B physics from BABAR to FCC

Zoltan Ligeti

BaBar 30th Anniversary, SLAC, March 7–8, 2024

Disclaimers...

- When Fabio asked me to give this talk, I got sad at first realizing that BaBar data taking ended halfway through these 30 years
- We celebrated BaBar's 25th Anniversary in Dec. 2018 — what has changed?
  - Significance of hint of new physics in $B \to K^{(*)}\ell^+\ell^-$ smaller
  - Direct CP violation in D decay established
  - Constraints on CP violation in D mixing improved a lot
- Try to be forward looking, even when talking about the past

Outline

- Personal recollections (mine $+$ few comments by others)
- New in the last 5 years
- $B \to D^{(*)} \tau \bar{\nu}$
- New physics in B mixing
- Future

My BaBar connections, before collisions

- Ph.D.: w/ Yossi Nir at Weizmann, right as he came from a SLAC postdoc in 1990; Yossi knew all about the B factory plans (and had drafts of Peskin & Schroeder, and the Higgs Hunter's Guide); Ben Grinstein visited and gave a mini-course on heavy quark effective theory, etc.

  Last papers in my Ph.D., inclusive $B \to X_c \tau \bar\nu$ [LEP; and recently Belle 2311.07248]

- Postdoc: Caltech 1994–97. It was fun to think independent of the available data (mainly CLEO & LEP), hoping BaBar & Belle will do everything one can imagine

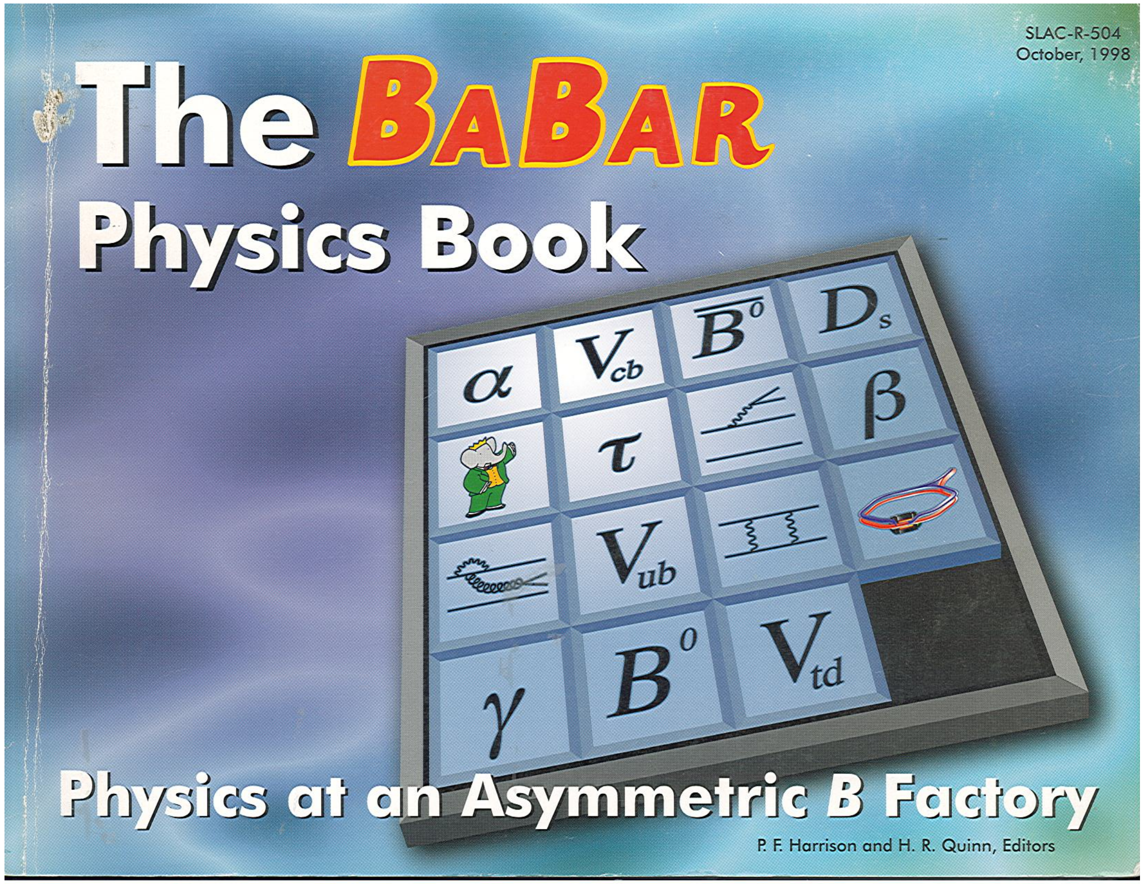
  Many were indeed done: $B \to X_s \gamma$ spectrum and moments, $B \to X_c \ell \bar\nu$ moments and $|V_{cb}|$, $B \to X_u \ell \bar\nu$ hadron mass spectrum, $B \to D^{**} \ell \bar\nu$ (LLSW)

  Some are still left for the future: $B \to X_s \nu \bar\nu$, etc.

- BaBar workshops — formative experiences: community, arguments, fun, work!

  (Rome; Princeton: guesses about seeing NP; Paris: identifying a referee from one word, etc.)

The BaBar Physics Book



- No executive summary, no killer apps, no list of gold-plated measurements...
- Some parts became folklore

R-Parity Violation	Can Do	Everything	Except Make	Coffee

From Yossi Nir: the sign of $\sin(2\beta)$

- "When Helen and I published our paper PRD 42 (1990) 1473, we got letters from Bigi and Wolfenstein, saying that one cannot extract the sign of (what is now known as $S_{f_{CP}}$), because one does not know the sign of Δm_B. They were wrong – either you define Δm_B to be positive $(m_H - m_L)$, and then there is no ambiguity, or you define it differently, say $M_S - M_L$, or $M_{CP+} - M_{CP-}$, in which case there are two ambiguities cancelling in the product. Either way, you can extract the sign of $\sin\delta$ (which is what we argued). For me there were two important lessons:
  - Choosing a convenient convention might be very helpful.
  - Leaders of the field might still make mistakes.

  I think I mentioned this story in my lecture in Helen's Fest. I also think I kept Lincoln's letter." (Yossi Nir)

- It's only more surprising that this resurfaced in 2004 (and withdrawn):
  Bigi & Sanda, "On the sign of ΔM_b, M_{12}, $\sin 2\phi_1$ and all that", [hep-ph/0411135]

Some signs are just conventions...

- The angle β_s was probably (?) first defined in the $B\textsc{A}B\textsc{AR}$ Physics Book

The angle β gives, to a good approximation, the Standard Model phase between the neutral B mixing amplitude and its leading decay amplitudes. It is interesting to define the analog phases for the B_s meson, β_s, and the K meson, β_K:

$$\beta_s \equiv \arg\left[-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right], \quad \beta_K \equiv \arg\left[-\frac{V_{cs}V_{cd}^*}{V_{us}V_{ud}^*}\right]. \tag{1.92}$$

Important to constrain new physics in mixing: $M_{12}^q = (1 + h_q e^{2i\sigma_q}) M_{12}^{q,\mathrm{SM}}$

$$S_{B_d\to\psi K_S} = \sin\left[2\beta + \arg\left(1 + h_d e^{2i\sigma_d}\right)\right]$$
$$S_{B_s\to\psi\phi} = \sin\left[2\beta_s - \arg\left(1 + h_s e^{2i\sigma_s}\right)\right]$$

Above definition is the origin of the sign in the relation: $\phi_s = -2\beta_s$

- Resulted in confusions, and some arguments, ever since...

Return later to status and prospects of this program

B(ee)hive or Apiary?

- Wow, BaBar's 30th birthday? Now I feel really old. When I was a postdoc at SLAC (1991–93), it was still in utero, I guess. I remember the group working on it the floor below us had a sign on their door, "The B Hive"

  "They had pictures of bees everywhere..." (Adam Falk)

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

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.

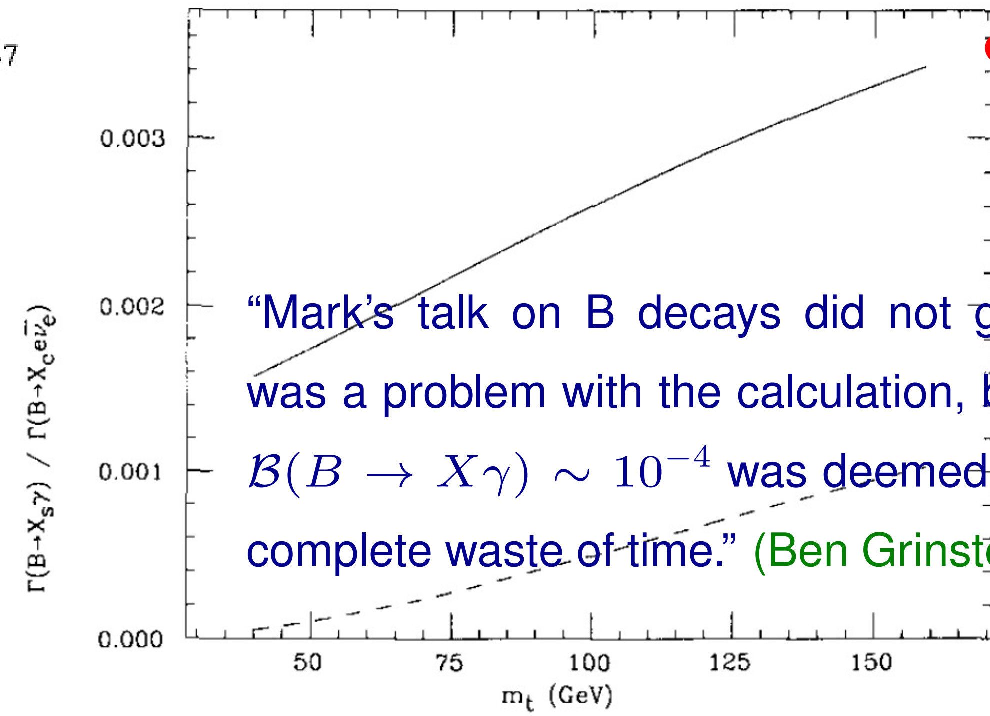
B physics instigated huge theory developments

- Multi-loop calculations of FCNC B decays started shortly before $B\small{A}B\small{AR}$

EFFECTIVE HAMILTONIAN FOR WEAK RADIATIVE B-MESON DECAY ☆

Benjamin GRINSTEIN [1], Roxanne SPRINGER and Mark B. WISE [2]
California Institute of Technology, Pasadena, CA 91125, USA

Received 18 November 1987



- Surprisingly accurate!

(Recall: sensitive to $|V_{tb}V_{ts}|$)

"Mark's talk on B decays did not go well. Not because there was a problem with the calculation, but because the prediction of $\mathcal{B}(B\to X\gamma)\sim 10^{-4}$ was deemed stupidly pie in the sky and a complete waste of time." (Ben Grinstein, confirmed by Mark Wise)

- CLEO discovered $B\to K^*\gamma\,,\ X_s\gamma$ (1993, '95)

Don't listen to the naysayers!

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γ

- *BaBar* book did not anticipate γ to be measurable with reasonable precision

PHYSICAL REVIEW D **67**, 071301(R) (2003)

Measuring γ in $B^{\pm}\to K^{\pm}(KK^*)_D$ decays

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Abner Soffer‡
Department of Physics, Colorado State University, Fort Collins, Colorado 80523
(Received 6 November 2002; published 24 April 2003)

- Then I was a naysayer... (Simultaneous work by Bondar & Poluektov)

PHYSICAL REVIEW D **68**, 054018 (2003)

Determining γ using $B^{\pm}\to DK^{\pm}$ with multibody D decays

Anjan Giri,[1] Yuval Grossman,[1] Abner Soffer,[2] and Jure Zupan[1,3]
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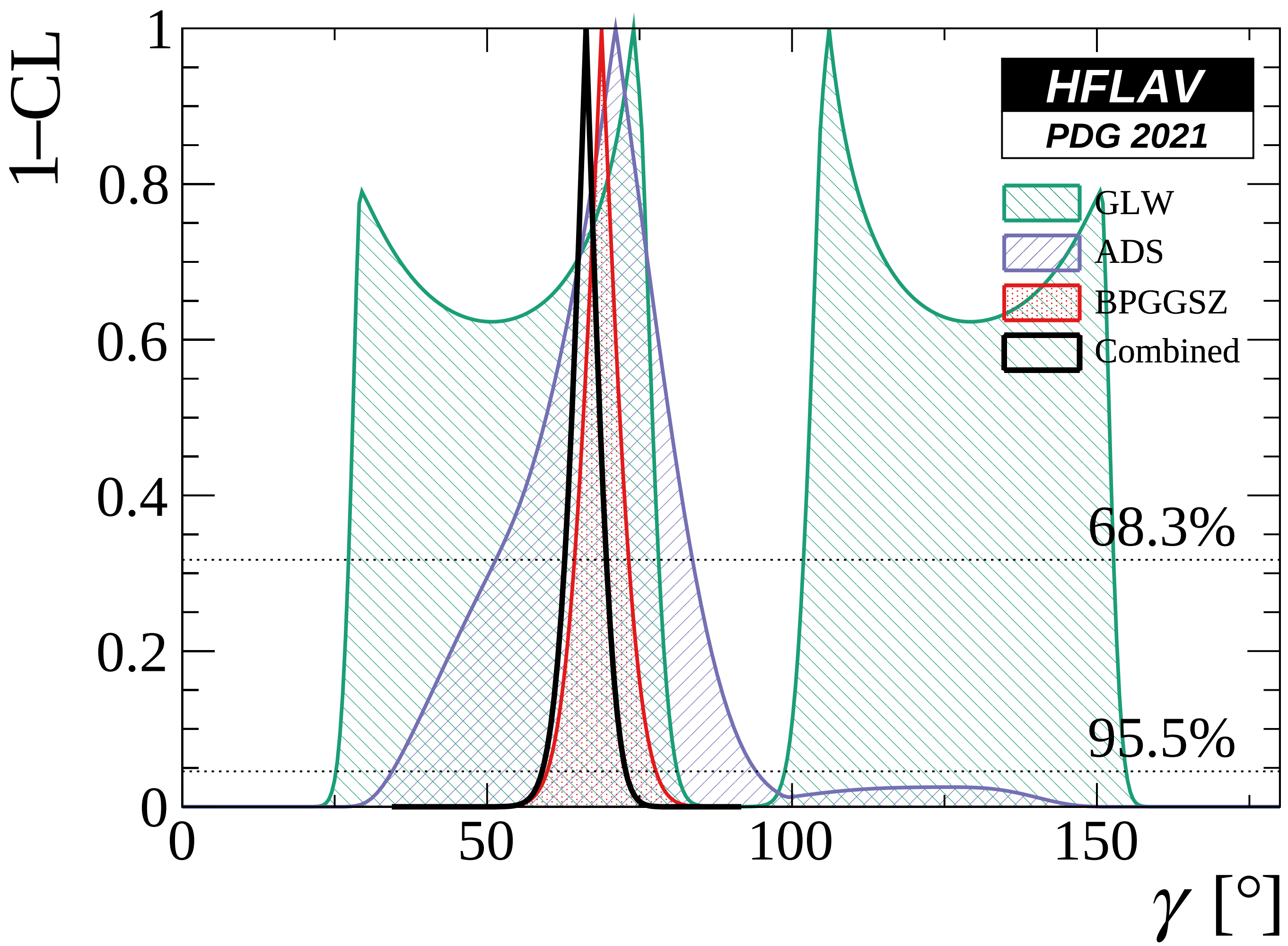
(Received 1 April 2003; published 24 September 2003)

γ


1−CL
HFLAV
PDG 2021
GLW
ADS
BPGGSZ
Combined
68.3%
95.5%
0
0.2
0.4
0.6
0.8
1
0
50
100
150
γ [°]

α

- *BaBar* book expected $\rho\pi$, $\pi\pi$ to dominate (unknown amplitudes, uncertain sensitivity)

  Experimental surprise: $\rho\rho$ mostly longitudinal, $(\rho^0\rho^0)/(\rho^+\rho^-) \ll (\pi^0\pi^0)/(\pi^+\pi^-)$

- Effects of Γ_ρ on isospin analysis — will be relevant soon

PHYSICAL REVIEW D **69**, 011502(R) (2004)

Comment on extracting α from $B \to \rho\rho$

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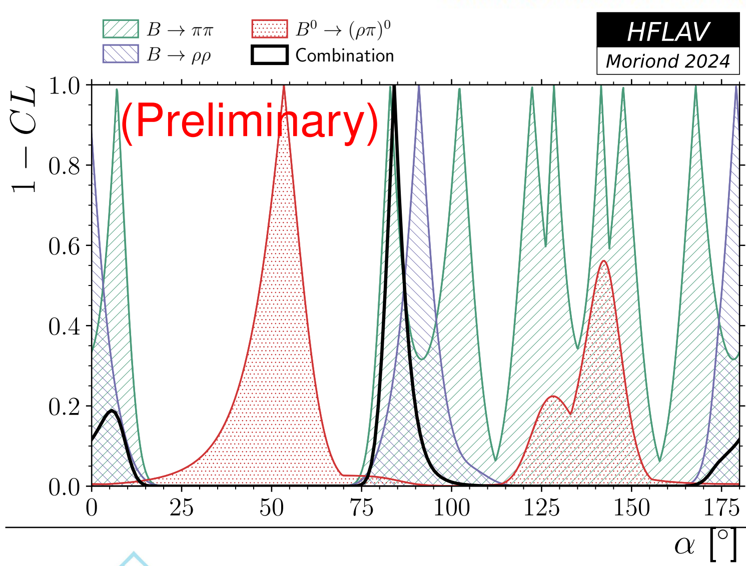
ed 25 October 2003; published 26 January 2004)



Helen had a big role in that *BaBar* physics could be done fast

Pioneering the $\rho\pi$ method, many other topics

Another item not in the BABAR book

- Huge stakes: robust deviation from expectations would indicate new physics
- Proliferation of blind analyses

[© Hitlin @ ICHEP 2000]

- In the BABAR book, I could only find “flavor-blind”, in the context of BSM :)
- Has pretty much become a norm for a lot of BSM searches

BaBar papers cited $>$ 1000

Measurement of an Excess of $\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau$ Decays and Implications for Charged Higgs Bosons #1

BaBar Collaboration • J.P. Lees (Annecy, LAPP) et al. (Mar 3, 2013)

Published in: *Phys.Rev.D* 88 (2013) 7, 072012 • e-Print: 1303.0571 [hep-ex]

pdf DOI cite claim reference search 1,080 citations

Evidence for an excess of $\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau$ decays #2

BaBar Collaboration • J.P. Lees (Annecy, LAPP) et al. (May, 2012)

Published in: *Phys.Rev.Lett.* 109 (2012) 101802 • e-Print: 1205.5442 [hep-ex]

pdf links DOI cite claim reference search 1,222 citations

Observation of a broad structure in the $\pi^+\pi^- J/\psi$ mass spectrum around 4.26-GeV/c^2 #3

BaBar Collaboration • Bernard Aubert (Annecy, LAPP) et al. (Jun, 2005)

Published in: *Phys.Rev.Lett.* 95 (2005) 142001 • e-Print: hep-ex/0506081 [hep-ex]

pdf links DOI cite claim reference search 1,013 citations

Observation of CP violation in the B^0 meson system #4

BaBar Collaboration • Bernard Aubert (Annecy, LAPTH) et al. (Jul, 2001)

Published in: *Phys.Rev.Lett.* 87 (2001) 091801 • e-Print: hep-ex/0107013 [hep-ex]

pdf links DOI cite claim reference search 1,093 citations

The BaBar detector #5

BaBar Collaboration • Bernard Aubert (Annecy, LAPP) et al. (Apr, 2001)

Published in: *Nucl.Instrum.Meth.A* 479 (2002) 1-116 • e-Print: hep-ex/0105044 [hep-ex]

pdf links DOI cite claim reference search 2,404 citations

[On 3/1/2024]

- While 1000 is arbitrary: detector, CP violation, spectroscopy, $B \to D^{(*)}\tau\bar{\nu}$

The B factory era

- 2022 PDG: $B^{\pm}$ 226 pages, B^{0} 258 pages, admixture 76 pages

- And most of the B decay modes are yet unknown!

- High average multiplicity, I do not think it's measured in this millennium, is it?

  Would be interesting to revisit some "global" measurements of $\Upsilon(4S)$ decay

Impressed me since $B\kern-0.1em{\scriptstyle A}\kern-0.1em B\kern-0.1em{\scriptstyle A\kern-0.2em R}$'s 25th

B_s mixing

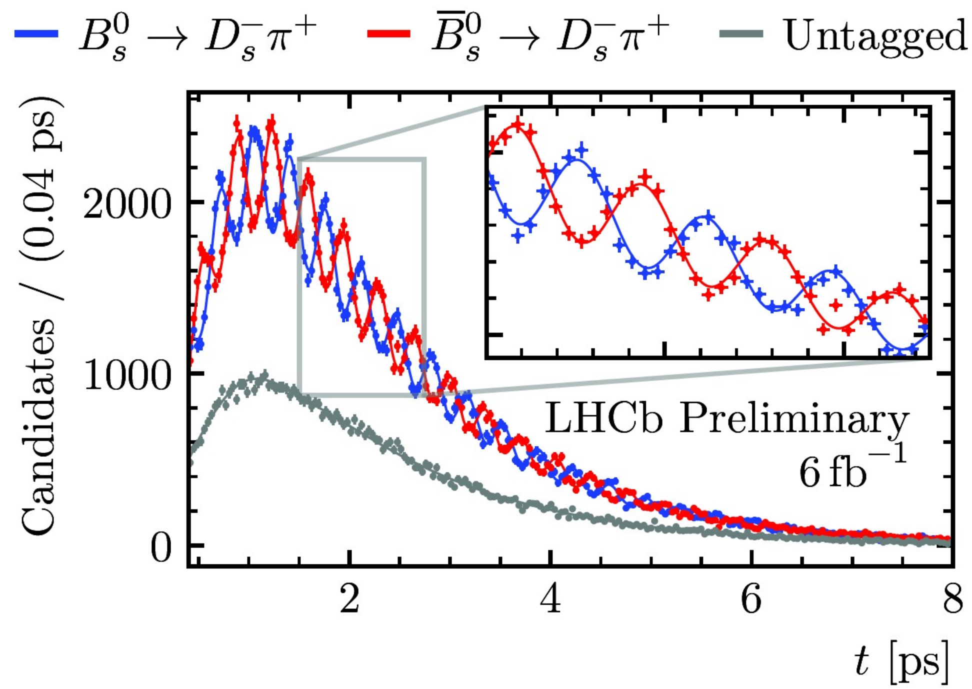
- Textbook measurement: exp. uncertainty of $|V_{tb}V_{ts}|$ similar to $|V_{ud}|$

- $\Delta m_{B_s} = (17.7656 \pm 0.0057)\,\text{ps}^{-1}$

  Relative precision: 3×10^{-4} [LHCb, 2104.04421]

  The most precise neutral meson mass difference (much better than Δm_K!)

  Possible tension with lattice QCD? [1602.03560]



- The most precise CKM-related measurement, except for $|V_{ud}|$

  Error of $|V_{ud}|$ is 1.4×10^{-4} — possibly underestimated

  Error of $|V_{tb}V_{ts}|$ would be 1.6×10^{-4}, if it were not dominated by lattice QCD

CP violation in D decays discovered

- CP violation in D decays:

  (a stretch in the SM, imho)

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

  LHCb, Mar. 2019: $\Delta A_{CP} = -(1.82 \pm 0.33) \times 10^{-3}$ [1903.08726]

- I think we still don't know how big an effect could (not) be due to SM physics

  CKM factors: $|V_{cb}V_{ub}/(V_{cd}V_{ud})| \simeq 7 \times 10^{-4}$

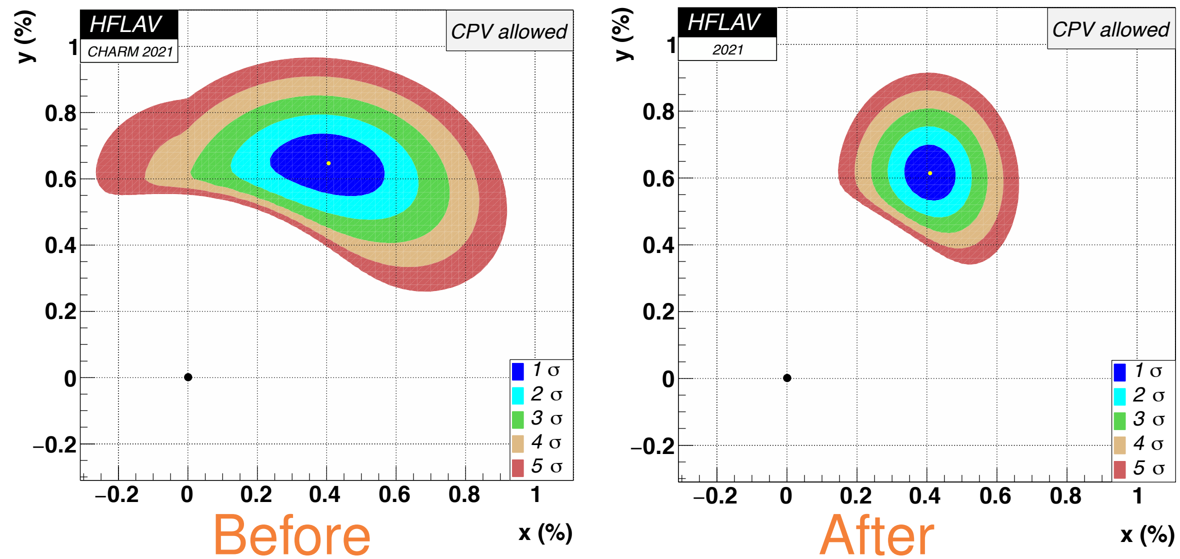
  Before data, everyone (working on it) thought (assumed) strong interaction to suppress this further

- Can we come up with a strategy to understand and test in which decays flavor symmetry relations work better or less well?

- Can we establish if CP violation in mixing would still be a clear probe of NP?

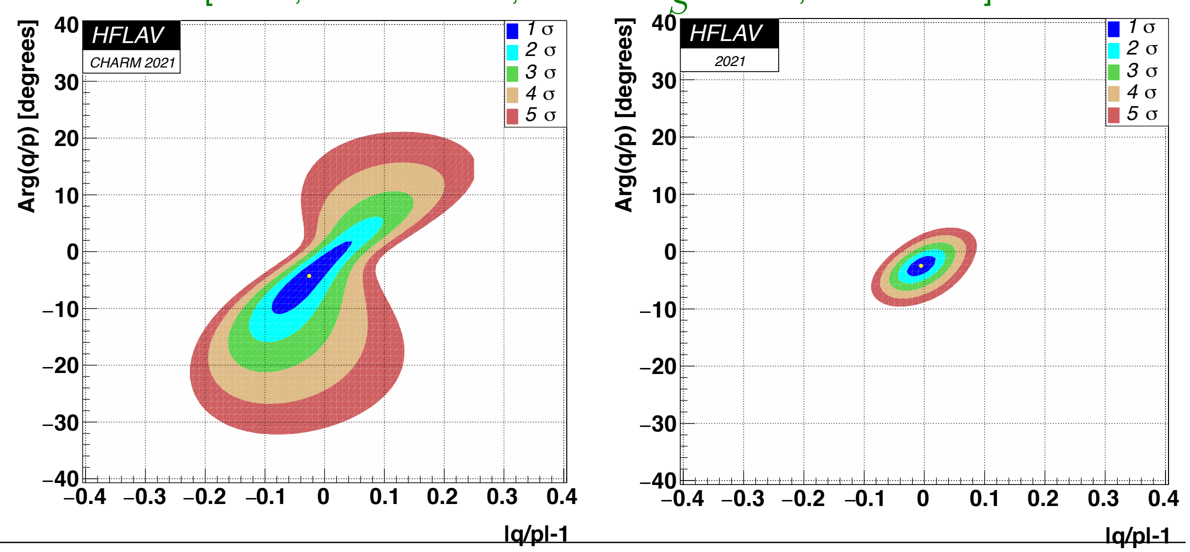
D mixing: large recent progress

- Mixing (and FCNC) generated by down quarks or in SUSY by up-type squarks in the loops
- SUSY and many BSM models: interplay of D and K bounds; e.g., alignment, universality, heavy squarks?



Before After

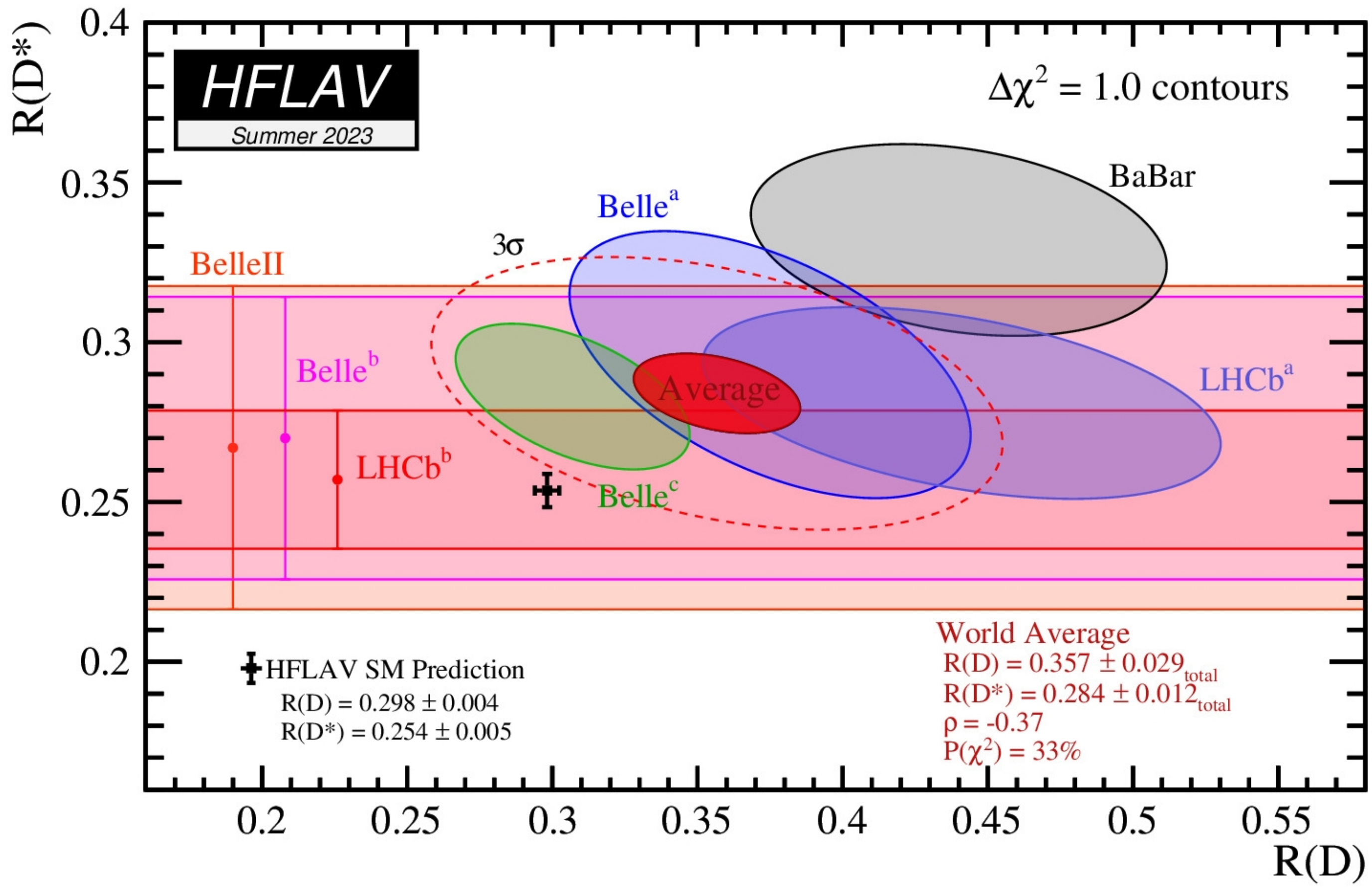
[LHCb, $B^\pm \to Dh^\pm$, $D^0 \to K_S^0\pi^+\pi^-$, 2110.02350]



Most recent BABAR home run

$R(D)$ and $R(D^*)$ — 3σ tension with SM

- BaBar, Belle, LHCb: enhanced τ rates, $R(D^{(*)}) = \dfrac{\Gamma(B \to D^{(*)}\tau\bar\nu)}{\Gamma(B \to D^{(*)}l\bar\nu)}$ $\quad (l = e, \mu)$



[Enhancement also seen in $\Gamma(B_c \to J/\psi\, \ell\bar\nu)$]

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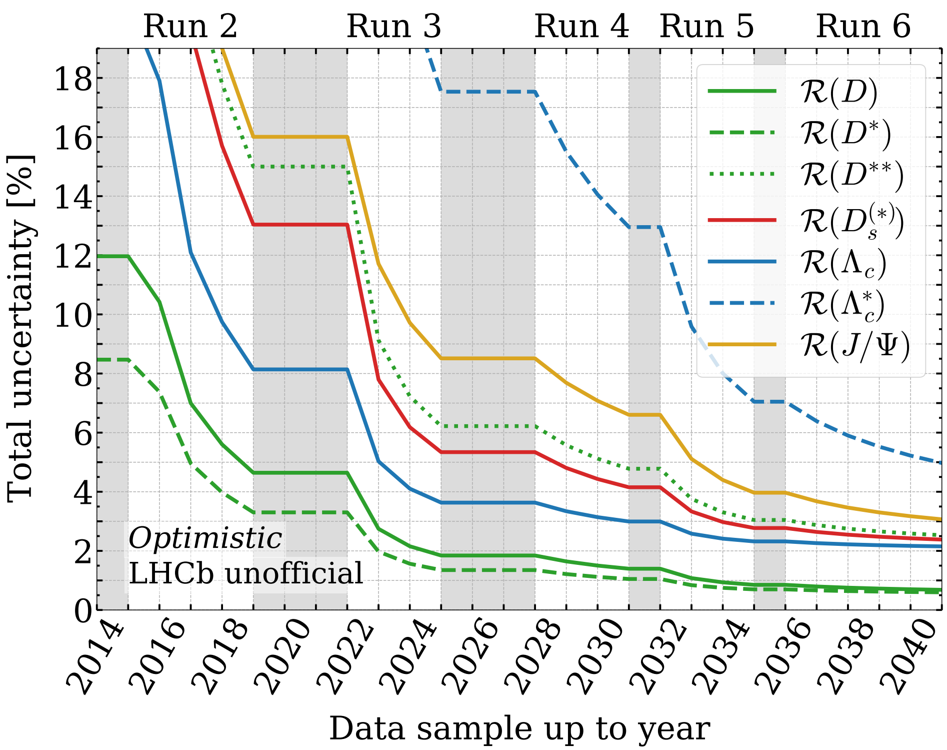
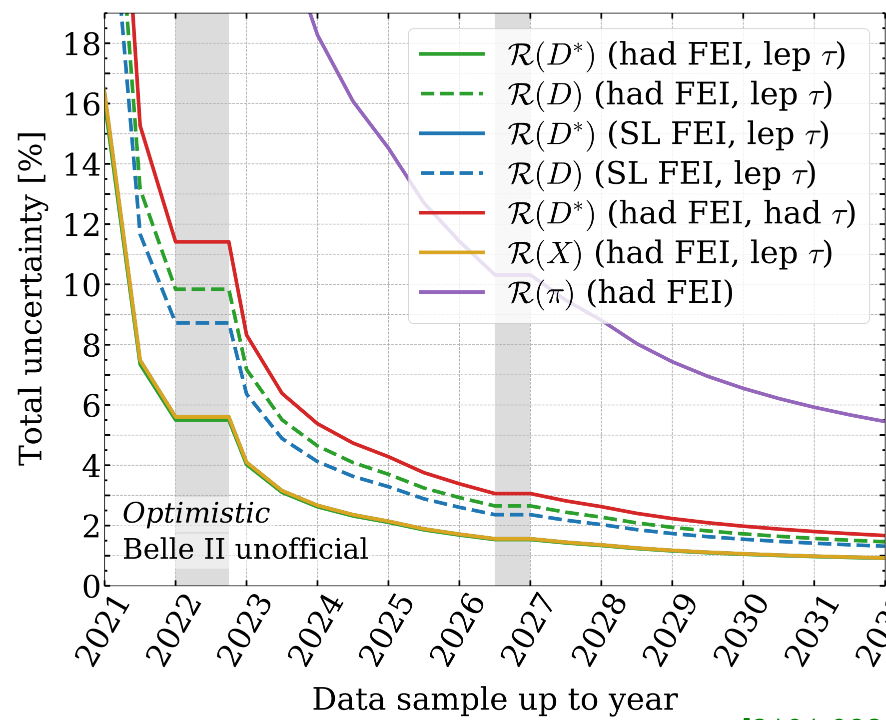
Exciting future prospects





[2101.08326]

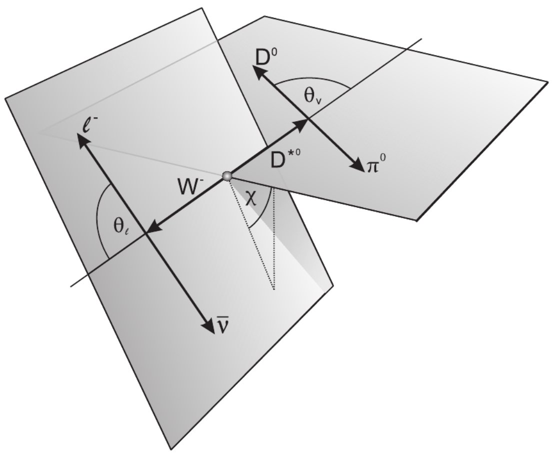
- Measurements will improve a lot!

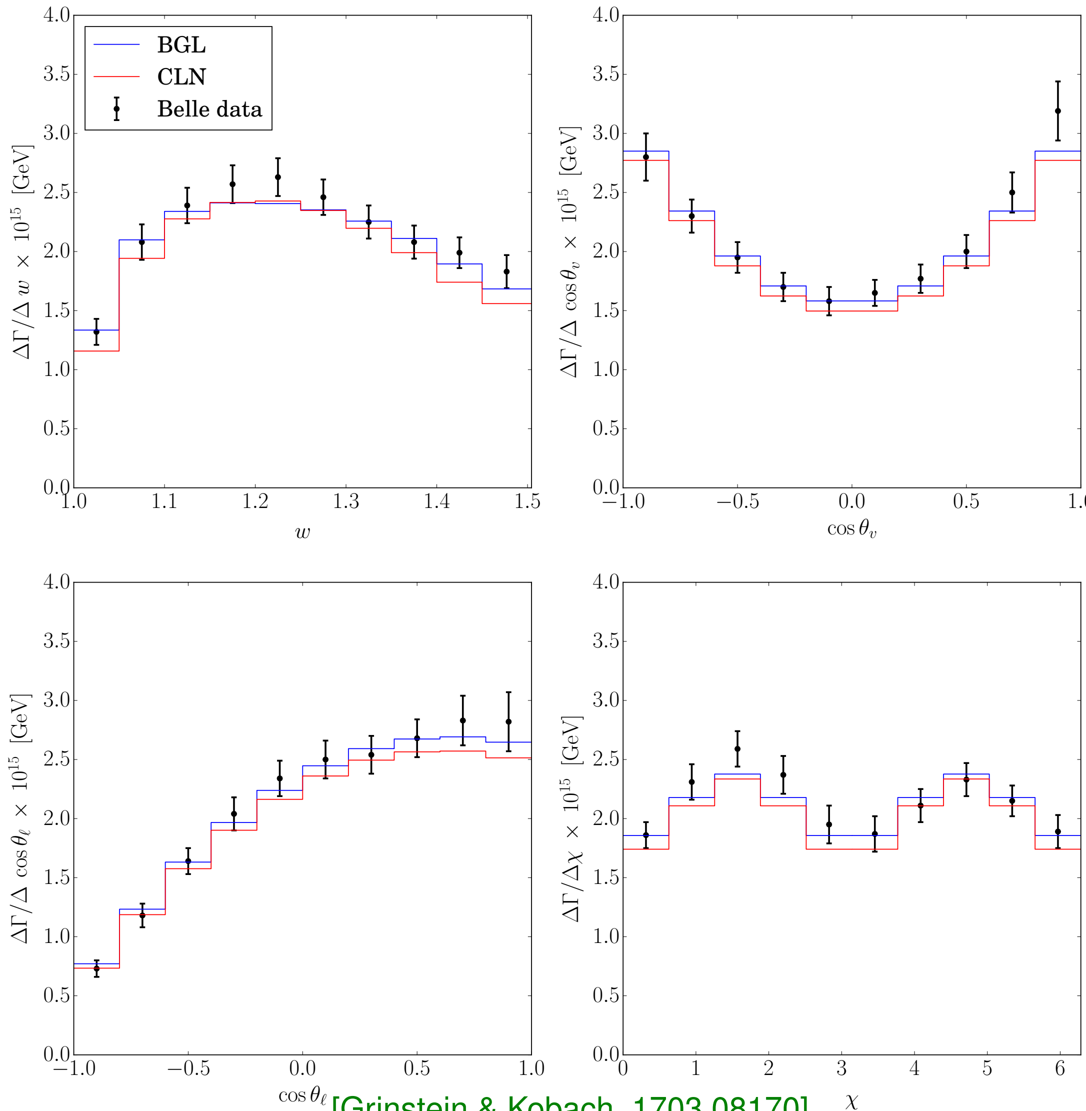
  Even if deviations from SM shrink, may establish presence of BSM

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

Unfolded distributions: never before 2017

- Belle published unfolded $B \to D^* l \bar\nu$ $(l = e, \mu)$ distributions [1702.01521]





[Grinstein & Kobach, 1703.08170]

- Input on the fitted shapes:

  BGL: Boyd, Grinstein, Lebed, '95–97

  CLN: Caprini, Lellouch, Neubert, '97

  1997–2017: all measurements used CLN

- Can perform different fits to data

Motivated pushing HQET further

- Much of this could have been worked out in the 1990s... (no one would have cared)

  'When you think you can finally forget a topic, it's just about to become important'

  [Polchinski]

- Lorentz invariance: 6 functions of q^2, only 4 measurable with e, μ final states

$$
\begin{aligned}
\langle D|\, \bar c \gamma^\mu b \,|\overline{B}\rangle &= f_+(q^2)(p_B+p_D)^\mu + \Big[f_0(q^2) - f_+(q^2)\Big]\frac{m_B^2-m_D^2}{q^2}\, q^\mu \\
\langle D^*|\, \bar c \gamma^\mu b \,|\overline{B}\rangle &= -ig(q^2)\, \epsilon^{\mu\nu\rho\sigma}\, \varepsilon^*_\nu\, (p_B+p_{D^*})_\rho\, q_\sigma \\
\langle D^*|\, \bar c \gamma^\mu \gamma^5 b \,|\overline{B}\rangle &= \varepsilon^{*\mu} f(q^2) + a_+(q^2)\,(\varepsilon^*\cdot p_B)\,(p_B+p_{D^*})^\mu + a_-(q^2)\,(\varepsilon^*\cdot p_B)\, q^\mu
\end{aligned}
$$

  The a_- and $f_0 - f_+$ form factors $\propto q^\mu = p_B^\mu - p_{D^{(*)}}^\mu$ do not contribute for $m_l = 0$

- HQET: One Isgur-Wise function (heavy quark limit) $+\,3$ at $\mathcal{O}(\Lambda_{\rm QCD}/m_{c,b}) + \ldots$

- "Idea": fit 4 functions of w with 4 observables (1 in $B \to D\, l\bar\nu$ and 3 in $B \to D^* l\bar\nu$)

- Uncertainties are $\mathcal{O}(\Lambda_{\rm QCD}^2/m_{c,b}^2\,,\ \alpha_s^2)$ [Bernlochner, ZL, Papucci, Robinson, 1703.05330]

$B \to D^{(*)}\tau\bar{\nu}$: BSM implications

- 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, $H^{\pm}$

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

- Connections to a large spectrum of lepton flavor violation searches

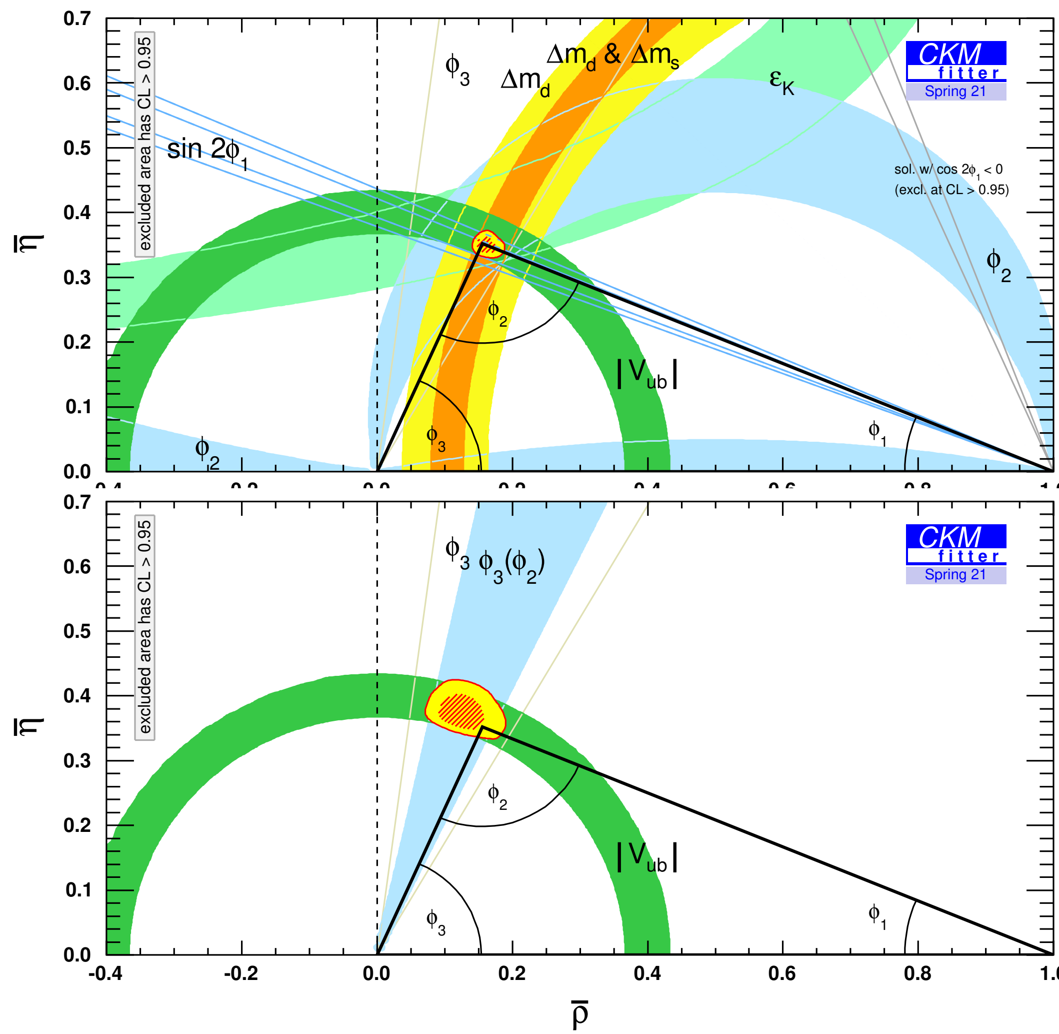
- Models built to fit these anomalies have impacted many ATLAS & CMS searches

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

New physics in B mixing

Plenty of room for new physics

- Impressive consistency — not as constraining as it may seem
- Larger allowed region if the SM is not assumed
- Loop-level (top) vs. tree-dominated (lower plot) measurements crucial
- LHCb: even better constraints, also in B_s sector (2nd–3rd generation)



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

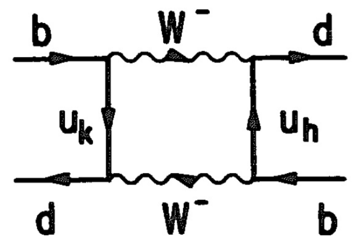
Constraining NP in B mixing

- Assume: (i) 3×3 CKM matrix is unitary; (ii) tree-level decays dominated by SM

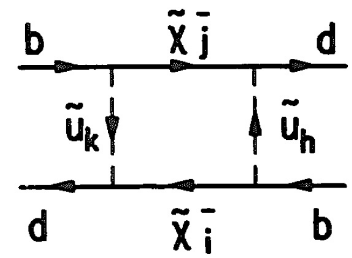
General parametrization of many models by two real parameters (in addition to SM):

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

↖ ↑ NP parameters



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



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

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

- Only in 2004 (with initial α, γ) was $h < 1$ established, i.e., BSM $<$ SM contribution

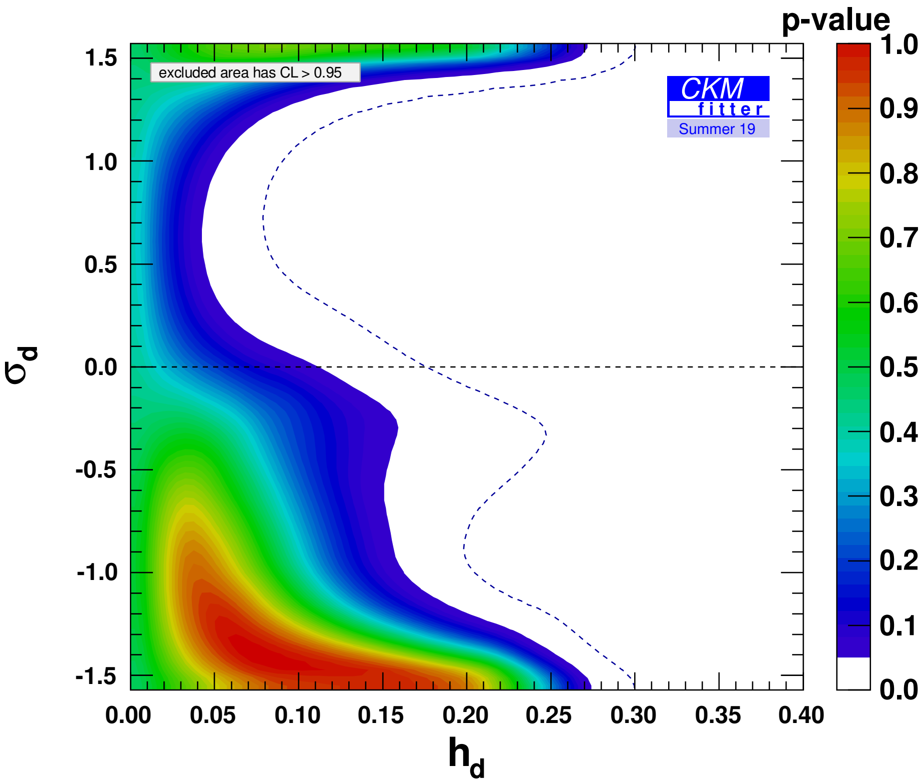
Relies on many measurements and theoretical inputs

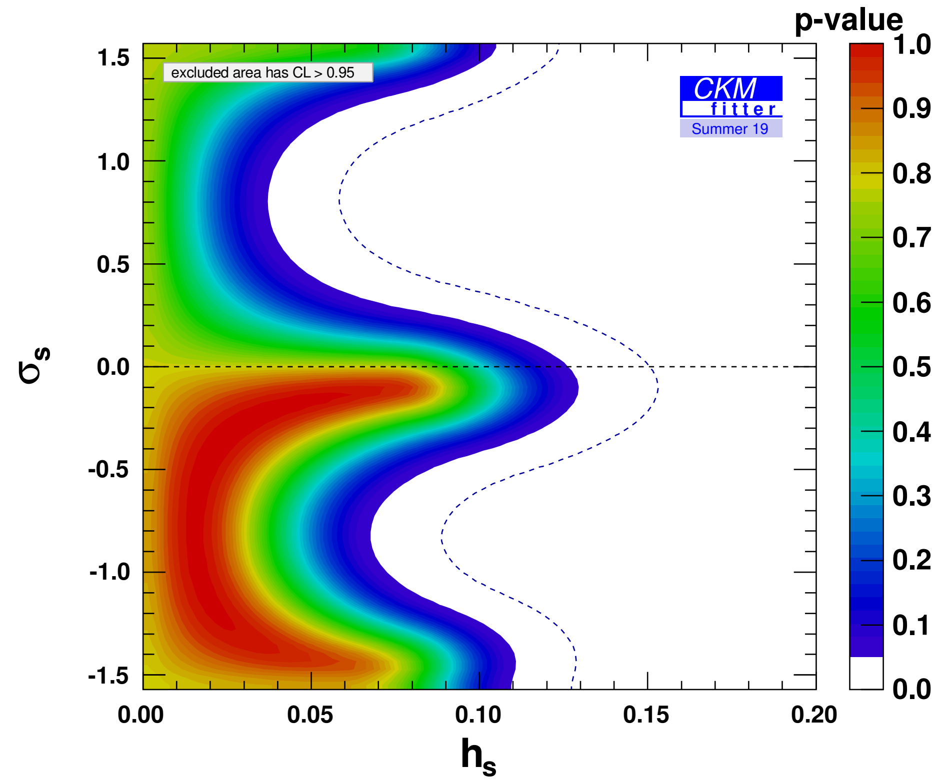
Redo CKM fit w/ NP param's: tree-dominated unchanged, loop-mediated modified

Importance known since 1970s ($\Delta m_K/m_K \sim 7 \times 10^{-15}$), conservative view of future progress

Bounds on new physics in mixing

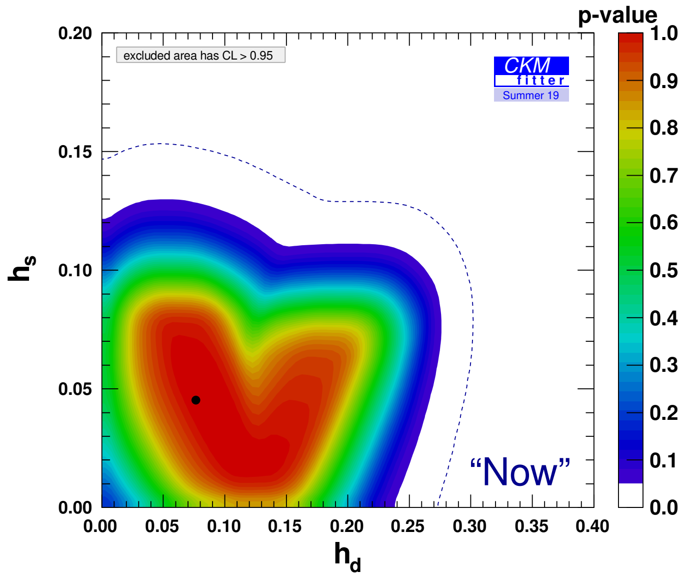
- Constraints on NP in B_s mixing became better than in B_d (as expected)





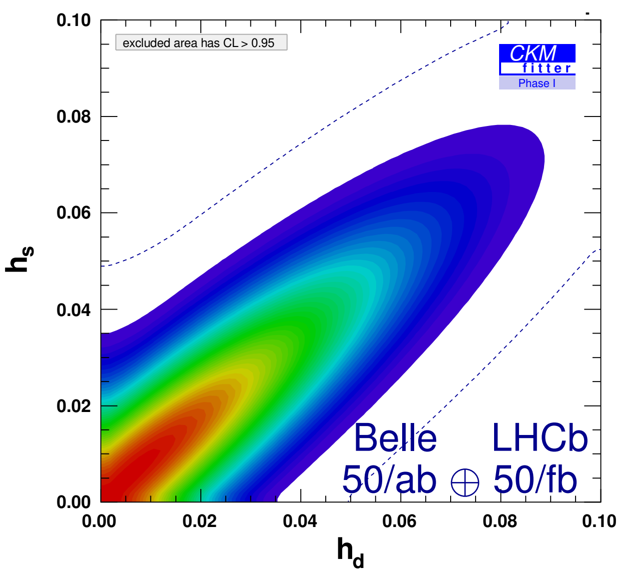
- h is the magnitude of the ratio of NP/SM contributions to M_{12}

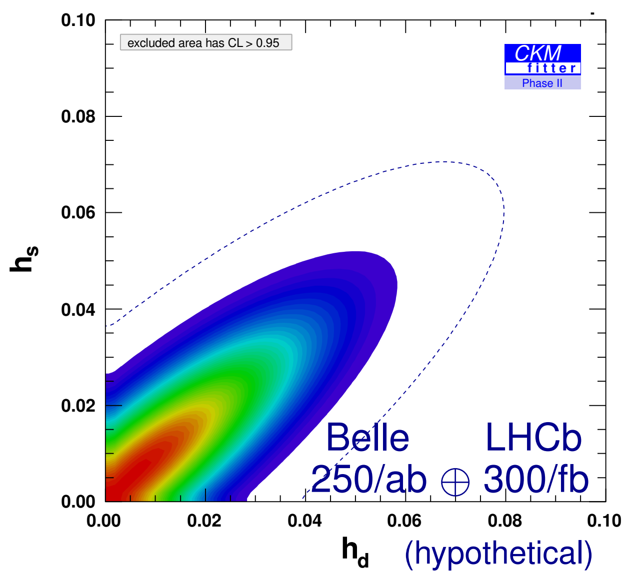
Future sensitivity to NP in B mixing



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

Main bottlenecks: (i) $|V_{cb}|$ precision,

(ii) mixing param's from LQCD and η_B

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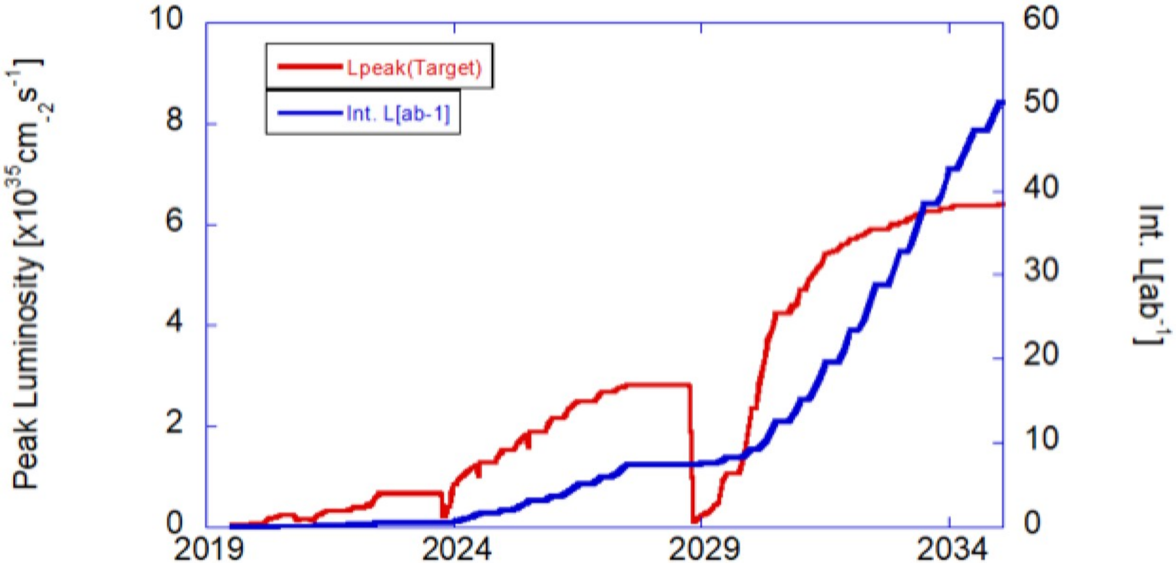
Future

Belle II and LHCb: clear plans



(Discussions about further upgrade)

	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}	$\longrightarrow$	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 $2\text{x}10^{34}\ cm^{-2}s^{-1}$

FCC*: impressive flavor program

- Very large and clean samples of B decays ($\sim 10^6 \times$ LEP)

- Production yields at tera-Z compared to Belle II (from CERN-ACC-2018-0056)

Particle production (10^9)	$B^0 + \overline{B}^0$	$B^\pm$	$B_s^0 + \overline{B}_s^0$	$\Lambda_b + \bar{\Lambda}_b$	$c\bar{c}$	$\tau^+\tau^-$
Belle II (50 ab^{-1})	27.5	27.5	—	—	65	45
FCC-ee (5×10^{12} Z)	400	400	100	100	550	170

Comparison with LHC(b) more complex: trigger at LHC is essential, LHCb has advantage if final state is fully reconstructed, tera-Z may win if there are neutrals

- WW threshold: $W \to b\bar{c}$ can give a qualitatively new determination of $|V_{cb}|$
Estimate 0.3% uncertainty, using 10^8 WW, independent of B measurements

[Schune @ 3rd FCC Physics and Experiments Workshop, Jan 2020; Azzurri @ 4th FCC Physics and Experiments Workshop, Nov 2020]

* A linear collider could do some of this, with less statistics

Semileptonic CPV: $A_{\rm SL}^{d,s}$ approach SM @ Tera-Z

- CPV in mixing, m_c^2/m_b^2 suppressions specific to the SM need not occur for NP

[hep-ph/0202010]

$$A_{\rm SL} = \frac{\Gamma[\overline{B}^0(t) \to \ell^+ X] - \Gamma[B^0(t) \to \ell^- X]}{\Gamma[\overline{B}^0(t) \to \ell^+ X] + \Gamma[B^0(t) \to \ell^- X]}$$

In large classes of BSM models, the dominant deviations from the SM may be in neutral meson mixing amplitudes, with smaller impacts on decay rates

- Current status:

Data: $A_{\rm SL}^d = -(2.1 \pm 1.7) \times 10^{-3}$ $\qquad A_{\rm SL}^s = -(0.6 \pm 2.8) \times 10^{-3}$

SM: $A_{\rm SL}^d = -(4.7 \pm 0.6) \times 10^{-4}$ $\qquad A_{\rm SL}^s = (2.22 \pm 0.27) \times 10^{-5}$ [1603.07770]

Plenty of room between current sensitivity and the SM predictions

(Hard to extrapolate whether LHCb becomes systematics limited)

- Tera-Z expectation: exp uncertainty $\sim 2.5 \times 10^{-5}$ for both

Aside: semileptonic CP violation and finance

- Work on new physics in mixing, if you want a career in finance

Cahn & Worah:

PHYSICAL REVIEW D, VOLUME 60, 076006

Constraining the CKM parameters using *CP* violation in semileptonic *B* decays

Robert N. Cahn
Theoretical Physics Group, Earnest Orlando Lawrence Berkeley National Laboratory, University of California, Berkeley, California 94720

Mihir P. Worah
Department of Physics, University of California, Berkeley, California 94720 and Theoretical Physics Group, Earnest Orlando Lawrence Berkeley National Laboratory, University of California, Berkeley, California 94720

(Received 10 May 1999; published 13 September 1999)

Mihir: Ph.D. with Rosner, postdoc at SLAC and Berkeley, then PIMCO, eventually CIO for asset allocation and real return; retired in 2019, many news articles...

(Best-known paper with Yuval Grossman in '96, on significance of $b \to s\bar{s}s$ CPV to probe NP)

Some key questions

- Will LHC see NP beyond the Higgs? (new particle $\Rightarrow$ new flavor sector, recall $H\tau\mu$, Htc?)
- Will NP be seen in the quark sector? (Current data: hints of possible deviations from SM)
- Will NP be seen in charged lepton sector? $\mu N \to eN$, $\mu \to e\gamma$, $\tau \to \mu\gamma$, $\tau \to 3\mu$?
- Will DM be discovered? Axions? EDMs? Something else?
- Neutrinos: Does 3 flavor paradigm hold? What is the nature of ν mass?

- No one knows — an exploratory era!

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

  (NB: 2 generations $+$ superweak is "more minimal" to accommodate CPV, than 3 generations...)

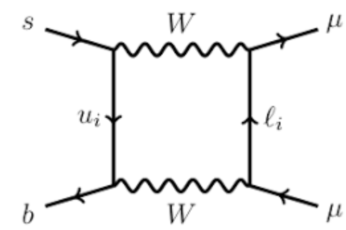
- Near future: "anomalies" might become first established

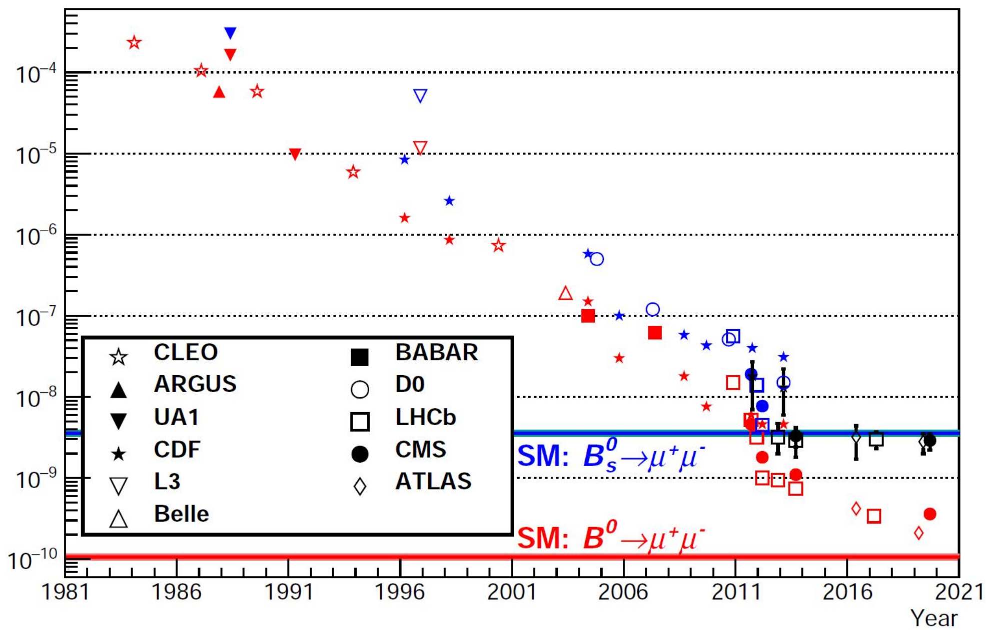
  Long term: large increase in discovery potential in many modes

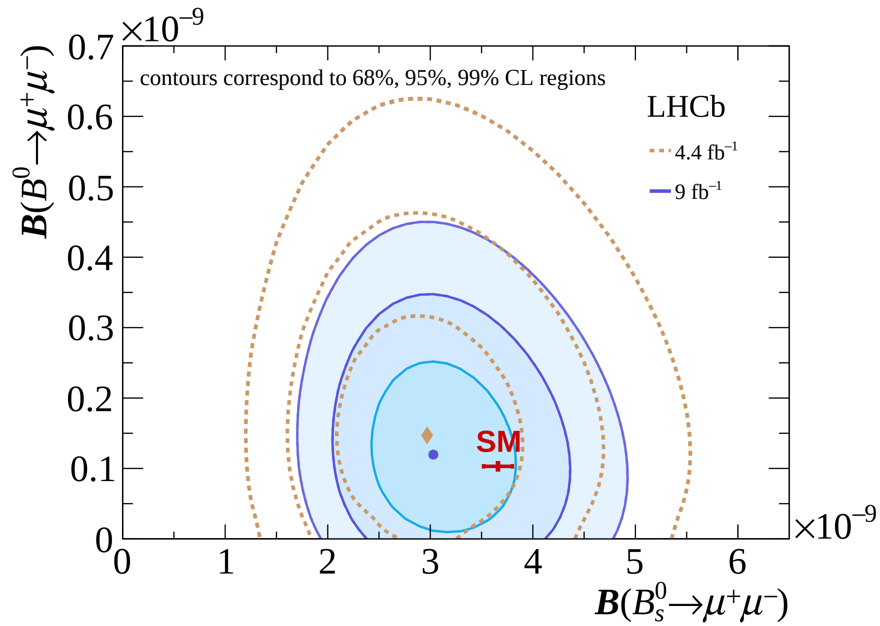
Standalone discovery modes: $B_{s,d} \to \mu^+\mu^-$

- $B_d \to \mu^+\mu^-$ sensitive to $\mathcal{O}(100\,\mathrm{TeV})$, similar to $K \to \pi\nu\bar{\nu}$

  SM prediction is very precise







- $\mathcal{B}(B_s \to \mu^+\mu^-) = (3.01 \pm 0.35) \times 10^{-9}$ consistent w/ SM, $B_d \to \mu^+\mu^-$ not yet seen

  LHCb expects $\lesssim 10\%$, and CMS expects $\lesssim 15\%$ during HL-LHC

- Theoretically cleanest (without lattice) "$|V_{ub}|$" I know: $\mathcal{B}(B_u \to \ell\bar{\nu})/\mathcal{B}(B_d \to \mu^+\mu^-)$

Final remarks

What are the largest useful data sets?

- No one has seriously explored it! (Recall, Sanda, 2003: the question is not 10^{35} or 10^{36}...)
- 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)
- 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!)
- Guess: until $100\times$ (Belle II & LHCb Phase 2), sensitivity to NP would improve
- FCC-ee in tera-Z phase could eclipse prior B factories (nb: Belle II / ARGUS $\sim 10^5$)

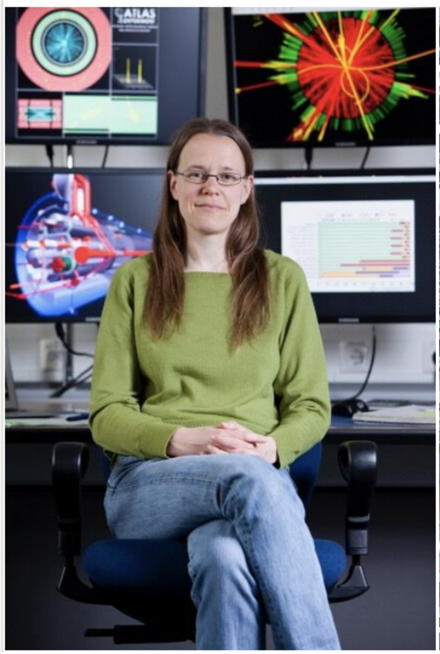
More success of *BaBar*-ians

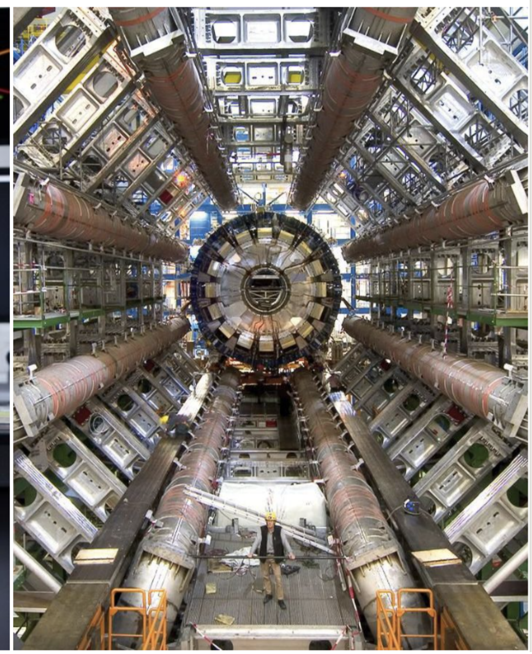
Deutsches Elektronen-Synchrotron DESY
24.247 Follower:innen
3 Std. •

+ Folgen

When physicists hear the word Atlas, they are not thinking of Greek mythology, but of the ATLAS detector at the Large Hadron Collider (LHC) at CERN. The international ATLAS collaboration at CERN has elected our colleague Kerstin Tackmann as its next Physics Coordinator. Physics coordination is a key task in this collaboration, as the ATLAS experiment at CERN is currently the largest experiment in particle physics: The collaboration counts about 3000 members from 182 institutes in 42 countries and is tasked with operating and sometimes modernizing the experiment with its many sub-detectors, and analyzing the extremely complex and large amounts of data. Congratulations!

Übersetzung anzeigen





BaBar is still young

If $R(D^{(*)})$ is established as evidence for new physics $\Rightarrow$ more parties!

Conclusions

- Flavor physics probes scales $\gg 1\,\mathrm{TeV}$; sensitivity limited by statistics

  New physics in FCNCs may still be $\gtrsim 20\%$ of SM, could show up any time measurements improve

- Discovering NP would give a target and upper bound on the next scale to explore

- Theory essential for fully exploiting the experimental program ($+$open questions)

- Complementarity between flavor & LHC probes of BSM (and understanding it)

- Large increases in data always triggered unforeseen developments

- Ample reasons to aim for the largest possible data sets that technology allows

Bonus slides

Factor of 2 improvements can 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-

Program planning in 1982

- “Lederman’s Shoulder, Weinberg’s Nose, and Other Lessons from the Past” [Politzer, 1982]

  “Planning for discovery is both absolutely necessary and fundamentally silly. We can’t know what will be. However, we can look back. The unexpected has come sometimes at the highest energy frontier ... and sometimes in a careful look over old ground, such as CP violation ... Whatever the current theoretical beliefs, our future plans should not stifle the possibility of discovery.”

- Before P5, there was P8! ☺ [Politzer, 1982]

  “Problems, Puzzles and Prospects: A Personal Perspective on Present Particle Physics”

  “When is the soonest that something dramatic might happen? The answer here is clearly tomorrow. The answer might even be yesterday”

  “I firmly believe that anything that can be measured well is worth doing.”

  “I think the experimental prospects are wide open. All we have to do is try.”

Lessons from the LHC

- Theoretical prejudices about new physics did not work as expected 10–20 yrs ago
- Hierarchy puzzle: fine tuning measures off? Is NP an order of magnitude heavier?
  Flavor may be even more important (deviation from SM $\to$ upper bound on scale)
- New physics at LHC — minimal flavor violation (MFV) probably a useful approx.
  $\Updownarrow$ "naturalness' loss = flavor's gain"
  New physics at $10 - 100\,\mathrm{TeV}$ — less flavor suppression (MFV less motivated)
- No guarantees after Higgs discovery... leave no stone unturned...
- Discovering deviations from the SM flavor sector is possible in either case
  (LHC-scale MFV-like, or heavier more generic scenarios)
- Unambiguous BSM discovery would change things qualitatively, and refocus field
  $\Rightarrow$ If any of the current anomalies become decisive, it would be a game changer

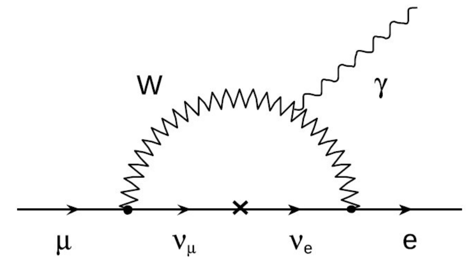
Theory challenges / opportunities

- 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?

Charged lepton flavor violation

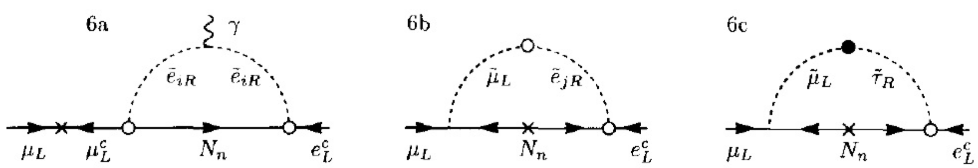
- SM predicted lepton flavor conservation with $m_\nu = 0$

  Given $m_\nu \neq 0$, no reason to impose it as a symmetry



$$\mathcal{B}(\mu \to e\gamma) \sim \alpha\, \frac{m_\nu^4}{m_W^4} \sim 10^{-52}$$

- If new TeV-scale particles carry lepton number (e.g., sleptons), then they have their own mixing matrices $\Rightarrow$ charged lepton flavor violation

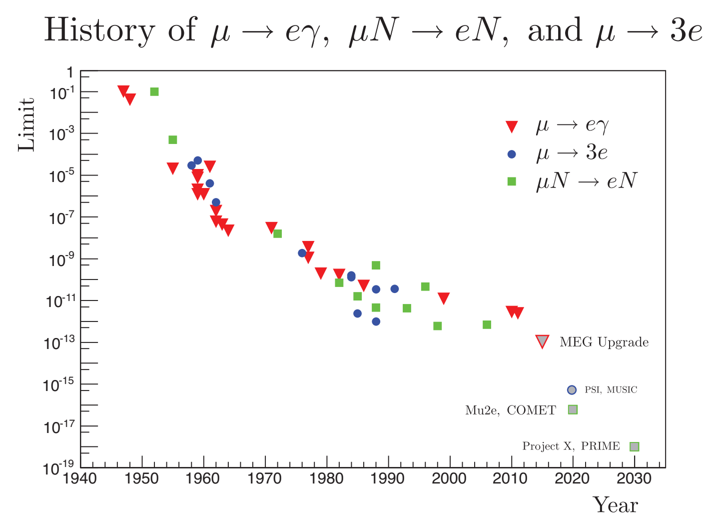


- Many interesting processes:

  $\mu + N \to e + N^{(\prime)},\ \mu \to e\gamma,\ \mu \to eee,\ \mu^+e^- \to \mu^-e^+$

  $\tau \to \mu\gamma,\ \tau \to e\gamma,\ \tau \to \mu\mu\mu,\ \tau \to eee,\ \tau \to \mu\mu e$

  $\tau \to \mu ee, \tau \to \mu\pi,\ \tau \to e\pi,\ \tau \to \mu K_S,\ eN \to \tau N$



- Next 10–20 years: 10^2–10^5 improvement; any signal would trigger broad program

Reasons to seek higher precision in flavor

- Expected deviations from the SM, induced by TeV-scale NP?

  Generic flavor structures ruled out; can find any size deviations, detectable effects in many models

- Theoretical uncertainties?

  Highly process dependent, under control in many key measurements

- Expected experimental precision?

  Useful data sets will increase by $\sim 10^2$, and probe fairly generic BSM predictions

- What will the measurements teach us if deviations from the SM are (not) seen?

  Complementary with LHC high-p_T program; synergy can teach us what the NP is (what it's not)

- No guaranteed discoveries — an exploratory era

  Near future: "anomalies" might first be established

  Long term: large increase in discovery potential in many modes