



Yale



U.S. DEPARTMENT OF
ENERGY

Office of
Science

Wright Lab Quantum Information Science in High Energy Physics

OKBaker, Yale-WL

8-April-2022

Wright Lab Quantum Sensing Workshop

Yale Quantum Week



Yale

Current Personnel



Wright
Laboratory



U.S. DEPARTMENT OF
ENERGY

Office of
Science

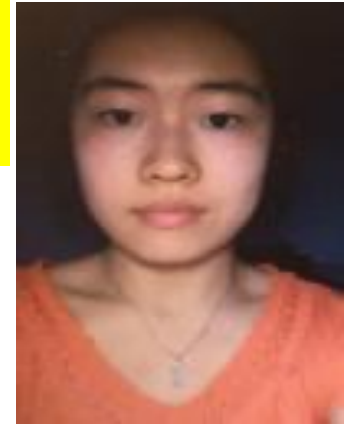


Daniel Qenani
Yale Undergraduate



Christian Weber
BNL Postdoc

Jingjing Pan
Yale Graduate
Student



Ryan Leong
Yale Graduate
Student

Argyris Manes
Yale Undergraduate



Kamal Benslama
LUM Professor



Theodota Lagourri
UTA Research
Scientist





Yale

Recent Past and Present



- Quantum Entanglement Quantum Information Science in High Energy Physics – **Christian Weber Lightning Talk**
- Unsupervised Quantum Machine Learning Algorithm in Higgs Boson Analysis – **Daniel Qenani Lightning Talk**
- Quantum Algorithm in Detector R&D for HL-LHC/ATLAS Inner Tracker Stave Core – **Argyris Manes Lightning Talk**
- Grover's Algorithm Applied to BSM Physics Search in Higgs Boson Decays to 4 leptons – **Anthony Armenakas (Harvard)**
- Quantum Entanglement in Higgs Boson Decays to 4 leptons at LHC/ATLAS



Yale



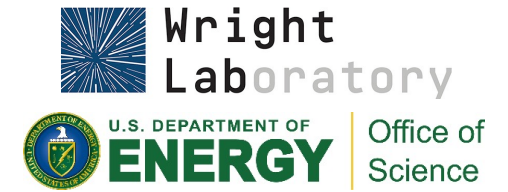
Quantum Entanglement in Higgs Boson Decays to 4 Leptons: Status

- OKB, Yale-WL
- 4-April-2022
- Wright Lab Quantum Sensing Workshop
- Yale Quantum Week



Yale

Overview



- Proposed Higgs boson decay to four leptons (electrons and muons)

$$H \rightarrow ZZ^* \rightarrow 4l$$

Reminder - spin and parity assignments

$$0^+ \rightarrow 1^- + 1^- \rightarrow 4 \times \frac{1}{2}$$

make use of all final states:

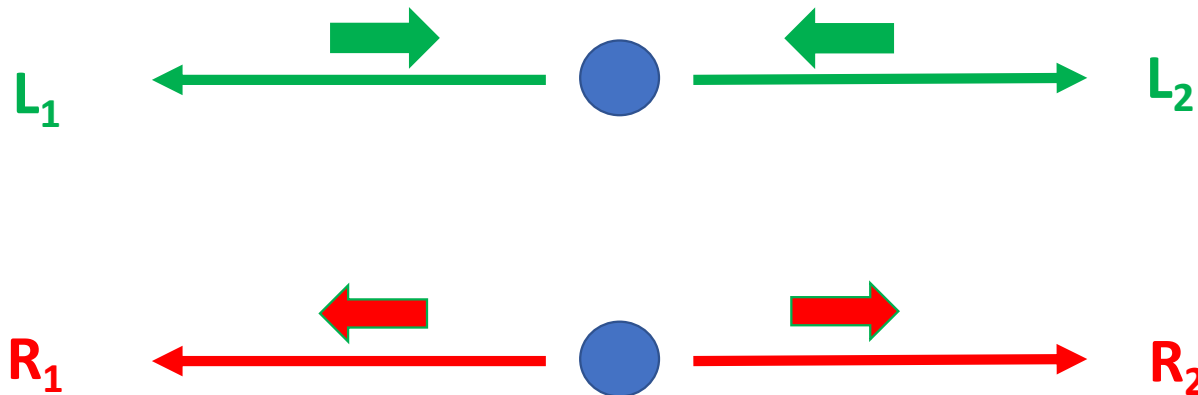
$$2e2\mu, 4e, 4\mu$$



Yale



Possible states of vector bosons emitted in decay



Three possible polarization states for the two vector bosons:
right-handed longitudinal and **left-handed longitudinal** (60%; shown)
and transverse (40%; not shown)



Yale



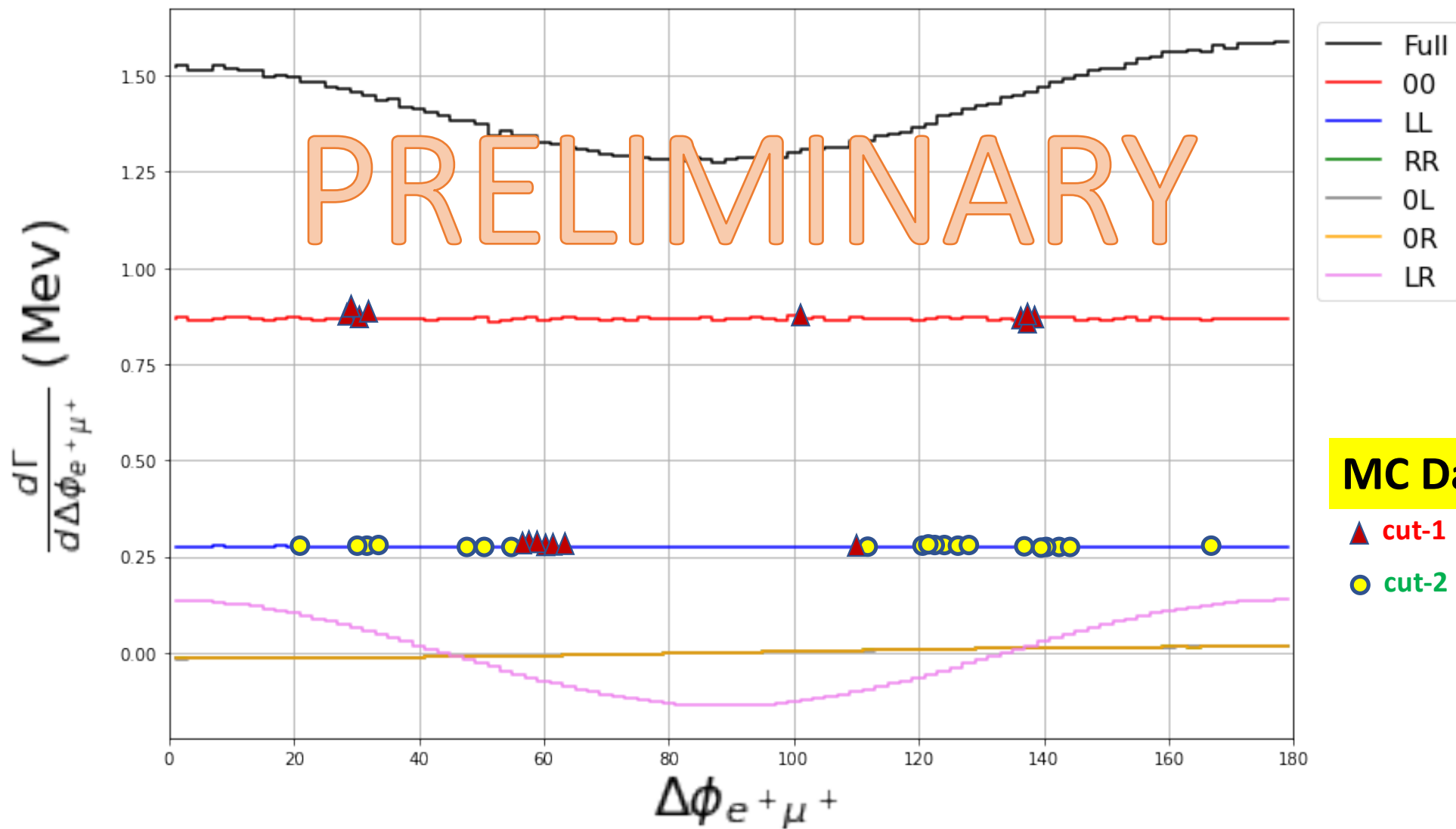
Consider the case of RR and LL handedness

$$\psi = \frac{1}{\sqrt{2}}[(R_1)(R_2) + (L_1)(L_2)]$$

- Both vector bosons linearly polarized
- Two separately distinct possibilities
- This correlation used to test Bell's Inequality
- Their total angular momentum sum to zero, as they must

1e-6

H → ZZ nocuts



MC Data

- ▲ cut-1
- cut-2



Yale

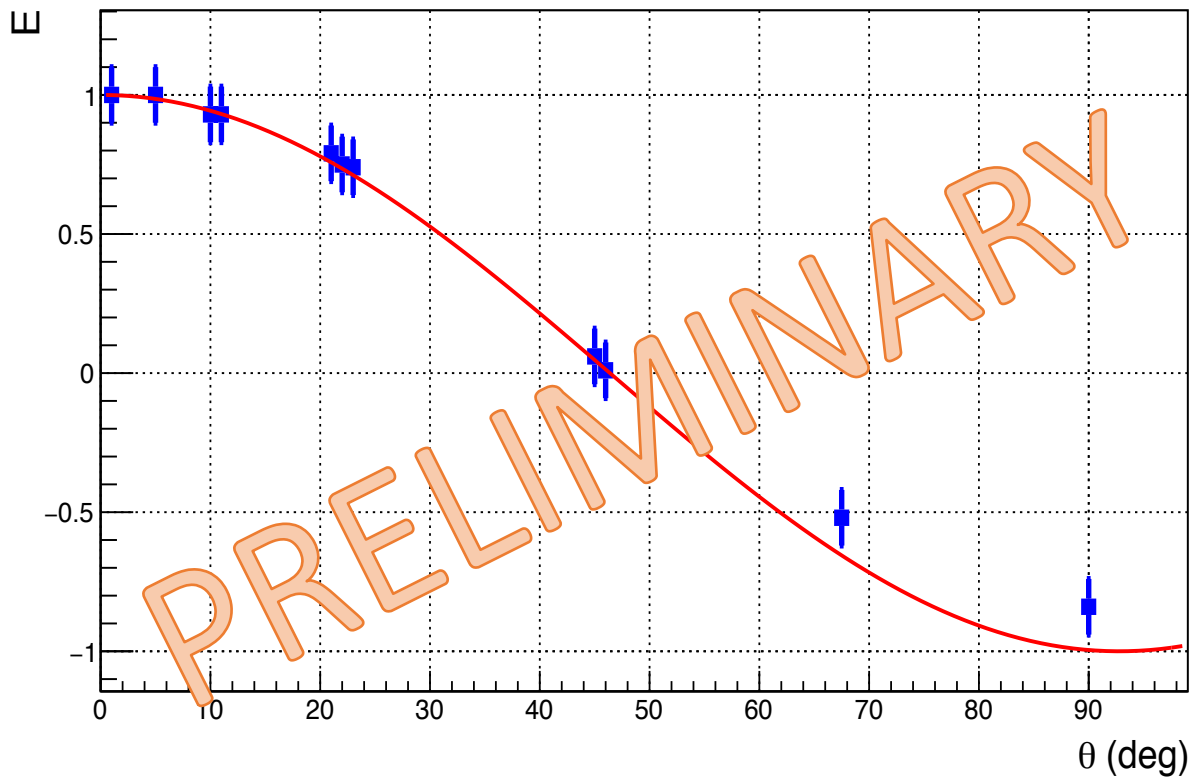


Wright
Laboratory



U.S. DEPARTMENT OF
ENERGY | Office of
Science

$H \rightarrow ZZ^* \rightarrow 4l$ MC analysis



A. Aspect results

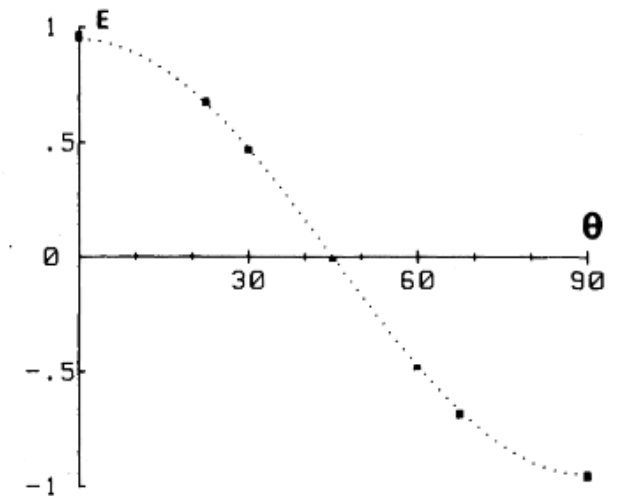


FIG. 3. Correlation of polarizations as a function of the relative angle of the polarimeters. The indicated errors are ± 2 standard deviations. The dotted curve is not a fit to the data, but quantum mechanical predictions for the actual experiment. For ideal polarizers, the curve would reach the values ± 1 .



Yale

Summary



• Testing Bell's Inequality with Higgs decays

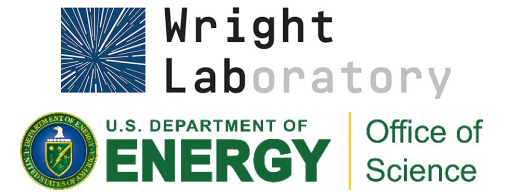
- Polarization analysis initial results
- Bell's inequality initial results
- Applications (future presentation)

• Application

- $H \rightarrow Z^* Z_d \rightarrow 4l$ for $Z_1\text{-mass} = Z_2\text{-mass}$ (60.0-65.0 GeV)
- $H \rightarrow Zq$
- **Di-Higgs \rightarrow 8 leptons?**
- ...



Yale

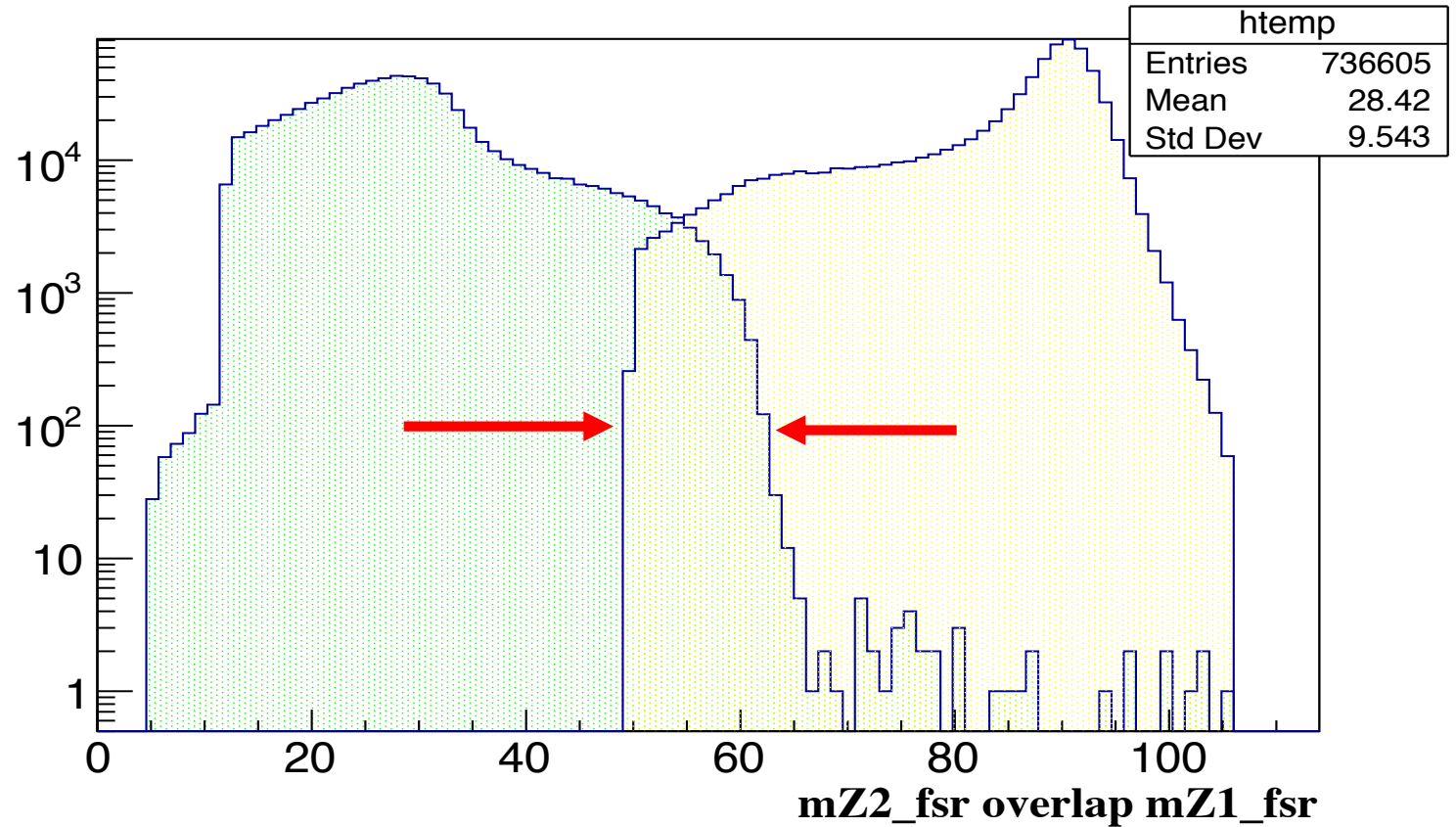


Backup

MC16

m_{Z1} and m_{Z2}
overlap region

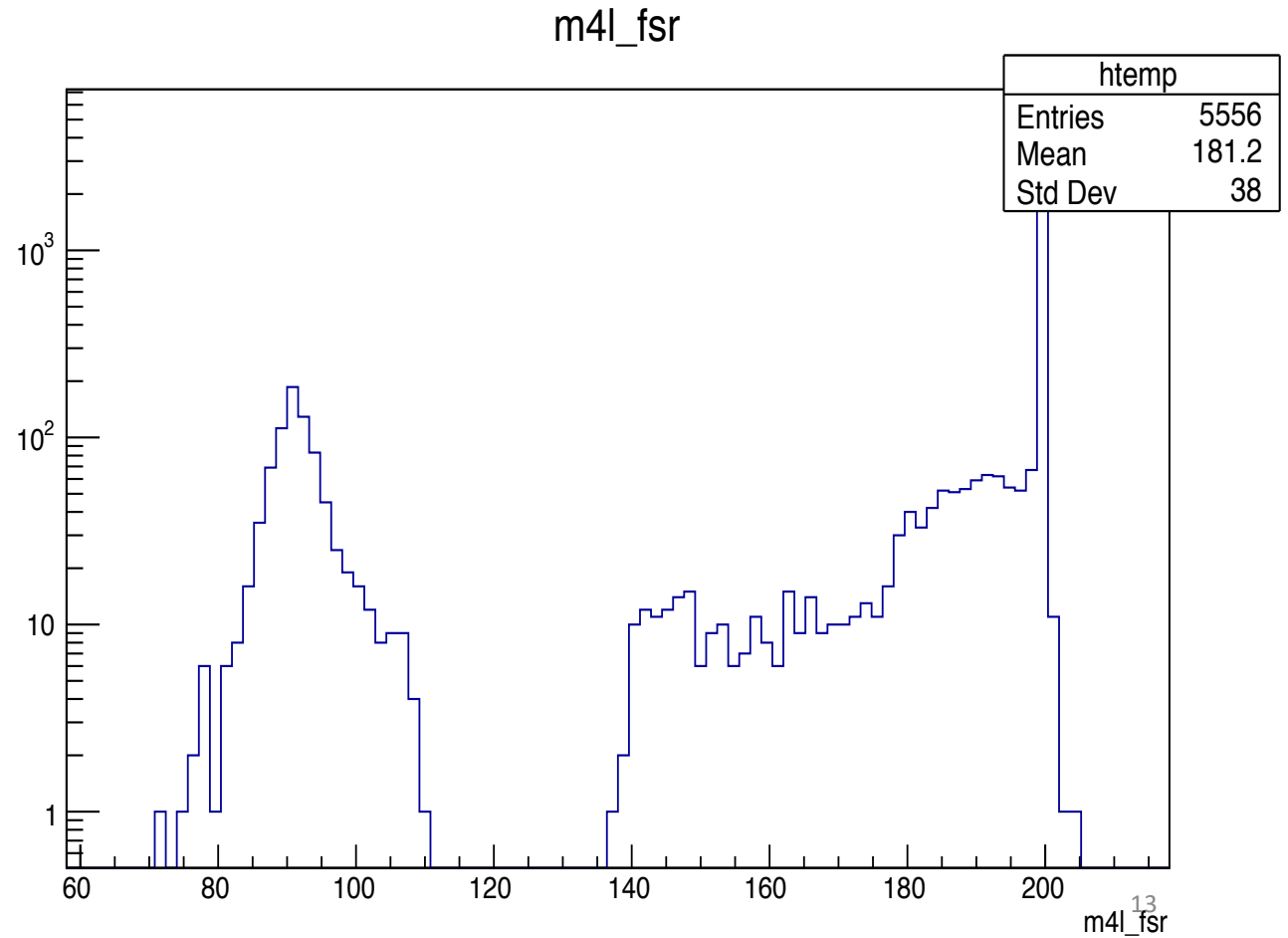
combined
mass
 $119 < m < 131$
GeV



Run2 actual collision data

Higgs boson mass
region excluded

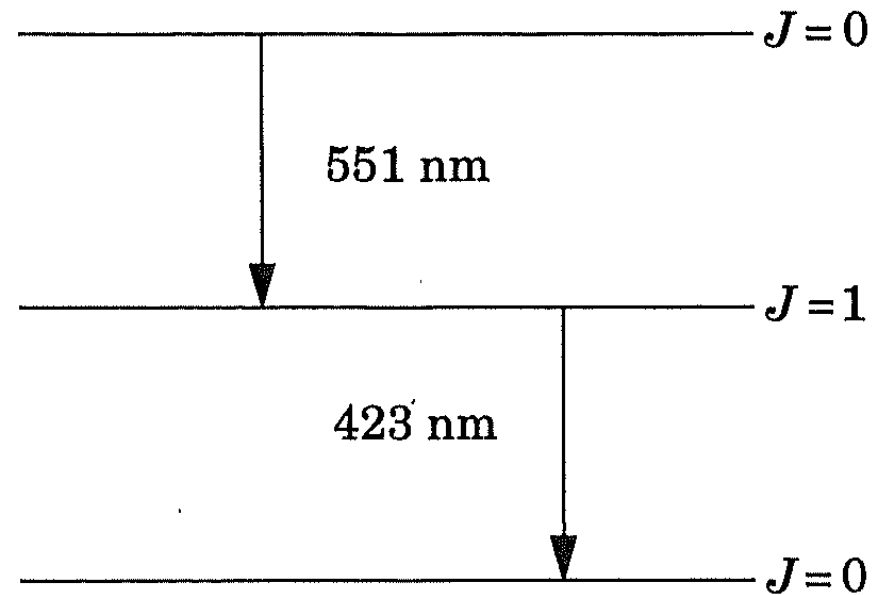
signal region excluded
“blind analysis”



Alain Aspect experiment for comparison

Atomic physics

Energy levels in Calcium showing states used in production of entangled pairs of photons



$m = 1$ or -1

Aspect paper

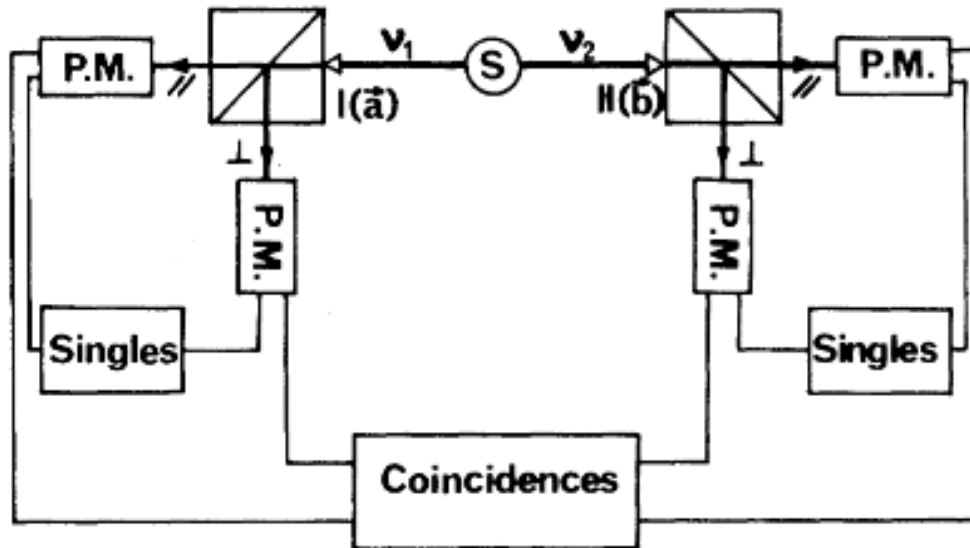
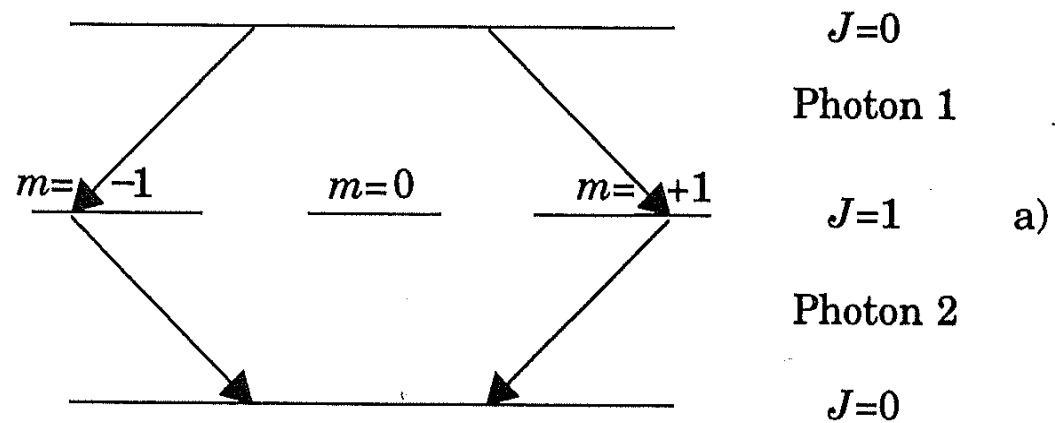


FIG. 2. Experimental setup. Two polarimeters I and II, in orientations \vec{a} and \vec{b} , perform true dichotomic measurements of linear polarization on photons ν_1 and ν_2 . Each polarimeter is rotatable around the axis of the incident beam. The counting electronics monitors the singles and the coincidences.



decay can pass through either of the two intermediate $J=1$ states, as illustrated.