Physics at LHCb $\&$ Belle II

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Preliminaries...

- ATLAS and CMS are not the only collider experiments — this talk: LHCb & Belle II
- A large number of reviews on key measurements, sensitivities, exclusion limits

  I will not show (large and impressive!) tables of sensitivity projections [links below]

- "Impact of the LHCb upgrade detector design choices on physics and trigger performance," LHCb-PUB-2014-040

  "EoI for Phase-II LHCb Upgrade," LHCC-2017-003

  "Physics case for an LHCb Upgrade-II" — by LHCC in May

  A nice recent talk by Vincenzo Vagnoni
- B2TIP workshop report (Belle II physics book), arXiv:1808.10567

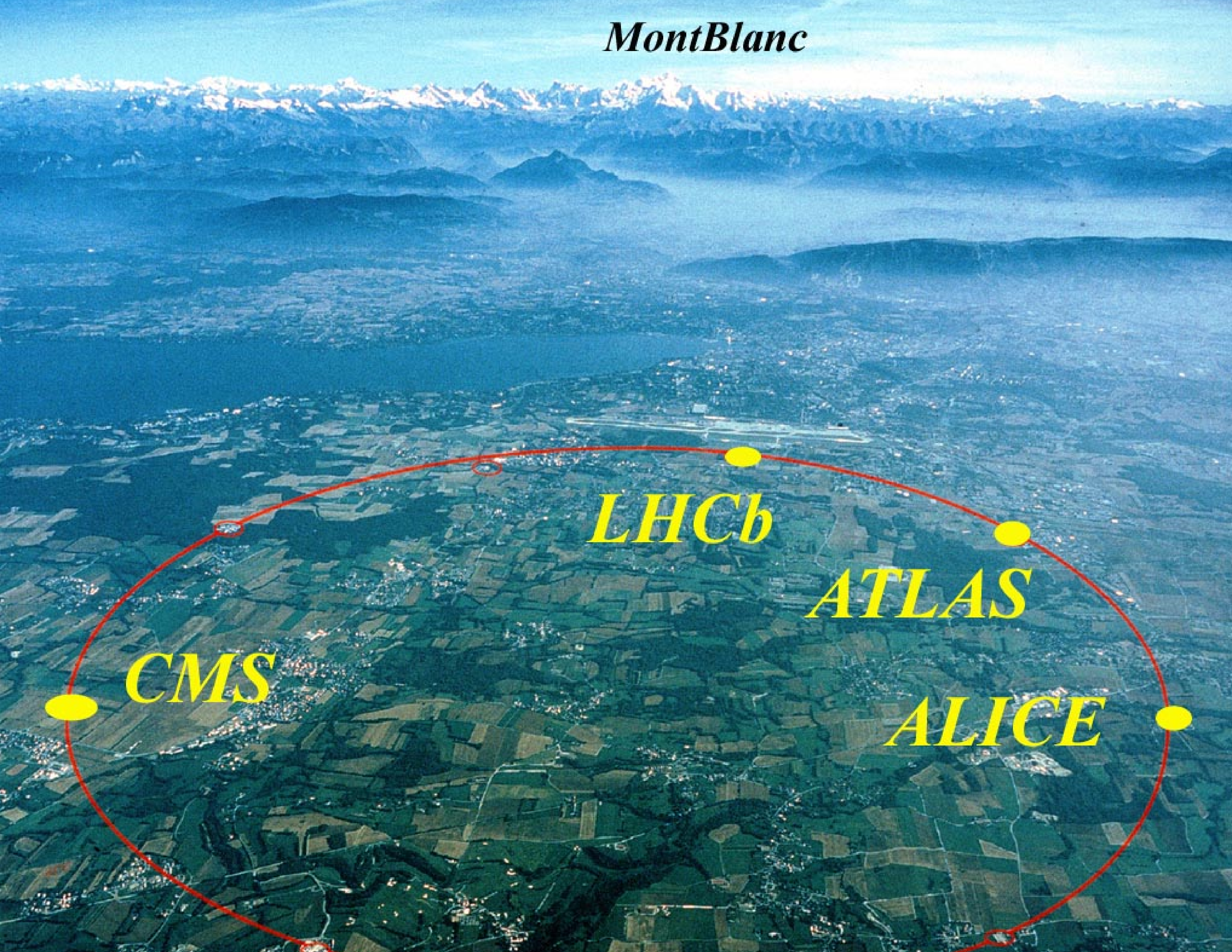
  "Impact of Belle II on flavor physics," BELLE2-NOTE-0021

LHCb — LHC at CERN

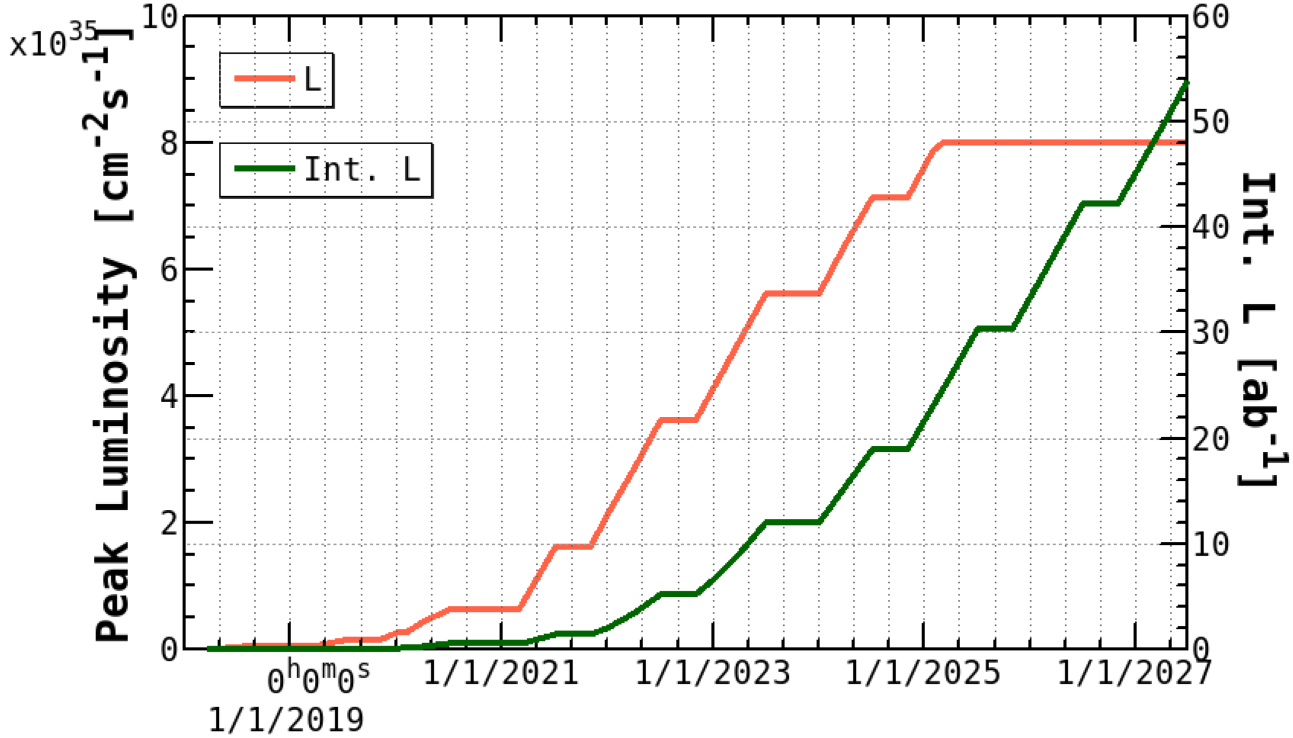
	LHC era			HL-LHC era	
	Run 1 (2010-12)	Run 2 (2015-18)	Run 3 (2021-24)	Run 4 (2027-30)	Run 5+ (2031+)
ATLAS, CMS	25 fb^{-1}	150 fb^{-1}	300 fb^{-1}	$\longrightarrow$	3000 fb^{-1}
LHCb	3 fb^{-1}	9 fb^{-1}	23 fb^{-1}	50 fb^{-1}	*300 fb^{-1}

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

- 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 $2 \times 10^{34}/\mathrm{cm}^2/\mathrm{s}$
- European Particle Physics Strategy Update will say something — to me, it is obviously an integral part of the full exploitation of the LHC

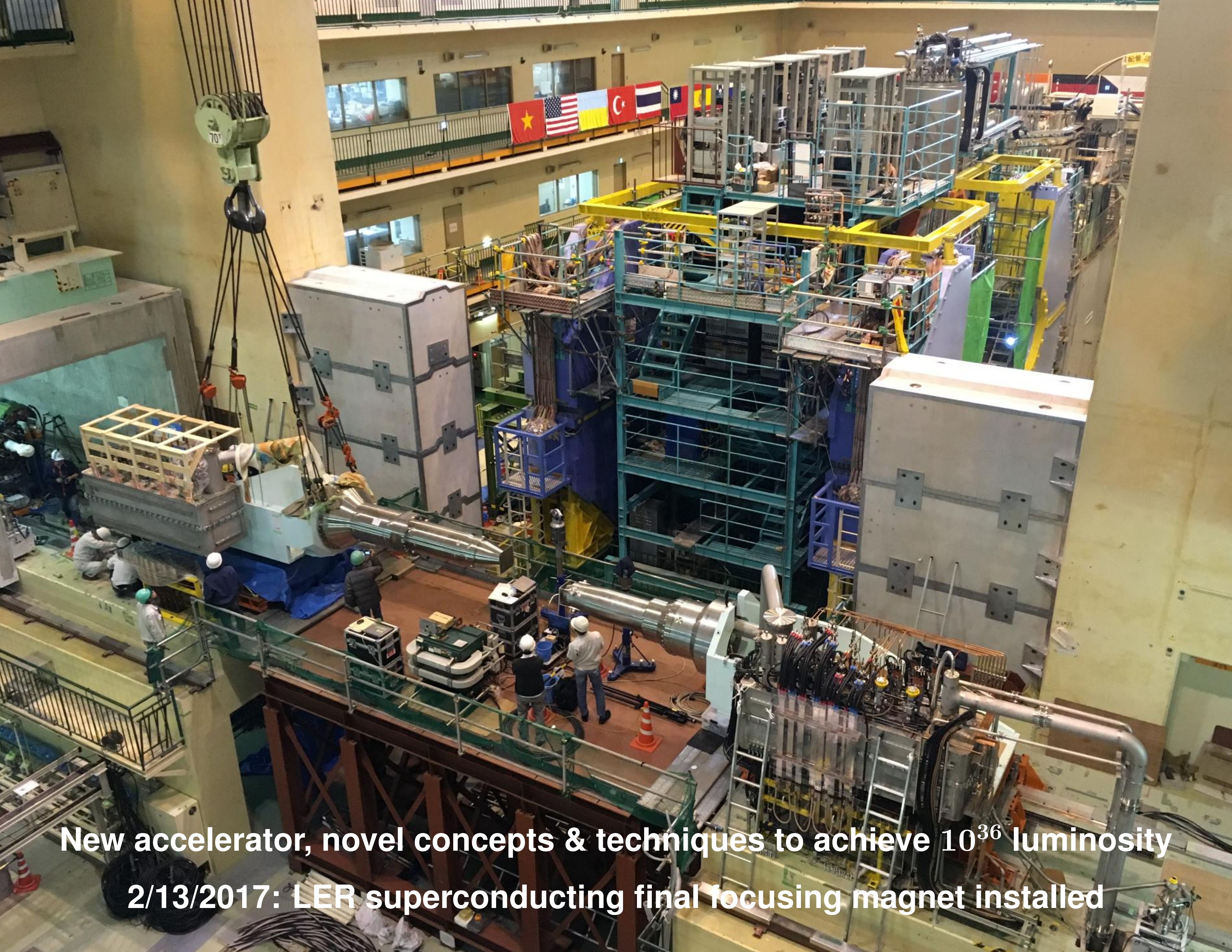

MontBlanc
LHCb
ATLAS
CMS
ALICE

Belle II — SuperKEKB at Tsukuba



- First collisions last year (unfinished detector), beams start again 3/11/2019
  Goal: $50\times$ the Belle and nearly $100\times$ the BaBar data set

- Discussions started about motivation for and feasibility of a factor ~ 5 upgrade, similar to LHCb Phase-II upgrade aiming 50/fb $\rightarrow$ 300/fb beyond LHC LS4

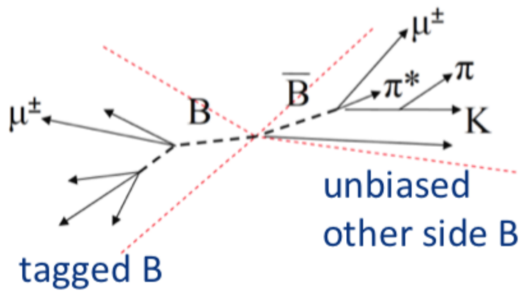


New accelerator, novel concepts & techniques to achieve 10^{36} luminosity

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

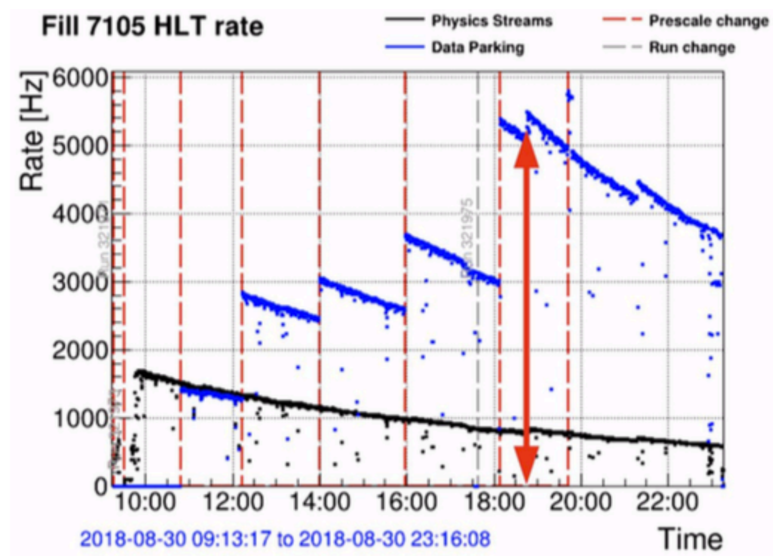
A surprise in 2018: CMS "B – parking"

- CMS collected $\sim 10^{10}$ B decays; goal: check an LHCb 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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Outline

- Introduction to flavor physics
- Mode / model independent: Large improvements in NP sensitivity — 3 examples

  Going from: $\text{NP} \lesssim (\text{few} \times \text{SM}) \to \text{NP} \lesssim (0.3 \times \text{SM}) \to \text{NP} \lesssim (0.05 \times \text{SM})$

  (-10 yrs) (now) ($+10$ yrs)

- Mode / model specific: Current tensions with SM — might soon become decisive

  Several $2-4\sigma$ tensions with SM: fluctuations? triggered lots of exp & theory work

- Richness of directions: top, higgs, DM, long lived, dark sectors, quirks, etc.

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Introduction

Hope to discover BSM physics...

- Most experimentally observed phenomena consistent with the "standard model"

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

- Clearest empirical evidence that SM is incomplete:
  - Dark matter — Maybe at
  - Baryon asymmetry of the Universe — TeV scale
  - Neutrino mass [can add in a straightforward way]
  - Inflation in the early universe [have a theoretical picture that might work]
  - Accelerating expansion [cosmological const.? need to know more to address?]

- Baryon asymmetry: nonzero in the SM, but too small by a factor $\sim 10^{10}$ [Yury's talk]

  [Sakharov conditions: (i) B violation; (ii) C and CP violation; (iii) deviation from thermal equilib.]

- Need BSM source(s) of CP violation

  What is the microscopic theory of CP violation? How precisely can we test it?

Some flavor-related questions

- Will LHC see new particles beyond the Higgs?

  Any new particle that couples to quarks and/or leptons $\Rightarrow$ many new flavor param's (e.g., SUSY)

- Will NP be seen in the quark sector?

  Current data: several hints of lepton flavor universality violation (see later)

- Will NP be seen in lepton sector (CLFV)? $\mu \to e\gamma$, $\mu \to eee$, $\tau \to \mu\gamma$, $\tau \to \mu\mu\mu$?

- Neutrinos? (3 flavors? Majorana / Dirac?)

  Dark matter may also relate to flavor

- No one knows — an exploratory era!

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

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- Near future: current tensions have the best chance to become significant

  Long term: large increase in discovery potential in many modes

Why is flavor physics interesting?

- Flavor: theoretically not well understood

  experimentally rich and sensitive ways to probe the SM and search for NP

- Uncertainty principle $\Rightarrow$ heavy particles, which cannot be produced, affect lower energy processes, E^2/M^2 suppressed if interference $\Rightarrow$ probe very high scales

- SM flavor: hierarchy of masses and mixing angles? why 3 generations?

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

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

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

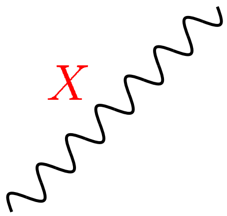
  E.g., SUSY: $\sim 10\times$ increase in flavor parameters (CP and flavor problems?)

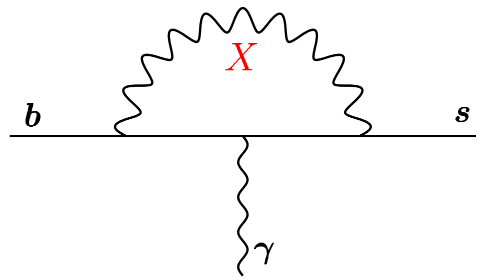
  Generic TeV-scale flavor structure excluded $\Rightarrow$ new mechanisms to reduce signals

- Flavor sector will be tested a lot better, many NP models have observable effects

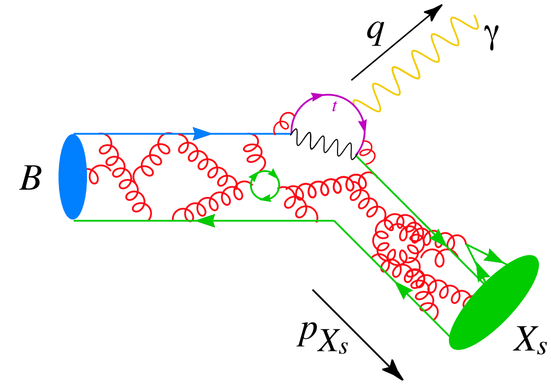
In cartoons...

(a) A new particle, X, solves all theoretical problems, unifies forces, etc., however ...





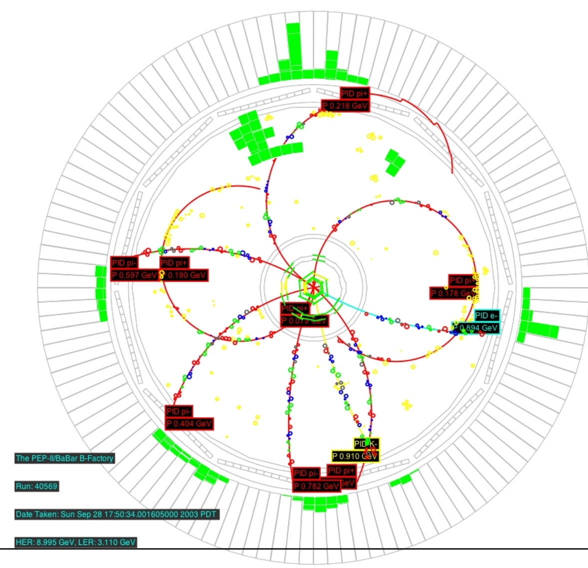
(b) ... it is too heavy to be produced directly, but contributes to properties of known particles



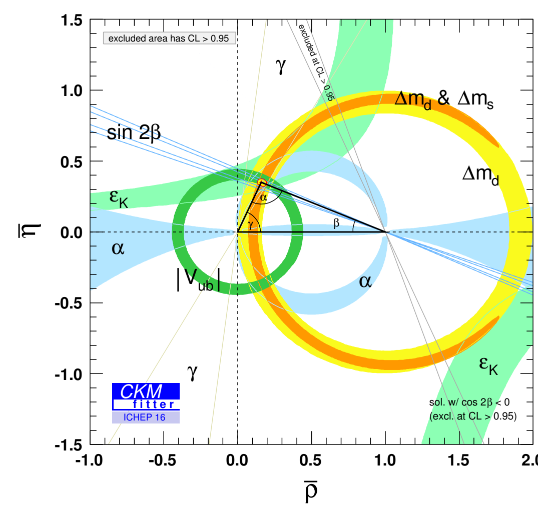
(c) ... which are complicated by known physics — electroweak and strong interactions

(d) ... which bind the quarks into confined hadrons (in some incalculable way)

(e) ... which eventually show up as tracks in someone's detector



(f) ... which is then combined with similar predictions for other processes to show evidence for X



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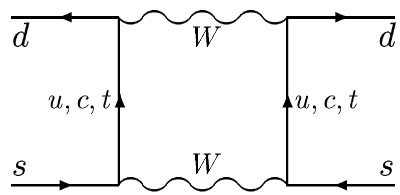
Spectacular track record

- High mass-scale sensitivity due to suppressed SM predictions
  - β-decay $\Rightarrow$ neutrino (Pauli)
  - Absence of $K_L \to \mu\mu \Rightarrow$ charm quark (Glashow, Iliopoulos, Maiani, 1970)
  - $\epsilon_K \Rightarrow$ 3rd generation (t, b quarks) (Kobayashi & Maskawa, 1973)
  - $\Delta m_K \Rightarrow m_c \sim 1.5\,\text{GeV}$ (Gaillard & Lee; Vainshtein & Khriplovich, 1974)

    Smallness of $\Delta m_K / m_K \approx 7 \times 10^{-15}$

    SM: $\Delta m_K / m_K \sim \dfrac{g_2^4}{16\pi^2} \dfrac{|V_{cs}V_{cd}|^2}{m_W^2} \dfrac{m_c^2}{m_W^2} f_K^2$

    BSM tree: $\Delta m_K^{(X)} \sim g^2\, \Lambda_{\text{QCD}}^3 / M_X^2 \;\Rightarrow\; M_X > g \times 2 \cdot 10^3\,\text{TeV}$



  - $\Delta m_B \Rightarrow m_t \gtrsim 100\,\text{GeV}$ (bound in 1987: $23\,\text{GeV}$) $\Rightarrow$ large CPV & FCNC
- Critical in developing SM; what can future data tell us about multi-TeV physics?

Quark mixing and unitarity triangle → Yury's talk

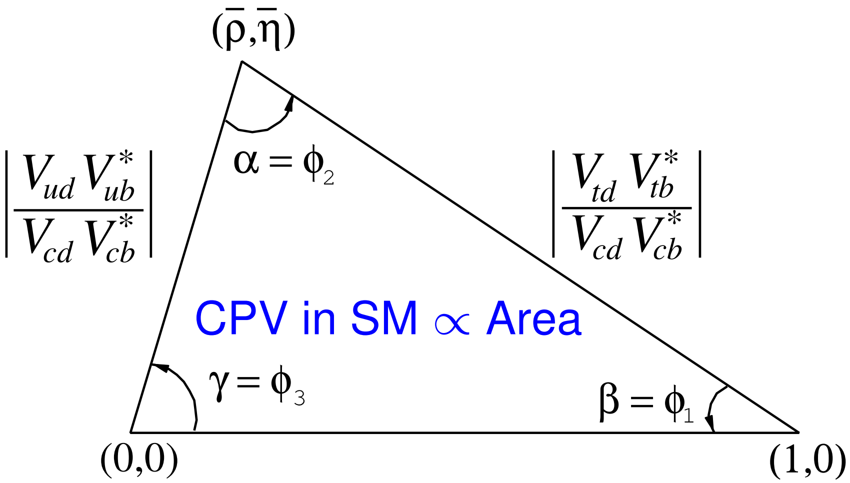
- The $(u,\, c,\, t)\ W^{\pm}\ (d,\, s,\, b)$ couplings: (Wolfenstein parm., $\lambda \sim 0.23$)

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

9 complex couplings depend on 4 real parameters $\Rightarrow$ many testable relations

One complex phase in $V_{\rm CKM}$: only source of CP violation in quark sector

- Unitarity triangle: visualize SM constraints and compare measurements



$$V_{ud}\,V_{ub}^* + V_{cd}\,V_{cb}^* + V_{td}\,V_{tb}^* = 0$$

Sides and angles measurable in many ways

Goal: overconstrain by many measurements sensitive to different short distance physics

Learned a lot, plenty of room for new physics

- SM dominates CP viol. $\Rightarrow$ Nobel 2008

Photo: Kyodo/Reuters

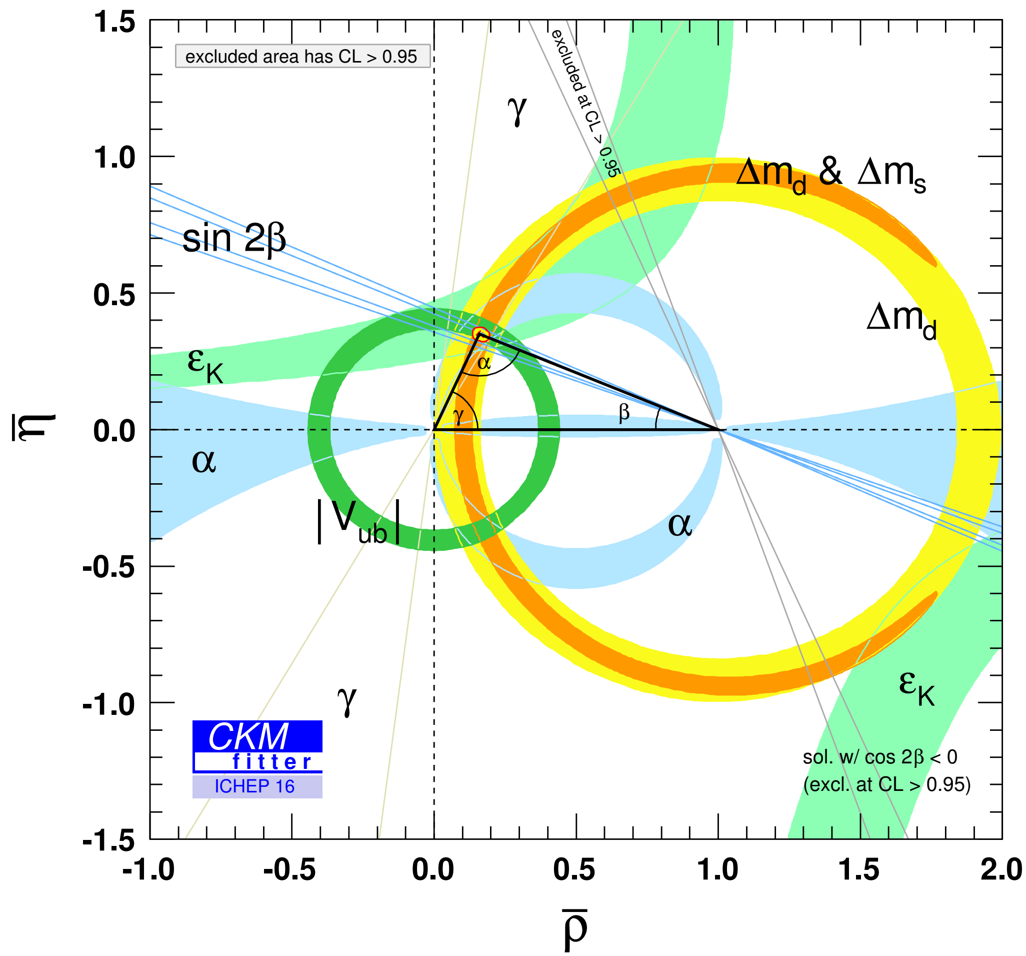
Makoto Kobayashi

Photo: Kyoto University

Toshihide Maskawa

Before BABAR & Belle, NP $\sim$ SM was possible in CP violating observables

Confirm SM $\Rightarrow$ look for corrections



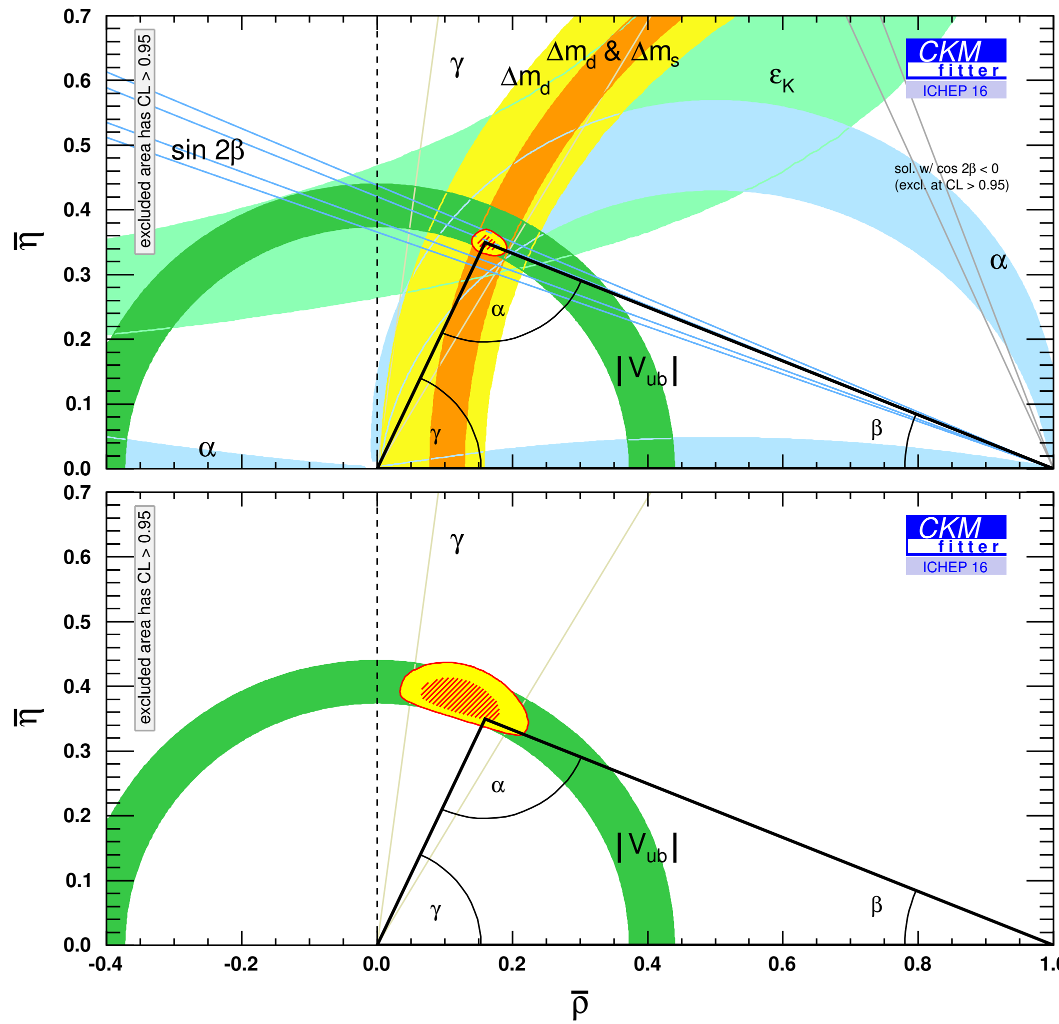
- The implications of the consistency of measurements is often overstated

Learned a lot, plenty of room for new physics

- Larger allowed region if the SM is not assumed

- Tree-level (lower plot) vs. loop-dominated 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

Model independent

(1) Compare HL-LHC and LHCb upgrade

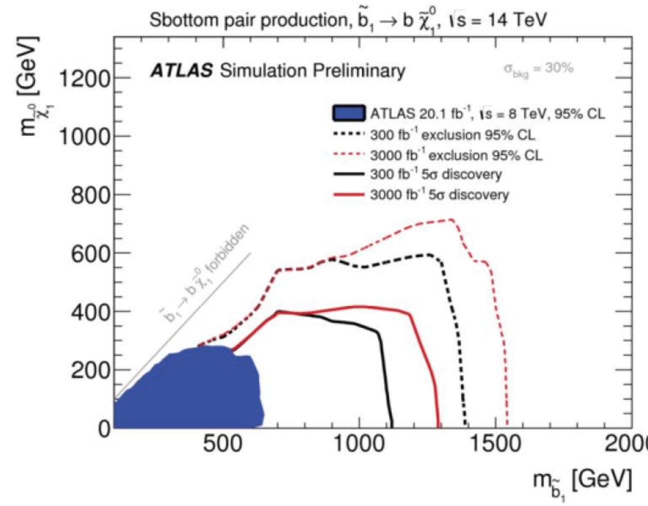
- Focus: ATLAS/CMS $300/\mathrm{fb} \to 3000/\mathrm{fb}$, LHCb $50/\mathrm{fb} \to 300/\mathrm{fb}$ (latter not yet approved)

  ATLAS & CMS searches for high-mass states: parton luminiosities fall rapidly

  LHCb Phase-2 upgrade compared to Phase-1: $\sqrt[4]{6} \sim 1.6$ mass scale (conservative)

  Do not know what new physics is $\Rightarrow$ mass-scale sensitivity (at fixed couplings)?

- It is often said that what's excluded at $300/\mathrm{fb}$, cannot be discovered at $3000/\mathrm{fb}$ — so why keep going...?
  - Holds for many high-mass particle searches
  - Not true for lighter / weakly coupled particles, Higgs couplings, flavor observables (uncert. $\sim 1/\sqrt{\mathcal{L}}$)

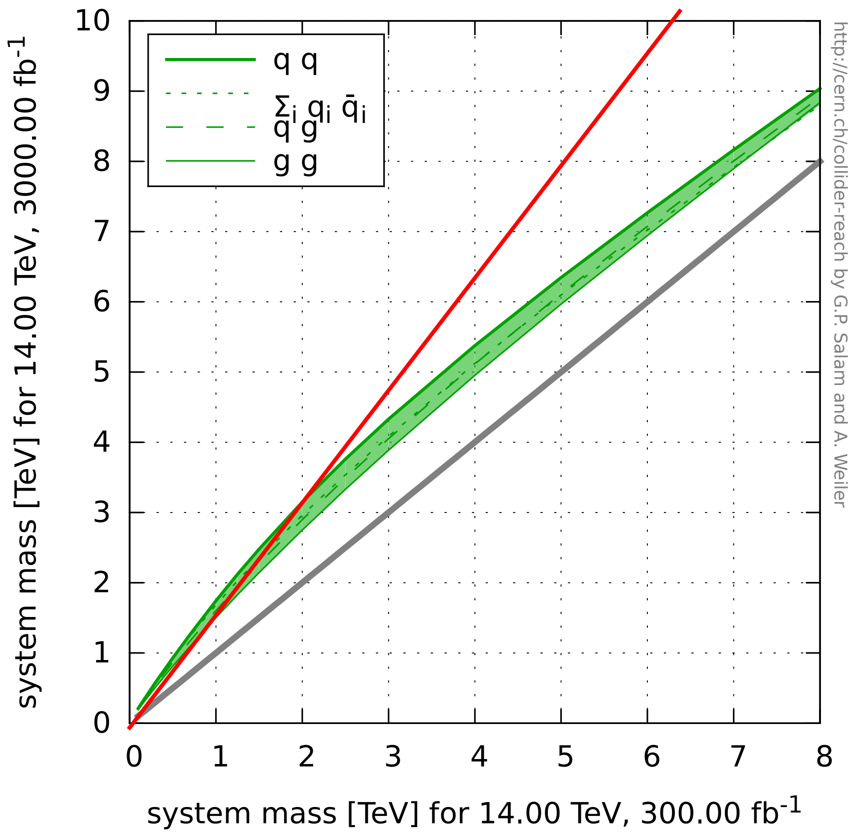


- Statistics $\times 10$ can make $1.5\sigma \to \sim 5\sigma$, even without analysis improvements

  (No one knows how many measurements are 1.5σ from SM expectation... which also improve)

At fixed energy, $1/\sqrt{\mathcal{L}}$ is the best

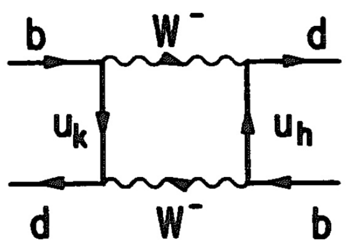
- $\sqrt[4]{6} \sim 1.6$ vs. mass-scale increase at $14\,\mathrm{TeV}$, $300 \to 3000/\mathrm{fb}$ [http://collider-reach.web.cern.ch/]

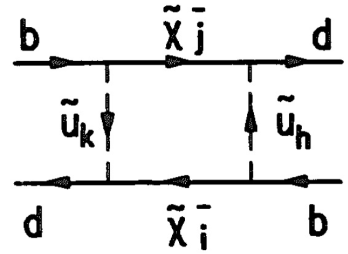


- Increase in mass limit > 1.6, iff (w/ caveats) limit with 300/fb at 14TeV is $\lesssim 1\,\mathrm{TeV}$
  Weakly produced particles ($H^{\pm}$, ...) or difficult decays — not the typical Z', $\tilde{q}$, $\tilde{g}$!

(2) New physics in B mixing

- Meson mixing:





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

General parametrization:

$$M_{12} = M_{12}^{\rm SM} \times (1 + h\, e^{2i\sigma})$$

NP parameters (h, σ)

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

If deviation from SM seen $\Rightarrow$ upper bound on Λ

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

- Modified: loop-mediated (Δm_d, Δm_s, β, β_s, α, ...)

  Unchanged: tree-dominated (γ, $|V_{ub}|$, $|V_{cb}|$, ...)

  (Importance of these constraints is known since the 70s, conservative picture of future progress)

Sensitivity to NP in B mixing

- At 95% CL: NP $\lesssim (0.3 \times$ SM)

  $\Rightarrow$ NP $< (0.05 \times$ SM)

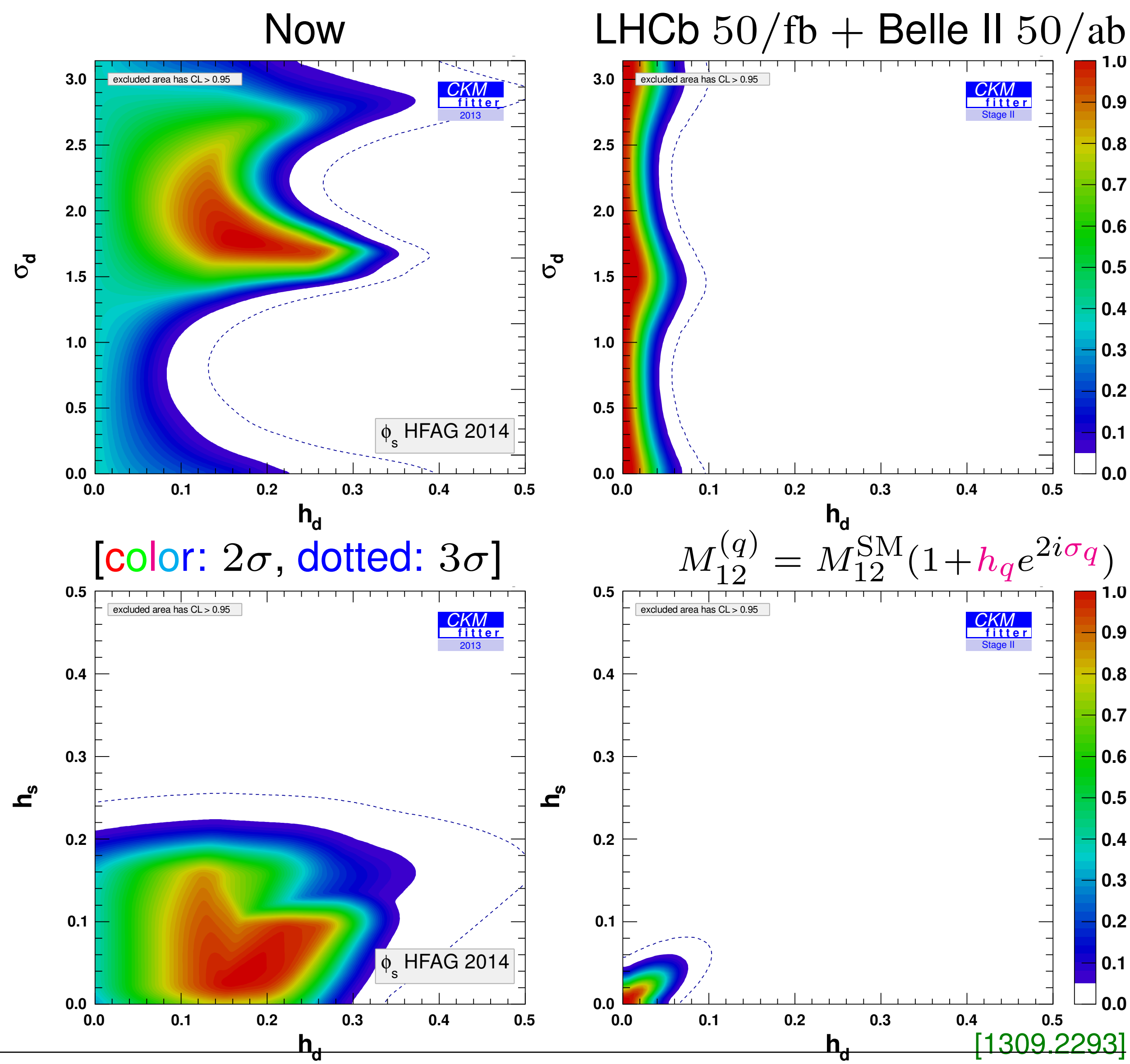
- Scale: $h \simeq \dfrac{|C_{ij}|^2}{|V_{ti}^* V_{tj}|^2} \left(\dfrac{4.5\,\text{TeV}}{\Lambda}\right)^2$

  $\Rightarrow \Lambda \sim \begin{cases} 2.3 \times 10^3\,\text{TeV} \\ 20\,\text{TeV} \text{ (tree + CKM)} \\ 2\,\text{TeV} \text{ (loop + CKM)} \end{cases}$

- Similar to LHC $m_{\tilde{g}}$ reach

- Sensitivity would continue to increase beyond 300/fb

  Complementary to high p_T



[1309.2293]

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(3) Sensitivity to vector-like fermions

- Add one vector-like fermion: mass term w/o Higgs, hierarchy problem not worse

  11 models in which new particles can Yukawa couple to SM fermions and Higgs

  $\Rightarrow$ FCNC Z couplings to leptons or quarks [Ishiwata, ZL, Wise, 1506.03484; Bobeth et al., 1609.04783]

Upper (lower) rows are current (future, 50/fb LHCb & 50/ab Belle II) sensitivities

Model	Quantum numbers	Bounds on M/TeV and $\lambda_i\lambda_j$ for each ij pair					
		$ij=12$		$ij=13$		$ij=23$	
		$\Delta F=1$	$\Delta F=2$	$\Delta F=1$	$\Delta F=2$	$\Delta F=1$	$\Delta F=2$
V	$(3,1,-1/3)$	66^d $[100]^e$	$\{42, 670\}^f$	30^g	25^h	21^i	6.4^j
		280^d	$\{100, 1000\}^f$	60^l	61^h	39^k	14^j
VII	$(3,3,-1/3)$	47^d $[71]^e$	$\{47, 750\}^f$	21^g	28^h	15^i	7.2^j
		200^d	$\{110, 1100\}^f$	42^l	68^h	28^k	16^j
XI	$(3,2,-5/6)$	66^d $[100]^e$	$\{42, 670\}^f$	30^g	25^h	18^k	6.4^j
		280^d	$\{100, 1000\}^f$	60^l	61^h	39^k	14^j

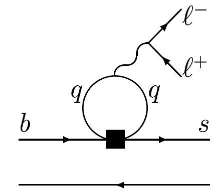
Strongest bounds arise from many processes, nominally 1-2 generation most sensitive, large variation across models

- LHCb 50/fb + Belle 50/ab increase mass scale sensitivity by factor $\sim 2.5 \sim \sqrt[4]{50}$

Mode / model dependent

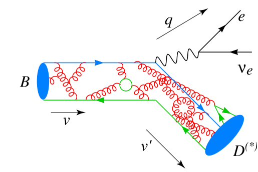
The current B "anomalies"

- Lepton non-universality would be clear evidence for NP



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

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



Scales: $R_{K^{(*)}} \lesssim$ few $\times 10^1\,\mathrm{TeV}$, $\quad R(D^{(*)}) \lesssim$ few $\times 10^0\,\mathrm{TeV}$ $\quad$ Bounds on 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: $C_{9,\mu}^{(\mathrm{NP})}/C_{9,\mu}^{(\mathrm{SM})} \sim -0.2\,,\ C_{9,\mu} = (\bar{s}\gamma_\alpha P_L b)(\bar{\mu}\gamma^\alpha\mu)$

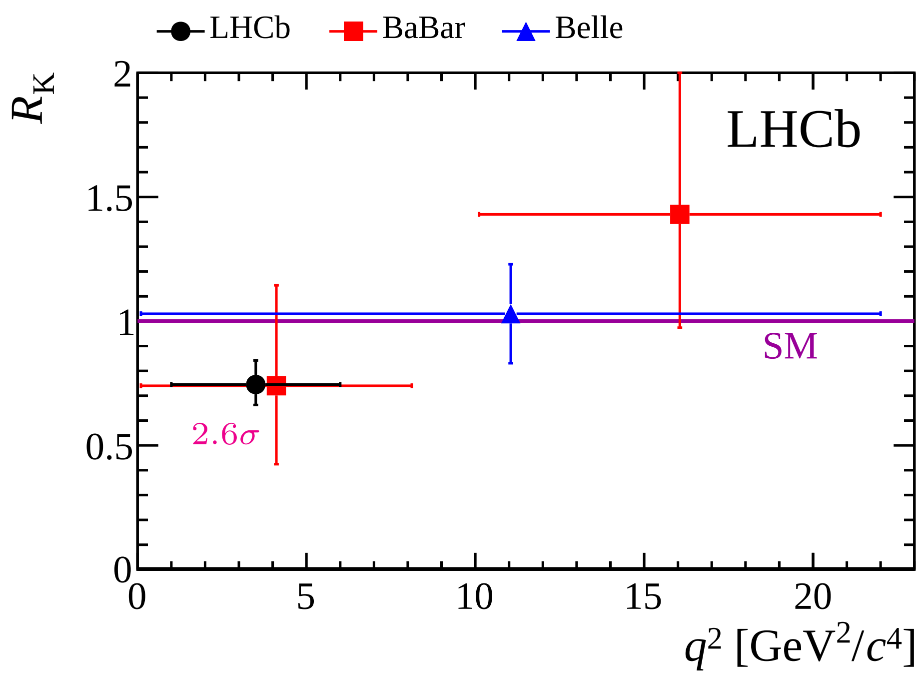
- Viable BSM models... leptoquarks? No clear connection to DM & hierarchy puzzle

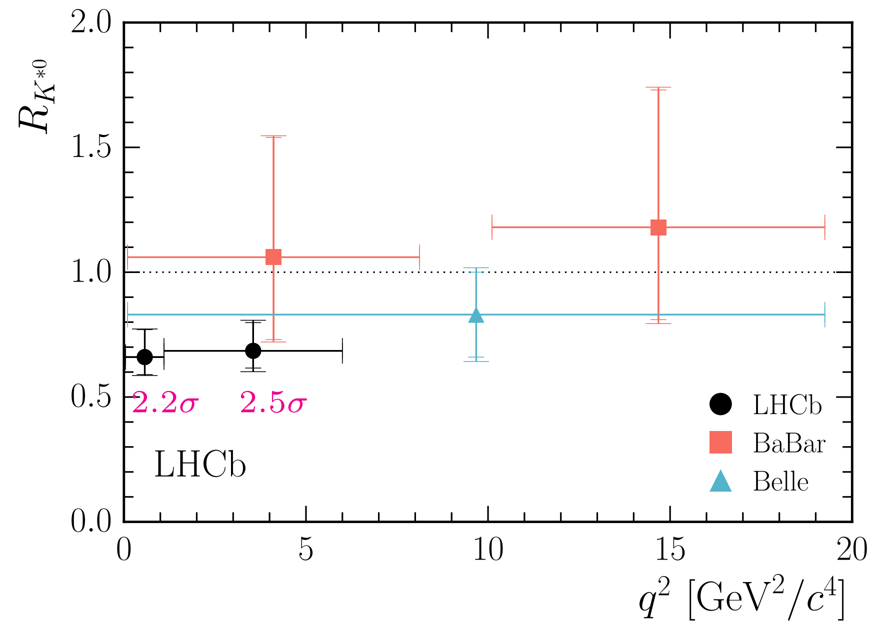
(Is the hierarchy problem or the flavor problem more pressing for Nature?)

- 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 over 2.5σ from lepton universality





- Theorists' fits quote $4-5\sigma$ (sometimes including P_5' and/or $B_s \to \phi\mu^+\mu^-$)

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

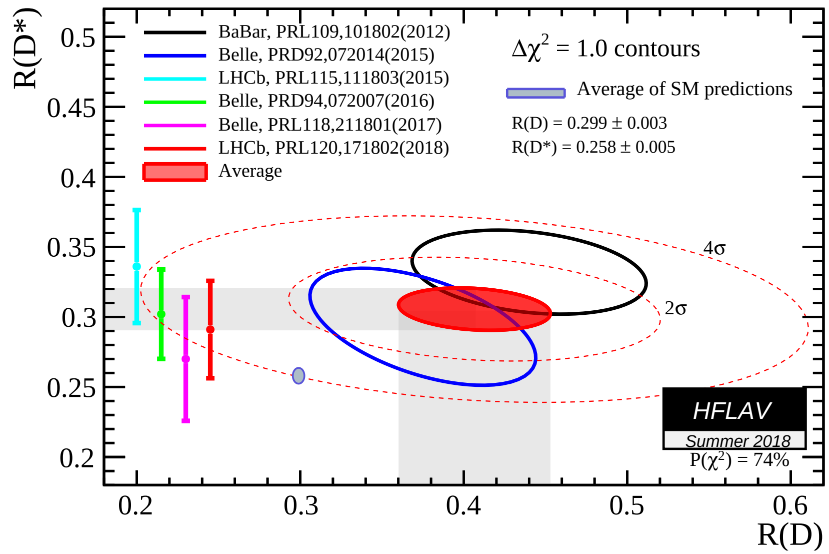
The $B \to D^{(*)}\tau\bar{\nu}$ decay rates

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

  $4\,\sigma$ 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

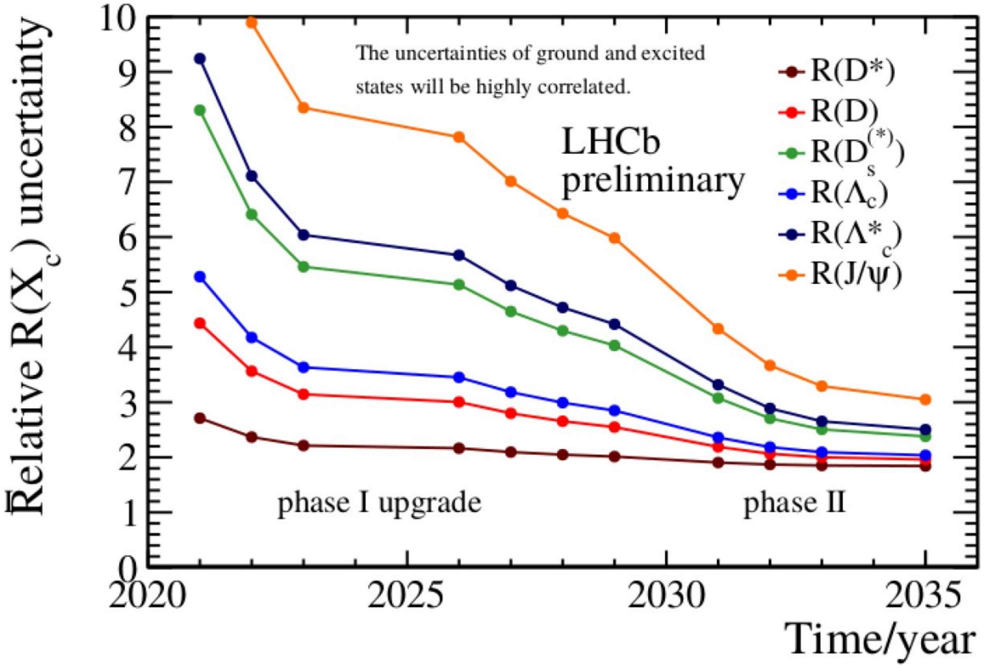
- Tree level: three ways to insert mediator: $(b\nu)(c\tau)$, $(b\tau)(c\nu)$, $(bc)(\tau\nu)$

  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 Run 1–2 data $> 5\sigma$ for current central values
- 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)

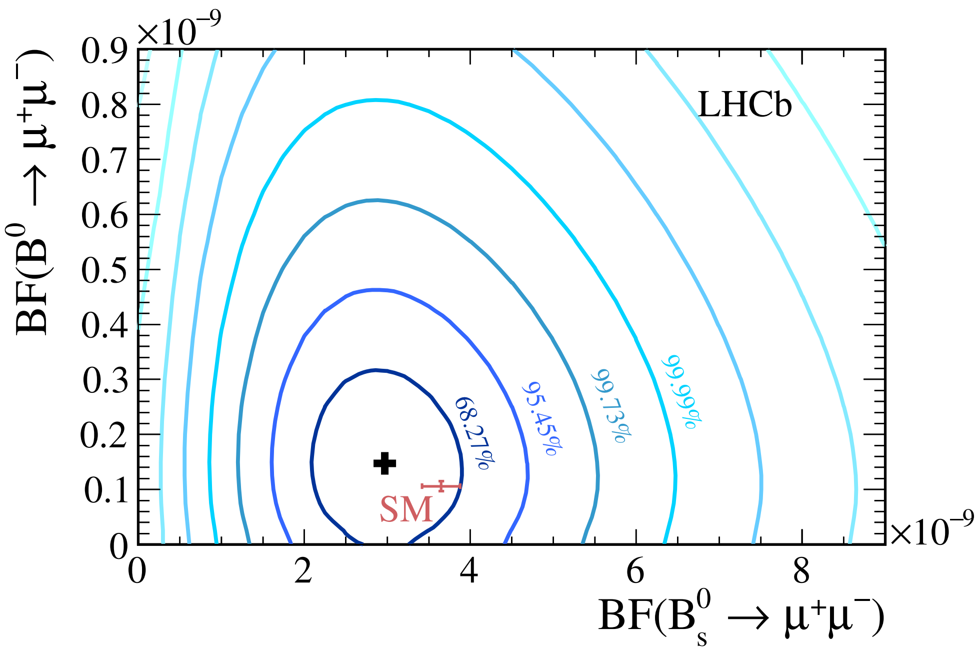
- Competition, complementarity, cross-checks between LHCb and Belle II

Richness of directions

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

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

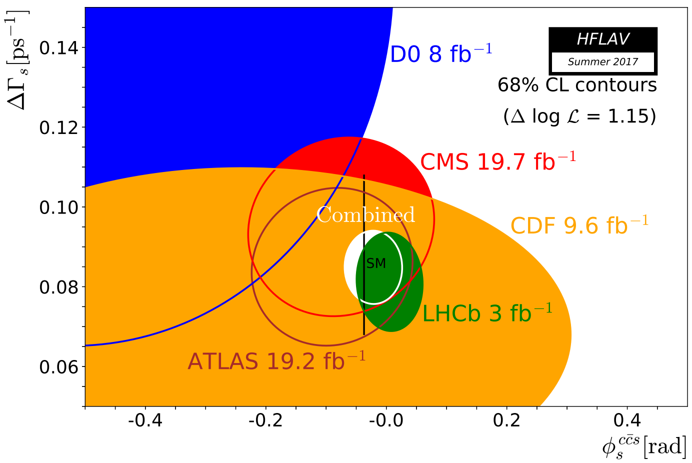
  SM uncertainty, as of now $\simeq (2\%) \oplus f_{B_q}^2 \oplus \text{CKM}$ [Bobeth, FPCP'15]

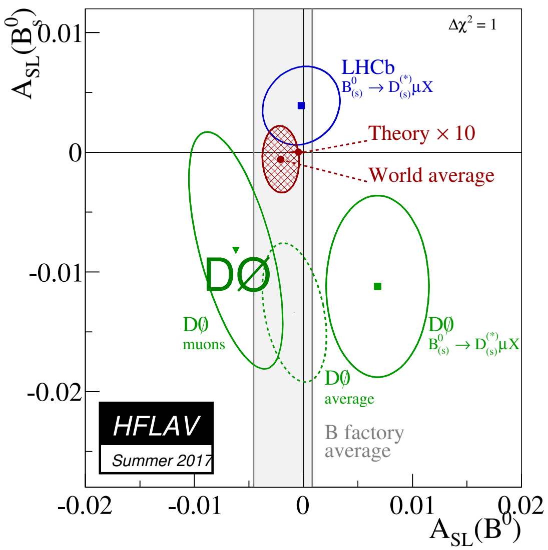


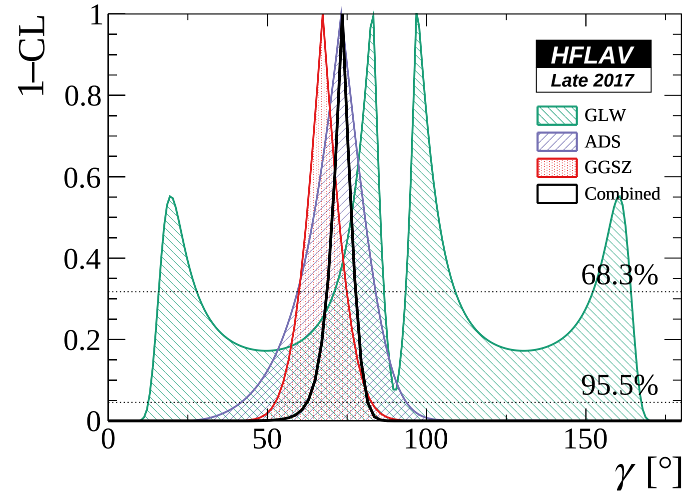
- Theoretically cleanest $|V_{ub}|$ I know, only isospin: $\mathcal{B}(B_u \to \ell\bar{\nu})/\mathcal{B}(B_d \to \mu^+\mu^-)$

- A decay with mass-scale sensitivity (dim.-6 operator) that competes w/ $K \to \pi\nu\bar{\nu}$

Some other key “core” measurements







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

- Uncertainty of predictions $\ll$ current experimental errors ($\Rightarrow$ seek lot more data)
- Breadth crucial, often have to combine many measurements and theory

(“The interesting messages are not simple, the simple messages are not interesting”)

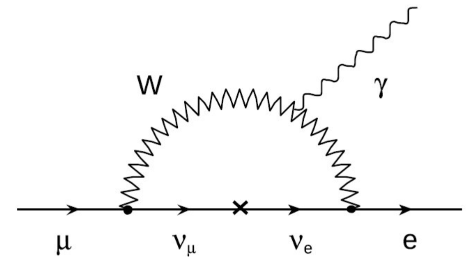
Very broad program: many directions

- Better tests of (exact or approximate) conservation laws
- Maximize sensitivity to $\tau \to 3\mu$, $\tau \to h\mu\mu$, etc.
- 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, $B \to N + \text{invis.}\ [+\text{mesons}]$ [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 ...

Charged lepton flavor violation

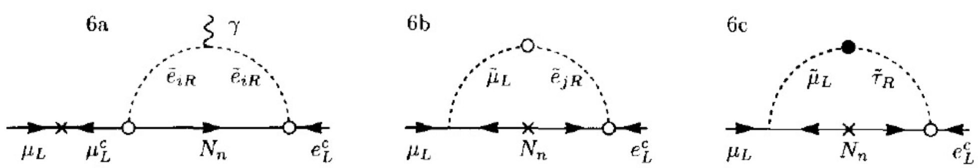
- SM predicted lepton flavor conservation with $m_\nu = 0$

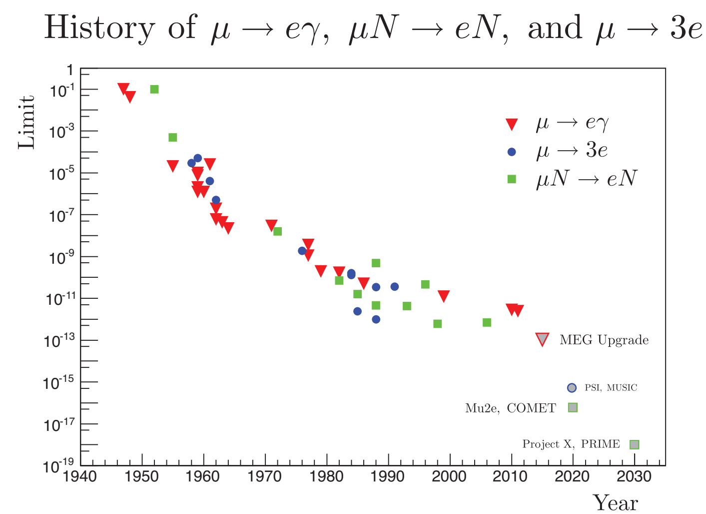
  Given $m_\nu \neq 0$, no reason to impose it as a symmetry



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

- 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:

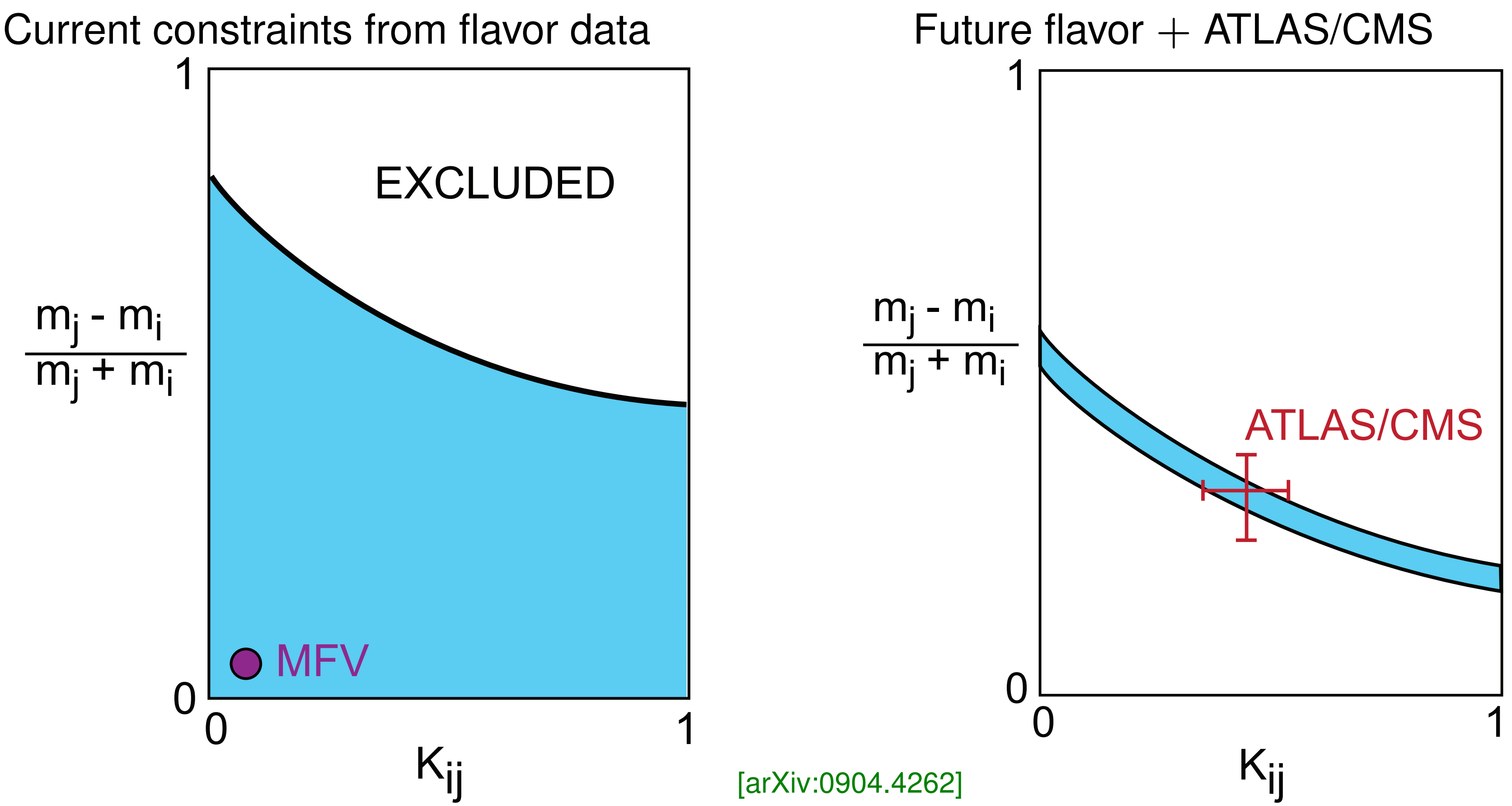
$$\mu \to e\gamma,\ \mu \to eee,\ \mu + N \to e + N^{(\prime)},\ \mu^+ e^- \to \mu^- e^+$$
$$\tau \to \mu\gamma,\ \tau \to e\gamma,\ \tau \to \mu\mu\mu,\ \tau \to eee,\ \tau \to \mu\mu e$$
$$\tau \to \mu ee,\ \tau \to \mu\pi,\ \tau \to e\pi,\ \tau \to \mu K_S,\ eN \to \tau N$$

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

Final remarks

Flavor / high-p_T complementarity

- Combination of LHC & flavor data can be very powerful; SUSY inspired example:



[arXiv:0904.4262]

- Let's hope we'll be in such a situation...

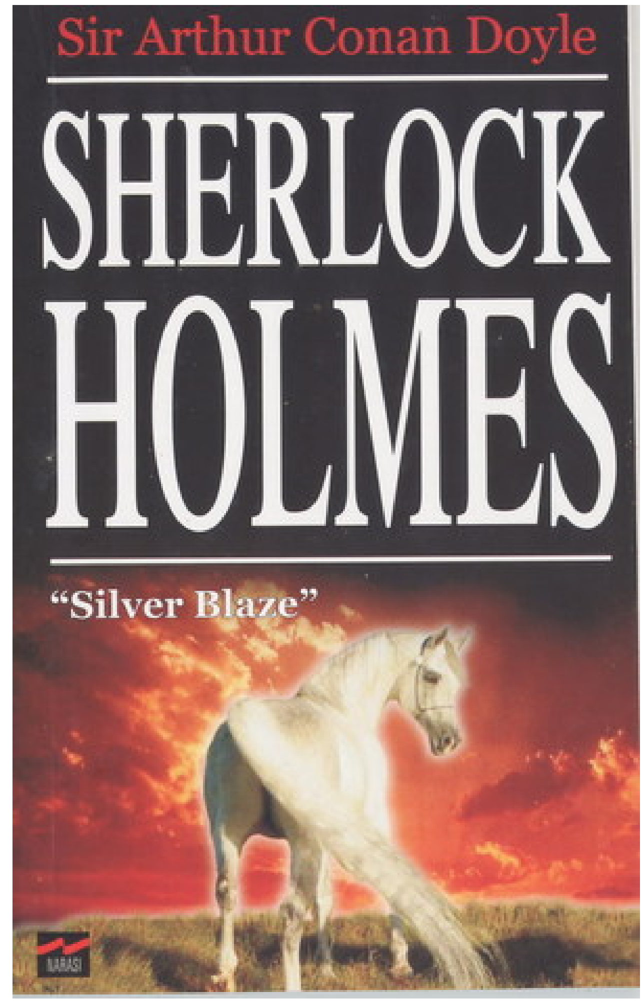
Lack of signals can also solve puzzles

- Gregory (Scotland Yard detective): "Is there any other point to which you would wish to draw my attention?"

  Holmes: "To the curious incident of the dog in the night-time."

  Gregory: "The dog did nothing in the night-time."

  Holmes: "That was the curious incident."



- Absence of a signal can also be critical

Conclusions

- Flavor physics probes scales $\gg 1\,\mathrm{TeV}$; sensitivity limited by statistics, not theory
- New physics in most FCNC processes may still be $\gtrsim 20\%$ of the SM or more
- Few discrepancies in SM fit; some of these (or others) may become decisive
- Precision tests of SM will improve in the next decade by 10–10^4 in some channels
- Many interesting theoretical questions relevant for optimal experimental sensitivity
- Flavor physics data in next decade will tell us a lot, whether NP is found or not

Evidence for BSM?		FLAVOR	
		yes	no
ATLAS & CMS	yes	complementary information	distinguish models
	no	tells us where to look next	flavor is the best telescope

- If new physics is discovered, many new questions about its structure and origin

  E.g., possible convergence between (s)quark and (s)lepton flavor physics

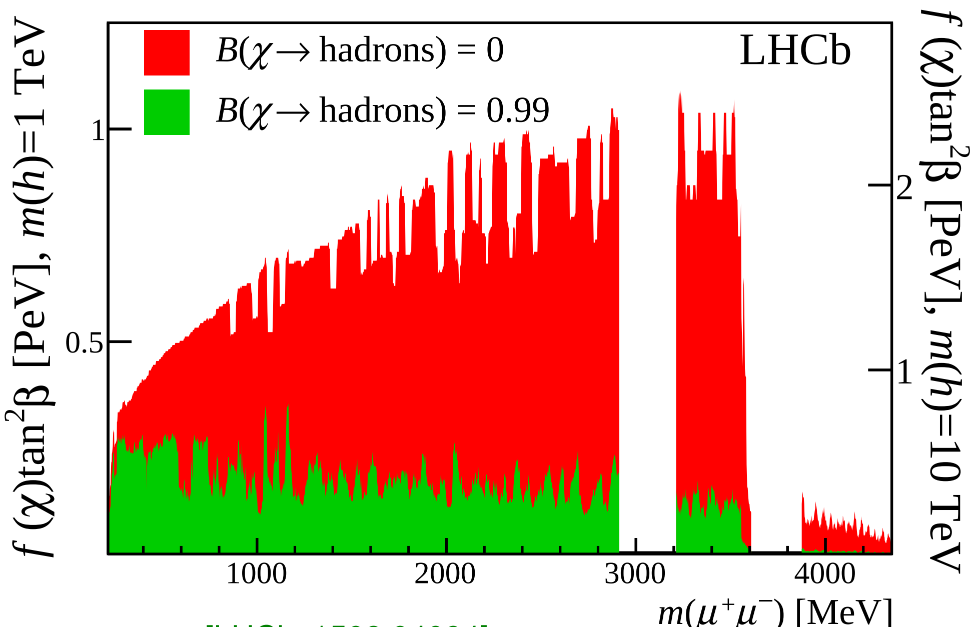
Extra slides

Dark sectors: broad set of searches

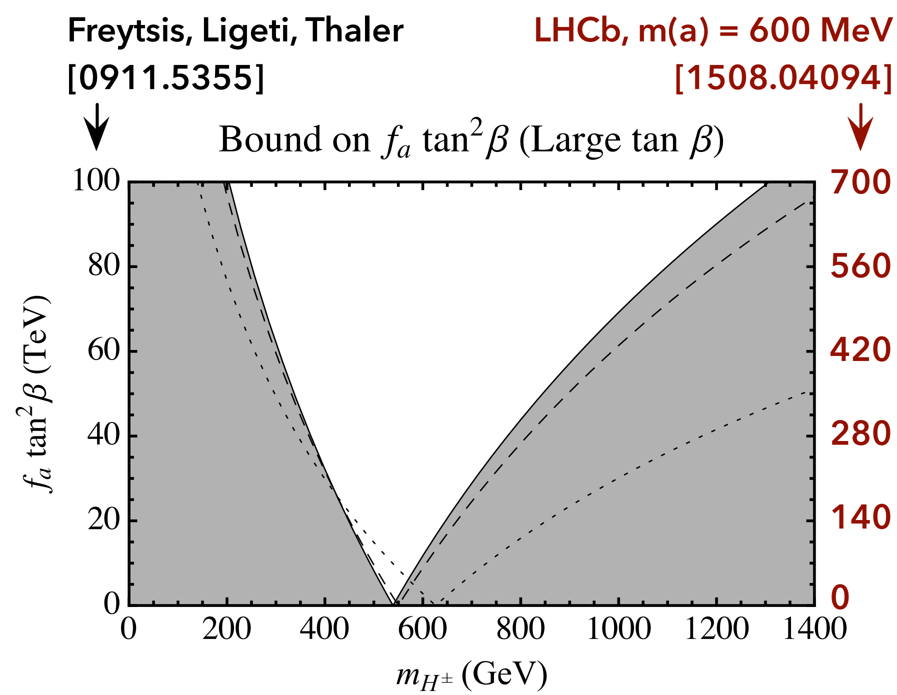
- Started with bump hunting in $B \to K^* \mu^+ \mu^-$

  Nearly an order of magnitude improvement due to dedicated LHCb analysis

  In axion portal models, scalar couples as $(m_\psi / f_a)\, \bar{\psi} \gamma_5 \psi\, a$ (m_t coupling in loops)



[LHCb, 1508.04094]



- Many other current / future LHCb dark photon searches [Ilten et al., 1603.08926, 1509.06765]

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

- CP violation in D decay

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

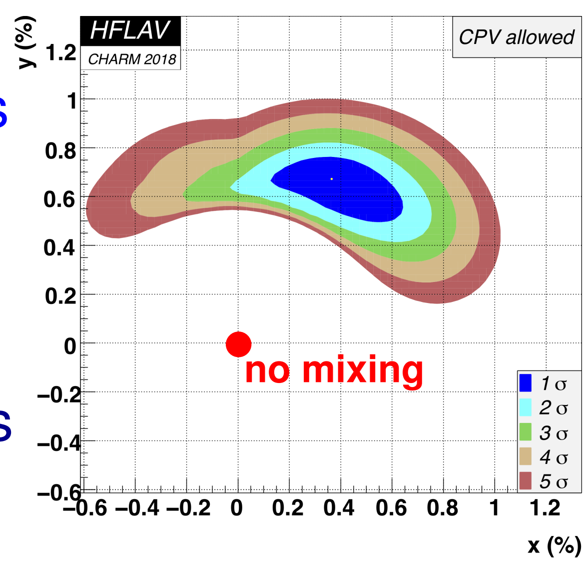
  Current WA: $\Delta A_{CP} = -(2.5 \pm 1.0) \times 10^{-3}$ ↖ (a stretch in the SM, imho)

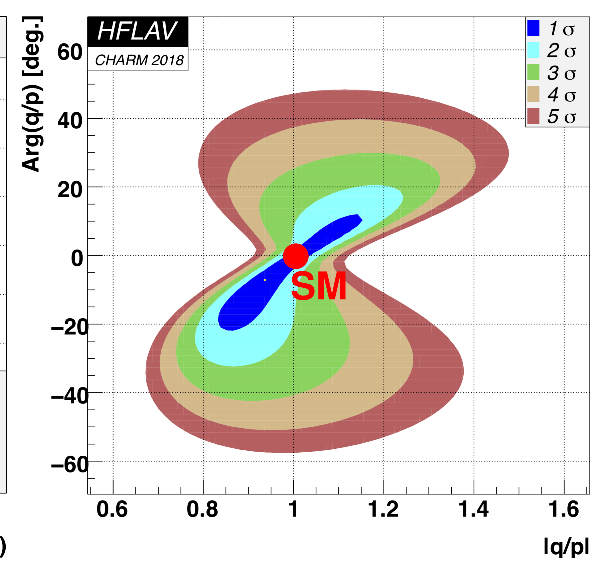
- I think we still don't know how big an effect could (not) be accommodated in SM

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

- Value of Δm? Not even 2σ yet

- Connections to FCNC top decays





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

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?
  - γ, theory limit only from higher order electroweak
  - $B_{s,d} \to \mu\mu$, $B \to \mu\nu$ and other leptonic decays (lattice QCD, [double] ratios)
  - CP violation in D mixing (firm up theory)
  - $A_{\rm SL}^{d,s}$ (work on exp. syst. issues)
  - CLFV, EDM, etc.
- In some decay modes, even in 2030 we'll have: (exp. bound)/SM $\gtrsim 10^3$

  E.g., $B \to e^+e^-$, $\tau^+\tau^-$ — can build models... (I hope to be proven wrong!)
- Guess: until $100\times$ (Belle II & LHCb Phase 2), sensitivity to NP would improve
- FCC-ee in terra-Z phase could eclipse all prior B factories!

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?

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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 $(B_{(s)} \to \ell^+\ell^-$, $\mu \to e\gamma)$

Example: SUSY in $K^0 - \overline{K}^0$ mixing

- $$\frac{(\Delta m_K)^{\rm SUSY}}{(\Delta m_K)^{\rm exp}} \sim 10^4 \left(\frac{1\,{\rm TeV}}{\tilde m}\right)^2 \left(\frac{\Delta\tilde m_{12}^2}{\tilde m^2}\right)^2 {\rm Re}\Big[(K_L^d)_{12}(K_R^d)_{12}\Big]$$ (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 models incorporate some of the above — known since the '70s

History of surprises: CP violation

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

Near misses: CP violation

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

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

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

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 $K_2^0 \to \pi^- + \pi^+$. 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 $R = (K_2 \to \pi^+ + \pi^-)/(K_2^0 \to \text{all charged modes}) = (2.0 \pm 0.4) \times 10^{-3}$ where the error is the standard deviation. As empha-