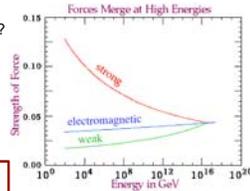


## If not the Standard Model, What?

- Standard Model predictions validated to high precision, however

Standard Model fails to answer many fundamental questions

- Gravity not a part of the SM
- What is the very high energy behaviour?
  - At the beginning of the universe?
  - Grand unification of forces?
- Dark Matter?
  - Astronomical observations indicate that there is more matter than we see
- Where is the Antimatter?
  - Why is the observed universe mostly matter?



Look for new physics that would explain these mysteries:  
SUSY, String Theory?

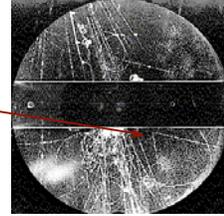
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## A Little History

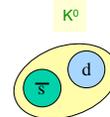
- Everything started with kaons

- Kaon: Discovered using a cloud chamber in 1947 by Rochester and Butler
- Could decay to pions and had a very long lifetime:  $10^{-10}$  sec



- Bound state of up or down quarks with a new particle: the strange quark!

- Needed the weak force to understand its interactions
- Neutral kaons were some of the most interesting kaons



Rich ground for studying new physics

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## Physics of Neutral Mesons

- New physics(at the time) of neutral particles and antiparticles
- $K^0$  and  $\bar{K}^0$
- Interacted differently with weak and strong force. Different allowed quantum states
  - Strong force: energy/mass of the particle
  - Weak force: how it decays

- The Schrödinger equation, equation that explains the mass/energy and decay of the particle

$$i \frac{\partial}{\partial t} \psi = \begin{pmatrix} M & M_{12} \\ M_{12}^* & M \end{pmatrix} - \frac{i}{2} \begin{pmatrix} \Gamma & 0 \\ 0 & \Gamma \end{pmatrix} \psi$$

- Difficult to understand, but this looks exactly like another physics system

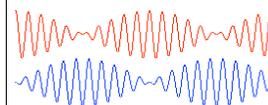
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## Classical Analogue

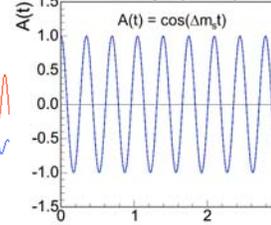
- Coupled spring system

- Start the system with one spring moving and over time it will evolve to a state where the other spring is moving.



Allowed Energy Quantum

Mixing Asymmetry



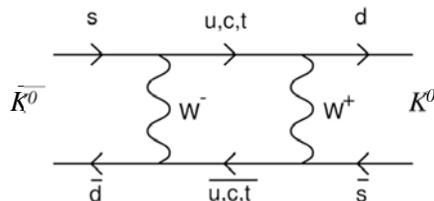
An oscillation or mixing from one state to the other

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## Why?

The Weak force is the cause!

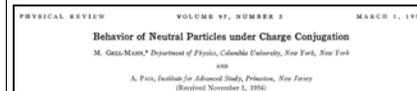


- The weak interaction is necessary to get from  $K^0$  to  $\bar{K}^0$
- The weak force provides the coupling between the states that leads to the oscillations

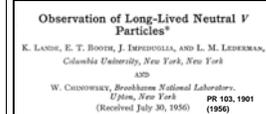
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## Neutral Kaons



1954: Mixing Predicted



1957: Mixing Observed

840 MHz



1980 Nobel Prize

1964: CP Violation Observed

CP violation: Something that happens differently for matter vs. antimatter

## B<sub>s</sub> and CKM Physics

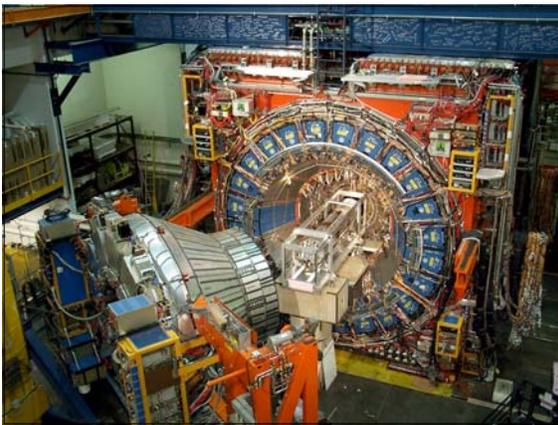
- CKM physics. All the parameters that tell how one type of quark decays to another.
- There are some relationships. For instance the top quark can decay to b, s and d so these must sum up to the total probability that the top quark decays. Relationships expressed as triangles. Below is the b quark triangle. Height of triangle gives the amount of CP violation.
- Mixing strength set by V<sub>ts</sub> parameter

M. Herndon, Pierini, et al.

## B<sub>s</sub> Oscillations

- With the first evidence of the B<sub>s</sub> meson we knew it oscillated fast.
  - How fast has been a challenge for a generation of experiments.

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## B<sub>s</sub> Mixing: Overview

- Measurement of the rate of conversion from matter to antimatter: B<sub>s</sub> ↔ B<sub>s</sub><sup>̄</sup>
  - Determine b meson flavor at production, how long it lived, and flavor at decay to see if it changed!

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## B<sub>s</sub> Mixing: A Real Event

- CDF event display of a mixing event

B<sub>s</sub> → D<sub>s</sub><sup>-</sup>π<sup>+</sup>, where D<sub>s</sub><sup>-</sup> → φπ<sup>-</sup>, φ → K<sup>+</sup>K<sup>-</sup>

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## B<sub>s</sub> Mixing: Signals and Tagging

- Fully reconstructed decays: B<sub>s</sub> → D<sub>s</sub><sup>-</sup>π<sup>+</sup>, three D<sub>s</sub><sup>-</sup> decays
- Also partially reconstructed decays: one particle missing, but can still tell how far the particle flew

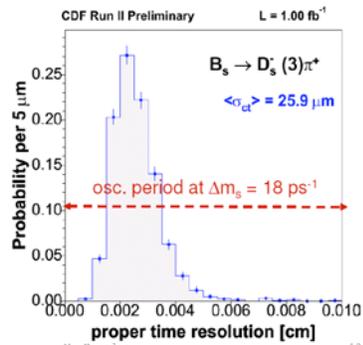
Decay	Candidates
B <sub>s</sub> → D <sub>s</sub> <sup>-</sup> π(2π)	5600
B <sub>s</sub> → D <sub>s</sub> <sup>-</sup> π <sup>+</sup> , B <sub>s</sub> → D <sub>s</sub> <sup>-</sup> ρ <sup>+</sup>	3100
B <sub>s</sub> → D <sub>s</sub> <sup>-</sup> X	61,500

Tag	Performance(εD <sup>2</sup> )
OST	1.8%
SST	3.7%(4.8%)

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## $B_s$ Mixing: Proper Time Resolution

- Measurement critically dependent on proper time resolution



M. Battistoni 13

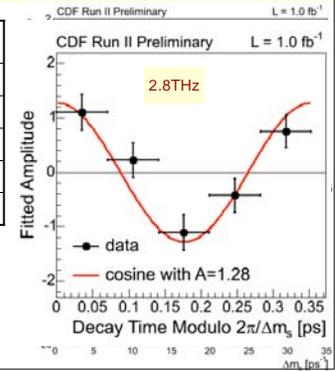
## $B_s$ Mixing: Results

Key Features	Result
Sen: 95%CL	31.3ps <sup>-1</sup>
Sen: $\sigma_A$ (@17.5ps <sup>-1</sup> )	0.2
$A/\sigma_A$	6
Prob. Fluctuation	$8 \times 10^{-8}$
Peak value: $\Delta m_s$	17.75ps <sup>-1</sup>

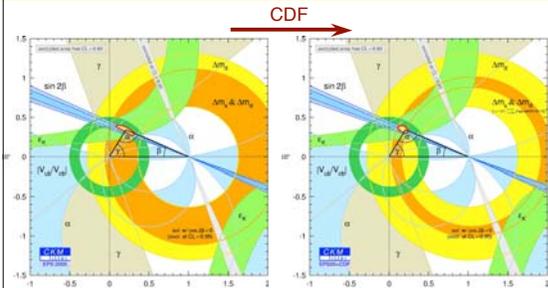
A >5 $\sigma$  Observation!

Submitted to PRL

Can we see the oscillation?



## $B_s$ Mixing: CKM Triangle



$$\Delta m_s = 17.77 \pm 0.10 \text{ (stat)} \pm 0.07 \text{ (syst)} \text{ ps}^{-1}$$

No SUSY or String Theory Here.

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