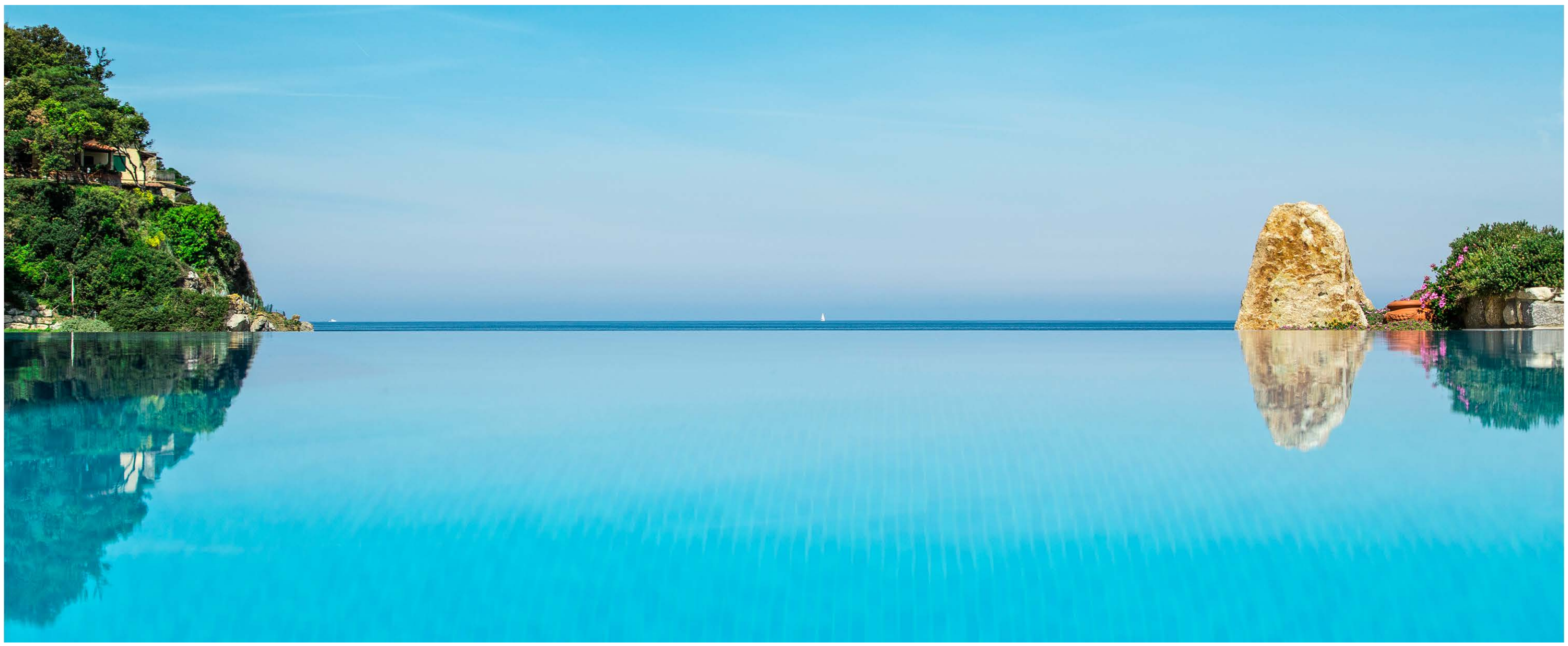
LHCb Phase-2 upgrade: a clear case

Zoltan Ligeti



Beyond the LHCb Phase-1 Upgrade, 28 – 31 May 2017, Elba

Snapshot: where I think we are

- Theoretical prejudices about new physics did not work as expected 10–20 yrs ago
- Incredibly exciting if any of the current anomalies become decisive

  Leave no stone unturned searching for NP — no guarantees after Higgs discovery

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- 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 — MFV probably useful approximation

  $\Updownarrow$ "naturalness' loss = flavor's gain"

  New physics at $10 - 100\,\mathrm{TeV}$ — less flavor suppression (MFV less motivated)

- 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

The SM cannot be the full story

- Evidence that the SM is incomplete:
  - Dark matter
  - Baryon asymmetry of the Universe
  - Neutrino mass (lepton number violated?)

  Maybe connected to the TeV scale: wimp, baryogenesis, but many other options

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- Experiments: ATLAS, CMS, LHCb, NA62, Belle II $+$ EDM, CLFV, DM, neutrinos, etc.
- Future: $\dfrac{\text{(LHCb Phase-2)}}{\text{(LHCb now)}} \sim \dfrac{\text{(Belle II data set)}}{\text{(Belle data set)}} \sim \dfrac{\text{(ATLAS \& CMS 3/ab)}}{\text{(ATLAS \& CMS now)}} \sim 50-100$
- New / improved methods: more progress than simply scaling with statistics

  New theory ideas motivated by data? New questions to address $+$ Surprises

BaBar, 6 top cited

[removed detector papers]

1. **Evidence for an excess of $\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau$ decays**
BaBar Collaboration (J.P. Lees (Annecy, LAPP) *et al.*). May 2012. 8 pp.
Published in **Phys.Rev.Lett. 109 (2012) 101802**
BABAR-PUB-12-012, SLAC-PUB-15028
DOI: 10.1103/PhysRevLett.109.101802
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Detailed record - Cited by 400 records 250+

2. **Observation of a broad structure in the $\pi^+\pi^- J/\psi$ mass spectrum around 4.26-GeV/c^2**
BaBar Collaboration (Bernard Aubert (Annecy, LAPP) *et al.*). Jun 2005. 7 pp.
Published in **Phys.Rev.Lett. 95 (2005) 142001**
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DOI: 10.1103/PhysRevLett.95.142001
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3. **Study of the $B \to J/\psi K^-\pi^+\pi^-$ decay and measurement of the $B \to X(3872)K^-$ branching fraction**
BaBar Collaboration (Bernard Aubert (Annecy, LAPP) *et al.*). Jun 2004. 7 pp.
Published in **Phys.Rev. D71 (2005) 071103**
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4. **Observation of a narrow meson decaying to $D_s^+\pi^0$ at a mass of 2.32-GeV/c^2**
BaBar Collaboration (B. Aubert (Annecy, LAPP) *et al.*). Apr 2003. 7 pp.
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SLAC-PUB-9711, BABAR-PUB-03-011
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ADS Abstract Service; OSTI Information Bridge Server; BaBar Publications Database; BaBar Password Protected Publications Database; Link to PRESSRELEASE; SLAC Document Server
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↑ Surprises: "new" states, $R(D^{(*)})$

↓ SM-like so far: CP violation

5. **Measurement of the CP-violating asymmetry amplitude $\sin 2\beta$**
BaBar Collaboration (Bernard Aubert (Annecy, LAPP) *et al.*). Jul 2002. 7 pp.
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SLAC-PUB-9293, BABAR-PUB-02-008
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6. **Observation of CP violation in the B^0 meson system**
BaBar Collaboration (Bernard Aubert (Annecy, LAPTH) *et al.*). Jul 2001. 8 pp.
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Belle, 6 top cited

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Belle Collaboration (Z.Q. Liu (Beijing, Inst. High Energy Phys.) *et al.*). Mar 30, 2013. 7 pp.
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DOI: 10.1103/PhysRevLett.110.252002
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Data: INSPIRE | HepData
Detailed record - Cited by 408 records 250+

2. **Observation of a resonance-like structure in the pi+- psi-prime mass distribution in exclusive B ---> K pi+- psi-prime decays**
Belle Collaboration (S.K. Choi (Gyeongsang Natl. U.) *et al.*). Aug 2007. 12 pp.
Published in **Phys.Rev.Lett. 100 (2008) 142001**
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DOI: 10.1103/PhysRevLett.100.142001
Presented at Conference: C07-08-13 Proceedings
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4. **Observation of a narrow charmonium - like state in exclusive B+- ---> K+- pi+ pi- J / psi decays**
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Detailed record - Cited by 1334 records 1000+

↑ Surprises: "new" states

↓ SM-like so far: CP violation

5. **Observation of large CP violation in the neutral B meson system**
Belle Collaboration (Kazuo Abe (KEK, Tsukuba) *et al.*). Jul 2001. 12 pp.
Published in **Phys.Rev.Lett. 87 (2001) 091802**
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Belle Collaboration (Kazuo Abe (KEK, Tsukuba) *et al.*). Mar 2001. 13 pp.
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LHCb Collaboration (Roel Aaij (CERN) *et al.*). Jul 13, 2015. 15 pp.
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CERN-PH-EP-2015-153, LHCB-PAPER-2015-029
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CERN Document Server; ADS Abstract Service; Interactions.org article; Link to BBC News article; Link to SYMMETRY; Link to Discovery.com news article; Link to Nature News article; Link to PBS website; Link to Scientific American article
Detailed record - Cited by 385 records 250+

2. **Test of lepton universality using $B^+ \to K^+ \ell^+ \ell^-$ decays**
LHCb Collaboration (Roel Aaij (NIKHEF, Amsterdam) *et al.*). Jun 25, 2014. 10 pp.
Published in **Phys.Rev.Lett. 113 (2014) 151601**
CERN-PH-EP-2014-140, LHCB-PAPER-2014-024
DOI: 10.1103/PhysRevLett.113.151601
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3. **Measurement of Form-Factor-Independent Observables in the Decay $B^0 \to K^{*0} \mu^+ \mu^-$**
LHCb Collaboration (R Aaij (NIKHEF, Amsterdam) *et al.*). Aug 7, 2013. 8 pp.
Published in **Phys.Rev.Lett. 111 (2013) 191801**
LHCB-PAPER-2013-037, CERN-PH-EP-2013-146
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4. **Measurement of the $B_s^0 \to \mu^+ \mu^-$ branching fraction and search for $B^0 \to \mu^+ \mu^-$ decays at the LHCb experiment**
LHCb Collaboration (R. Aaij (NIKHEF, Amsterdam) *et al.*). Jul 18, 2013. 9 pp.
Published in **Phys.Rev.Lett. 111 (2013) 101805**
CERN-PH-EP-2013-128, LHCB-PAPER-2013-046
DOI: 10.1103/PhysRevLett.111.101805
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5. **First Evidence for the Decay $B_s^0 \to \mu^+ \mu^-$**
LHCb Collaboration (R Aaij (NIKHEF, Amsterdam) *et al.*). Nov 2012. 9 pp.
Published in **Phys.Rev.Lett. 110 (2013) no.2, 021801**
CERN-PH-EP-2012-335, LHCB-PAPER-2012-043
DOI: 10.1103/PhysRevLett.110.021801
e-Print: **arXiv:1211.2674 [hep-ex]** | PDF
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Detailed record - Cited by 431 records 250+

6. **Evidence for CP violation in time-integrated $D^0 \to h^- h^+$ decay rates**
LHCb Collaboration (R. Aaij (NIKHEF, Amsterdam) *et al.*). Dec 2011. 8 pp.
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CERN Document Server; ADS Abstract Service
Detailed record - Cited by 320 records 250+

LHCb, 6 top cited

[removed detector papers]

Surprises: more “new” QCD

Hints: lepton universality viol.?
(started @ BaBar & Belle)

Come & gone: D direct CP viol.

SM-like so far: $B_s \to \mu^+ \mu^-$
CPV in B_s sector

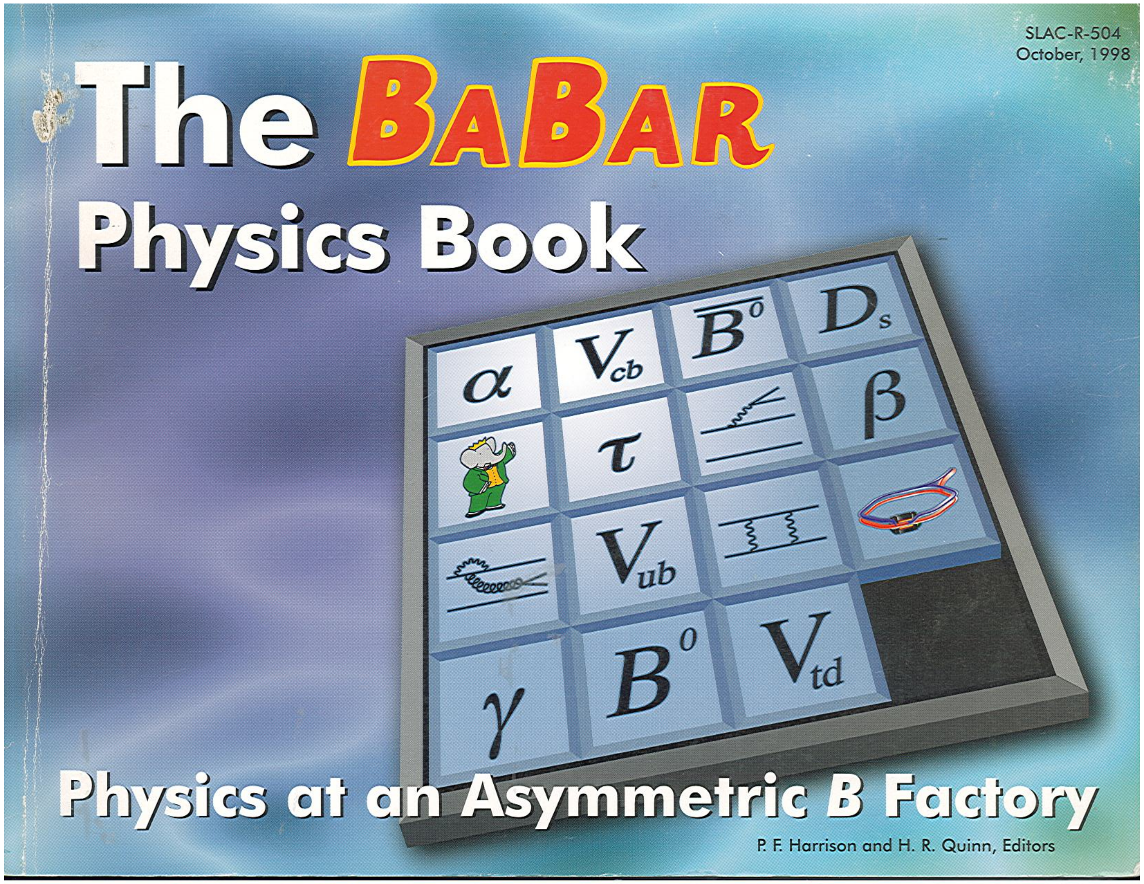
Future surprises...?

- It's now 18 years before the end of Run-5 around 2035
- 18 years ago, 1999: nonzero ϵ'/ϵ measured, had no info about CPV in B sector

  start of SCET, QCD factorization; theory will develop in unpredictable ways
- Predict Belle & BaBar physics from 1992, 18 yrs before end of Belle data taking:
  - ICHEP 1992 was at Dallas, anticipating the SSC
  - The arXiv just started, access via email only
  - Handwritten slides, no laptops yet in academia
  - Start inclusive B decay OPE calculations, γ methods ('91), $B \to \rho\pi$ Dalitz ('93)
  - Before CLEO observation of $B \to K^*\gamma$ ('93) and $B \to K\pi$ (large penguins, '97)
  - Windows 3.1, Mathematica 2, first linux release

($\Rightarrow$ Who are we kidding?)

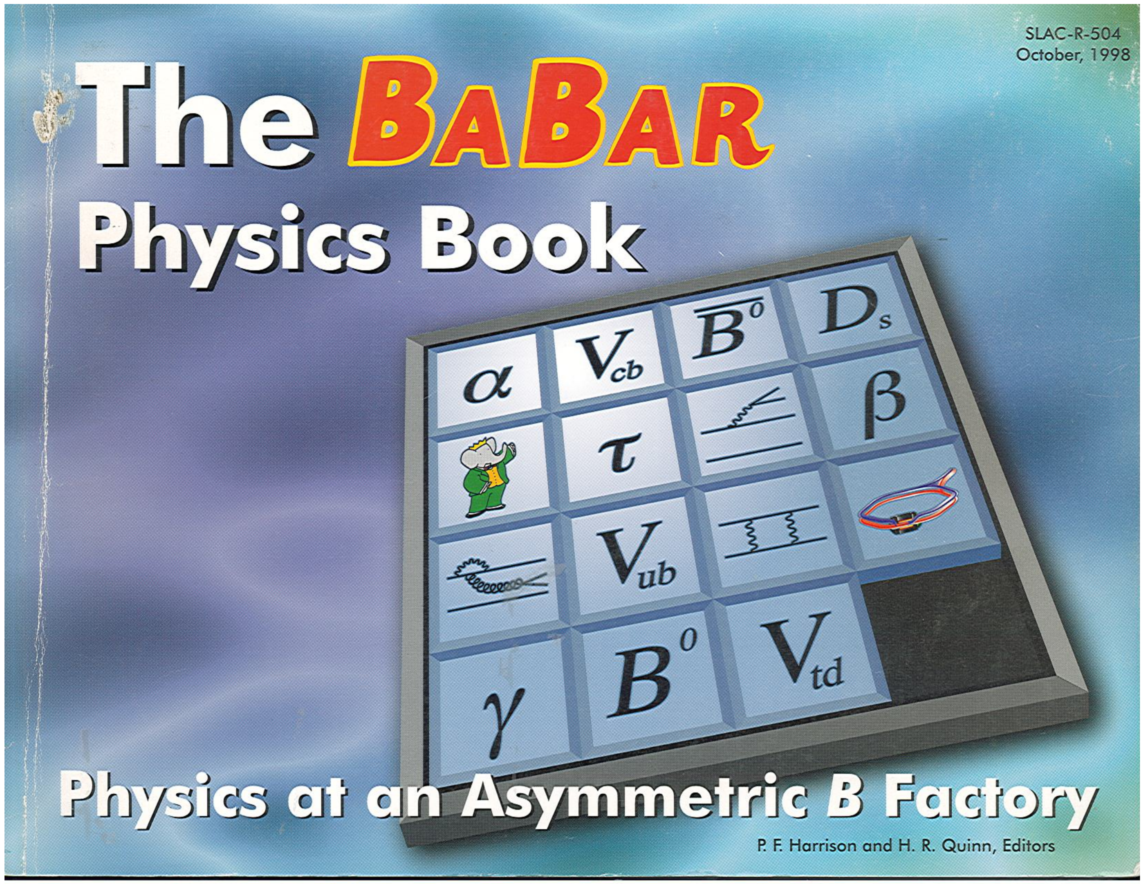
Searching for “killer apps” may be a trap...



- No executive summary... Neither a list of gold-plated measurements...

Already stated that NP (R-parity violation) “can do everything except make coffee”

Searching for “killer apps” may be a trap...



- No executive summary... Neither a list of gold-plated measurements...

Despite amazing progress, Δm_K and ϵ_K still give some of the strongest constrains on NP

Outline — rest of this talk

- Mode / model independent: Large improvements in new physics sensitivity

  Combinations of many measurements — 3 examples

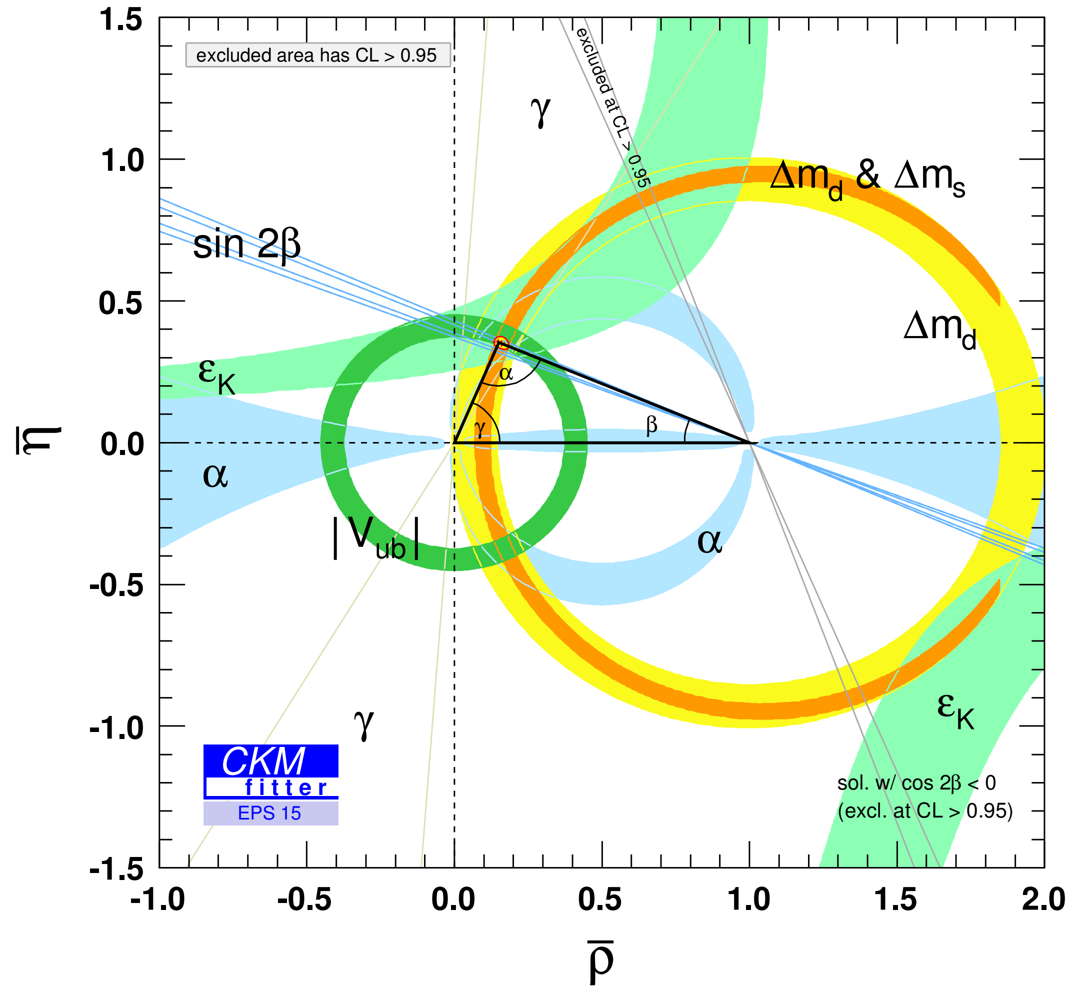
- Mode / model specific: Current tensions with SM — may become dedcisive soon

  Long term: forget current data, many key observables...

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

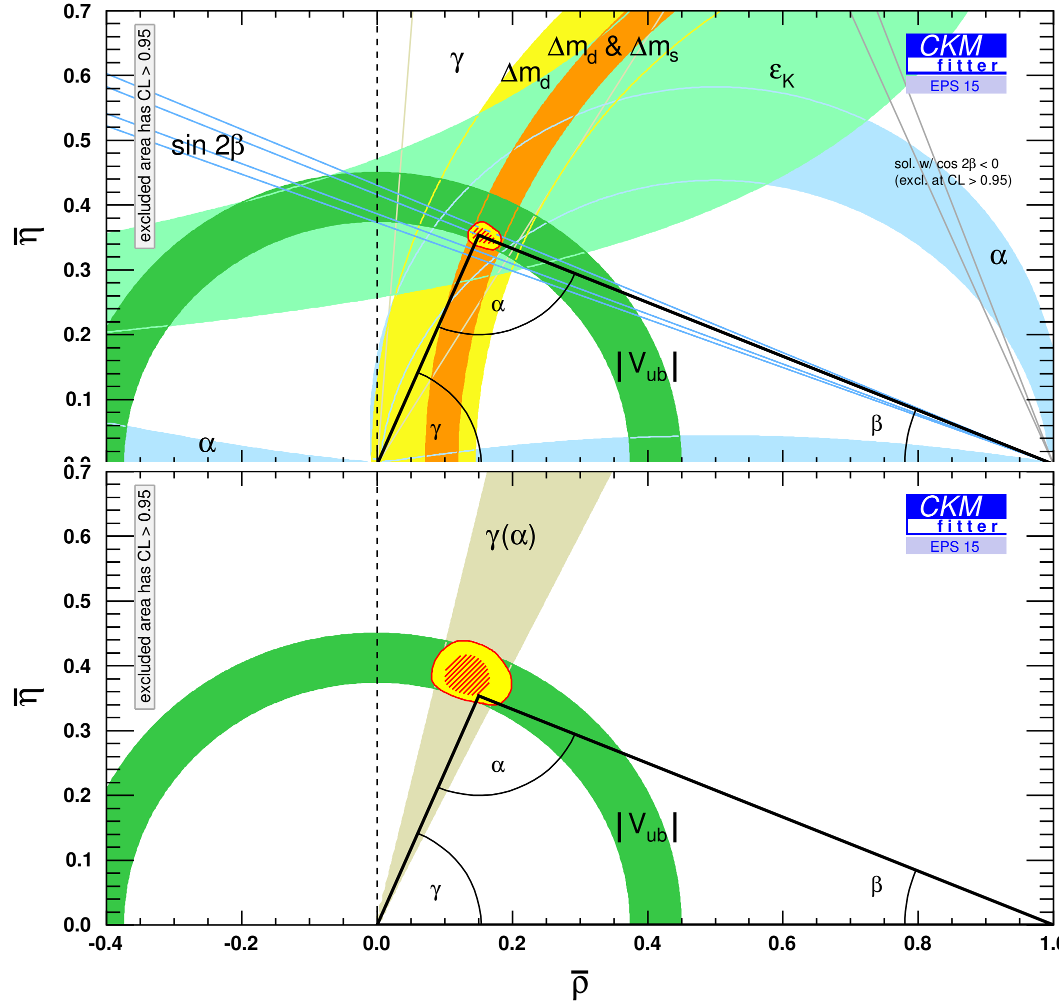
The standard model CKM fit

- SM dominates CP viol. $\Rightarrow$ KM Nobel
- The implications of the consistency often overstated



The standard model CKM fit

- SM dominates CP viol. $\Rightarrow$ KM Nobel
- The implications of the consistency often overstated
- Larger allowed region if the SM is not assumed
- Tree-level (mainly V_{ub} & γ) vs. loop-dominated measurements crucial



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

Reasons to seek higher precision

- What are the expected deviations from the SM induced by TeV-scale NP?

  Generic flavor structure already ruled out by orders of magnitudes — can find any size deviations below the current bounds. In a large class of scenarios expect observable deviations.

- What are the theoretical uncertainties?

  Highly process dependent, in many key measurements theory uncertainties will be under control

- What to expect in terms of experimental precision?

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

- What will the measurements teach us if deviations from the SM are [not] seen?

  The new flavor physics data will be complementary with the high-p_T part of the LHC program. The synergy of measurements can teach us about what the new physics at the TeV scale is [not].

(1) The scaling of scales

- How do the scales probed (for a dimension-6 operator) depend on the precision?
- $(\text{NP})^2$ rates: $\Lambda \sim (\text{uncertainty})^{-1/4}$

  e.g., $\mu \to e\gamma$ [$\sim (\text{bound})^{-1/4}$ iff background free]
- NP amplitude: $\Lambda \sim (\text{uncertainty})^{-1/2} \sim (\text{stat.})^{-1/4}$

  e.g., $K \to \pi\nu\bar{\nu}$

  e.g., $B_s \to \mu\mu,\ \sin 2\beta_s$

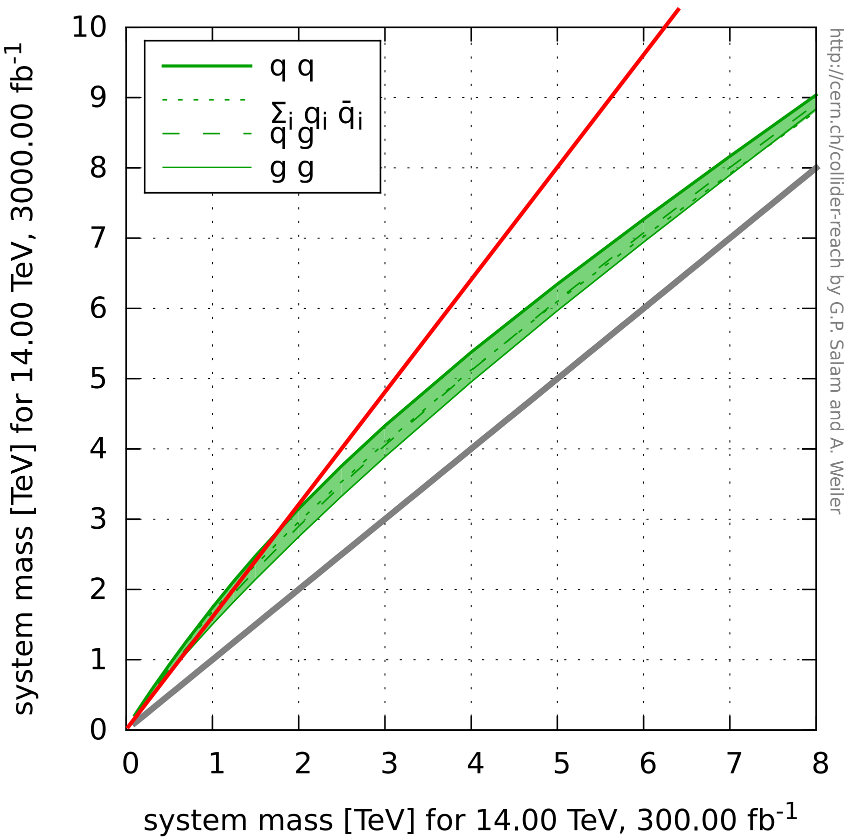
  e.g., EDMs

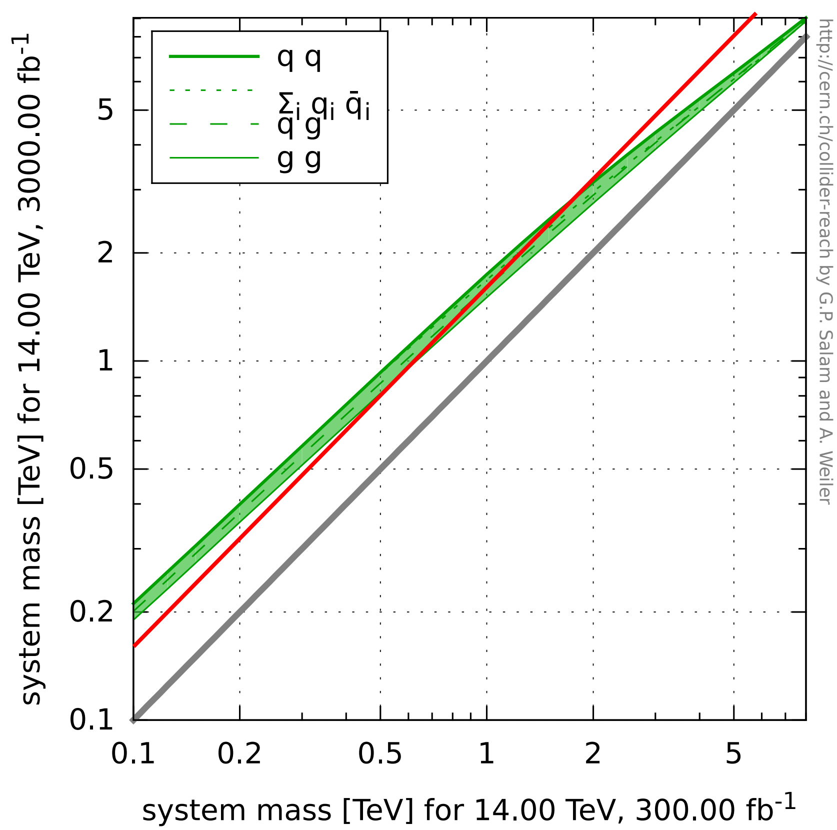
  e.g., Higgs couplings
- Conservatively: mass scales increase compared to today $\sqrt[4]{50} \sim 2.7$

  Phase-2 upgrade compared to Phase-1: $\sqrt[4]{6} \sim 1.6$
- Search for high-mass states @ ATLAS & CMS: parton luminiosities fall rapidly

A rough comparison with high-p_T searches

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



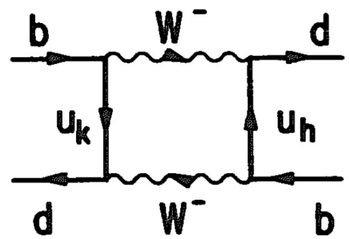


- Increase in mass limit > 1.6, iff limit with 300/fb at 14TeV is below $\sim 1\,\mathrm{TeV}$

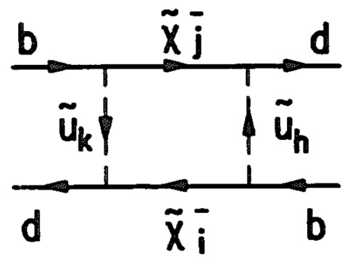
  Weakly produced particles and/or difficult decays — not your typical Z', $\tilde{q}$, $\tilde{g}$, ...!

(2) New physics in B mixing

- Meson mixing:



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



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

General parametrization:

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

NP parameters

What is the scale Λ? How different is $C_{\rm NP}$ 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)

Phase-1 sensitivity to NP in B mixing

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

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

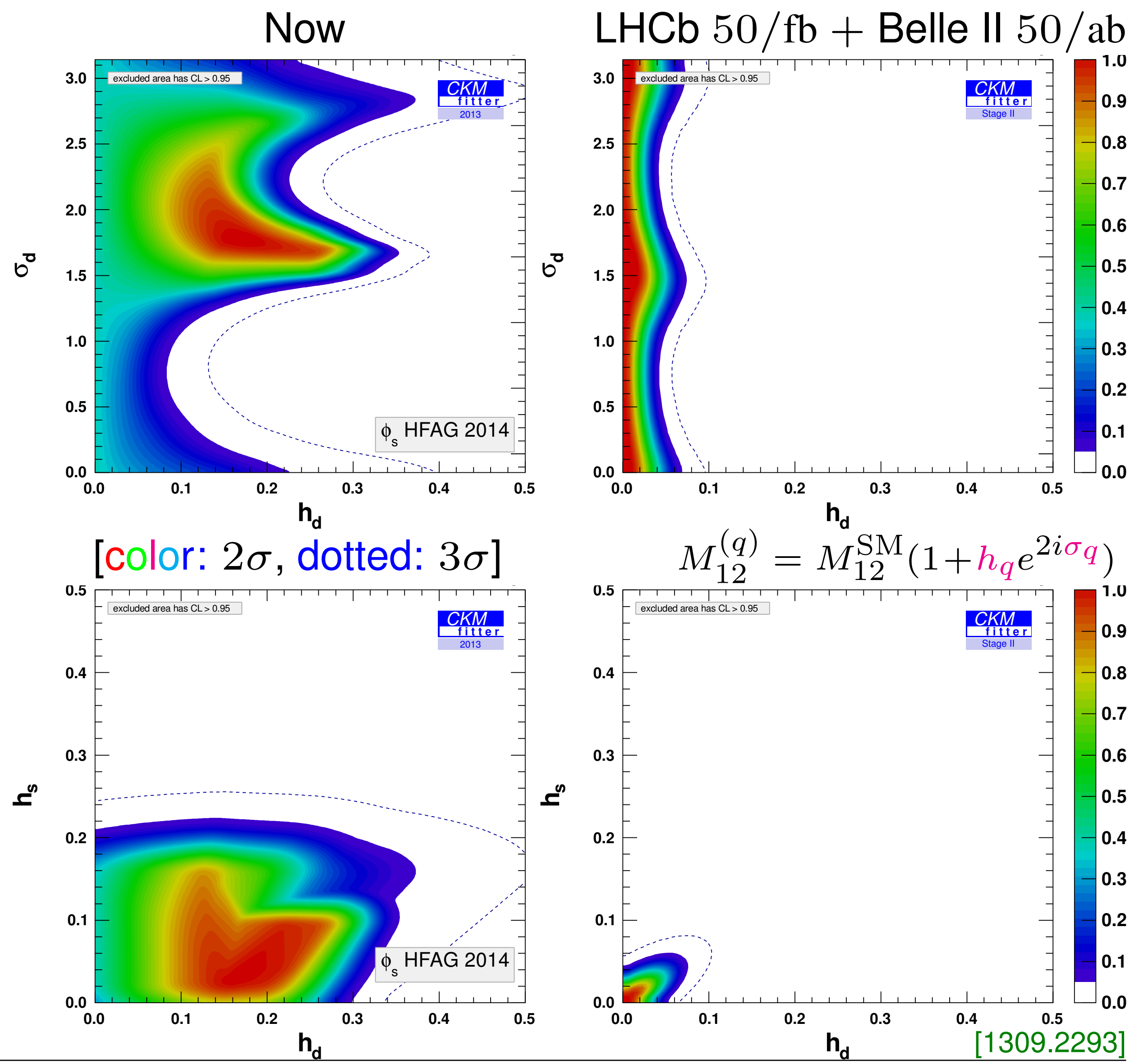
- Scale: $h \simeq \dfrac{|C_{ij}|^2}{|V_{ti}^* V_{tj}|^2} \left(\dfrac{4.5\,\text{TeV}}{\Lambda}\right)^2$

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

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

- Sensitivity will not stop to increase before 300/fb

  Complementary to high p_T



(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]

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

  Upper (lower) rows are current (future, 50/fb) sensitivities for 4 scenarios

  Strongest bounds from many processes, nominally 1-2 generation is most sensitive, many options in concrete models

- LHCb 50/fb $+$ Belle 50/ab increase mass scale sensitivity by factor ~ 2.5

Mode / model dependent

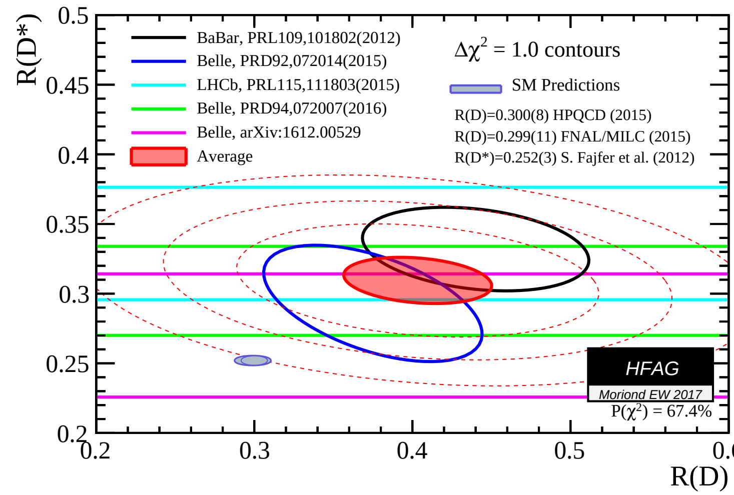
Current tensions with the SM

- Intriguing tensions, one of these might become the first clear sign of NP
  - R_K and R_{K^*}
  - $R(D)$ and $R(D^*)$
  - P_5' and other angular distributions $\Rightarrow$ Dedicated talks (th + exp) on each
- Except for theoretically cleanest observables, cross-checks are essential: measurements of related observables $+$ independent theory / lattice calculations
- I am working on $R(D^{(*)})$ related topics, because I think a lot can be improved, independent of the central values of the current data

  Likely lead (at least) to resolving the 20-some yr inclusive / exclusive $|V_{cb}|$ tension

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

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



$$R(D) = 0.403 \pm 0.047\,, \quad R(D^*) = 0.310 \pm 0.017$$

Nearly 4σ from SM predictions — robust due to heavy quark symmetry $+$ lattice QCD (only D so far)

- Tension: $R(D^{(*)})$ vs. $\mathcal{B}(b \to X\tau^+\nu) = (2.41 \pm 0.23)\%$ (LEP) [Freytsis, ZL, Ruderman]

  SM: $R(X_c) = 0.223 \pm 0.004$ — no $\mathcal{B}(B \to X\tau\bar{\nu})$ measurement since LEP

  Need NP at a fairly low scale (leptoquarks, W', etc.), likely visible at the LHC

- Awaiting LHCb result with hadronic τ decays, measure $R(D)$, maybe Λ_b decay

- Future experimental precision will be much better than current uncertainties

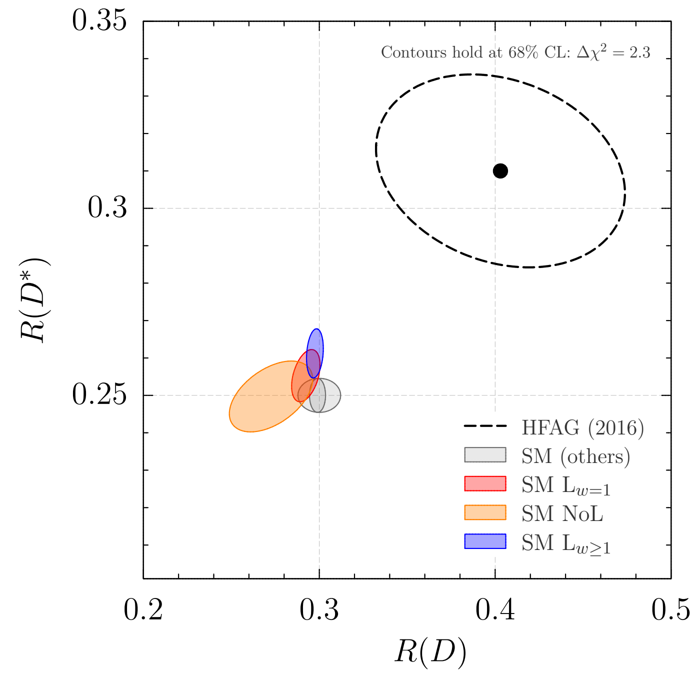
New predictions related to $B \to D^{(*)} \tau \bar{\nu}$

- All past calculations of $R(D^{(*)})$ (except $R(D)$ in LQCD) did not account for uncertainties properly

  Related to use of QCD sum rule inputs   plot without ⇒

  Also an issue for past $B \to D^* l \bar{\nu}$ form factor measurements

  Explored 7 fits w/ various theory / experiment inputs: significance of the tension is (surprisingly) stable



[Bernlochner, ZL, Papucci, Robinson, 1703.05330]

- Study $B \to D^{**} \ell \bar{\nu}$: both signal and background

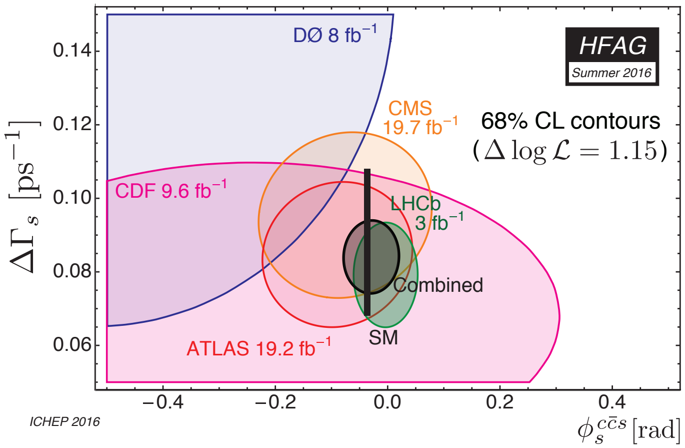
- Goal: fully implement all 6 $B \to D^{(*,**)} \ell \bar{\nu}$ modes

  Even if the anomaly goes away, it will likely result in understanding inclusive vs. exclusive $|V_{cb}|$

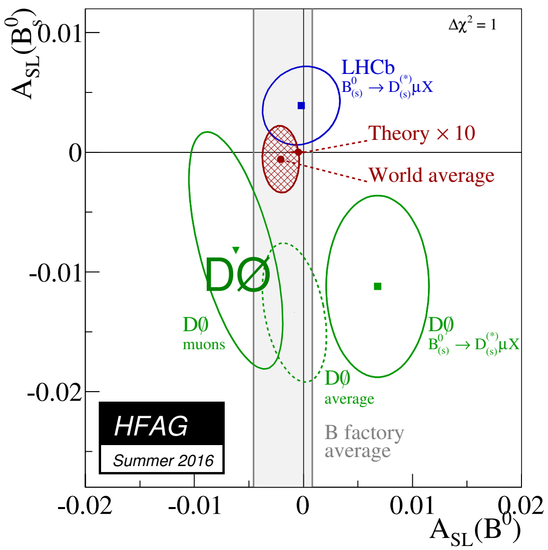
- None of the NP models appear to nicely fit together with mainstream expectations

  If experimentally established beyond doubt, there will be a lot to figure out...

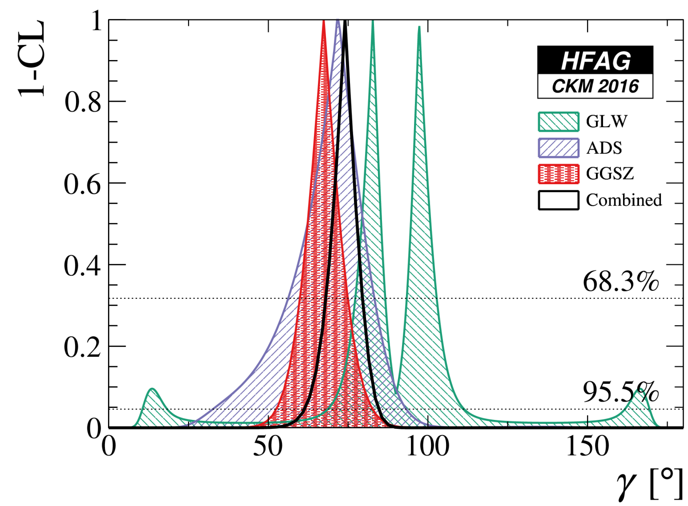
Other key measurements (well known)



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



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



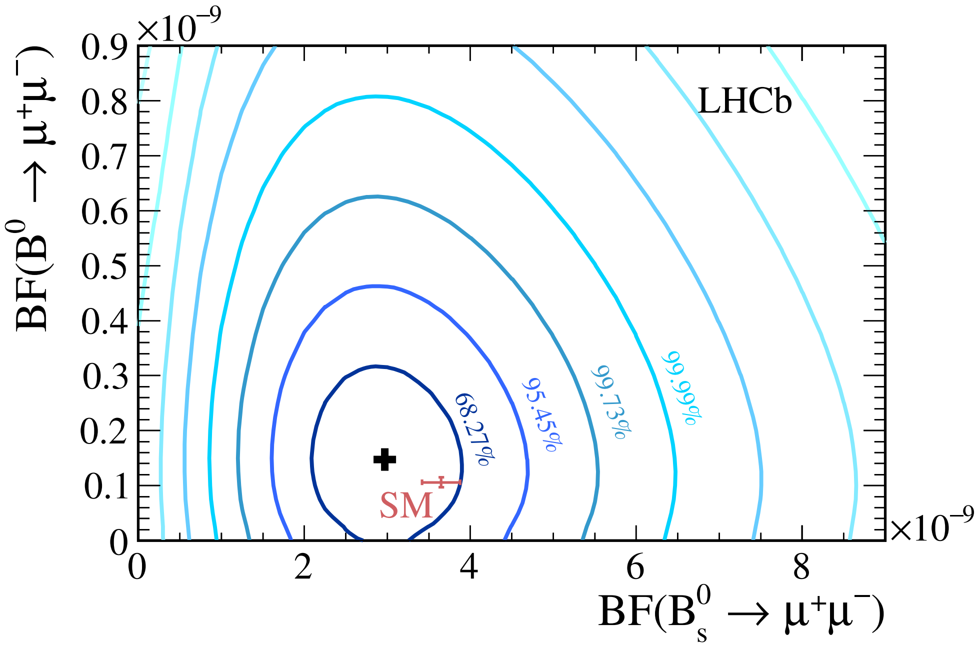
Measurements of γ crucial, LHCb is now most precise

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

$B \to \mu^+\mu^-$: interesting well beyond 300/fb

- B_d if SM level: CMS expects ultimately 15–20%, LHCb expected 30–40% (50/fb)

  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/ $K \to \pi\nu\bar{\nu}$

Richness of directions

Charm mixing and CP violation

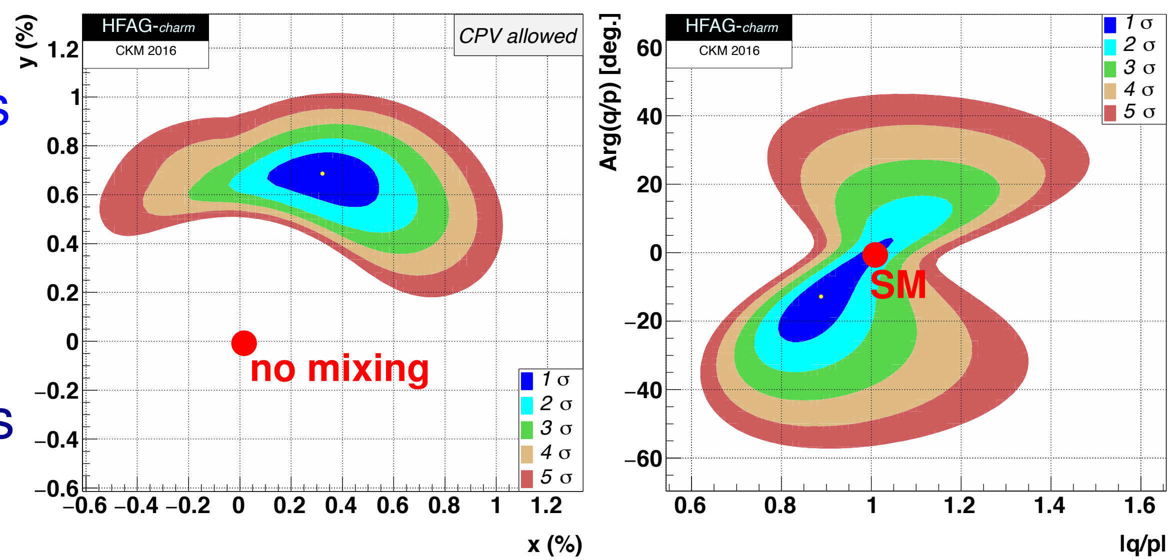
- CP violation in D decay

  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?

$B^+ \to K^+\pi^0$ at LHCb

- Observe 3.7σ mass peak in decay w/ photons and no reconstructed decay vertex

http://cds.cern.ch/record/1988475 [LHCb-CONF-2015-001]

At LHCb, this study also serves as a prototype for analyses with similar topologies, such as $B^0 \to K^0\pi^0$, $\Lambda_b \to \Lambda\gamma$, and $B^0 \to K^0\pi^0\gamma$

Important modes to study, yet very challenging at LHCb

- No secondary vertex, photons in final state

Analysis of $B^+ \to K^+\pi^0$ is a critical first step, and a proof-of-concept

Encouraged by the outcome of this analysis, a dedicated software trigger is being developed for use in Run II

[Andrews, Moriond EW 2015]

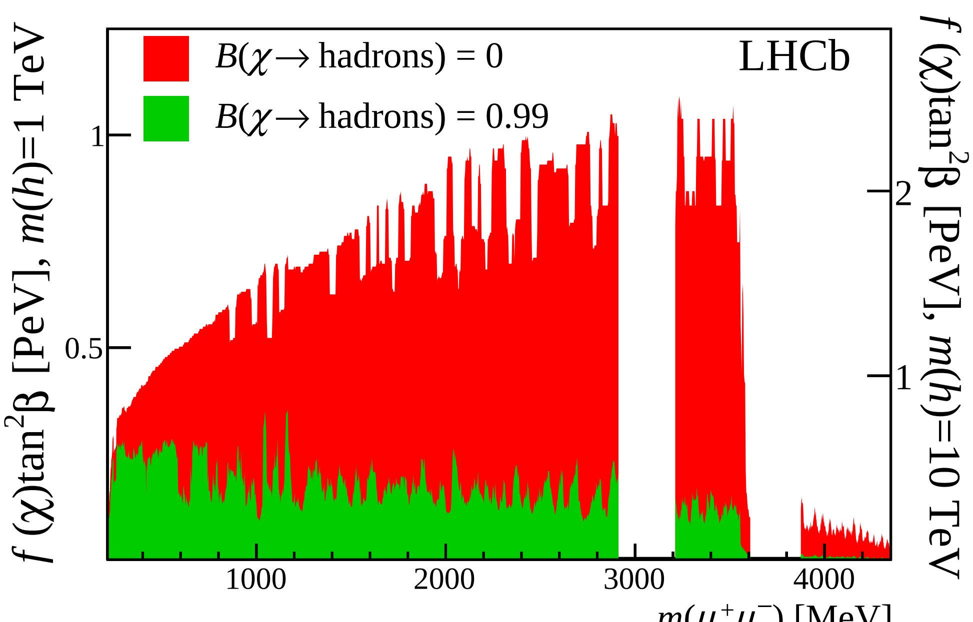
- Large set of "new" processes to explore — how well does it work in Run-2?

What are ultimate uncertainties? Increasing overlap between LHCb and Belle II

Dark sectors: bump hunting in $B \to K^* \mu^+ \mu^-$

- Nearly and order of magnitude improvement due to dedicated LHCb analysis

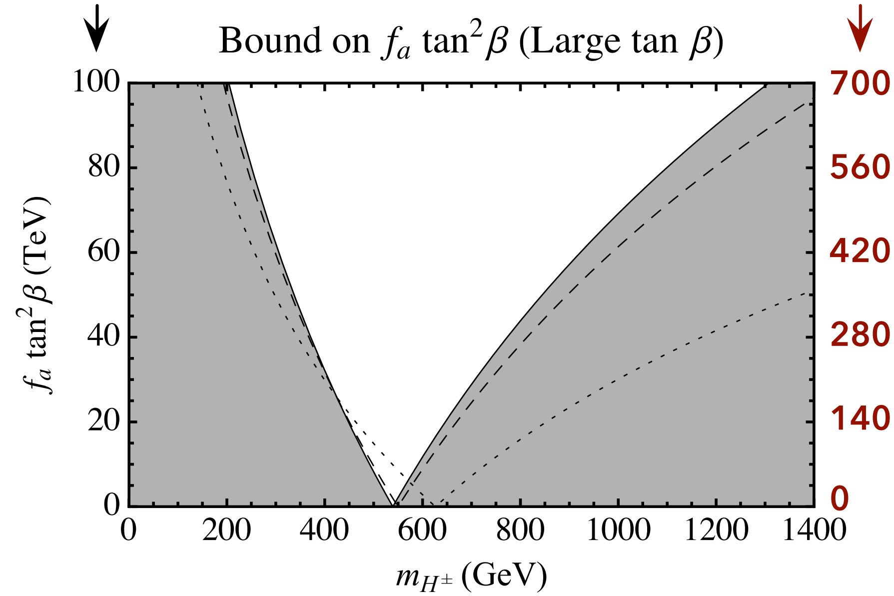
In "axion portal" models, scalar couples as $(m_\psi / f_a)\, \bar\psi \gamma_5 \psi\, a$ (m_t coupling in loops)



[LHCb, 1508.04094]

Freytsis, Ligeti, Thaler [0911.5355]

LHCb, m(a) = 600 MeV [1508.04094]



- Several future LHCb dark photon search proposals [Ilten et al., 1603.08926, 1509.06765]

Covered better in Mike Williams' talk than I could :–)

Future trends prediction attempt...

- Increase in papers dealing with new scenarios where LHCb can be competitive:
- Besides $h \to c\bar{c}$, search for exotic Higgs decays: e.g., high multiplicity decays, or modest multiplicity with displaced vertices (e.g., $h \to XX \to abab$)
- Searching for “quirks” at LHCb using many velo layers (new “quarks” with low confinement scale; non-straight “tracks”)
- Hidden valey inspired scenarios, e.g., multiple displaced vertices, even with $\ell^+\ell^-$
- FCNC in some top decay (since $t_L \leftrightarrow b_L$, obvious connections to B decay data)
- Hot topics of the 2030s are probably (certainly?) not what we have thought about (Whether or not NP is discovered by then)

Some other interesting channels...

- Any chance for even better sensitivity to $\tau \to 3\mu$, $\tau \to h\mu\mu$, etc.?
- Any $M^0 \to \mu^- e^+$, $B^+ \to h^+\mu^- e^+$, etc., type searches?
- If any (approximate) conservation law can be tested orders of magnitude better than before, to me, that's very interesting

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- My apologies, if I forgot to mention your favorite topics!

Final remarks

What are the largest useful data sets?

- Which measurements will remain far from being limited by theory uncertainties?
  - For $\gamma \equiv \phi_3$, theory uncertainty only from higher order EW
  - $B_{s,d} \to \mu\mu$, $B \to \mu\nu$ and other leptonic decays (lattice QCD, [double] ratios)
  - Probably CP violation in D mixing (firm up theory)
  - $A_{\rm SL}^{d,s}$ — can it keep scaling with statistics?
  - Lepton flavor & universality violation searches, etc.

  I guess that until 1000/fb LHCb data, sensitivity to higher scales would improve

- In some decay modes, even in 2030s we'll have: (exp. bound)/SM $\gtrsim 10^3$

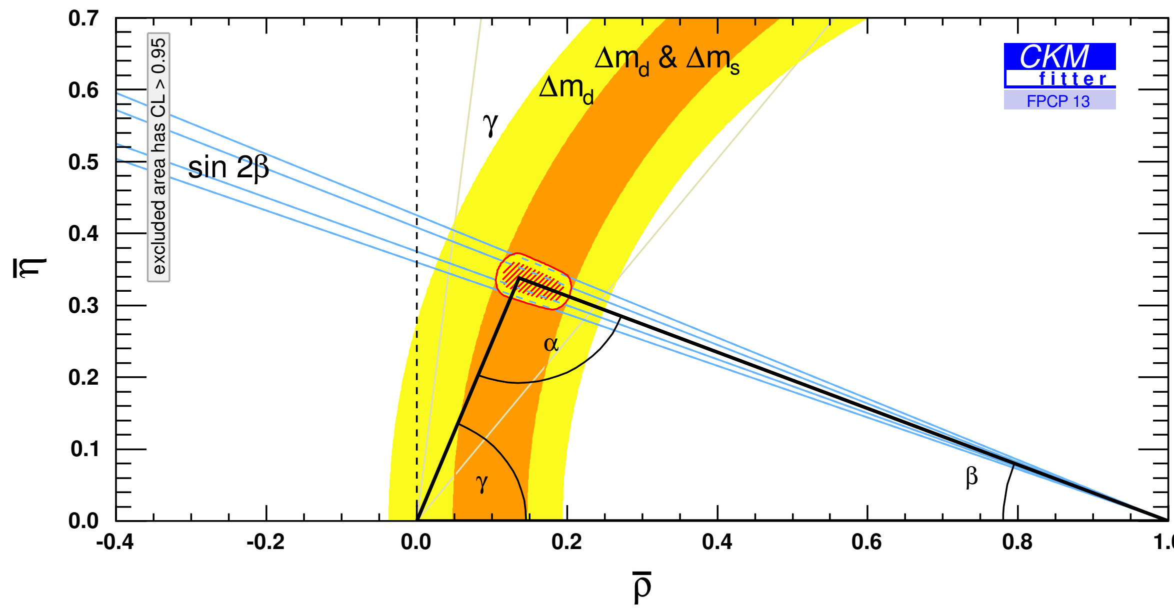
  E.g., $B_{d,s} \to \tau^+\tau^-$, e^+e^- — can build models... Please prove me wrong!

- Precision of f_s/f_d? 0.259 ± 0.015 appears near the $\sim 5\%$ systematic limit [LHCb-CONF-2013-011]

  Ultimately normalize to semileptonic, e.g., $\dfrac{\mathcal{B}(B_s \to \mu^+\mu^-)}{\mathcal{B}(B_s \to D_s^- \mu^+\nu)} \times \dfrac{\mathcal{B}(B_d \to D\mu\nu)}{\mathcal{B}(B_d \to \mu^+\mu^-)}$?

A test that will remain statistics limited

- Order of magnitude improvement in this comparison is possible



- More data will directly translate to improved sensitivity to new physics

- Ultimate reach does depend on theory progress (uncertainty of β and $\Delta m_{d,s}$)

  (On this time scale improvements in $\sin 2\beta$ needed)

Some theory challenges

- 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?

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; some of these (or others) may become decisive
- Discovering NP would also give upper bound and target for next scale to explore
- Many interesting theoretical questions relevant for experimental sensitivity

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- Ample physics reasons to study much larger b hadron samples

  LHC is a one-time opportunity — aim for the most that technology might allow

Extra slides

Reducing theory uncertainty of $\beta \equiv \phi_1$

- Hadronic uncertainty: $|V_{ub}V_{us}/(V_{cb}V_{cs})| \times (\text{“}P/T\text{”}) \simeq 0.02 \times$ (ratio of matrix elem.)

  Claims of large effects, many proposals, encouraging experimental bounds

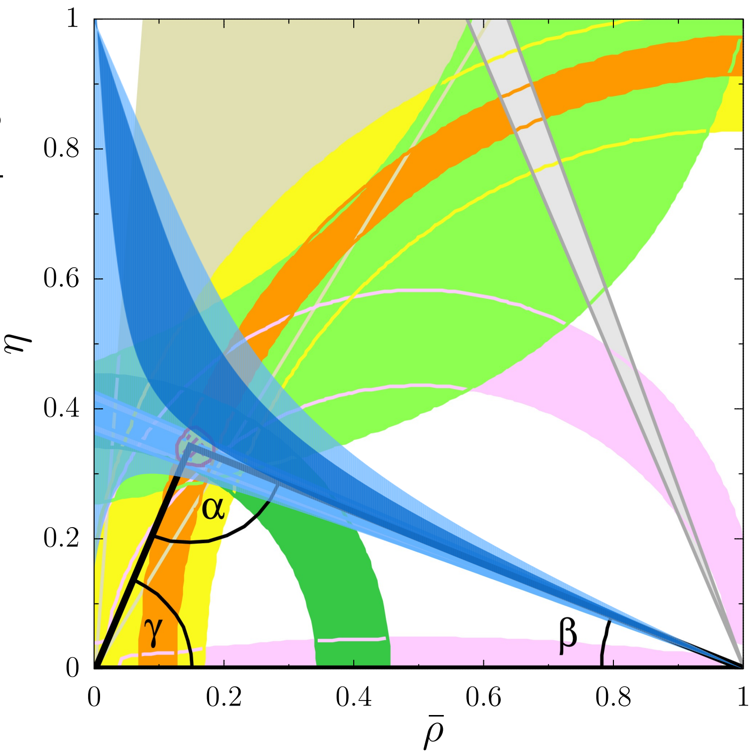
  Complicated literature: diagrammatic assumptions, there is no $SU(3)$ relation between ϕ and ρ

- Can suppress V_{ub} contribution by $SU(3)$ breaking:

$$\sin 2\beta = \frac{S_{K_S} - \lambda^2 S_{\pi^0} - 2(\Delta_K + \lambda^2\Delta_\pi)\tan\gamma\cos 2\beta}{1+\lambda^2}$$

$$\Delta_K = \frac{\bar\Gamma(B_d \to J/\psi K^0) - \bar\Gamma(B^+ \to J/\psi K^+)}{\bar\Gamma(B_d \to J/\psi K^0) + \bar\Gamma(B^+ \to J/\psi K^+)}$$

$$\Delta_\pi = \frac{2\bar\Gamma(B_d \to J/\psi \pi^0) - \bar\Gamma(B^+ \to J/\psi \pi^+)}{2\bar\Gamma(B_d \to J/\psi \pi^0) + \bar\Gamma(B^+ \to J/\psi \pi^+)}$$



- Control uncertainties with data [ZL & Robinson, 1507.06671]

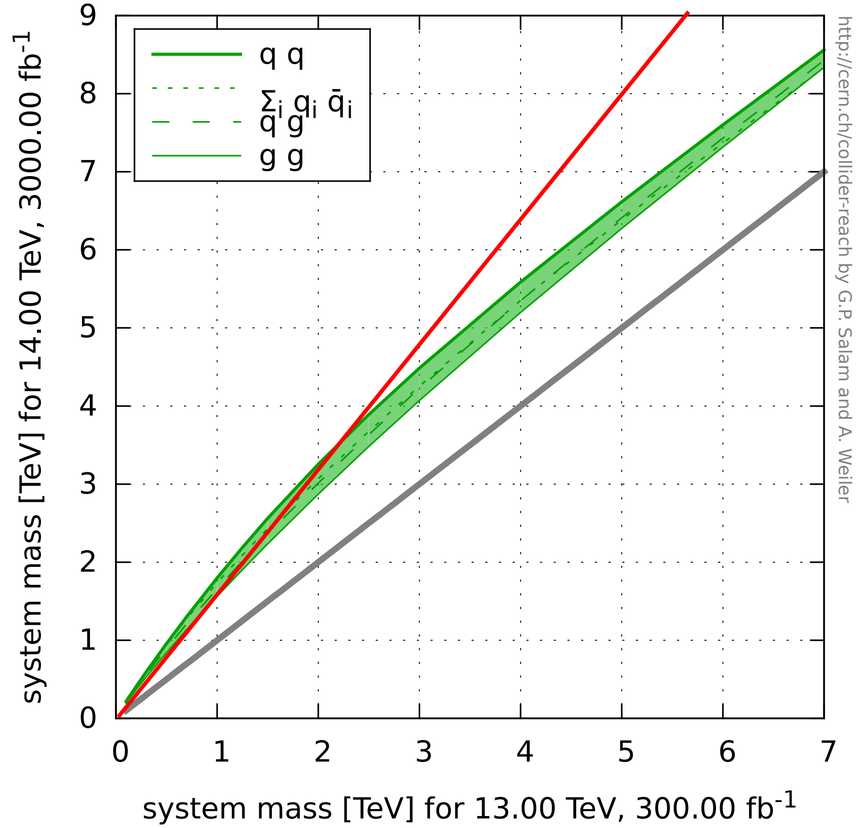
  Get: $\beta = (27.2 \pm 2.6)^\circ$ vs. CKM fit: $(21.9 \pm 0.7)^\circ$

  Isospin asymmetries are difficult [Jung, 1510.03423]

- Mild tension: fluctuation in $\Delta_K = -(4.3 \pm 2.4) \times 10^{-2}$? isospin violation? ...?

A rough comparison with high-p_T searches

- $\sqrt[4]{6} \sim 1.6$ vs. mass-scale increase from $13\,\mathrm{TeV}$ & $300/\,\mathrm{fb} \to 14\,\mathrm{TeV}$ & $3000\,\mathrm{fb}$



- Increase in mass scale >1.6, iff limit with 300/fb at 13TeV is below $\sim 1.5\,\mathrm{TeV}$

  Probably an unrealistic comparison, but a strong case for LHCb still prevails!

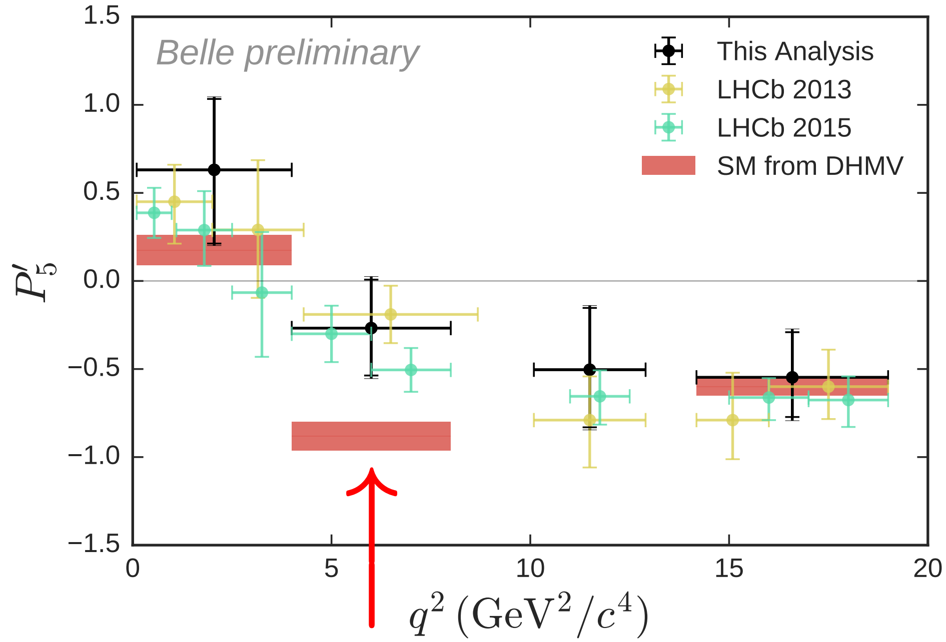
$B \to K^* \mu^+ \mu^-$: the P_5' anomaly

- "Optimized observables" [1202.4266 + long history]
  (some assumptions about what's optimal)

  Global fits: best solution: NP reduces C_9

  [Altmannshofer, Straub; Descotes-Genon, Matias, Virto; Jager, Martin Camalich; Bobet, Hiller, van Dyk; many more]

  Difficult for lattice QCD, large recoil



- Tests: other observables, q^2 dependence, B_s and Λ_b decays, other final states

- Connected to many other processes: Is the $c\bar{c}$ loop tractable perturbatively at small q^2? Can one calculate form factors (ratios) reliably at small q^2?
  Impacts many observables: semileptonic & nonleptonic, interpreting CP viol., etc.

Not understood: the $B \to K\pi$ puzzle

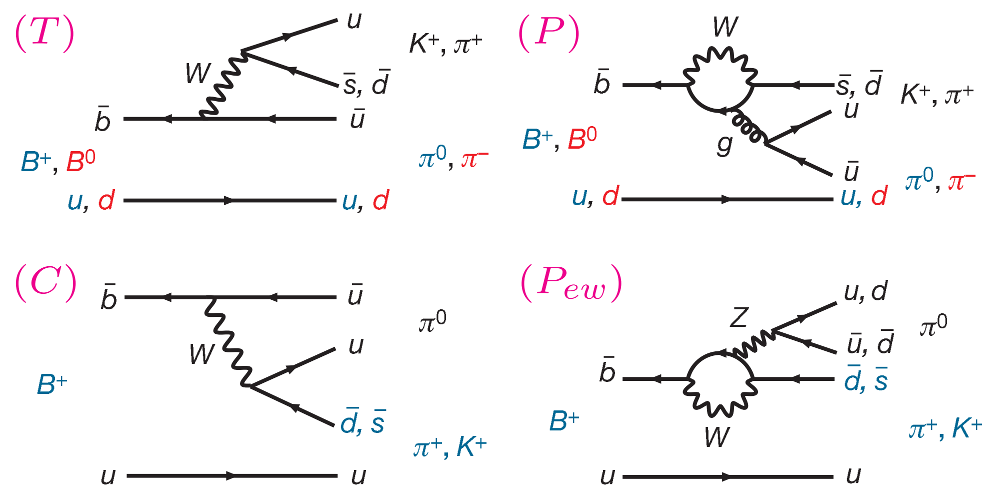
- Have we seen new physics in CPV?

$$A_{K^+\pi^-} = -0.082 \pm 0.006 \quad (P+T)$$

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

- Large difference — small SM sources?

$$A_{K^+\pi^0} - A_{K^+\pi^-} = 0.122 \pm 0.022$$



(Annihilation not shown)

[Belle, Nature 452, 332 (2008)]

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

- Large fluctuations? Breakdown of $1/m$ exp.? Missing something subtle? BSM?

No similar tension in branching ratio sum rules and $SU(3)$ relations

- Can we unambiguously understand theory, so that such data could disprove SM?

Hide flavor ⇔ high-p_T signals (Run 1 plots)

- Despite lore, squarks need not be as degenerate as often thought / assumed (triggered by studying charm CPV) [Gedalia, Kamenik, ZL, Perez]

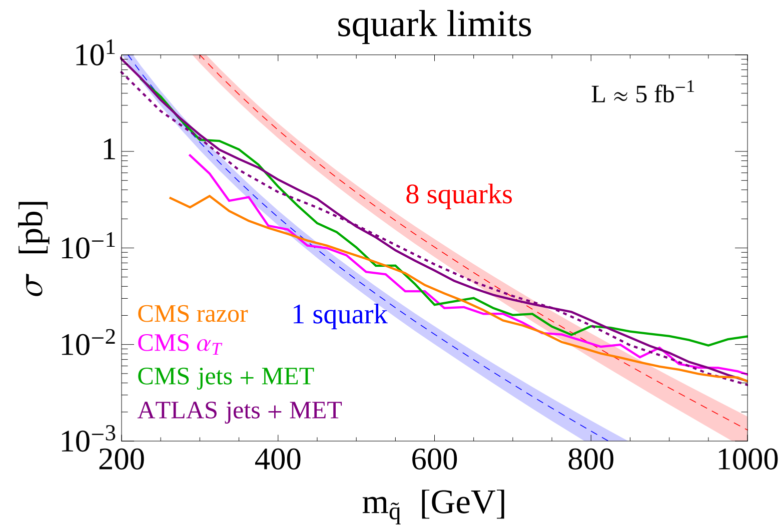
  Top plot: each LHC search becomes weaker

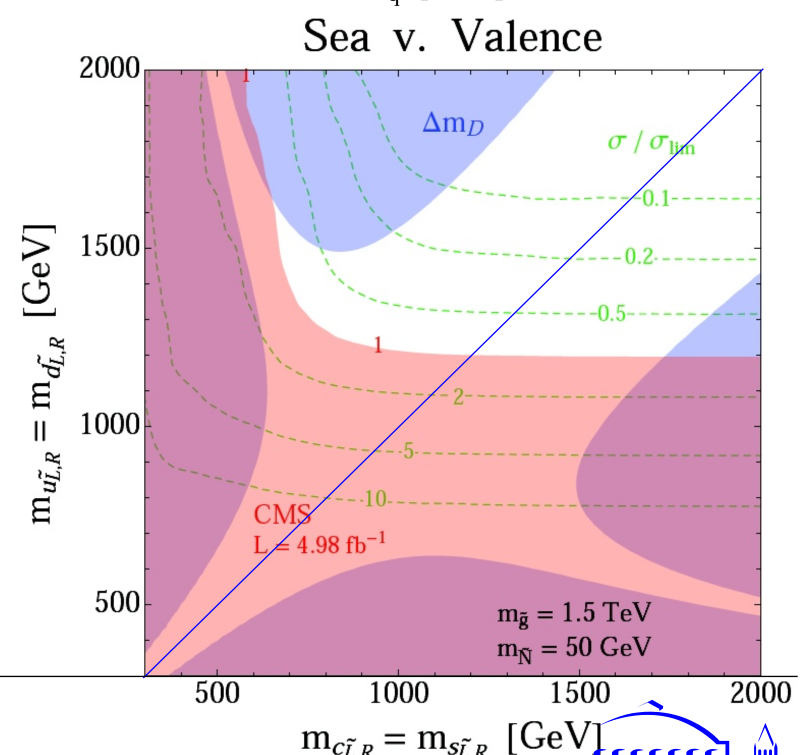
  [Mahbubani, Papucci, Perez, Ruderman, Weiler]

  Bottom plot: unshaded region still allowed if 4–4 squarks (but not all 8) are degenerate

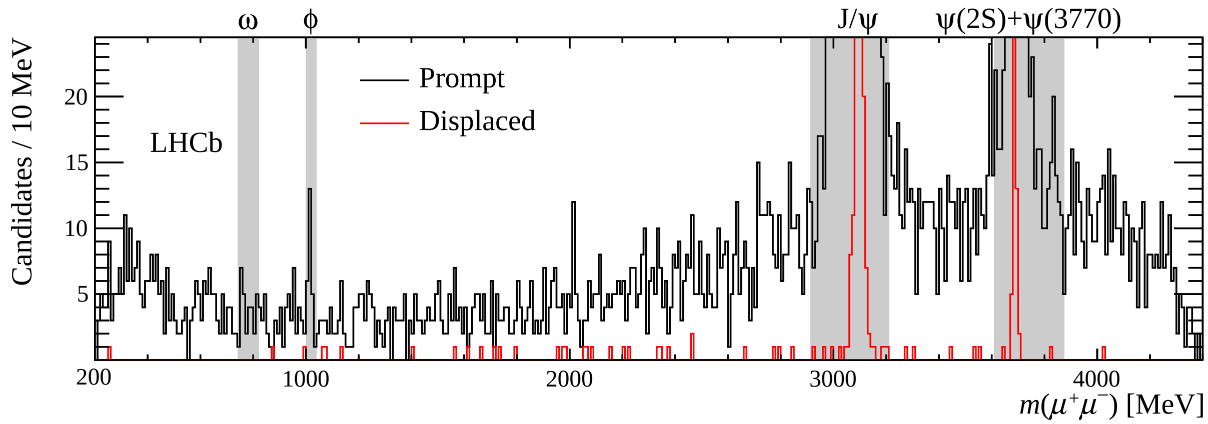
- If 4 pairs of u, d, s, c squarks not degenerate, lot weaker LHC bounds: $1.2\,\mathrm{TeV} \;\Rightarrow\; 600\,\mathrm{GeV}$

- Ways for naturalness to survive...



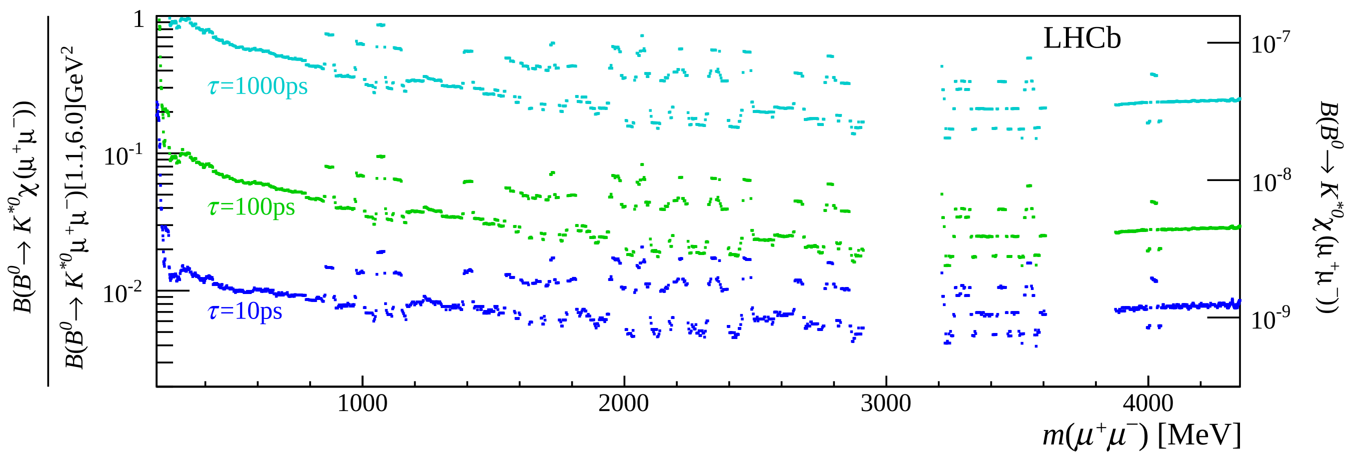


LHCb results on $B^0 \to K^{*0}\chi(\mu^+\mu^-)$



[LHCb, 1508.04094]

Distribution of $m(\mu^+\mu^-)$ in the (black) prompt and (red) displaced regions. The shaded bands denote regions where no search is performed due to (possible) resonance contributions.

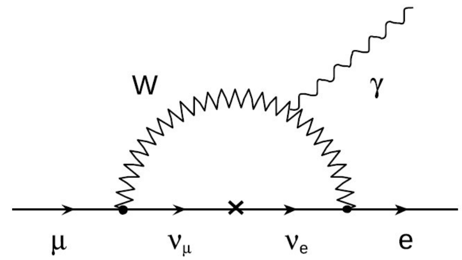


Upper limits at 95% CL. The sparseness of the data leads to rapid fluctuations in the limits.

Aside: Charged lepton flavor violation

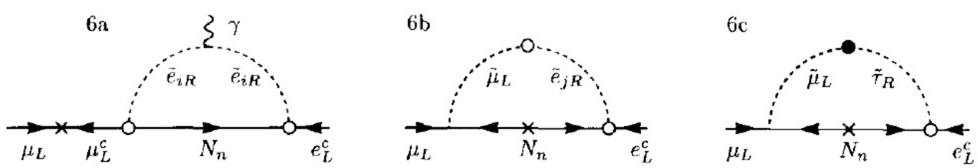
- SM predicted lepton flavor conservation with $m_\nu = 0$

  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



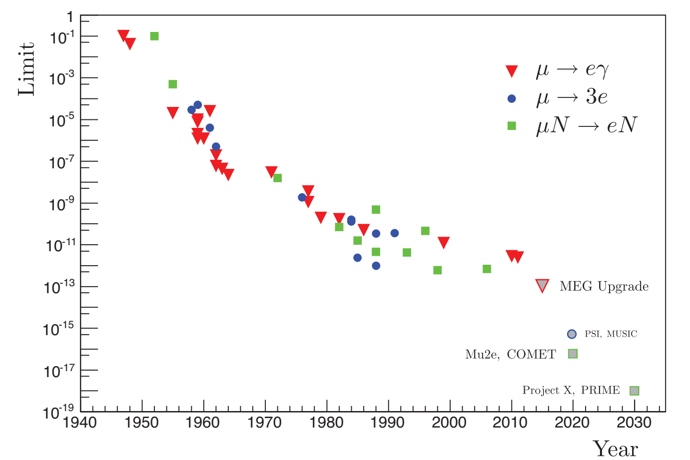
- Many interesting processes:

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

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

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

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



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

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