Flavor physics: past & future

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Belle II

Academie

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Outline

- Why are we (still) interested in all these measurements?
  (i) Many open questions
  (ii) Unexpected discoveries are... unpredictable

- Introduction

- Kaons

- B past

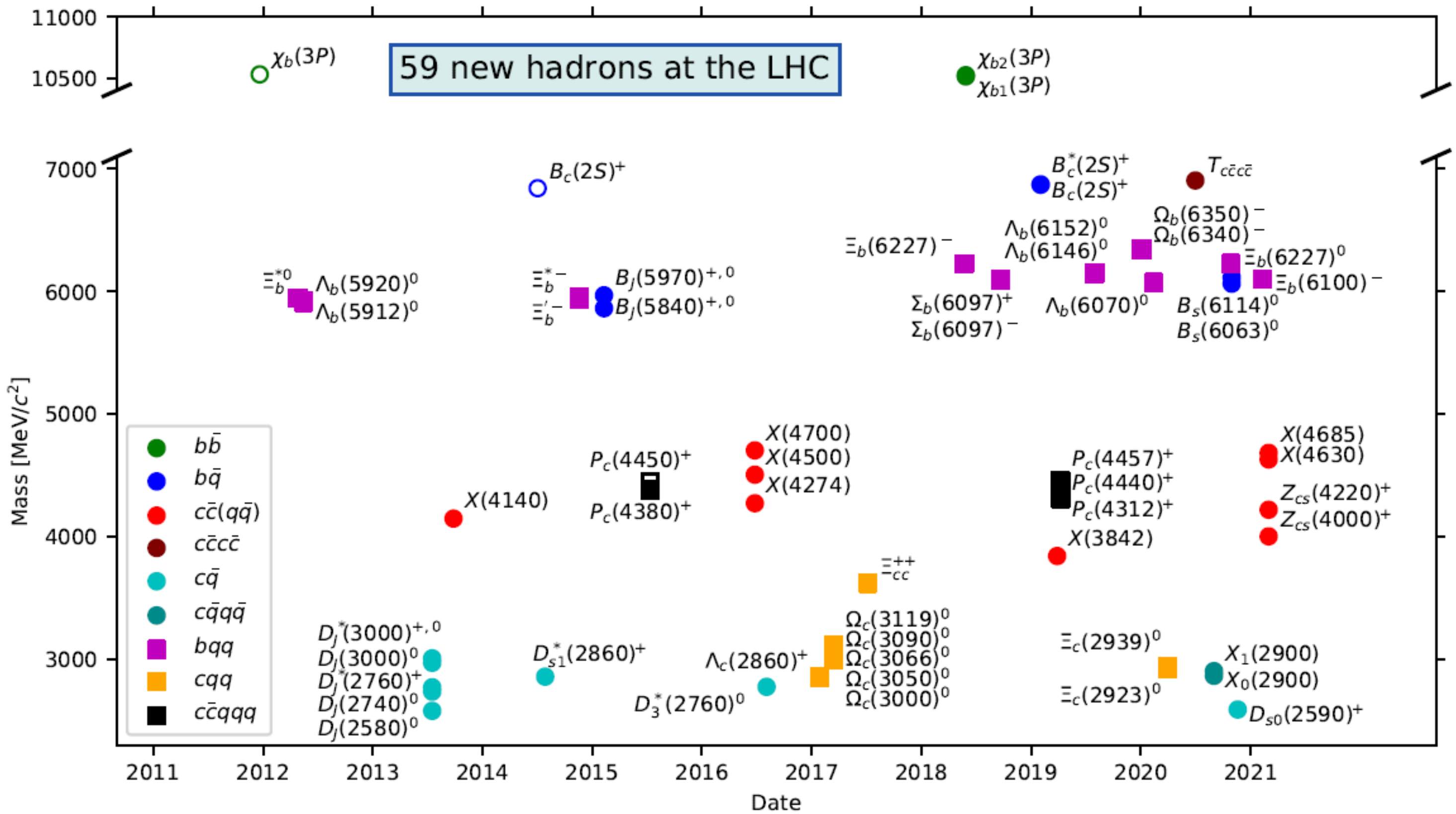
- B future

  $+$ other probes: charm, top, EDMs, higgs

- Please interrupt with any questions or comments. I mean it! (Can't see raised hands)

Disclaimer: won’t talk about spectroscopy

- Most cited Belle & LHCb and 2nd most cited BaBar papers are on spectroscopy (main detector papers aside)



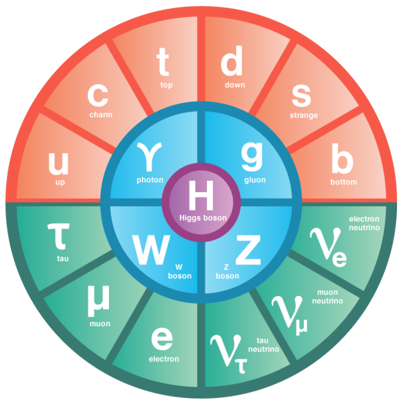
- Could easily be the subject of many talks

What is particle physics?

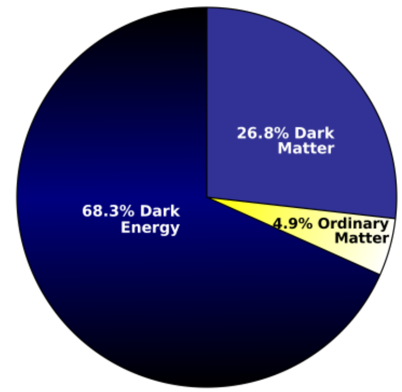
- Elementary interactions and d.o.f.? Observed phenomena consistent with SM

  (Michelson 1894: "... it seems probable that most of the grand underlying principles have been firmly established ...")

- Standard Model of particle physics:



Standard Model of cosmology:



- Inconsistent: Two very successful theories, but this cannot be the full story
  - Dark matter
  - Baryon asymmetry of the Universe
  - Neutrino mass
  - Inflation in the early universe
  - Dark energy

The crucial role of symmetries

- Intimate connection between symmetries and conservation laws [Noether]

  Much of what we know is determined by symmetries, their range of validity, if and how they are violated... interactions, conservation laws, selection rules, forbidden / suppressed processes

  – Continuous symmetries... e.g.: translation — momentum conservation
  – Gauge (internal) symmetries... e.g.: $U(1)$ — electromagnetic interaction

- Discrete symmetries:

  $C =$ charge conjugation

  $P =$ parity ($\vec{x} \leftrightarrow -\vec{x}$)

  $T =$ time reversal ($t \leftrightarrow -t$, initial $\leftrightarrow$ final states)

  CPT cannot be violated in a relativistically covariant local quantum field theory

- Discovered 1957: weak interactions (maximally) violate P and C [Lee & Yang, Nobel 1957]

The Universe: matter vs. antimatter

- Gravity, electromagnetism, strong interaction are same for matter and antimatter
- As the early Universe cooled,
  quarks and antiquarks annihilated

$$\frac{N(\text{baryon})}{N(\text{photon})} \sim 10^{-9} \quad \Rightarrow \quad \frac{N_q - N_{\bar{q}}}{N_q + N_{\bar{q}}} \sim 10^{-9}$$

$$t < 10^{-6}\,\mathrm{s} \;\; (T > 10^{13}\,\mathrm{K} \sim 1\,\mathrm{GeV})$$

- SM prediction: $\sim 10^{10}$ times smaller

  [Nonzero! Sakharov (1966): (i) baryon number violation; (ii) charge (C) and charge-parity (CP) violation; (iii) deviation from thermal equilibrium]

- All present in SM; additional CP violation is required
  What is the microscopic theory of CP violation? How precisely can we probe it?

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What is CP violation?

- Different behavior for particles and antiparticles

  E.g.: $\Gamma(A \to B) \neq \Gamma(\bar{A} \to \bar{B})$, such as $\Gamma(B^0 \to \pi^+\pi^-) \neq \Gamma(\overline{B}^0 \to \pi^+\pi^-)$

- CP violation does not exist classically, requires interference (physical phases)

Why is CP violation interesting?

- SM cannot explain baryon asymmetry $\Rightarrow$ additional CP violation must exist
  - Electroweak baryogenesis? (testable at LHC)
  - Leptogenesis? (Connection to neutrinos?)
  - Something else?

- SM: a single CP violating parameter

  (In the quark sector, neglecting strong CP phase, θ_{QCD}, negligible in flavor changing processes)
  - Strong predictive power (correlations, zeros)
  - Stringent tests of the standard model

- NP: many sources of CP violation possible — neutral current, Higgs, new sectors

CP violation involving known particles: 2, 3, 5?

- Gauge symmetry: $SU(3)_c \times SU(2)_L \times U(1)_Y$ — param's (CPV)

  8 gluons $W^\pm$, Z^0, γ — $3\ (+\theta_{\rm QCD})$

- Particle content: 3 generations of quarks and leptons

  $Q_L(3,2)_{1/6},\ u_R(3,1)_{2/3},\ d_R(3,1)_{-1/3}$ — $10\ (1)$

  $L_L(1,2)_{-1/2},\ \ell_R(1,1)_{-1}$ — $12\ (3)$ or $10\ (1)$

  quarks: $\begin{pmatrix} u & c & t \\ d & s & b \end{pmatrix}$ leptons: $\begin{pmatrix} \nu_1 & \nu_2 & \nu_3 \\ e & \mu & \tau \end{pmatrix}$

- Symmetry breaking: $SU(2)_L \times U(1)_Y \ \to\ U(1)_{\rm EM}$

  $\phi(1,2)_{1/2}$ Higgs, with vev: $\langle\phi\rangle = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}$ — $2\ (0)$

Not known: $\mathcal{L}_Y = -Y_e^{ij}\, \overline{L^I_{Li}}\, \phi\, e^I_{Rj} - \begin{cases} \frac{Y_\nu^{ij}}{\Lambda}\, L^I_{Li} L^I_{Lj}\, \phi\, \phi & \text{violates lepton number} \\ Y_\nu^{ij}\, \overline{L^I_{Li}}\, \tilde\phi\, \nu^I_{Rj} & \text{requires } \nu_R \text{ fields} \end{cases}$

- We do not know what is the Lagrangian that describes the observed particles!

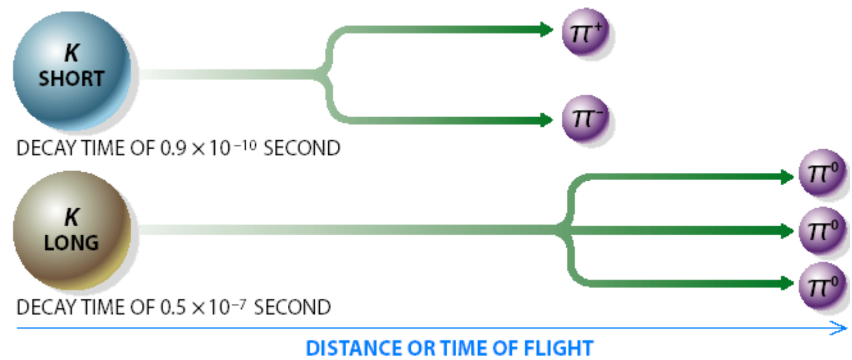
Brief history of CP violation

- 1964 – 1999: CP violation discovered in K decay, "ϵ" [fitted w/ CKM phase, not a test]
- 1999: second CP violation measured in kaons, "ϵ'/ϵ" [notoriously hard to calculate]
- 1999 – 2010:
  e^+e^- B-factory experiments, BaBar (Stanford) and Belle (Tsukuba), measured dozens of CP violating observables in B meson processes
- 2009 – 2019:
  LHCb: improvements + CP violation in B_s mesons with comparable precision
- 2019:
  LHCb: discovery of CP violation in D meson decay $(A_{K^+K^-} - A_{\pi^+\pi^-})$
- CP violation in itself is no longer automatically interesting, only if sensitive to NP
- One CP violating parameter (KM phase) can account for it all so far

Kaons

1964: CP symmetry is broken

- The CP symmetry was expected to hold



- Two neutral states, nearly equal mass, but lifetime ratio > 500 — phase space

  $CP\,|K^0\rangle = e^{i\varphi}|\overline{K}^0\rangle,\ CP|\overline{K}^0\rangle = e^{-i\varphi}|K^0\rangle$

  If CP conserved: CP eigenstates $=$ mass eigenstates $|K_{S,L}\rangle = \frac{1}{\sqrt{2}}(|K^0\rangle \pm e^{i\varphi}|\overline{K}^0\rangle)$

  $\pi\pi$ in $J=0$ state has $CP=+1$, so only $K_S \to \pi\pi$

- Discovered in 1964:

(0.2%) (Nobel prize, 1980)

- A new CP violating interaction? Is CP an approximate symmetry?

  [Before charm and much of the SM; could involve new particles / interactions; SM not “minimal”]

  Many options... No other independent observation of CP violation until 1999

It was a surprise...

PROPOSAL FOR K^o_2 DECAY AND INTERACTION EXPERIMENT

J. W. Cronin, V. L. Fitch, R. Turlay

(April 10, 1963)

I. INTRODUCTION

The present proposal was largely stimulated by the recent anomalous results of Adair et al., on the coherent regeneration of K^o_1 mesons. It is the purpose of this experiment to check these results with a precision far transcending that attained in the previous experiment. Other results to be obtained will be a new and much better limit for the partial rate of $K^o_2 \to \pi^+ + \pi^-$, a new limit for the presence (or absence) of neutral currents as observed through $K_2 \to \mu^+ + \mu^-$. In addition, if time permits, the coherent regeneration of K_1's in dense materials can be observed with good accuracy.

II. EXPERIMENTAL APPARATUS

Fortuitously the equipment of this experiment already exists in operating condition. We propose to use the present 30° neutral beam at the A.G.S. along with the di-pion detector and hydrogen target currently being used by Cronin, et al. at the Cosmotron. We further propose that this experiment be done during the forthcoming μ-p scattering experiment on a parasitic basis.

The di-pion apparatus appears ideal for the experiment. The energy resolution is better than 4 Mev in the m^* or the Q value measurement. The origin of the decay can be located to better than 0.1 inches. The 4 Mev resolution is to be compared with the 20 Mev in the Adair bubble chamber. Indeed it is through the greatly improved resolution (coupled with better statistics) that one can expect to get improved limits on the partial decay rates mentioned above.

III. COUNTING RATES

We have made careful Monte Carlo calculations of the counting rates expected. For example, using the 30° beam with the detector 60-ft. from the A.G.S. target we could expect 0.6 decay events per 10^{11} circulating protons if the K_2 went entirely to two pions. This means that one can set a limit of about one in a thousand for the partial rate of $K_2 \to 2\pi$ in one hour of operation. The actual limit is set, of course, by the number of three-body K_2 decays that look like two-body decays. We have not as yet made detailed calculations of this. However, it is certain that the excellent resolution of the apparatus will greatly assist in arriving at a much better limit.

If the experiment of Adair, et al. is correct the rate of coherently regenerated K_1's in hydrogen will be approximately 80/hour. This is to be compared with a total of 20 events in the original experiment. The apparatus has enough angular acceptance to detect incoherently produced K_1's with uniform efficiency to beyond 15°. We emphasize the advantage of being able to remove the regenerating material (e.g., hydrogen) from the neutral beam.

IV. POWER REQUIREMENTS

The power requirements for the experiment are extraordinarily modest. We must power one 18-in. x 36-in. magnet for sweeping the beam of charged particles. The two magnets in the di-pion spectrometer are operated in series and use a total of 20 kw.

⇒ Cronin & Fitch, Nobel Prize, 1980

⇒ 3 generations, Kobayashi & Maskawa, Nobel Prize, 2008

A near miss: factor-of-2 improvements matter

ANNALS OF PHYSICS: 5, 156–181 (1958)

Long-lived Neutral K Mesons*

M. BARDON, K. LANDE, AND L. M. LEDERMAN

Columbia University, New York, New York, and Brookhaven National Laboratories, Upton, New York

AND

WILLIAM CHINOWSKY

Brookhaven National Laboratories, Upton, New York

set an upper limit $<0.6\%$ on the reactions

$$K_2^0 \rightarrow \begin{cases} \mu^{\pm} + e^{\mp} \\ e^+ + e^- \\ \mu^+ + \mu^- \end{cases}$$

and on $K_2^0 \rightarrow \pi^+ + \pi^-$.

VOLUME 6, NUMBER 10 PHYSICAL REVIEW LETTERS MAY 15, 1961

DECAY PROPERTIES OF K_2^0 MESONS*

D. Neagu, E. O. Okonov, N. I. Petrov, A. M. Rosanova, and V. A. Rusakov
Joint Institute of Nuclear Research, Moscow, U.S.S.R.
(Received April 20, 1961)

Combining our data with those obtained in reference 7, we set an upper limit of 0.3 % for the relative probability of the decay $K_2^0 \rightarrow \pi^- + \pi^+$. Our

"At that stage the search was terminated by administration of the Lab."

[Okun, hep-ph/0112031]

VOLUME 13, NUMBER 4 PHYSICAL REVIEW LETTERS 27 JULY 1964

EVIDENCE FOR THE 2π DECAY OF THE K_2^0 MESON*†

J. H. Christenson, J. W. Cronin,‡ V. L. Fitch,‡ and R. Turlay§
Princeton University, Princeton, New Jersey
(Received 10 July 1964)

We would conclude therefore that K_2^0 decays to two pions with a branching ratio $R = (K_2 \rightarrow \pi^+ + \pi^-)/(K_2^0 \rightarrow \text{all charged modes}) = (2.0 \pm 0.4) \times 10^{-3}$ where the error is the standard deviation. As empha-

Timeline of discovery, superweak, KM paper

- History often different from what may seem "obvious" later:

EVIDENCE FOR THE 2π DECAY OF THE K_2^0 MESON*†

J. H. Christenson, J. W. Cronin,‡ V. L. Fitch,‡ and R. Turlay§
Princeton University, Princeton, New Jersey
(Received 10 July 1964)

VIOLATION OF *CP* INVARIANCE AND THE POSSIBILITY OF VERY WEAK INTERACTIONS*

L. Wolfenstein
Carnegie Institute of Technology, Pittsburgh, Pennsylvania
(Received 31 August 1964)

_CP_-Violation in the Renormalizable Theory of Weak Interaction

Makoto KOBAYASHI and Toshihide MASKAWA

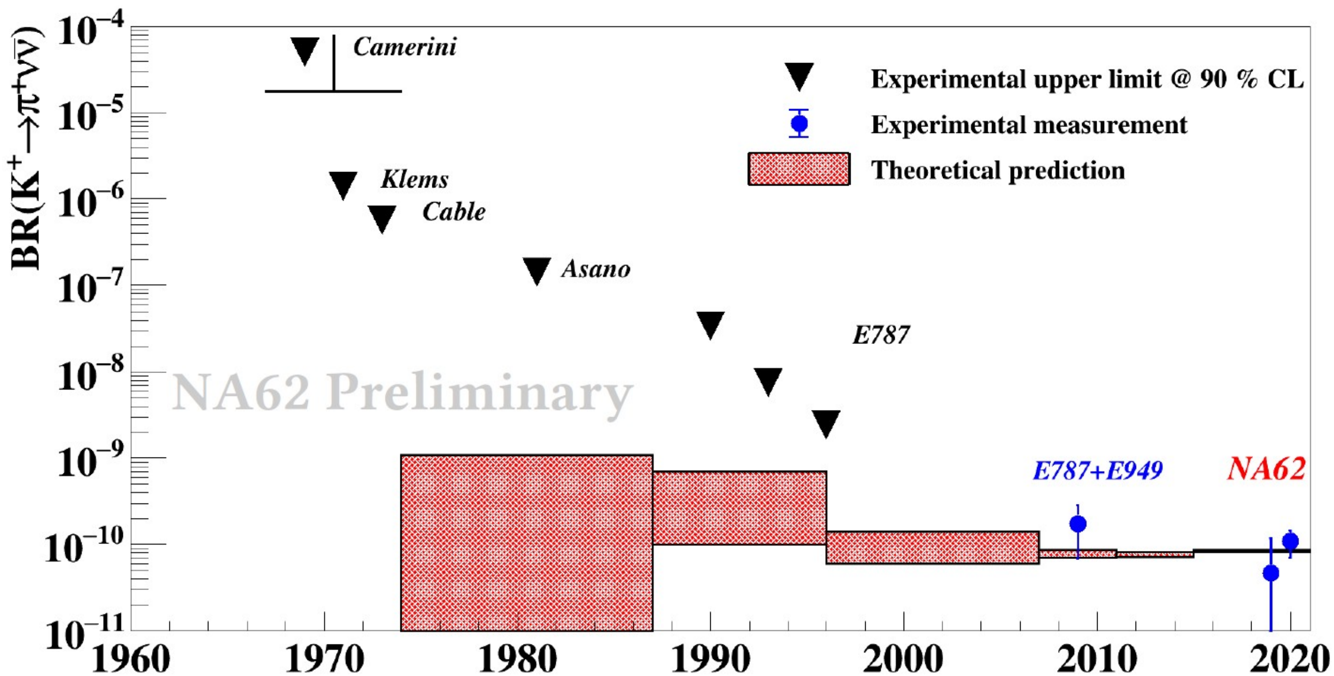
Department of Physics, Kyoto University, Kyoto

(Received September 1, 1972)

The quest for $K \to \pi\nu\bar{\nu}$

- Theoretically clean: $K_L \to \pi^0\nu\bar{\nu}$ is CP violating, $K^+ \to \pi^+\nu\bar{\nu}$ is dominantly so

  50 years of searches, sensitive to $\mathcal{O}(100\,\text{TeV})$ ("longer than for Higgs" — Mary K Gaillard)

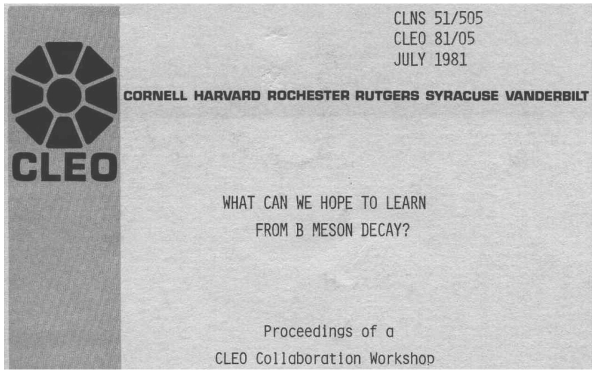


- NA62 @ ICHEP: $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (11.0^{+4.0}_{-3.5}) \times 10^{-11}$ — at the SM level
- KOTO, 2019: 4 events in $K_L \to \pi^0\nu\bar{\nu}$ search; @ ICHEP: $4 \to 3$ w/ 1.05 ± 0.28 BG

CP violation in B decays

b quark (Υ resonance) discovered 1977

1981 plans: not mixing nor CPV


CLNS 51/505
CLEO 81/05
JULY 1981

CLEO

CORNELL HARVARD ROCHESTER RUTGERS SYRACUSE VANDERBILT

WHAT CAN WE HOPE TO LEARN
FROM B MESON DECAY?

Proceedings of a
CLEO Collaboration Workshop

Fig. 3. A Program to Understand B Decay

1. Search for exotic B decays.
   If found, explore details;
   -otherwise-

⇒ dark sector searches? symmetry violations?

2. Search for flavor changing neutral currents.
   If found, measure $(b \to dZ^o)/(b \to sZ^o)$;
   -otherwise-

⇒ big part of the program

3. Measure semileptonic decay branching ratio.

⇒ big part of the program

4. Measure ratio $(b \to uW^-)/(b \to cW^-)$.

⇒ $|V_{ub}/V_{cb}|$: essential to constrain NP

5. Measure $e\nu:\mu\nu:\tau\nu$ ratio in semileptonic decay.

⇒ Prophecy of $R(D^{(*)})$?
(Hardly ever discussed 1982 – 2012, as far as I know)

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Non-b-Decay Features of B Decay

6. Look for lifetime difference between $B^{\pm}$ and B^o.

⇒ Less important

7. Look for B^o–$\bar{B}^o$ mixing.

⇒ Was the first on this list discovered

[8. CP violation?]

⇒ Became a central focus of the field

[Ed Thorndike, overview at a CLEO planning workshop, 1981]

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Past surprises exploring b quark properties

- 1977: Υ discovery — after $6\,\mathrm{GeV}$ "Oops-Leon" in 1976 [Lederman et al. @ Fermilab]

- 1983: Long B meson lifetime $\Rightarrow |V_{cb}|$ is small [MAC & Mark II @ SLAC]

  If $|V_{cb}|$ were as large as $|V_{us}|$, no time dependent measurements...

- 1987: $B^0 - \overline{B}^0$ mixing discovered, ARGUS, PLB 192 (1987) 245

  $$r = 0.21 \pm 0.08 = \text{(decay, after mixing)}\big/\text{(decay, no mixing)}$$

  Few months earlier: CLEO, PRL 58 (1987) 183: $r < 0.24$ $(90\%$ CL)

  (Took 2 more years to confirm ARGUS — can be rather different to set limits vs. observe signals)

  Implied: $m_t > m_W$ (bound was $23\,\mathrm{GeV}$) $\Rightarrow$ no top hadrons, maximal B_s mixing

  $\Rightarrow$ SM predicts large CP violation, and large FCNC B decay rates

- Also in 1987: idea of asymmetric e^+e^- B factory [P. Oddone]

The Machine (1989)

LBL PUB-5244
SLAC-352
CALT-68-1589

FEASIBILITY STUDY for an ASYMMETRIC B FACTORY BASED ON PEP

October 1989

Lawrence Berkeley Laboratory
1 Cyclotron Road
Berkeley, California 94720

Stanford Linear Accelerator Center
Stanford University • Stanford, California 94305

California Institute of Technology
Pasadena, California 91125

Prepared for the U.S. Department of Energy under Contract Numbers DE-AC03-76SF00098, DE-AC03-76SF00515, and DE-AC03-81-ER40050.

1.2. APIARY: PEP plus a New 3.1-GeV Ring

We have conducted preliminary investigations of a design for a B factory to be sited at SLAC. The specific scenario we consider, APIARY (Asymmetric Particle Interactions Accelerator Research Yard), involves a high-luminosity, asymmetric, 9 GeV $\times$ 3.1 GeV electron-positron collider with a high-energy storage ring based on PEP and a newly constructed low-energy ring.

(APIARY is no more contrived than BaBar as an abbreviation)

SLAC-353
LBL PUB-5245
CALT-68-1588
UC-414
(T/E)

THE PHYSICS PROGRAM
OF A
HIGH-LUMINOSITY ASYMMETRIC B FACTORY AT SLAC

ABSTRACT

A high-luminosity asymmetric energy B Factory, proposed as an upgrade to the PEP storage ring at SLAC, provides the best opportunity to study CP violation as a means of testing the consistency of the Standard Model. If the phenomenon of CP violation is explained by the Standard Model simply through the non-zero angles and phase of the Kobayashi-Maskawa matrix, then there are precise relations between the K-M parameters and the various measurable CP-violating asymmetries in B meson decay. Should these consistency relations fail, the origin of CP violation must lie outside the Standard Model framework. Our measurements would then lead to the first experiment-driven extensions of the Standard Model.

The B Factory will also carry out a varied, high-quality program of studies of other aspects of the physics of b quarks, as well as high-precision measurements in τ and charm physics. We describe a detailed series of measurements to be carried out in the first few years at a peak luminosity of 3×10^{33} cm^{-2}sec^{-1}, the initial luminosity goal of the B Factory, as well as the program accessible to a larger data sample.

Work supported in part by the Department of Energy
under contracts DE-AC03-76SF00515, DE-AC03-76SF00098 and DE-AC03-81-ER40050

Printed in the United States of America. Available from the National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Road, Springfield, Virginia 22161. Price: Printed Copy A12, Microfiche A01.

The Physics (1989)

Questions, 1999: is SM qualitatively correct?

- Until 1999, ϵ was the only measured CPV; $\epsilon'/\epsilon \neq 0$ only established in 1999
- Not known if the SM picture of CPV even approx. correct; other sources of CPV?
  - CPV in $\Delta F = 2$ only (superweak)? Also in $\Delta F = 1$?
  - Are all CPV effects small? Or only small in kaons due to small mixing angles?
  - One or more CPV parameters?
  - CPV relates to charged currents only? Also in neutral currents?
  - Does CPV treat 3rd generation special? Up / down sectors?
  - CPV in flavor changing interactions only? EDM searches?
  - CPV only in quark sector? Also in lepton sector?
  - Find new sources of CPV that could help with baryogenesis?

Questions, now: solutions to flavor puzzles?

- Flavor $\equiv$ what distinguishes generations? [break $U(3)_Q \times U(3)_u \times U(3)_d \times U(3)_L \times U(3)_e$]

  Experimentally, rich and sensitive ways to probe SM, and search for NP

- SM flavor: masses? mixing angles? 3 generations? — most of the SM param's

  Flavor in SM is simple: only Higgs – fermion couplings break flavor symmetries

- BSM flavor: TeV scale (hierarchy problem) $\ll$ "naive" flavor & CP viol. scale

  Most TeV-scale new physics contain new sources of CP and flavor violation

  E.g., SUSY: $\sim 10\times$ increase in flavor parameters (CP and flavor problems?)

  Generic TeV-scale flavor structure excluded $\Rightarrow$ new mechanisms to reduce signals

- Many BSM models have observable signals, baryogenesis remains a puzzle

- Any new particle that couples to quarks or leptons $\Rightarrow$ new flavor parameters

  (Understanding these param's can be crucial; e.g., Higgs, or squark & slepton couplings [if exists])

B physics: key ingredients

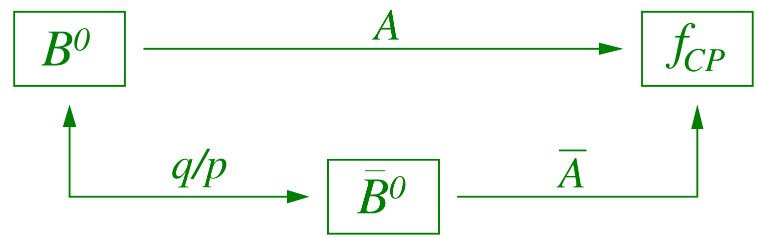
- Many interesting processes with clean theoretical interpretations:
  - Top quark loops not strongly suppressed (GIM less effective)
  - Large CP violating effects possible, some with clean interpretation
  - Some of the hadronic physics understood model independently $(m_b \gg \Lambda_{\rm QCD})$
- Experimentally feasible to study:
  - $\Upsilon(4S)$ resonance is clean source of B mesons
  - Long B meson lifetime

    (If $|V_{cb}|$ were as large as $|V_{us}|$, no B factories built, this talk would not take place, etc.)
  - Timescale of oscillation and decay comparable: $\Delta m/\Gamma \simeq 0.77$ (and $\Delta\Gamma \ll \Gamma$)
- Time-dependent measurements: asymmetric e^+e^- colliders (essential before LHC)

$\Bigg($ CP violation

CPV in interference between decay and mixing

- Can get theoretically clean information in some cases when B^0 and $\overline{B}^0$ decay to same final state



Mass eigenstates: $|B_{H,L}\rangle = p|B^0\rangle \mp q|\overline{B}^0\rangle$

- Time-dependent CP asymmetry:

$$a_{f_{CP}} = \frac{\Gamma[\overline{B}^0(t) \to f_{CP}] - \Gamma[B^0(t) \to f_{CP}]}{\Gamma[\overline{B}^0(t) \to f_{CP}] + \Gamma[B^0(t) \to f_{CP}]}$$

- If amplitudes with one weak phase dominate, hadronic physics drops out:

$$a_{f_{CP}} = (\pm 1)\sin(\text{phase difference between decay paths})\,\sin(\Delta m\, t)$$

$$\arg[(q/p)(\overline{A}/A)]$$

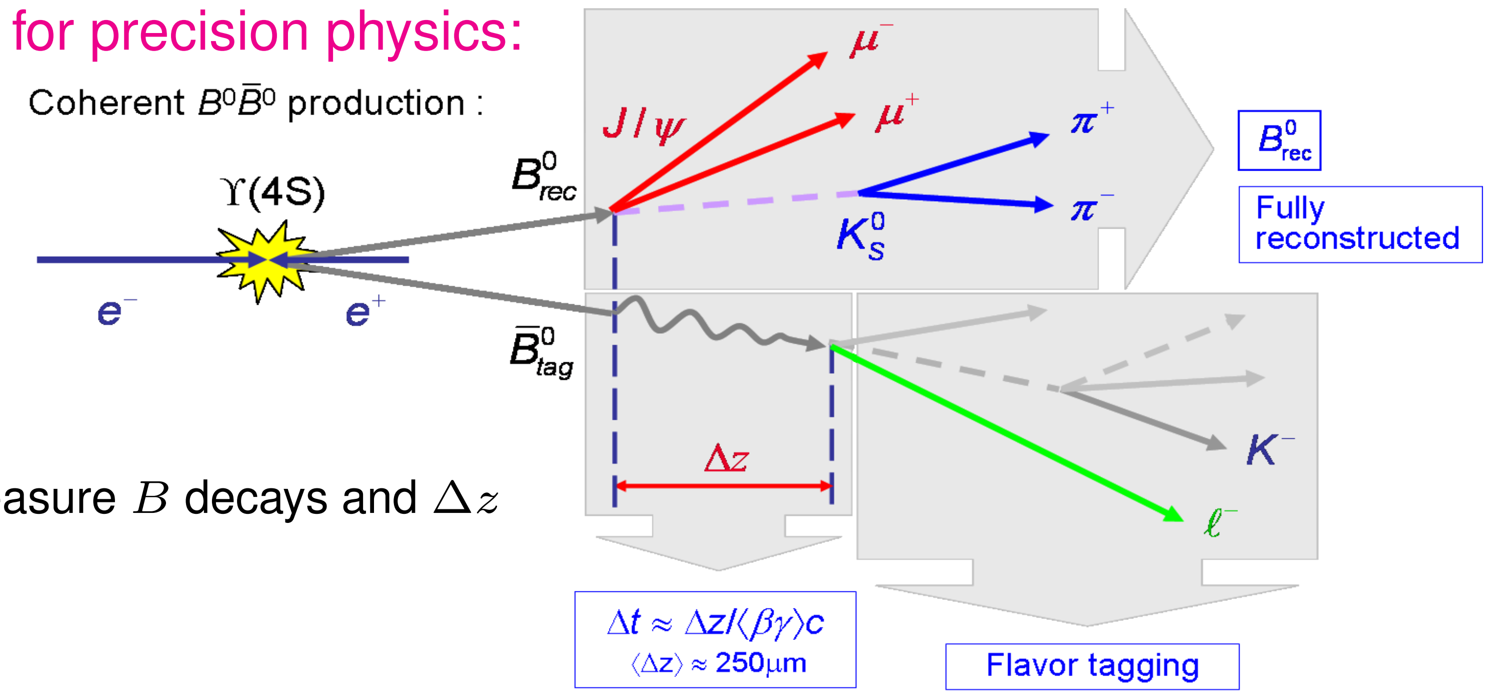
- Measure phases in the Lagrangian with small theoretical uncertainties

Quantum entanglement — use EPR

- $B^0\overline{B}^0$ pair created in a p-wave ($L = 1$) evolve coherently and undergo oscillations

  Two identical bosons must be in a symmetric state — if one decays as a B^0 ($\overline{B}^0$), then at the same time the other B must be $\overline{B}^0$ (B^0)

- EPR effect used for precision physics:



Measure B decays and Δz

- First decay ends quantum correlation and determines flavor of other B at $t = t_1$

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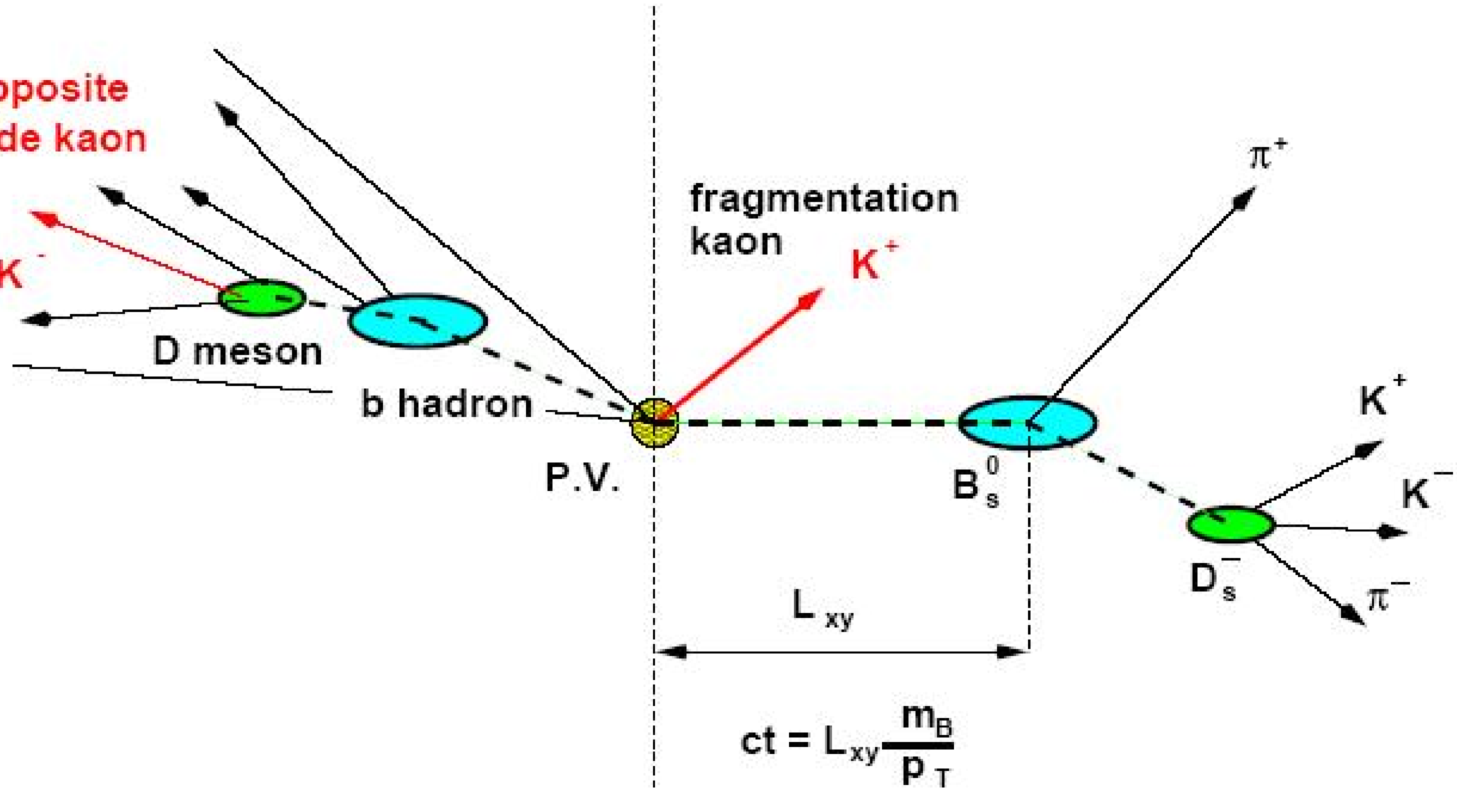
Hadron colliders — no quantum correlation

- B_s^0 with sufficient boost to study CPV at Tevatron & LHC (+ Belle data on rates)



- $gg,\ q\bar{q} \to b\bar{b}$: measure flavor of a b hadron, and flavor of B_s^0 as a function of time

Need excellent time resolution, and fully reconstructed B_s^0 to know its boost

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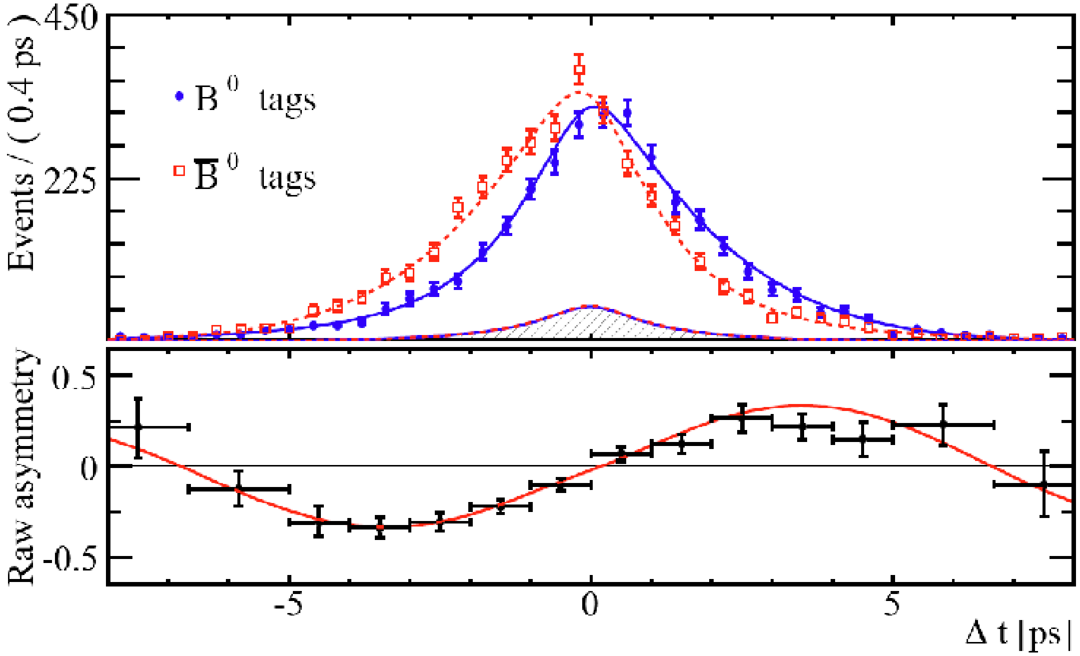
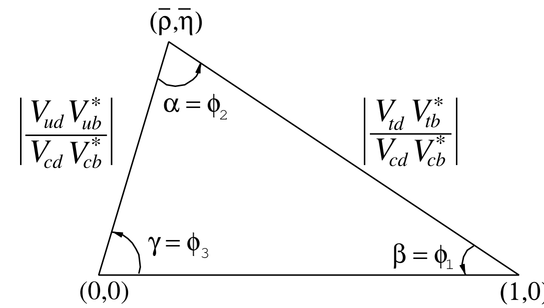
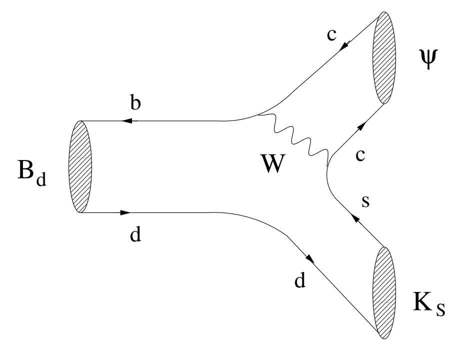
CP violation in $B \to \psi K_S$ by the naked eye

- CP violation is an $\mathcal{O}(1)$ effect: $\sin 2\beta = 0.699 \pm 0.017$







$$a_{f_{CP}} = \frac{\Gamma[\overline{B}^0(t) \to \psi K] - \Gamma[B^0(t) \to \psi K]}{\Gamma[\overline{B}^0(t) \to \psi K] + \Gamma[B^0(t) \to \psi K]} = \sin 2\beta \, \sin(\Delta m \, t)$$

- CP violation in K decays is small because of small CKM elements, not because CP violation is generically small — it is $\mathcal{O}(1)$ in some B decays

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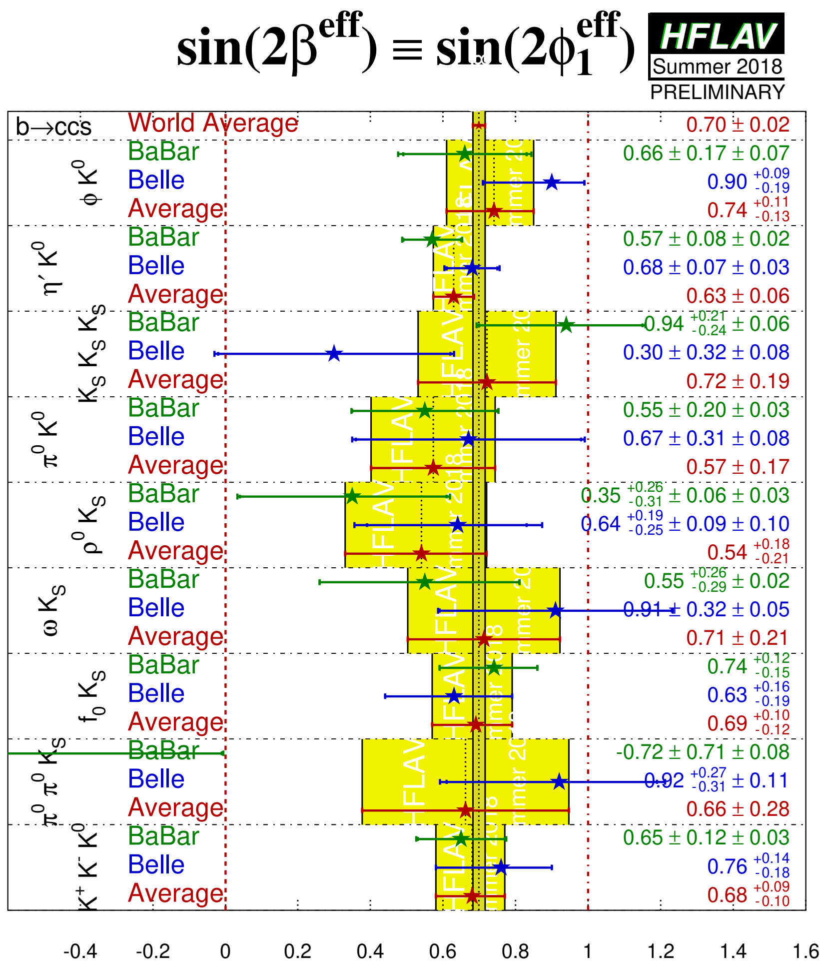
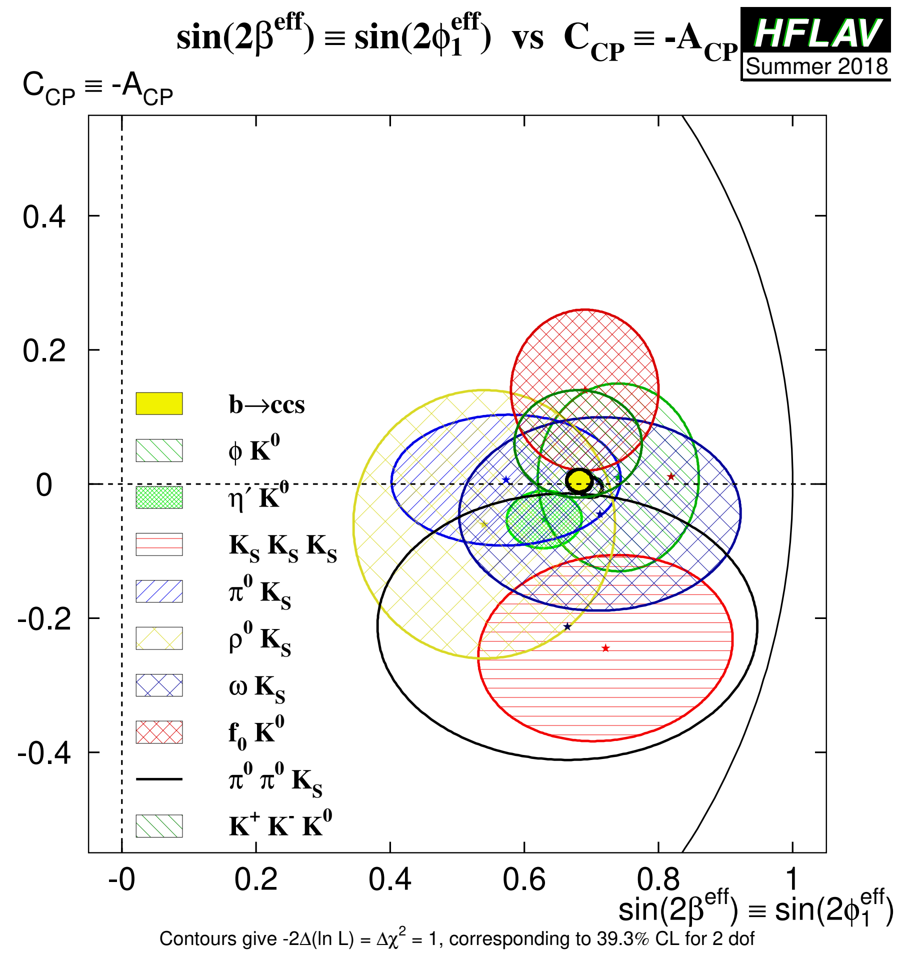
$\sin 2\beta$ in $b \to s\bar{s}s$ "penguin" modes

- In the SM, very close to $S_{\psi K}$ — earlier hints of tensions gone, e.g., in $S_{\phi K}$, $S_{\eta' K}$





- Interesting to significantly reduce current experimental uncertainties

CP violation $\Big)$

Testing quark flavor (take I)

- The $(u,\, c,\, t)\ W^{\pm}\ (d,\, s,\, b)$ couplings:

$$V_{\rm CKM} = \underbrace{\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}}_{\text{CKM matrix}} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \ldots$$

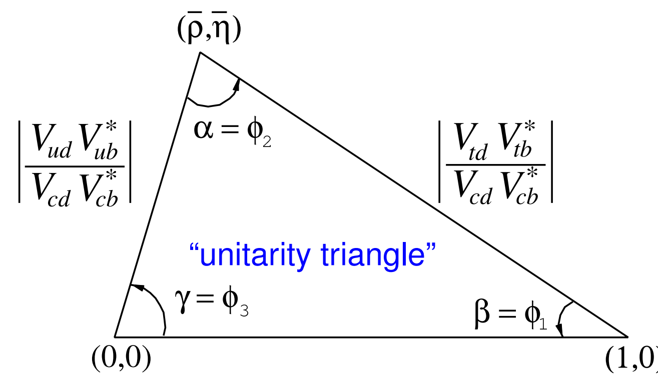
Only 4 parameters: λ ("Cabibbo angle", from $K \to \pi\ell\nu$), A (from $b \to c\ell\nu$)

used to be less precise: $\bar\rho$ and $\bar\eta$ (only source of CP violation)

CKM measurements: magnitudes $\sim$ decay rates, phases $\sim$ CP violation

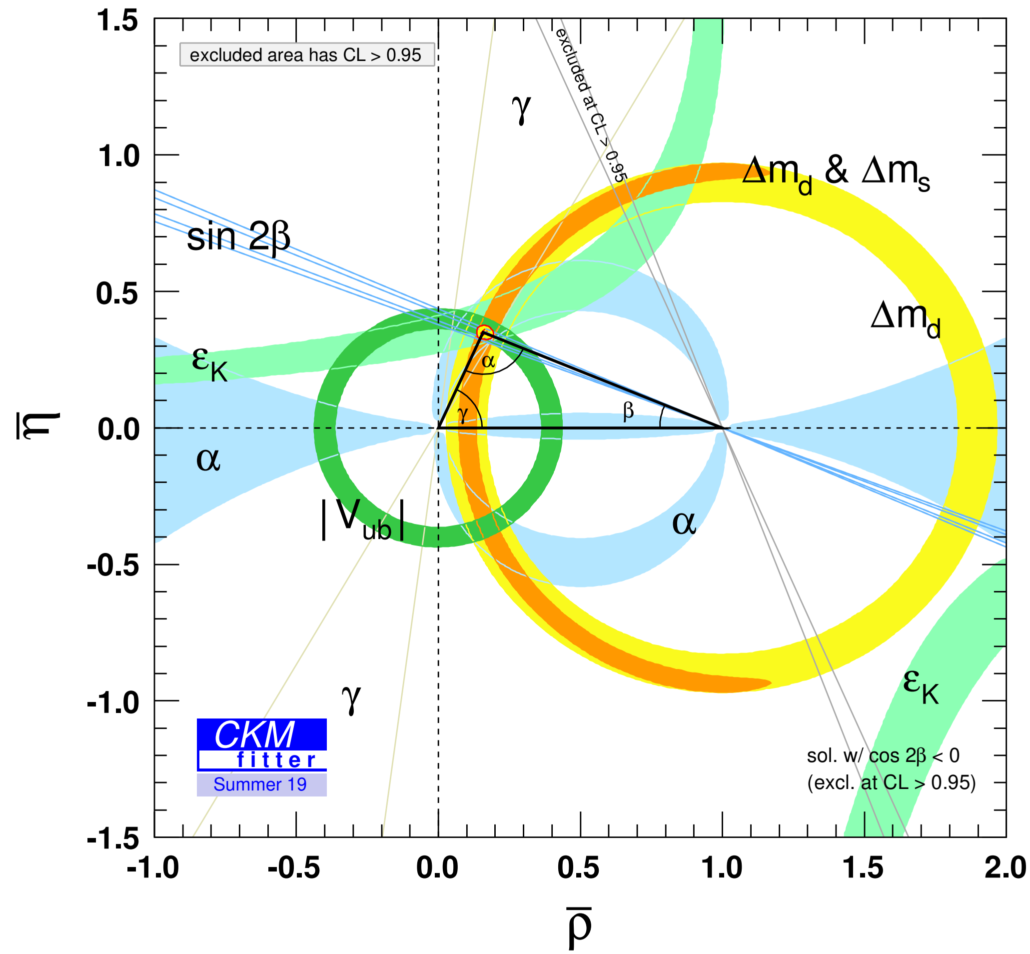
9 complex observables $\Rightarrow$ many testable relations

- Many observables are $f(\rho, \eta)$ — want to compare:
  - $b \to u\ell\bar\nu \ \Rightarrow\ |V_{ub}/V_{cb}|^2 \propto \rho^2 + \eta^2$
  - $\Delta m_{B_d}/\Delta m_{B_s} \ \Rightarrow\ |V_{td}/V_{ts}|^2 \propto (1-\rho)^2 + \eta^2$
  - CP violation in K, B, B_s decay



The B-factories money plot

- Spectacular progress in last 20 years
- The CKM mechanism dominates CP violation & flavor changing processes
- The implications of the consistency of measurements are often overstated
- Larger allowed region if there is NP



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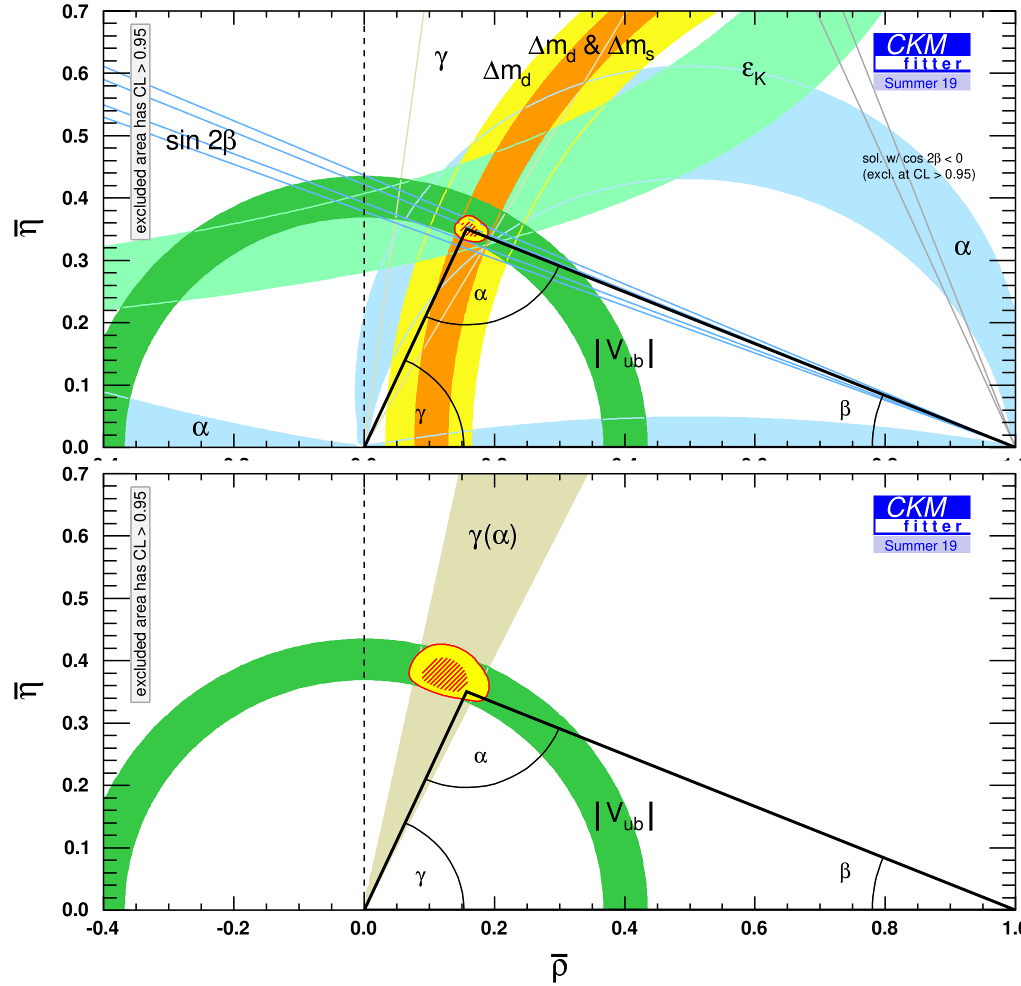
The B-factories money plot

- Spectacular progress in last 20 years
- The CKM mechanism dominates CP violation & flavor changing processes
- The implications of the consistency of measurements are often overstated
- Larger allowed region if there is NP
- Compare tree-level (lower plot) and loop-dominated measurements
- LHCb: constraints in the B_s sector (2nd–3rd gen.) caught up with B_d



- $\mathcal{O}(20\%)$ NP contributions to most loop-level processes (FCNC) are still allowed

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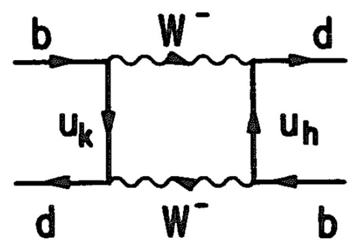
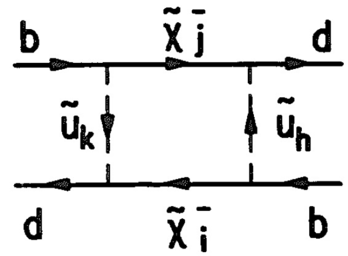
Testing quark flavor (take II)

- Assume that NP is negligible in tree-level processes, arbitrary in FCNCs (loops)
- Consider tree-level $+$ meson mixing:





SM: $\dfrac{C_{\rm SM}}{m_W^2}$ NP: $\dfrac{C_{\rm NP}}{\Lambda^2}$

General parametrization of many models by two real parameters (in addition to SM):

$$h\, e^{2i\sigma} = A_{\rm NP}(B^0 \to \overline{B}^0) / A_{\rm SM}(B^0 \to \overline{B}^0)$$

↖ ↑ NP parameters

What is the scale Λ? How different is the $C_{\rm NP}$ coupling from $C_{\rm SM}$?

- Is $h = \mathcal{O}(1)$ allowed? If not, the CKM mechanism dominates

To answer, redo CKM fit: tree-dominated unchanged, loop-mediated modified

(Importance of these constraints known since the 1970s, conservative picture of future progress)

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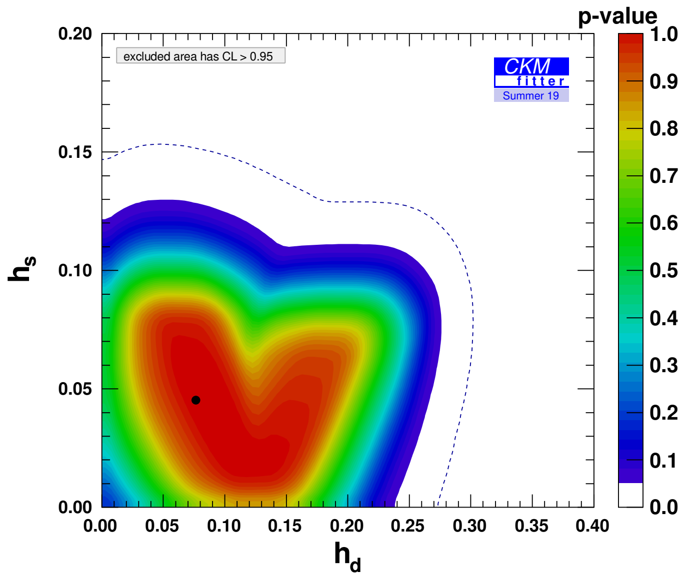
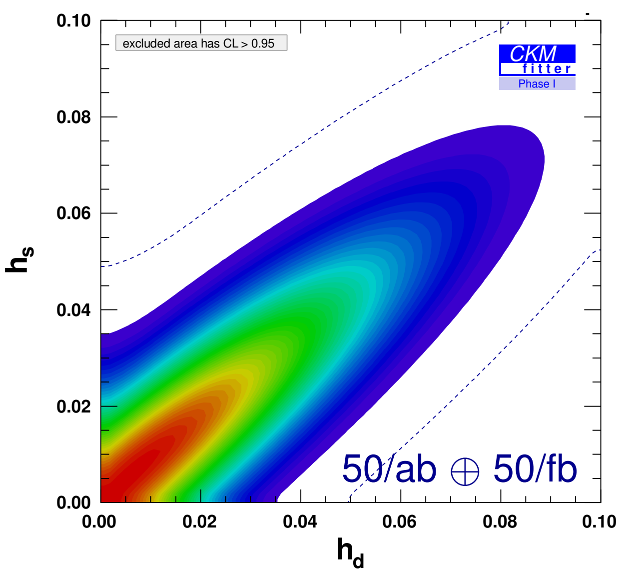
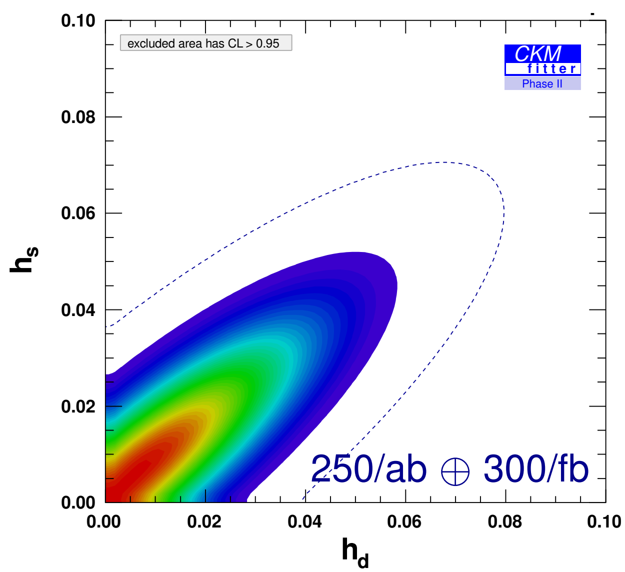
Future sensitivity to NP in B mixing



- What NP parameter space can be probed?
- $h_{d,s} \Leftrightarrow$ NP scale: $h \simeq \dfrac{|C_{ij}|^2}{|V_{ti}^* V_{tj}|^2} \left(\dfrac{4.5\ \text{TeV}}{\Lambda} \right)^2$ [2006.04824]

Couplings	NP loop order	Sensitivity for Summer 2019 [TeV]		Phase I Sensitivity [TeV]		Phase II Sensitivity [TeV]	
		B_d mixing	B_s mixing	B_d mixing	B_s mixing	B_d mixing	B_s mixing
$\lvert C_{ij}\rvert = \lvert V_{ti}V_{tj}^*\rvert$	tree level	9	13	17	18	20	21
(CKM-like)	one loop	0.7	1.0	1.3	1.4	1.6	1.7
$\lvert C_{ij}\rvert = 1$	tree level	1×10^3	3×10^2	2×10^3	4×10^2	2×10^3	5×10^2
(no hierarchy)	one loop	80	20	2×10^2	30	2×10^2	40





Big improvements in 2020s

Complementary to high-p_T searches

Then theory improves or progress slows

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Future

Huge increases in data sets

Does not matter if CP violating or conserving — only sensitivity to NP

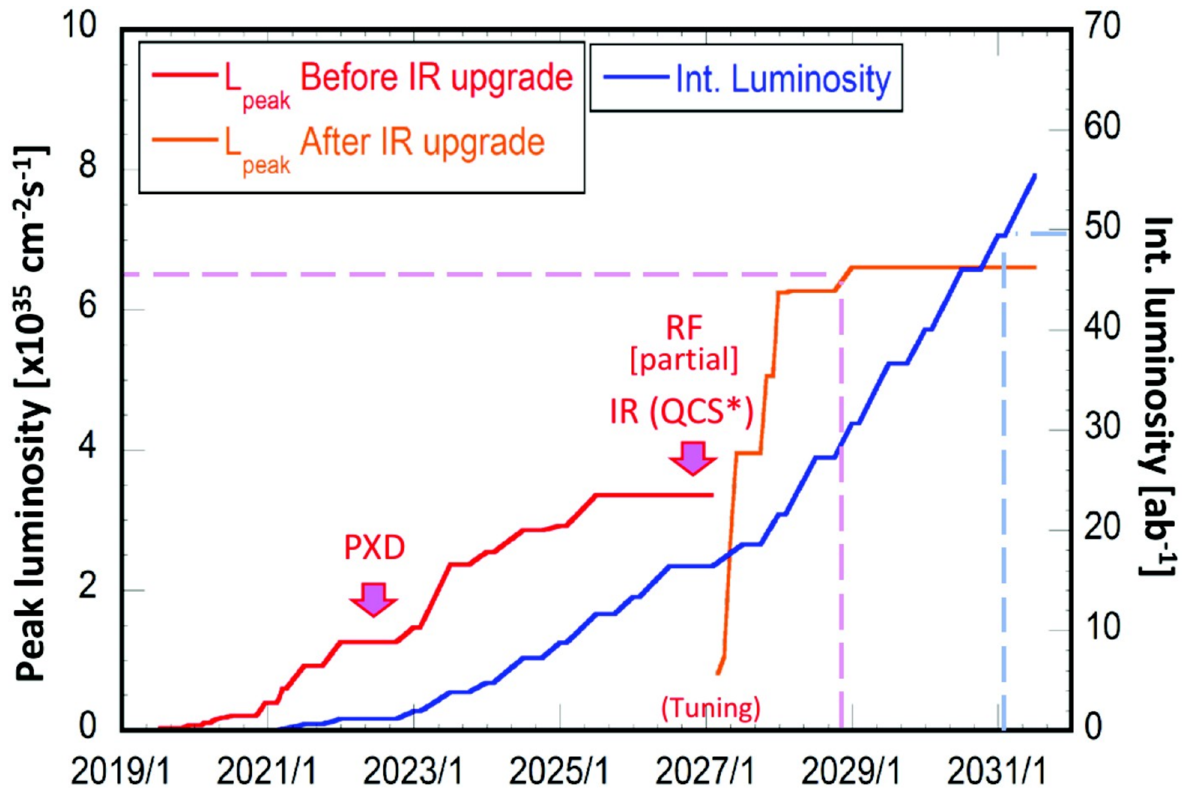
LHCb — LHC at CERN

	LHC era			HL-LHC era	
	Run 1 (2010-12)	Run 2 (2015-18)	Run 3 (2021-24)	Run 4 (2027-30)	Run 5+ (2031+)
ATLAS, CMS	25 fb^{-1}	150 fb^{-1}	300 fb^{-1}	⟶	3000 fb^{-1}
LHCb	3 fb^{-1}	9 fb^{-1}	23 fb^{-1}	50 fb^{-1}	*300 fb^{-1}

* assumes a future LHCb upgrade to raise the instantaneous luminosity to 2x10^{34} $cm^{-2}s^{-1}$

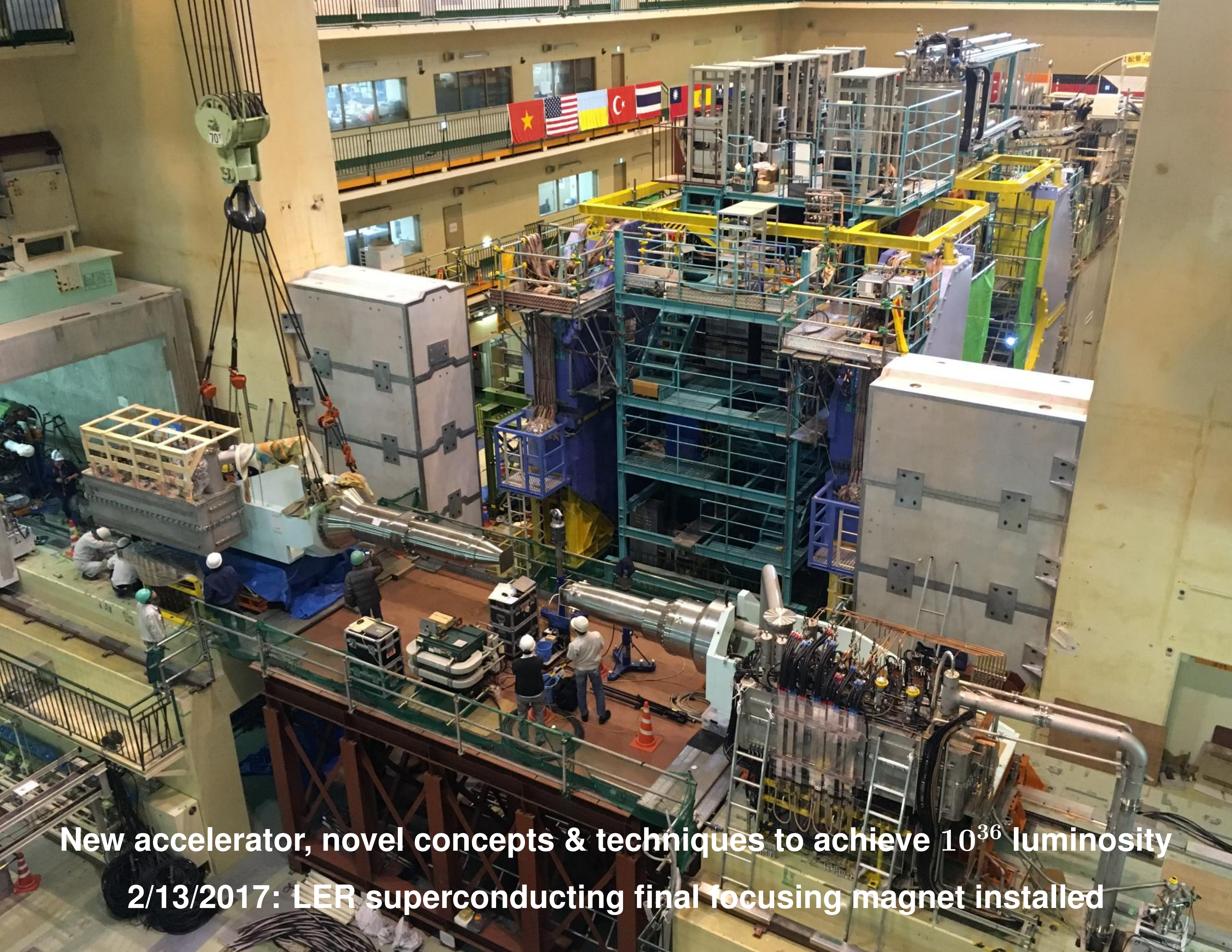
- Major LHCb upgrade in LS2 (raise instantaneous luminosity to $2 \times 10^{33}/\mathrm{cm}^2/\mathrm{s}$)
  Major ATLAS and CMS upgrades come in LS3 for HL-LHC
- LHCb, 2017, Expression of Interest for an upgrade in LS4 to $2 \times 10^{34}/\mathrm{cm}^2/\mathrm{s}$

Belle II — SuperKEKB in Japan



- First collisions 2018 (unfinished detector), with full detector starting spring 2019
  Goal: $50\times$ the Belle and nearly $100\times$ the *BaBar* data set

- Discussions started about physics case and feasibility of a factor ~ 5 upgrade, similar to LHCb Phase-II upgrade aiming 50/fb $\to$ 300/fb, after LHC LS4



New accelerator, novel concepts & techniques to achieve 10^{36} luminosity

2/13/2017: LER superconducting final focusing magnet installed

$D-\overline{D}$ mixing and CP violation

- CP violation in D decays:

  LHCb, Nov. 2011: $\Delta A_{CP} \equiv A_{K^+K^-} - A_{\pi^+\pi^-} = -(8.2 \pm 2.4) \times 10^{-3}$

  LHCb, Mar. 2019: $\Delta A_{CP} = -(1.82 \pm 0.33) \times 10^{-3}$ (a stretch in the SM, imho)

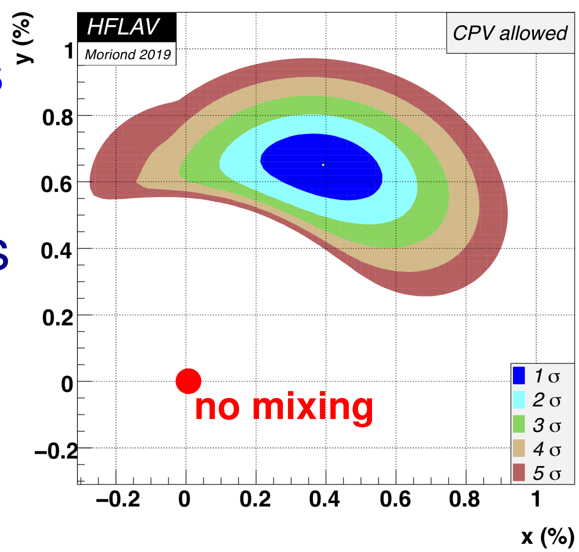
- I think we still don't know how big an effect could (not) be accommodated in SM

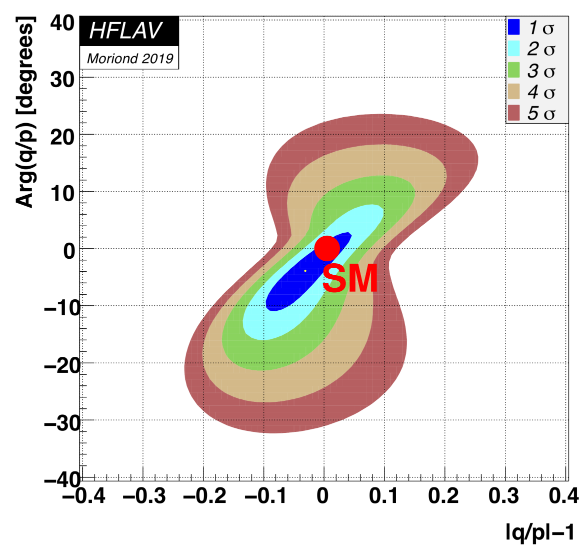
- Mixing generated by down quarks or in SUSY by up-type squarks

  Connections to FCNC top decays

- Value of Δm? Not even 3σ yet

- SM allowed range of $|q/p| - 1$?





- SUSY: interplay of D & K bounds: alignment, universality, heavy squarks?

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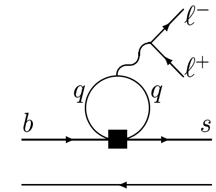
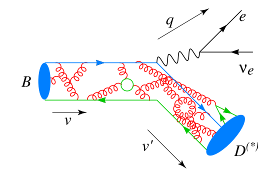
The current B “anomalies”

- Lepton non-universality would be clear evidence for NP



1) R_K and R_{K^*} $(B \to X\mu^+\mu^-)/(B \to Xe^+e^-) \sim 20\%$ correction to SM loop



2) $R(D)$ and $R(D^*)$ $(B \to X\tau\bar\nu)/(B \to X(e,\mu)\bar\nu) \sim 20\%$ correction to SM tree

Scales: $R_{K^{(*)}} \lesssim$ few $\times 10^1\,\mathrm{TeV}$, $R(D^{(*)}) \lesssim$ few $\times 10^0\,\mathrm{TeV}$ Would bound NP scale!

- Theor. less clean: 3) P_5' angular distribution $(B \to K^*\mu^+\mu^-)$
  4) $B_s \to \phi\mu^+\mu^-$ rate

Can fit 1), 3), 4) with one operator: $C_{9,\mu}^{(\mathrm{NP})}/C_{9,\mu}^{(\mathrm{SM})} \sim -0.2\,,\ O_{9,\mu} = (\bar s\gamma_\alpha P_L b)(\bar\mu\gamma^\alpha\mu)$

- Viable BSM models... leptoquarks? No clear connection to DM & hierarchy puzzle

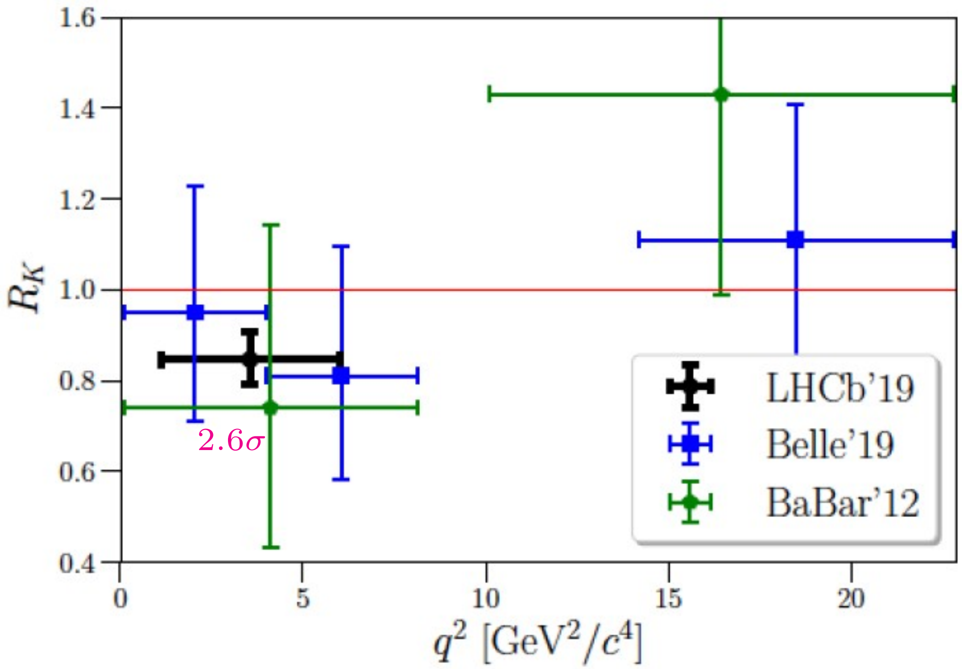
Attention to many BSM scenarios previously less explored

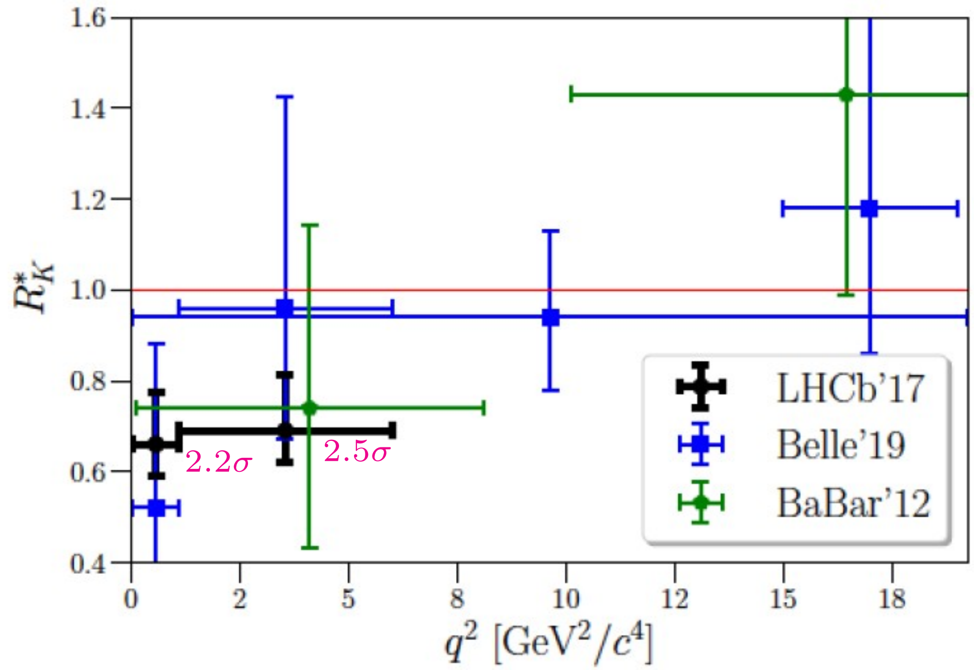
- What are smallest deviations from SM, which can be unambiguously established?

R_K and R_{K^*}: theoretically cleanest

- LHCb: $R_{K^{(*)}} = \dfrac{B \to K^{(*)}\mu^+\mu^-}{B \to K^{(*)}e^+e^-} < 1$ both ratios $\sim 2.5\sigma$ from lepton universality

[Tomorrow: https://indico.cern.ch/event/976688/]





- Combined fits only by theorists (some include P_5' and/or $B_s \to \phi\mu^+\mu^-$)

- Modifying one Wilson coefficient in $\mathcal{H}_{\text{eff}}$ gives good fit: $\delta\, C_{9,\mu} \sim -1$ (NP or QCD?)

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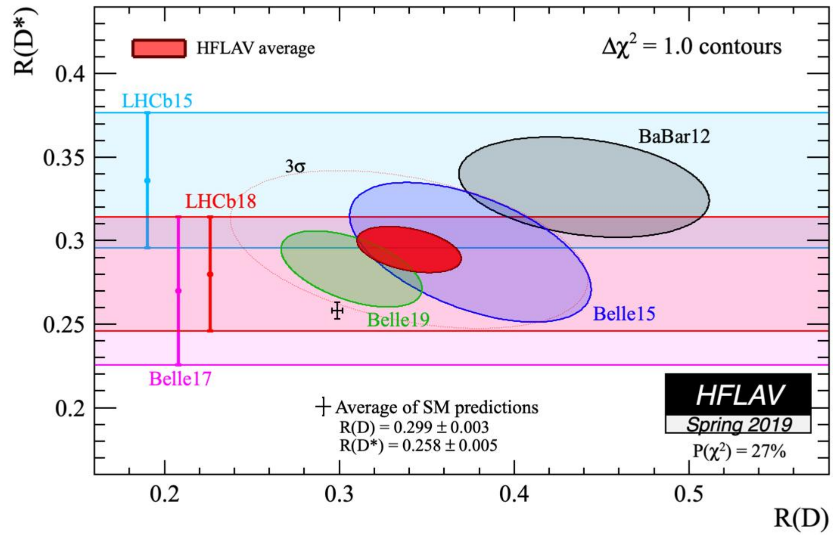
The $B \to D^{(*)}\tau\bar{\nu}$ decay rates

- BaBar, Belle, LHCb: $R(X) = \dfrac{\Gamma(B \to X\tau\bar{\nu})}{\Gamma(B \to X(e/\mu)\bar{\nu})}$

  3.1σ from SM predictions — robust due to heavy quark symmetry + lattice QCD (only D so far)

  more than statistics: $R(D^*)$ with $\tau \to \nu 3\pi$ [1708.08856]

  $B_c \to J/\psi\, \tau\bar{\nu}$ [1711.05623]



- Imply NP at a fairly low scale (leptoquarks, W', etc.), likely visible at ATLAS / CMS

  Some of the models Fierz (mostly) to the same (SM) operator: distributions, τ polarization = SM

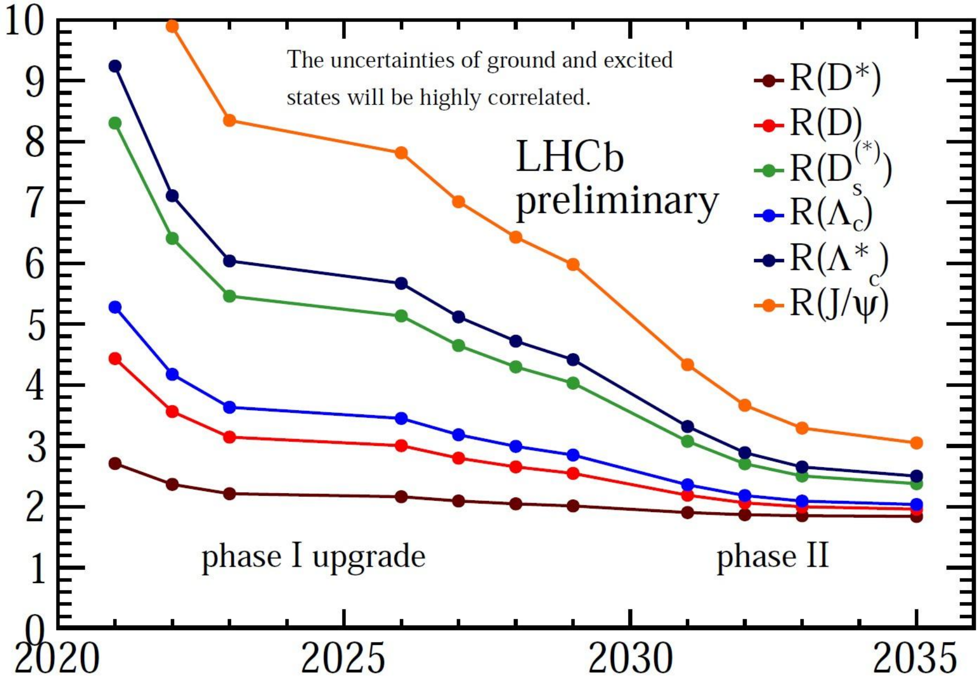
- Tree level: three ways to insert mediator: $(b\nu)(c\tau)$, $(b\tau)(c\nu)$, $(bc)(\tau\nu)$

  overlap with ATLAS & CMS searches for $\tilde{b}$, leptoquark, $H^\pm$

- Models built to fit these anomalies have impacted many ATLAS & CMS searches

Exciting future

- LHCb: $R_{K^{(*)}}$ sensitivity with existing Run 1–2 data can still improve a lot
- LHCb and Belle II: increase $pp \to b\bar{b}$ and $e^+e^- \to B\overline{B}$ data sets by factor ~ 50
- LHCb:



Belle II ($50/$ab, at SM level):

$\delta R(D) \sim 0.005\ (2\%)$

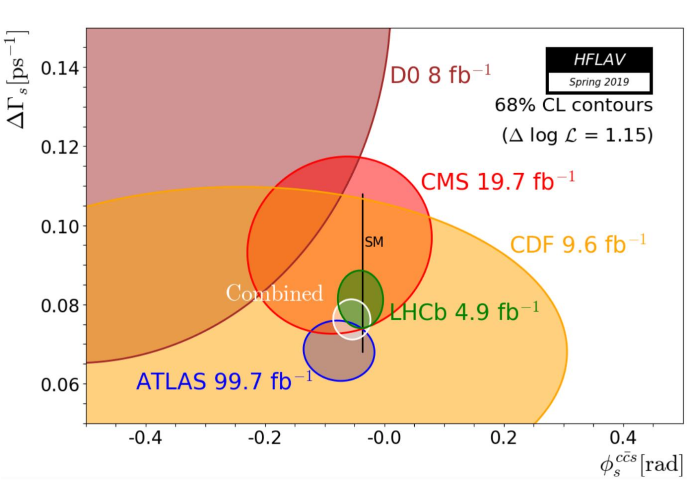
$\delta R(D^*) \sim 0.010\ (3\%)$

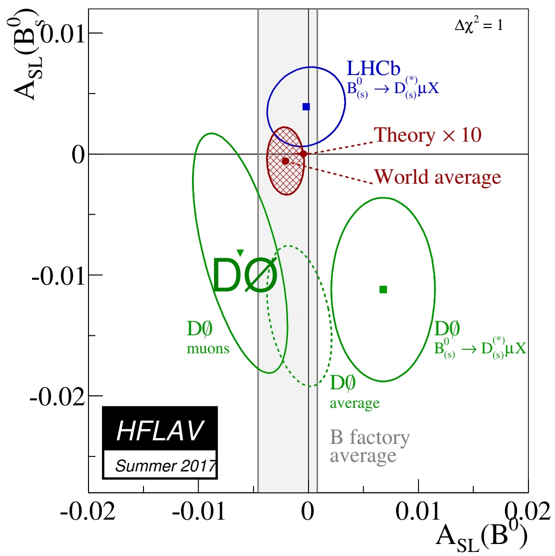
Measurements will improve a lot!

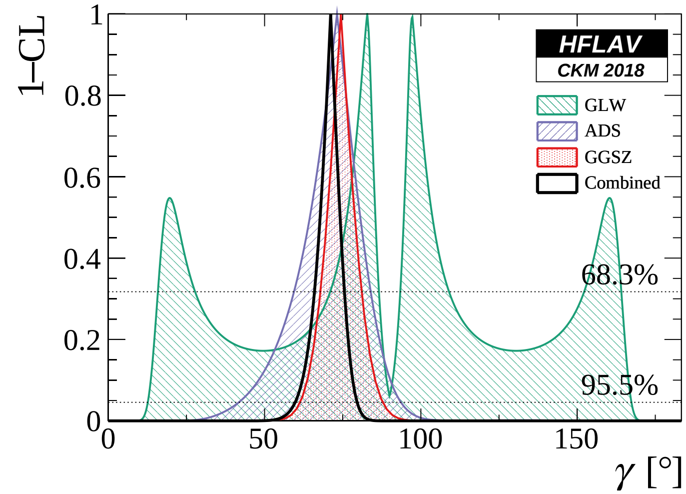
(Even if central values change, plenty of room for establishing deviations from SM)

- Competition, complementarity, cross-checks between LHCb and Belle II

Some key measurements, done much better







CP violation in $B_s \to \psi\phi$ now consistent with SM

$A_{\rm SL}$: important, indep. of DØ anomaly

Measurements of γ crucial, LHCb is now most precise

- Breadth crucial, often have to combine many measurements and theory

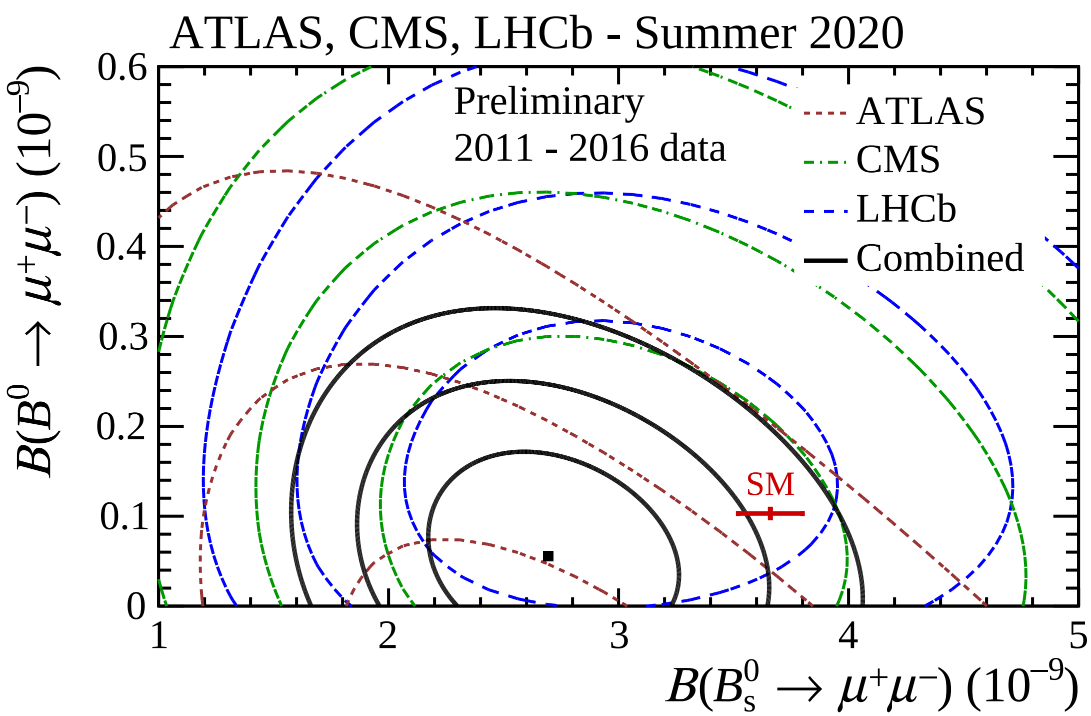
  ("The interesting messages are not simple, the simple messages are not interesting")

- Uncertainty of predictions $\ll$ current experimental errors ($\Rightarrow$ seek lot more data)

$B \to \mu^+\mu^-$: interesting well beyond HL-LHC

- $B_d \to \mu^+\mu^-$ in SM, 10^{-10} : LHCb expects 10% $(300/\text{fb})$, CMS expects 15% $(3/\text{ab})$

  SM uncertainty $\simeq (2\%) \oplus f_{B_q}^2 \oplus \text{CKM}$ [Bobeth, FPCP'15] and may be further reduced



- Theoretically cleanest $|V_{ub}|$ I know, use isospin: $\mathcal{B}(B_u \to \ell\bar{\nu})/\mathcal{B}(B_d \to \mu^+\mu^-)$
- A decay with mass-scale sensitivity (dim.-6 operator) that competes w/ $K \to \pi\nu\bar{\nu}$

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Final remarks

What are the largest useful data sets?

- Which measurements will remain far from being limited by theory uncertainties?
  - For $\gamma \equiv \phi_3$, theory uncertainty only from higher order EW
  - $B_{s,d} \to \mu\mu$, $B \to \mu\nu$ and other leptonic decays (lattice QCD, [double] ratios)
  - $A_{\rm SL}^{d,s}$ — can it keep scaling with statistics?
  - Lepton flavor violation & lepton universality violation searches
  - Possibly CP violation in D mixing (firm up theory)
- Very broad program
- In some decay modes, even in 2030s we'll have: (exp. bound)/SM $\gtrsim 10^3$

  E.g., $B_{d,s} \to e^+e^-$, $\tau^+\tau^-$, etc. — can build models... (Please prove me wrong!)
- Sensitivity to NP would improve with data $\gg$ LHCb & Belle II (nb: Belle II / ARGUS $\sim 10^5$)

Many "exotic" searches

- Better tests of (exact or approximate) conservation laws
- Exhaustive list of dark / hidden sector searches
- LFV meson decays, e.g., $M^0 \to \mu^- e^+$, $B^+ \to h^+ \mu^- e^+$, etc.
- Invisible modes, even baryonic, $B \to N + \text{invis.}\ [+\text{mesons}]$ [1907.10612, 1810.00880, 1708.01259]
- Hidden valley inspired scenarios, e.g., multiple displaced vertices, even with $\ell^+\ell^-$
- Exotic Higgs decays, e.g., high multiplicity, displaced vertices ($H \to XX \to abab$)
- Search for "quirks" (non-straight "tracks") at LHCb using many velo layers
- I do not know how many CP violating quantities have been measured...
  neither how many new hadronic states discovered by BaBar, Belle, LHCb ...

Theory challenges / opportunities

- New methods & ideas: recall that the best α and γ measurements are in modes proposed in light of Belle & BaBar data (i.e., not in the BaBar Physics Book)
  - Better SM upper bounds on $S_{\eta' K_S} - S_{\psi K_S}$, $S_{\phi K_S} - S_{\psi K_S}$, and $S_{\pi^0 K_S} - S_{\psi K_S}$ And similarly in B_s decays, and for $\sin 2\beta_{(s)}$ itself
  - How big can CP violation be in $D^0 - \overline{D}^0$ mixing (and in D decays) in the SM?
  - Better understanding of semileptonic form factors; bound on $S_{K_S \pi^0 \gamma}$ in SM?
  - Many lattice QCD calculations (operators within and beyond SM)
  - Inclusive & exclusive semileptonic decays
  - Factorization at subleading order (different approaches), charm loops
  - Can direct CP asymmetries in nonleptonic modes be understood enough to make them "discovery modes"? [$SU(3)$, the heavy quark limit, etc.]
- We know how to make progress on some + discover new frameworks / methods?

Some conclusions

- Flavor physics probes scales $\gg 1\,\text{TeV}$; sensitivity limited by statistics, not theory
  $\Rightarrow$ New physics could show up any time measurements improve
- In FCNCs, NP/SM $\gtrsim 20\%$ still allowed; any discovery $\Rightarrow$ upper bound on NP scale
- Precision tests of SM will improve in the next decade by $10-10^4$
- Few tensions with SM; some of these (or others) could soon become decisive
- Discovering lepton universality violation would focus even more attention on LFV
- Many interesting theoretical questions relevant for optimal experimental sensitivity
- Flavor measurements will tell us a lot, whether NP is discovered or not:

Evidence for BSM?		FLAVOR: yes	FLAVOR: no
ATLAS & CMS	yes	complementary information	distinguish models
	no	points to where to look next	sensitive to highest scales

Extra slides

Direct CPV is also $\mathcal{O}(1)$

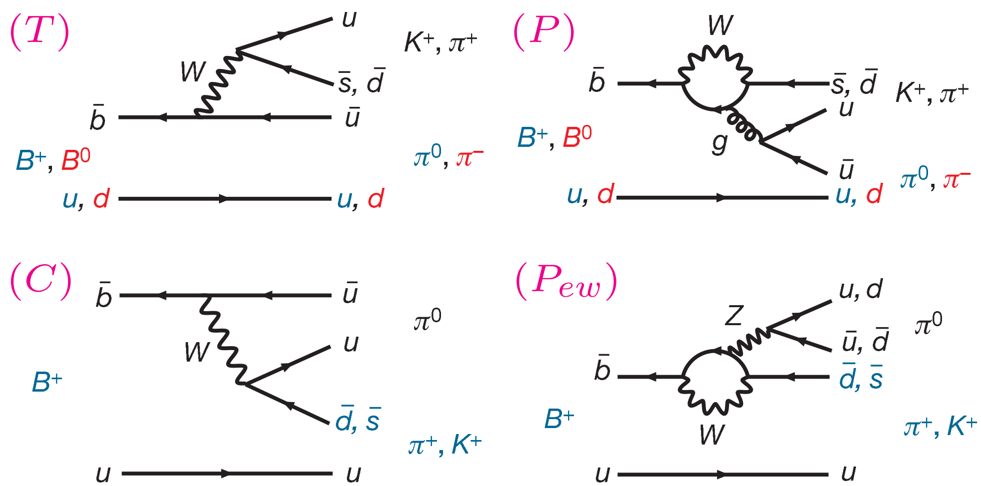
- Have we seen new physics in CPV?

$$A_{K^+\pi^-} = -0.084 \pm 0.004 \quad (P+T)$$

$$A_{K^+\pi^0} = 0.040 \pm 0.021 \quad (P+T+C+A+P_{ew})$$

- Large difference — small SM sources?

$$A_{K^+\pi^0} - A_{K^+\pi^-} = 0.124 \pm 0.022$$



(Annihilation not shown)

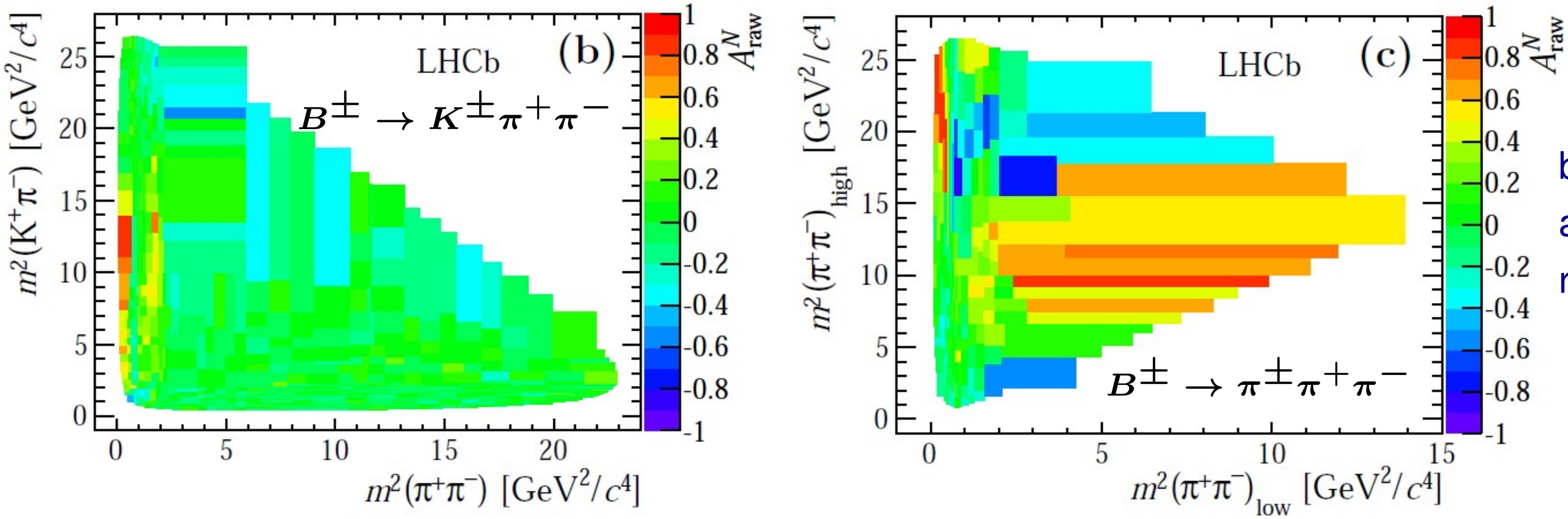
[Belle, Nature 452, 332 (2008)]

SCET / factorization $\Rightarrow$ $\arg(C/T) = \mathcal{O}(\Lambda_{\rm QCD}/m_b)$ and $A + P_{ew}$ small

- Large fluctuations? Breakdown of $1/m$ exp.? Missing something subtle? BSM?
- Can we understand theory well enough, to possibly disprove SM?
- Even larger $A_{CP}(B_s \to \pi^+ K^-) = 0.213 \pm 0.017$ understood in terms of $SU(3)$

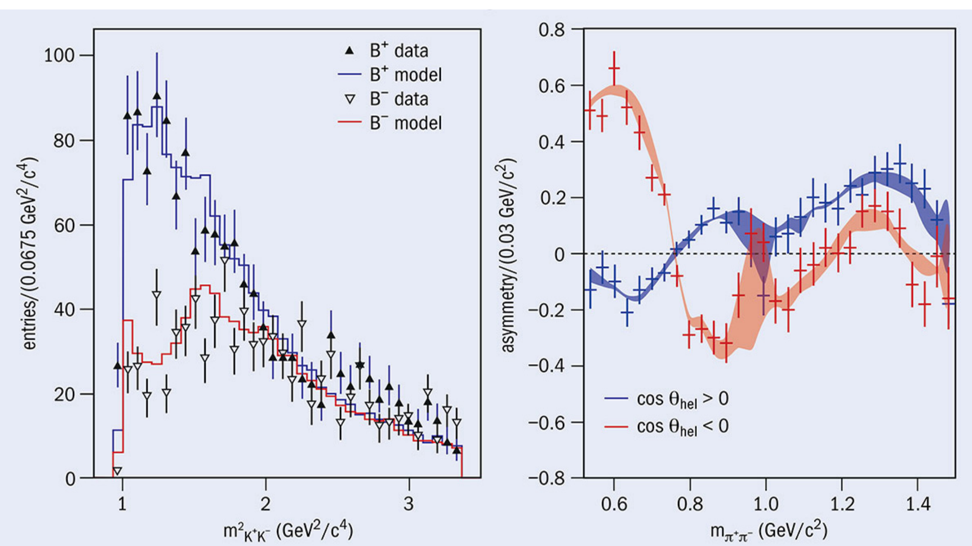
[Grossman, ZL, Robinson, 1308.4143]

CP violation everywhere: three-body decays



background subtracted and acceptance corrected asymmetries

[LHCb, arXiv:1408.5373]



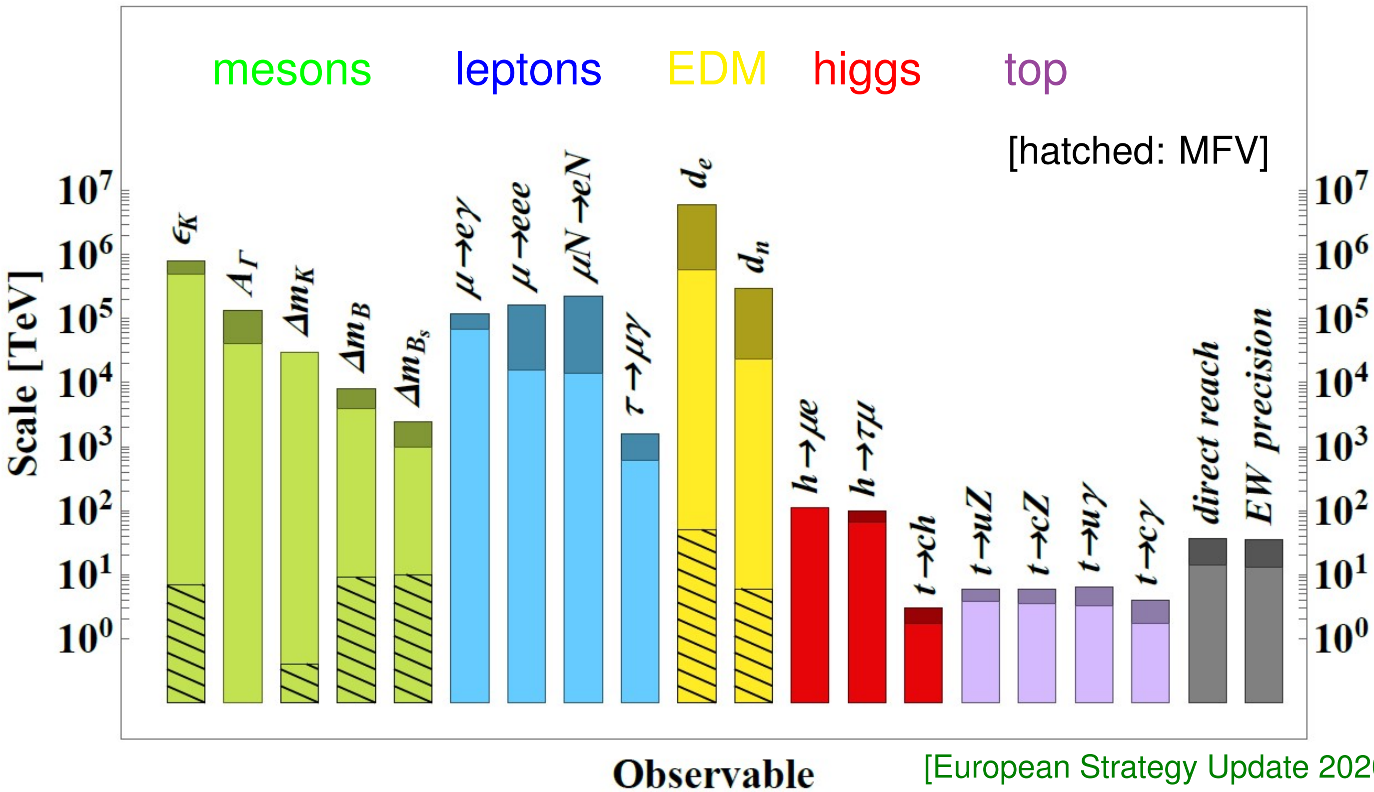
Left: $B^\pm \to \pi^\pm K^+ K^-$ yields

Right: $B^\pm \to \pi^\pm \pi^+ \pi^-$ CP asymmetry

[CERN Courier, 2019]

Anticipated increases in sensitivity

- Scales of dim-6 operators probed — various mechanisms devised to let TeV-scale NP obey these bounds (Pattern and orders of magnitudes matter more than precise values)



[European Strategy Update 2020, arXiv:1910.11775]

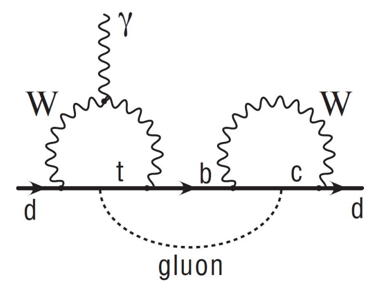
- $\mu N \to eN$ may be the largest increase in mass-scale sensitivity in next 10–15 yrs

Electric dipole moments

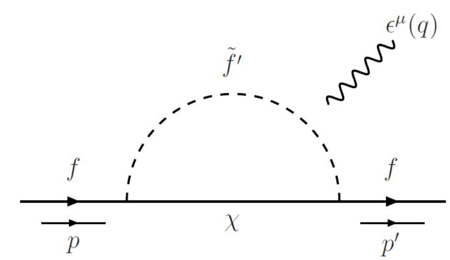
- SM $+ m_\nu$: CPV can occur in: (i) quark mixing; (ii) lepton mixing; and (iii) $\theta_{\rm QCD}$
  Only observed $\delta_{\rm KM} \neq 0$, baryogenesis implies there must be more

- Neutron EDM bound: "the strong CP problem", $\theta_{\rm QCD} < 10^{-10}$ — axion?
  $\theta_{\rm QCD}$ is negligible for CPV in flavor-changing processes

- EDMs from CKM: vanish at one- and two-loop
  large suppression at three-loop level



- E.g., SUSY: quark and lepton EDMs can be generated at one-loop
  Generic prediction ($\rm TeV$-scale, no small param's) above current bounds; if $m_{\rm SUSY} \sim \mathcal{O}(10\,{\rm TeV})$, may still discover EDMs



- Expected 10^2–10^3 improvements: complementary to LHC
  Discovery would give (rough) upper bound on NP scale

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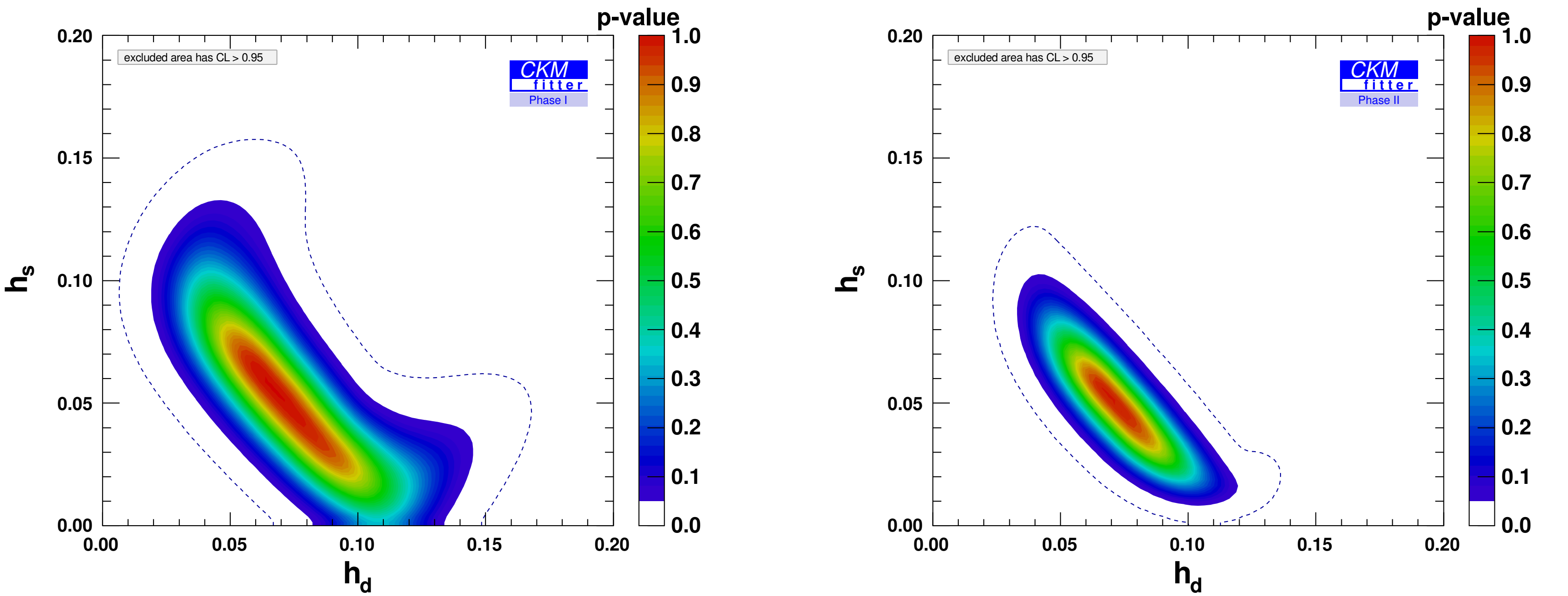
Example of discovery potential

- Discovery significance at Phase I (left) and Phase II (right), if central values (CKM param's, $h_{d,s}$, and $\sigma_{d,s}$) remain as in the current fit (on p.12)

(Assume future measurements have the corresponding central values, with uncertainties as in the Table on p.11)



- If new physics contributes to semileptonic decays, as hinted at by the $R(D^{(*)})$ anomaly, then things get more complicated, may still isolate sources (see paper)

New particles, e.g., supersymmetry

- Any new particle that couples to quarks or leptons $\Rightarrow$ new flavor parameters

  The LHC will measure: masses, production rates, decay modes (some), etc.

  Details of interactions of new particles with quarks and leptons will be important

- New physics flavor structure can be: new physics mass scale:
  - Minimally flavor violating (mimic the SM) — can be "light"
  - Related but not identical to the SM — $\uparrow\downarrow$
  - Unrelated to the SM, or even completely anarchic — must be heavy

  Some aspects will be understood from ATLAS & CMS data (masses, decays, etc.)

- New sources of CP violation: squark & slepton couplings, flavor diagonal processes (e, n EDM), neutral currents; may enhance FCNCs $(B_{(s)} \to \ell^+\ell^-, \mu \to e\gamma)$

Known for decades: $K^0 - \overline{K}^0$ mixing and BSM

- E.g.: $\dfrac{(\Delta m_K)^{\rm SUSY}}{(\Delta m_K)^{\rm exp}} \sim 10^4 \left(\dfrac{1\,{\rm TeV}}{\tilde m}\right)^2 \left(\dfrac{\Delta\tilde m_{12}^2}{\tilde m^2}\right)^2 {\rm Re}\Big[(K_L^d)_{12}(K_R^d)_{12}\Big]$ (oversimplified)

  $K^d_{L(R)}$: mixing in gluino couplings to left-(right-)handed down quarks and squarks

- Constraint from ϵ_K: replace $10^4\,{\rm Re}\big[(K_L^d)_{12}(K_R^d)_{12}\big]$ with $\sim 10^6\,{\rm Im}\big[(K_L^d)_{12}(K_R^d)_{12}\big]$

  (44 CPV phases: CKM $+$ 3 flavor diagonal $+$ 40 in mixing of fermion-sfermion-gaugino couplings)

- Classes of models to suppress each terms (structures imposed to satisfy bounds)

  (i) Heavy squarks: $\tilde m \gg 1\,{\rm TeV}$ (e.g., split SUSY)

  (ii) Universality: $\Delta m^2_{\tilde Q,\tilde D} \ll \tilde m^2$ (e.g., gauge mediation)

  (iii) Alignment: $|(K^d_{L,R})_{12}| \ll 1$ (e.g., horizontal symmetry)

- All viable BSM models incorporate some of the above — known since the ’70s

The MSSM parameters and flavor

- Superpotential: [Haber, hep-ph/9709450]

$$W = \sum_{i,j} \left(Y^u_{ij} H_u\, Q_{Li} \bar{U}_{Lj} + Y^d_{ij} H_d\, Q_{Li} \bar{D}_{Lj} + Y^\ell_{ij} H_d\, L_{Li} \bar{E}_{Lj} \right) + \mu H_u H_d$$

- Soft SUSY breaking terms: $(S = \tilde{Q}_L, \tilde{\bar{D}}_L, \tilde{\bar{U}}_L, \tilde{L}_L, \tilde{\bar{E}}_L)$

$$\mathcal{L}_{\rm soft} = -\left(A^u_{ij} H_u \tilde{Q}_{Li} \tilde{\bar{U}}_{Lj} + A^d_{ij} H_d \tilde{Q}_{Li} \tilde{\bar{D}}_{Lj} + A^\ell_{ij} H_d \tilde{L}_{Li} \tilde{\bar{E}}_{Lj} + B H_u H_d \right)$$
$$- \sum_{\rm scalars} (m^2_S)_{ij}\, S_i \bar{S}_j - \frac{1}{2} \left(M_1 \tilde{B}\tilde{B} + M_2 \tilde{W}\tilde{W} + M_3 \tilde{g}\tilde{g} \right)$$

$3\ Y^f$ Yukawa and $3\ A^f$ matrices — $6\times$(9 real $+\ 9$ imaginary) parameters

$5\ m^2_S$ hermitian sfermion mass-squared matrices — $5\times$(6 real $+\ 3$ imag.) param's

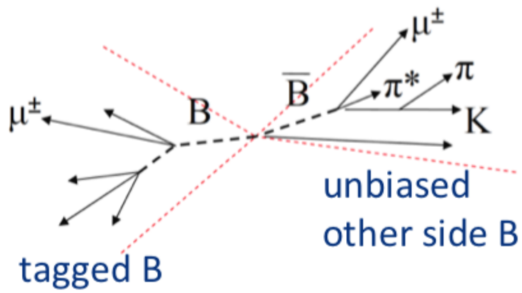
Gauge and Higgs sectors: $g_{1,2,3},\, \theta_{\rm QCD},\, M_{1,2,3},\, m^2_{h_{u,d}},\, \mu,\, B$ — 11 real $+\ 5$ imag.

Parameters: $(95 + 74) - (15 + 30)$ from $U(3)^5 \times U(1)_{\rm PQ} \times U(1)_R \to U(1)_B \times U(1)_L$

- 44 CPV phases: CKM $+\ 3$ in M_1, M_2, μ (set $\mu B^*, M_3$ real) $+\ 40$ in mixing matrices of fermion-sfermion-gaugino couplings ($+80$ real param's)

CMS "B – parking" in 2018

- Collected 10^{10} B-s; hope to compete w/ LHCb on $R_{K^{(*)}}$ anomaly [CMS @ LHCC, Nov 2018]

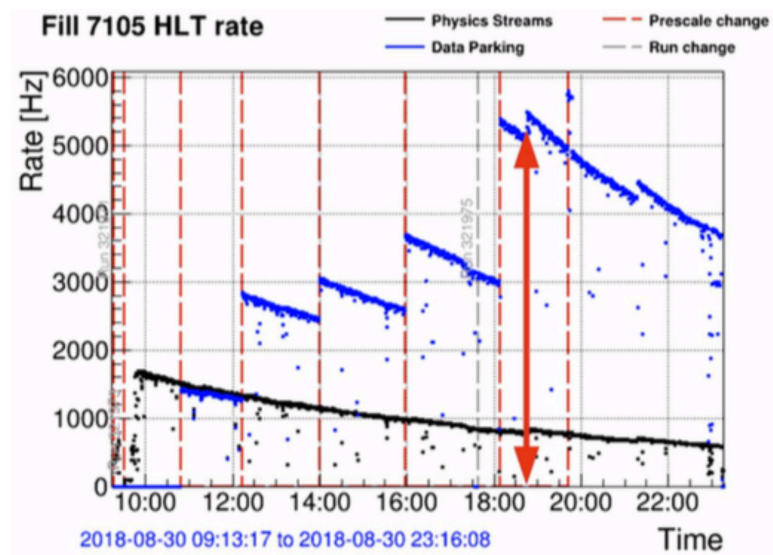


Effort in 2018 paid off, 12B triggered events on tape

- Up to 5.5 kHz in the second part of the fill where events are smaller

Now studying processing strategy

- 1.1B events were already fully processed in order to help development of trigger/ reconstruction



7.6 PB on tape
Avg event size is 0.64 MB
(1MB for standard events)

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