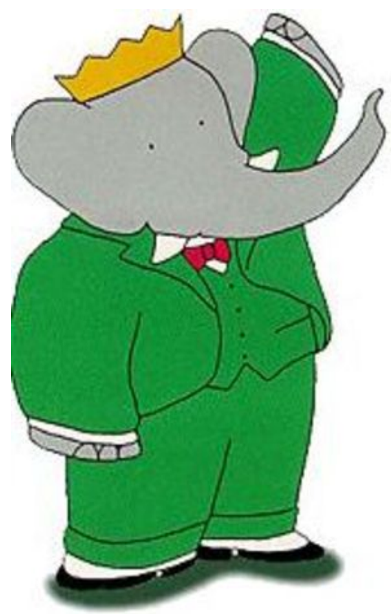
Flavor physics beyond BABAR

Zoltan Ligeti



BaBar 25th Anniversary

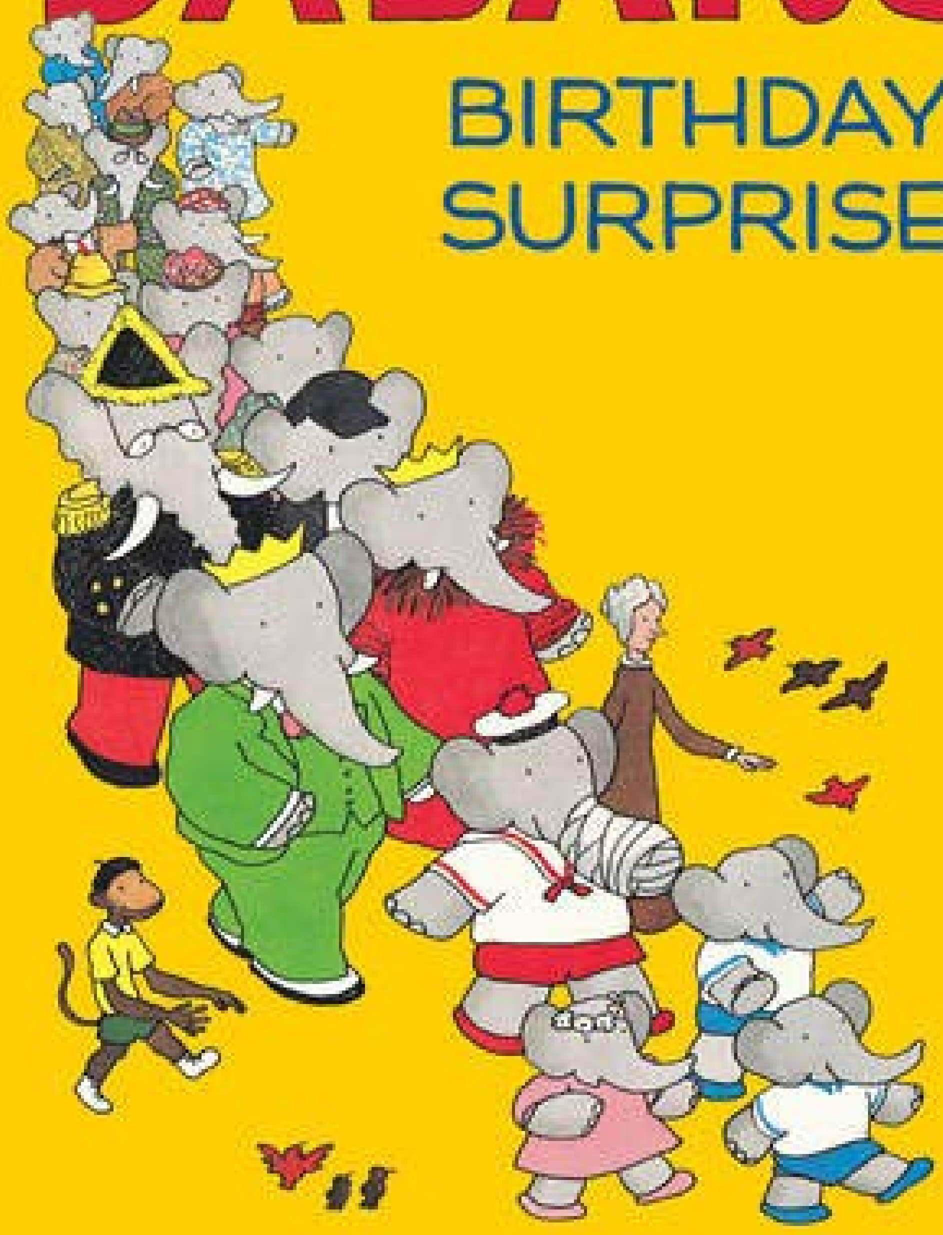
SLAC, December 11, 2018

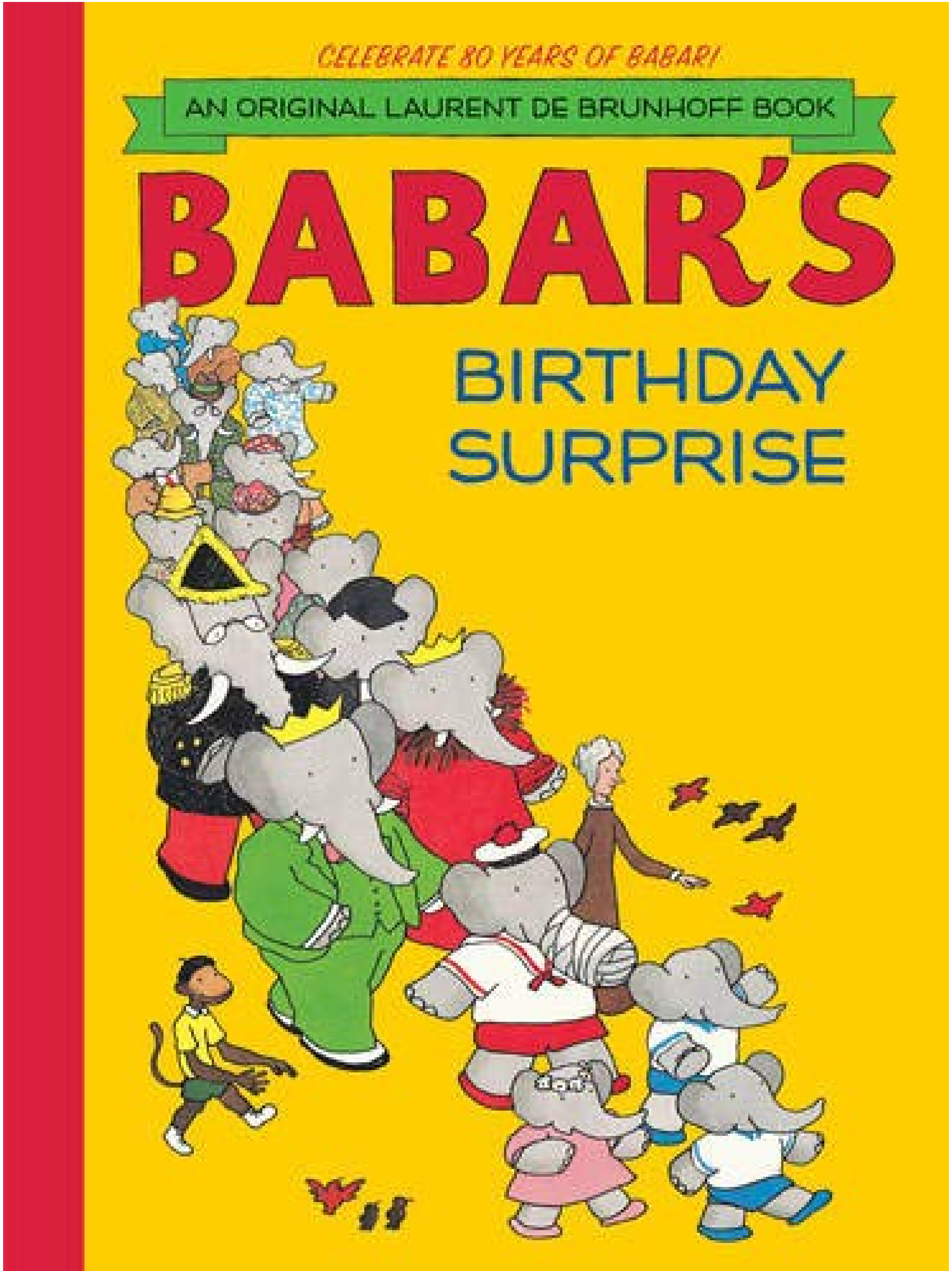
CELEBRATE 80 YEARS OF BABAR!

AN ORIGINAL LAURENT DE BRUNHOFF BOOK

BABAR'S

BIRTHDAY SURPRISE





Luckily, not yet at 80!

Preliminaries...

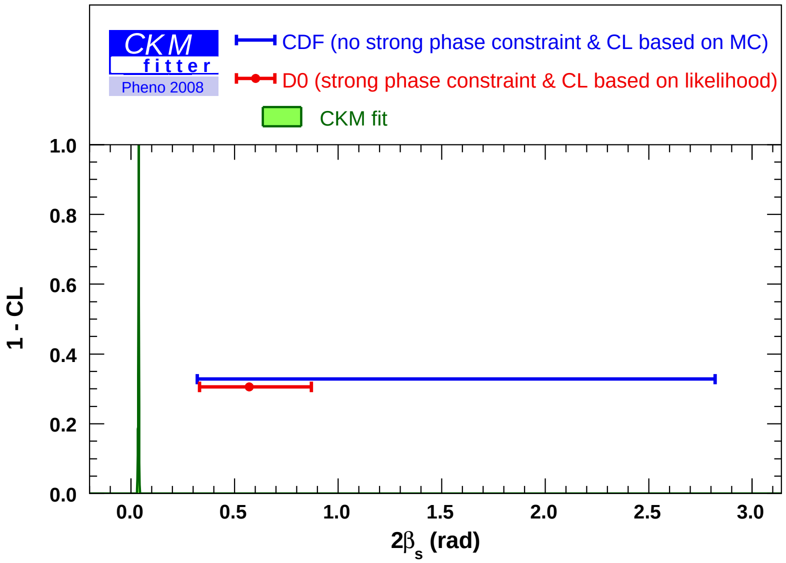
- LHCb and Belle II are obviously key players — many reports...
- The Belle II Physics Book, arXiv:1808.10567
- LHC: HL-LHC Physics Workshop Report WG4: Opportunities in Flavor Physics [arXiv:any.day]

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

- I will not show (large and impressive!) tables of sensitivity projections...

The year *BaBar* was shut down...

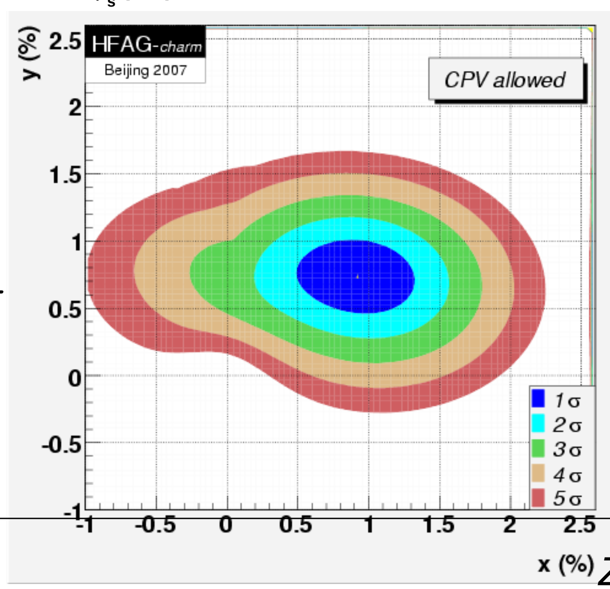
- Start β_s “anomaly”, excluded by LHCb

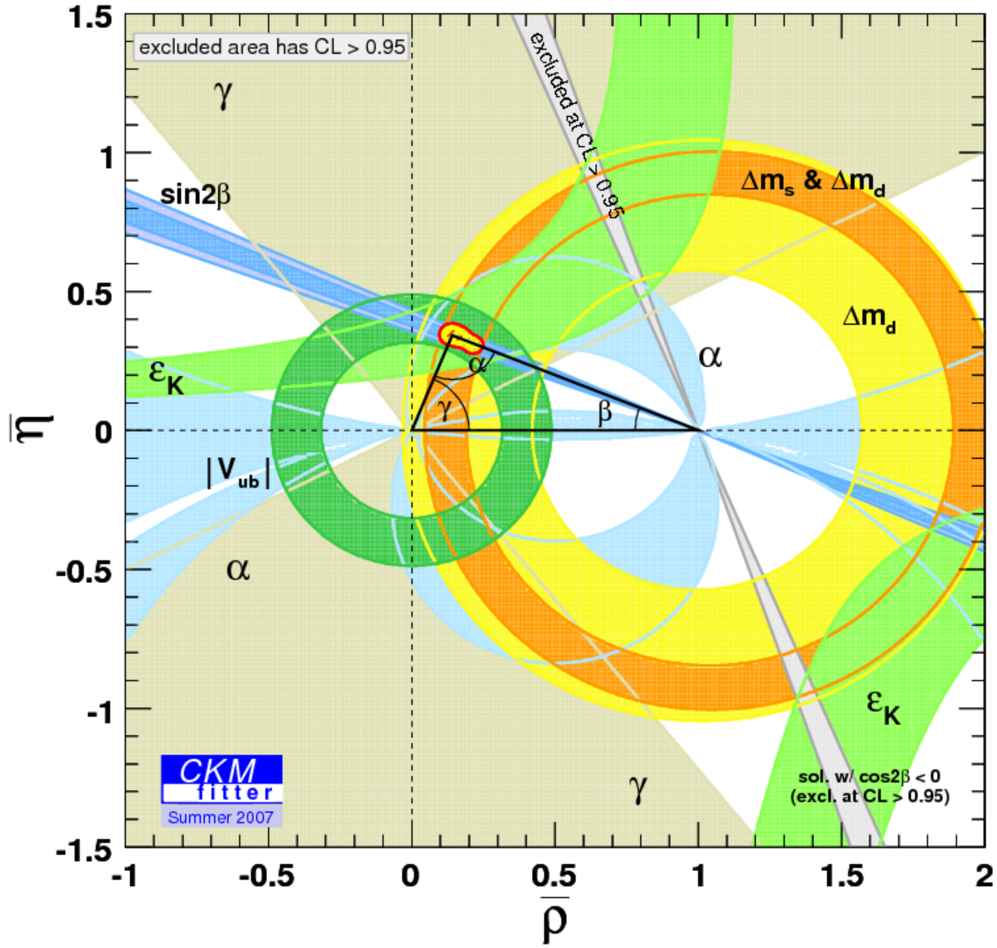


2007:

D mixing $> 5\sigma$

[only HFAG comb.]





Many papers on how $B_s \to \mu^+\mu^-$ will discover NP

Learned a lot, plenty of room for new physics

- Before *BaBar* & Belle, only CP violation in kaons, SM could be way off

  [I agree with Guy Wormser, 2004 was critical: α, γ, penguins]

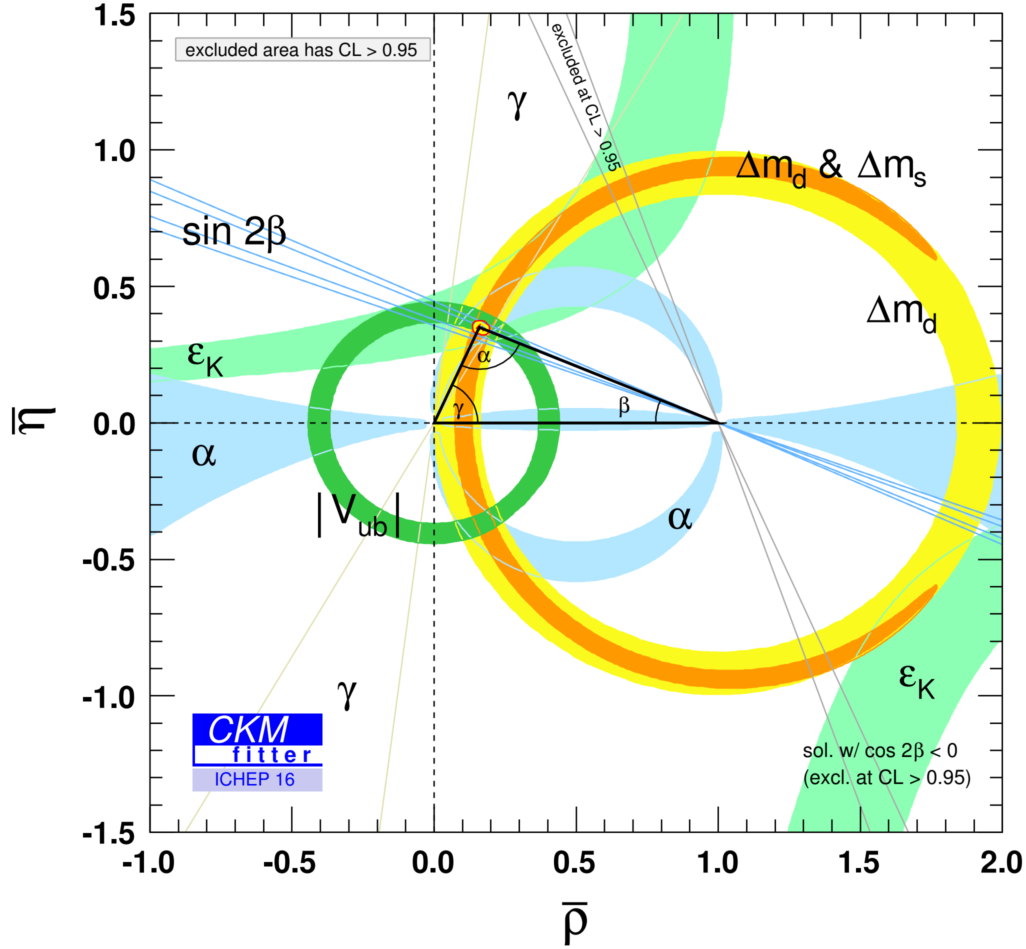
  SM dominates CP viol. $\Rightarrow$ Nobel 2008

Photo: Kyodo/Reuters

Makoto Kobayashi

Photo: Kyoto University

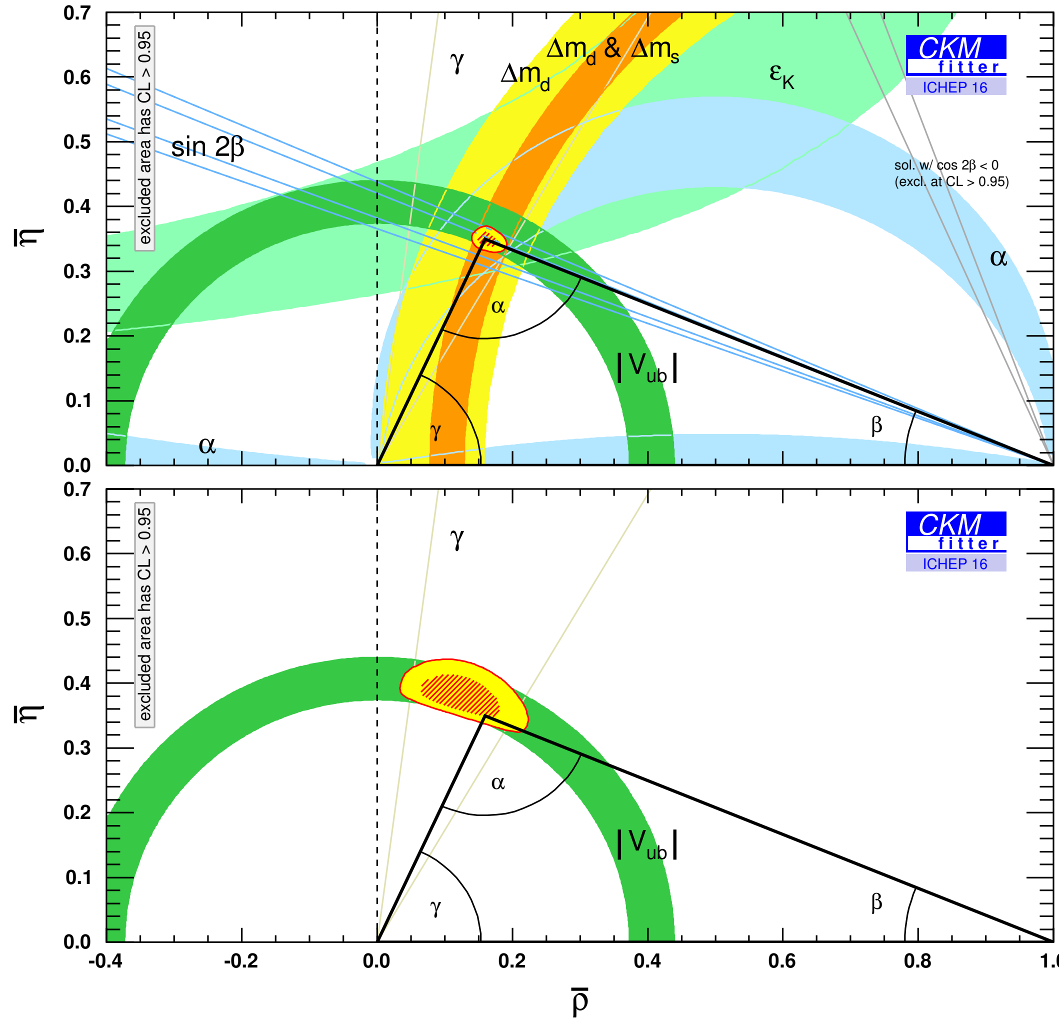
Toshihide Maskawa



- The implications of the consistency of the measurements are often overstated

Learned a lot, plenty of room for new physics

- 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

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 $\rightarrow$ 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

Reasons to seek higher precision in flavor

- Expected deviations from the SM, induced by TeV-scale NP? [from 0904.4262]

  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 LHC program; the synergy can teach us what the NP is [not]

$\Rightarrow$ No physics reason to stop exploring (can be technological, financial, political)

Exciting prospects

- Experiments: ATLAS, CMS, LHCb, Belle II, NA62 + EDM, CLFV, DM, neutrinos, etc.
- Future: $\dfrac{\text{(Belle II data set)}}{\text{(Belle data set)}} \sim \dfrac{\text{(LHCb Phase-2)}}{\text{(LHCb now)}} \sim \dfrac{\text{(HL–LHC total)}}{\text{(ATLAS \& CMS now)}} \sim 50$

  E.g., for $B \to \mu^+\mu^-$ it will be CMS, and not Belle II, that competes with LHCb
- New / improved methods: more progress than simply scaling with statistics

  New theory ideas motivated by data? New questions to address + surprises
- Deviations from SM may be discovered, whether or not within ATLAS / CMS reach

  Unambiguous BSM discovery would give upper bound on next scale to explore

Some flavor-related questions

- Will LHC see new particles beyond the Higgs?

  SUSY, something else, understand in detail?

- Will NP be seen in the quark sector?

  Currently, several hints of lepton flavor universality violation

- 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?) DM searches?

  No one knows — an exploratory era!

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

Some flavor-related questions

- Will LHC see new particles beyond the Higgs?

  SUSY, something else, understand in detail?

- Will NP be seen in the quark sector?

  Currently, several hints of lepton flavor universality violation

- 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?) DM searches?

  No one knows — an exploratory era!

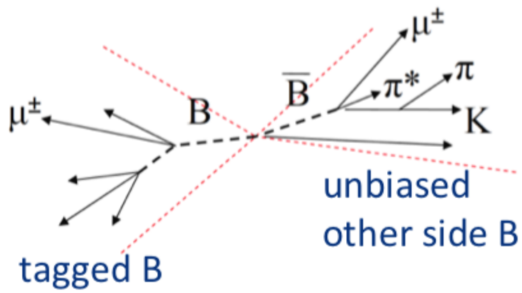
  (n.b., 2 generations $+$ superweak is "more minimal" to accommodate CPV, than 3 generations...)

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

  Long term: large increase in discovery potential in many modes

Surprises: CMS "B – parking"

- CMS collected $\sim 10^{10}$ B decays in 2018; goal: compete on $R_{K^{(*)}}$ [CMS @ LHCC, Nov 2018]

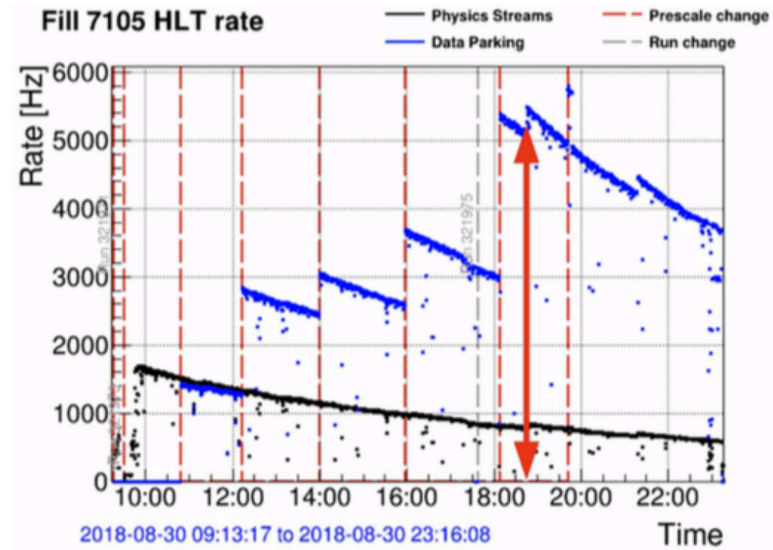


Effort in 2018 paid off, 12B triggered events on tape

- 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)

Simone.Gennai@cern.ch

The rest of this talk

- Mode / model independent: Large improvements in NP sensitivity — 2 examples

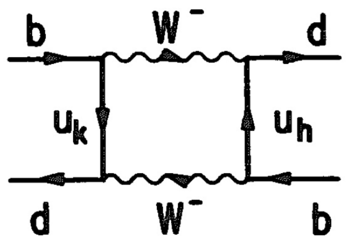
- Mode / model specific: Current tensions with SM — might soon become decisive

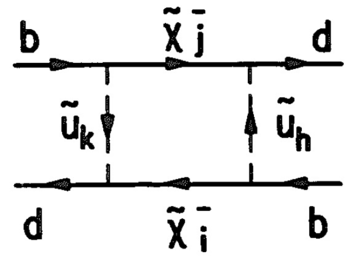
  (Clear case independent of current data; hints are nice to have...)

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

(1) New physics in B mixing

- Meson mixing:





General parametrization:

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

NP parameters (h, σ)

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

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

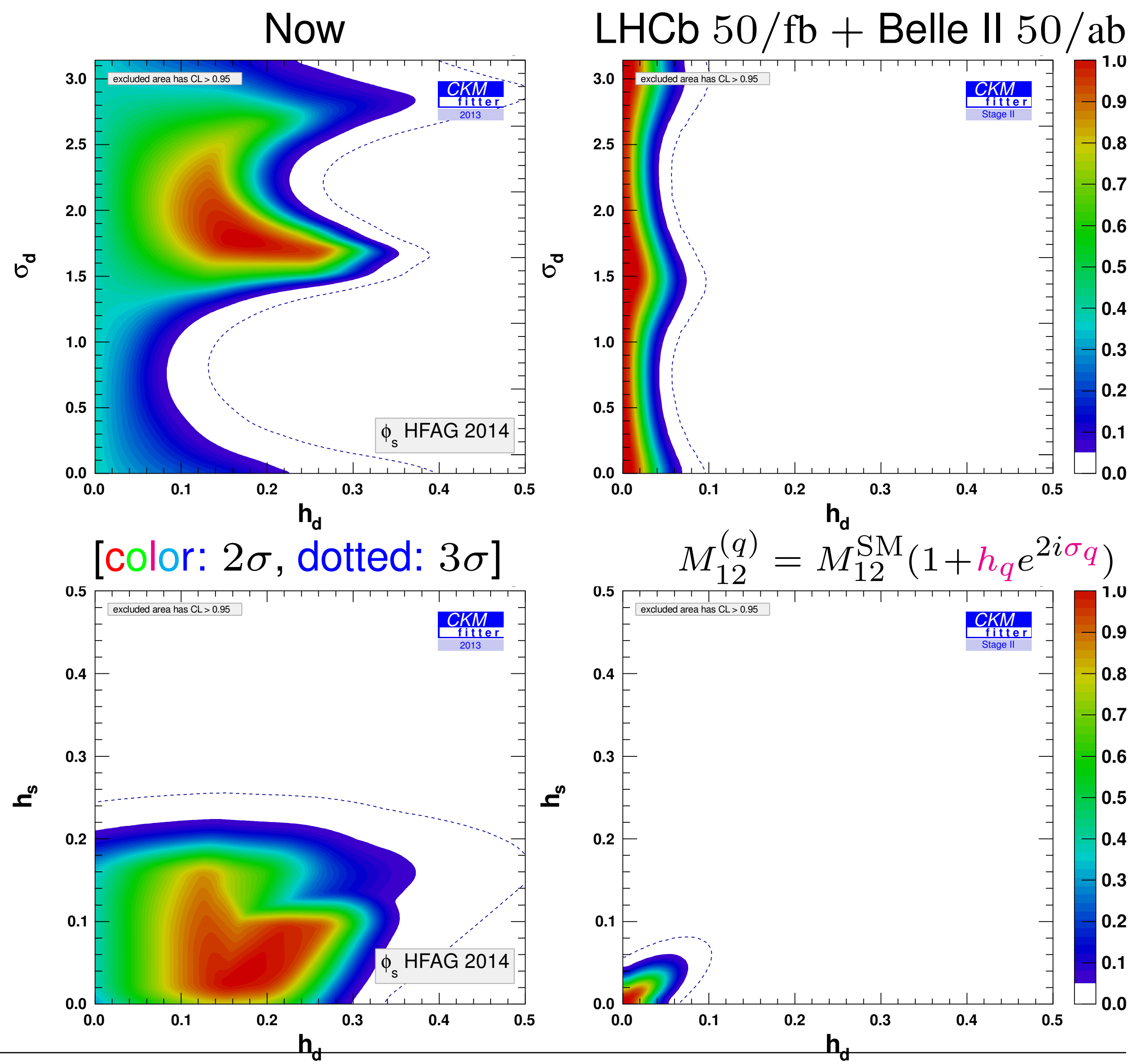
$$\Rightarrow \Lambda \sim \begin{cases} 2.3 \times 10^3\,\text{TeV} \\ 20\,\text{TeV (tree + CKM)} \\ 2\,\text{TeV (loop + CKM)} \end{cases}$$

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

- Sensitivity would continue to increase beyond 300/fb

  Complementary to high p_T

  [1309.2293; update to LHCb 300/fb soon]



(2) 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 [TeV]

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 $\sim 2.5 \sim \sqrt[4]{50}$

The current B "anomalies"

- Lepton non-universality would be clear evidence for NP

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

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

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

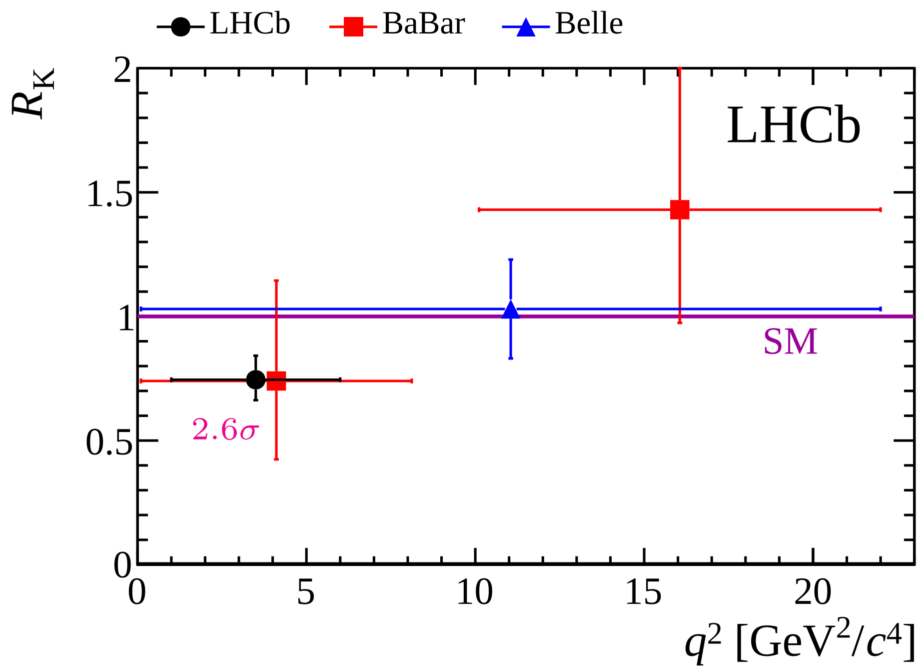
- Viable BSM models... leptoquarks? No clear connection to DM & hierarchy puzzle

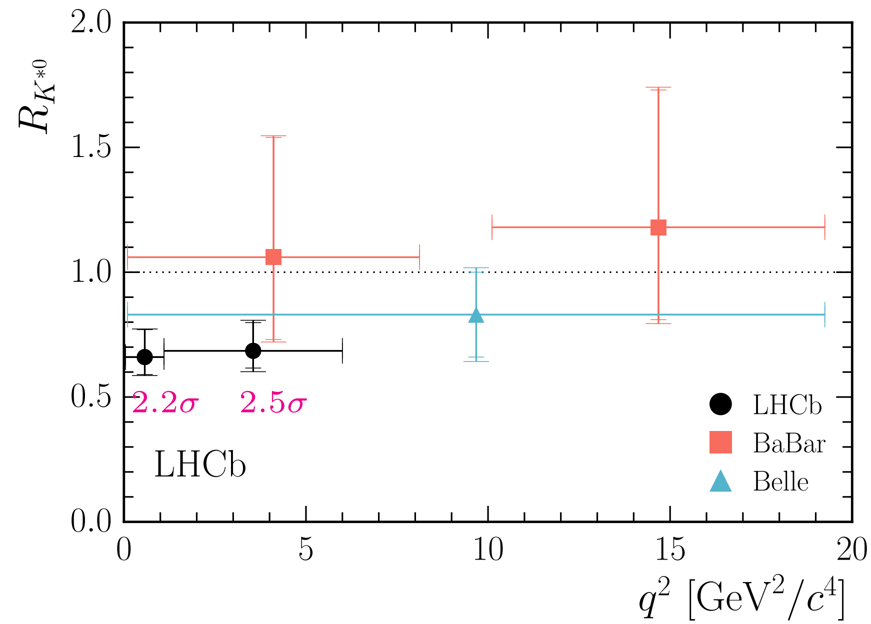
  (Is the hierarchy problem or the flavor problem more pressing for Nature?)

- 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 $\mathcal{H}_{\rm eff}$ gives good fit: $\delta\, C_{9,\mu} \sim -1$

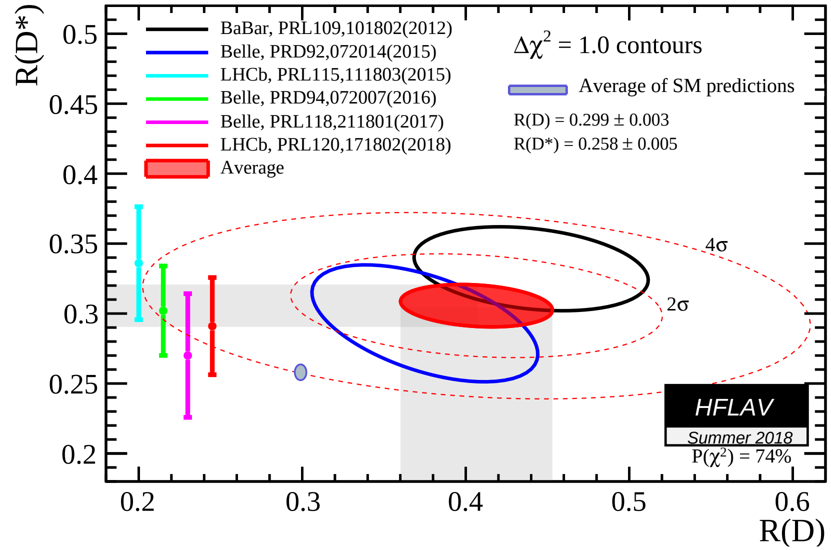
The $B \to D^{(*)}\tau\bar\nu$ decay rates

- 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

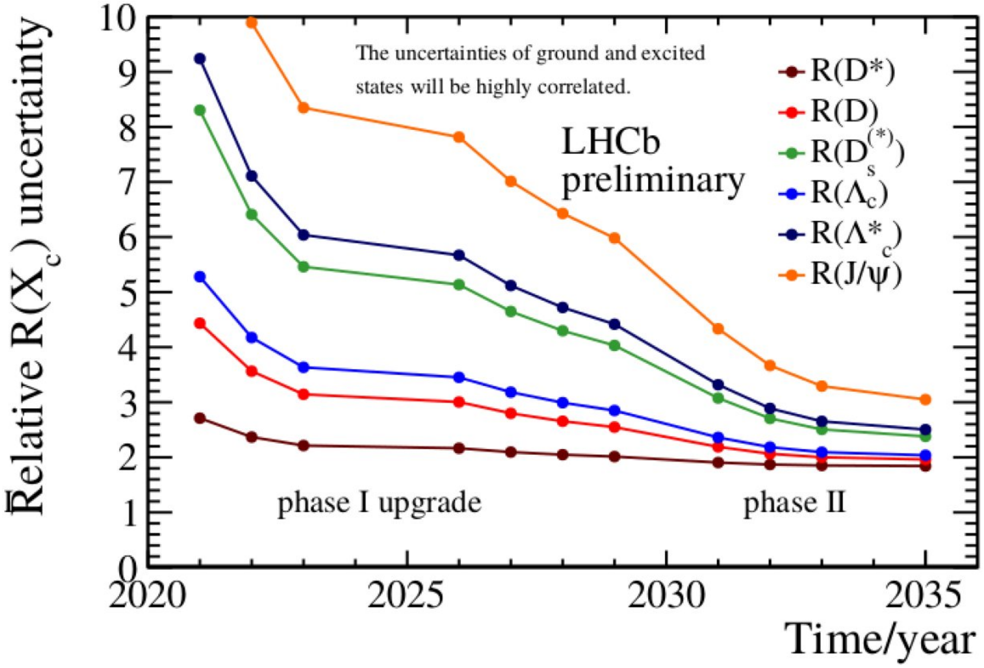
- Tree level: three ways to insert mediator: $(b\nu)(c\tau)$, $(b\tau)(c\nu)$, $(bc)(\tau\nu)$

  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!

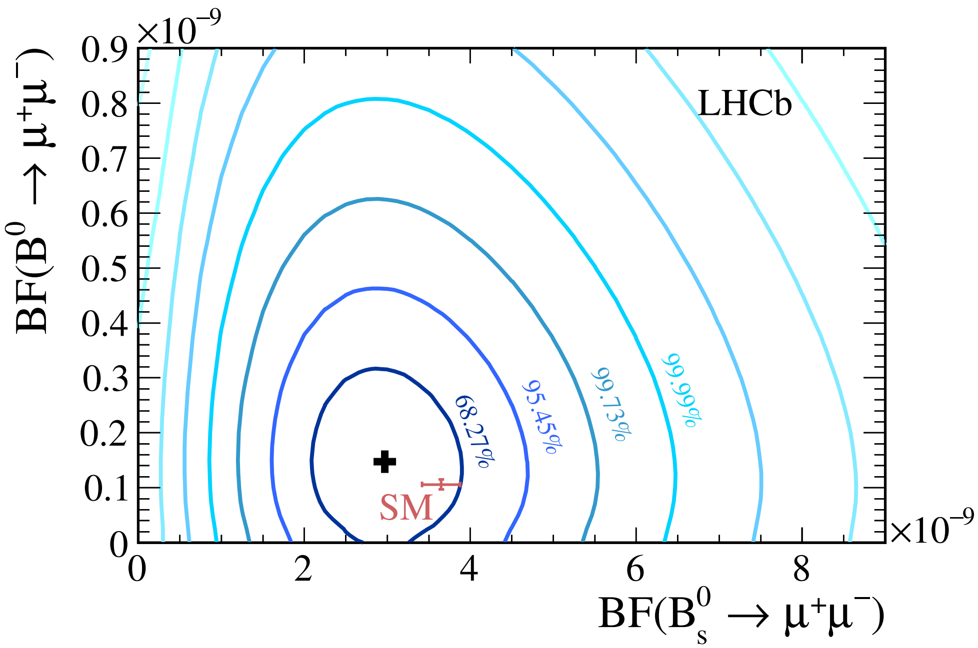
(Even if central values change, plenty of room for establishing deviations from SM)

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

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

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

  SM uncertainty, currently $\simeq (2\%) \oplus f_{B_q}^2 \oplus \text{CKM}$



- 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/ $K \to \pi\nu\bar\nu$

Richness of directions

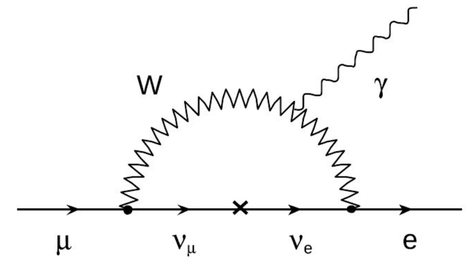
Very broad program: many directions

- Better tests of (exact or approximate) conservation laws
- Maximize sensitivity to $\tau \to 3\mu$, $\tau \to h\mu\mu$, etc.
- LFV meson decays, e.g., $M^0 \to \mu^- e^+$, $B^+ \to h^+ \mu^- e^+$, etc.
- Invisible modes, hidden sectors, even baryonic, $B \to N + \text{invis.}\ [+\text{mesons}]$ [1708.01259]
- 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
- Hidden valley inspired scenarios, e.g., multiple displaced vertices, even with $\ell^+\ell^-$
- FCNC in top decay (since $t_L \leftrightarrow b_L$, obvious connections to B decay data)
- I do not know how many CP violating quantities have been measured, neither how many new hadronic states discovered by BaBar, Belle, LHCb ... Anyone...?

Charged lepton flavor violation

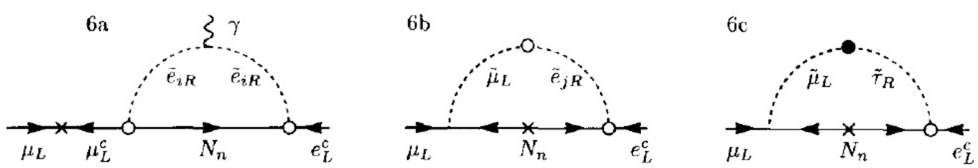
- SM predicted lepton flavor conservation with $m_\nu = 0$

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

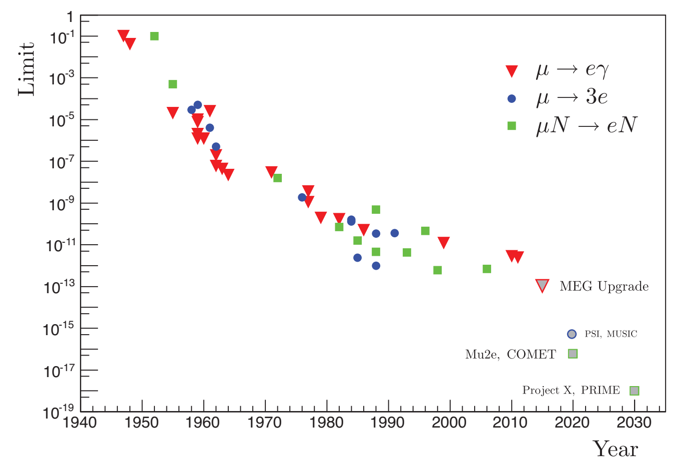


$$\mathcal{B}(\mu \to e\gamma) \sim \alpha\, \frac{m_\nu^4}{m_W^4} \sim 10^{-52}$$

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



History of $\mu \to e\gamma$, $\mu N \to eN$, and $\mu \to 3e$



- 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

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

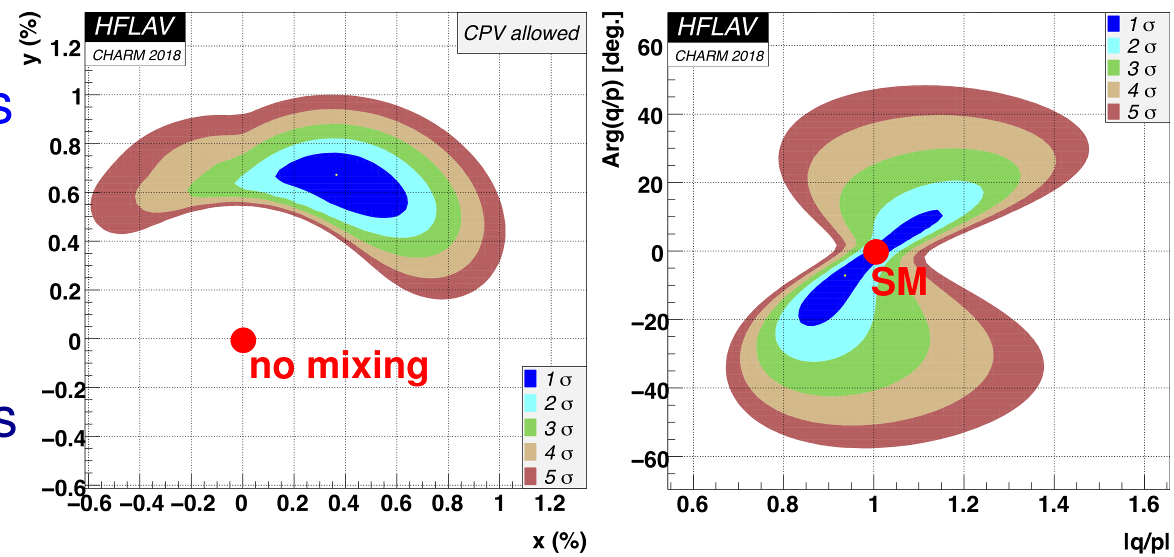
- CP violation in D decay

  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?

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?
  - 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! [See: Dave Hitlin's p.13, this am]

Conclusions

- Flavor physics probes scales $\gg 1\,\mathrm{TeV}$, sensitivity limited by statistics
- New physics in FCNCs may still be $\gtrsim 20\%$ of the SM
- Several tensions with the SM; could become decisive soon
- Discovering NP would give a target and upper bound on next scale to explore
- Many interesting theoretical questions, relevant for optimal sensitivity
- Complementarity between flavor $\&$ high-p_T searches for NP in all scenarios
- Ample physics reasons to study the largest heavy flavor data sets allowed by available technologies

Bonus slides

A case for HL-LHC

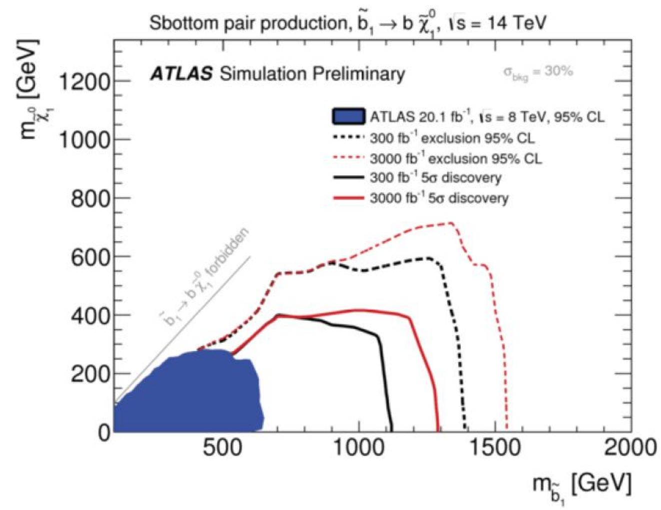
- Focus: ATLAS/CMS $300/\mathrm{fb} \to 3000/\mathrm{fb}$, LHCb $50/\mathrm{fb} \to 300/\mathrm{fb}$ (latter not yet approved)

  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. $\sim 1/\sqrt{\mathcal{L}}$)

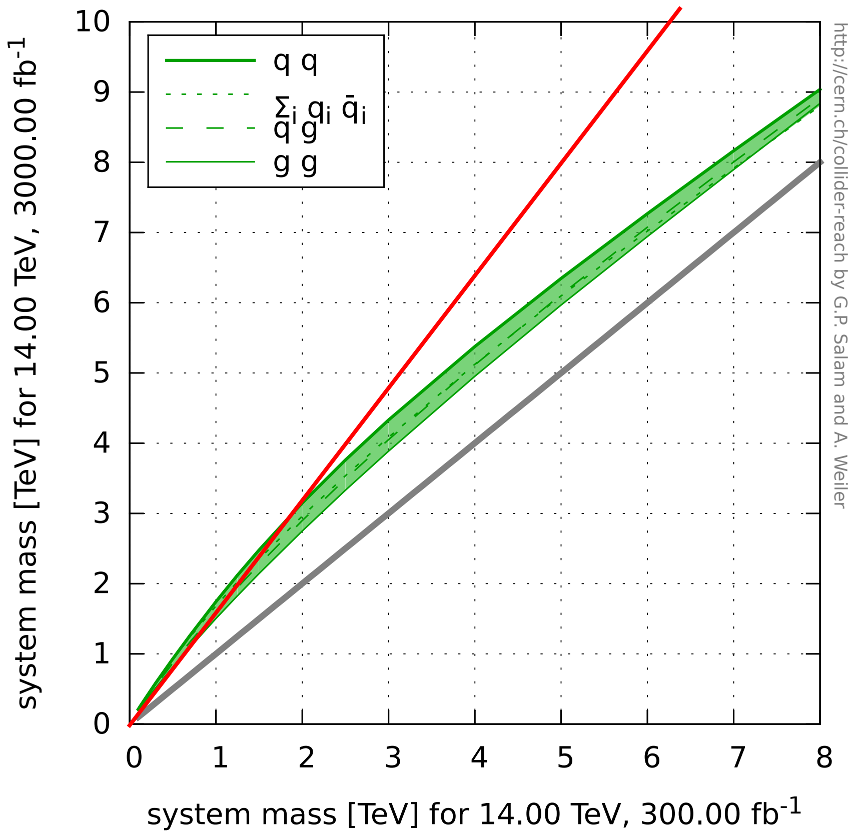


- Statistics $\times 10$ can make $1.5\sigma \to \sim 5\sigma$, even without analysis improvements

  (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', $\tilde{q}$, $\tilde{g}$!

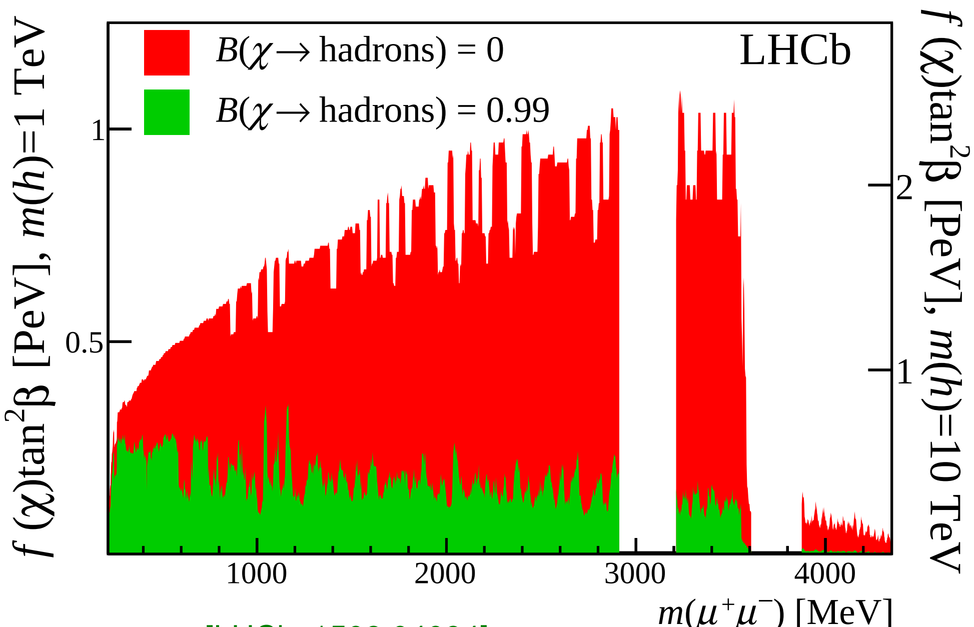
Theory challenges / opportunities

- 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?

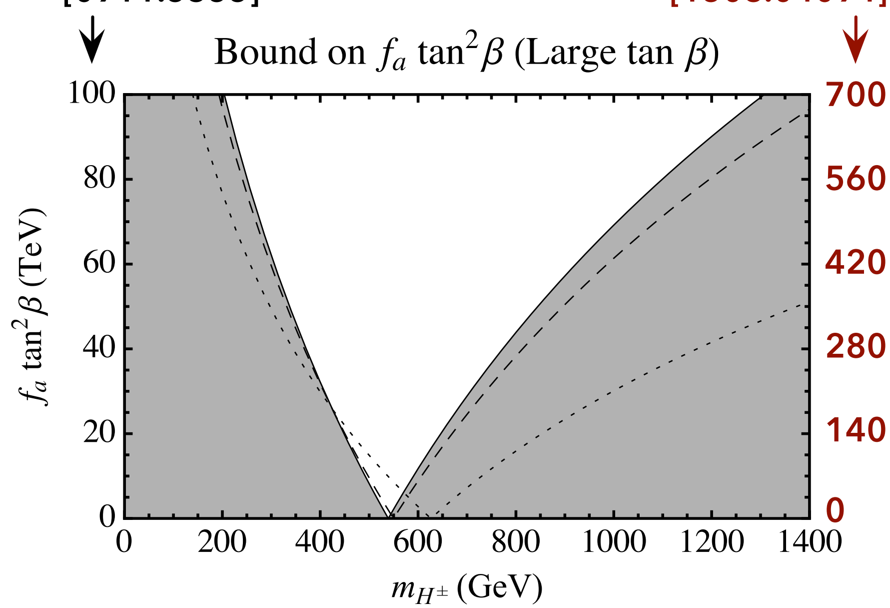
Dark sectors: broad set of searches

- 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)

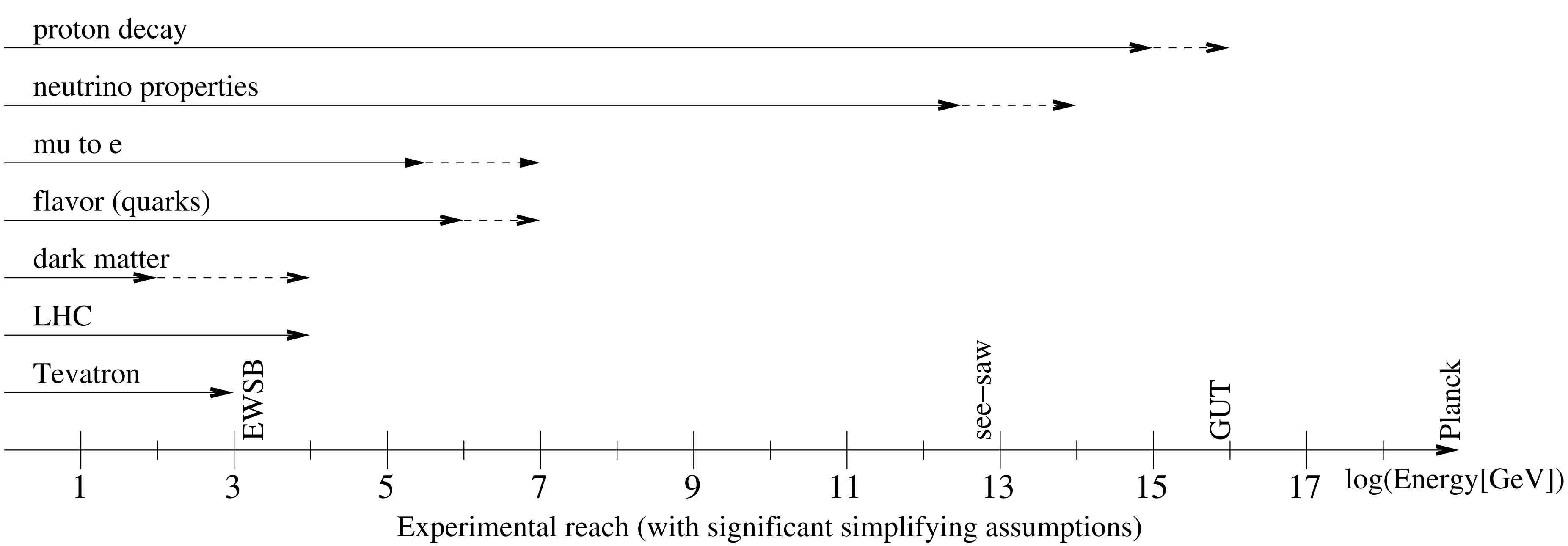


[LHCb, 1508.04094]



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

The big question: where is new physics?



Dashed arrows show anticipated improvements in next generation of experiments

- Proton decay already ruled out simplest version of grand unification
- Neutrino experiments hope to probe see-saw mechanism
- Flavor physics probes TeV-scale new physics with even SM-like suppressions
- LHC was in a unique situation that a discovery was virtually guaranteed (known since 80's)