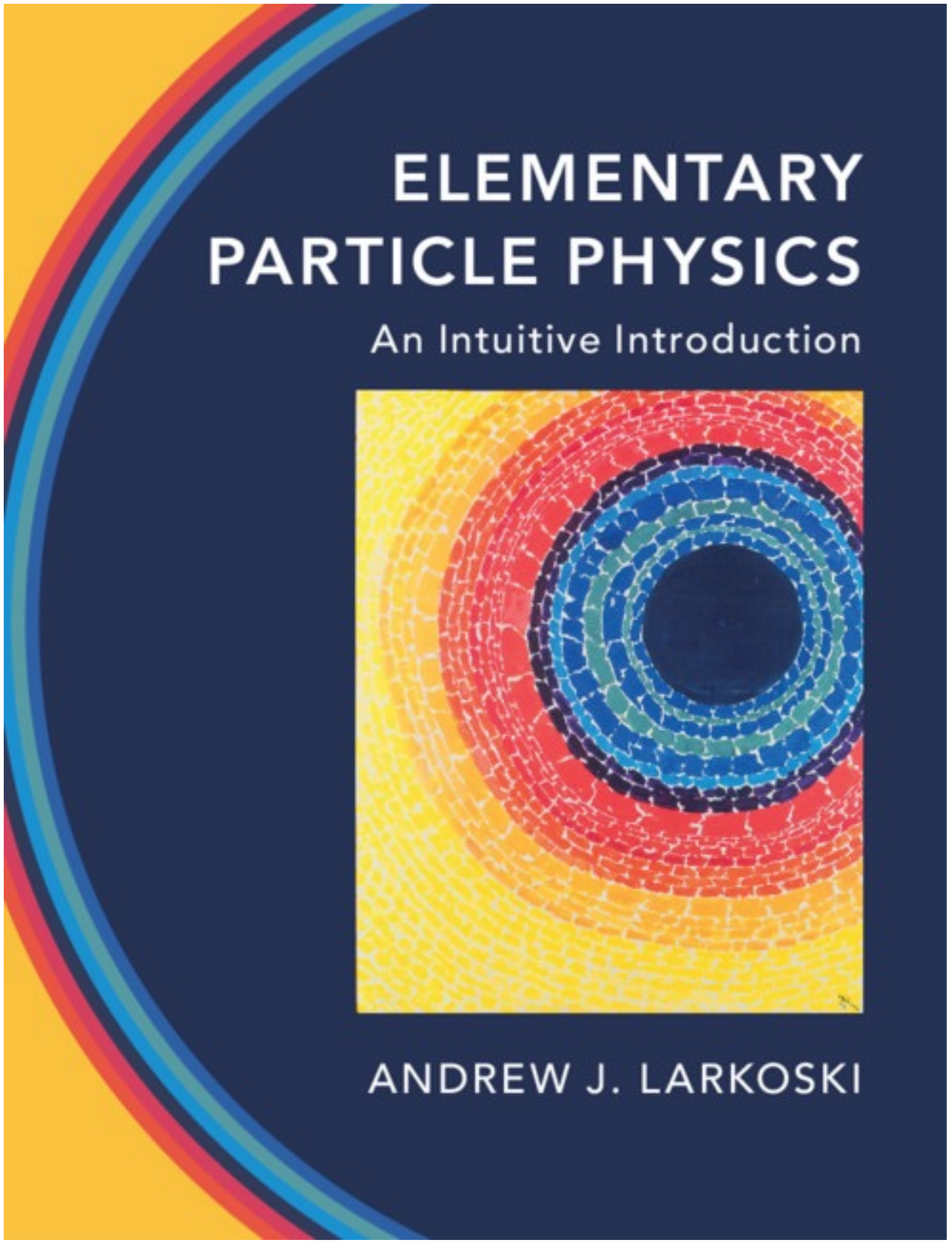
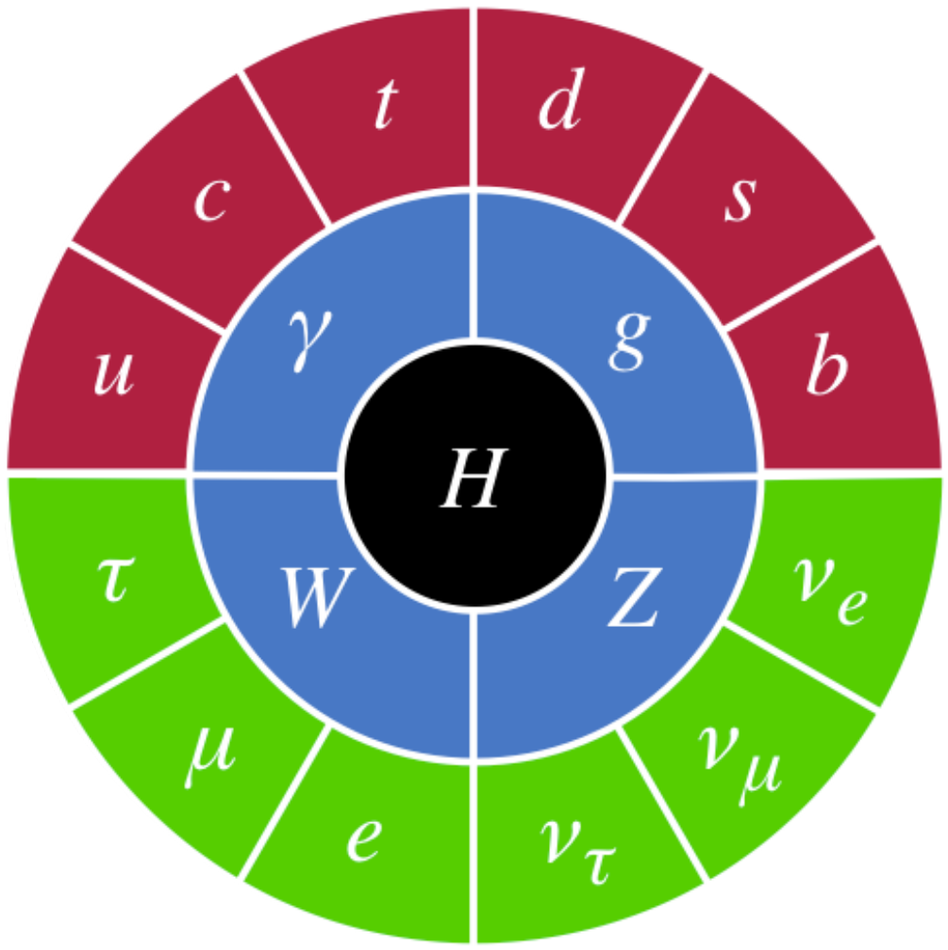
An Introduction to the Standard Model

Andrew Larkoski
SLAC National Accelerator Lab

larkoski@slac.stanford.edu


ELEMENTARY
PARTICLE PHYSICS
An Intuitive Introduction
ANDREW J. LARKOSKI



Courtesy Particle Fever LLC

CERN

V--1

Exp. 06/07/2012

[redacted]

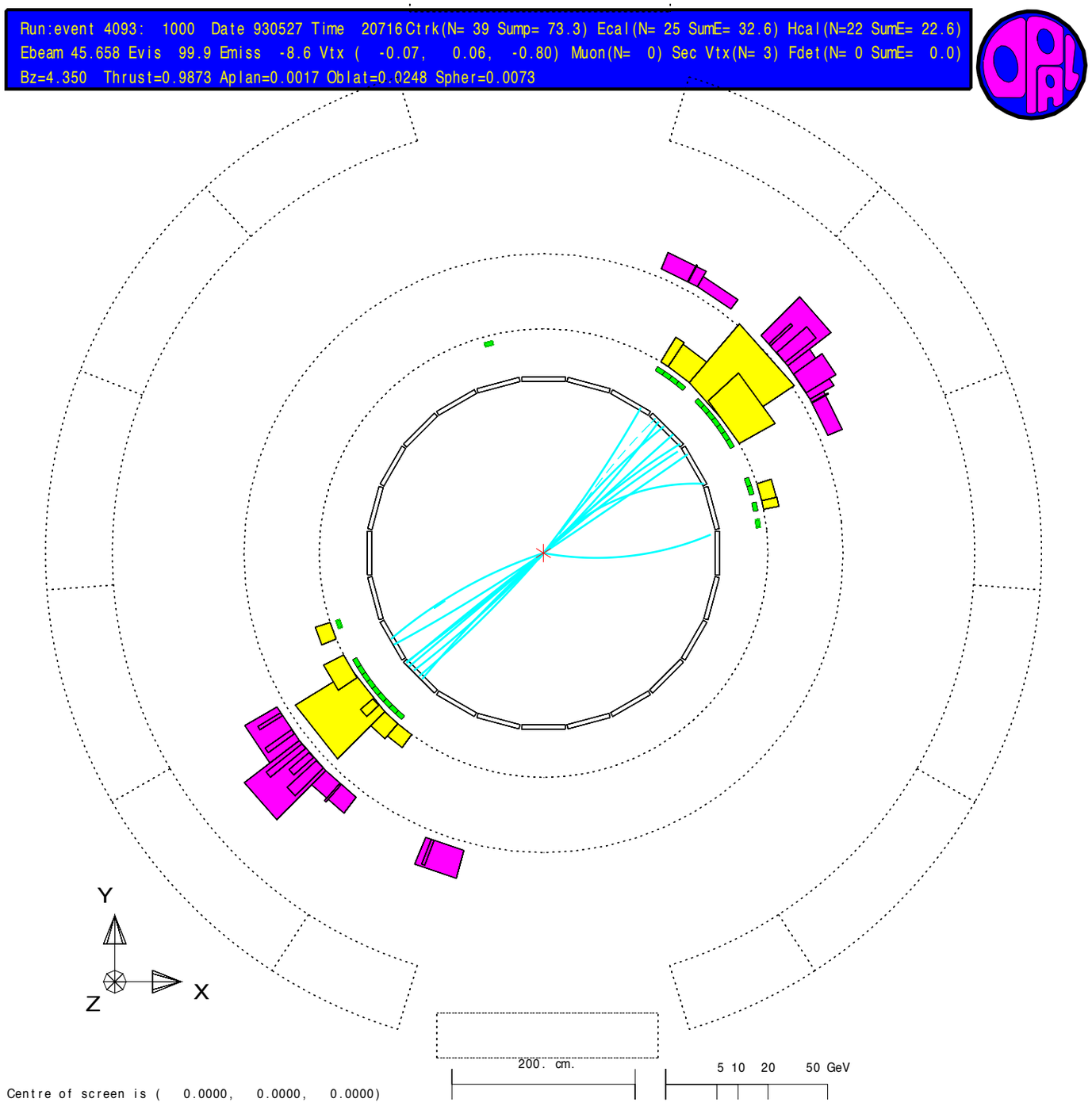
Andrew LARKOSKI

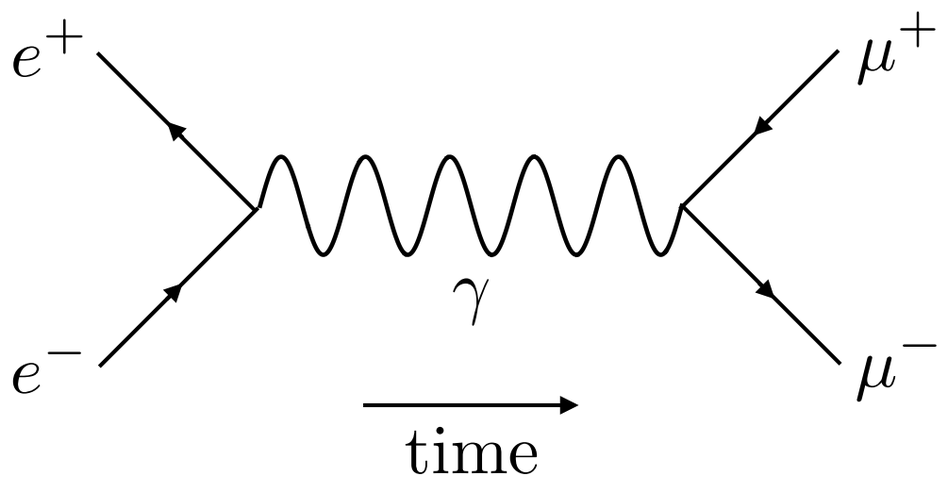
[redacted]

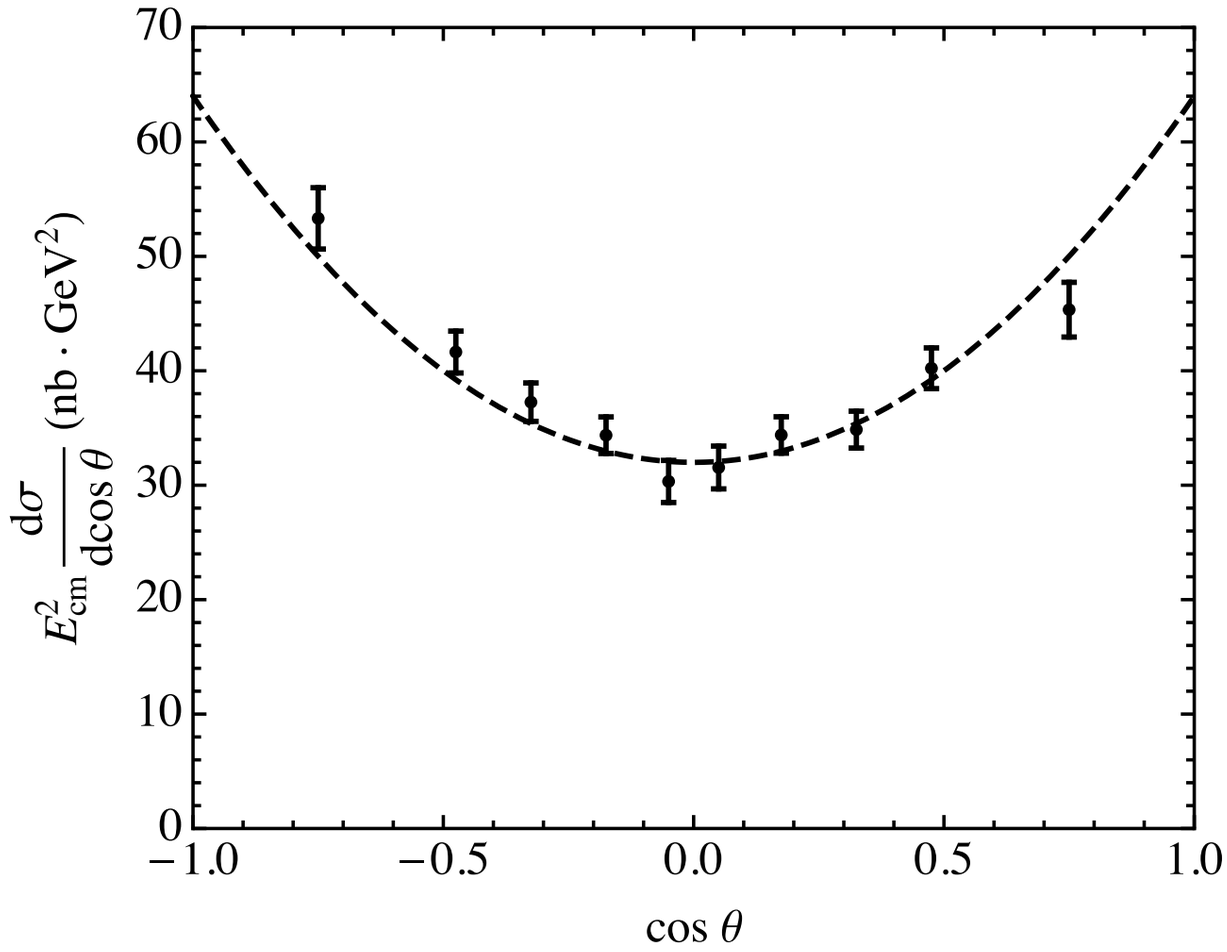
735661

D

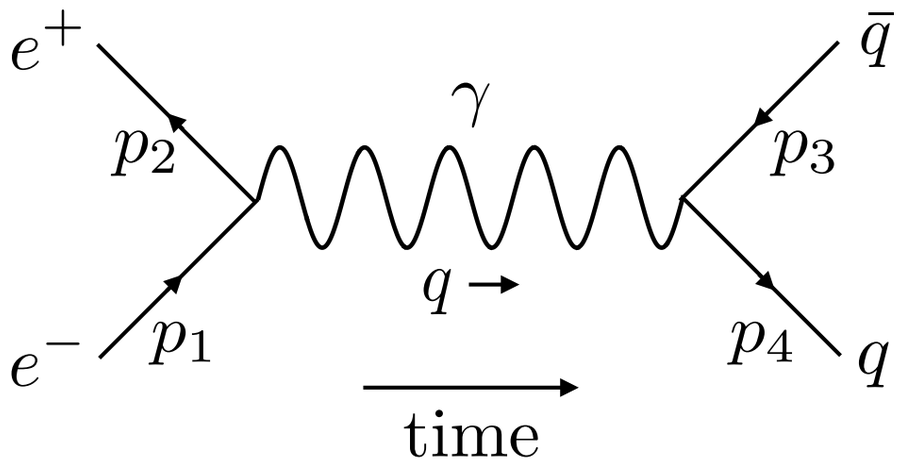
QCD

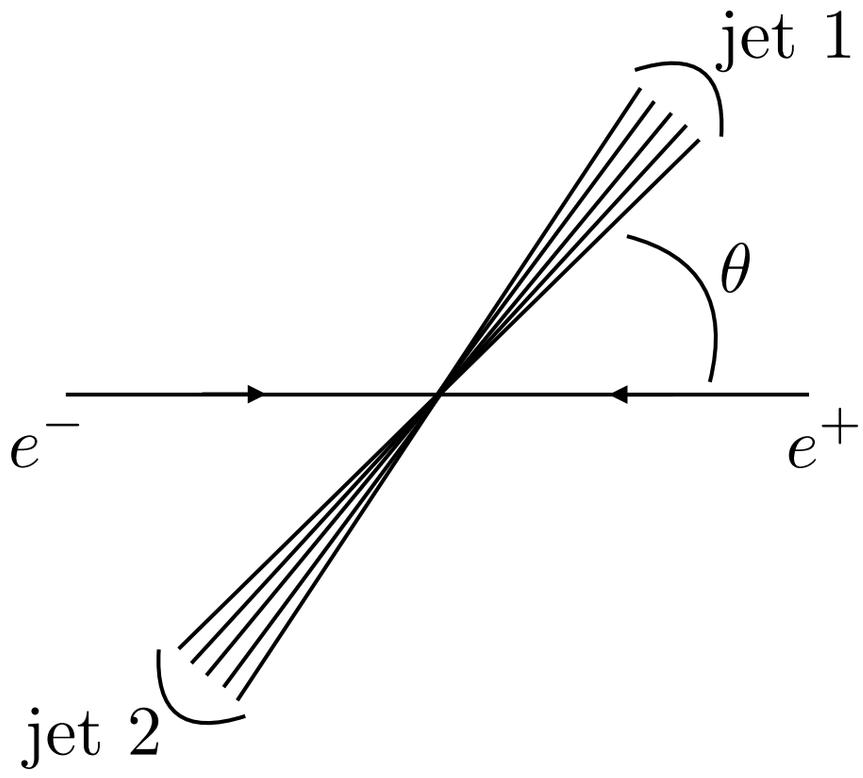


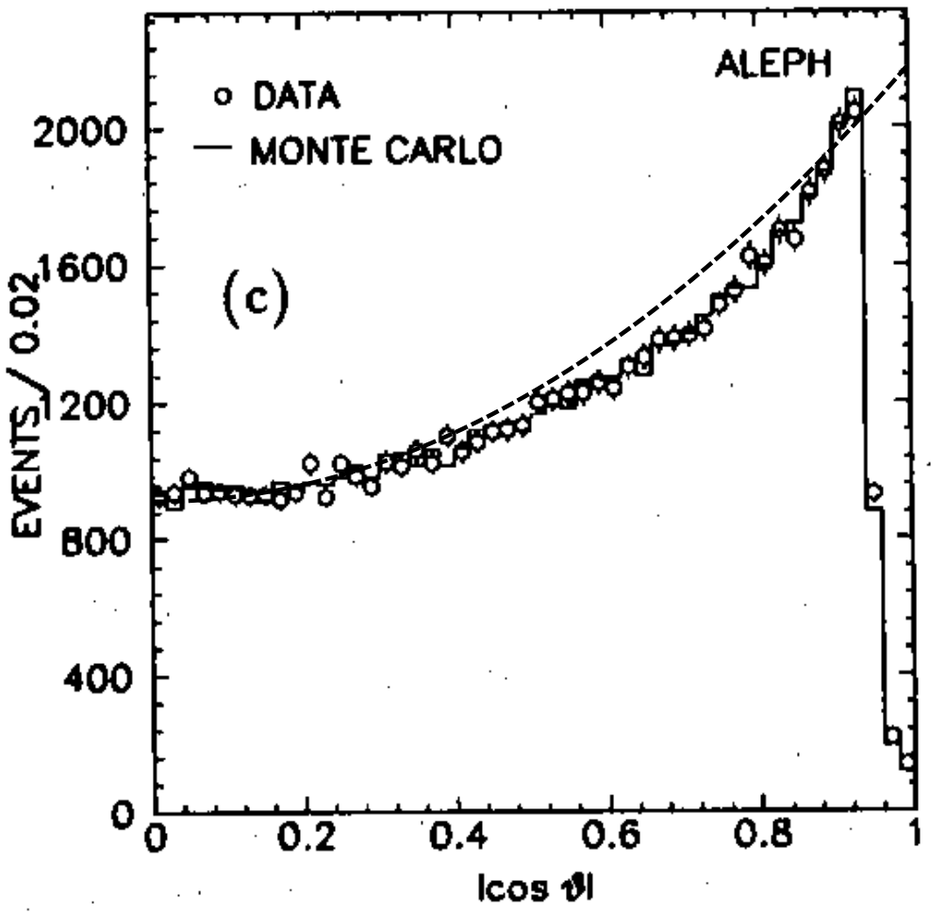

e^+
μ^+
γ
e^-
μ^-
time



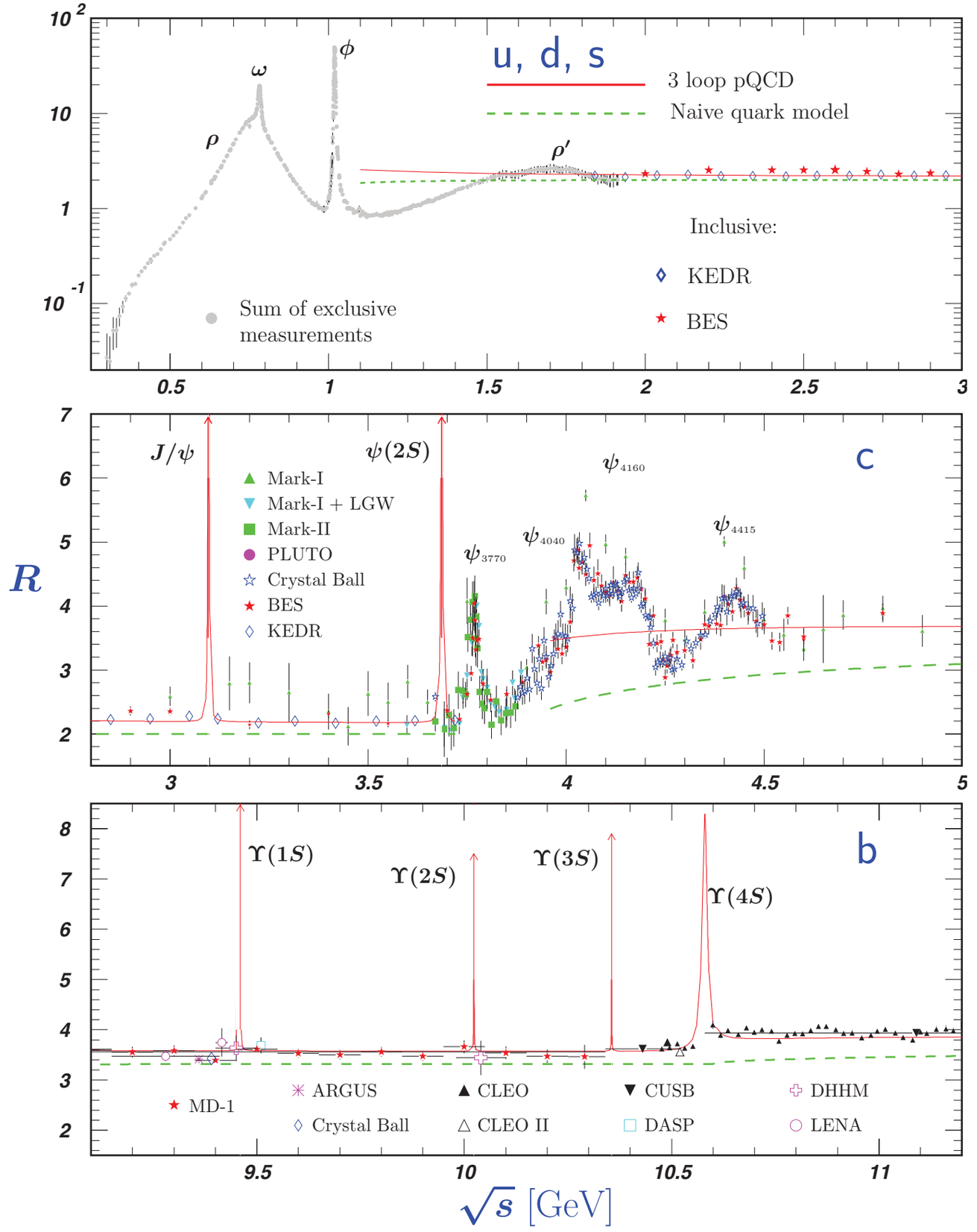
M. Derrick *et al.* [HRS Collaboration],
"New results on the reaction $e^+e^- \to \mu^+\mu^-$ at $\sqrt{s} = 29$ GeV," Phys. Rev. D **31**, 2352 (1985)


e^+
$\bar{q}$
γ
p_2
p_3
$q \rightarrow$
e^-
p_1
p_4
q
time

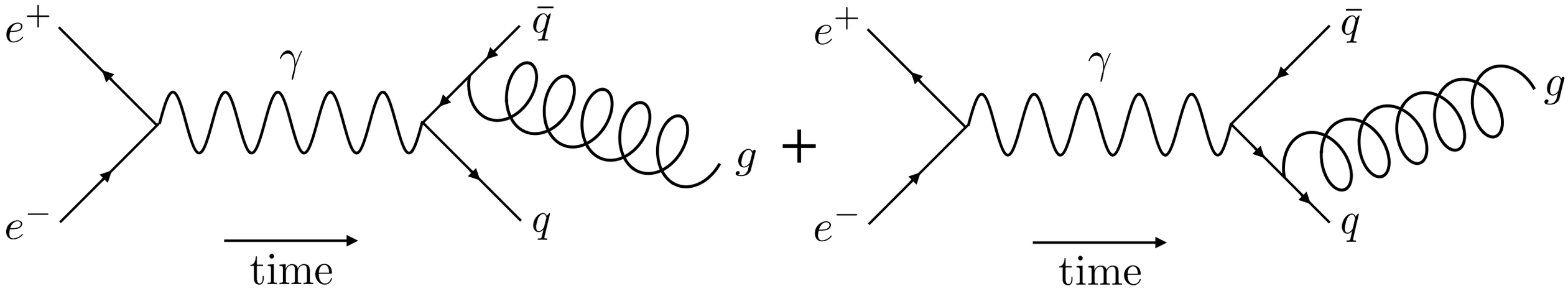


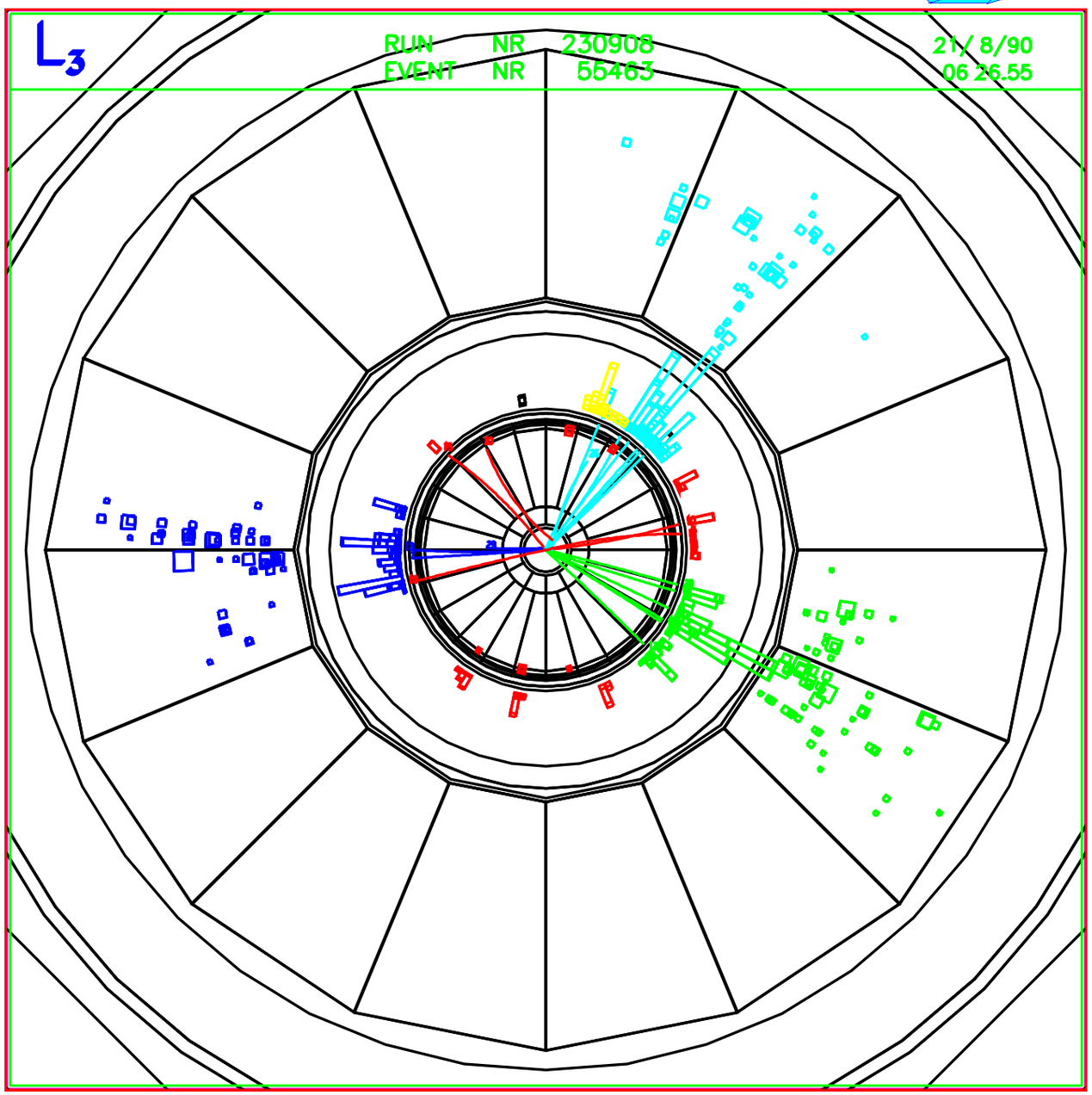


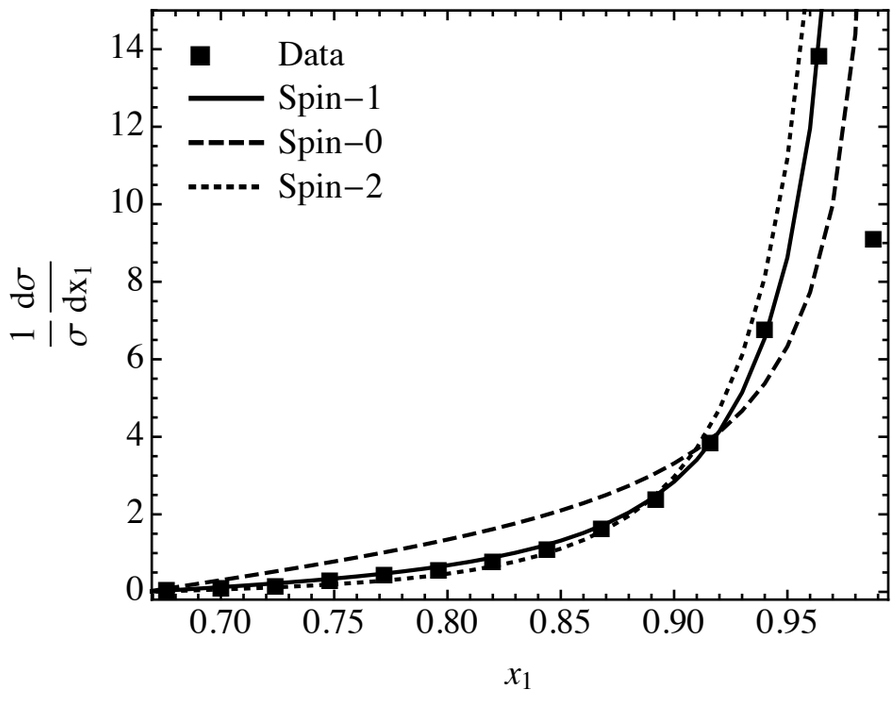
D. Decamp *et al.* [ALEPH],
"Measurement of electroweak parameters from Z decays into Fermion pairs,"
Z. Phys. C **48**, 365-392 (1990)

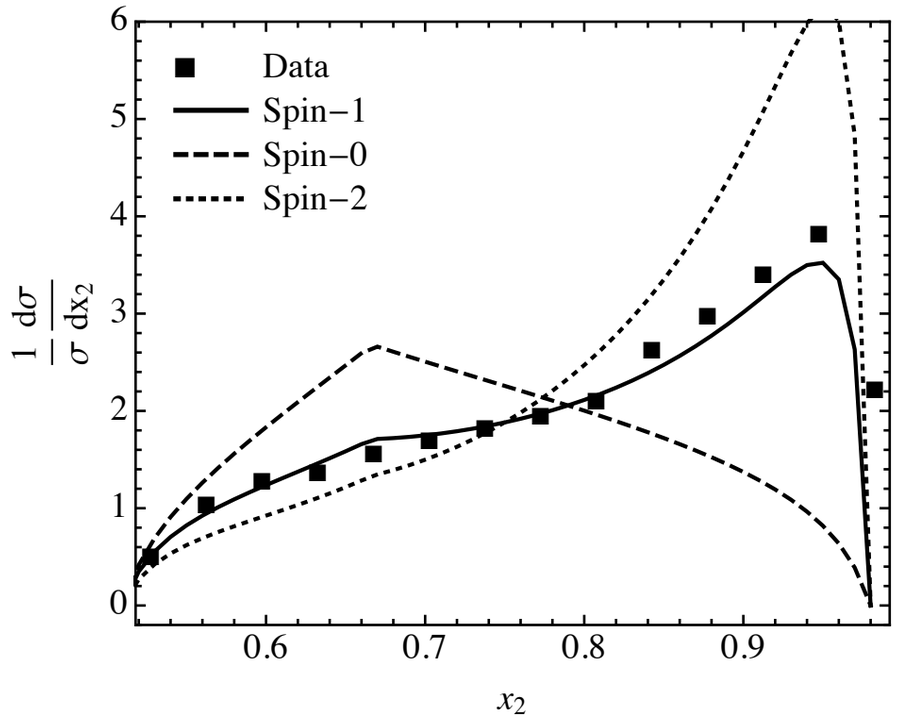


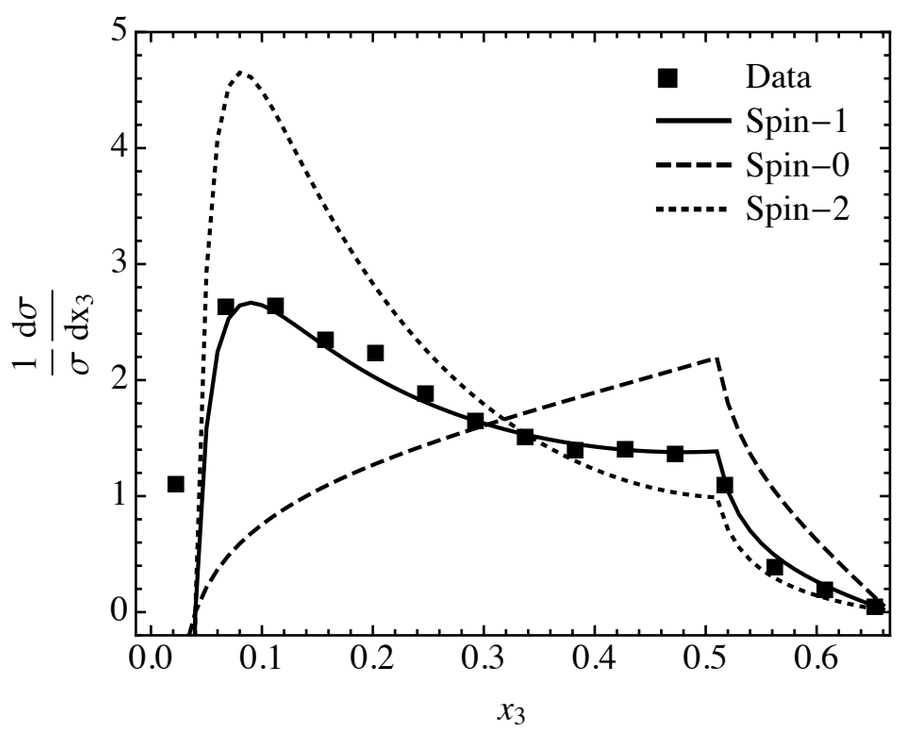
M. Tanabashi *et al.* [Particle Data Group],
"Review of particle physics," Phys. Rev. D **98**, 030001 (2018)


e^+
e^-
γ
$\bar{q}$
g
q
time
+
e^+
e^-
γ
$\bar{q}$
g
q
time



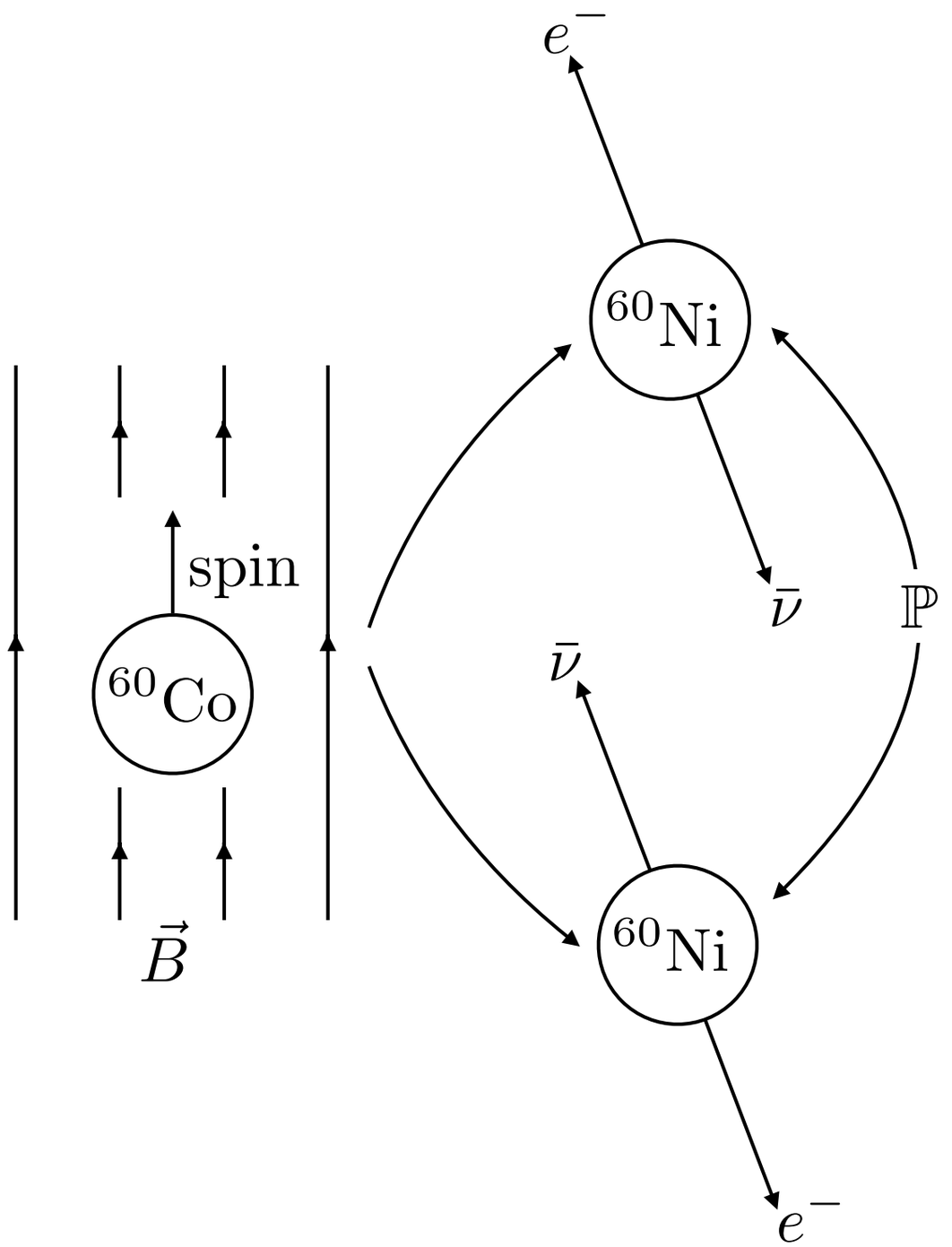


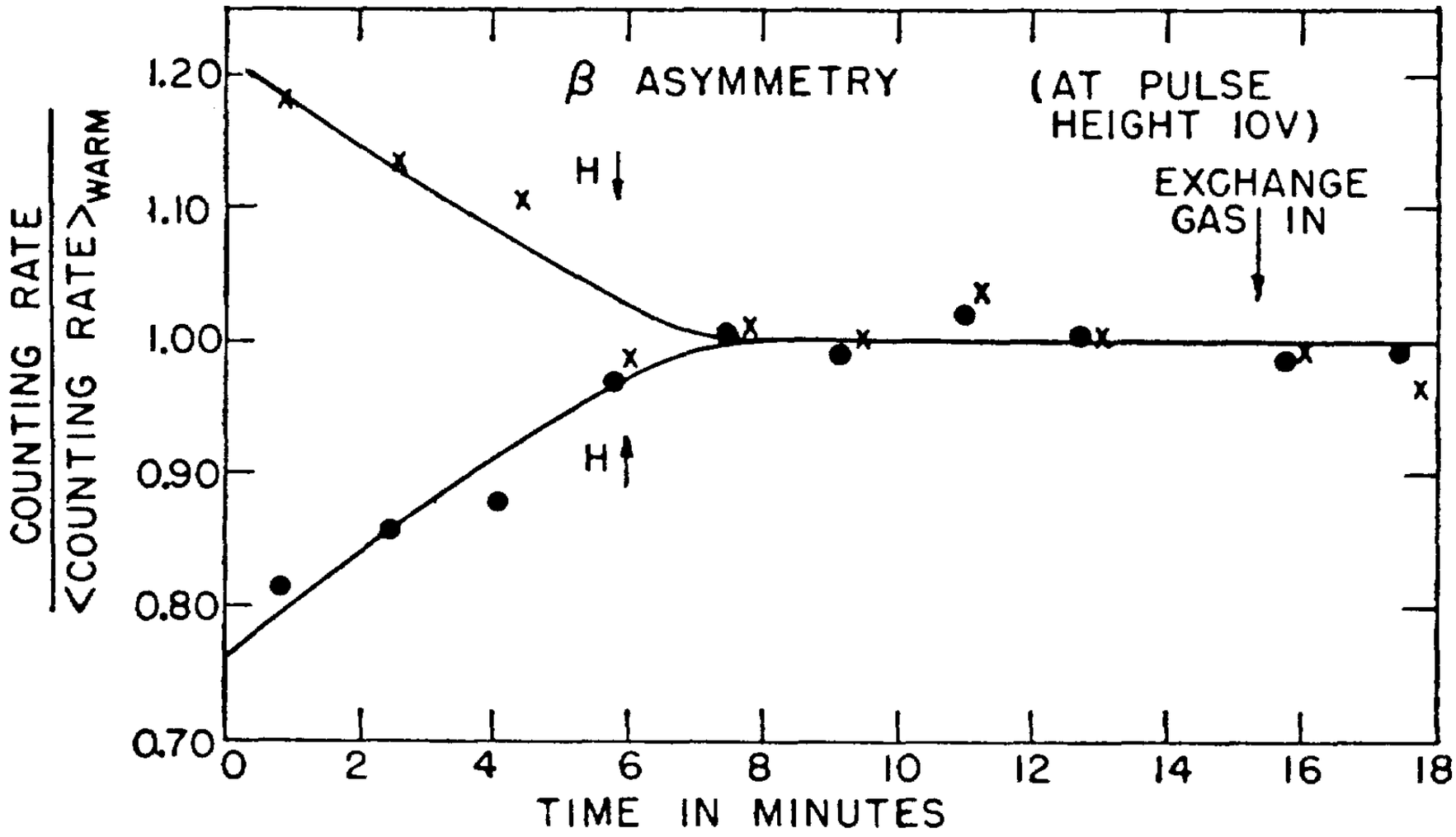




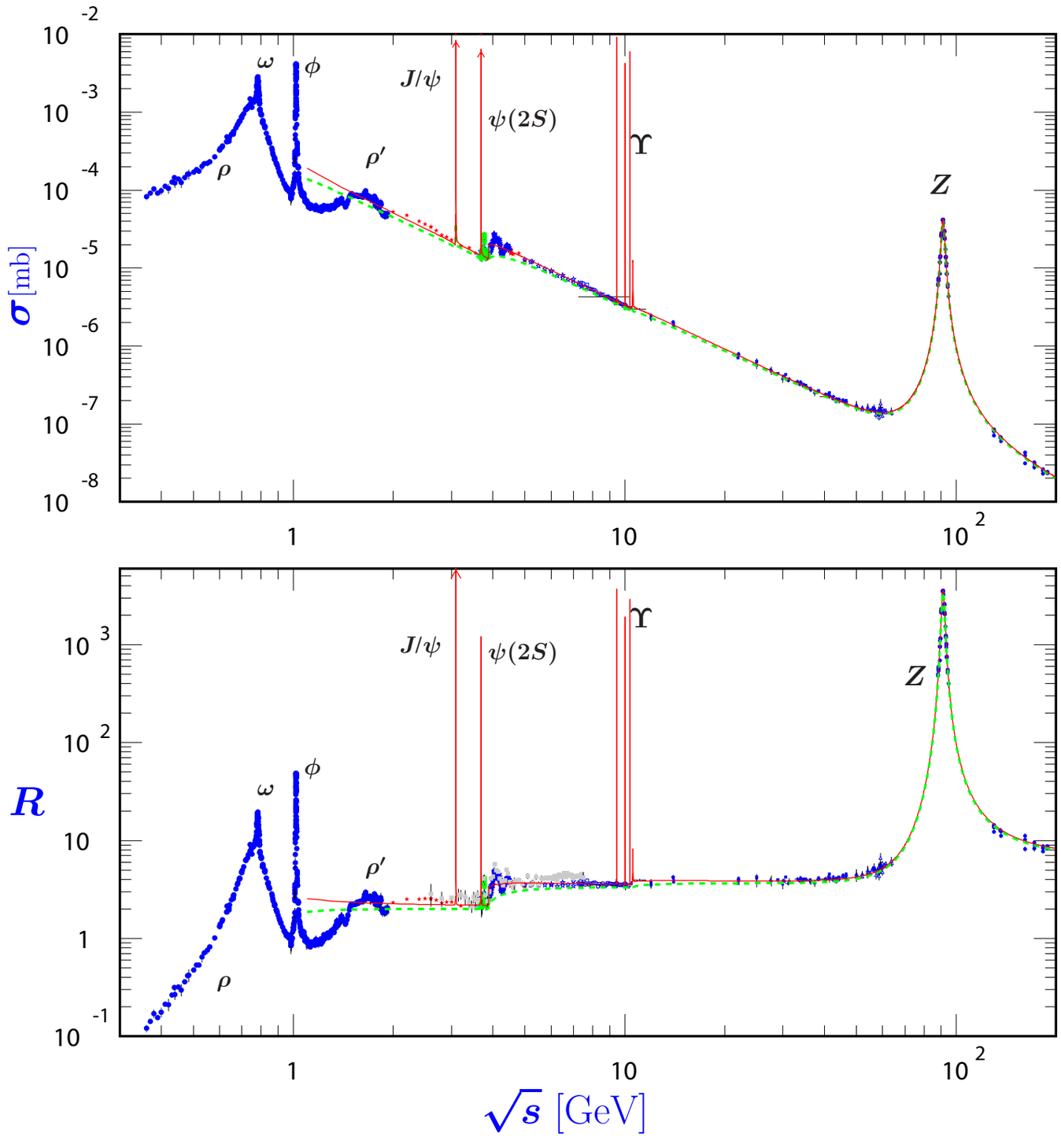
K. Abe *et al.* [SLD Collaboration], Phys. Rev. D **55**, 2533 (1997)

Electroweak

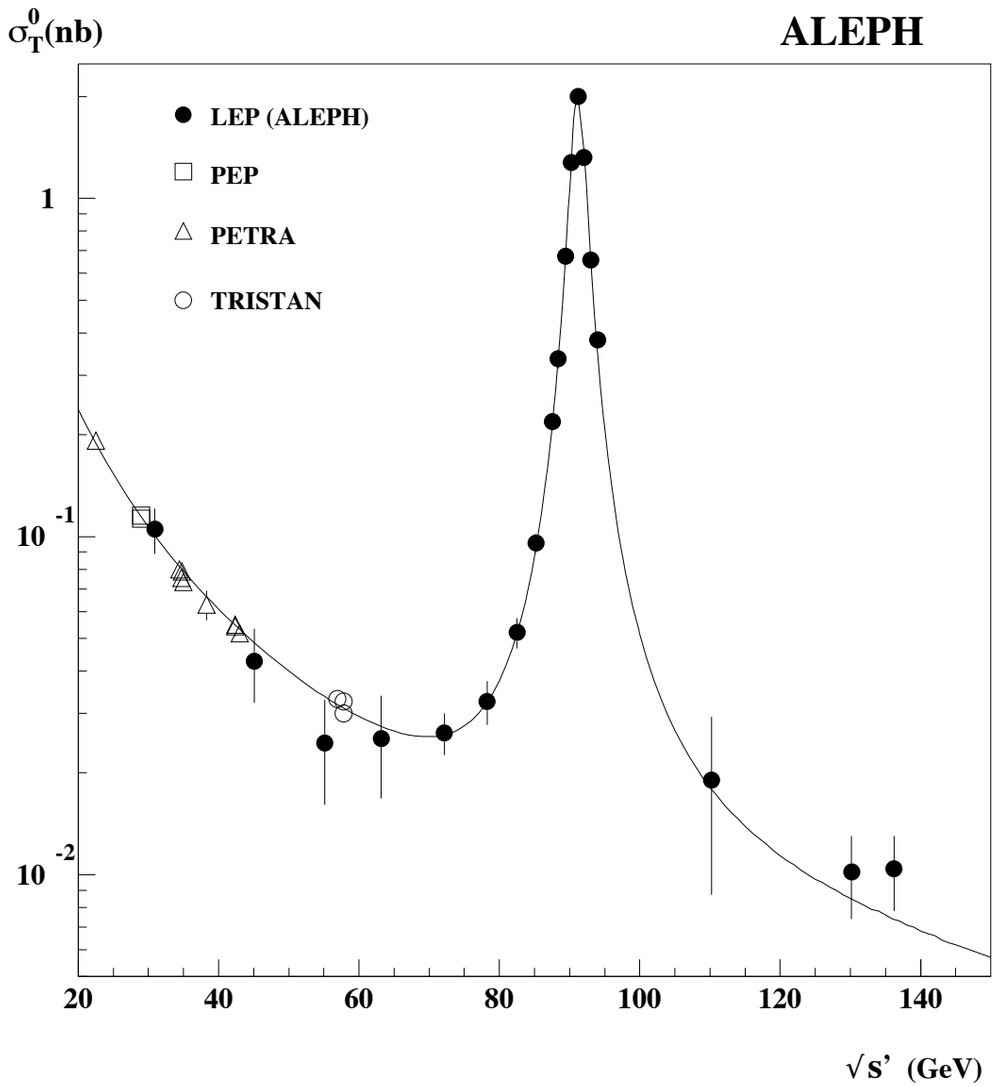

e^-
^{60}Ni
spin
^{60}Co
$\vec{B}$
$\bar{\nu}$
$\mathbb{P}$
$\bar{\nu}$
^{60}Ni
e^-



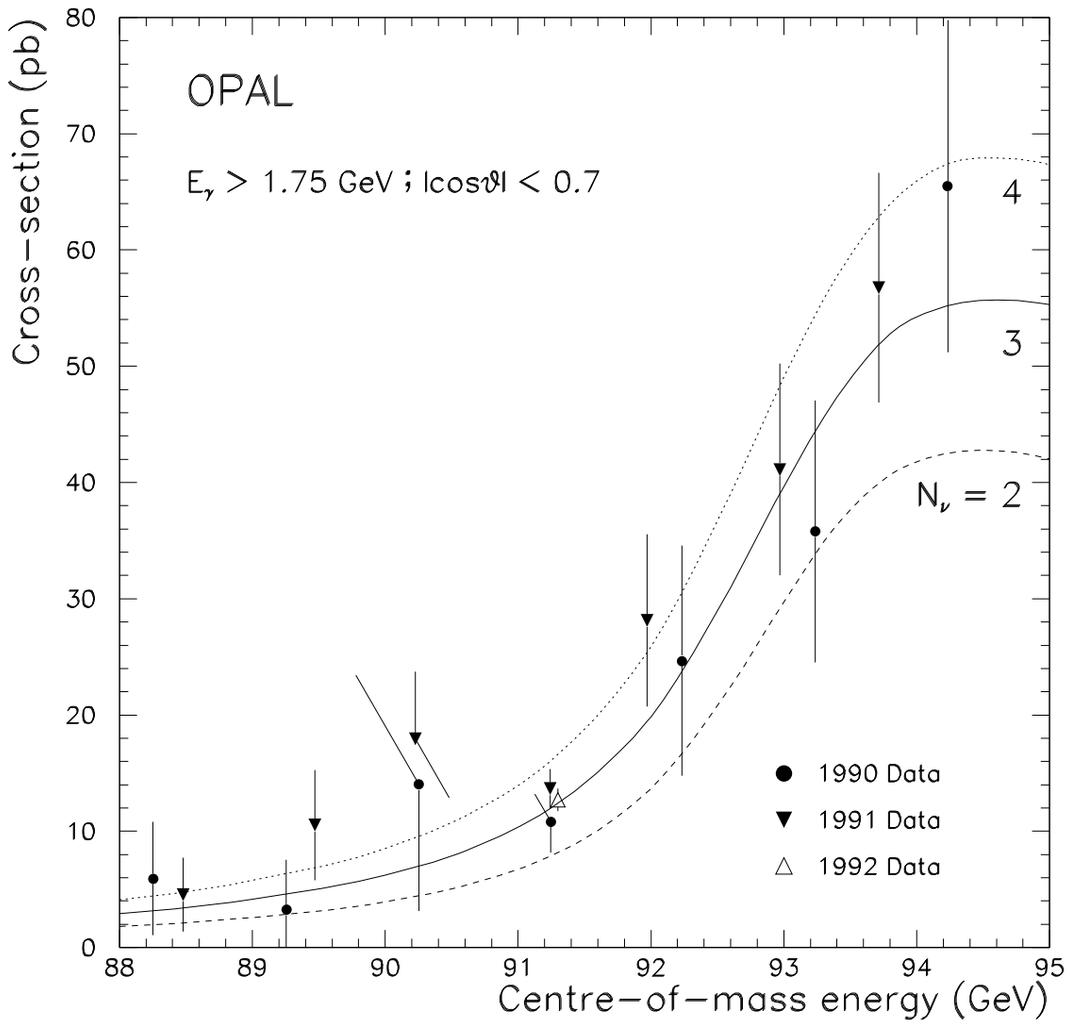
C. S. Wu, E. Ambler, R. W. Hayward, D. D. Hoppes and R. P. Hudson,
"Experimental Test of Parity Conservation in β Decay,"
Phys. Rev. **105**, 1413-1414 (1957)



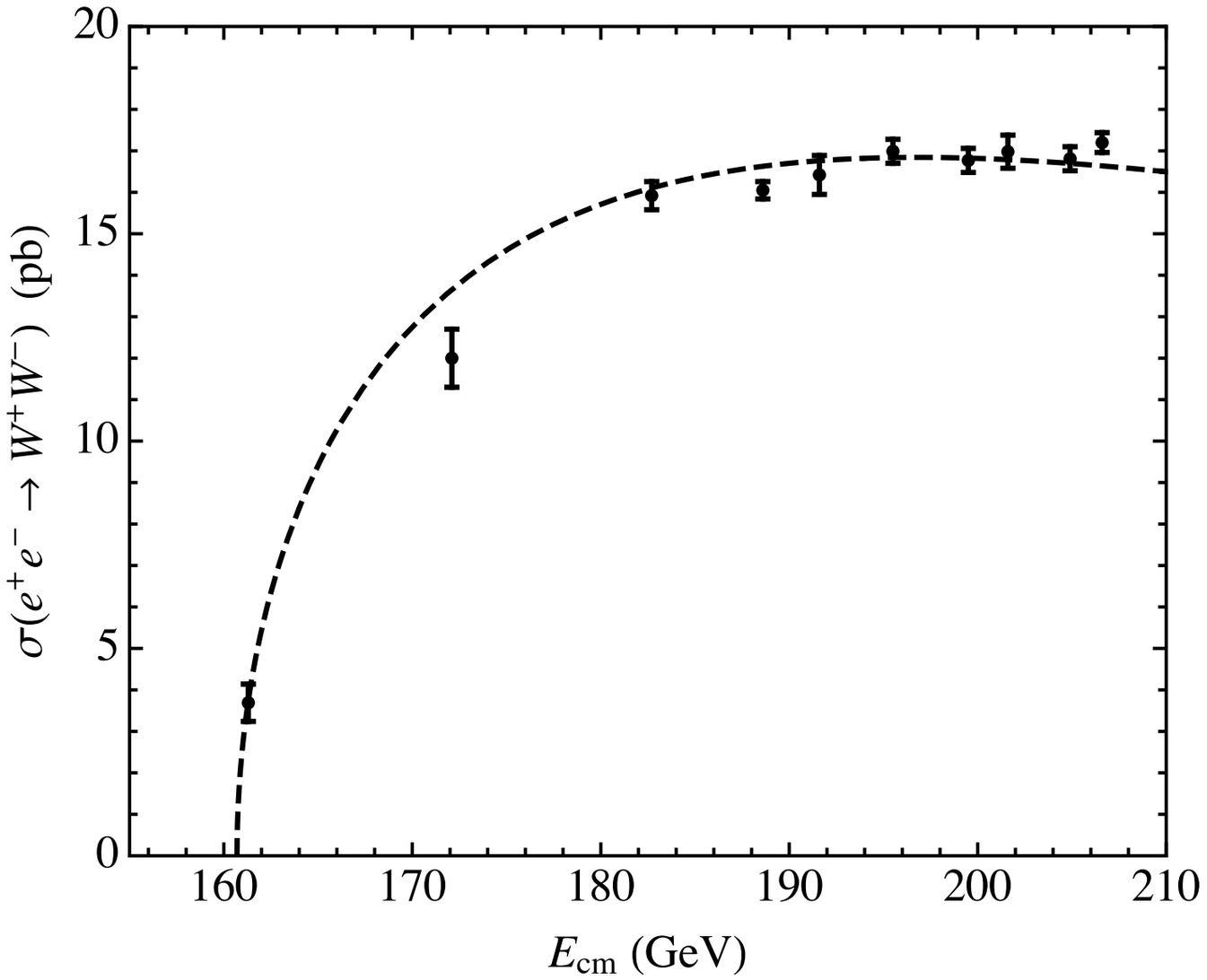
M. Tanabashi *et al.* [Particle Data Group],
"Review of particle physics," Phys. Rev. D **98**, 030001 (2018)



R. Barate *et al.* [ALEPH Collaboration],
"Study of the muon pair production at center-of-mass energies from 20 GeV to 136 GeV with the ALEPH detector," Phys. Lett. B **399**, 329 (1997)

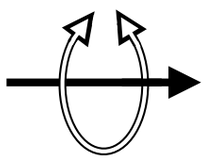


R. Akers *et al.* [OPAL Collaboration],"Measurement of single photon production in e^+e^- collisions near the Z0 resonance," Z. Phys. C (1995)



S. Schael *et al.* [ALEPH and DELPHI and L3 and OPAL and LEP Electroweak Collaborations], "Electroweak measurements in electron positron collisions at W-boson-pair energies at LEP," Phys. Rept. **532**, 119 (2013)

Higgs

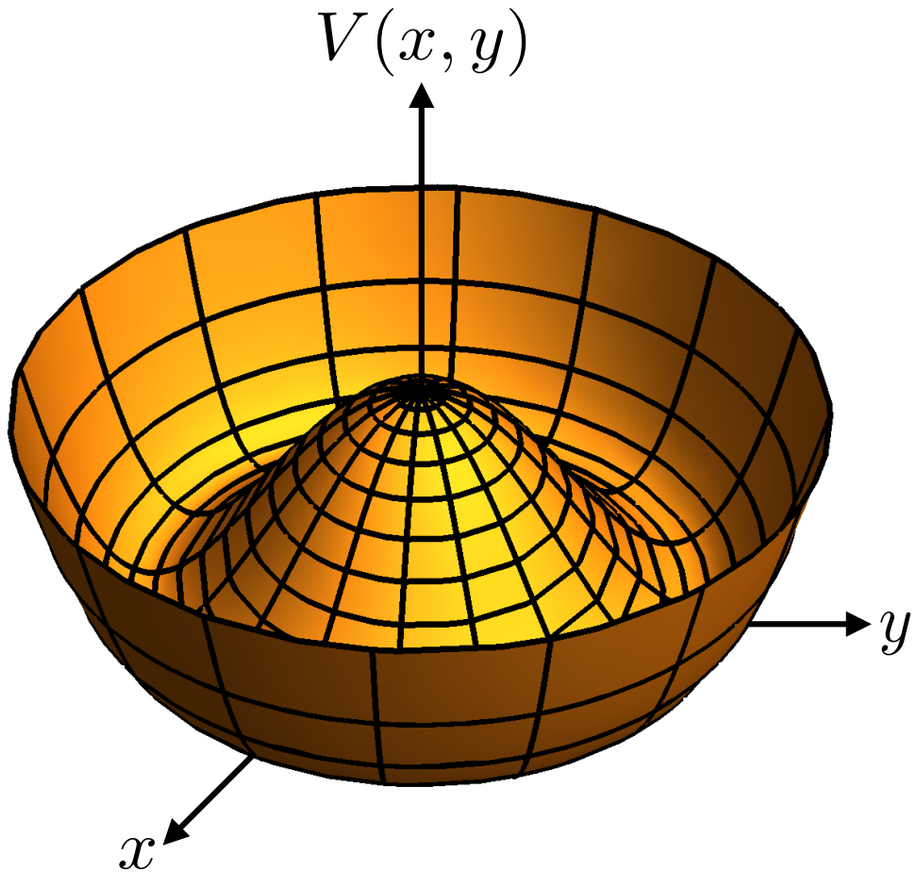


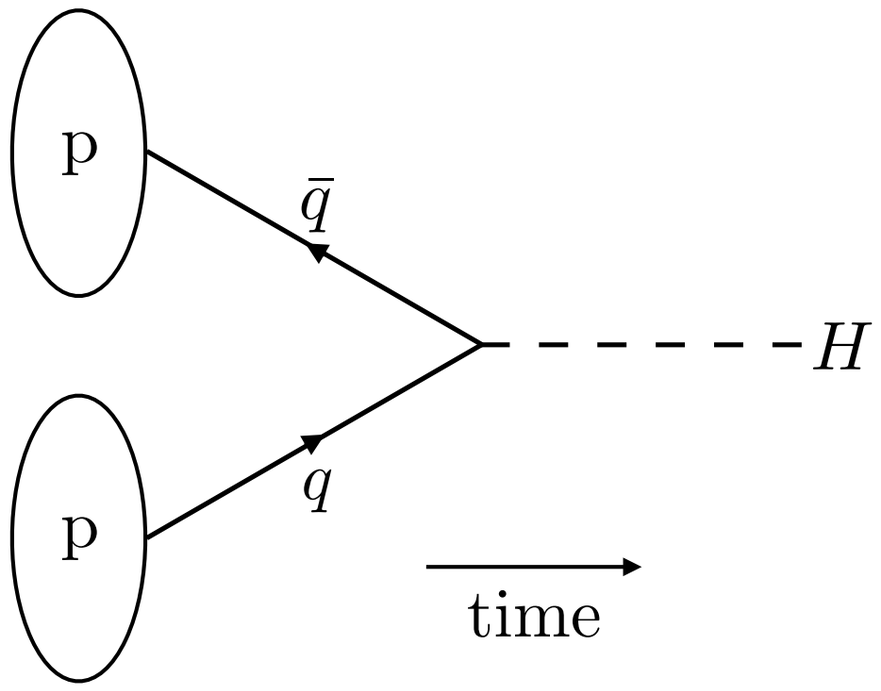
$p = (E, 0, 0, E)$

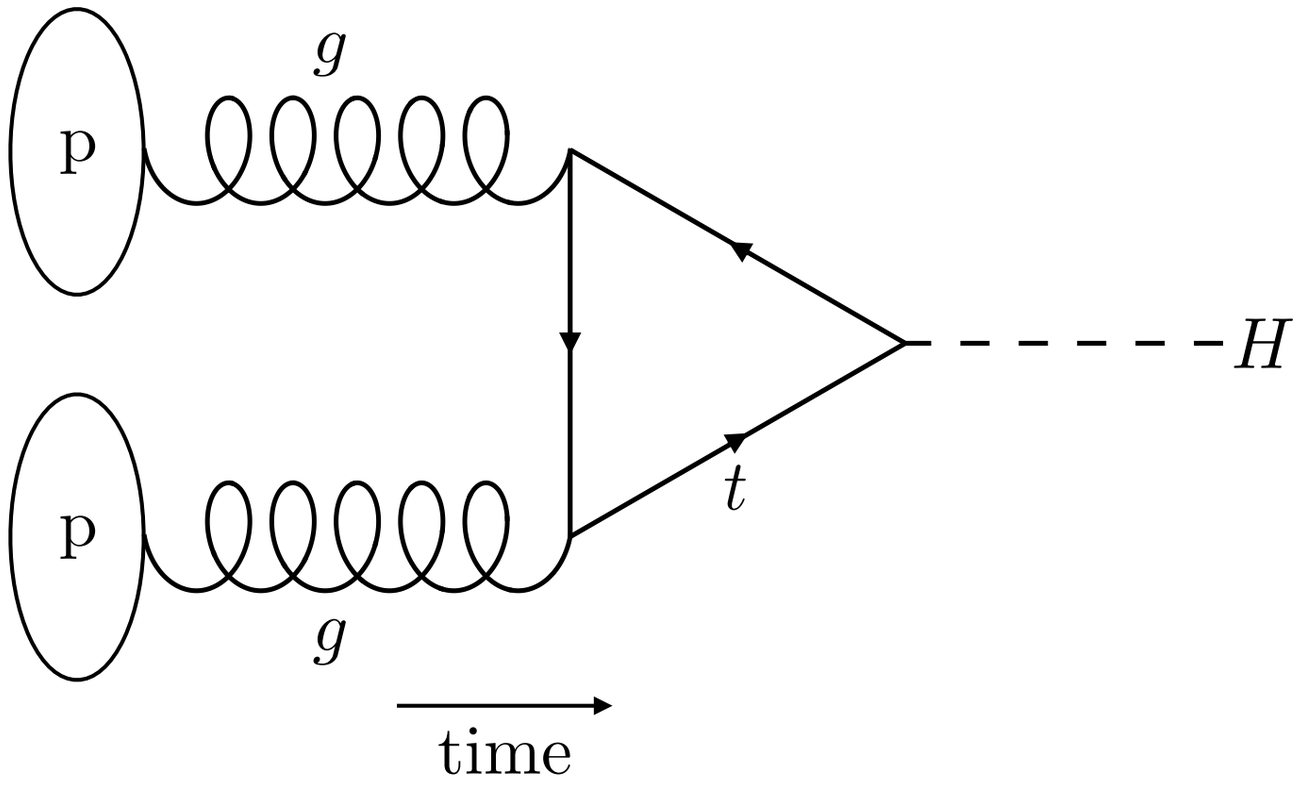
Massless

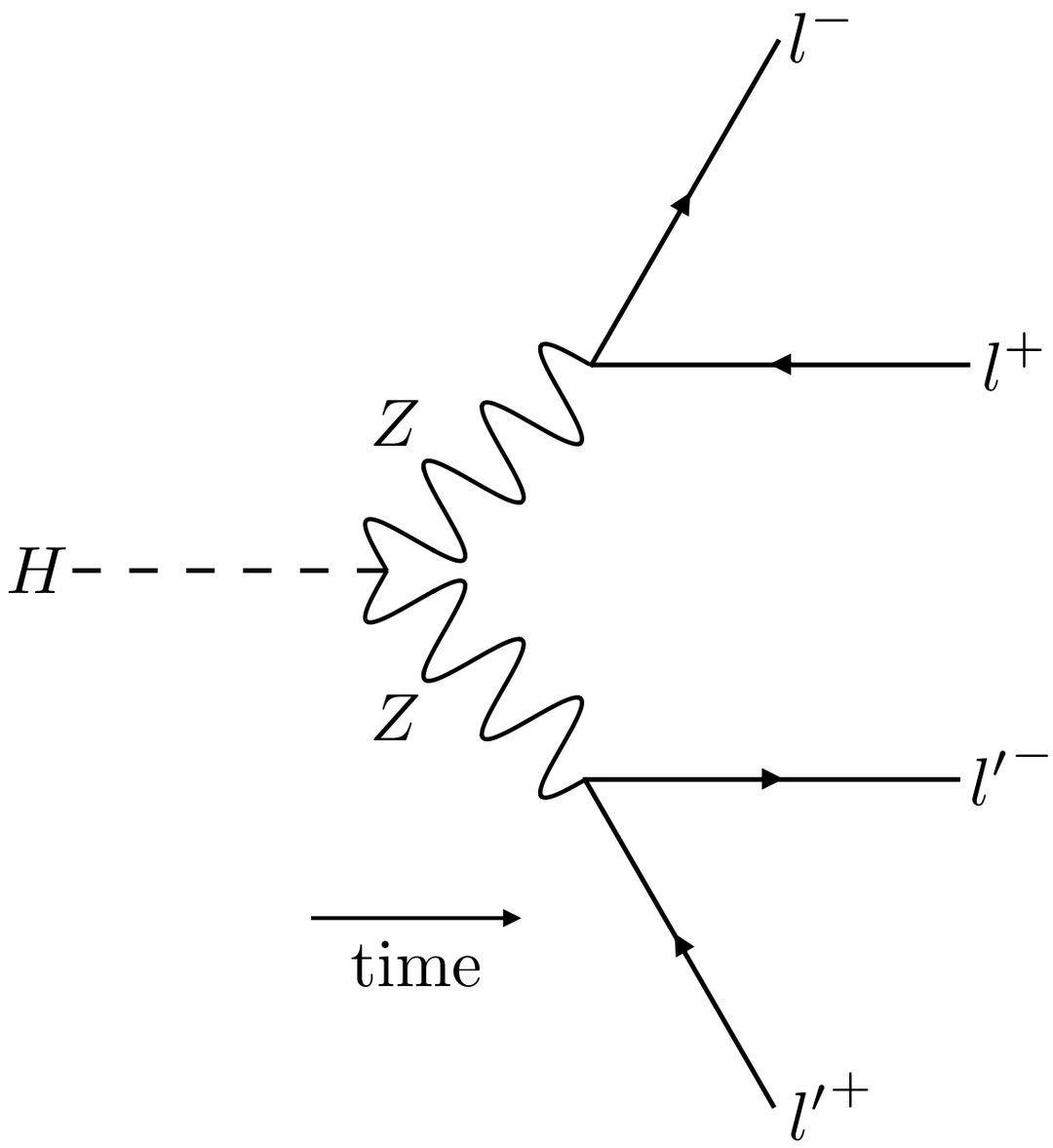
$p = (m, 0, 0, 0)$

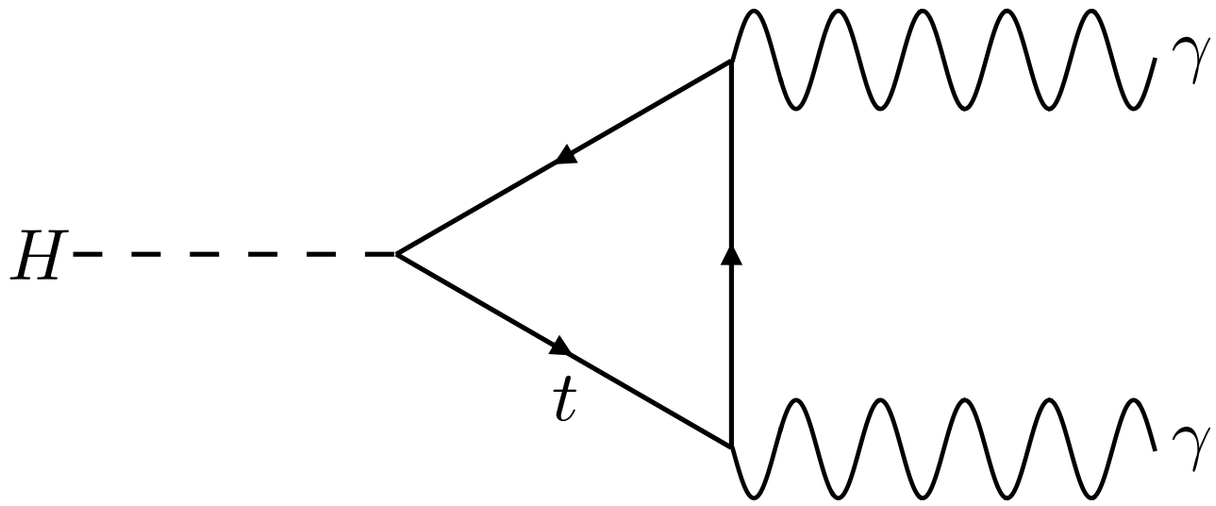
Massive


$V(x, y)$
y
x

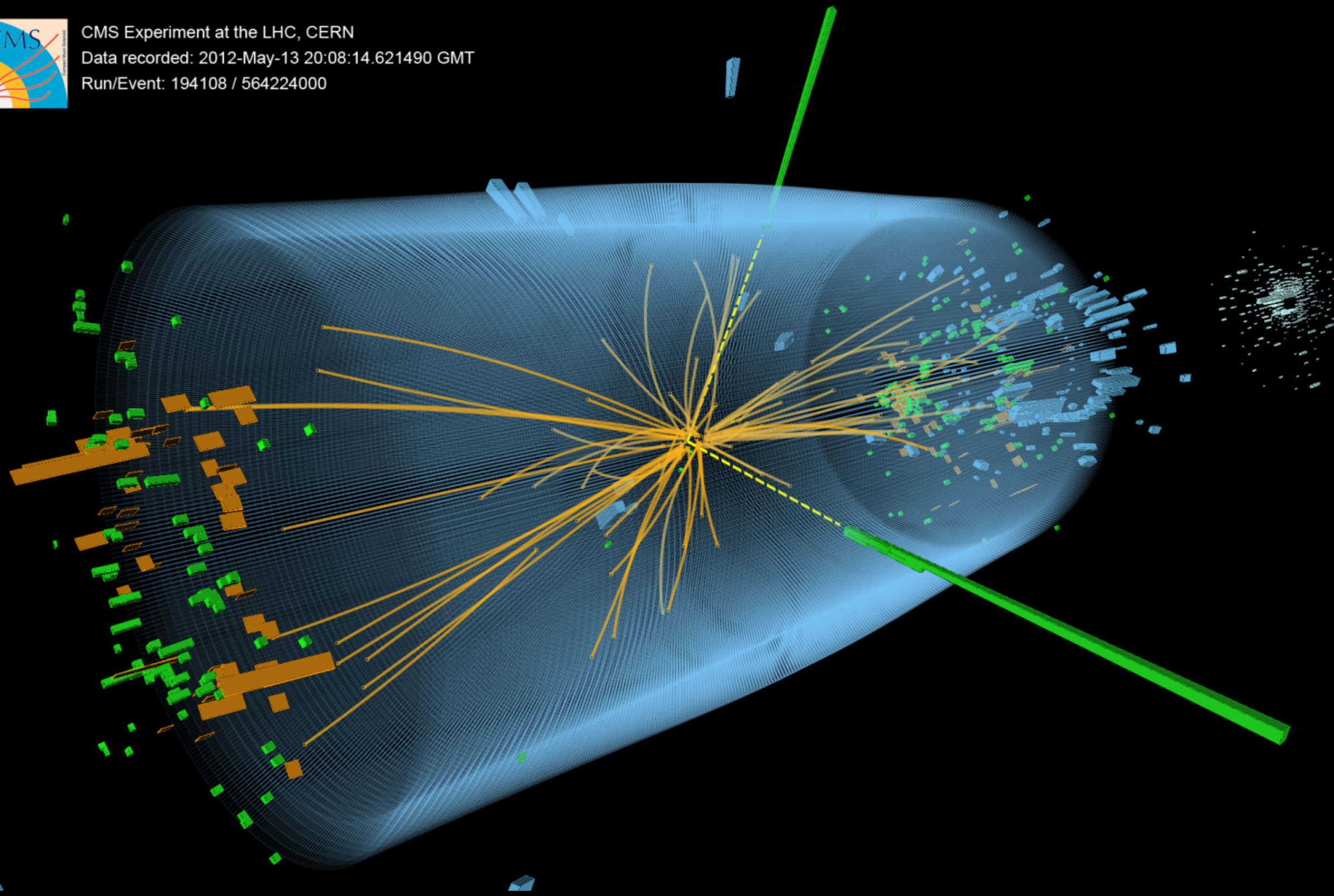

p
$\bar{q}$
H
q
p
time

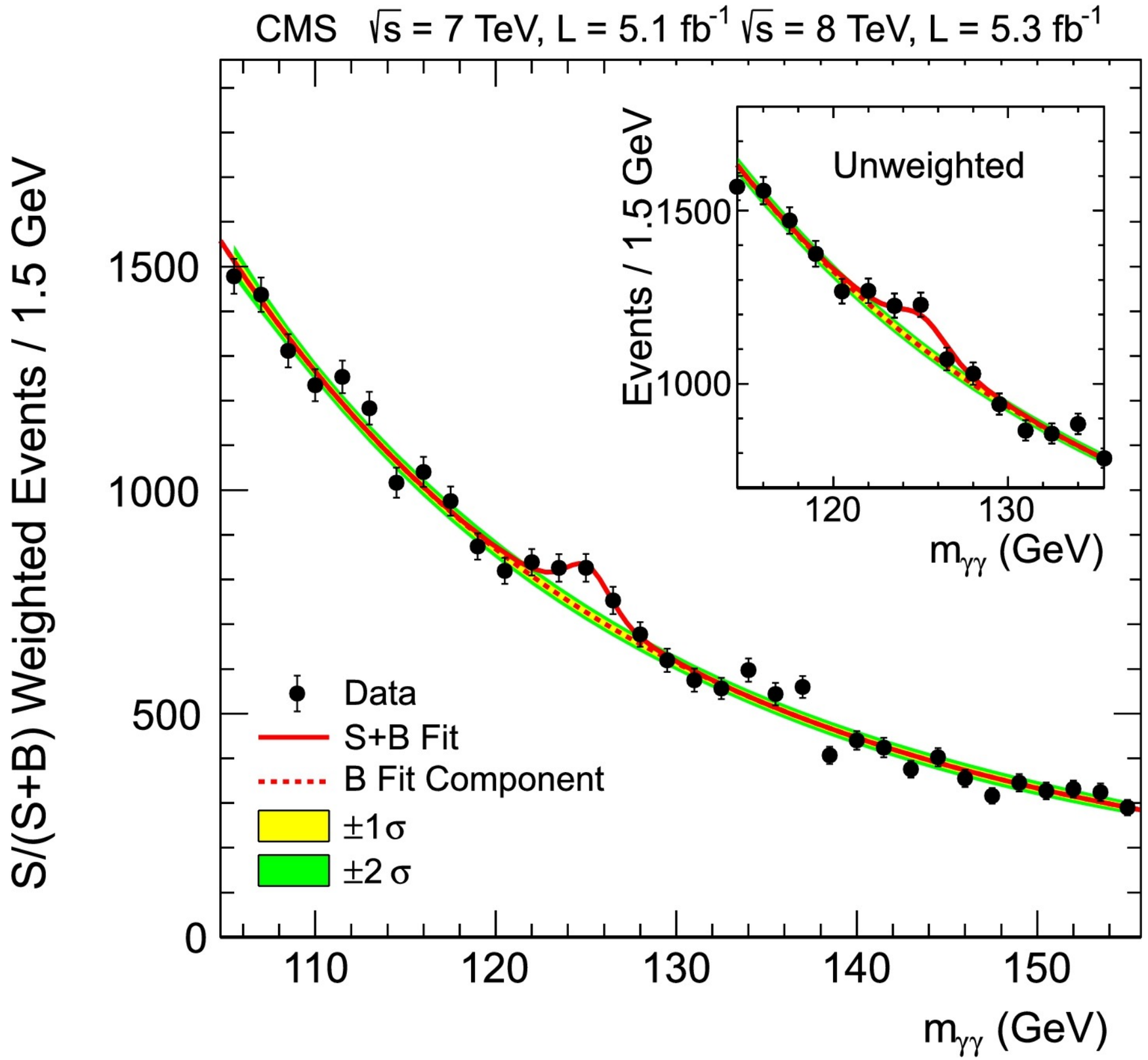

g
p
H
t
p
g
time


l^-
l^+
Z
H
z
l'^-
time
l'^+

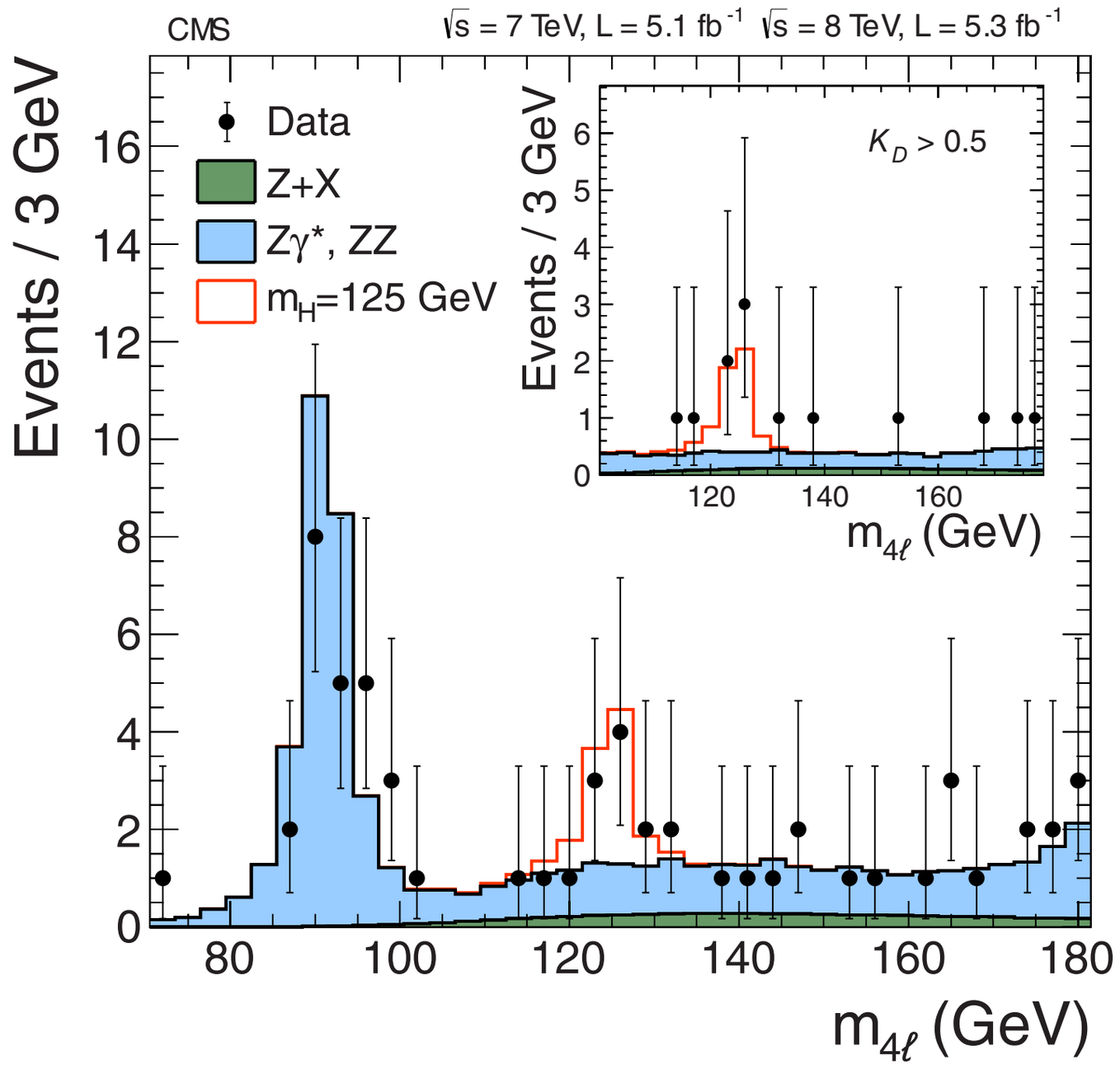

γ
H
t
γ

CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000

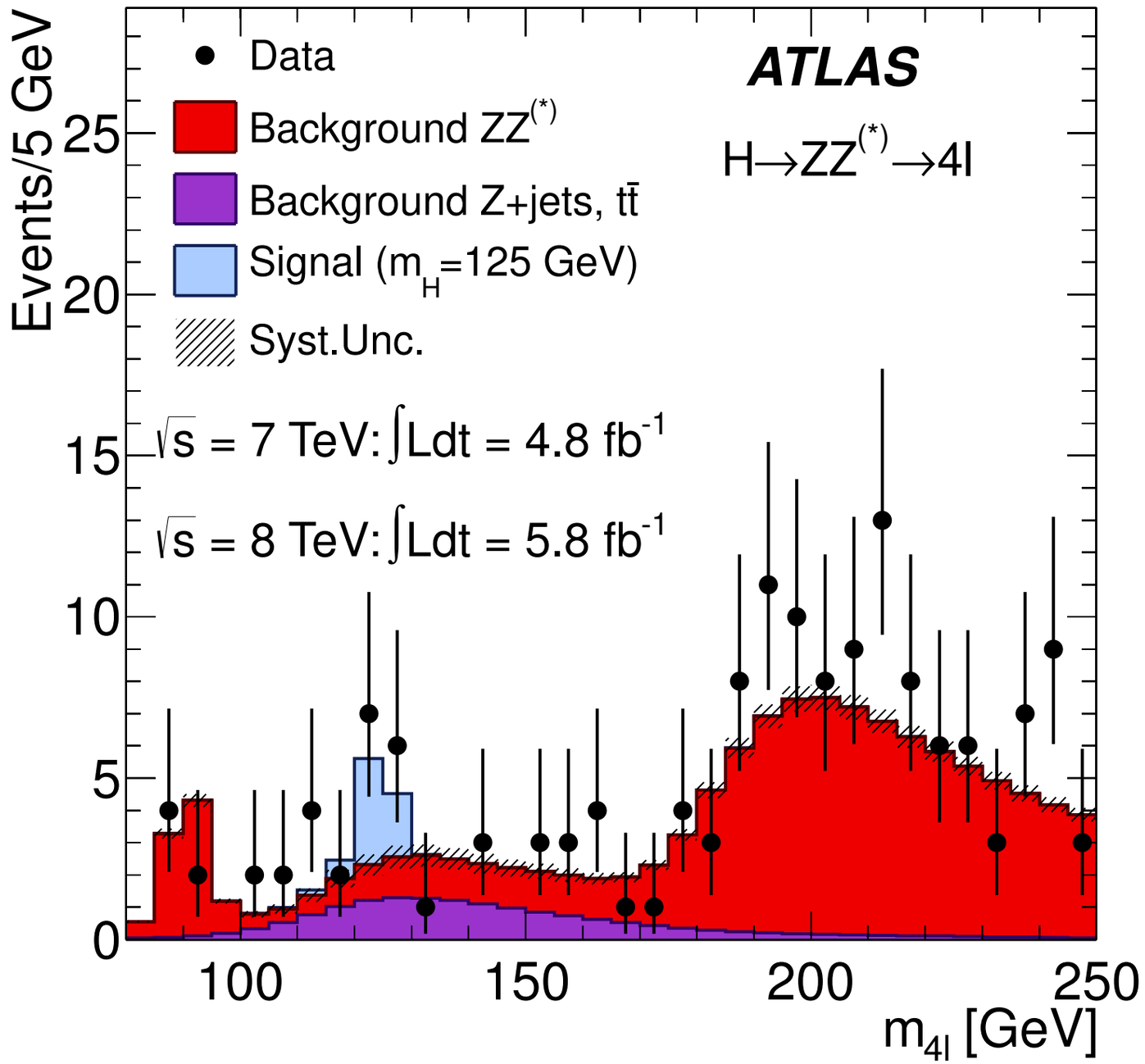




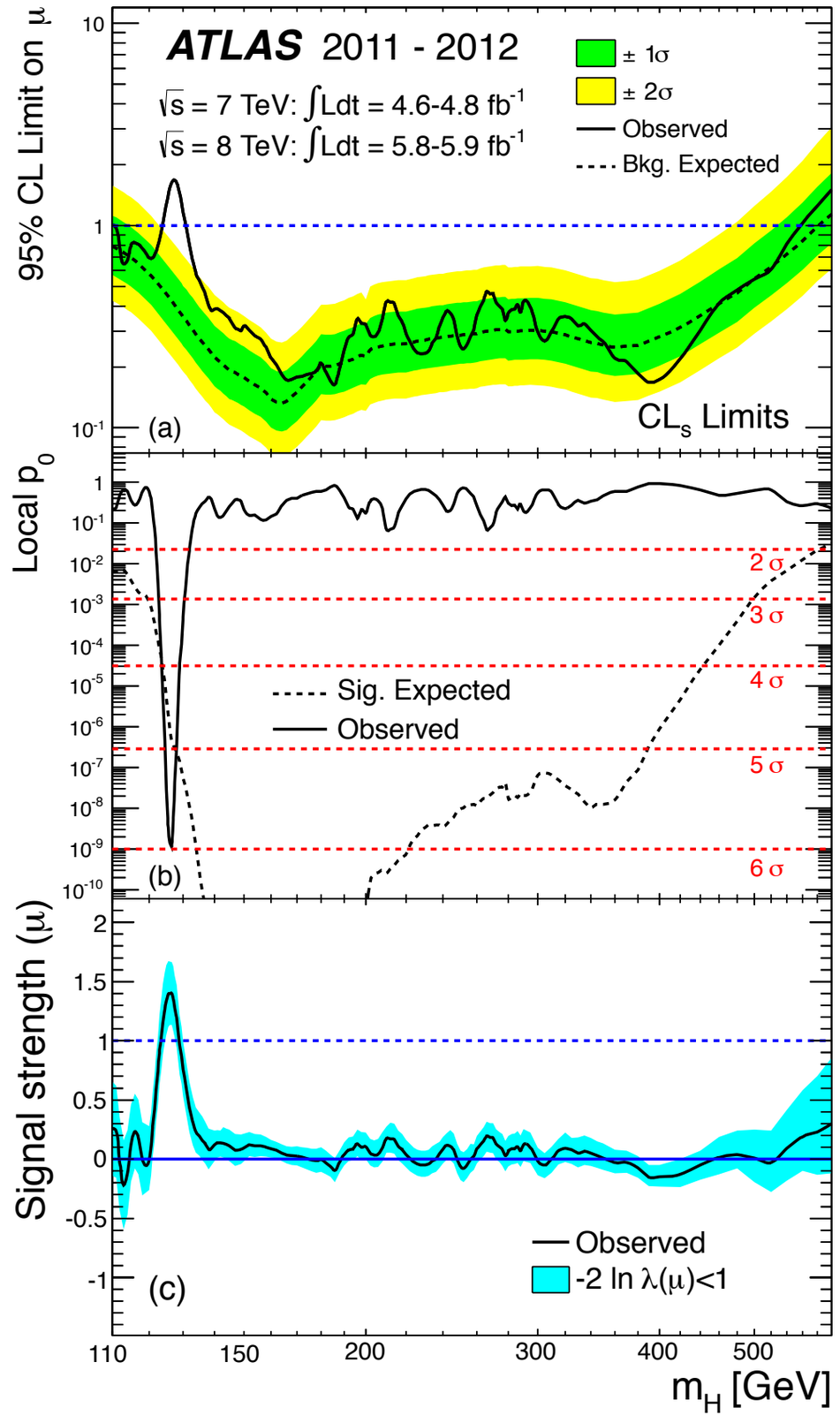
S. Chatrchyan *et al.* [CMS Collaboration], "Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC," Phys. Lett. B **716** 30 (2012)



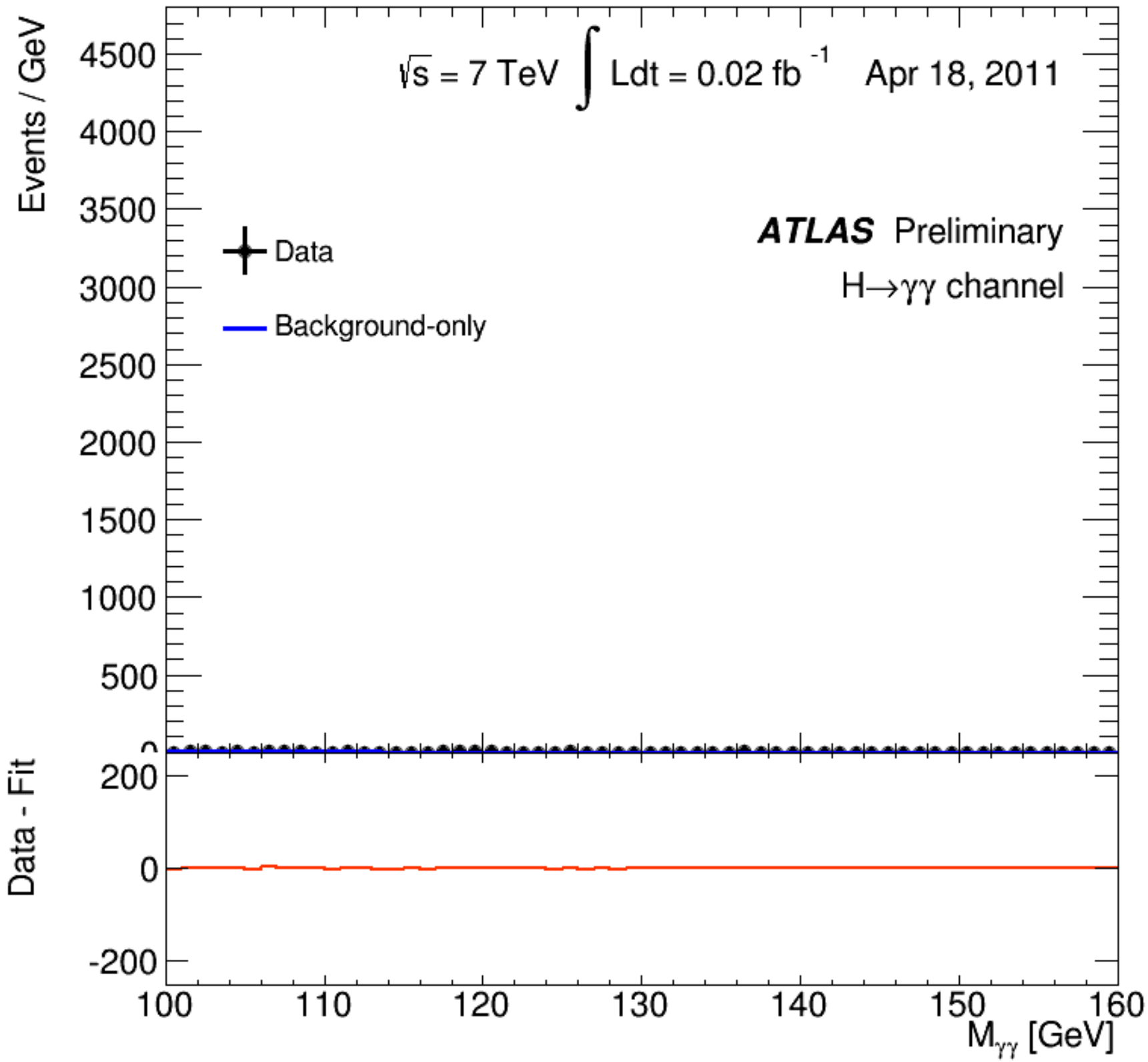
S. Chatrchyan *et al.* [CMS Collaboration], "Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC," Phys. Lett. B **716** 30 (2012)

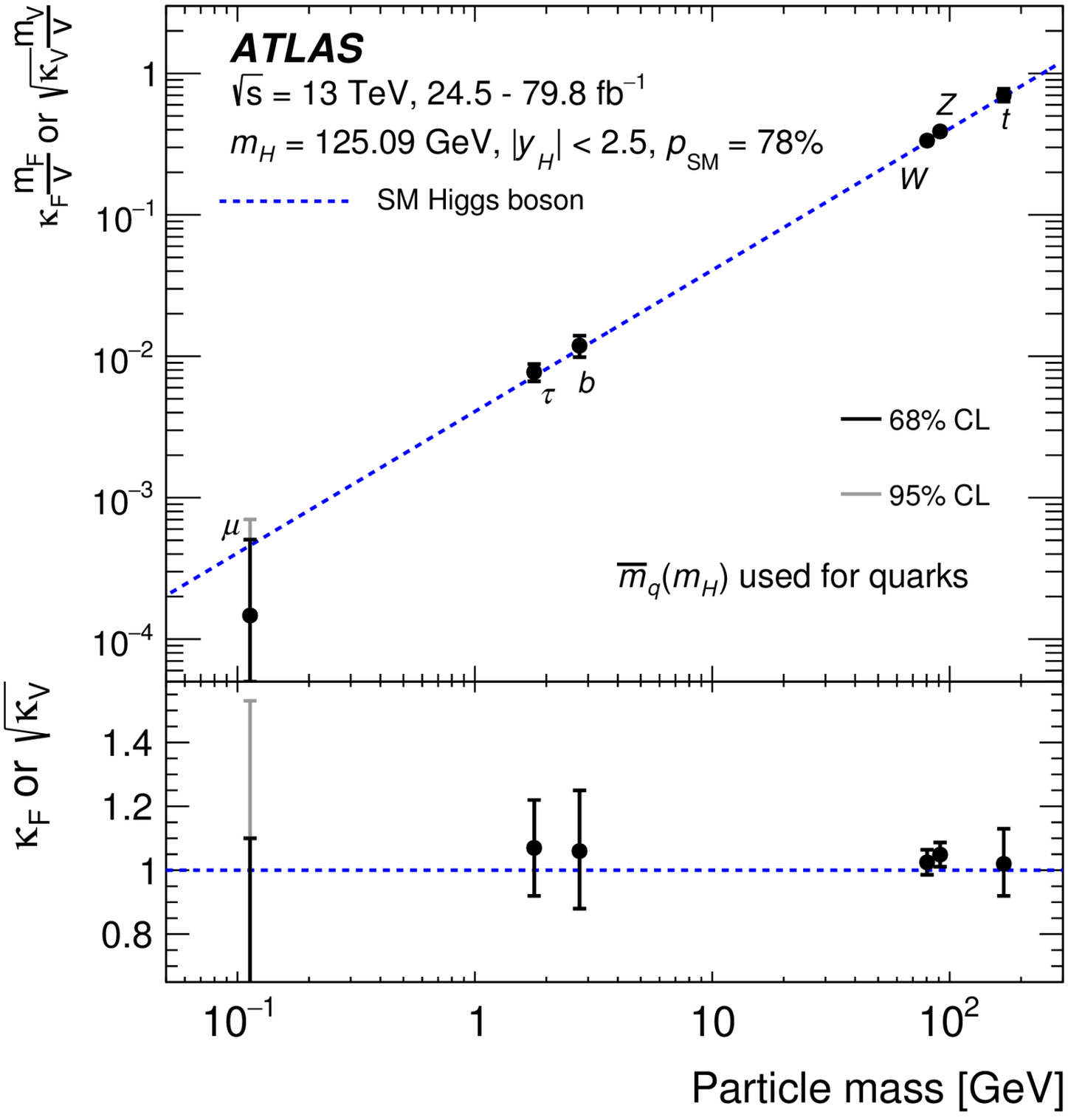


G. Aad *et al.* [ATLAS Collaboration], "Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC," Phys. Lett. B **716** 1 (2012)

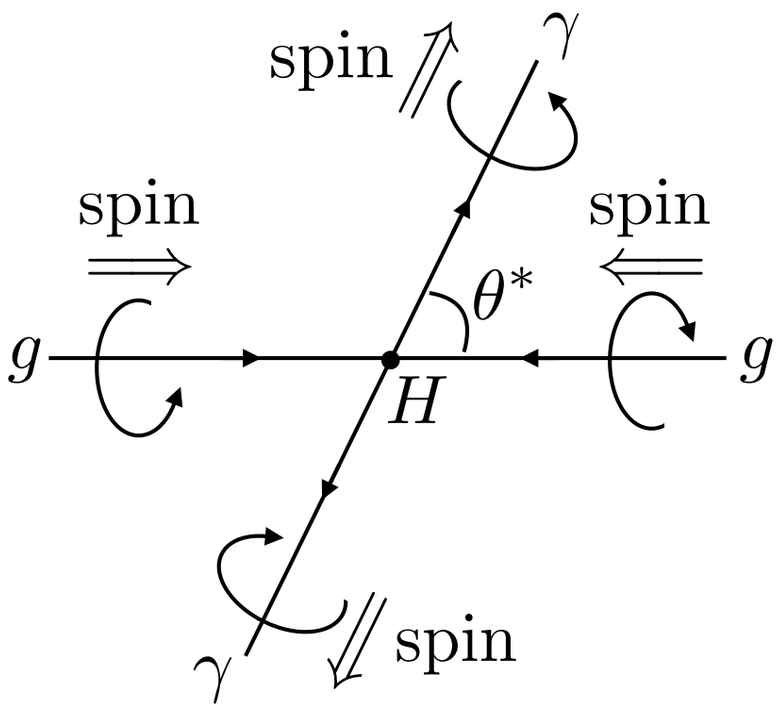


G. Aad *et al.* [ATLAS Collaboration], "Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC," Phys. Lett. B **716** 1 (2012)

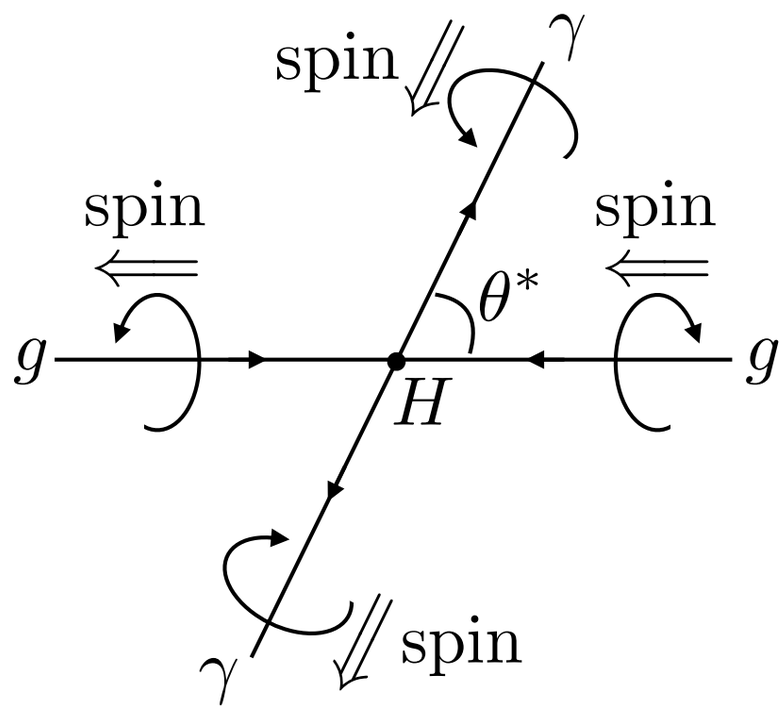




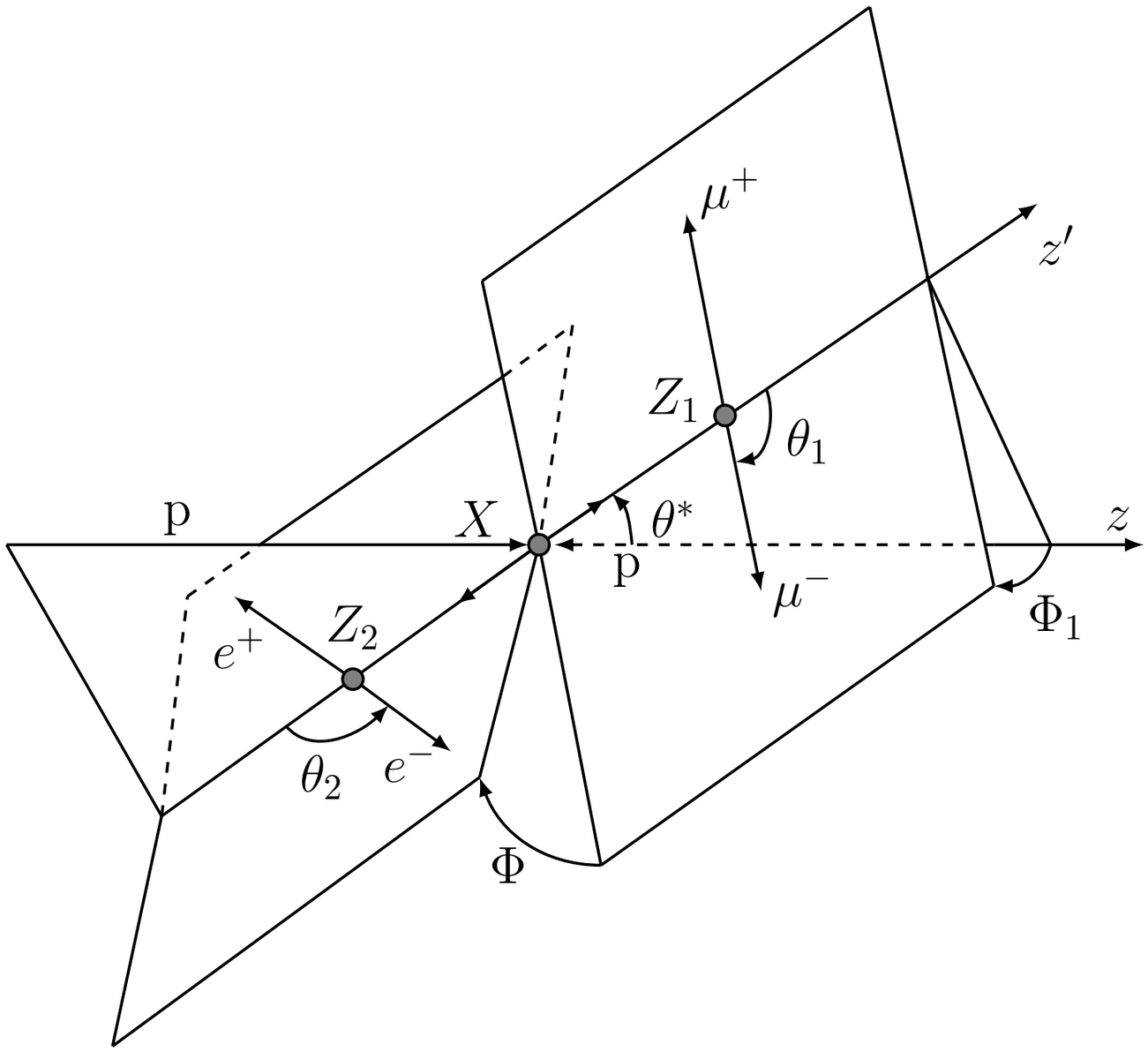
G. Aad *et al.* [ATLAS], "Combined measurements of Higgs boson production and decay using up to 80 fb^{-1} of proton-proton collision data at $\sqrt{s} = 13$ TeV collected with the ATLAS experiment," Phys. Rev. D **101**, no.1, 012002 (2020) 2022


spin
γ
spin
spin
θ^*
g
g
H
γ
spin

Spin-0


spin
γ
spin
spin
θ^*
g
g
H
γ
spin

Spin-2



G. Aad *et al.* [ATLAS Collaboration], “Study of the spin and parity of the Higgs boson in diboson decays with the ATLAS detector,” Eur. Phys. J. C **75**, no. 10, 476 (2015)

H^0

$J = 0$

Mass $m = 125.25 \pm 0.17$ GeV (S = 1.5)
Full width $\Gamma = 3.2^{+2.8}_{-2.2}$ MeV (assumes equal on-shell and off-shell effective couplings)

H^0 Signal Strengths in Different Channels

Combined Final States $= 1.13 \pm 0.06$
$WW^* = 1.19 \pm 0.12$
$ZZ^* = 1.01 \pm 0.07$
$\gamma\gamma = 1.10 \pm 0.07$
$c\bar{c}$ Final State $= 37 \pm 20$
$b\bar{b} = 0.98 \pm 0.12$
$\mu^+\mu^- = 1.19 \pm 0.34$
$\tau^+\tau^- = 1.15^{+0.16}_{-0.15}$
$Z\gamma <$ 3.6, CL = 95%
$\gamma^*\gamma$ Final State $= 1.5 \pm 0.5$
$t\bar{t}H^0$ Production $= 1.10 \pm 0.18$
tH^0 production $= 6 \pm 4$
H^0 Production Cross Section in pp Collisions at $\sqrt{s} = 13$ TeV $=$ 56 ± 4 pb