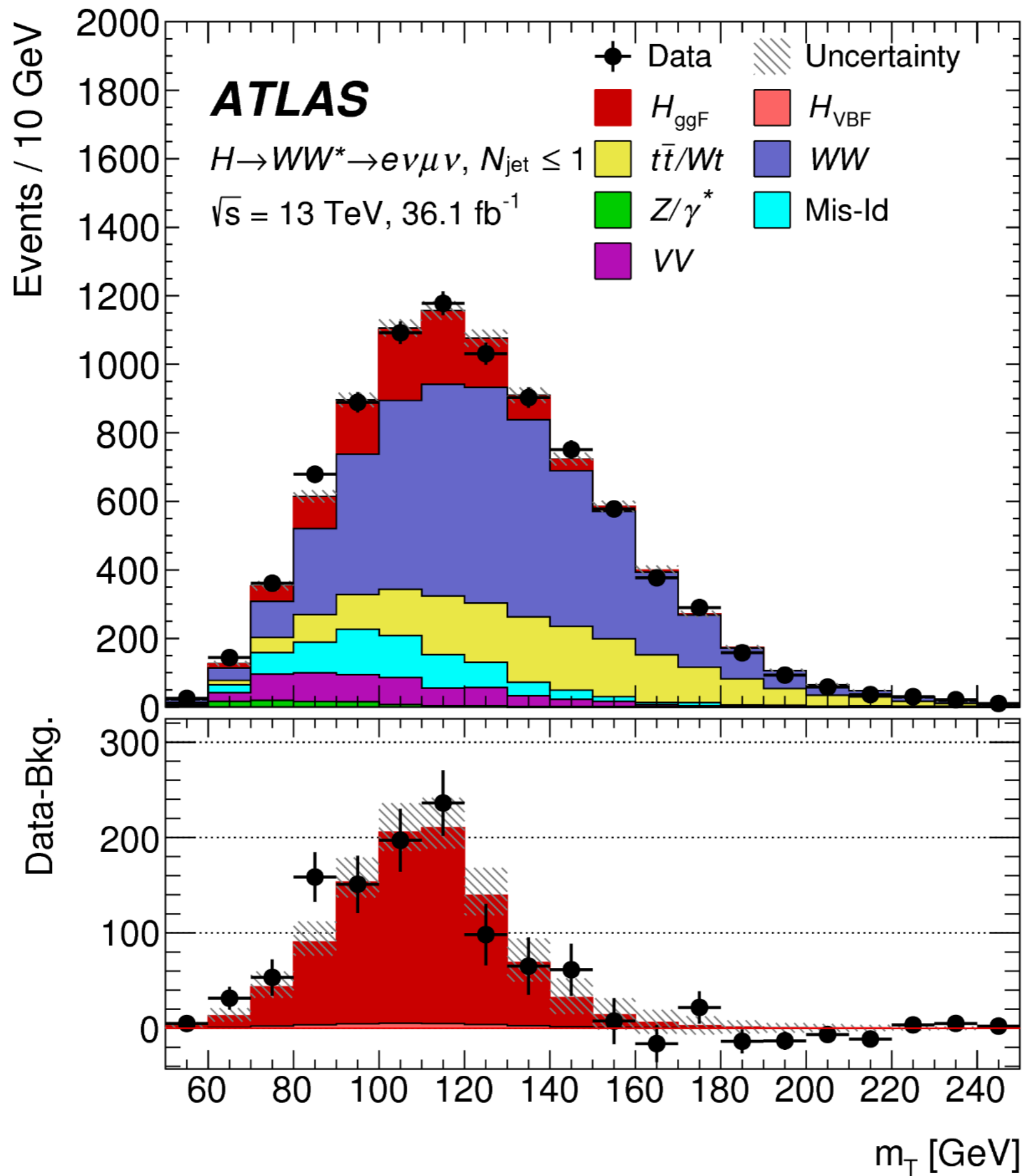
Run / Event / LS: 282735 / 1316770314 / 669





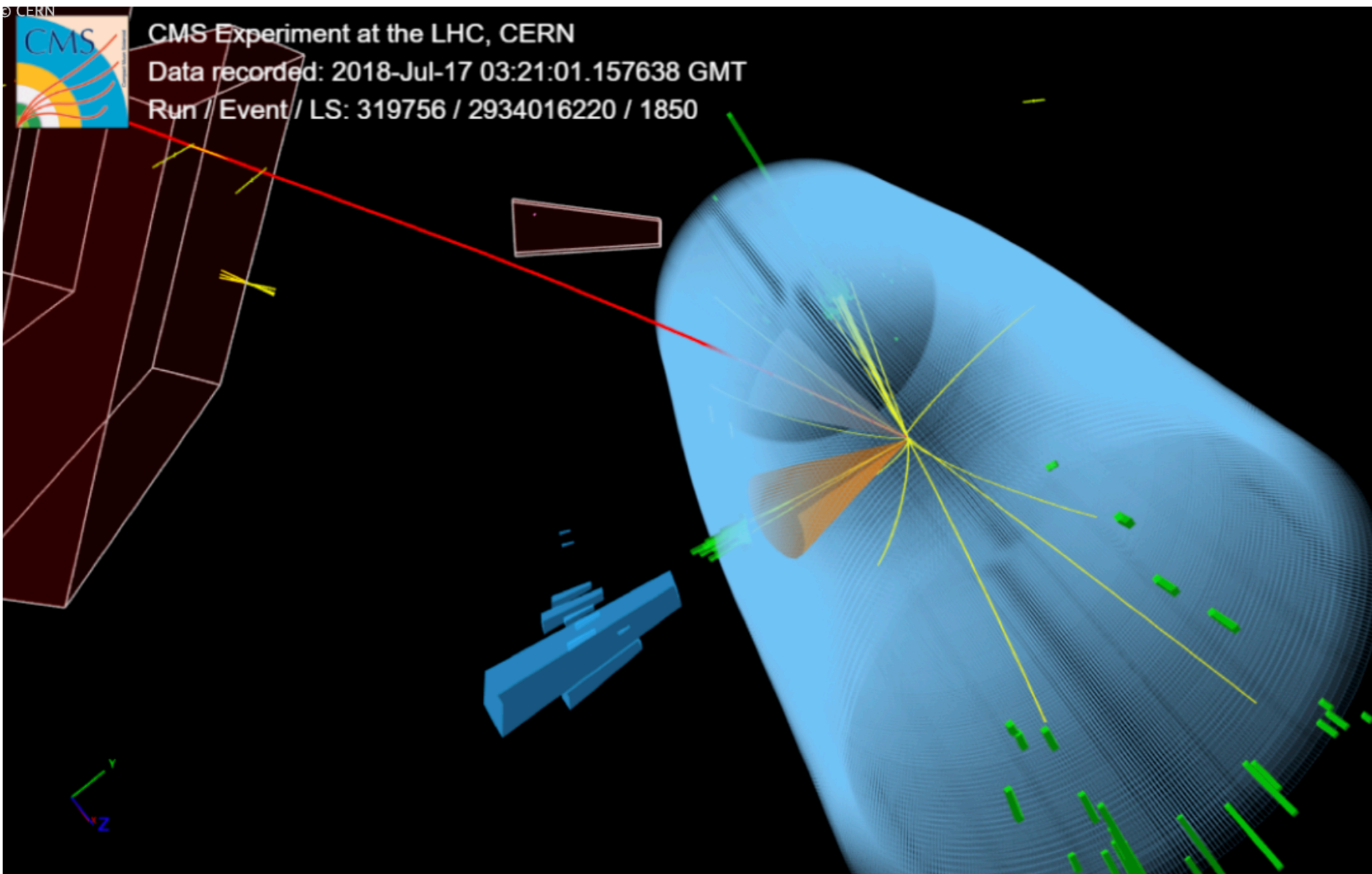
$h \rightarrow W^+ W^-$ candidate





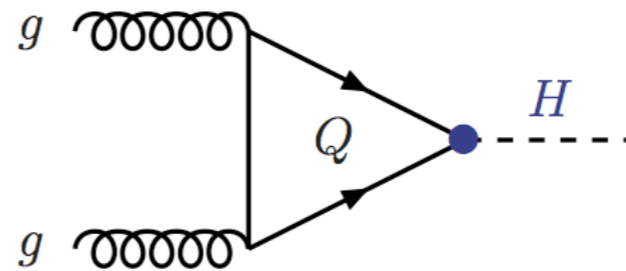
ATLAS
2019

$h \rightarrow \tau^+ \tau^-$ candidate

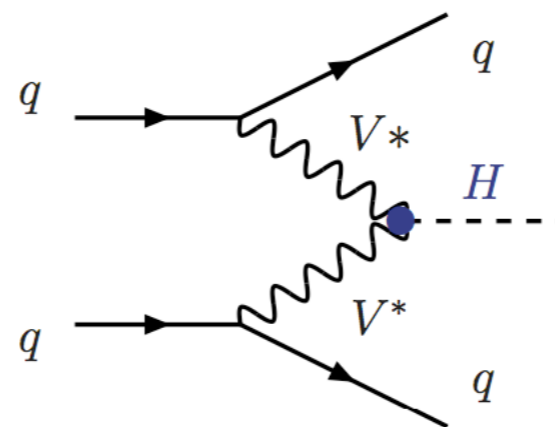


Production modes for the Higgs boson:

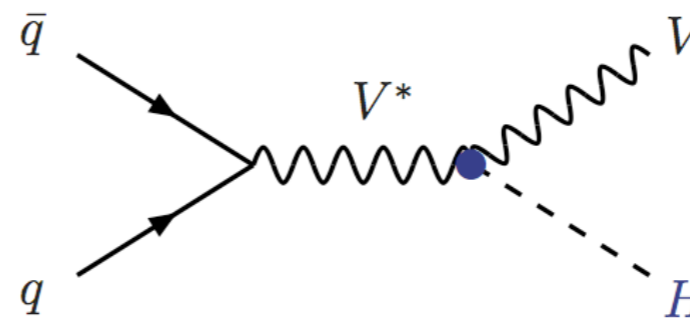
gluon-gluon fusion



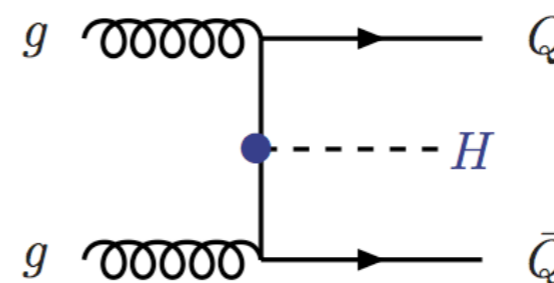
W boson fusion



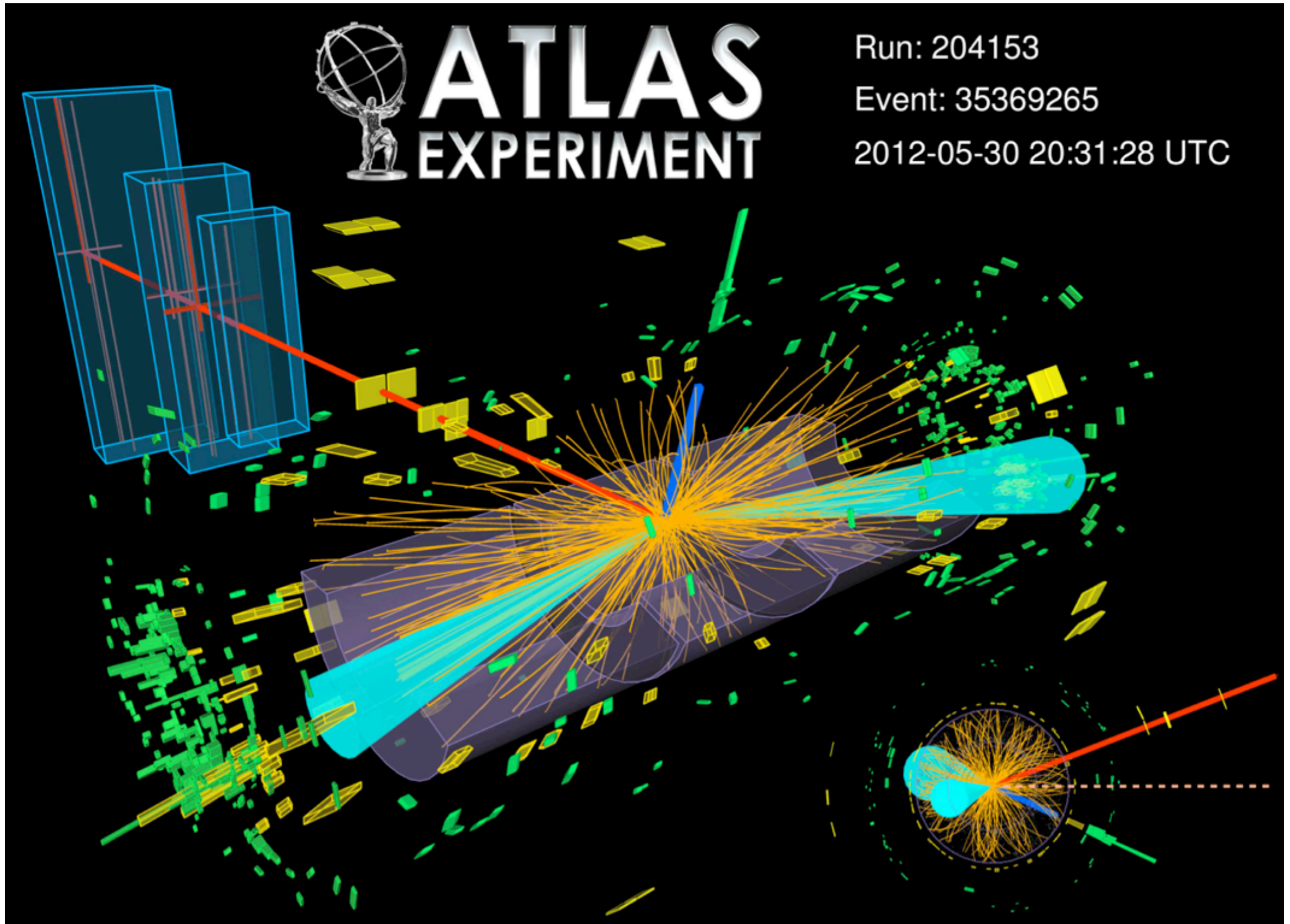
“Higgsstrahlung”
associated production
w. W, Z

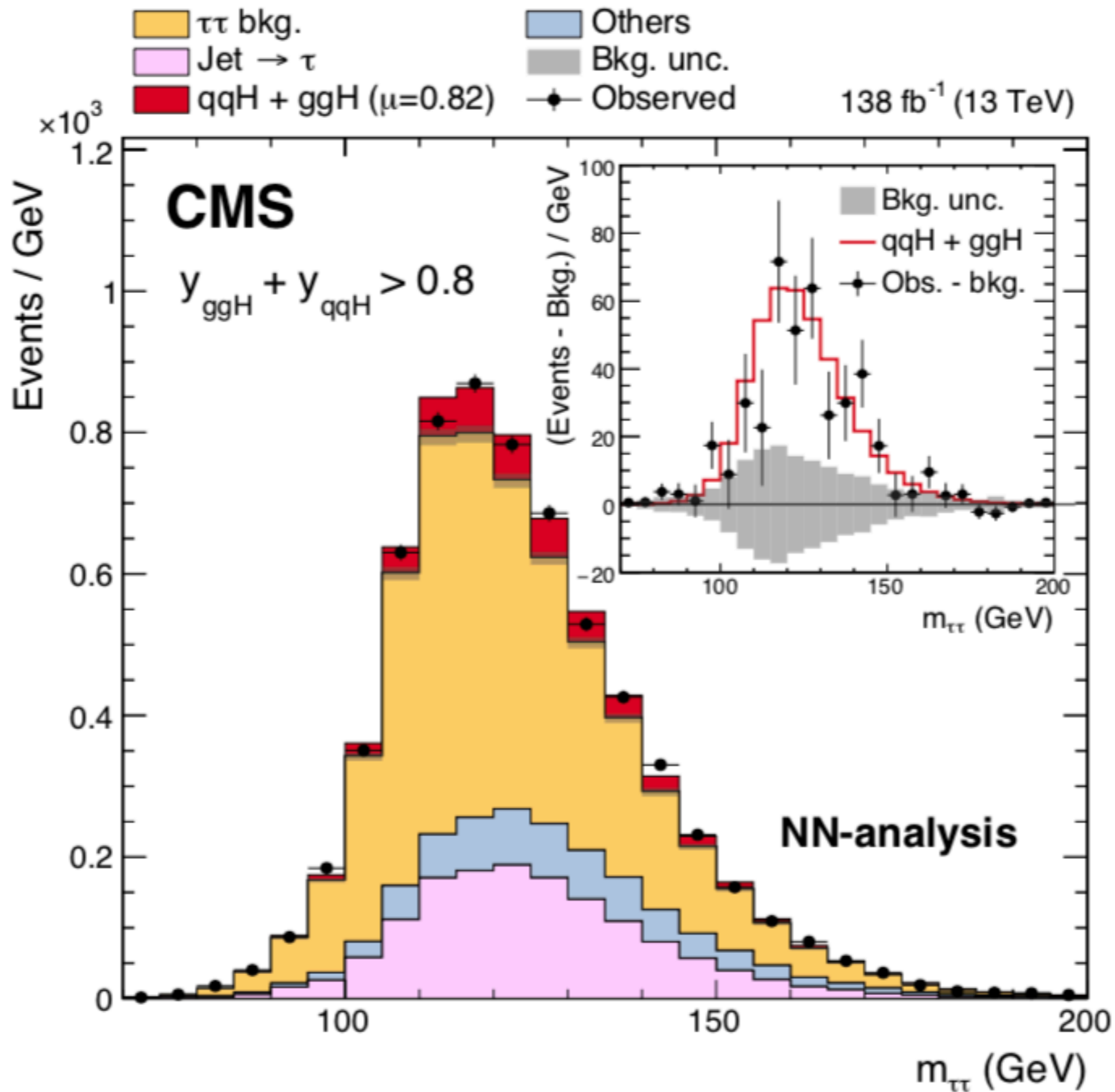


associated production
with the top quark

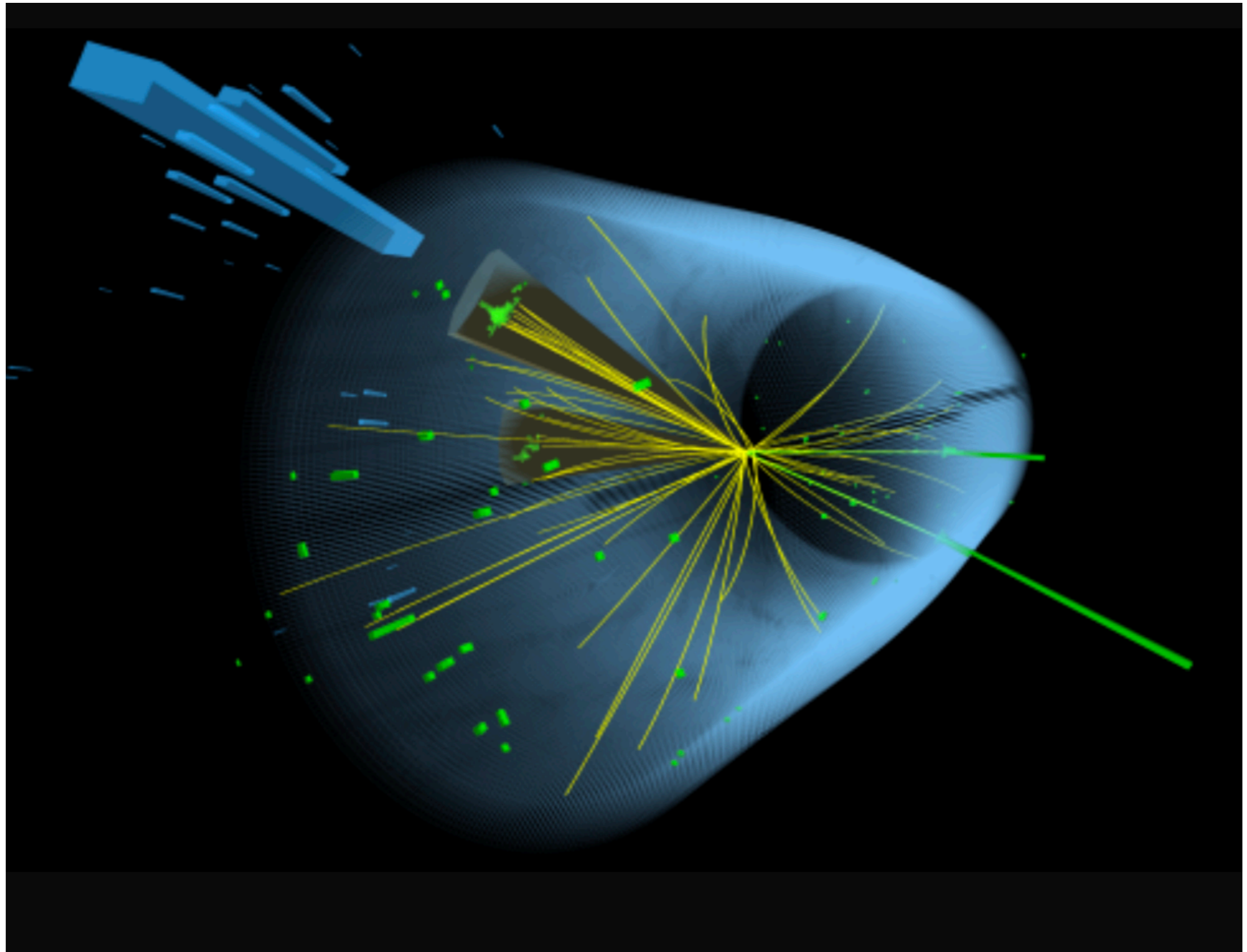


$h \rightarrow \tau^+ \tau^-$ candidate using W boson fusion





$h \rightarrow b\bar{b}$ candidate using Higgsstrahlung with Z



This gets very problematical. We have

$$q\bar{q} \rightarrow Zh \rightarrow Zb\bar{b}$$

$$q\bar{q} \rightarrow ZZ \rightarrow Z b\bar{b}$$

$$q\bar{q} \rightarrow Zg \rightarrow Z b\bar{b}$$

not to mention processes such as

$$gg \rightarrow t\bar{t} \rightarrow b\bar{b}q\bar{q}\ell^+\ell^-\nu\bar{\nu}$$

with some products not associated or invisible.

The separation of these components relies on sophisticated machine learning.

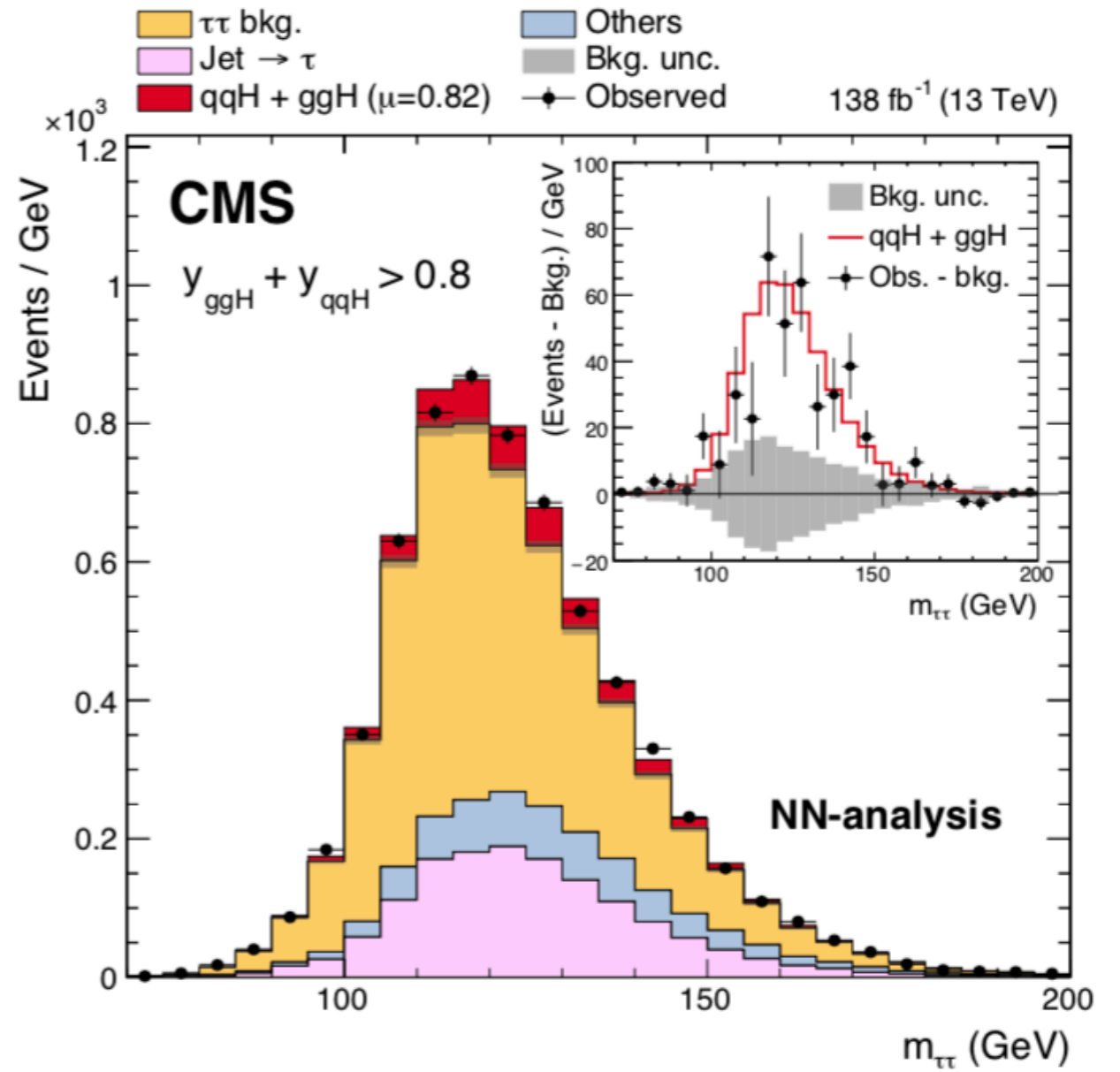
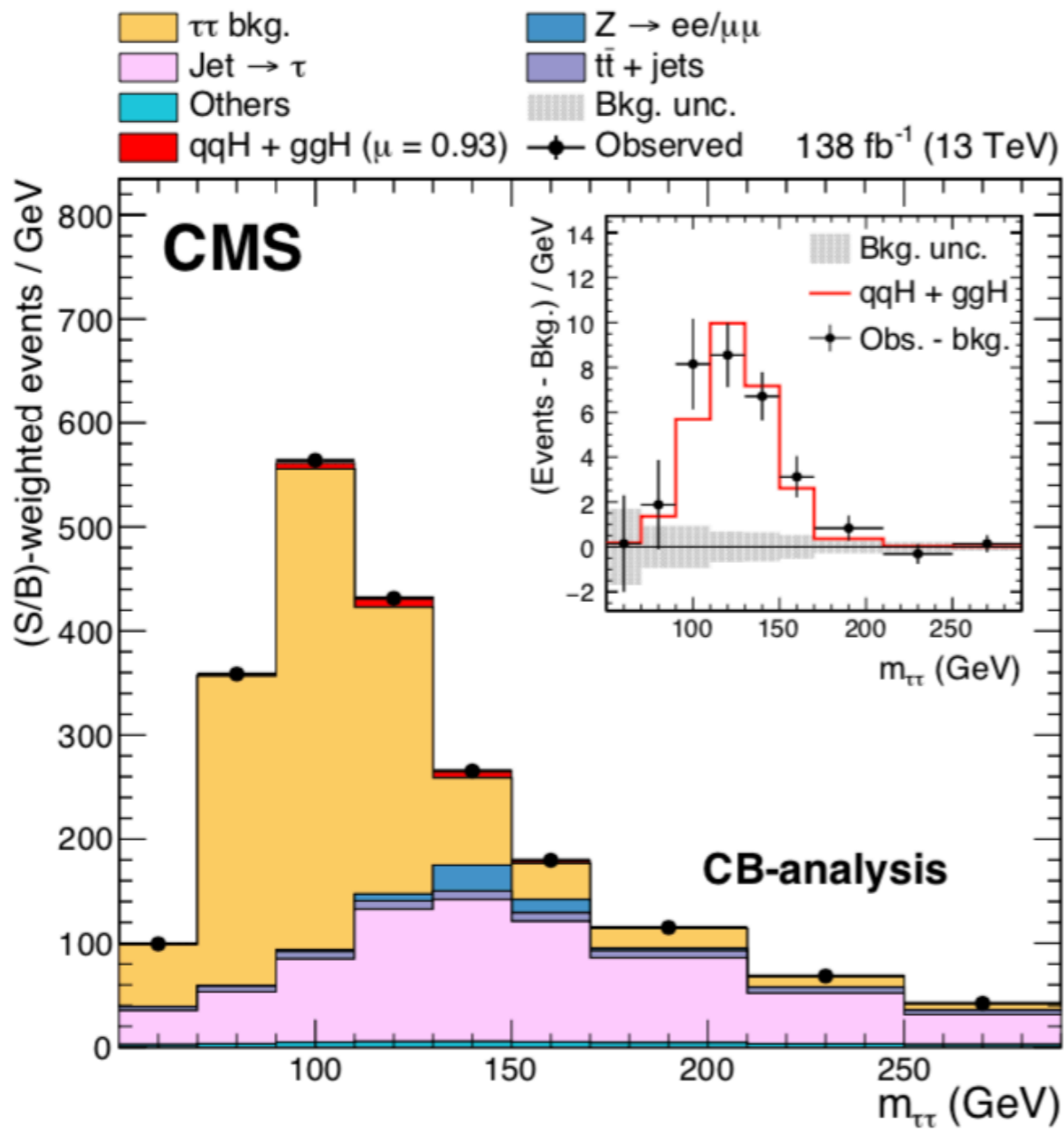


Joaquim Alves Gaspar

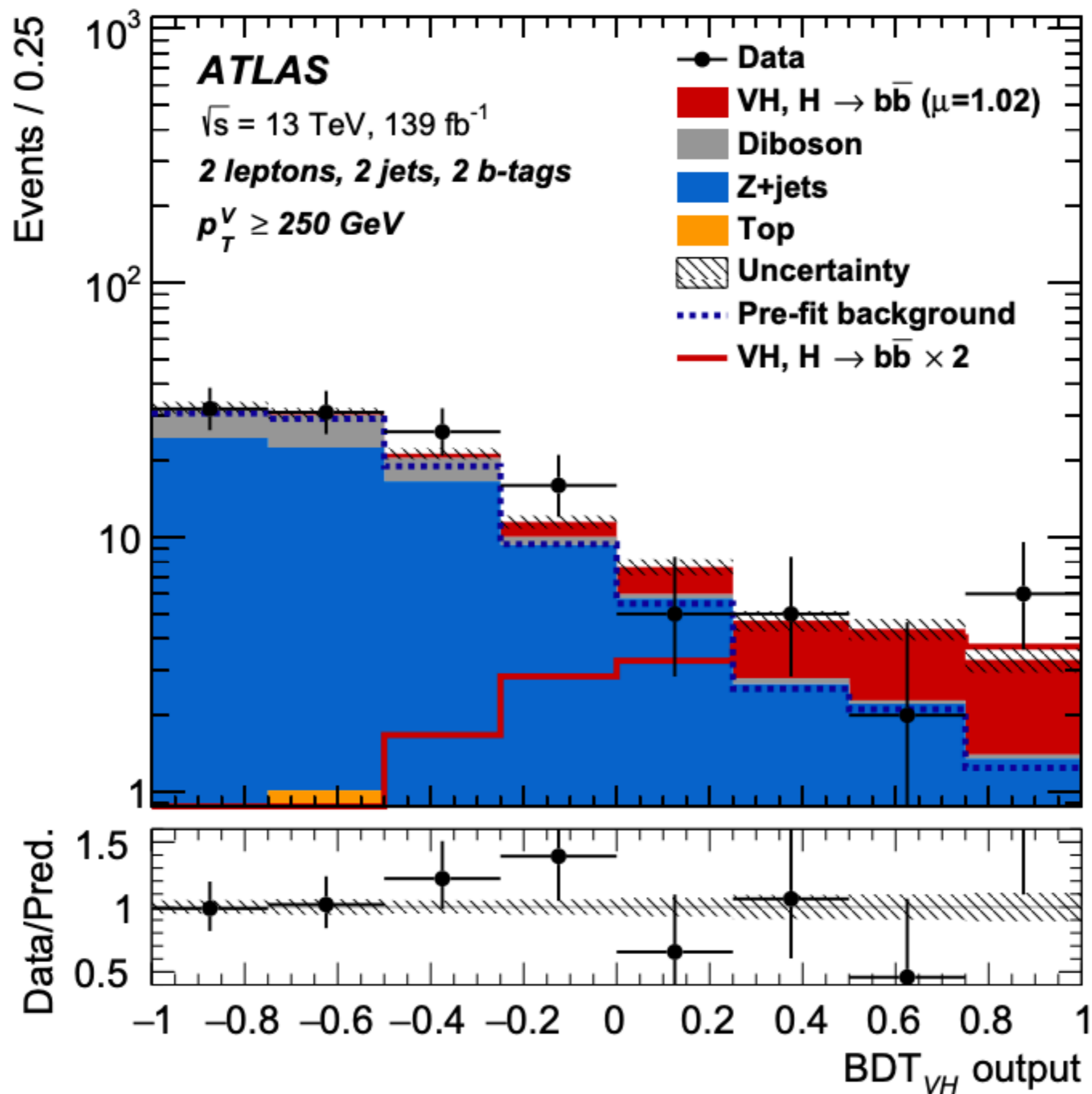


Mary Bloom

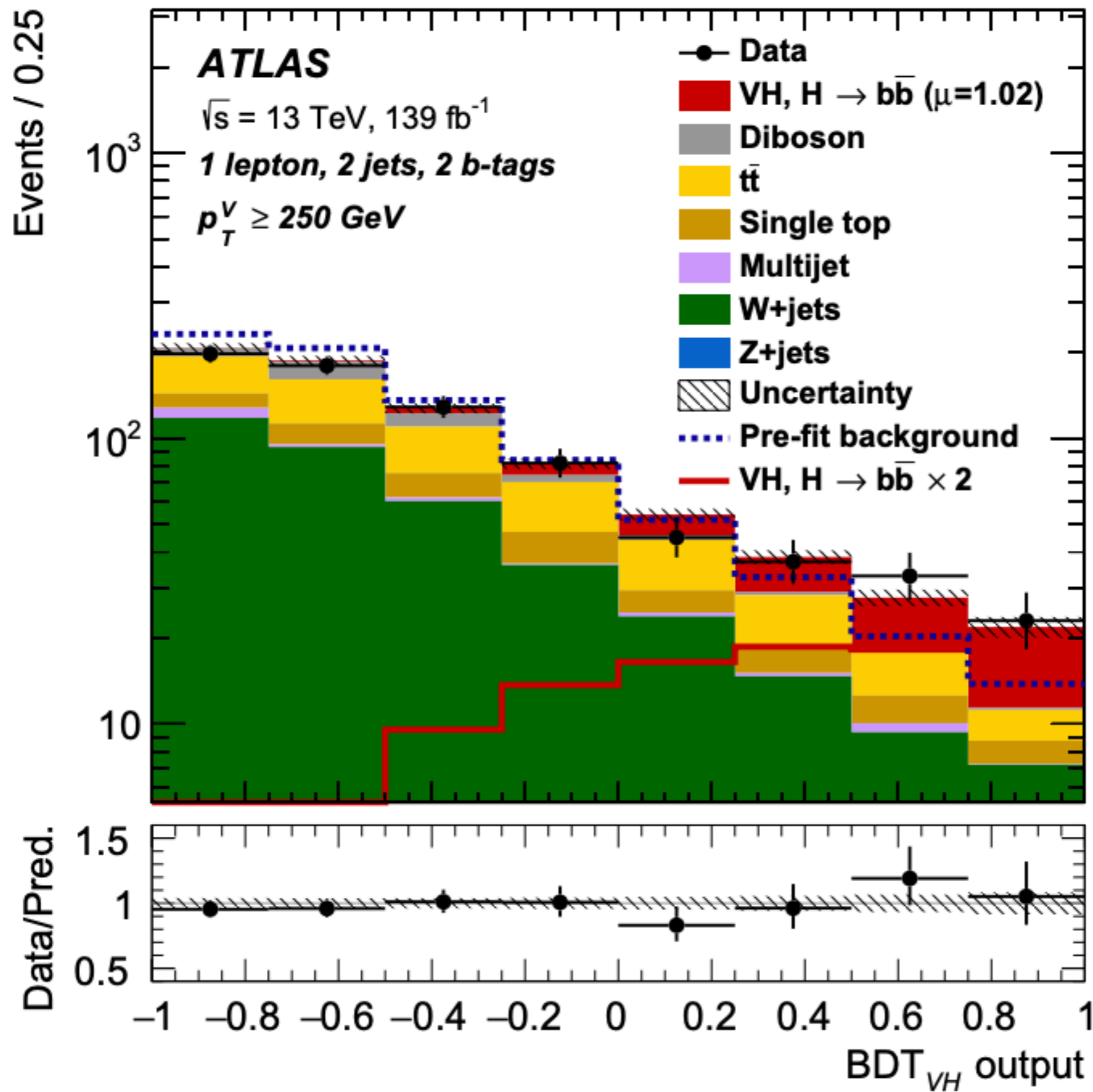
and understanding of the detailed properties of leptons, jets, vertices, ... that we use to train the sorting machines.



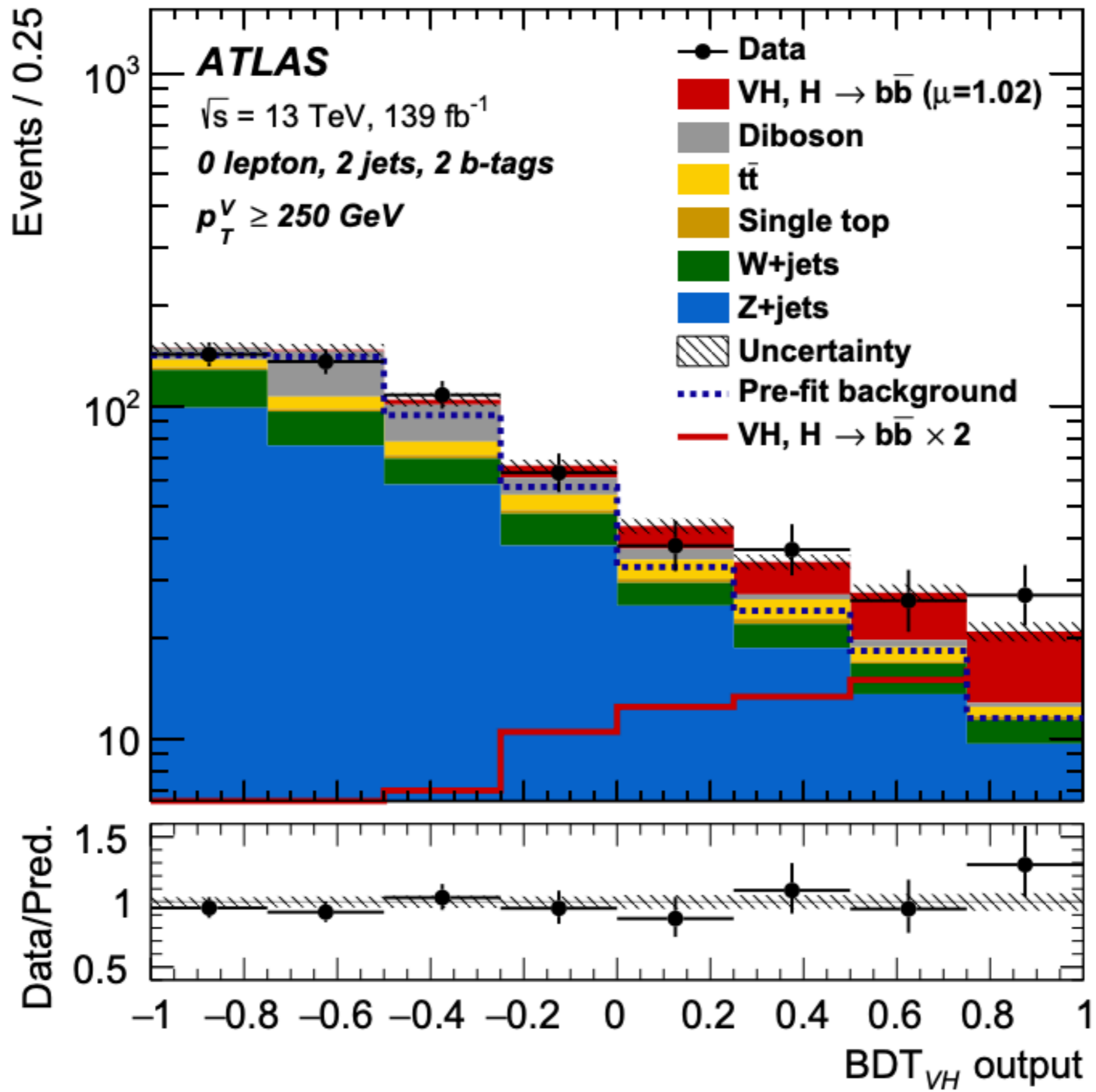
CMS 2022



ATLAS
2021

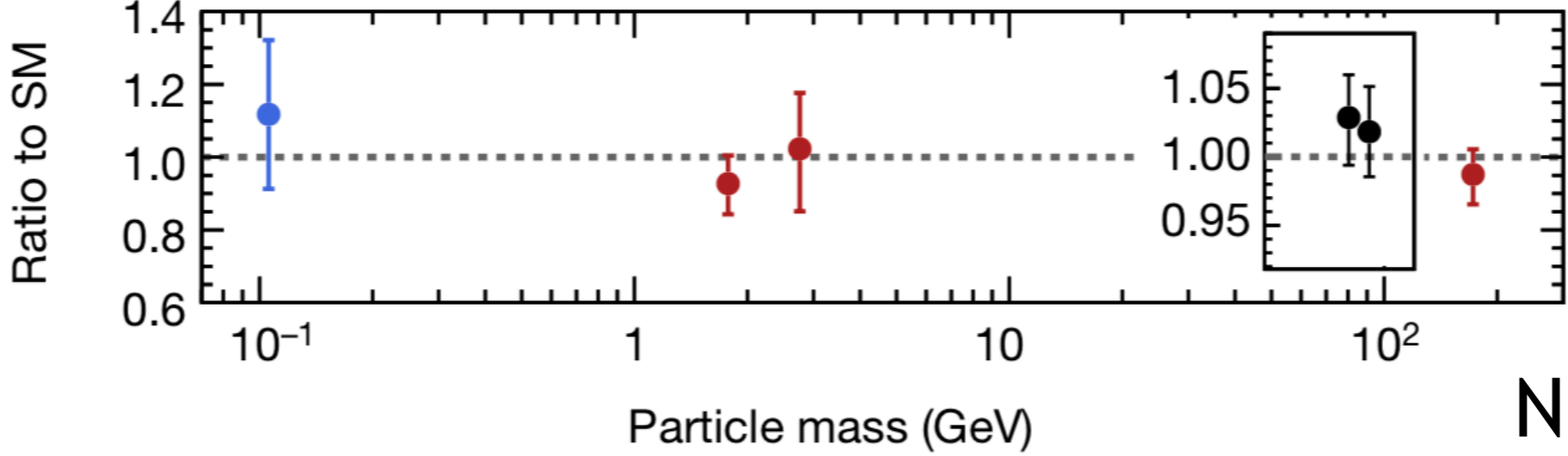
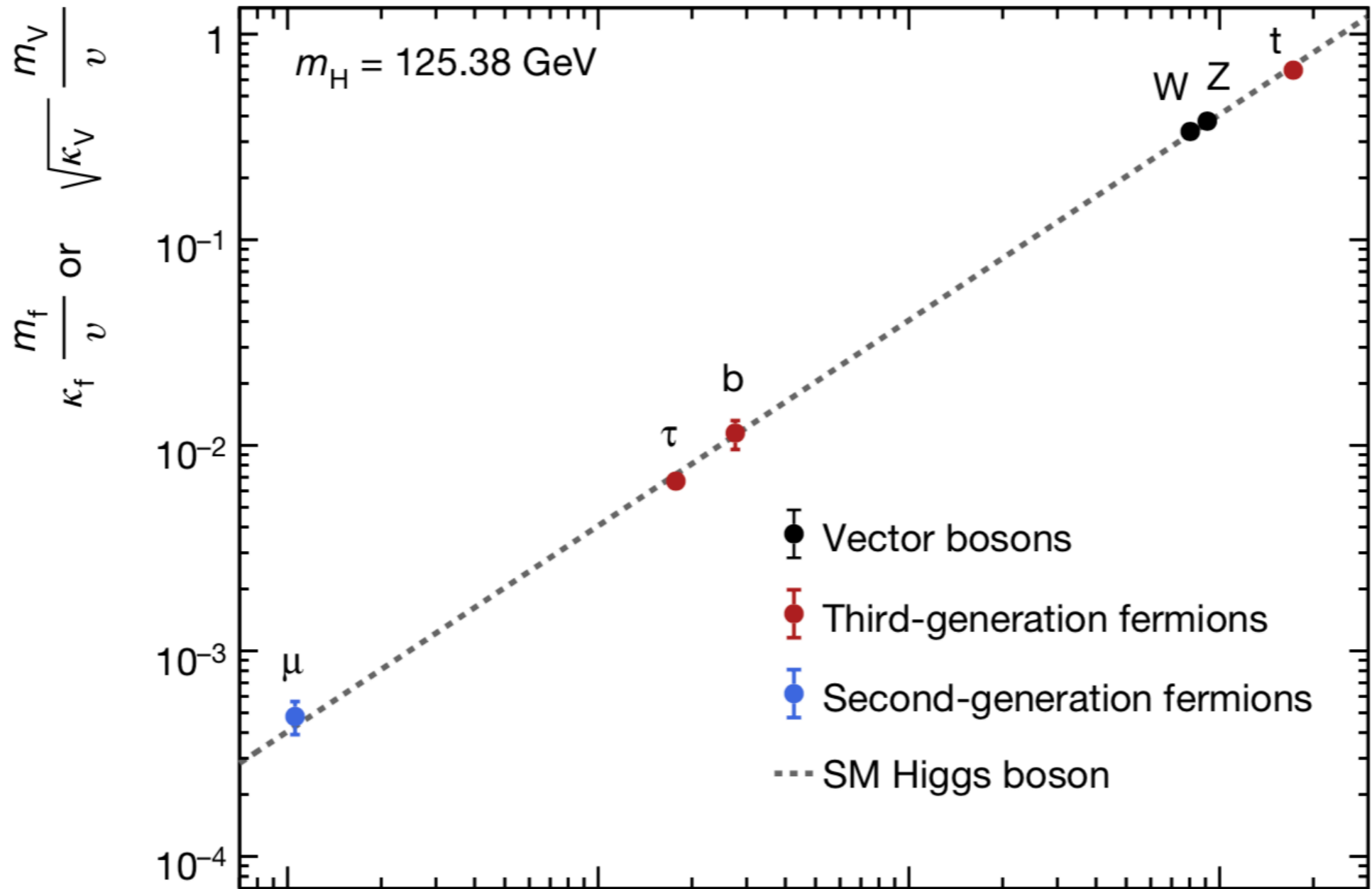


ATLAS
2021



CMS

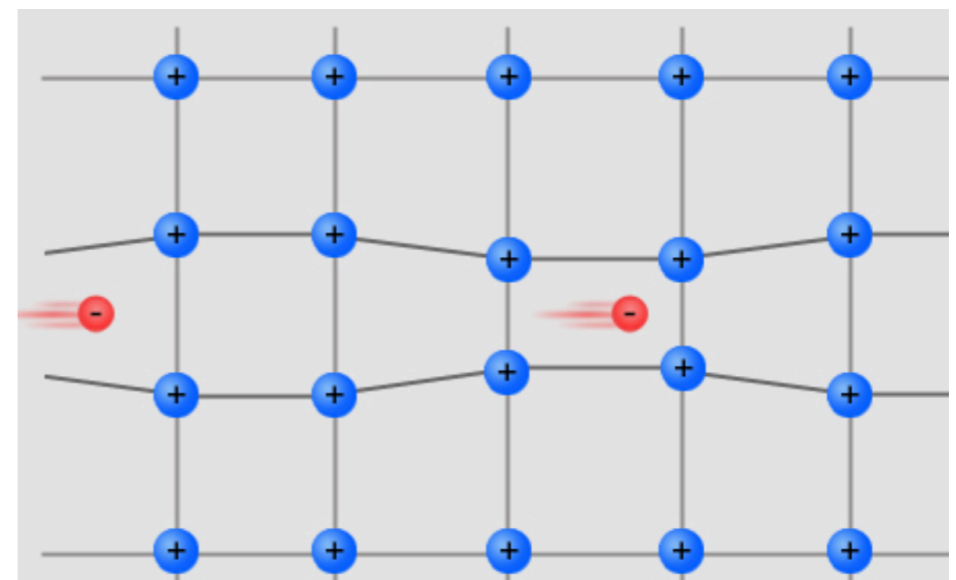
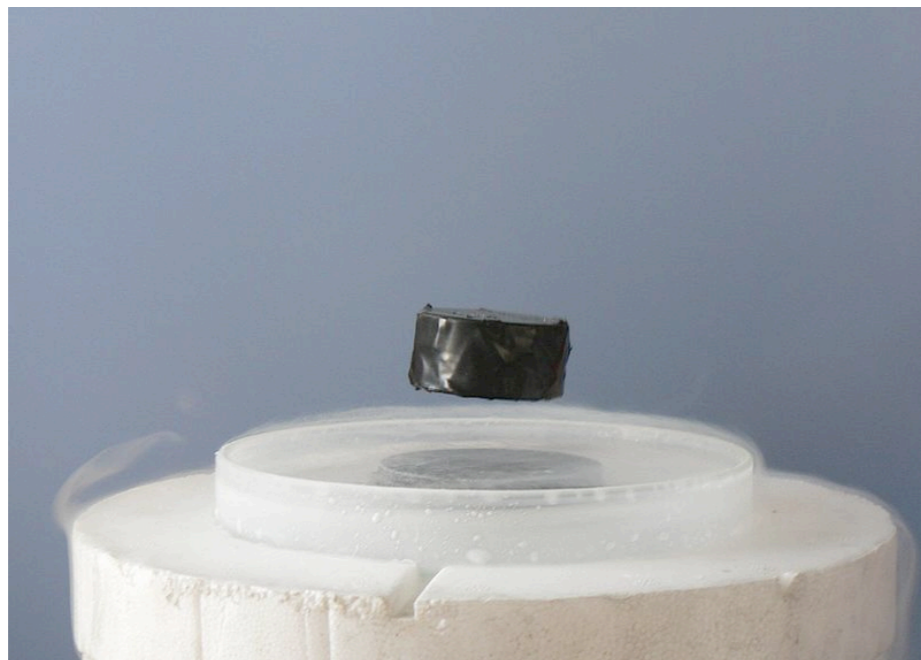
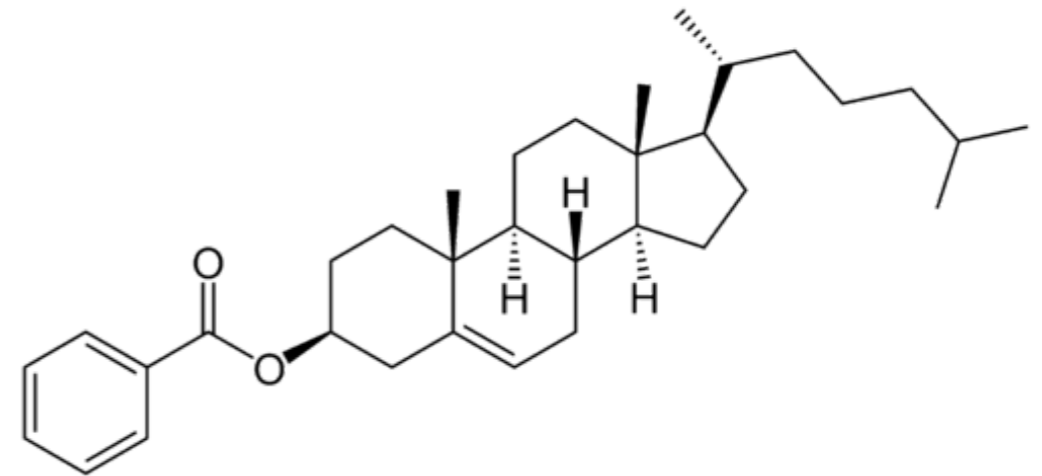
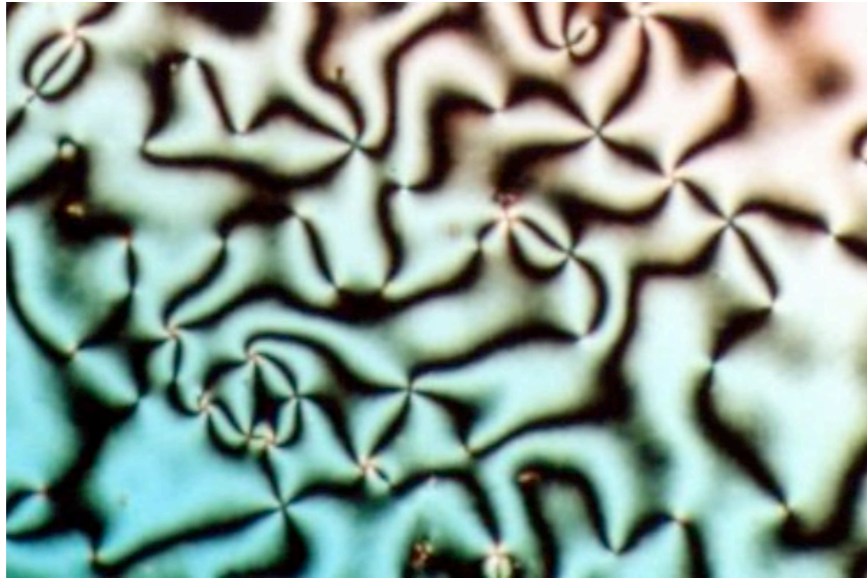
138 fb⁻¹ (13 TeV)

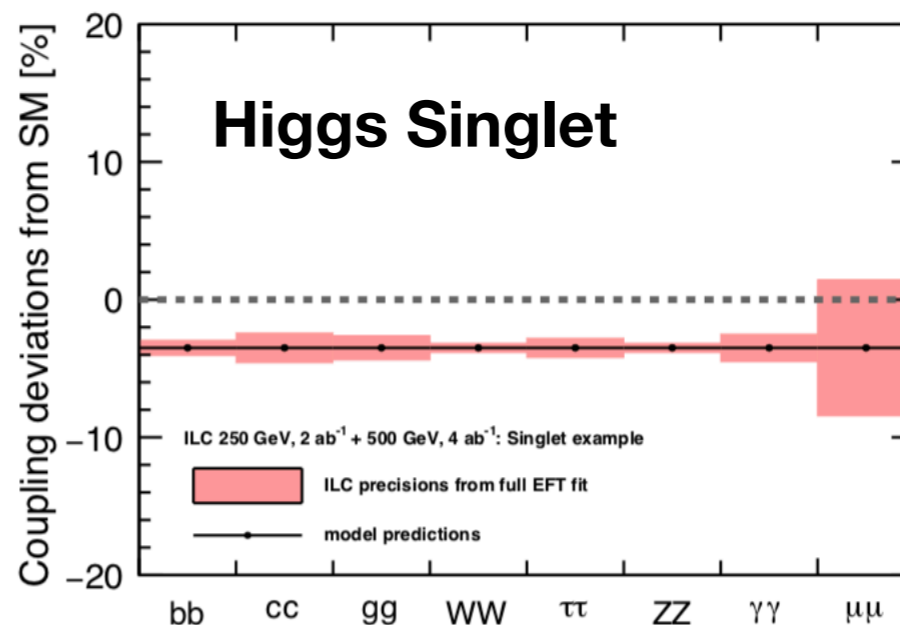
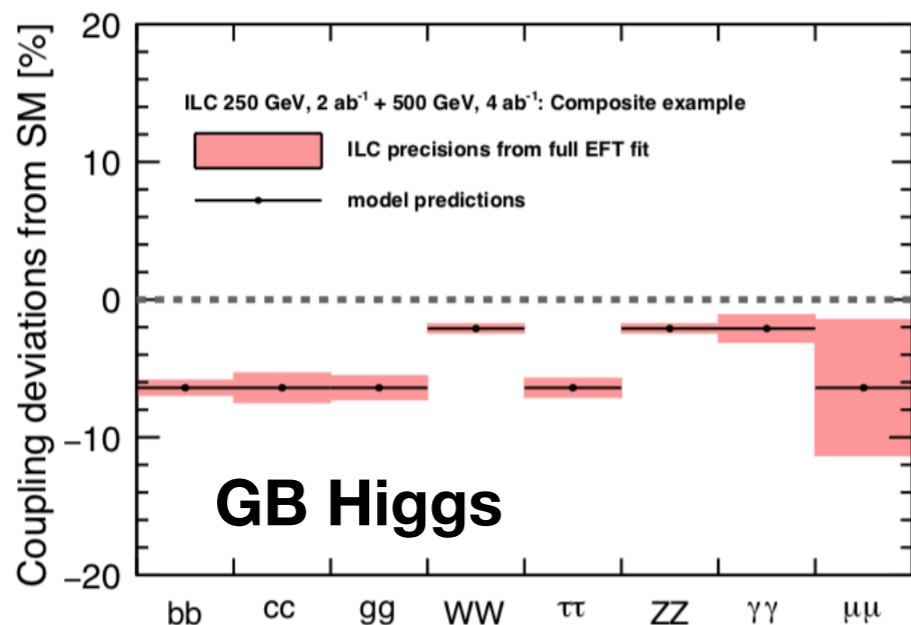
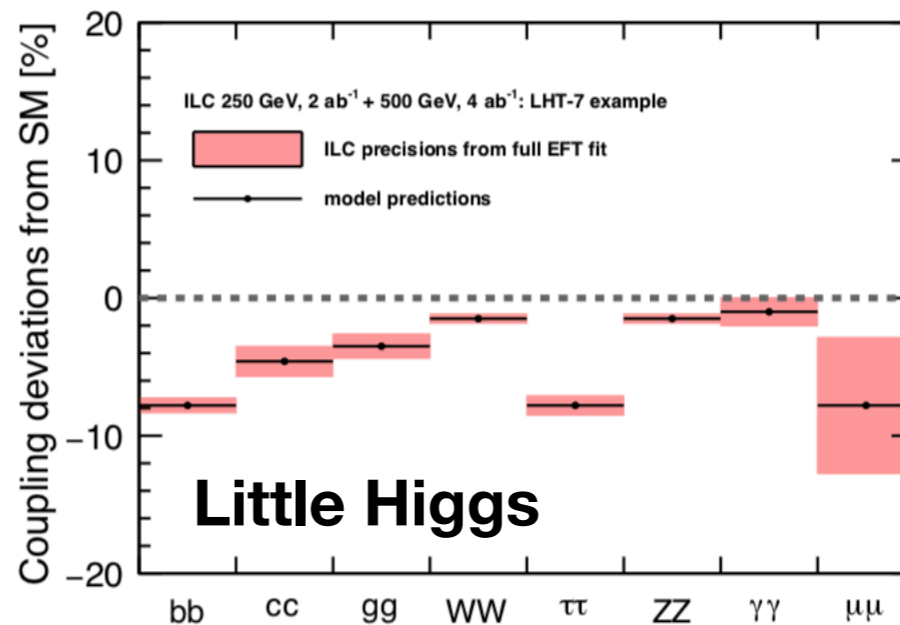
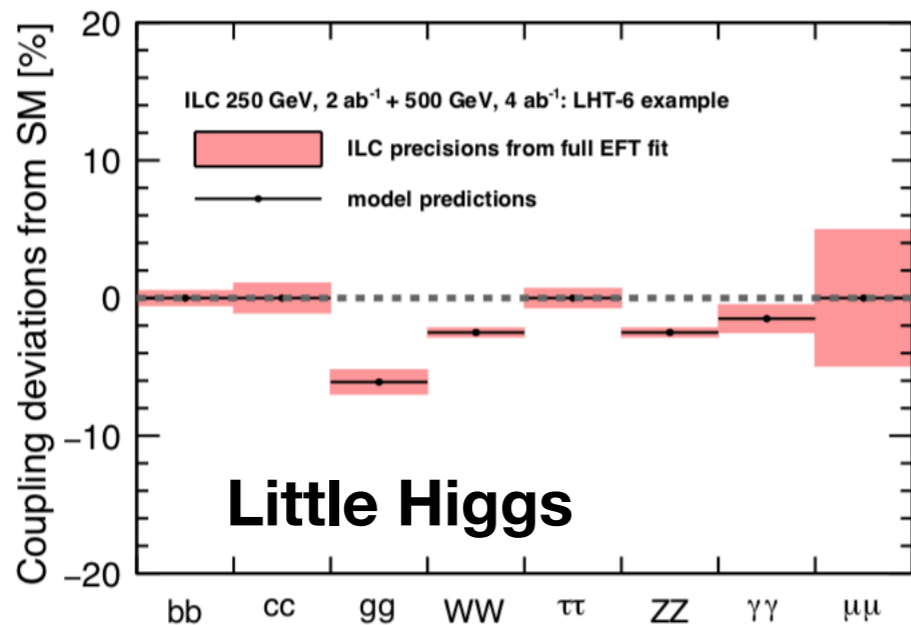
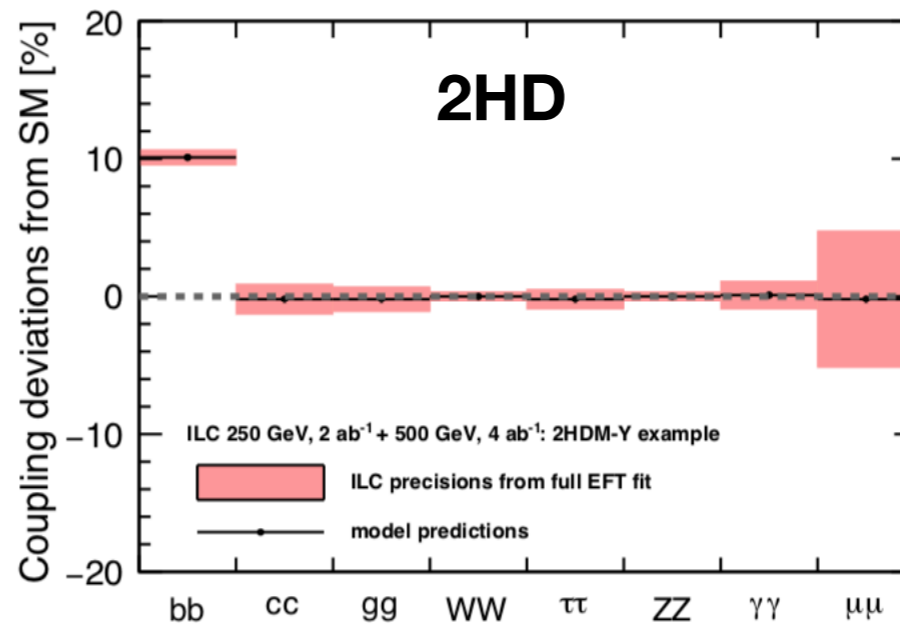
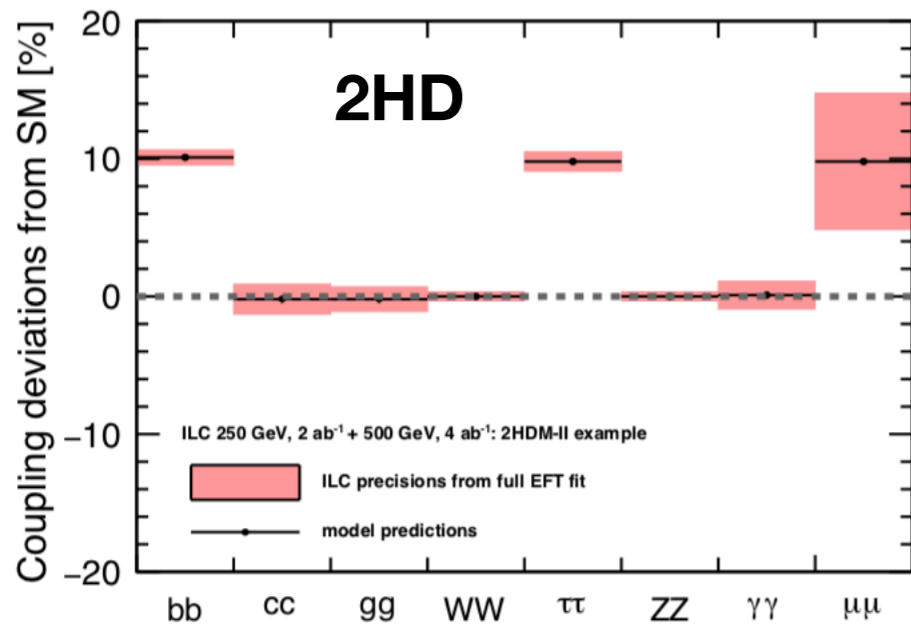


What is missing ?

We know the **how**. We don't know the **why** .

What is the origin of this fluid that permeates all of space ?





Barklow,
et al.

Auguries of Innocence

by William Blake

To see a World in a grain of Sand
And a Heaven in a Wild Flower
Hold Infinity in the palm of your hand
And Eternity in an hour.

...