Discovery of the tau lepton

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Outline

- World in 1974
- Motivation to look for third generation leptons
- Discovery of the tau lepton
  - Mark I detector at SPEAR e+e- collider
  - Physics analysis
- Confirmation of tau discovery
- Tau research today

World in 1974

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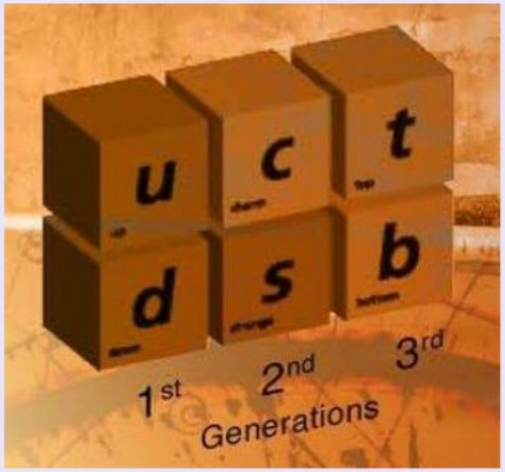
THE DISCOVERY OF THE TOP QUARK

Lina Galtieri (LBNL)

- Historical review of particle discoveries.
- Cosmic Rays gave the first information about particles beyond the electron and the proton.
- 1955:the first accelerators were developed by Lawrence, here at Berkeley(pbar discovered)
- 1960:the Hydrogen Bubble Chamber developed by L. Alvarez at LBL, allowed finding many particles.
- 1964: Gell-Mann and Zweig developed the quark model SU(3) Symmetry) to explain the existence of these particles.
- 1967-70 Glashow, Weinberg and Salam proposed the Standard Model
- 1973 Neutral Currents were found.
- 1974: The J/psi, bound state of c-c quarks is found
- 1975: the tau lepton was observed, confirmed in 1977
- 1977: the bottom quark is found
- 1995 : the top quark is found



The building blocks of matter today.
u, d, s and t are the ones LBL contributed the most.

The discovery of the top Quark: Lina Galtieri, Feb 5-2020 1

Motivation for third generation of leptons

- Two leptons then:
  - Electron: m=0.5MeV, discovered in 1897
  - Muon: m=105MeV, discovered in 1937
- 1968-1974 time period
- The e-μ problem:
  - How does the muon differ from electrons?
  - Studies compared e-p vs. μ-p inelastic differential crosssections but did not show any anamolies. i.e. the muon interaction with hadrons was exactly similar to electron
  - Same is true for elastic scattering of e-p vs. μ-p
  - These results were not helpful in figuring out the differences between electron and muon
- Proposition(?):
  - May be there is another charged lepton out there that will explain what is different between electron, muon and this new lepton

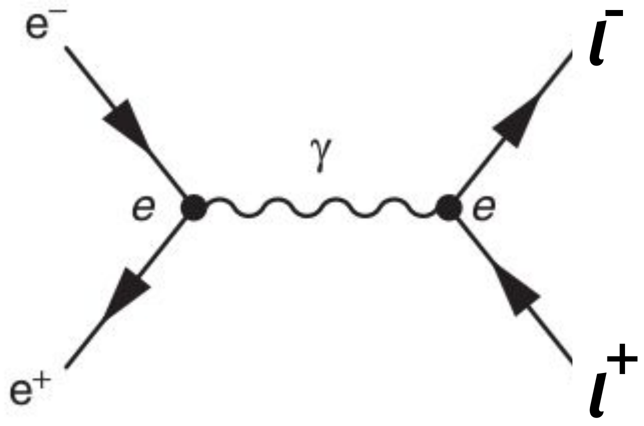
Varieties of leptons considered

- Sequential leptons (tau like lepton)
- Excited leptons
- Paraleptons
- Ortholeptons
- Long-lived particles
- Stable leptons

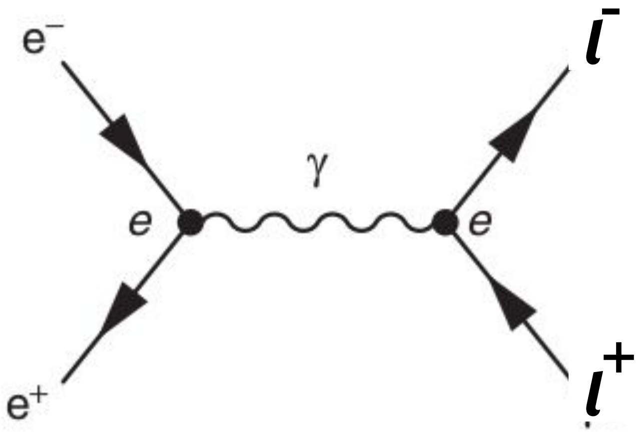
How to search for sequential leptons?

- Searches in particle beams
- Production of new leptons by e+e- annihilation
- Photoproduction of new leptons
- Production of new leptons in p - p collisions
- Searches in lepton bremsstrahlung
- Searches in charged lepton-proton inelastic scattering
- Searches in neutrino-nucleon inelastic scattering

Something like



e+ e- → γ →*l*+*l*-



$$\ell^- \rightarrow \nu_\ell + e^- + \bar{\nu}_e$$

$$\ell^- \rightarrow \nu_\ell + \mu^- + \bar{\nu}_\mu$$

- Final state:
  - $l^+ \rightarrow e^+$ + neutrinos and $l^- \rightarrow \mu^-$ + neutrinos
  - $l^+ \rightarrow \mu^+$ + neutrinos and $l^- \rightarrow e^-$ + neutrinos
- Advantages:
  - Allows search up to m_l = beam energy
  - Detecting e+μ- or e-μ+ with any missing energy would be dramatic
  - Clean final state with no other background

Theory and other calculations..

- Detailed calculations of cross sections and decay branching modes and ratios were available as of 1971.
- Refer to Phys. Rev. **D4** 2821 for detailed calculations

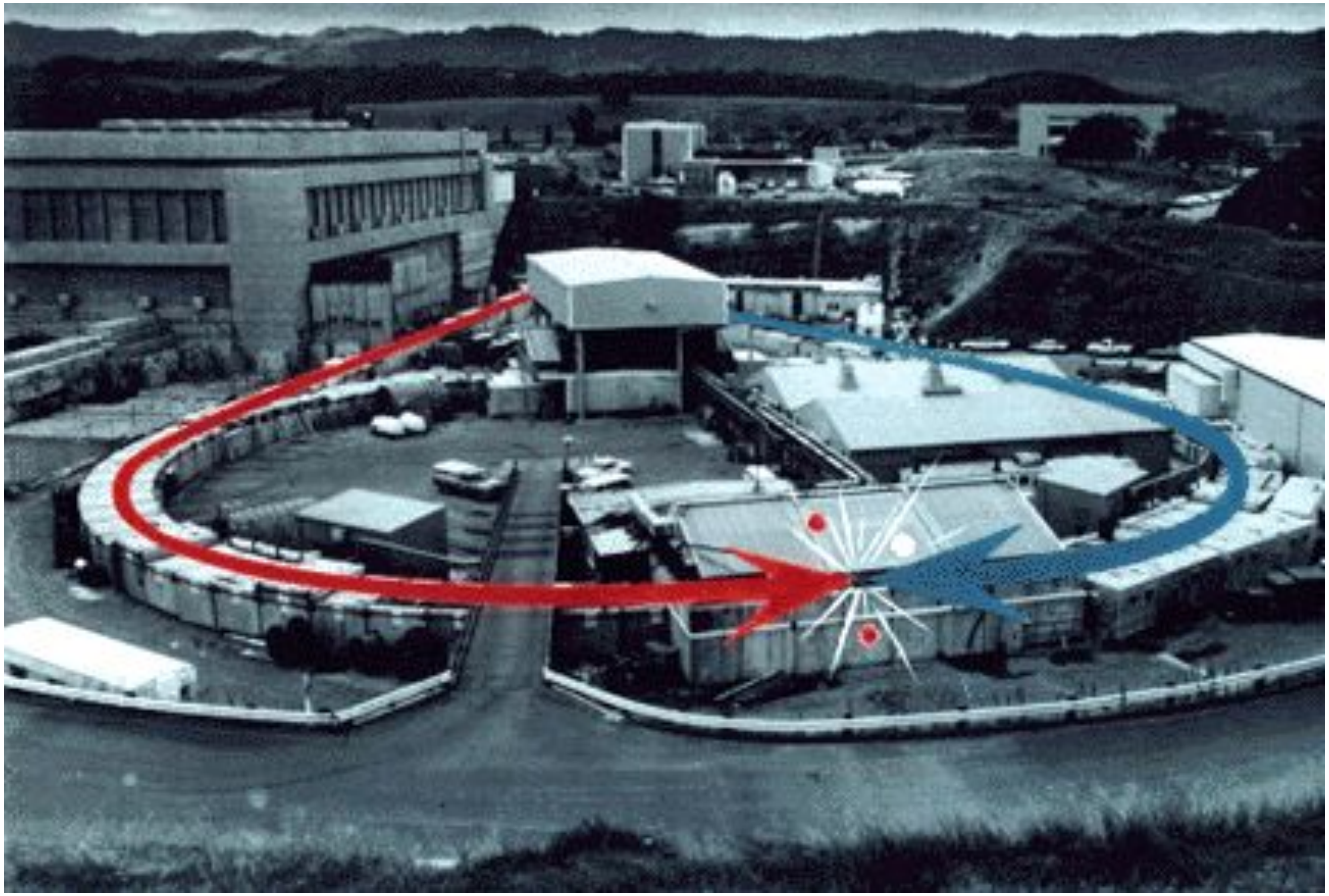
Theory and other calculations..

TABLE II. Partial and total decay rates of l for various values of M_l. Decay rate $(10^{10}\ \mathrm{sec}^{-1}) = (\Gamma/\hbar) = 1/\tau$.

M_l (GeV)	0.6	0.8	0.938	1.2	1.8	3.0	6.0
Decay mode							
$l \to \nu_l + \nu_e + e$	0.266	1.12	2.46	8.5	64.6	831	26 600
$\nu_l + \nu_\mu + \mu$	0.2	0.96	2.21	7.97	63	823	26 533
$\pi + \nu_l$	1.02	2.57	4.17	9.0	30	143	1145
$K + \nu_l$	0.0092	0.09	0.2	0.55	2.3	11.7	98
$\rho + \nu_l$	0	0.21	3.8	19	96	486	3900
$K^* + \nu_l$	0	0	0.03	0.96	6.3	33	280
$A_1 + \nu_l$	0	0	0	0.6	33.7	364	1550
$Q + \nu_l$	0	0	0	0	0.17	15.2	133
ν_l + hadron continuum	0	0	0	0.5	27	737	25 900
$l \to \nu$ + hadrons	1.03	2.87	8.2	29.6	195	1790	33 006
Total rate	1.5	4.95	12.9	46.1	323	3444	85 539
Decay length in cm at $E_l = 5$ GeV	16.5	3.73	1.2	0.26	0.024	...	...
Decay length in cm at $E_l = 50$ GeV	167	37.7	12.2	2.7	0.257	0.0145	...

The discovery story

- The tau lepton was discovered using MARK I detector at SPEAR accelerator, SLAC in 1975



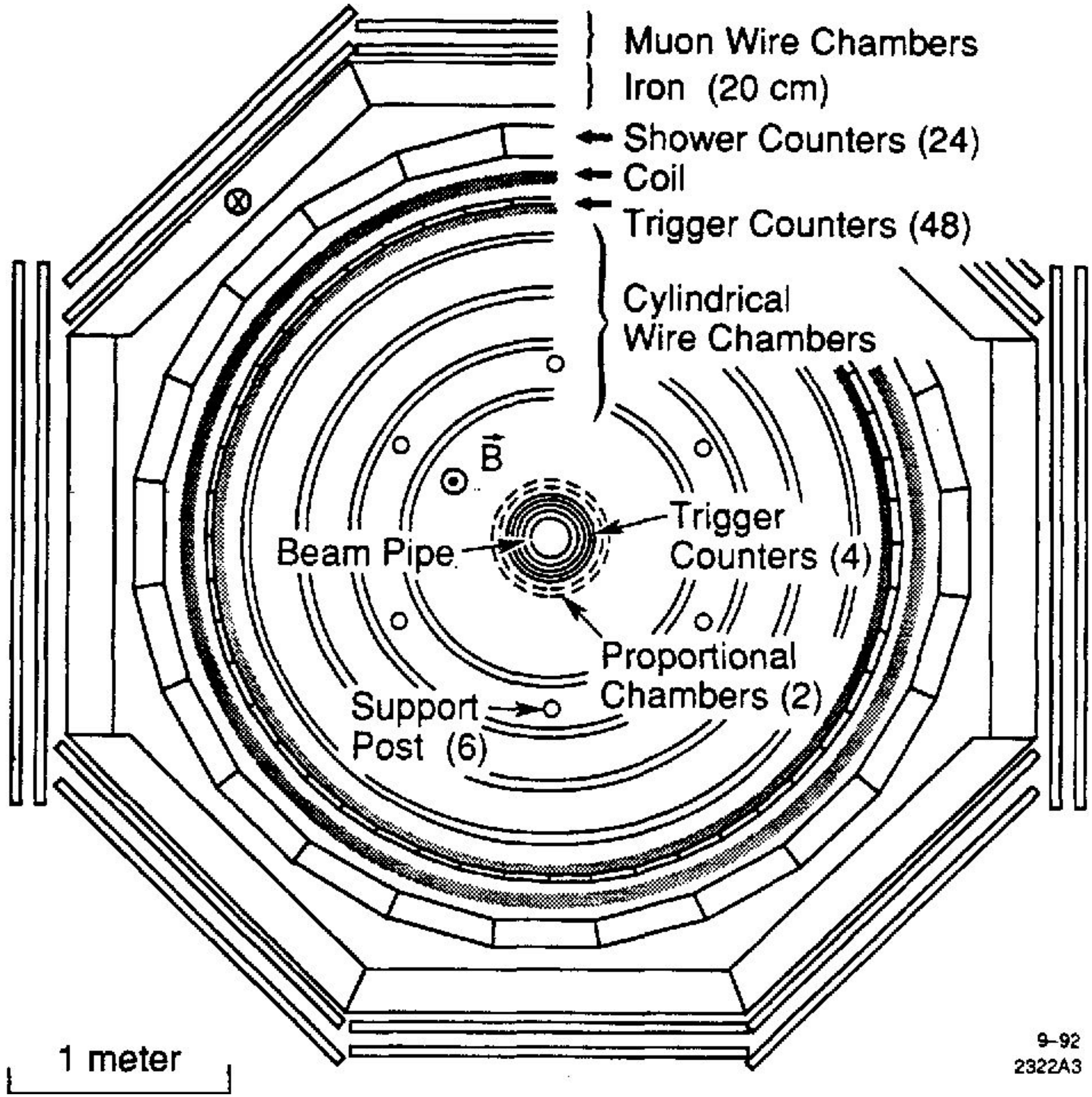
SPEAR accelerator

- SPEAR used to stand for Stanford Positron Electron Asymmetric Rings
- It consists of a ring - 80m in diameter
- Electrons and positrons were circulated at energies up to 4 GeV (The dataset used for tau lepton discovery was at center-of-mass energy of 4.8 GeV)
- Two outstanding discoveries at SPEAR:
  - J/ψ (charmonium) in 1974
  - Tau lepton in 1975
- Since 1990, SPEAR is exclusively used for s[illegible]on physics
- In fact it was the world's first synchrotron radiation laboratory

MARK I detector

- Also known as the SLAC-LBL Magnetic Detector
- First detector to have 4π hermetic coverage around the interaction point
- Made out of many layers of different subdetector systems - Much like today’s ATLAS and CMS
- Operational between 1973 - 1977
- J/ψ and tau lepton were discovered using this detector

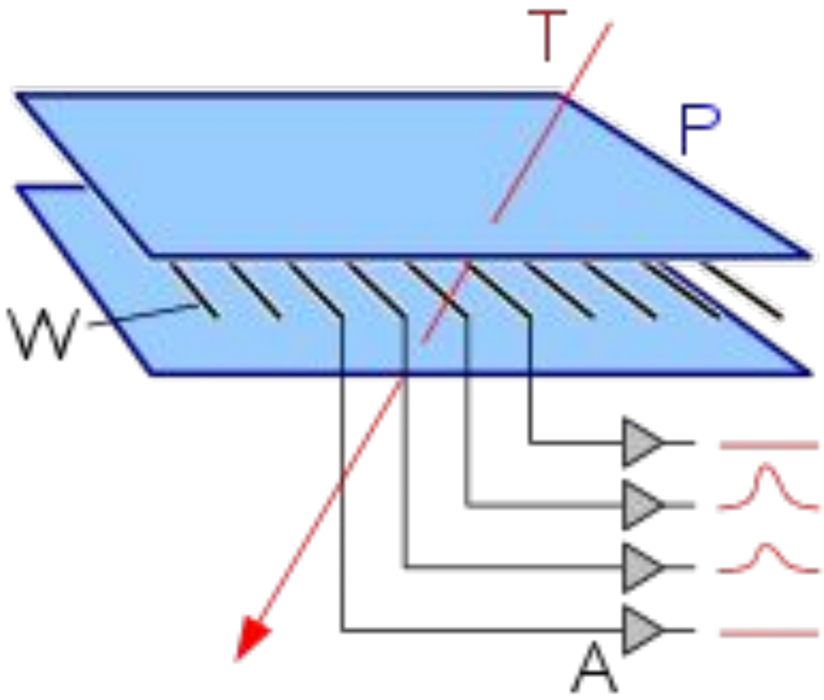
MARK I detector



Charged particle detection

- Charged particle detection:
  - Used a 1.5 meter radius solenoid with 0.4 Tesla magnetic field
  - Cylindrical multiwire proportional chambers and spark chambers measure momenta and trajectories of charged particles

- Modern parallels:
  - Magnetic field ~ 2-4 T
  - Resistive plate, drift and thin gap chambers (think ATLAS muon detector)



ECAL and muon systems

- Electromagnetic calorimeter:
  - 24 lead-scintillator shower counters
  - Election ID:
    - Require that the shower energy be at least 0.5 GeV
    - Electron position in shower is determined by comparing pulse heights on photomultipliers at the two ends
  - Modern parallel:
    - ATLAS Lead-LAr electromagnetic calorimeter
- Muon chamber:
  - 20 cm thick iron flux return provides magnetic field for muon detection system (similar to today's CMS experiment)
  - Spark chambers are used for muon identification

Object selection for the analysis

- Electrons:
  - Charged particle
  - Required to have large pulse heights in the shower counters in the calorimeter
  - No deposit in the muon chamber
- Muons:
  - Depost in the muon chambers
  - Shower counter pulse should be small
- Hadrons:
  - All other charged particles are hadrons
- Photons:
  - Neutral particle
  - Large shower counter pulse
- Neutrinos: Infer their presence using missing energy

Event selection

- Dataset:
  - center of mass energy = 4.8 GeV
  - 9550 three-or-more-prong events
  - A large(!) number of two prong events which include $e^+e^- \to e^+e^-$, $e^+e^- \to \mu^+\mu^-$, $e^+e^- \to$ two-prong hadrons and **$e^+e^- \to e^+\mu^-$, $e^+e^- \to e^-\mu^+$**
- Coplanarity angle $\Theta_{copl} > 20^o$

$$\cos\theta_{copl} = -(\underset{\sim}{n}_1 \times \underset{\sim}{n}_{e^+}) \cdot (\underset{\sim}{n}_2 \times \underset{\sim}{n}_{e^+}) / (|\underset{\sim}{n}_1 \times \underset{\sim}{n}_{e^+}| \; |\underset{\sim}{n}_2 \times \underset{\sim}{n}_{e^+}|) \qquad (2)$$

where $\underset{\sim}{n}_1$, $\underset{\sim}{n}_2$, $\underset{\sim}{n}_{e^+}$ are unit vectors along the directions of particles 1, 2, and the e^+ beam. The contamination of events from the reactions $e^+e^- \to e^+e^-$ and $e^+e^- \to \mu^+\mu^-$ is greatly reduced if we require $\theta_{copl} > 20^o$.

Event selection

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  - A large(!) number of two prong events which include e+e- → e+e- , e+e- →μ+μ- , e+e- → two-prong hadrons and **e+e- → e+μ- , e+e- → e-μ+**
    - Coplanarity angle Θ_{copl} > 20º to reduce e+e- and μ+μ- final states
    - After this cut, we have 2493 two-prong events
- Electrons and muons: p_T> 0.65 GeV
  - Electrons with pT<0.5 GeV are misidentified as pions >50% of the time due to small pulse height
  - Muons need at least pT>0.55 GeV to make it to the muon chamber
- Results in 513 two-prong events

513 two-prong events in categories

	Total Charge = 0			Total Charge = ± 2		
Number Photons =	0	1	> 1	0	1	> 1
ee	40	111	55	0	1	0
eμ	24	8	8	0	0	3
μμ	16	15	6	0	0	0
eh	20	21	32	2	3	3
μh	17	14	31	4	0	5
hh	14	10	30	10	4	6

Background?

- Data: 24 emu events observed
- Can this be explained by any other known process?
  - $e^+e^- \rightarrow e^+e^-\mu^+\mu^-$ is a possible source but it is negligible
    - Claim: No. of emu events from this source with charge=+/-2 should be the same as no. of events in charge 0 $e\mu$ (Why?)

Background?

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        - Claim: No. of emu events from this source with charge=+/-2 should be the same as no. of events in charge 0 eμ (Why?)
    - Hadron misidentification or decay
        - Use 9550 three-or-more prong events assuming each of e/μ was fake
        - Use $P(h\rightarrow b)$: probability of a fake lepton b from a hadron h. Note that this probability is momentum dependent.
        - Use the eh,μh and hh events in table on Slide 19 to get hadron momentum spectrum
        - Final result averaged over momentum: $P(h\rightarrow e)$=0.183+/-.007 and $P(h\rightarrow \mu)$ = 0.198+/-0.007

Background closure test

- Background estimation closure test:
  - To demonstrate that their misidentified backgrounds are estimated correctly, they apply same strategy to 1photon and >1photon category on Slide 19
  - Below table shows that the closure test works

	eμ 1 photon channel	eμ >1 photon channel
Predicted background (using same method)	5.6+/-1.5	8.6+/-2.0
Observed events	8	8

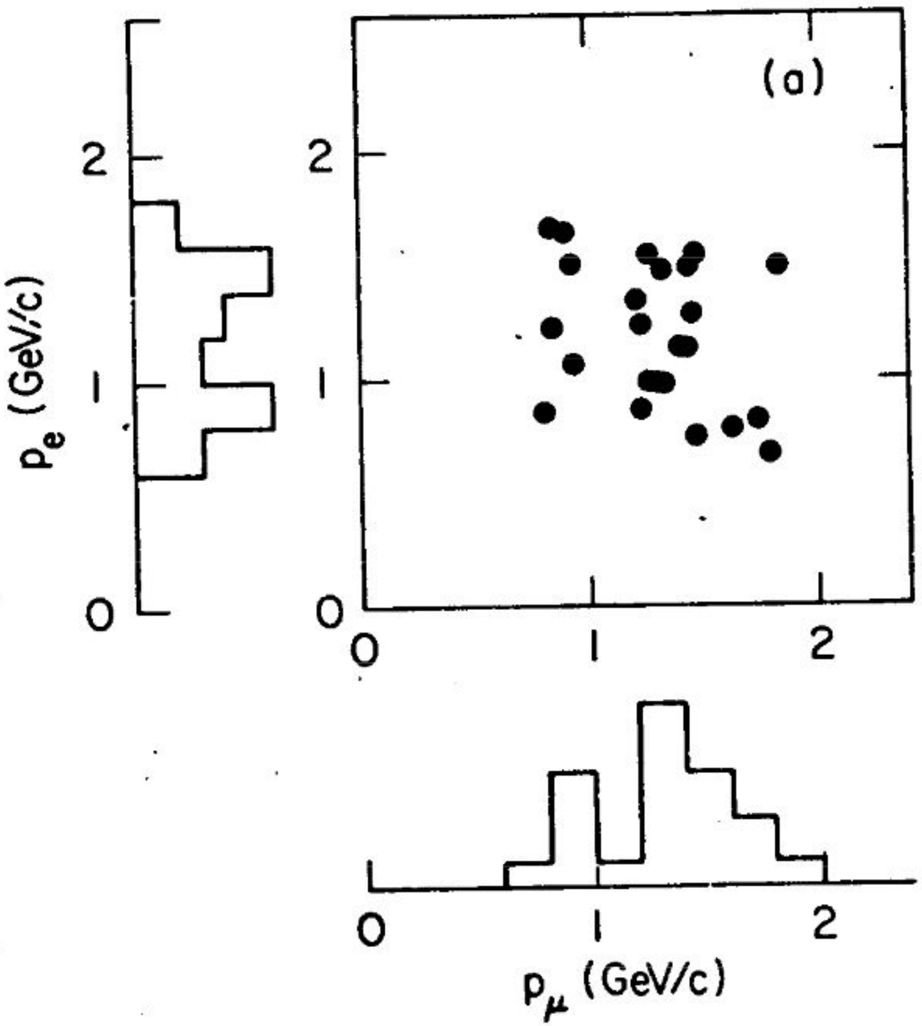
Final background yield

- Misidentified ee backgrounds 1+/-1
- Misidentified μμ backgrounds <0.3
- Misidentified hh backgrounds = 3.7 +/-0.6
- Total background = 4.7 +/-1.2

- Observed no. of events = 24
- S/sqrt(B) ~ 5.1

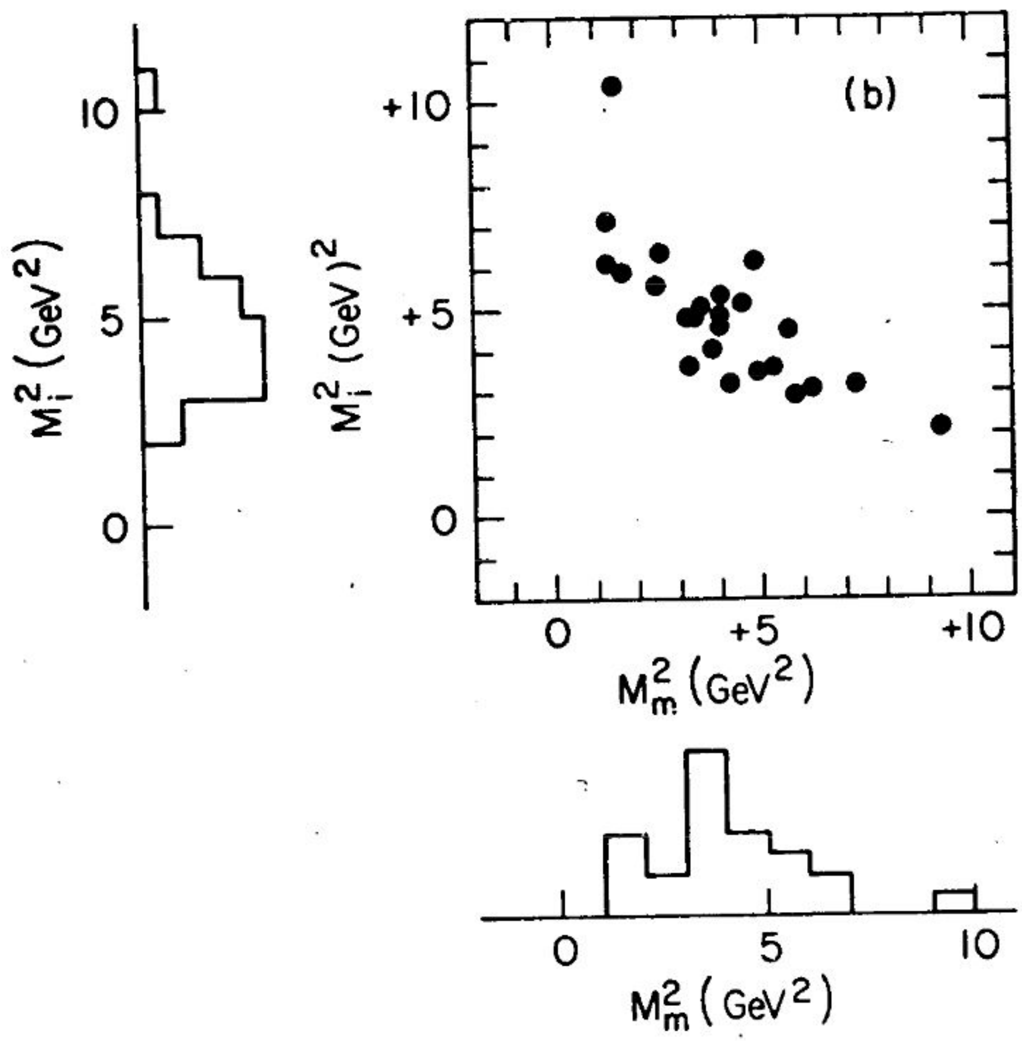
Event kinematics

- Electron and Muon momentum



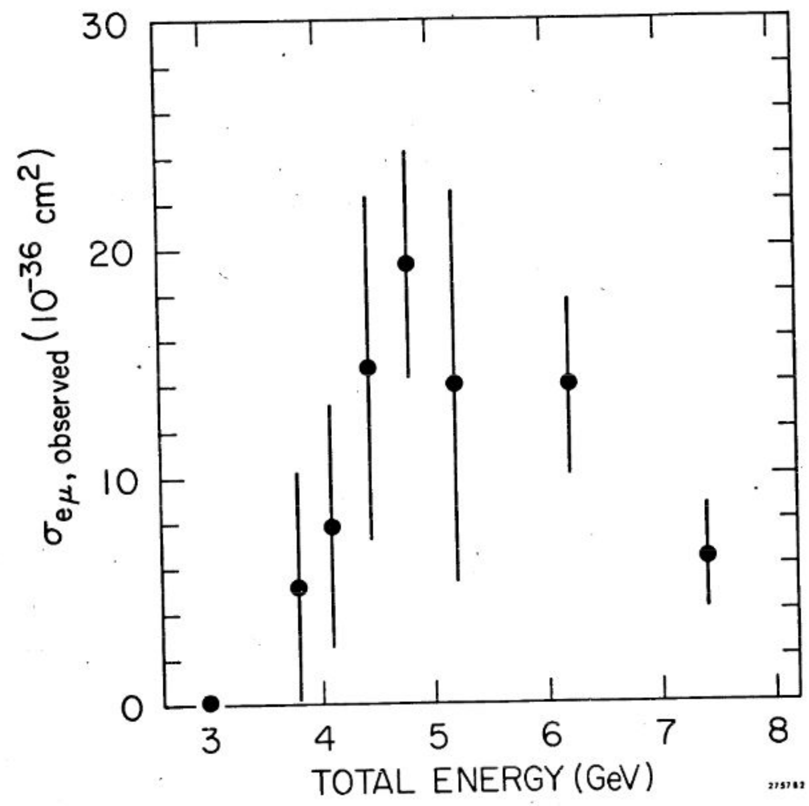
Invariant mass^2 vs. missing mass^2

- At least two particles escaped detection
- If it was only one particle, then we should see one peak in M_i^2
- In the paper, they note that this could be neutrons, K_L^0 mesons or neutrinos



Observed cross section vs. center-of-mass energy

- Integrating over all center-of-mass energies,
  - Total background = 22
  - Total events observed = 86
  - S/sqrt(B) ~ 4



What could this new signature be?

- One explanation provided was pair production of heavy charged leptons (taus)
- Other one:
  - Pair production of charged boson with decays

$$B^- \rightarrow e^- + \bar{\nu}_e,\ B^+ \rightarrow e^+ + \nu_e,\ B^- \rightarrow \mu^- + \bar{\nu}_\mu,\ B^+ \rightarrow \mu^+ + \nu_\mu.$$

  - Charm quark theories predict such bosons
  - They note that their mass (even if they exist) would probably be large enough that they won't see it at SPEAR

Tau lepton confirmation

- In 1977, it was confirmed that this excess was indeed from a tau lepton
  - Observed excesses in e/μ events coming from

$$\ell^- \rightarrow \nu_\ell + e^- + \bar{\nu}_e$$

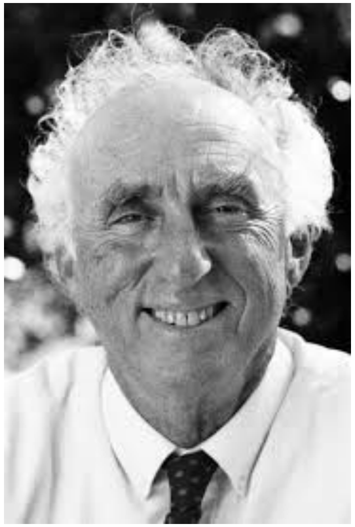
$$\ell^- \rightarrow \nu_\ell + \mu^- + \bar{\nu}_\mu$$

  - Excess in e-hadron events from

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

$$\tau^+ \rightarrow \bar{\nu}_\tau + e^+ + \nu_e$$

$$\tau^- \rightarrow \nu_\tau + \text{hadrons}$$



Tau research today

- Precision standard model physics
  - Example:
    - BR(Higgs $\rightarrow \tau^+ \tau^-$)~6%
    - Observed at ATLAS and CMS. Find the ATLAS result here
- Handle to search for beyond standard model physics
  - Given that taus are third generation leptons and the heaviest, it can be used to search for “new” physics
    - Example: Find a search for stau (scalar tau) particle predicted in many supersymmetric theories here

Summary

- Tau lepton was discovered in 1975 using MARK I detector at SPEAR (e+e- collider)
- Confirmation of tau lepton followed in 1977 with the observation of more of tau decay modes
- Resulted in a Nobel prize in 1995 for Martin Perl
- These days, taus are an excellent handle to probe precision Standard Model physics and also a great tool to search for beyond standard model physics

References

- Main reference: https://slac.stanford.edu/pubs/slacpubs/1500/slac-pub-1626.pdf
- Chapter 9 from "The experimental foundations of particle physics" by Robert Cahn and Gerson Goldhaber
- Theory calculations: Phys. Rev. **D4** 2821 available at https://journals.aps.org/prd/pdf/10.1103/PhysRevD.4.2821
- PDG: http://pdg.lbl.gov/2019/listings/rpp2019-list-tau.pdf
- Historical note: https://www.slac.stanford.edu/cgi-bin/getdoc/slac-pub-5937.pdf