Outline of classical experiment #1:
TEST QED in the time-like region in 1966
(designed by a German physicist Yost)

1. Physics:
a. Significance: **TEST QED in time-like region with large e^+e^- invariant masses**;
b. Unique signature: cross section ~ **$Z^2\,\Theta^{-7}$ for given e^+e^- invariant mass**.

2. What has been achieved so far? Two previous experiments found increasingly large deviations from the predictions of QED with increasing e^+e^- invariant masses

3. Design consideration:
a. The source: high-energy photons, produced by higher energy electrons, collide with targets of large nuclear charge Z, to coherently produce **e^+e^- pairs**
b. Detector design: since **e^+e^- invariant mass $M^2 \sim 2\,p^2\,(1-\cos 2\,\Theta) \sim 4\,p^2\,\Theta^2$,**
$dM/M \sim dp/p + d\Theta/\Theta$' or $(dM/M)^2 \sim (dp/p)^2 + (d\Theta/\Theta)^2$+ a cross correlation term $dp\,d\Theta$, thus in order to measure M precisely, p and Θ should be independently precisely measured, to minimize the cross correlation term $dp\,d\Theta$. Use horizontal double arm spectrometer with Θ focusing, good mass resolution and excellent hadron rejection capability.
c. Θ focusing: let Bi and Li be the magnetic field strength (in kG) and length (m) of the ith magnet, $x\Theta$ and xi be the longitudinal coordinates of the ith magnet and the Θ detector along the central trajectory of the spectrometer and y be the corresponding perpendicular horizontal coordinate. Since
$y\Theta \sim \Sigma 30\ Bi\ Li/p\ (x\Theta - xi) + x\,\Theta$,
$y\Theta$ will be independent of p, i.e. achieving Θ focusing, if
$\Sigma\ 30\ Bi\ Li/p\ (x\Theta - xi) = 0$.
c. The measurable and the selection method. **Use Cherenkov counters separated by magnets, to achieve high electron ID efficiency.**

4. Background: There are four major types of background:
a. The forward production of electrons and photon, very intense, thus must be attenuated quickly, before they reach the detectors;
b. Photon emissions: detectors must be shielded from the large numbers of direct photon emitted at the target;
c. Pion pairs: use Cherenkov counters, separated by magnets, to reject pions and to achieve high electron ID efficiency.
d. Electrons (pairs) produced from the photon conversions in the spectrometer, etc.: use Cherenkov counters, separated by magnets, and shower counters to achieve high single electron ID efficiency.

5. **Signal:**

a. **Experimental signal:** measure $d\sigma/dM$ as a function of M, to compare with QED predictions.
b. **Intrinsic resolution:** $d\sigma/dM$ decreases rapidly with M, thus one must eliminate background, and unfold the smearing effect due to the mass resolution, before comparison with QED predictions.
c. **Detector resolution:**
$(dM/M)^2 \sim (dp/p)^2 + (d\Theta/\Theta)^2$; with $(dp/p) \sim 15 \text{ sqrt }(XR)/\Sigma\, 30\, B_i L_i$ and $d\Theta \sim 15 \text{ sqrt }(XR)/p$, where XR is the effective material thickness in unit of radiation length for all the material (target, He bags, Cherenkov counter windows and gas inside, detector thickness, etc.) in the spectrometer.

Outline of classical experiment #2:
J particle Discovery (1970-74)

1. Physics:

a. To search for narrow resonance in the **e^+e^-** mode.
b. Its unique signature: Breit-Wagner resonance form with very narrow width.
c. The unexpected discovery of the charmonium states established the notion of quarks being the fundamental building blocks of matter similar to the hydrogen spectrum established the atomic model.

2. What were known then? Broad vector mesons ρ, ω, ϕ were well established. Prof. S. Ting speculated that additional particles at higher masses might exist.

3. Kinematics: (by Harvard Prof. T.T. Wu)
Since the mass of a new particle was unknown, the signal to background ratio would be best for e^+e^- produced at 90 degree with respect to the beams in the the proton-nucleon center of mass frame. Thus the production angle Θ in the laboratory, would be artan(1/γ)~ 14.6 degee for 30 GeV proton beams at AGS of BNL, independent of the new particle mass.

4. Detector design (by Min Chen):

a. The source: high-energy protons collide with **targets of large ratio of A/Z, e.g. beryllium, to** produce **e^+e^-, pion-k pairs.**
b. The detector: **To further improve the momentum and thus the mass resolution, the bending of all magnets should be in the same direction to maximize their total bending power Σ 30 Bi Li /p. Again,** since e^+e^- invariant mass $M^2 \sim 2\,p^2\,(1-\cos 2\,\Theta) \sim 4\,p^2\,\Theta^2$, $dM/M \sim dp/p + d\Theta/\Theta$, or $(dM/M)^2 \sim (dp/p)^2 + (d\Theta/\Theta)^2$+ a cross correlation term dp dΘ , thus in order to measure M precisely, p and Θ should be independently precisely measured, to minimize the cross correlation term dp dΘ.
$(dM/M)^2 \sim (dp/p)^2 + (d\Theta/\Theta)^2$; with $(dp/p) \sim 15\ \mathrm{sqrt}\,(XR)/\ \Sigma\ 30\ Bi\ Li$ and $d\Theta \sim 15\ \mathrm{sqrt}\,(XR)/p$, where XR is the effective material thickness in unit of radiation length for all the material (target, He bags, Cherenkov counter windows and gas inside, detector thickness, etc.) in the spectrometer.

c. Instead of **Θ focusing, use vertical bending precision double arm spectrometer to measure Θ and p independently, i.e. Θ in the horizontal plane and p in the vertical plane to obtain good mass resolution.**

d. To eliminate the following six types of major background:

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i. The forward produced particles, especially neutrons, are very intense. They can not be attenuated quickly, before they reach the detector region. Therefore these forward produced particles should not be touched until they have well passed through the entire detector region and only then be buried deep inside concrete blocks;
ii. The particles produced at intermediate angles (3 to 12 degrees) need to be attenuated, first using heavy metal (tungsten, uranium, iron, bronze, in this sequence) and then using concrete and finally using boron soap and water tanks to absorb slow neutrons.
iii. Photon emissions: detectors must be shielded from direct emissions of photon at the target using heavy metals;
iv. Pion pairs: use Cherenkov counters inside magnets and separated by magnets, to reject pions, and to achieve high electron ID efficiency. MeV electrons may be knocked out by particles like pions or protons inside one Cherenkov counter, to trigger that Cherenkov counter and must be swept away before they trigger the next Cherenkov counter.
v. High energy pion pairs with momentum p, accompanied by electrons (energy E) produced, for example, from the photon conversions in the spectrometer can be eliminated by comparing the measured values of p versus p and their dE/dx values using a matrix of dE/dx (lead glass) counters and segmented shower counters to identify the electron and pion trajectories separately.
vi. Non-resonant continuous $\underline{\mathbf{e^+e^-}}$ pair production, which must be subtracted out using precisely measured mass spectrum $d\sigma/dM$.