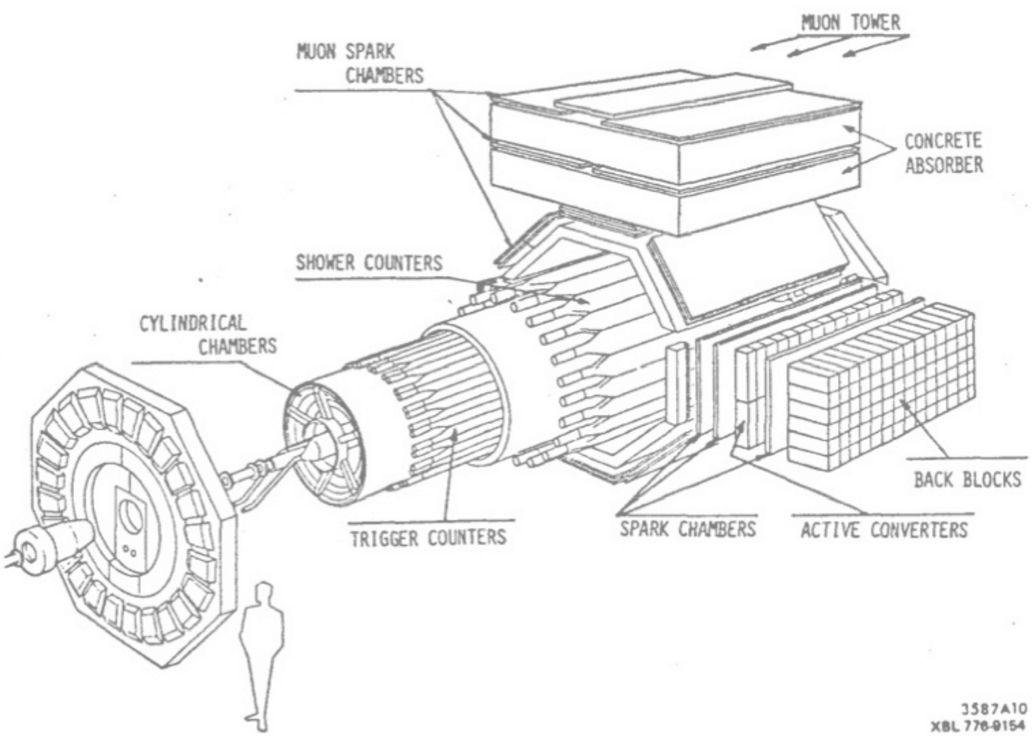
Discovery of the Tau Lepton



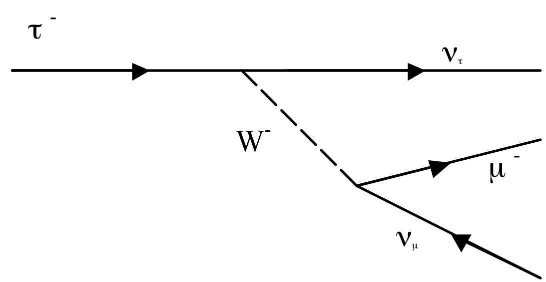
Curt Nehrkorn
Physics 145 Seminar
4/28/2010

Leptons before 1975

- "*e*-*μ* problem"
  - Searching for differences between *e* and *μ* by studying elastic/inelastic scattering with protons
- "sequential leptons"
  - Theory that there could be many leptons (and associated neutrinos) with different masses
- But until Perl's paper *Evidence for Anomalous Lepton Production in e^+e^- Annihilation* was published in 1975, there was no evidence supporting the existence of heavier leptons

Theory and Motivation

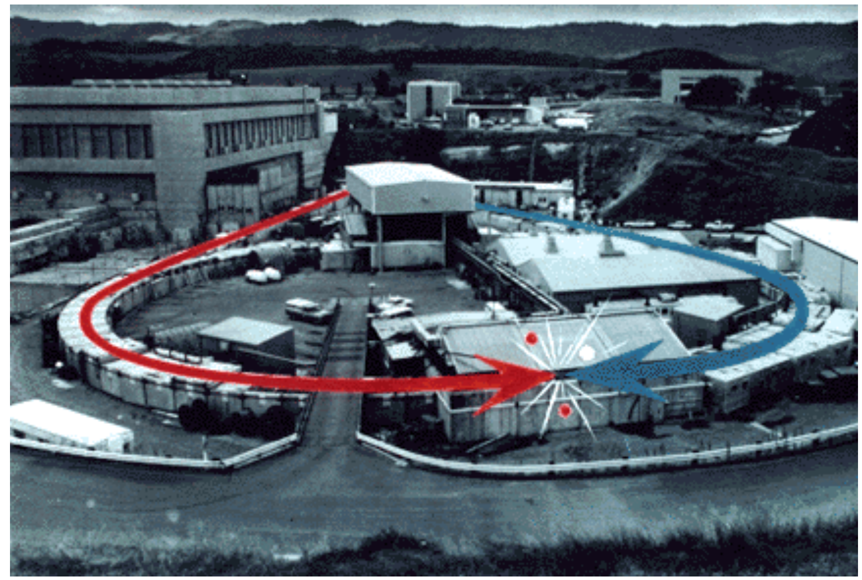
- Predicted reaction:
  - $e^+ + e^- \rightarrow \tau^+ + \tau^-$
  - Subsequent decay of τ:
    - $\tau \rightarrow \mu + \nu_\mu + \nu_\tau$ OR $\tau \rightarrow e + \nu_e + \nu_\tau$

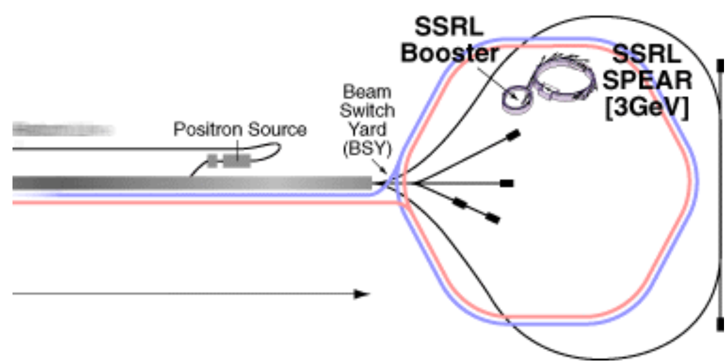


    - These predictions based on analogous decays of the muon, not on rigorous theoretical requirements
- To find these events, need a collider…

The Collider: SPEAR

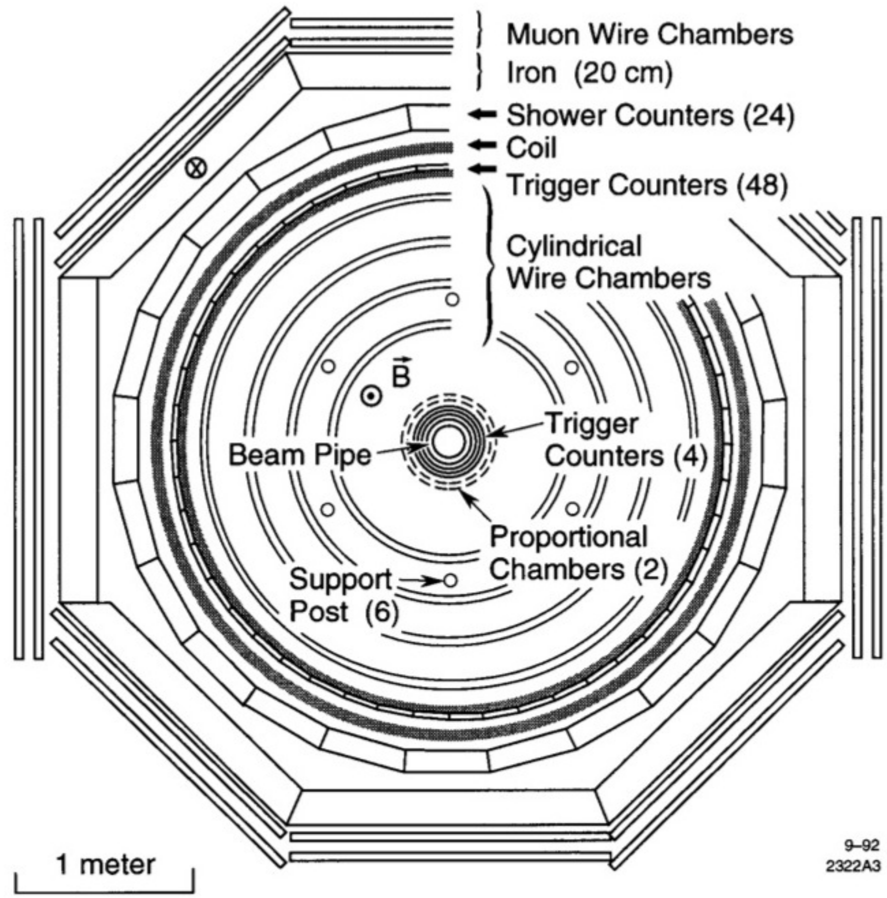
- Standford Positron Electron Accelerating Ring
  - Source: SLAC linac
  - Built in parking lot
  - SPEAR stored and circulated beams of electrons and positrons in opposite directions
  - The ring was ~80 m in diameter, eventually achieved 4 GeV per beam
  - The ring had two interaction points: one for specialized experiments, the other for the main detector





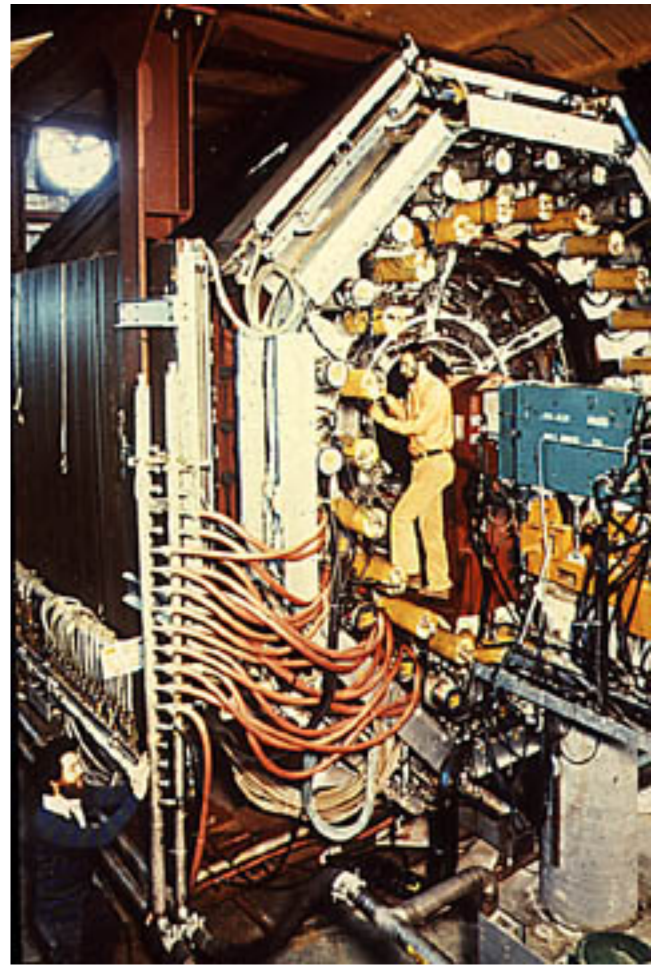
SLAC-LBL Magnetic Detector

- Mark I Detector
  - First of its kind in many ways, especially in terms of solid angle coverage
  - Solenoid produced nominal field of 4 kG in beam direction for momentum calculations
  - Iron flux return and endcaps produce enclosed, uniform field
  - Flux return also doubled as a hadron filter (~1.7 radiation lengths of thickness)



SLAC-LBL Magnetic Detector

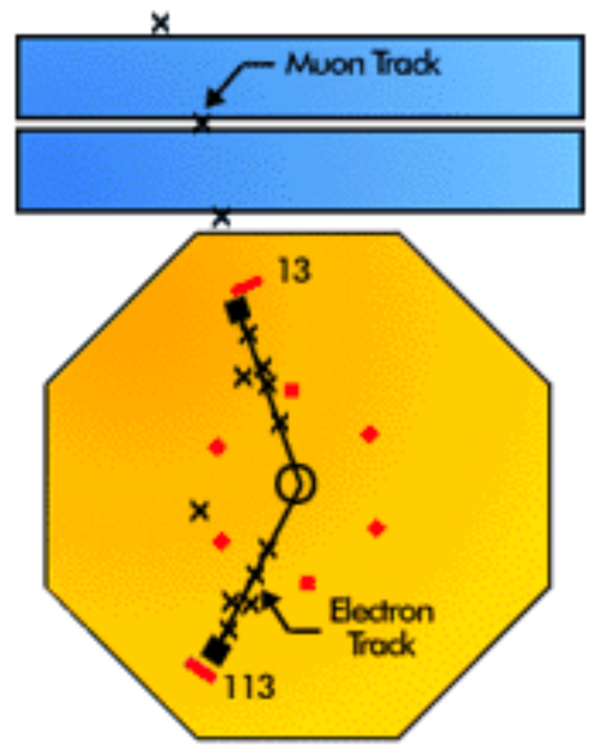
- Calorimetry:
  - 24 shower counters, lead-scintillator sandwiches
  - Pulse height corresponds to energy of particle
- Tracking:
  - Mulitple layers of counting and tracking chambers
- Muon Chambers
  - Wire spark chambers



The Experiment

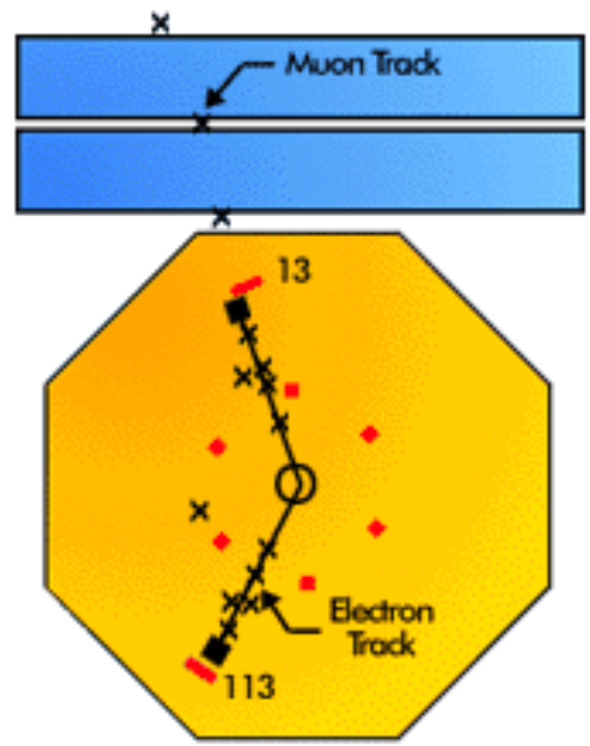
- Event of interest:
  - $e^+ + e^- \rightarrow \tau^+ + \tau^- \rightarrow \mu^+ + e^- +$ neutrinos

  (or $\tau^+ + \tau^- \rightarrow \mu^- + e^+ +$ neutrinos)
- In detector, would measure only electron and muon plus missing energy
- So the signature event involves:
  - 1*e* and 1 μ
  - Missing energy characteristic of at least 2 unidentified particles



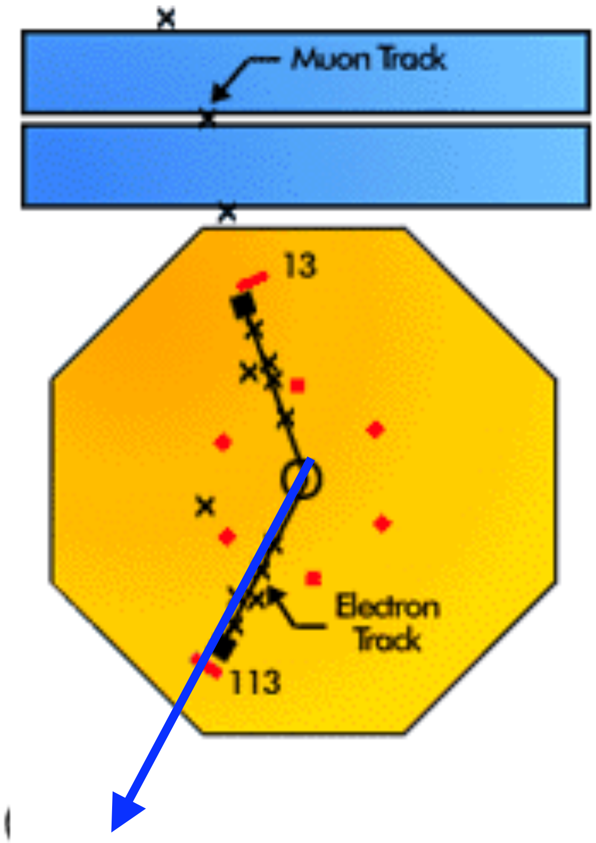
Particle Identification

- Perl only considered "two-pronged" events, i.e. events with only two showers in the calorimeter
  - Electrons identified by requiring shower pulse height to be greater than that expected for 0.5 GeV *e*
  - Muons identified by requiring:
    - Hits in the muon chambers
    - Small pulse in the shower counter (muons are heavier than electrons, and therefore lose less energy to Brehmsstrahlung in the calorimeter.
- So Perl's first cut was two-pronged e - μ events



Coplanarity Angle

- Background processes:
  - $e^+ + e^- \longrightarrow e^+ + e^-$
  - $e^+ + e^- \longrightarrow \mu^+ + \mu^-$
    - In both, the two products will be coplanar with the beam axis by conservation of momentum
  - To filter out these events, Perl made the cut $\theta_{copl} \geq 20°$



$$\cos\theta_{\text{copl}} = -(\vec{n}_1 \times \vec{n}_{e^+}) \cdot (\vec{n}_2 \times \vec{n}_{e^+}) / |\vec{n}_1 \times \vec{n}_{e^+}||\vec{n}_2 \times \vec{n}_{e^+}|,$$

where $\vec{n}_1$, $\vec{n}_2$, and $\vec{n}_{e^+}$ are unit vectors along the directions of particles 1, 2, and the e^+ beam.

The Data

TABLE I. Distribution of 513 two-prong events, obtained at $E_{c.m.} = 4.8$ GeV, which meet the criteria $|\vec{p}_1| > 0.65$ GeV/c, $|\vec{p}_2| > 0.65$ GeV/c, and $\theta_{copl} > 20°$. Events are classified according to the number N_γ of photons detected, the total charge, and the nature of the particles. All particles not identified as e or μ are called h for hadron.

Particles \ N_γ	0	1	>1	0	1	>1
	Total charge = 0			Total charge = ±2		
e-e	40	111	55	0	1	0
e-μ	24	8	8	0	0	3
μ-μ	16	15	6	0	0	0
e-h	20	21	32	2	3	3
μ-h	17	14	31	4	0	5
h-h	14	10	30	10	4	6

- In his paper, Perl presents a data sample with E_{CM} = 4.8 GeV
  - To ensure particle ID accuracy, a 0.65 GeV/c cut was made on the particle momenta
  - Out of 513 two-prong events that passed the cuts, 24 were *e*-*μ* events.
  - In all of these events, the calculated position of *e* in the shower counter matches the measured *e* track, indicating that there is no misidentification of *e*
  - The hadron background was calculated to be 4.7±1.2 events, well under the measured number

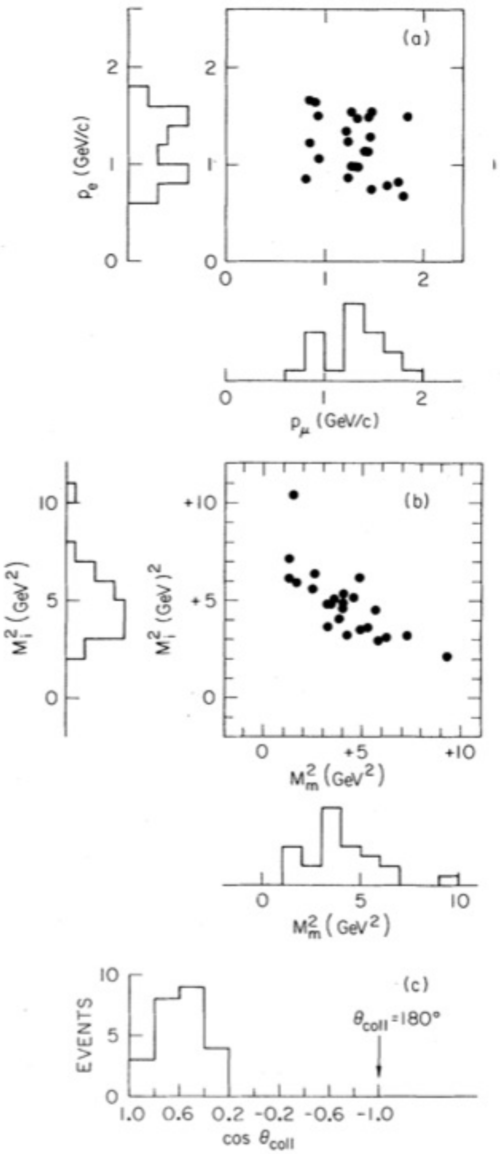


FIG. 1. Distribution for the 4.8-GeV e-μ signature events of (a) momenta of the e (p_e) and μ (p_μ); (b) square of the invariant mass (M_i^2) and square of the missing mass (M_m^2); and (c) $\cos\theta_{coll}$.

The Data

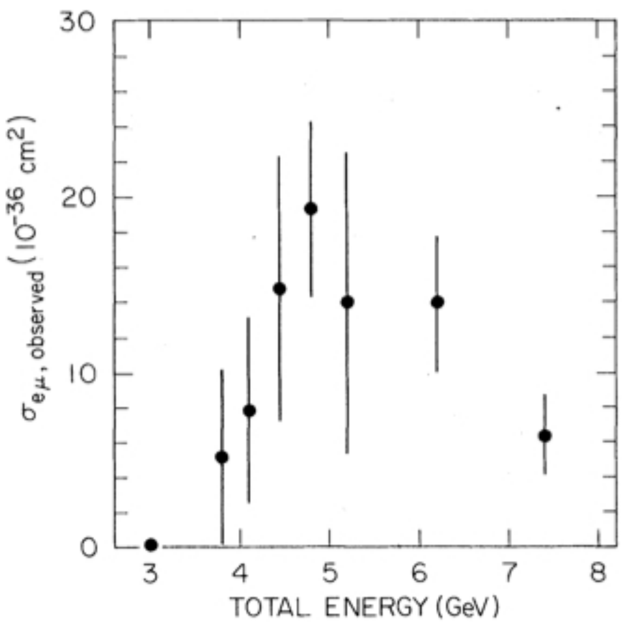
Missing energy vs. invariant mass

- There is a general trend, but points are not restricted to the trend line
- From this, Perl deduces existence of least two undetected particles (similar to neutron decay and the variable KE of electron as a result of neutrino missing energy)

θ_{coll} : "collinear angle" between trajectories of e and μ

Conclusion and Significance

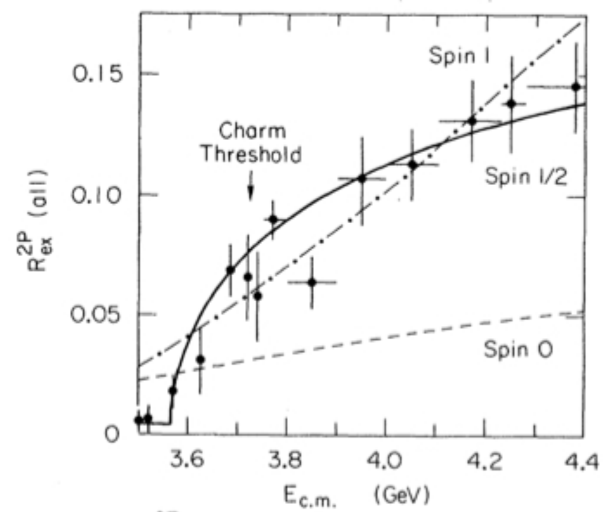
- Summing over all the energy samples gives a crude estimate for the mass of the anomalous particles:
  - 1.6 - 2.0 GeV/c^2
- However…
  - The particle is not necessarily the lepton!



In the beginning of the paper, Perl acknowledges that the events being studied might *not* be heavy lepton pair production and decay, but instead be pair production of some charmed meson and subsequent decay
So in the end, Perl can only conclude that he's found *something* new

Future Study and Confirmation

- At the time of publication, Perl's paper generated a lot of excitement
  - Also, confusion over the validity/interpretation of the results
- By 1979…
  - Discovery of tau events below energy threshold for charm events
  - Widespread discovery of other, expected tau decay modes
    - e.g. $\tau^- \rightarrow \pi^- + \nu_\tau$
  - Tau discovery verified!!



Sources

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