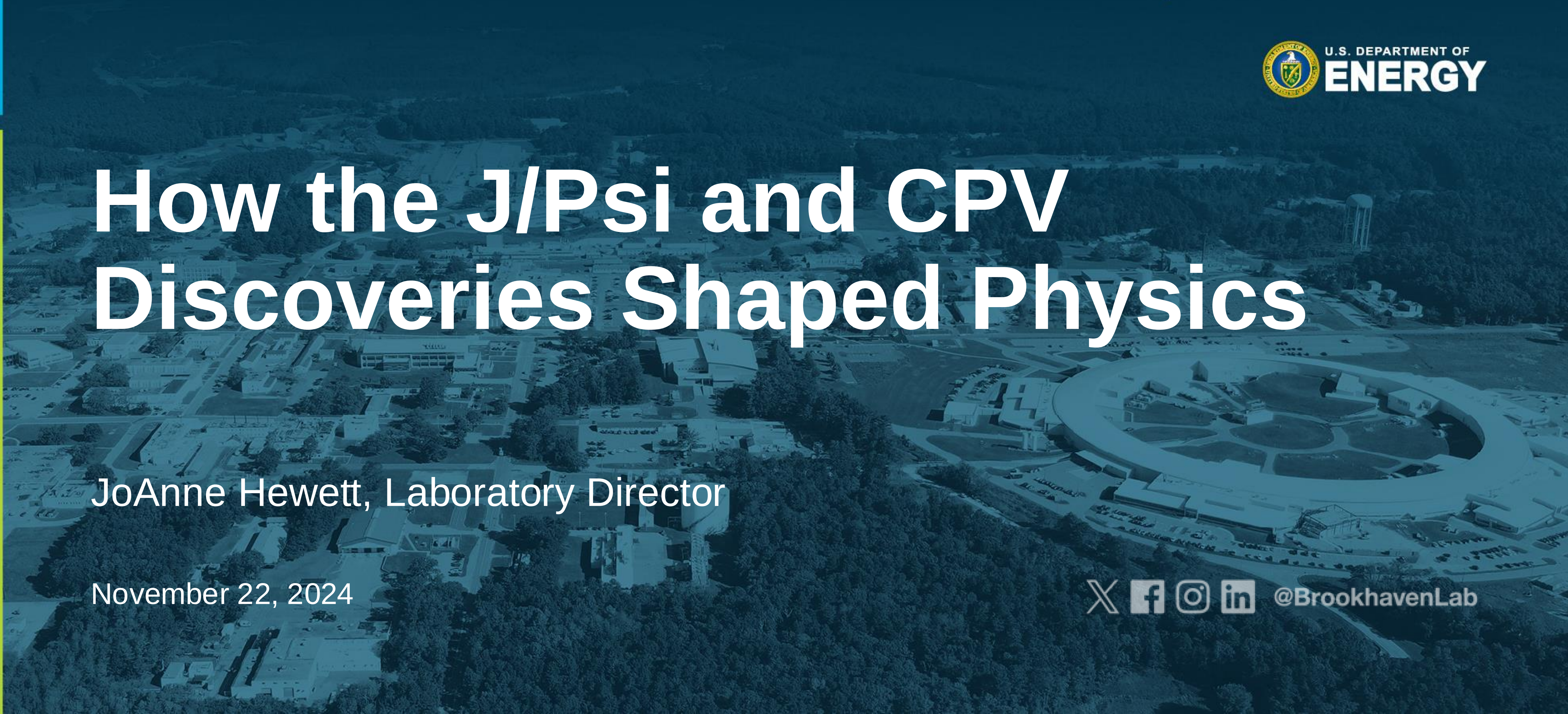
Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY



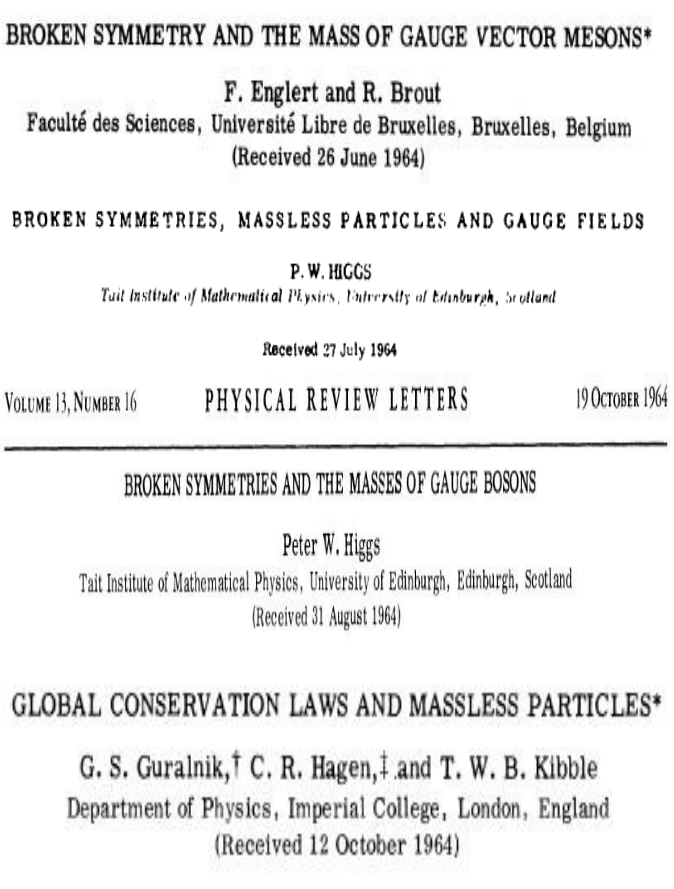
How the J/Psi and CPV Discoveries Shaped Physics

JoAnne Hewett, Laboratory Director

November 22, 2024

@BrookhavenLab

1964 was a good year!



BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout

Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium

(Received 26 June 1964)

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

P. W. HIGGS

Tait Institute of Mathematical Physics, University of Edinburgh, Scotland

Received 27 July 1964

VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs

Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland

(Received 31 August 1964)

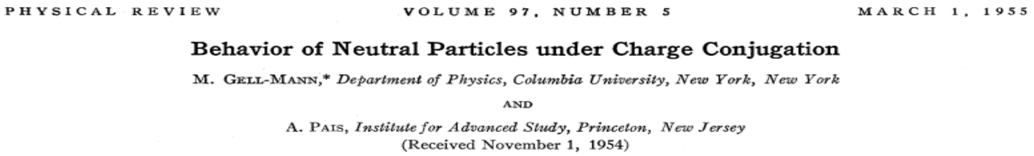
GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble

Department of Physics, Imperial College, London, England

(Received 12 October 1964)

A Surprising Discovery of Indirect CP Violation



PHYSICAL REVIEW VOLUME 97, NUMBER 5 MARCH 1, 1955

Behavior of Neutral Particles under Charge Conjugation

M. GELL-MANN,* *Department of Physics, Columbia University, New York, New York*

AND

A. PAIS, *Institute for Advanced Study, Princeton, New Jersey*

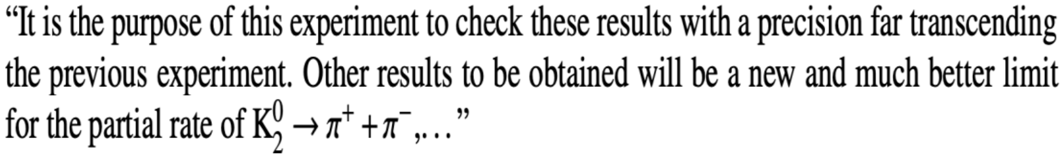
(Received November 1, 1954)

Physics Reports

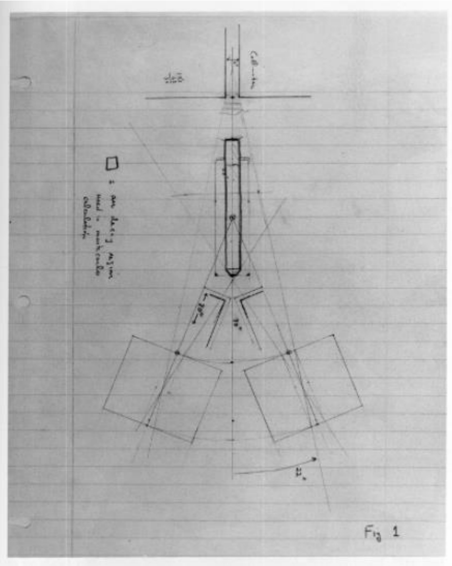
Volume 9, Issue 2, January 1974, Pages 143-177

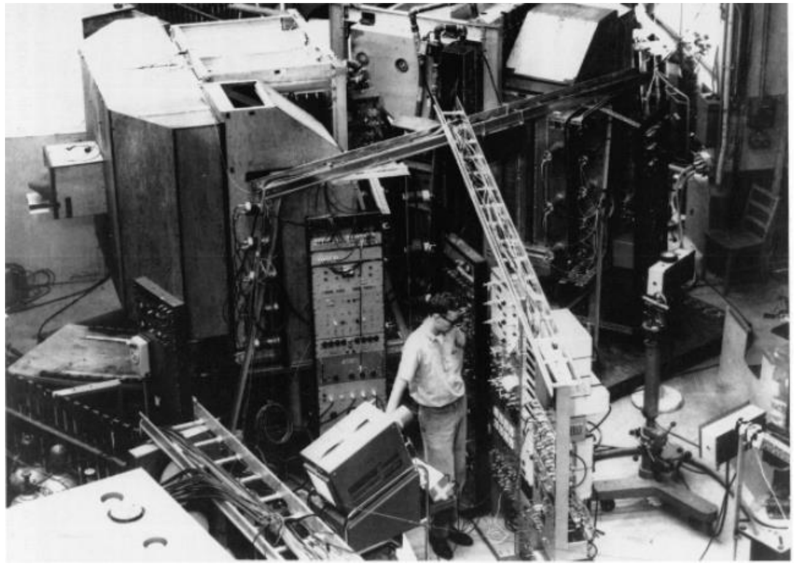
CP nonconservation and spontaneous symmetry breaking ☆

T.D. Lee



"It is the purpose of this experiment to check these results with a precision far transcending the previous experiment. Other results to be obtained will be a new and much better limit for the partial rate of $K_2^0 \rightarrow \pi^+ + \pi^-$,…"





Proposal was 2 pages!

State of the art spectrometer with optical spark chambers

IBM model 526 card punch

ππ final states are CP even

CP eigenstates K_S(K_L) are CP-even(odd)

Measured

- K_L- K_S mass difference
- B($K_S \rightarrow \pi\pi$) = (2.0 +- 0.4) x 10^{-3}

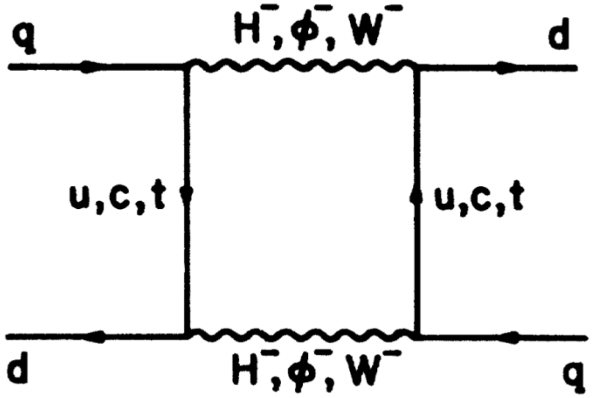
Cronin Tokyo Lecture 1993

K-Kbar Mixing

Flavor Changing Neutral Currents

GIM mechanism (1970)

SM + BSM participates in loops or new tree-level interactions



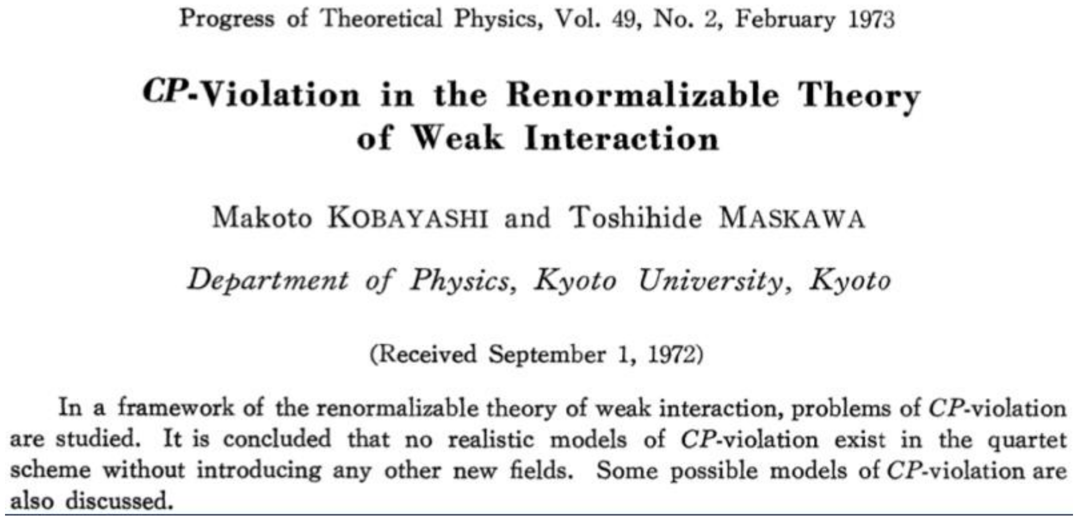
Neutral meson – antimeson mixing

$\Delta M = 2|\mathrm{Re}\, M_{12}|$

$\varepsilon \sim \mathrm{Im}\, M_{12} / \Delta M$

The advent of FCNC sparked the first ideas of charm

The "KM" Matrix of quark mixing



Progress of Theoretical Physics, Vol. 49, No. 2, February 1973

CP-Violation in the Renormalizable Theory of Weak Interaction

Makoto KOBAYASHI and Toshihide MASKAWA

Department of Physics, Kyoto University, Kyoto

(Received September 1, 1972)

In a framework of the renormalizable theory of weak interaction, problems of *CP*-violation are studied. It is concluded that no realistic models of *CP*-violation exist in the quartet scheme without introducing any other new fields. Some possible models of *CP*-violation are also discussed.

$$V_{\mathrm{CKM}} \equiv V_L^u V_L^{d\dagger} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

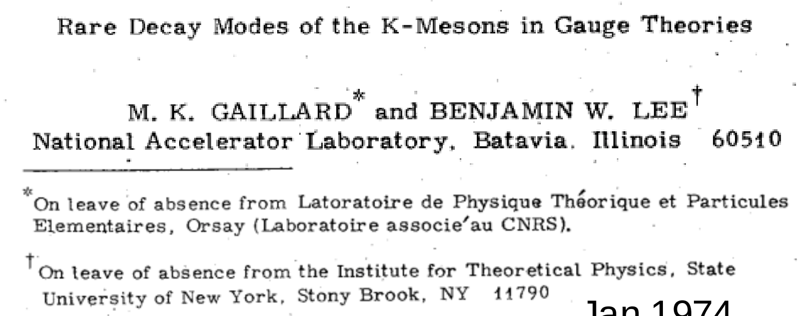
$$= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

Kobayashi and Maskawa receive Nobel prize in 2008

A single source of CPV in the SM: Predictive!

Incorporating CPV into quark mixing required 3 generations of quarks

A Theoretical Birth of Charm



Rare Decay Modes of the K-Mesons in Gauge Theories

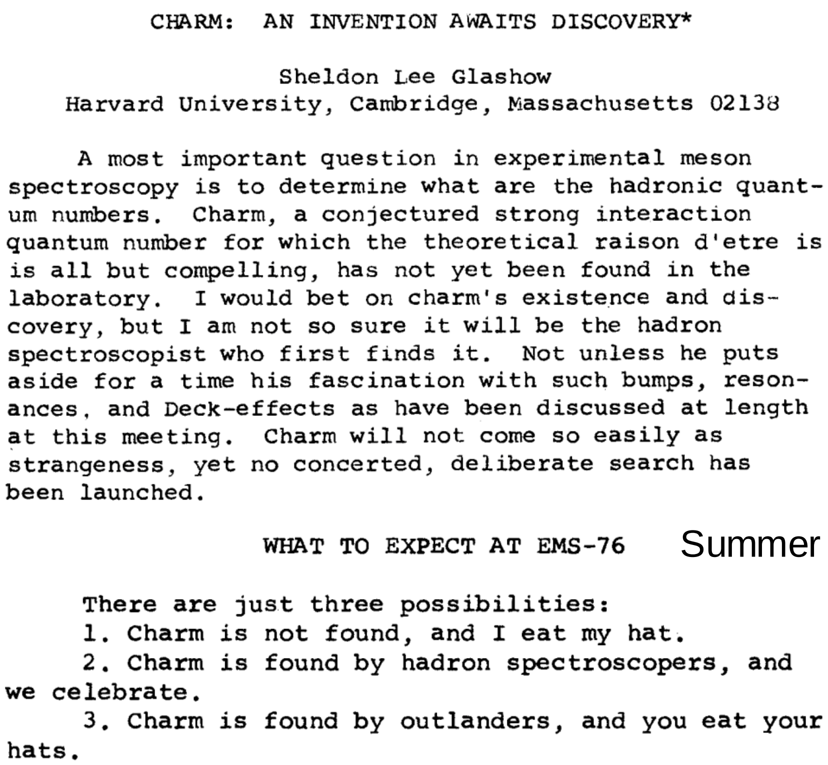
M. K. GAILLARD* and BENJAMIN W. LEE†
National Accelerator Laboratory, Batavia, Illinois 60510

---

*On leave of absence from Latoratoire de Physique Théorique et Particules Elementaires, Orsay (Laboratoire associé au CNRS).

†On leave of absence from the Institute for Theoretical Physics, State University of New York, Stony Brook, NY 11790

Jan 1974



CHARM: AN INVENTION AWAITS DISCOVERY*

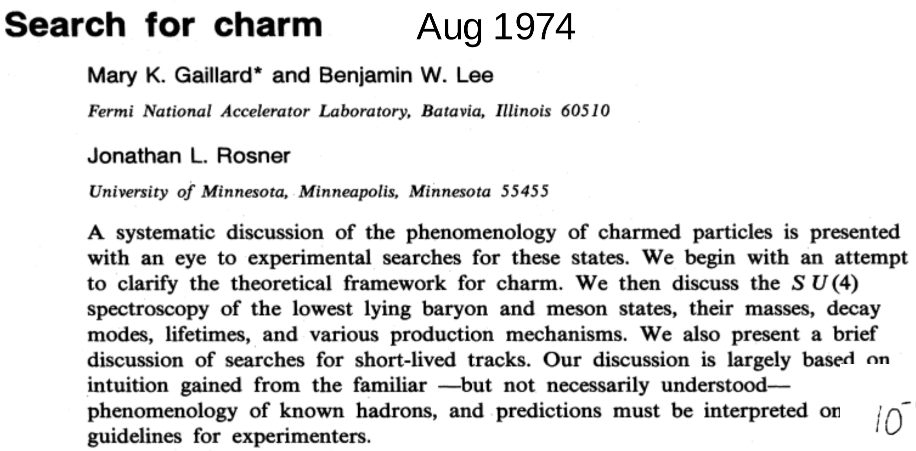
Sheldon Lee Glashow
Harvard University, Cambridge, Massachusetts 02138

A most important question in experimental meson spectroscopy is to determine what are the hadronic quantum numbers. Charm, a conjectured strong interaction quantum number for which the theoretical raison d'etre is is all but compelling, has not yet been found in the laboratory. I would bet on charm's existence and discovery, but I am not so sure it will be the hadron spectroscopist who first finds it. Not unless he puts aside for a time his fascination with such bumps, resonances, and Deck-effects as have been discussed at length at this meeting. Charm will not come so easily as strangeness, yet no concerted, deliberate search has been launched.

WHAT TO EXPECT AT EMS-76

There are just three possibilities:
1. Charm is not found, and I eat my hat.
2. Charm is found by hadron spectroscopers, and we celebrate.
3. Charm is found by outlanders, and you eat your hats.

Summer 1974



Search for charm

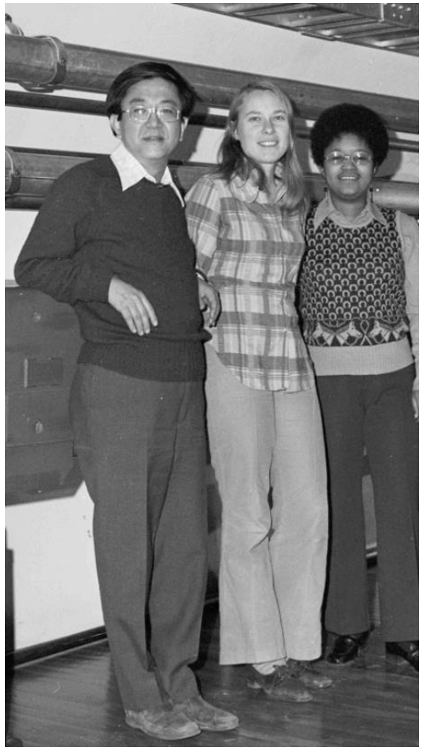
Aug 1974

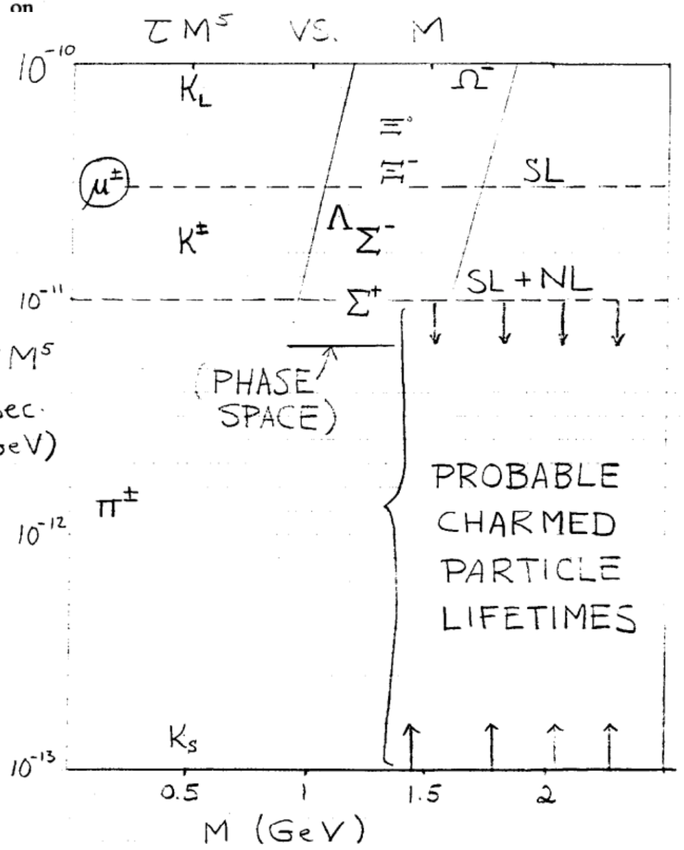
Mary K. Gaillard* and Benjamin W. Lee
Fermi National Accelerator Laboratory, Batavia, Illinois 60510

Jonathan L. Rosner
University of Minnesota, Minneapolis, Minnesota 55455

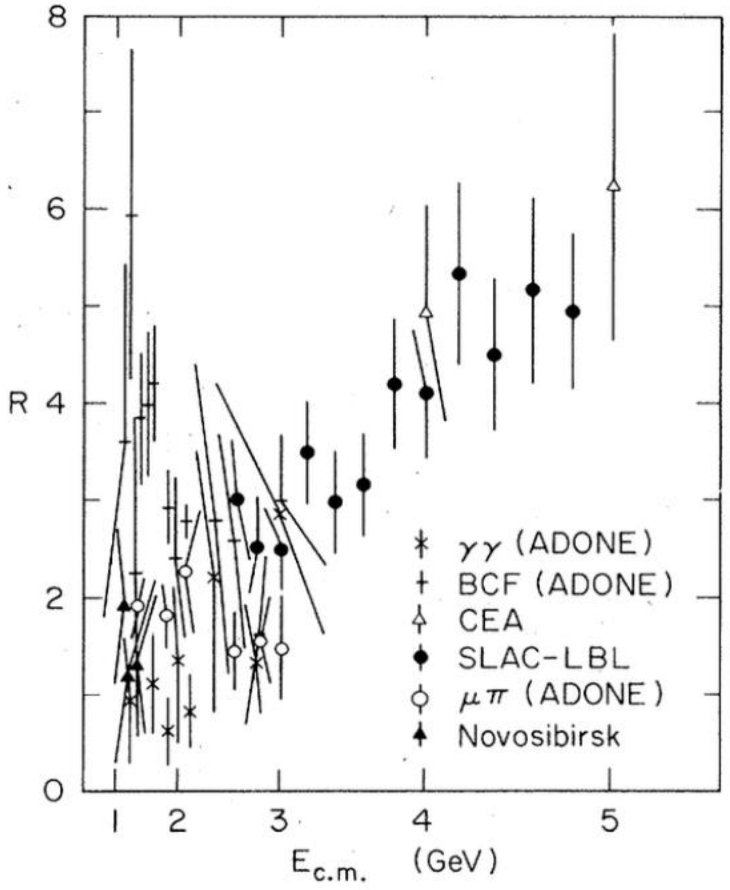
A systematic discussion of the phenomenology of charmed particles is presented with an eye to experimental searches for these states. We begin with an attempt to clarify the theoretical framework for charm. We then discuss the $SU(4)$ spectroscopy of the lowest lying baryon and meson states, their masses, decay modes, lifetimes, and various production mechanisms. We also present a brief discussion of searches for short-lived tracks. Our discussion is largely based on intuition gained from the familiar —but not necessarily understood— phenomenology of known hadrons, and predictions must be interpreted on guidelines for experimenters.

Prediction:
$\Phi(c\bar{c})$: $M \sim 3$ GeV,
$\Gamma \sim 2$ MeV, BR(ee) ~ 1%





R-Ratio: Status in Summer 1974



Theoretical Predictions
for R-ratio

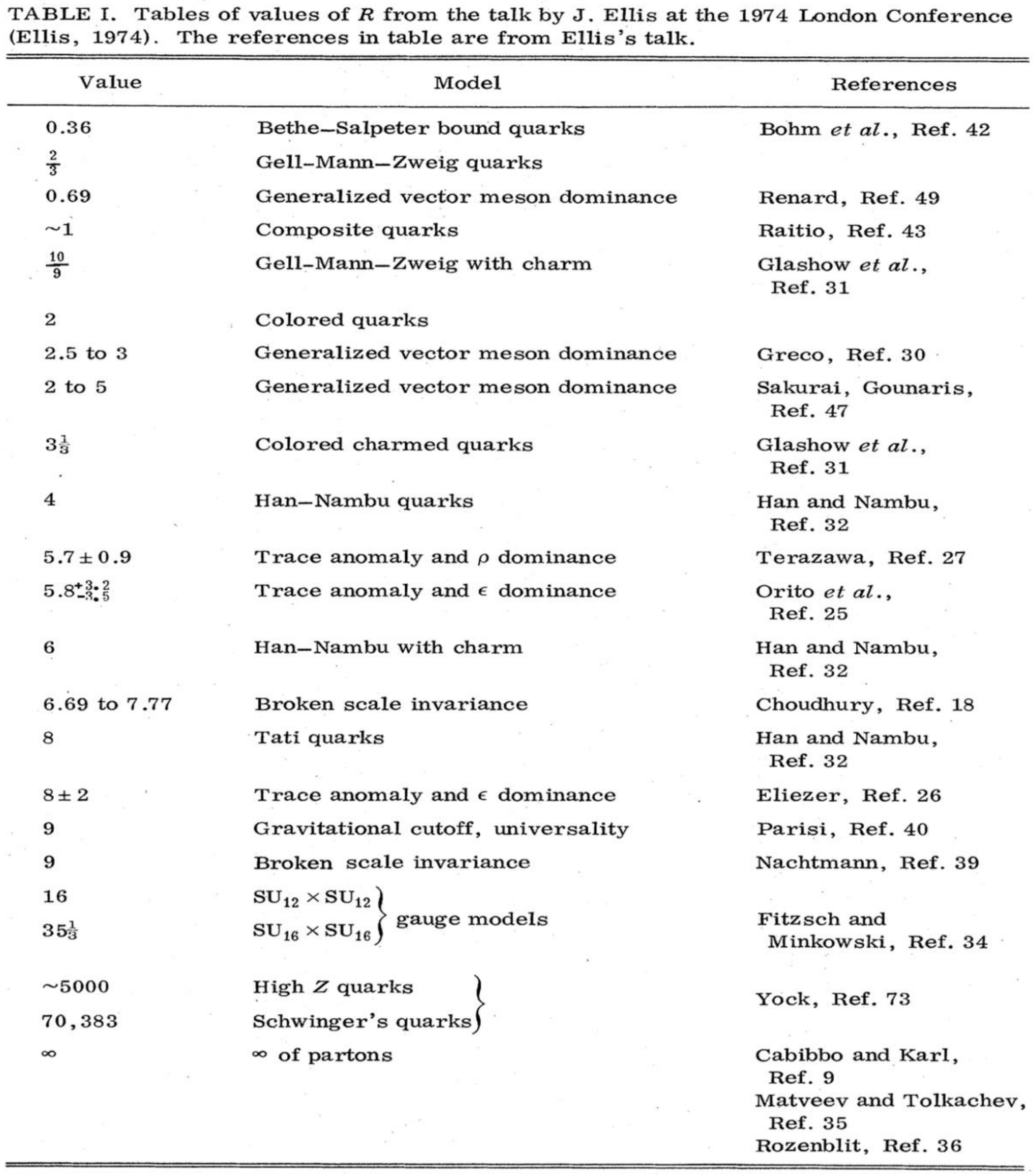


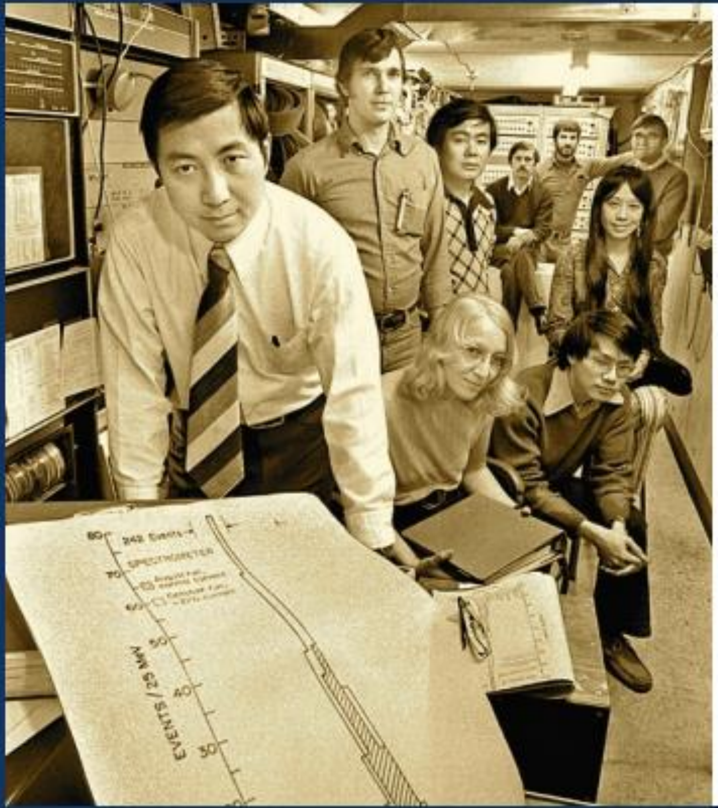
TABLE I. Tables of values of *R* from the talk by J. Ellis at the 1974 London Conference (Ellis, 1974). The references in table are from Ellis's talk.

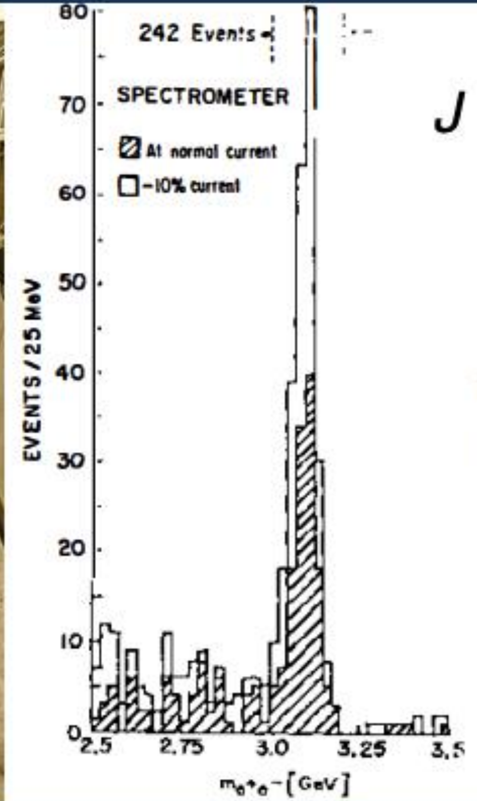
Value	Model	References
0.36	Bethe–Salpeter bound quarks	Bohm *et al.*, Ref. 42
$\frac{2}{3}$	Gell-Mann–Zweig quarks	
0.69	Generalized vector meson dominance	Renard, Ref. 49
~1	Composite quarks	Raitio, Ref. 43
$\frac{10}{9}$	Gell-Mann–Zweig with charm	Glashow *et al.*, Ref. 31
2	Colored quarks	
2.5 to 3	Generalized vector meson dominance	Greco, Ref. 30
2 to 5	Generalized vector meson dominance	Sakurai, Gounaris, Ref. 47
$3\frac{1}{3}$	Colored charmed quarks	Glashow *et al.*, Ref. 31
4	Han–Nambu quarks	Han and Nambu, Ref. 32
5.7 ± 0.9	Trace anomaly and ρ dominance	Terazawa, Ref. 27
$5.8^{+3.2}_{-3.5}$	Trace anomaly and ϵ dominance	Orito *et al.*, Ref. 25
6	Han–Nambu with charm	Han and Nambu, Ref. 32
6.69 to 7.77	Broken scale invariance	Choudhury, Ref. 18
8	Tati quarks	Han and Nambu, Ref. 32
8 ± 2	Trace anomaly and ϵ dominance	Eliezer, Ref. 26
9	Gravitational cutoff, universality	Parisi, Ref. 40
9	Broken scale invariance	Nachtmann, Ref. 39
16	$SU_{12}\times SU_{12}$ gauge models	Fitzsch and Minkowski, Ref. 34
$35\frac{1}{3}$	$SU_{16}\times SU_{16}$ gauge models	
~5000	High *Z* quarks	Yock, Ref. 73
70,383	Schwinger's quarks	
∞	∞ of partons	Cabibbo and Karl, Ref. 9 Matveev and Tolkachev, Ref. 35 Rozenblit, Ref. 36

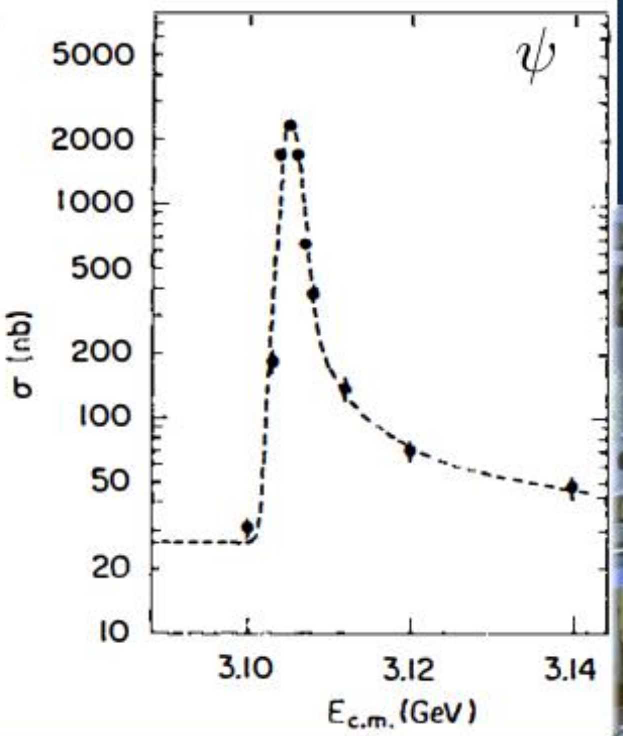
Burt Richter Nobel Lecture, Reviews of Modern Physics 1977

Slide from C. Quigg

11 November 1974



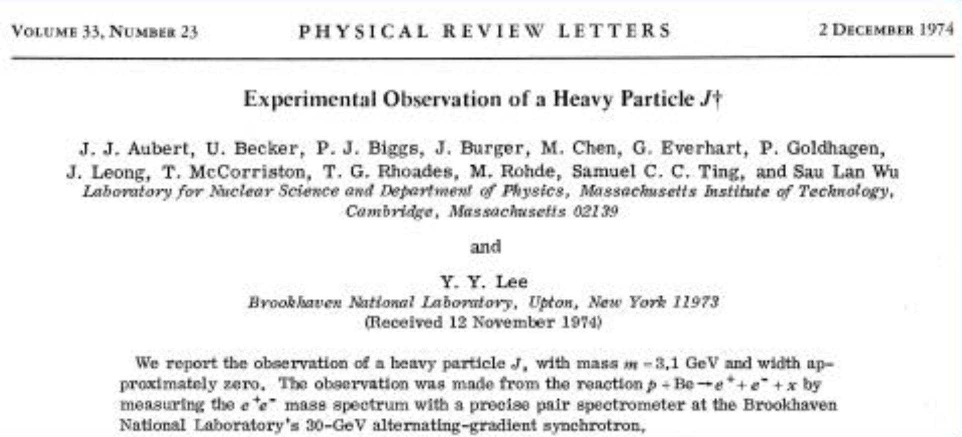





Vera Lüth photo

$p + \mathrm{Be} \to e^+e^- + X$

$e^+e^- \to$ hadrons



Volume 33, Number 23 PHYSICAL REVIEW LETTERS 2 December 1974

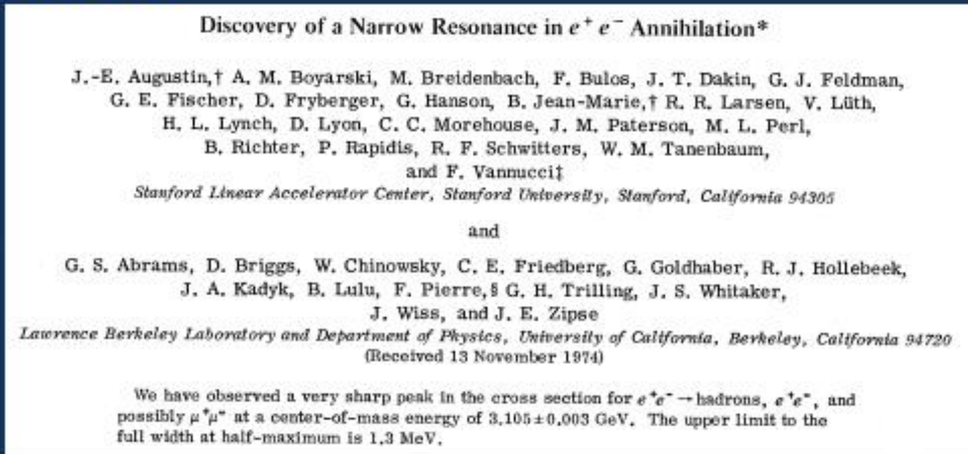
Experimental Observation of a Heavy Particle J†

J. J. Aubert, U. Becker, P. J. Biggs, J. Burger, M. Chen, G. Everhart, P. Goldhagen,
J. Leong, T. McCorriston, T. G. Rhoades, M. Rohde, Samuel C. C. Ting, and Sau Lan Wu
Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology,
Cambridge, Massachusetts 02139

and

Y. Y. Lee
Brookhaven National Laboratory, Upton, New York 11973
(Received 12 November 1974)

We report the observation of a heavy particle J, with mass $m = 3.1$ GeV and width approximately zero. The observation was made from the reaction $p + \mathrm{Be} \to e^+ + e^- + x$ by measuring the e^+e^- mass spectrum with a precise pair spectrometer at the Brookhaven National Laboratory's 30-GeV alternating-gradient synchrotron.



Discovery of a Narrow Resonance in e^+e^- Annihilation*

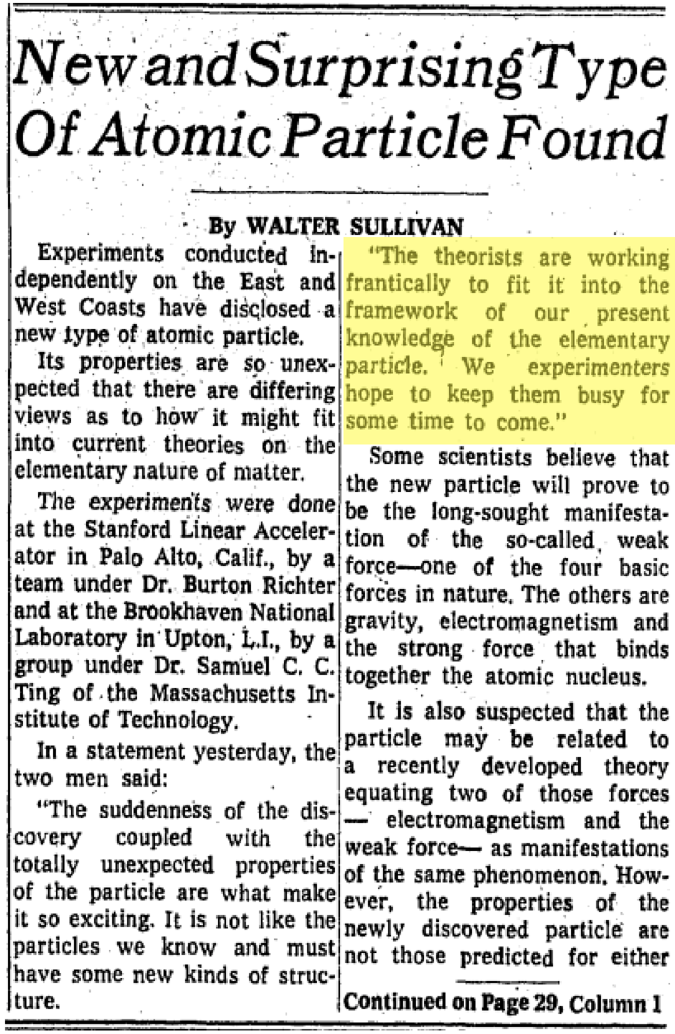
J.-E. Augustin,† A. M. Boyarski, M. Breidenbach, F. Bulos, J. T. Dakin, G. J. Feldman,
G. E. Fischer, D. Fryberger, G. Hanson, B. Jean-Marie,† R. R. Larsen, V. Lüth,
H. L. Lynch, D. Lyon, C. C. Morehouse, J. M. Paterson, M. L. Perl,
B. Richter, P. Rapidis, R. F. Schwitters, W. M. Tanenbaum,
and F. Vannucci‡
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

and

G. S. Abrams, D. Briggs, W. Chinowsky, C. E. Friedberg, G. Goldhaber, R. J. Hollebeek,
J. A. Kadyk, B. Lulu, F. Pierre,§ G. H. Trilling, J. S. Whitaker,
J. Wiss, and J. E. Zipse
Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 94720
(Received 13 November 1974)

We have observed a very sharp peak in the cross section for $e^+e^- \to$ hadrons, e^+e^-, and possibly $\mu^+\mu^-$ at a center-of-mass energy of 3.105 ± 0.003 GeV. The upper limit to the full width at half-maximum is 1.3 MeV.

The Theory World was a Flutter



New and Surprising Type Of Atomic Particle Found

By WALTER SULLIVAN

Experiments conducted independently on the East and West Coasts have disclosed a new type of atomic particle.

Its properties are so unexpected that there are differing views as to how it might fit into current theories on the elementary nature of matter.

The experiments were done at the Stanford Linear Accelerator in Palo Alto, Calif., by a team under Dr. Burton Richter and at the Brookhaven National Laboratory in Upton, L.I., by a group under Dr. Samuel C. C. Ting of the Massachusetts Institute of Technology.

In a statement yesterday, the two men said:

"The suddenness of the discovery coupled with the totally unexpected properties of the particle are what make it so exciting. It is not like the particles we know and must have some new kinds of structure.

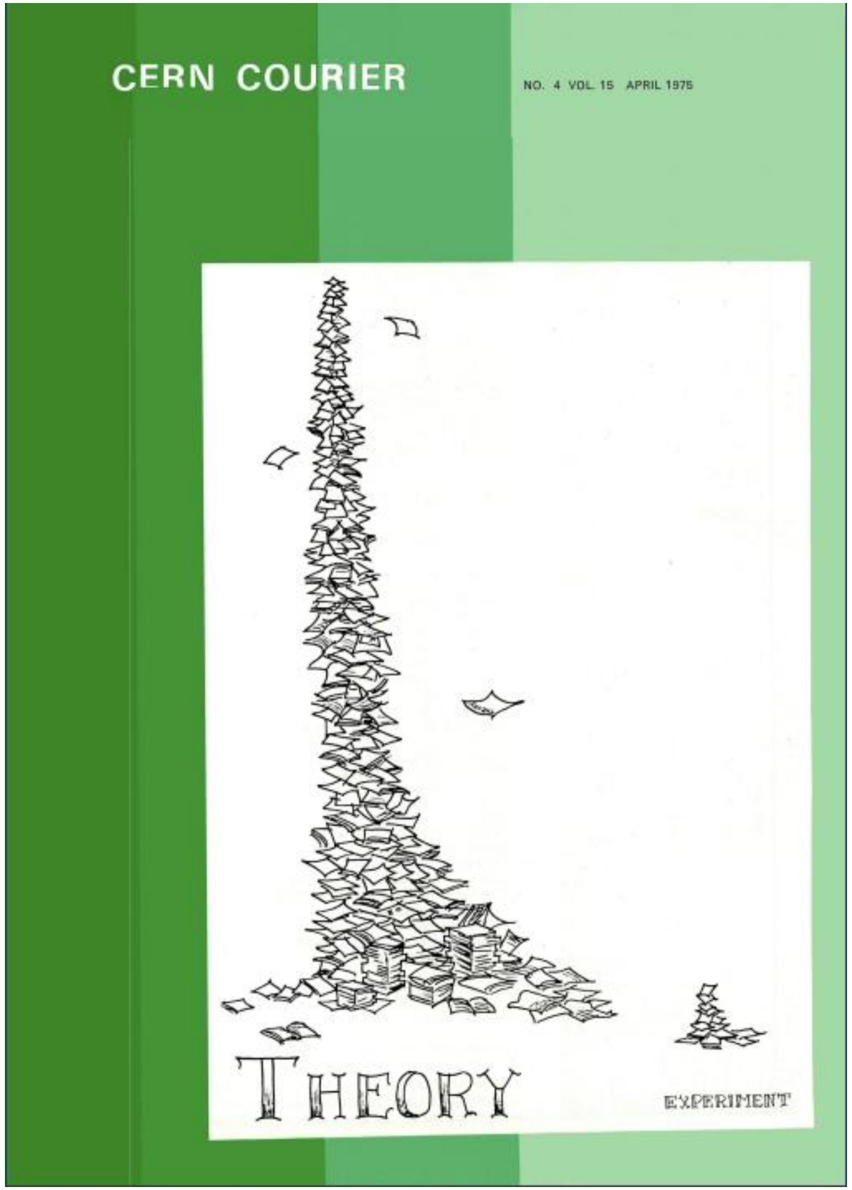
"The theorists are working frantically to fit it into the framework of our present knowledge of the elementary particle. We experimenters hope to keep them busy for some time to come."

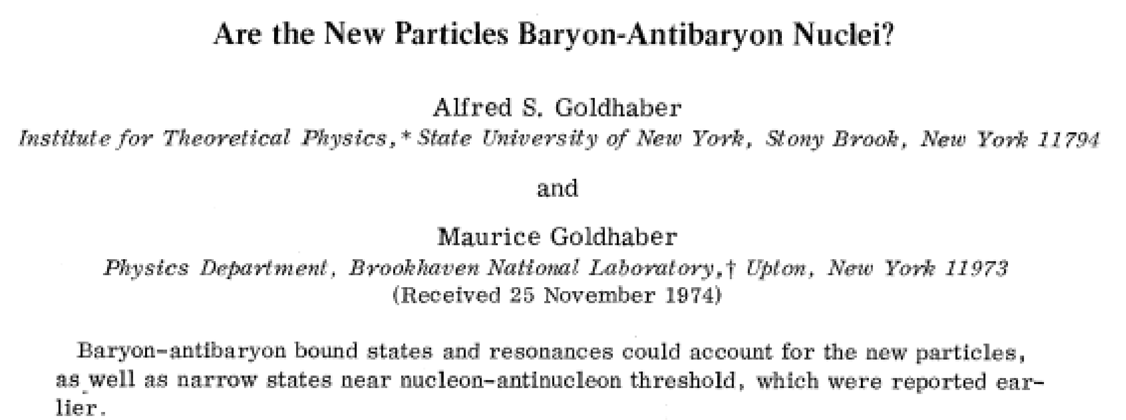
Some scientists believe that the new particle will prove to be the long-sought manifestation of the so-called weak force—one of the four basic forces in nature. The others are gravity, electromagnetism and the strong force that binds together the atomic nucleus.

It is also suspected that the particle may be related to a recently developed theory equating two of those forces — electromagnetism and the weak force— as manifestations of the same phenomenon. However, the properties of the newly discovered particle are not those predicted for either

Continued on Page 29, Column 1

The New York Times
Published: November 17, 1974





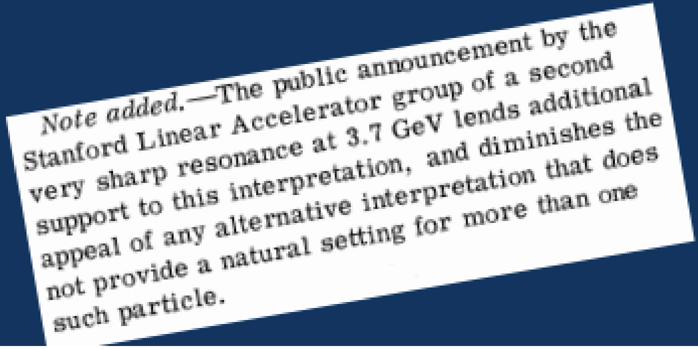
Are the New Particles Baryon-Antibaryon Nuclei?

Alfred S. Goldhaber
Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11794*

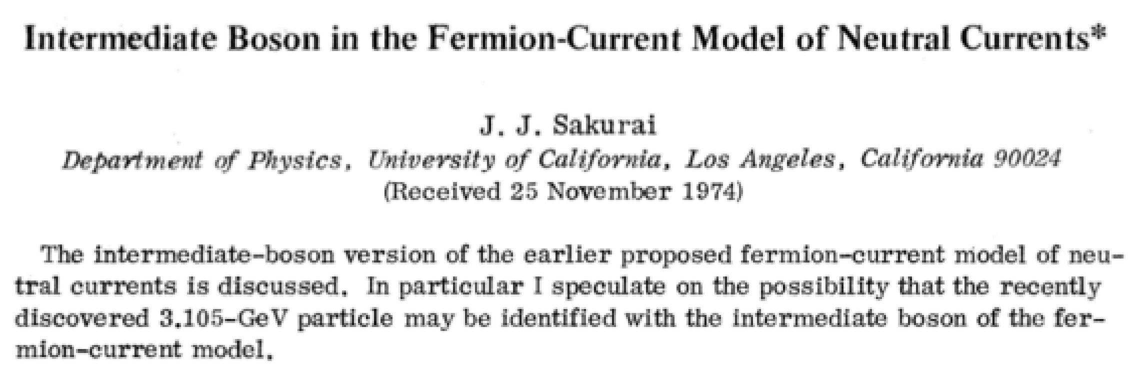
and

Maurice Goldhaber
Physics Department, Brookhaven National Laboratory,† Upton, New York 11973
(Received 25 November 1974)

Baryon-antibaryon bound states and resonances could account for the new particles, as well as narrow states near nucleon-antinucleon threshold, which were reported earlier.



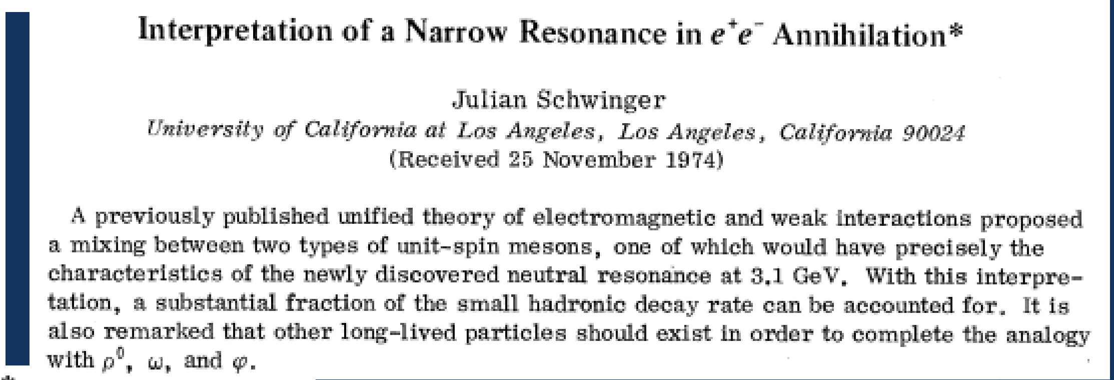
Note added.—The public announcement by the Stanford Linear Accelerator group of a second very sharp resonance at 3.7 GeV lends additional support to this interpretation, and diminishes the appeal of any alternative interpretation that does not provide a natural setting for more than one such particle.



Intermediate Boson in the Fermion-Current Model of Neutral Currents*

J. J. Sakurai
Department of Physics, University of California, Los Angeles, California 90024
(Received 25 November 1974)

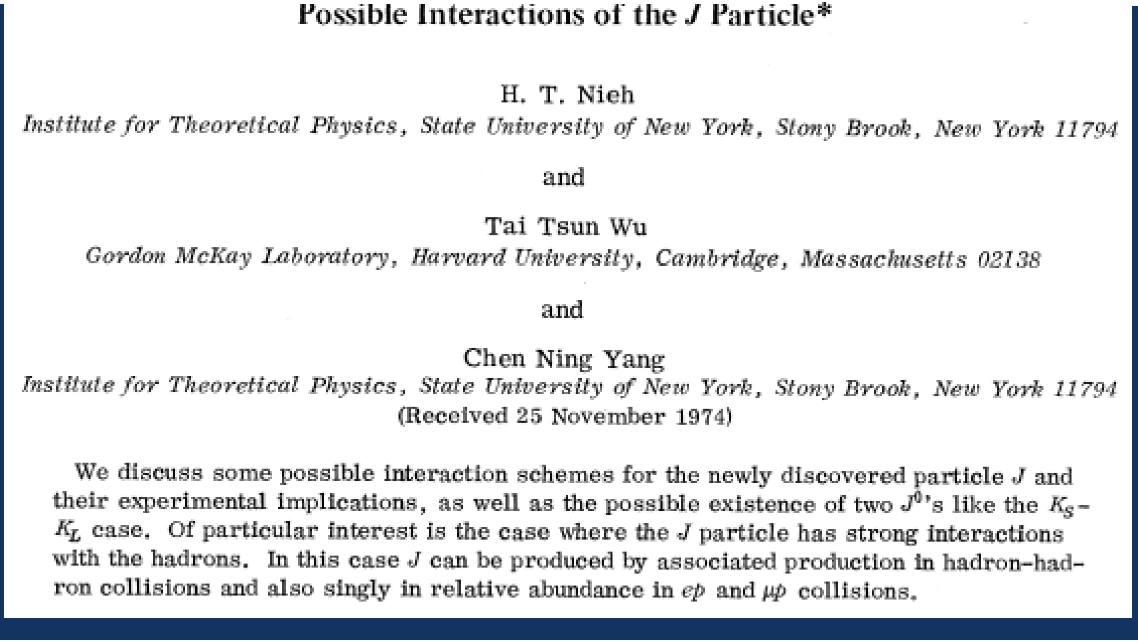
The intermediate-boson version of the earlier proposed fermion-current model of neutral currents is discussed. In particular I speculate on the possibility that the recently discovered 3.105-GeV particle may be identified with the intermediate boson of the fermion-current model.



Interpretation of a Narrow Resonance in e^+e^- Annihilation*

Julian Schwinger
University of California at Los Angeles, Los Angeles, California 90024
(Received 25 November 1974)

A previously published unified theory of electromagnetic and weak interactions proposed a mixing between two types of unit-spin mesons, one of which would have precisely the characteristics of the newly discovered neutral resonance at 3.1 GeV. With this interpretation, a substantial fraction of the small hadronic decay rate can be accounted for. It is also remarked that other long-lived particles should exist in order to complete the analogy with ρ^0, ω, and φ.



Possible Interactions of the *J* Particle*

H. T. Nieh
Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11794

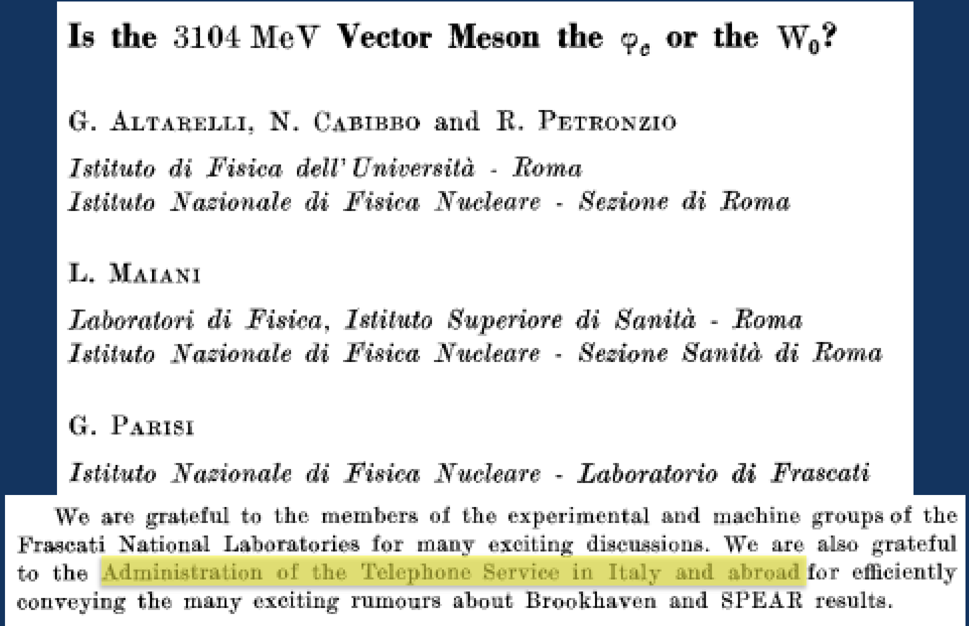
and

Tai Tsun Wu
Gordon McKay Laboratory, Harvard University, Cambridge, Massachusetts 02138

and

Chen Ning Yang
Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11794
(Received 25 November 1974)

We discuss some possible interaction schemes for the newly discovered particle J and their experimental implications, as well as the possible existence of two J^0's like the K_S-K_L case. Of particular interest is the case where the J particle has strong interactions with the hadrons. In this case J can be produced by associated production in hadron-hadron collisions and also singly in relative abundance in ep and μp collisions.



Is the 3104 MeV Vector Meson the φ_c or the W_0?

G. Altarelli, N. Cabibbo and R. Petronzio
Istituto di Fisica dell'Università - Roma
Istituto Nazionale di Fisica Nucleare - Sezione di Roma

L. Maiani
Laboratori di Fisica, Istituto Superiore di Sanità - Roma
Istituto Nazionale di Fisica Nucleare - Sezione Sanità di Roma

G. Parisi
Istituto Nazionale di Fisica Nucleare - Laboratorio di Frascati

We are grateful to the members of the experimental and machine groups of the Frascati National Laboratories for many exciting discussions. We are also grateful to the Administration of the Telephone Service in Italy and abroad for efficiently conveying the many exciting rumours about Brookhaven and SPEAR results.

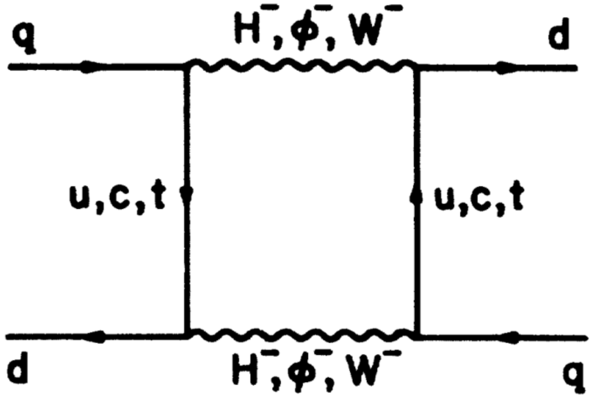
Slide from C. Quigg

K-Kbar Mixing Provides Strong Constraints on BSM

Flavor Changing Neutral Currents

GIM mechanism (1970)

SM + BSM participates in loops or new tree-level interactions



Neutral meson – antimeson mixing

$\Delta M_K = 2|\mathrm{Re}\, M_{12}| \sim 3 \times 10^{-15}$ GeV

$\varepsilon_K \sim \mathrm{Im}\, M_{12} / \Delta M \sim 2 \times 10^{-3}$

ΔM_K provided strongest constraint on right-handed charged gauge bosons for ~3 decades until LHC results

Beall, Bander, Soni PRL 1982

Super-GIM mechanism

Gluino-Squark contributions to ε

$$\mathrm{Im}\,(K_1 - K_2) \Rightarrow \Delta m_{\mathrm{sq}}^2 / m_{\mathrm{sq}}^2 < O(10^{-3})$$

Guides all of SUSY phenomenology

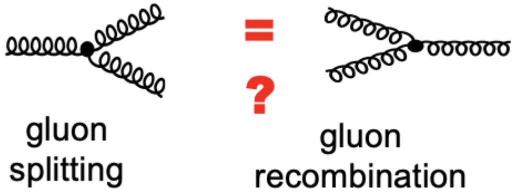
Ellis, Nanopoulos, PLB 1982

The advent of FCNC sparked an entire field

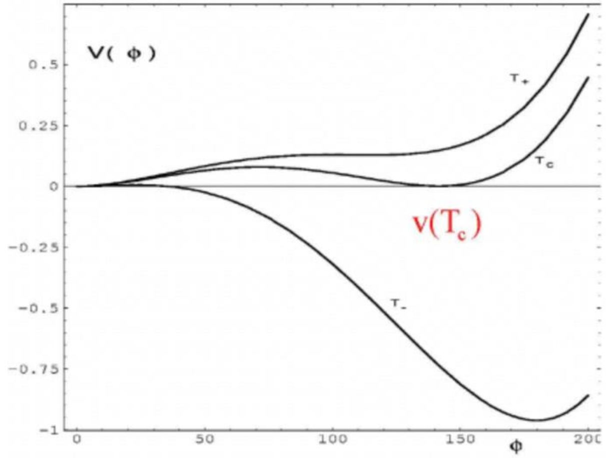
Baryon Asymmetry of the Universe

Sakharov Conditions to generate BAU

- Baryon number violation (anomalous processes)
- CP violation (Quark CKM mixing)
- Depart from thermal equilibrium (EW phase transition)



SM Baryogenesis requires EWB to be 1st-order cosmological phase transition

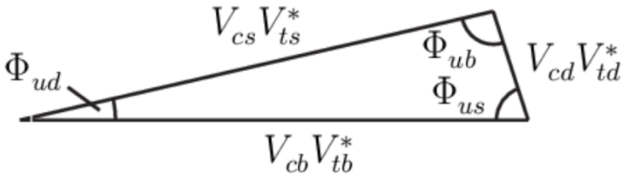


BAU observations require one excess quark for every quark-antiquark pair

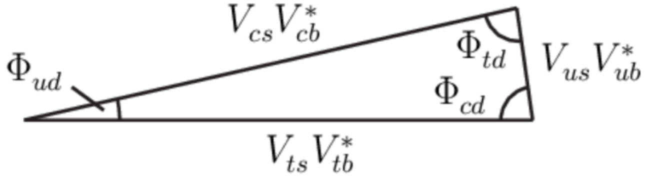
CPV is not large enough in the SM to reproduce the BAU

One of today’s outstanding questions

CPV in B Decays – Search for new CPV sources

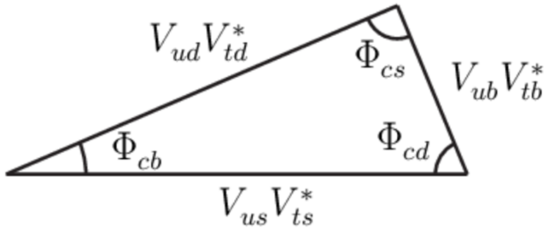


$(\triangle_u)$

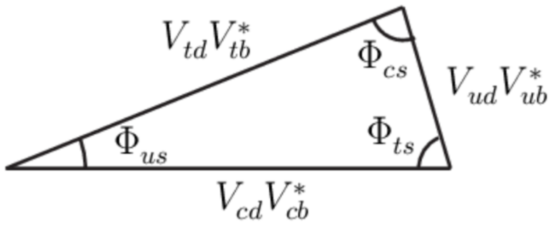


$(\triangle_d)$

B_s system



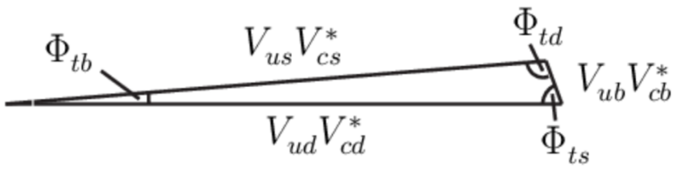
$(\triangle_c)$



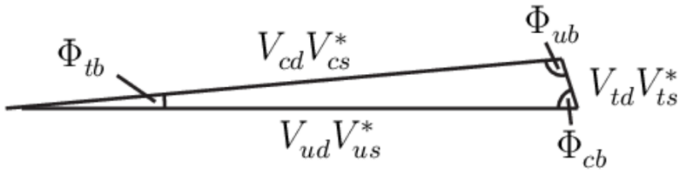
$(\triangle_s)$

B_d system

D system



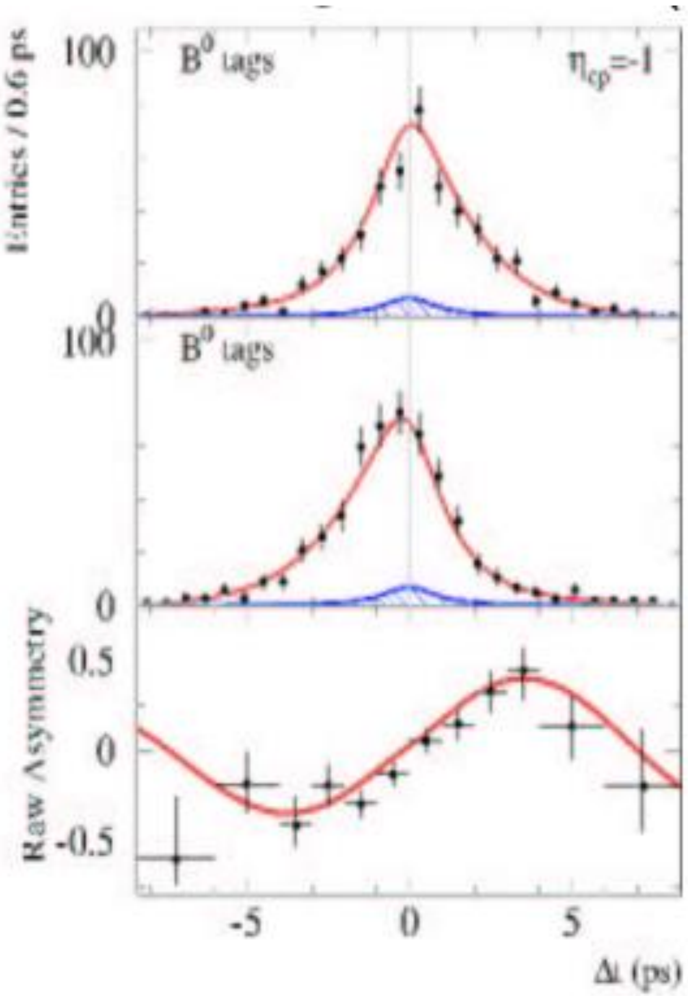
$(\triangle_t)$

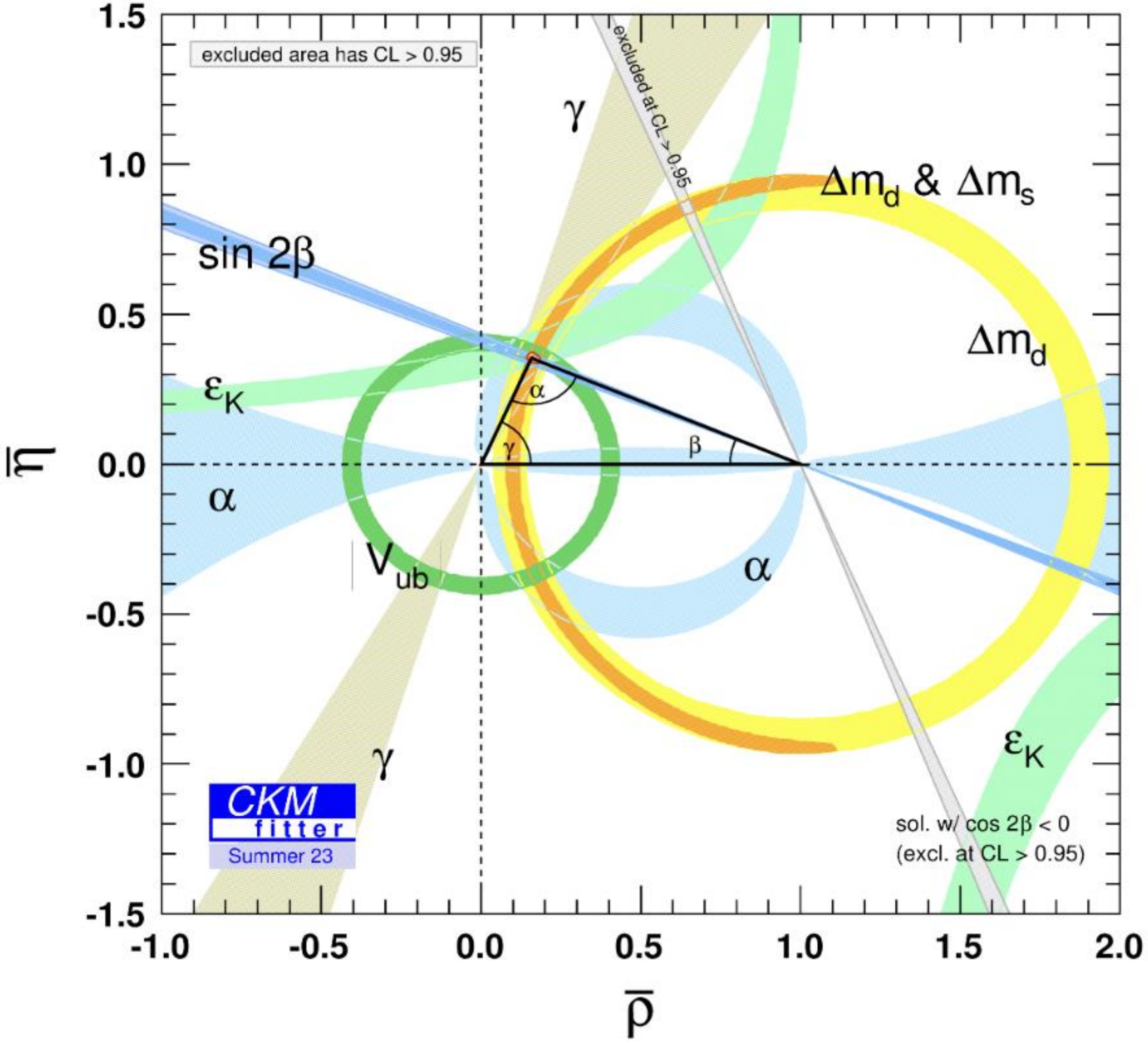


$(\triangle_b)$

K system

B-Factory Legacy: CPV in B System @SM Prediction





Asymmetry between B^0 and B^0–bar tags at BaBar/Belle led to Nobel Prize for Kobayashi & Maskawa

Mixing in the Charm Meson Sector

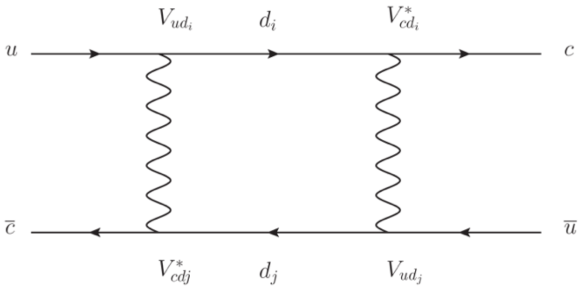
First observation by BaBar & Belle in March 2007

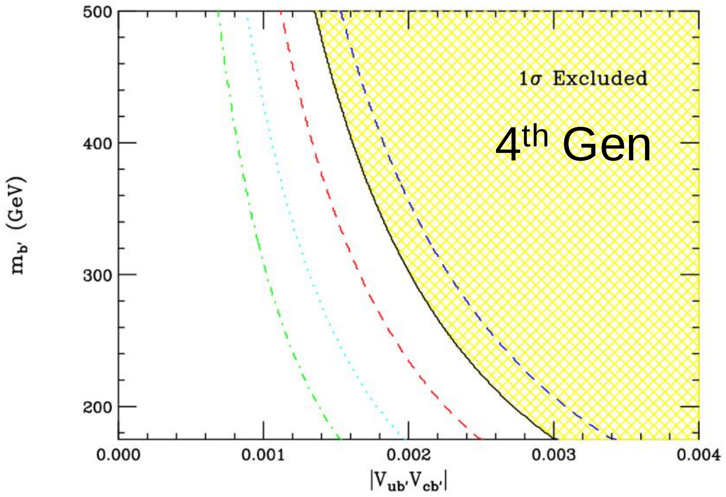
Strong hadronic effects must be incorporated

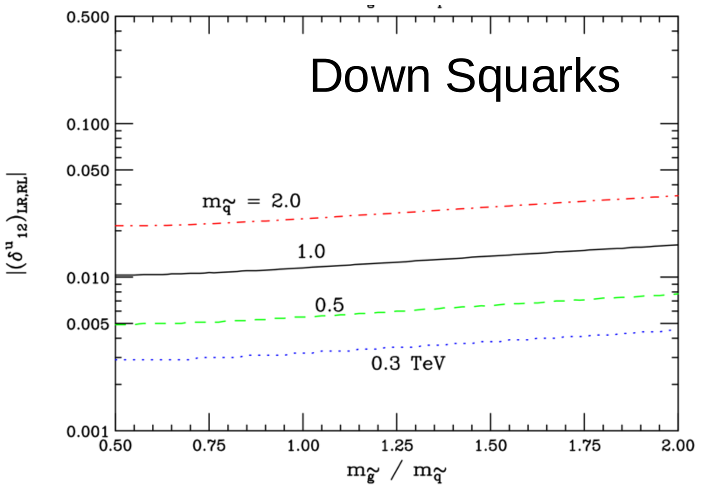
$\Delta M_D \sim 10^{-14}$ GeV

New constraints on ~20 models

Provided complementary probe to $\Delta M_{K,B}$



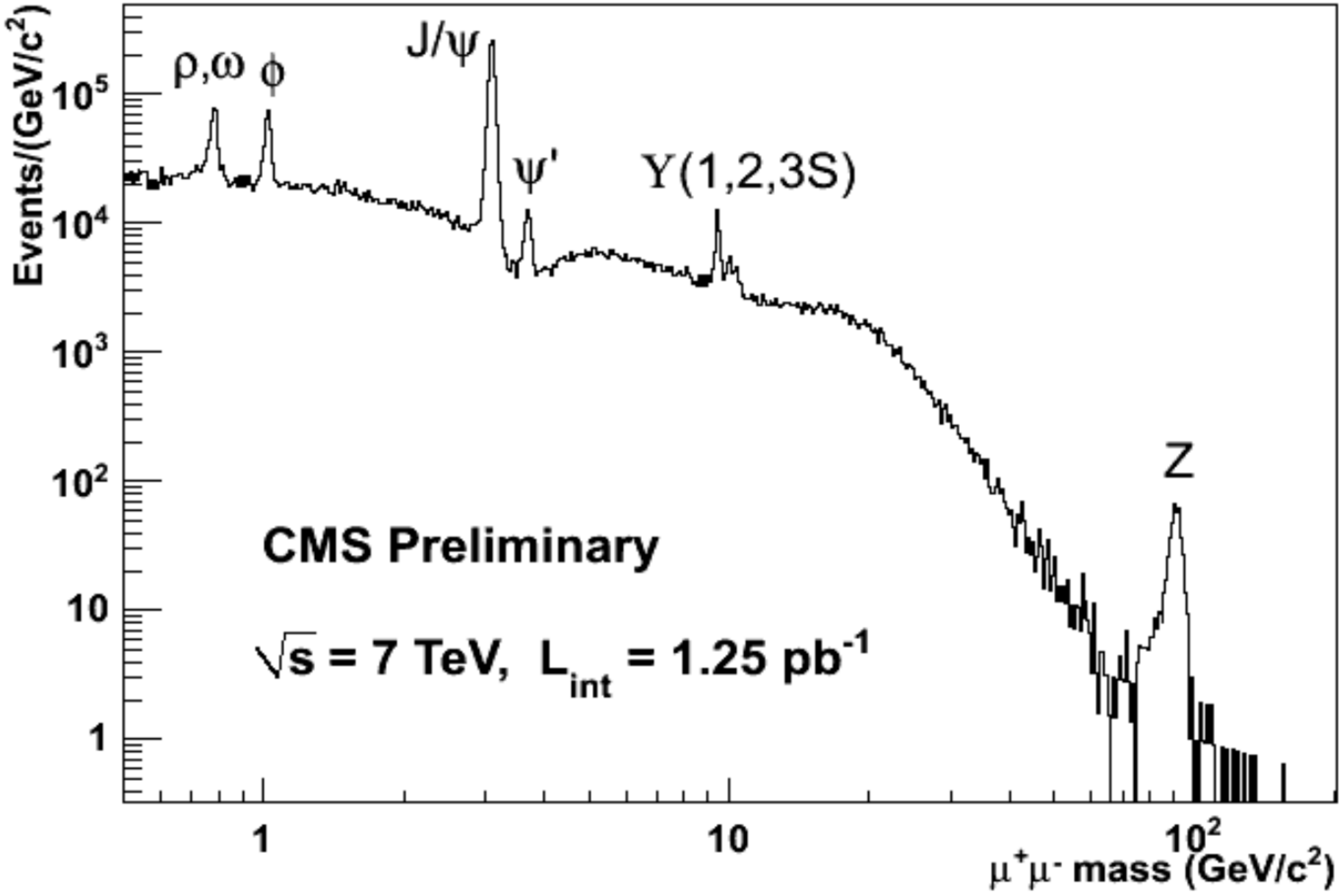




Golowich, Hewett, Pakvasa, Petrov, PRD, Sep 2007

First FCNC observation in up-quark sector

LHC Detectors Rediscover the SM

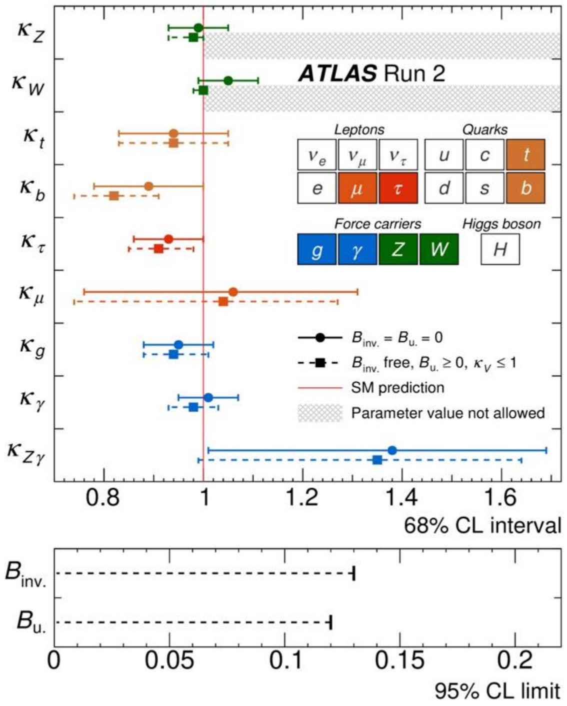


Dimuon data
@7 TeV
45 pb^{-1}

J/Psi provides detector calibration

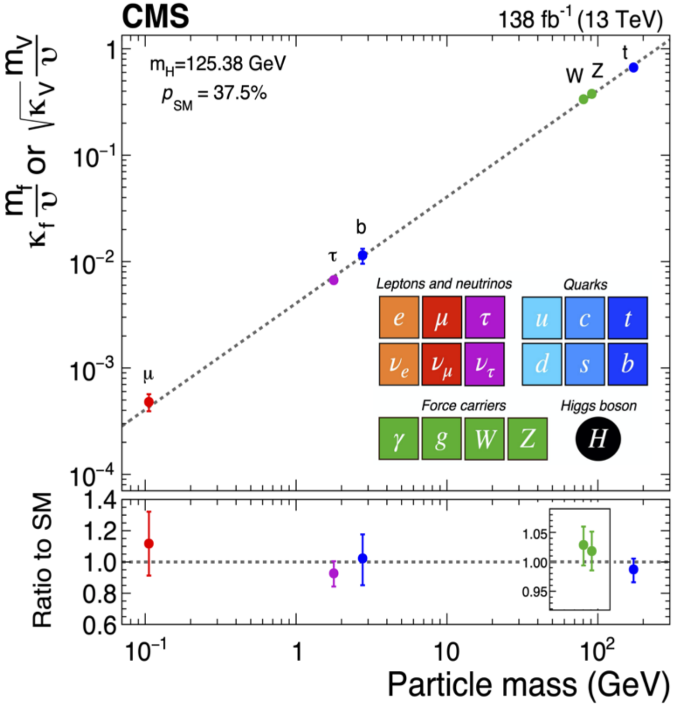
Higgs Coupling Measurements @LHC

Nature 607 (2022) 52

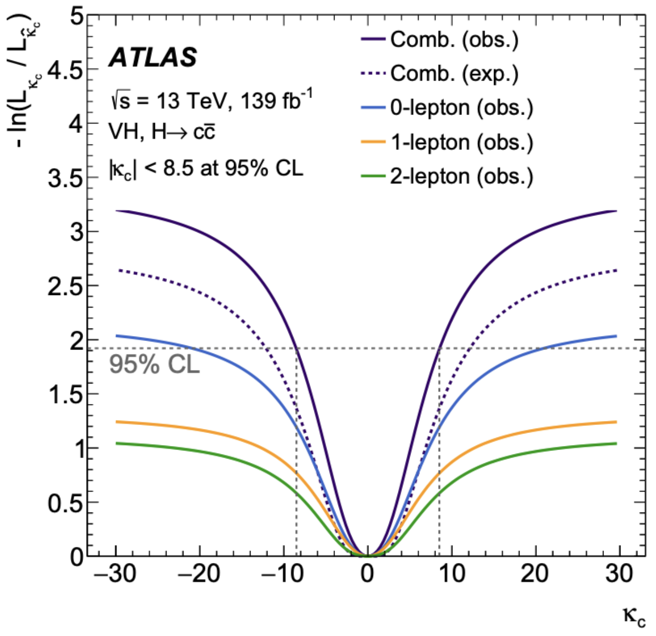


Fermion and Boson couplings measured to ~10% (20% in some cases)

Nature 607 (2022) 60



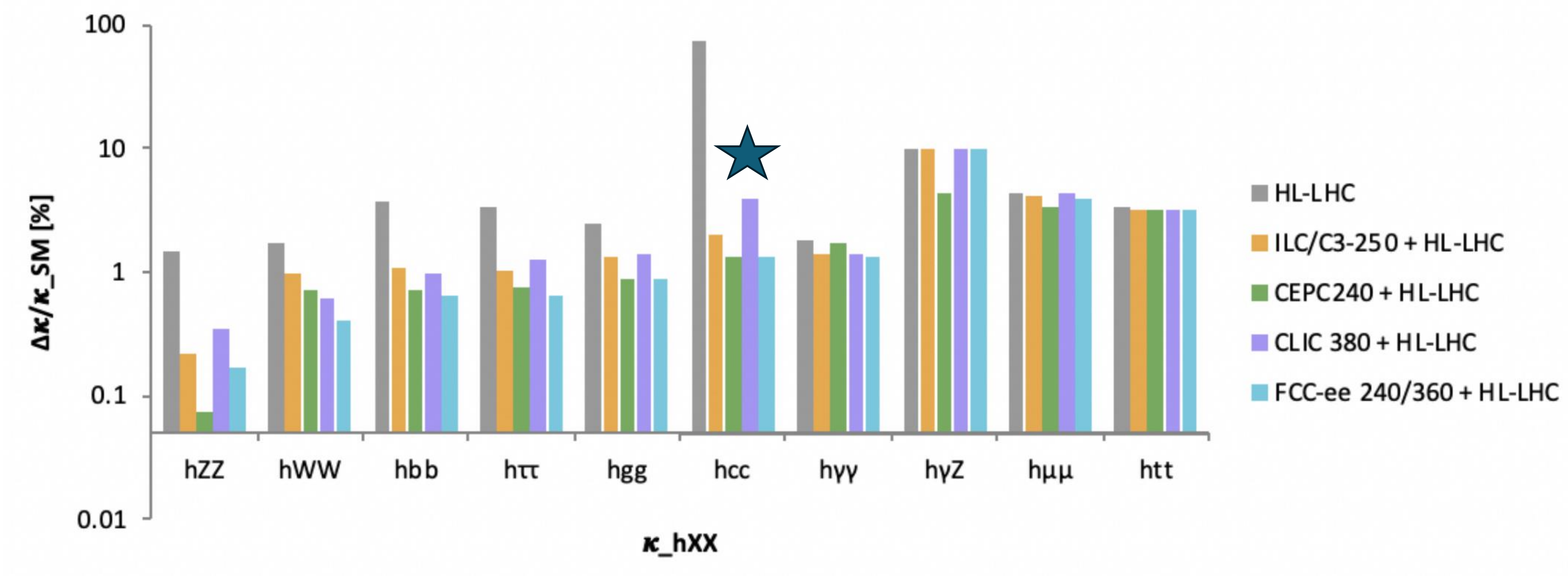
2201.11428



Constraint on charm coupling $\kappa_c < 8.5$ @95% CL

This is a great achievement!

Precision Higgs Coupling Measurements @ Future Colliders



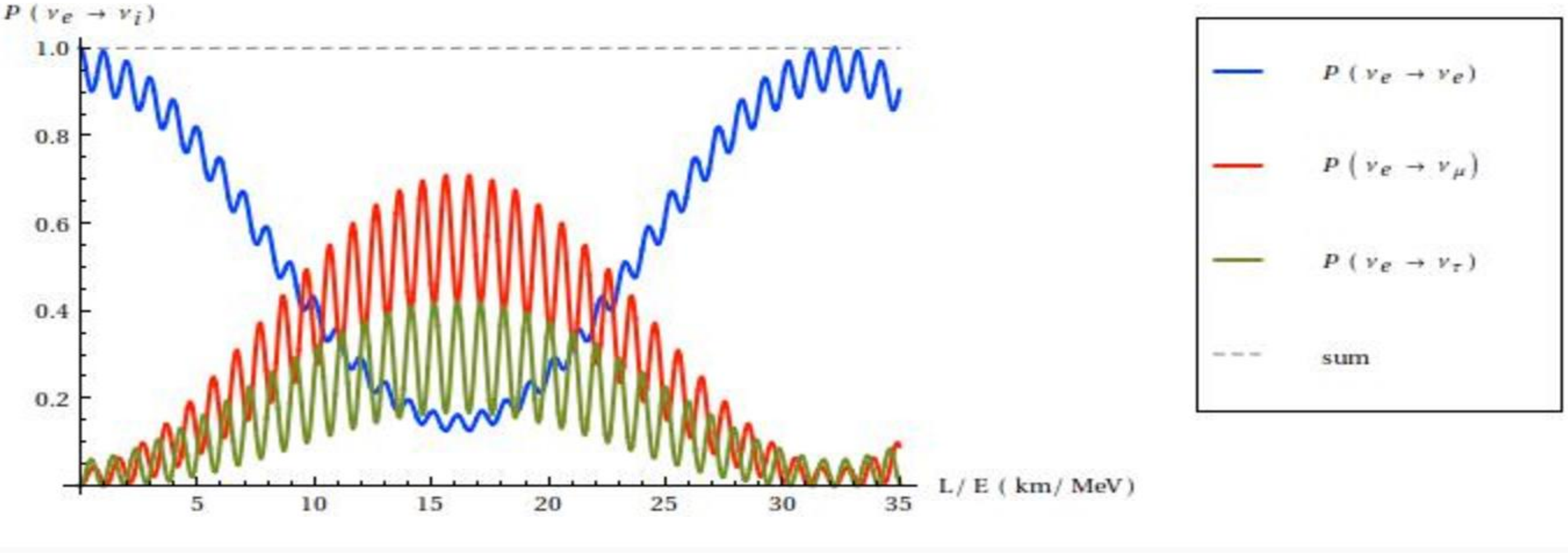
Sub-1% measurement of most couplings
H charm coupling measured to %-level

Dawson etal, 2209.07510

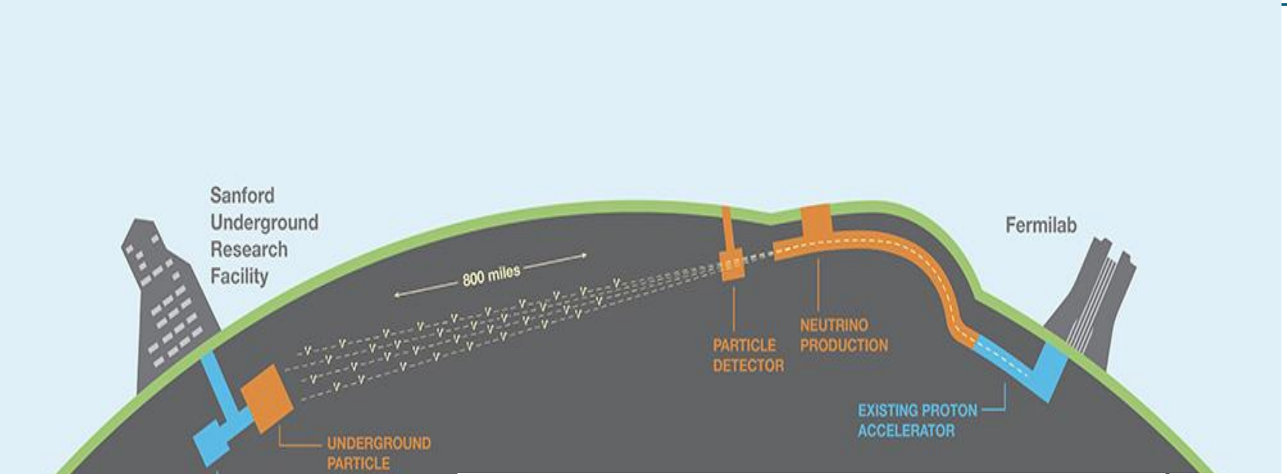
Study of Neutrino Oscillations

- Neutrino flavor eigenstates are linear combinations of their mass eigenstates
- The flavor states oscillate as they propagate

$$\boxed{P_{e\mu}(L) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)}$$

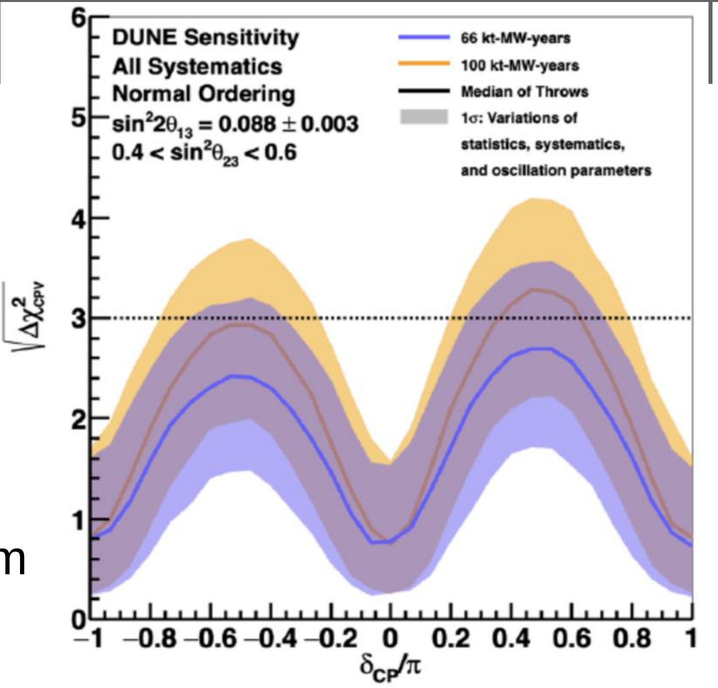


Search for CP Violation in the Lepton Sector

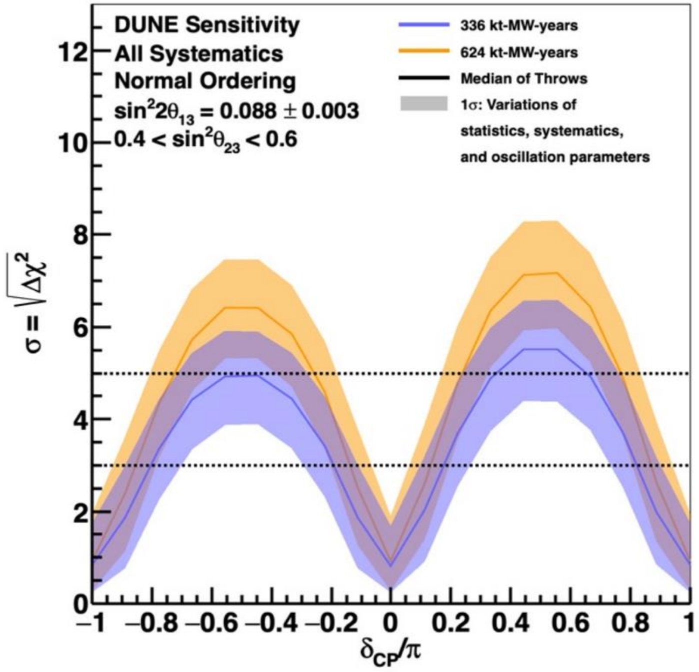


LBNF/DUNE
International Facility

Phase I and Phase II sensitivity to CP Violation



Phase I = 2 far detectors, near detector, 1.2 MW beam



Phase II = 4 far detectors, upgraded near detector, 2.4 MW beam

Snowmass 2022

Search for the origin of the matter anti-matter asymmetry

J/Psi Science at RHIC

John Harris and Berndt Mueller Review of RHIC Science 2023
https://arxiv.org/pdf/2308.05743

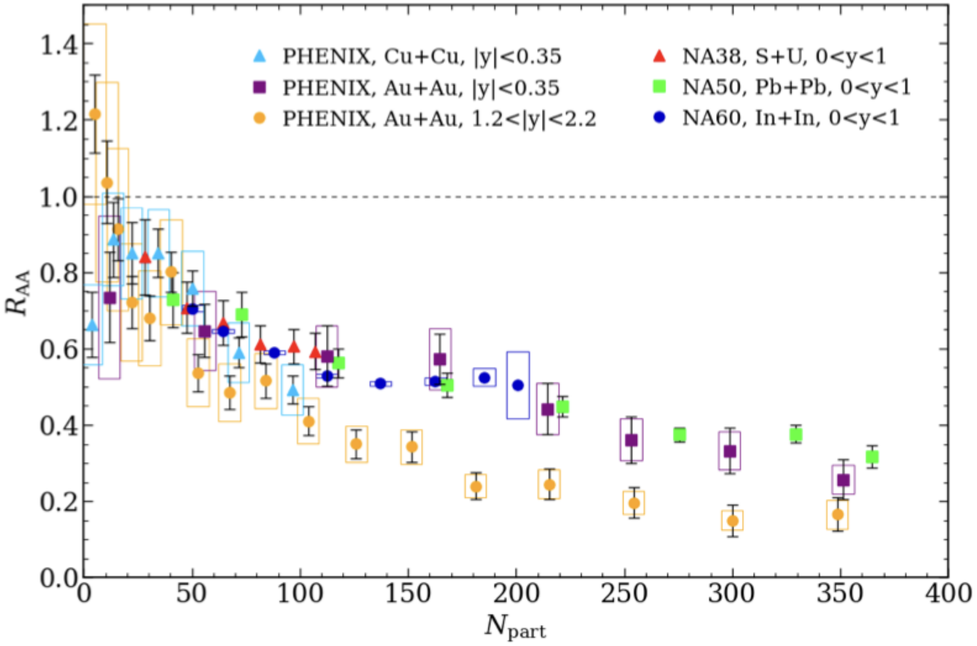


Fig. 9 The nuclear modification factor $R_{AA}(J/\psi)$ as a function of the number of participating nucleons N_{part} at mid-rapidity from NA38, NA50, NA60 and PHENIX [51]. Collision system, rapidity window and centrality are given for each in the legend. See text for more details.

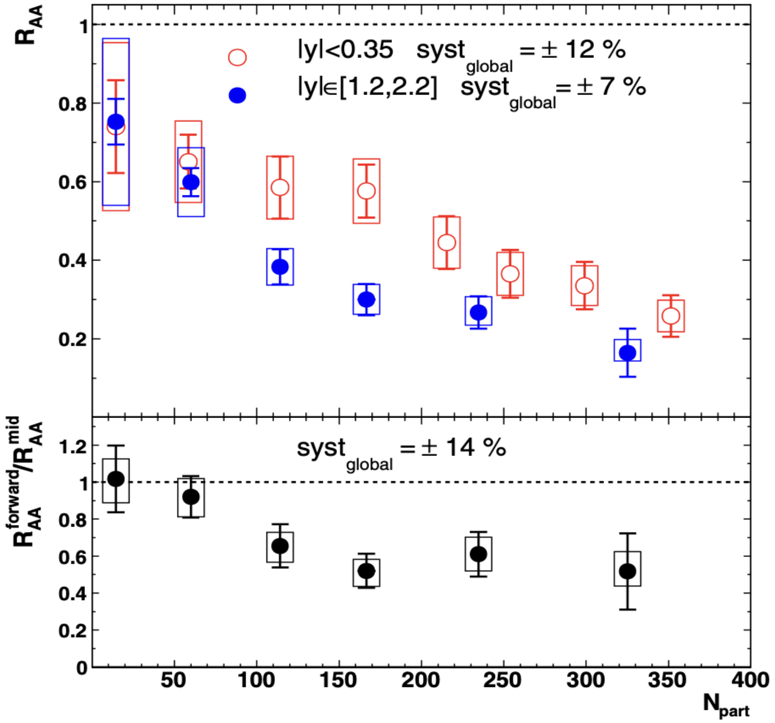
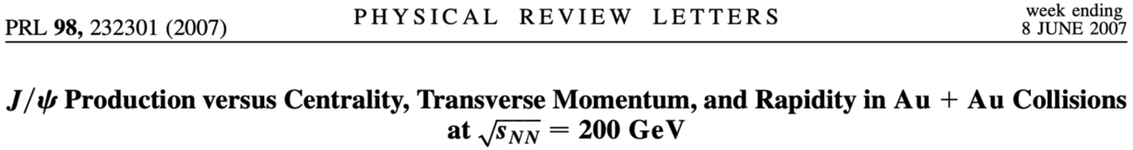


FIG. 5 (color online). (a) J/ψ R_{AA} versus N_{part} for Au + Au collisions. Mid (forward) rapidity data are shown with open (solid) circles. (b) Ratio of forward or midrapidity J/ψ R_{AA} versus N_{part}. For the two most central bins, midrapidity points have been combined to form the ratio with the forward rapidity points. See text for description of the errors and Ref. [21] for data tables.

One of the most cited publications 776 citations

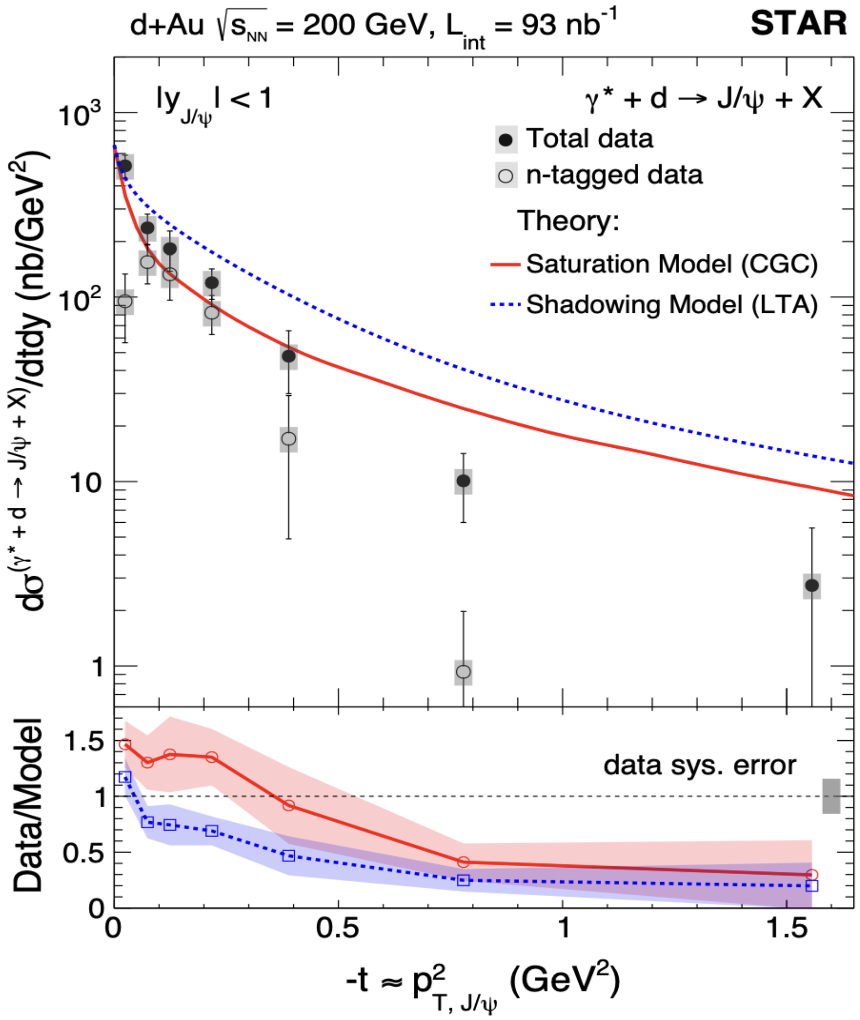
PHENIX



PRL **98,** 232301 (2007) PHYSICAL REVIEW LETTERS week ending 8 JUNE 2007

J/ψ Production versus Centrality, Transverse Momentum, and Rapidity in Au + Au Collisions at $\sqrt{s_{NN}} = 200$ GeV

Probing the gluonic structure of the deuteron with J/ψ photoproduction in d+Au ultra-peripheral collisions



Ultra-peripheral collisions at RHIC.
Precise J/Psi production cross section investigates the difference between Color Glass Condensate vs. nuclear shadowing

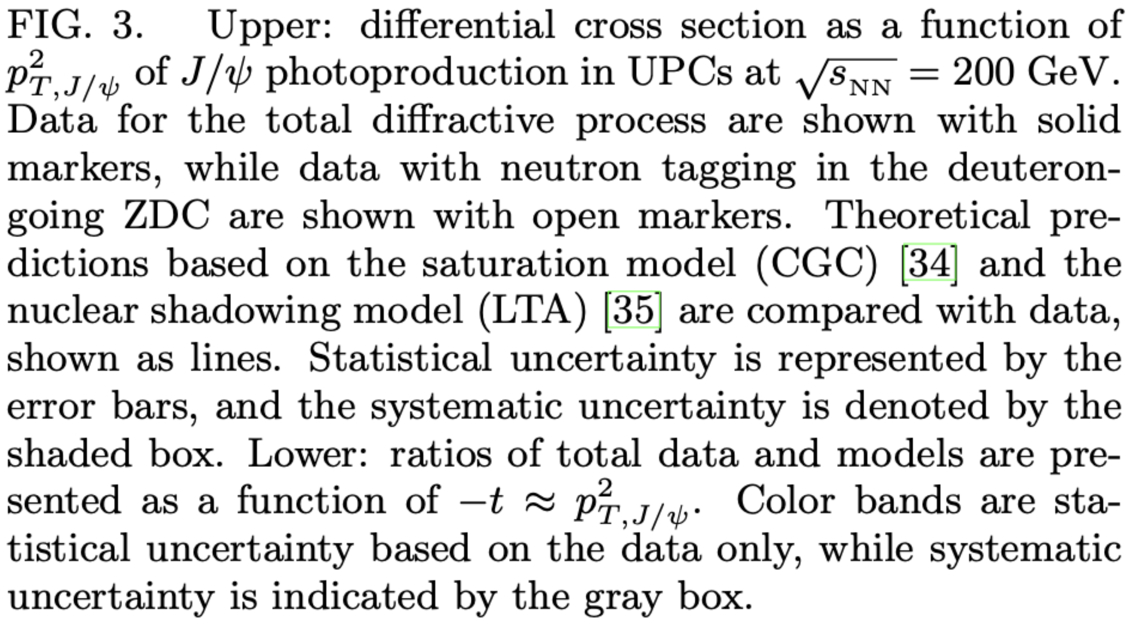
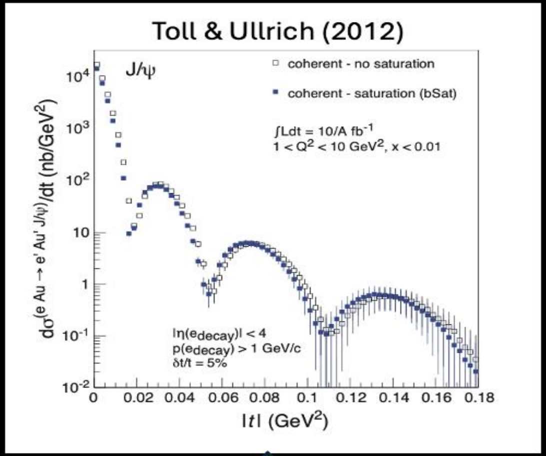


FIG. 3. Upper: differential cross section as a function of $p^2_{T,J/\psi}$ of J/ψ photoproduction in UPCs at $\sqrt{s_{\rm NN}} = 200$ GeV. Data for the total diffractive process are shown with solid markers, while data with neutron tagging in the deuteron-going ZDC are shown with open markers. Theoretical predictions based on the saturation model (CGC) [34] and the nuclear shadowing model (LTA) [35] are compared with data, shown as lines. Statistical uncertainty is represented by the error bars, and the systematic uncertainty is denoted by the shaded box. Lower: ratios of total data and models are presented as a function of $-t \approx p^2_{T,J/\psi}$. Color bands are statistical uncertainty based on the data only, while systematic uncertainty is indicated by the gray box.

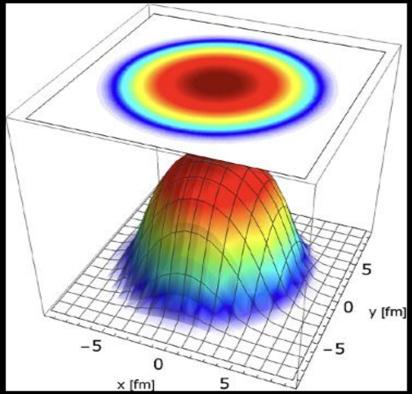
https://arxiv.org/pdf/2109.07625

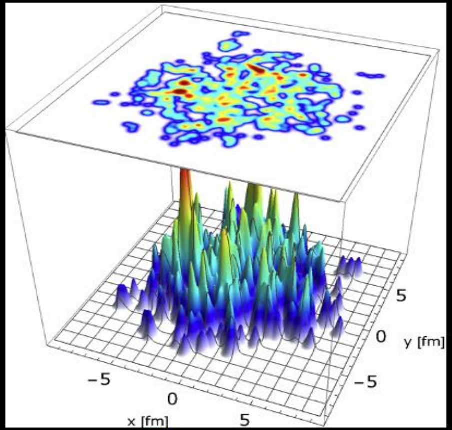
J/Psi Science at the EIC

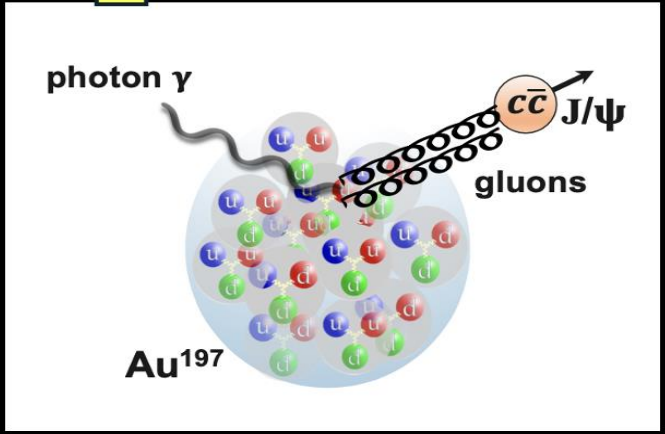
Diffractive J/Psi Production at EIC


Toll & Ullrich (2012)

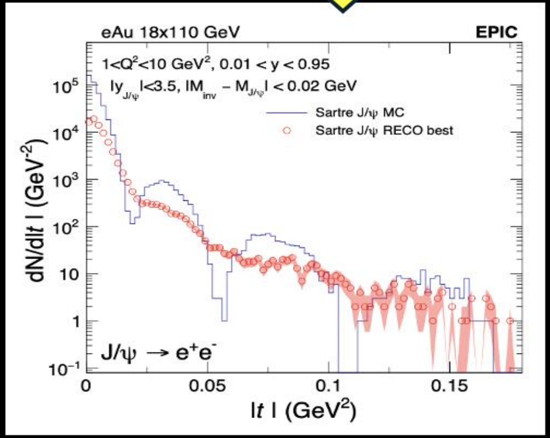
Arjun Kumar





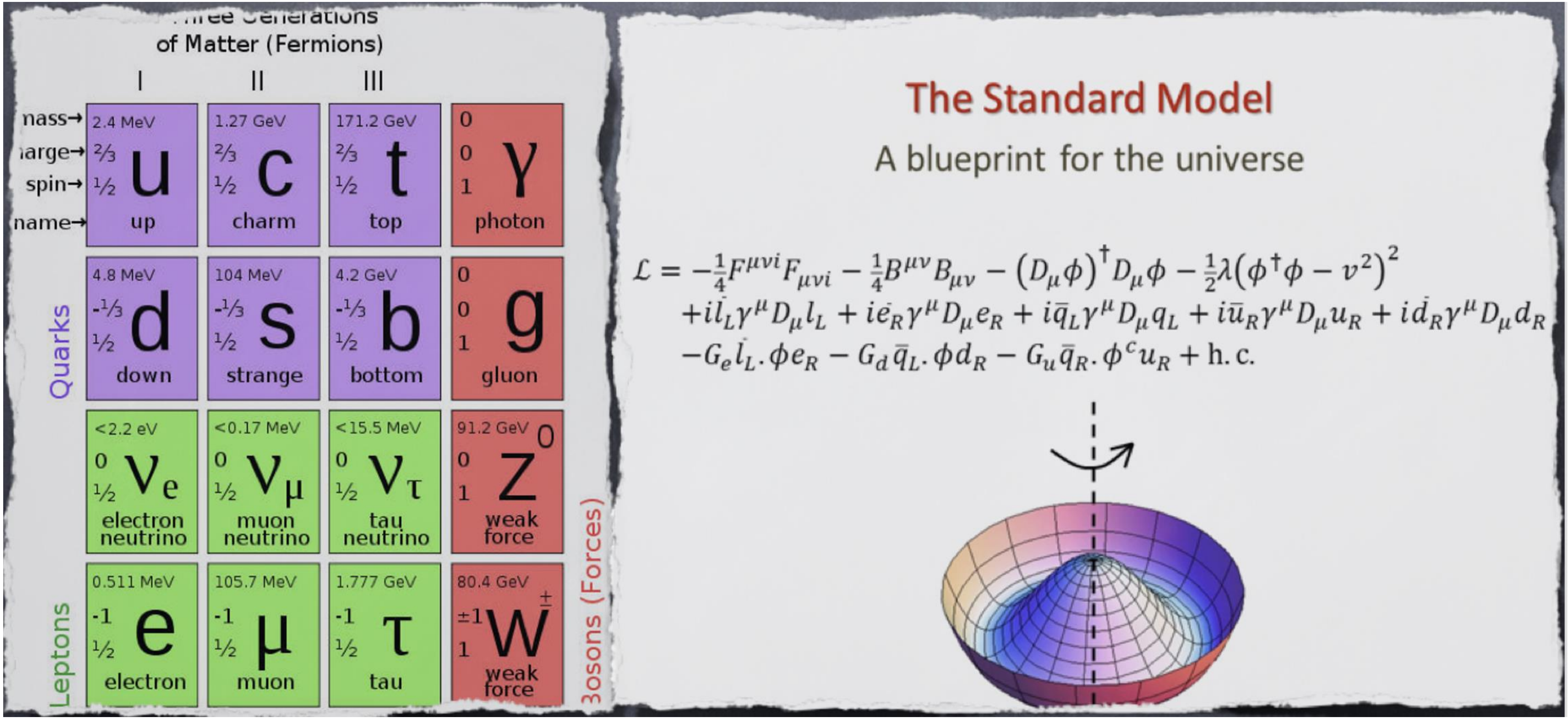


ePIC Detector Simulation



Plots suggestion by Kong Tu

The Standard Model



Three Generations of Matter (Fermions)

	I	II	III	
mass→ iarge→ spin→ name→	2.4 MeV ⅔ ½ u up	1.27 GeV ⅔ ½ c charm	171.2 GeV ⅔ ½ t top	0 0 1 γ photon
Quarks	4.8 MeV -⅓ ½ d down	104 MeV -⅓ ½ s strange	4.2 GeV -⅓ ½ b bottom	0 0 1 g gluon
	<2.2 eV 0 ½ ν_e electron neutrino	<0.17 MeV 0 ½ ν_μ muon neutrino	<15.5 MeV 0 ½ ν_τ tau neutrino	91.2 GeV 0 1 Z^0 weak force
Leptons	0.511 MeV -1 ½ e electron	105.7 MeV -1 ½ μ muon	1.777 GeV -1 ½ τ tau	80.4 GeV ±1 1 $W^\pm$ weak force

Bosons (Forces)

The Standard Model

A blueprint for the universe

$$\mathcal{L} = -\tfrac{1}{4}F^{\mu\nu i}F_{\mu\nu i} - \tfrac{1}{4}B^{\mu\nu}B_{\mu\nu} - (D_\mu\phi)^\dagger D_\mu\phi - \tfrac{1}{2}\lambda(\phi^\dagger\phi - v^2)^2 + i\bar{l}_L\gamma^\mu D_\mu l_L + i\bar{e}_R\gamma^\mu D_\mu e_R + i\bar{q}_L\gamma^\mu D_\mu q_L + i\bar{u}_R\gamma^\mu D_\mu u_R + i\bar{d}_R\gamma^\mu D_\mu d_R - G_e\bar{l}_L.\phi e_R - G_d\bar{q}_L.\phi d_R - G_u\bar{q}_R.\phi^c u_R + \text{h.c.}$$

The Discovery of CPV and the J/Psi provide the foundation for the Standard Model and modern facilities