Quark, Lepton Flavor and CP
[the next decade(s) of flavor]

Zoltan Ligeti

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Overlap with several working groups

- Quark Flavor Physics

  Conveners: Joel Butler, Zoltan Ligeti, Jack Ritchie

  Final draft: `http://www.ph.utexas.edu/quarkflavor`

- Charged Lepton Processes

  Conveners: Brendan Casey, Yuval Grossman, David Hitlin

  `http://www.snowmass2013.org/tiki-index.php?page=Charged+Lepton`

- Nucleons, Nuclei and Atoms

  Conveners: Krishna Kumar, Zheng-Tian Lu, Michael Ramsey-Musolf

  `http://www.snowmass2013.org/tiki-index.php?page=Nucleons%2C+Nu`

- Flavor Mixing and CP Violation at High Energy

  Conveners: Marina Artuso, Michele Papucci, Soeren Prell

  `http://www.snowmass2013.org/tiki-index.php?page=Flavor+Mixing+`

Outline

- Introduction
- Flavor probes of new physics
- EDMs
- Charged lepton flavor
- Kaons
- B and charm physics
- Conclusions

What is particle physics?

- Central question of particle physics:

$$\mathcal{L} = ?$$

... What are the elementary degrees of freedom and how do they interact?

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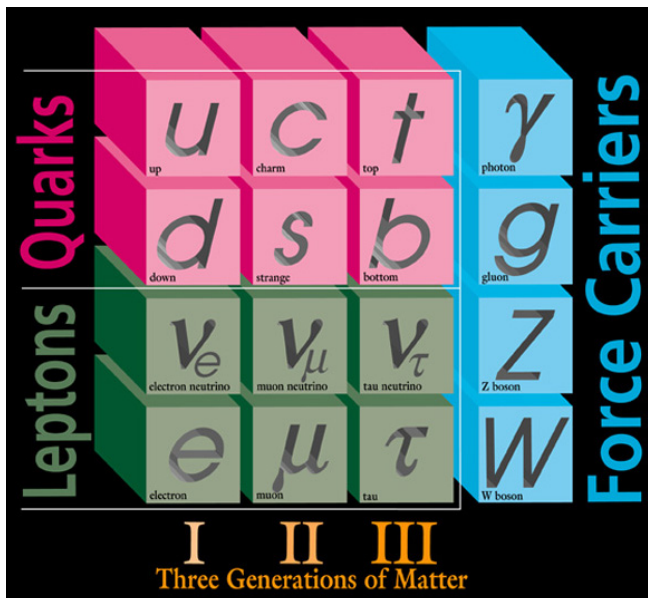
- Standard model (SM) consistent with most experimentally observed phenomena



What is particle physics?

- Central question of particle physics:

$$\mathcal{L} = ?$$

... What are the elementary degrees of freedom and how do they interact?

- Standard model (SM) consistent with most experimentally observed phenomena
- Clearest empirical evidence that SM is incomplete:
  - Dark matter
  - Baryon asymmetry of the Universe
  - Neutrino mass (is L conserved?)

May be at TeV scale

  - Hierarchy problem ($126\,\mathrm{GeV}$ scalar $=$ SM Higgs? why so light? why so heavy?)
  - Dark energy (cosmological constant? need to know more to understand?)

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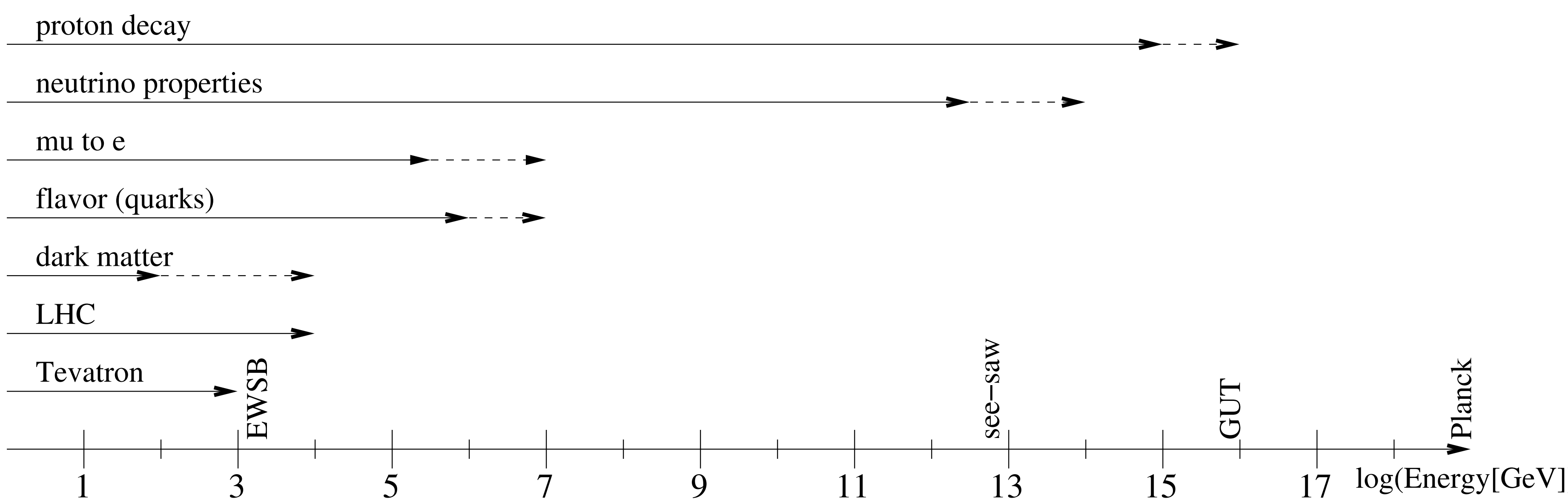
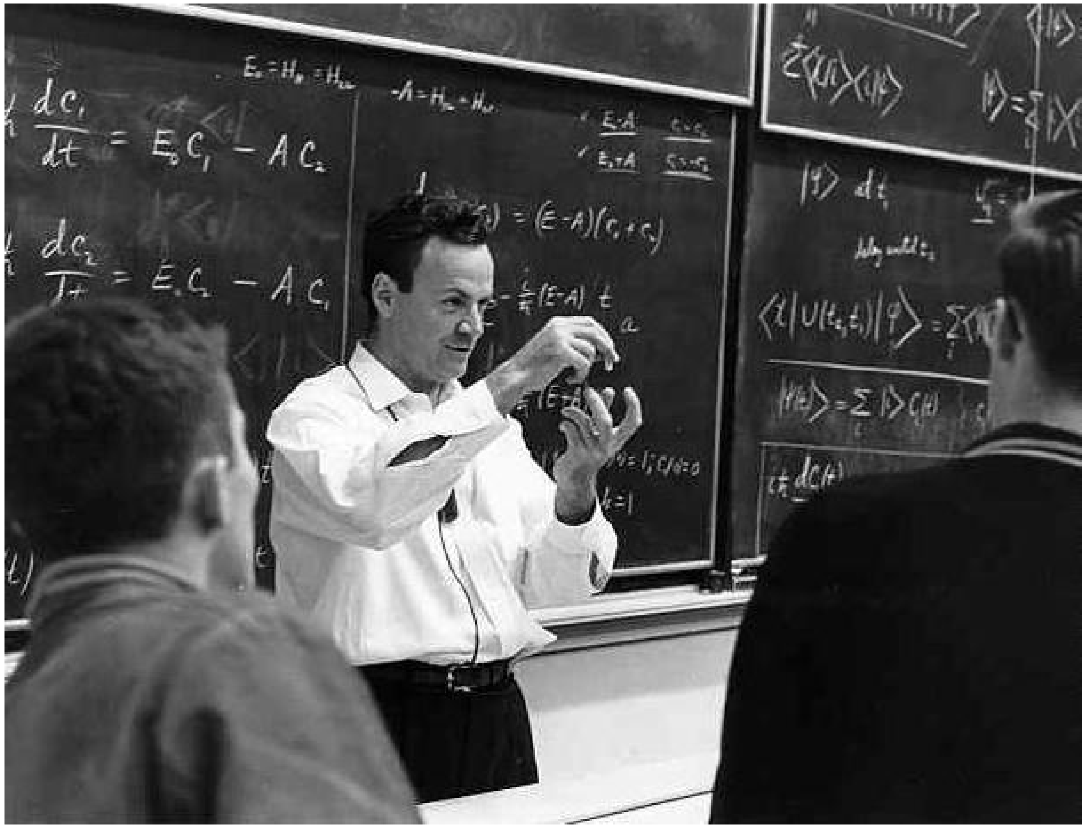
The big question: where is new physics?



Experimental reach (with significant simplifying assumptions)

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)



“It doesn’t matter how beautiful your theory is, it doesn’t matter how smart you are. If it doesn’t agree with experiment, it’s wrong.” [Feynman]

New physics and flavor

What is flavor physics?

- Theorist: flavor physics $\equiv$ what breaks $U(3)^5$ global symmetry
- Experimentalist: rich and sensitive ways to probe the SM and search for NP
- SM flavor problem: flavor put in by hand, Yukawa couplings to Higgs (condensate)
  why 3 generations? hierarchy of masses and mixing angles?
- NP flavor problem: TeV scale (hierarchy) $\ll$ "naive" flavor & CPV scale
  - Most TeV-scale NP contains new CP and flavor violation beyond Yukawas
  - The observed baryon asymmetry of the Universe requires CPV beyond the SM
    (Not necessarily in flavor changing processes, nor necessarily in quark sector)
- Flavor sector will be tested a lot better, many NP models have observable effects

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Recent LHC discoveries and bounds

- 2012–13: SM-like Higgs discovered, couplings consistent with SM

  SM-like $B_s \to \mu^+\mu^-$ rate

  We don't know if and what LHC14 will discover — if NP, great program $\to 2050+$

- Higgs mass: is $m_H \sim 126\,\text{GeV}$ compatible with SUSY and views of fine tuning?

  Some options to make it less tuned: Extended Higgs sector beyond 2HDM

  Large A-terms

- Tension of naturalness vs. no observation of other heavy particles yet; e.g.,

  "Natural SUSY": light $\tilde{t}, \tilde{b}$, while 1st & 2nd generation (a lot) heavier

  Flavor can help naturlaness: w/o degeneracy, squark bounds $1.2\,\text{TeV} \;\Rightarrow\; 0.5\,\text{TeV}$

- Typically, expect to yield richer flavor structure, more synergy w/ high-p_T searches

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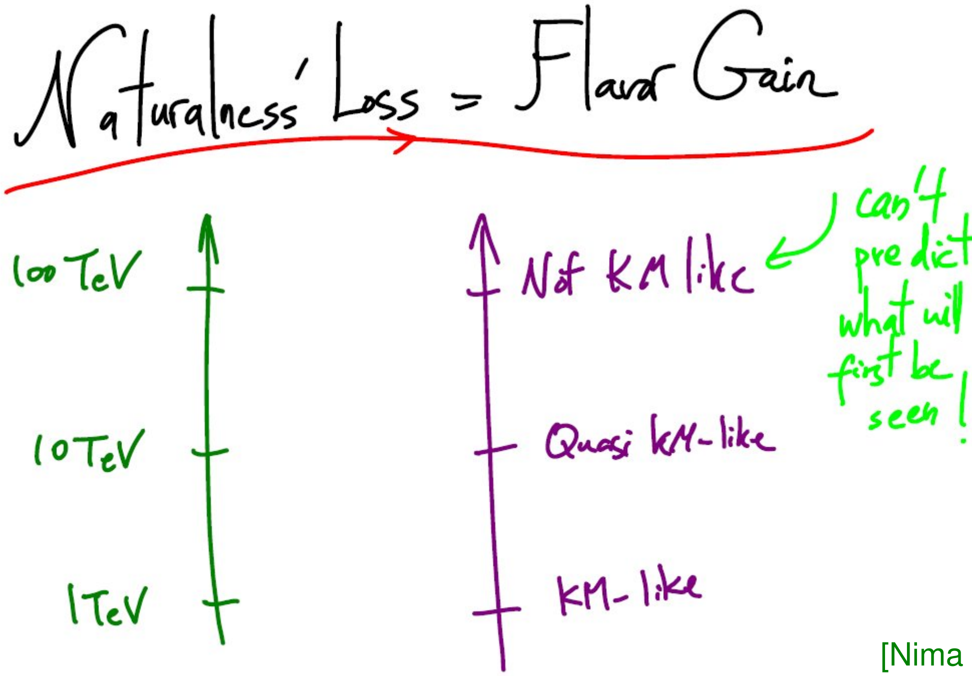
The new physics scale and flavor

- As NP scale is pushed up, flavor structure needs to be less and less SM-like



[Nima @ Rockville]

- Flavor measurements can discover NP signals due to TeV-scale NP with SM-like flavor structure, or $100–1000\ \mathrm{TeV}$ NP with generic flavor

- We do not know where NP will show up — cast a wide net

Spectacular track record

- Probes high scales — flavor was crucial to figure out $\mathcal{L}_{\rm SM}$:
  - β-decay predicted neutrino (Pauli)
  - Absence of $K_L \to \mu\mu$ predicted charm (Glashow, Iliopoulos, Maiani)
  - ϵ_K predicted 3rd generation (Kobayashi & Maskawa)
  - Δm_K predicted m_c (Gaillard & Lee; Vainshtein & Khriplovich)
  - Δm_B predicted large m_t
- Most parameters of the SM (and many of its extensions) are related to flavor

  Likely to be important to figure out $\mathcal{L}_{\rm BSM}$ as well
- If there is NP at the TEV scale, it must have a very special flavor & CP structure

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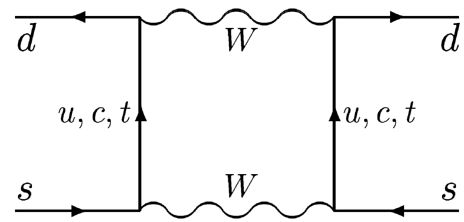
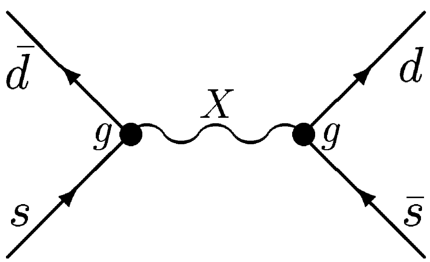
Δm_K — built into all NP models

- In the SM: $\Delta m_K \sim \alpha_w^2 \, |V_{cs}V_{cd}|^2 \, \frac{m_c^2}{m_W^4} \, f_K^2 \, m_K$
  (severe suppressions!)



- If exchange of a heavy gauge boson was responsible for a large fraction of Δm_K



$$\left|\frac{M_{12}^{(X)}}{\Delta m_K}\right| \sim \left|\frac{g^2\,\Lambda_{\rm QCD}^3}{M_X^2\,\Delta m_K}\right| \;\Rightarrow\; M_X \gtrsim g \times 2 \cdot 10^3\,\text{TeV}$$

- Multi-TeV particles w/ loop-suppressed coupling can still be visible $[g \sim \mathcal{O}(10^{-3})]$

- In many NP scenarios the constraints from kaons are the strongest

  ... since so are the SM suppressions — these are built into models since the 70's

SUSY in $K^0 - \overline{K}^0$ mixing (oversimplified)

- $$\frac{(\Delta m_K)^{\rm SUSY}}{(\Delta m_K)^{\rm exp}} \sim 10^4 \left(\frac{1\,{\rm TeV}}{\tilde m}\right)^2 \left(\frac{\Delta \tilde m^2_{12}}{\tilde m^2}\right)^2 {\rm Re}\big[(K_L^d)_{12}(K_R^d)_{12}\big]$$

  $K^d_{L(R)}$: 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 $\sim 10^6\,{\rm Im}\big[(K_L^d)_{12}(K_R^d)_{12}\big]$

- 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

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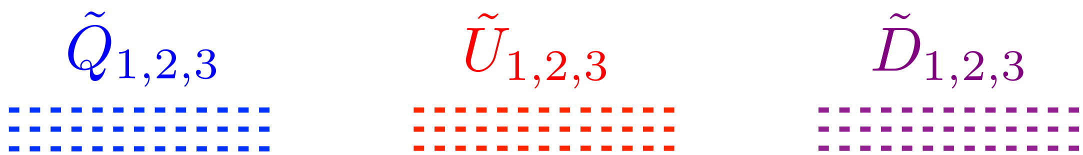
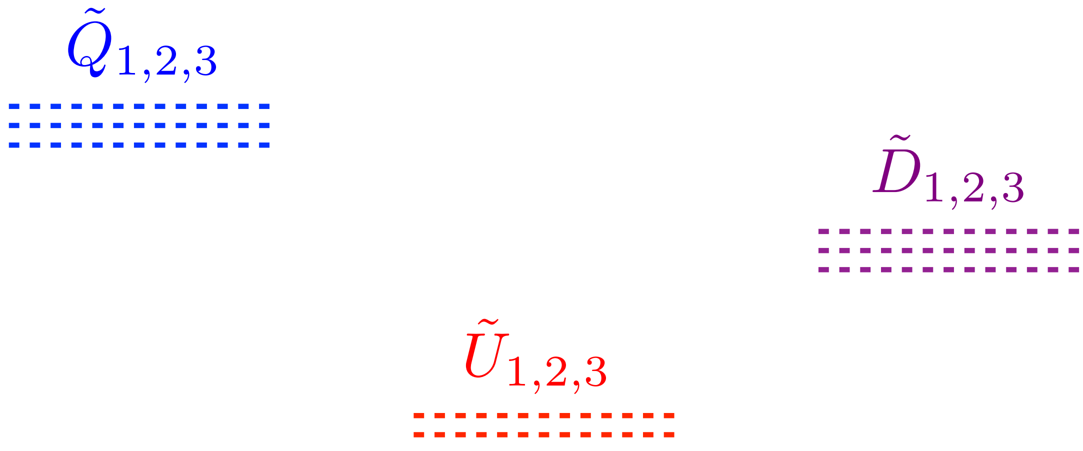
Squark spectra, LHC, flavor

- Exploring more general spectra is motivated by both LHC and flavor bounds
- All degenerate:



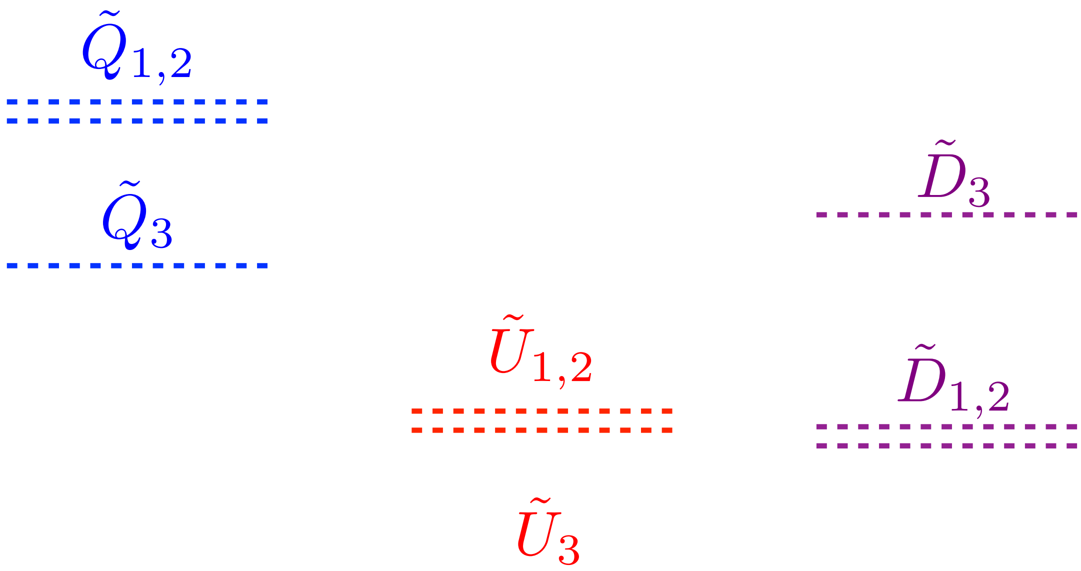
Squark spectra, LHC, flavor

- Exploring more general spectra is motivated by both LHC and flavor bounds
- Gauge split



Squark spectra, LHC, flavor

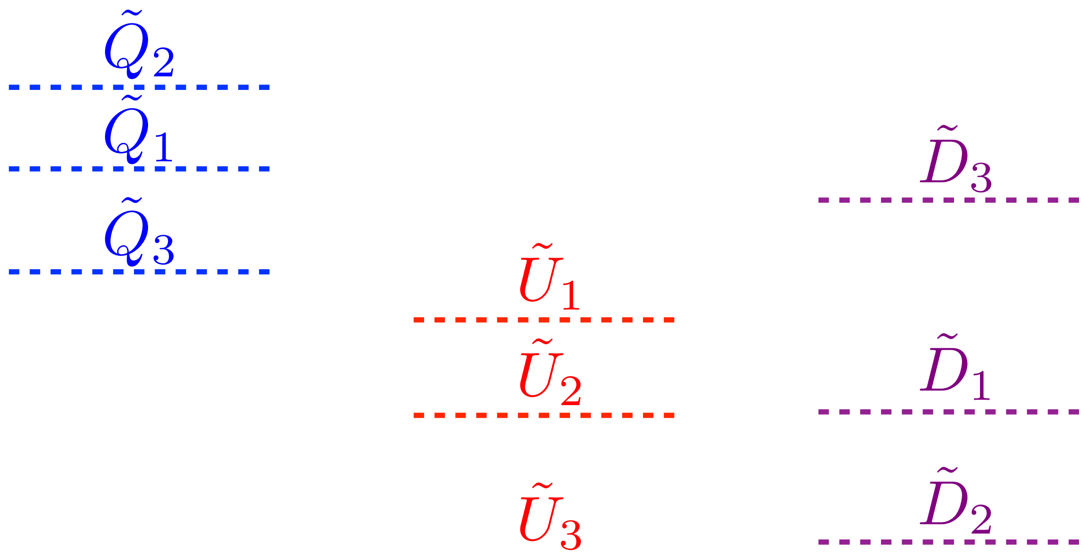
- Exploring more general spectra is motivated by both LHC and flavor bounds
- Minimal flavor violating



$$m^2_{\tilde{U}} = (1 + Y_u^\dagger Y_u + \ldots)$$

Squark spectra, LHC, flavor

- Exploring more general spectra is motivated by both LHC and flavor bounds
- Quark-squark alignment:

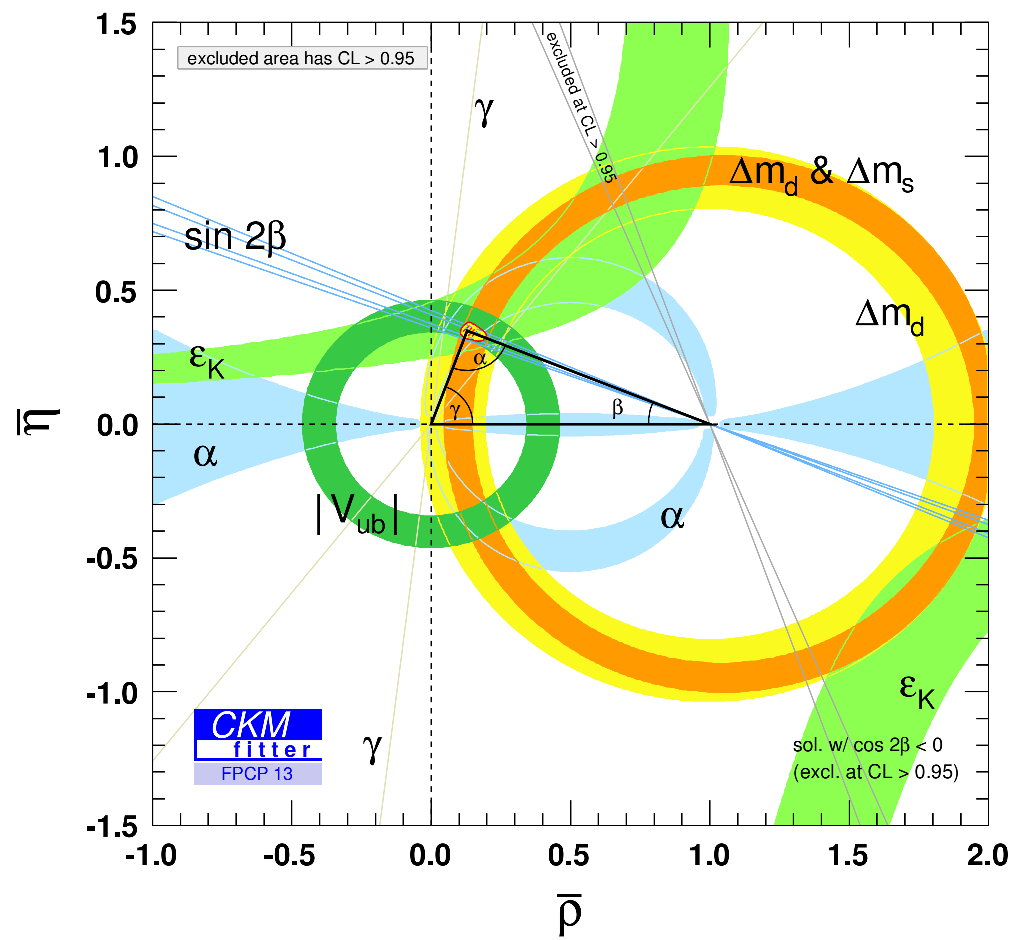


May come from horizontal symmetries

- We do not know which is right — need broad set of searches (both LHC & flavor)

Status of the CKM fit

- The level of agreement between the measurements is often misinterpreted
- Allowed region is much larger if NP is included in the fit, more parameters, which changes the fit completely
- $\mathcal{O}(20\%)$ NP contributions to most loop processes (FCNS) are still allowed



- Need experimental precision and theoretical cleanliness to increase NP sensitivity

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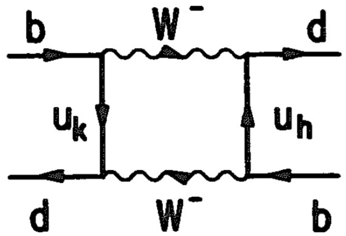
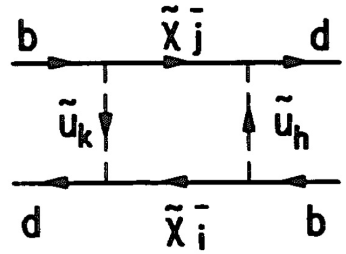
What are we after?

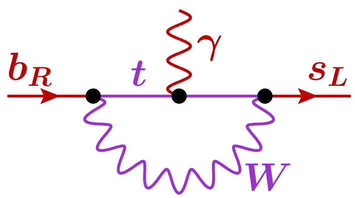
- Meson mixing:

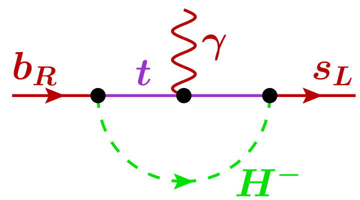




Simple parametrization:
$M_{12} = M_{12}^{\rm SM}\,(1+h\,e^{2i\sigma})$

- FCNC decays:





Many operators

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

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

Flavor probes $10^2 - 10^5$ TeV scale

- Neutral meson mixings: dimension-6 operators, come with coefficients C/Λ^2

Operator	Bounds on Λ [TeV] ($C=1$)		Bounds on C ($\Lambda = 1$ TeV)		Observables
	Re	Im	Re	Im	
$(\bar{s}_L \gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	$\Delta m_K; \epsilon_K$
$(\bar{s}_R\, d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	$\Delta m_K; \epsilon_K$
$(\bar{c}_L \gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	$\Delta m_D; \lvert q/p \rvert, \phi_D$
$(\bar{c}_R\, u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	$\Delta m_D; \lvert q/p \rvert, \phi_D$
$(\bar{b}_L \gamma^\mu d_L)^2$	6.6×10^2	9.3×10^2	2.3×10^{-6}	1.1×10^{-6}	$\Delta m_{B_d}; S_{\psi K_S}$
$(\bar{b}_R\, d_L)(\bar{b}_L d_R)$	2.5×10^3	3.6×10^3	3.9×10^{-7}	1.9×10^{-7}	$\Delta m_{B_d}; S_{\psi K_S}$
$(\bar{b}_L \gamma^\mu s_L)^2$	1.4×10^2	2.5×10^2	5.0×10^{-5}	1.7×10^{-5}	$\Delta m_{B_s}; S_{\psi\phi}$
$(\bar{b}_R\, s_L)(\bar{b}_L s_R)$	4.8×10^2	8.3×10^2	8.8×10^{-6}	2.9×10^{-6}	$\Delta m_{B_s}; S_{\psi\phi}$

If $\Lambda = \mathcal{O}(1\,\mathrm{TeV})$ then $C \ll 1$; alternatively, if $C = \mathcal{O}(1)$ then $\Lambda \gg 1\,\mathrm{TeV}$

- If NP is $10-100\,\mathrm{TeV}$ (split, spread, etc.), flavor physics discoveries could point to the next energy scale to explore

Aren't the kaon constraints "enough"?

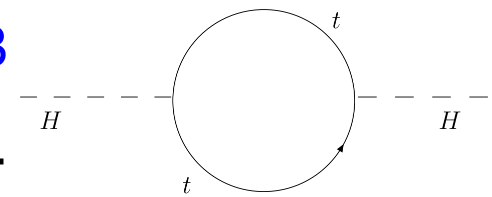
- Hopefully the LHC will discover new particles

  Some subleading couplings probably not measurable (V_{td}, V_{ts} from B not t decay)

  Important to figure out underlying structure (soft SUSY breaking terms)

- In many models: large $m_t \Rightarrow$ non-universal coupling to EWSB

  Motivated scenarios: NP $\Leftrightarrow$ 3rd gen. $\neq$ NP $\Leftrightarrow$ 1st & 2nd gen.



- Is the physics of 3rd–1st, 3rd–2nd, and 2nd–1st generation transitions the same?

- If no NP is seen in flavor sector: similar constraints as LEP tests of gauge sector

- If non-SM flavor physics is seen: get detailed information
  - One / many sources of CPV?
  - In charged / neutral currents?
  - Modify SM operators / new operators?
  - Couples to up / down sector?
  - Quarks / leptons / other sectors?
  - To 3rd / all generations?

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The scaling of scales

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

  e.g., $\mu \to e\gamma$

- NP amplitude: $\Lambda \sim (\text{uncertainty})^{-1/2}$

  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

What I will (not) talk about

- Compelling flavor physics experimental program (even w/o theory progress)

  1) Processes not yet observed, suppressed, or forbidden in the SM

  2) Measurements sensitive to highest scales, and how much they can improve

  3) Measurements when "room" can shrink the most between experiment and SM

- Only talk about: (i) sensitive to different NP

  (ii) measurements can improve by a factor ~ 10 or more

  (iii) theoretically clean

[Skip many important processes, many interesting theory challenges, will get them "automatically" with the program]

Electric dipole moments

Electric dipole moments

- SM $+ m_\nu$: CPV can occur in quark mixing (1), lepton mixing $(1+2?)$, and $\theta_{\rm QCD}$
  - We have only observed $\delta_{\rm KM} \neq 0$, baryogenesis implies there must be more
  - Many NP models predict EDMs that may be observable
- Experimental bounds:

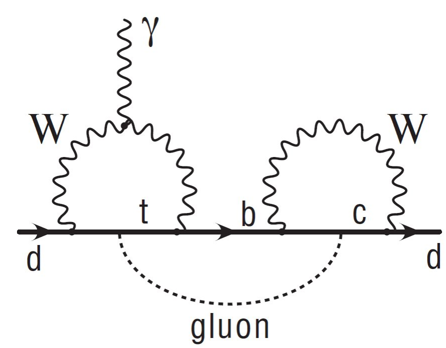
  Hope for $\sim 10^3$ progress

Sector	Exp Limit (e-cm)	Method	Standard Model
Electron	1 x 10^{-27}	YbF in a beam	10^{-38}
Neutron	3 x 10^{-26}	UCN in a bottle	10^{-31}
^{199}Hg	3 x 10^{-29}	Hg atoms in a cell	10^{-33}

- Neutron EDM from $\theta_{\rm QCD}$: data imply $\theta_{\rm QCD} < 10^{-10}$ — axion?

  $\theta_{\rm QCD}$ is negligible for CPV in flavor-changing processes
- EDMs from CKM: vanish at one- and two-loop

  large suppression of this contribution

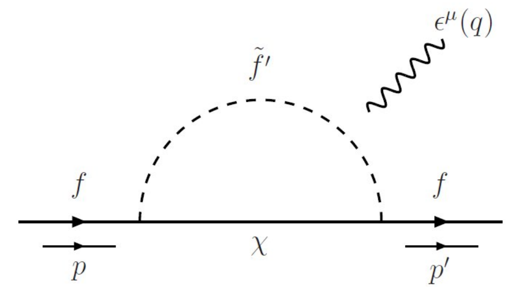


EDMs and SUSY

- In MSSM, both quark and lepton EDMs can be generated at one-loop

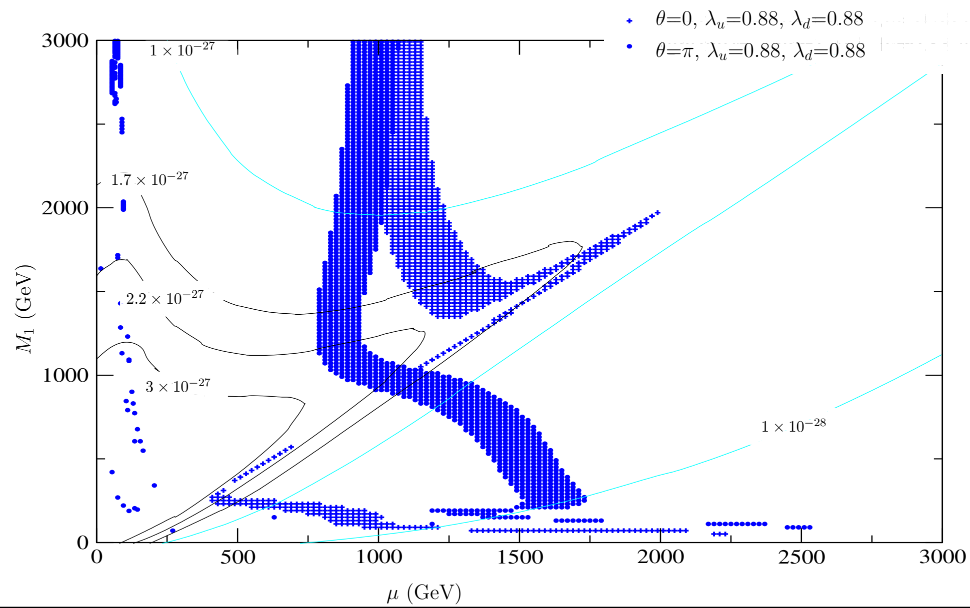
  (44 CPV phases: CKM $+$ 3 flavor diagonal $+$ 40 in mixing of fermion-sfermion-gaugino couplings)

  Generic prediction (TeV-scale, no small parameters) above current bounds



- If SUSY is at 10–$100\ \mathrm{TeV}$, less constraints from FCNC bounds, can still discover EDMs

  E.g., electron EDM constraints on DM models in split SUSY [hep-ph/0510064]



Charged lepton flavor

Lepton flavor violation

- In its simplest version with $m_\nu = 0$, SM predicted lepton flavor conservation

  This is not the case $\Rightarrow$ no reason to impose it as a symmetry on new physics

- If there are new TeV-scale particles that carry lepton number (sleptons), then they have their own mixing matrices $\Rightarrow$ charged lepton flavor violation (CLFV)

- Charged lepton flavor violation exists in general

  SM background incredibly small (penguins w/ neutrinos): $\mathcal{B}(\mu \to e\gamma) \propto \alpha\,(m_\nu/m_W)^4 \sim 10^{-52}$

- Many interesting processes:

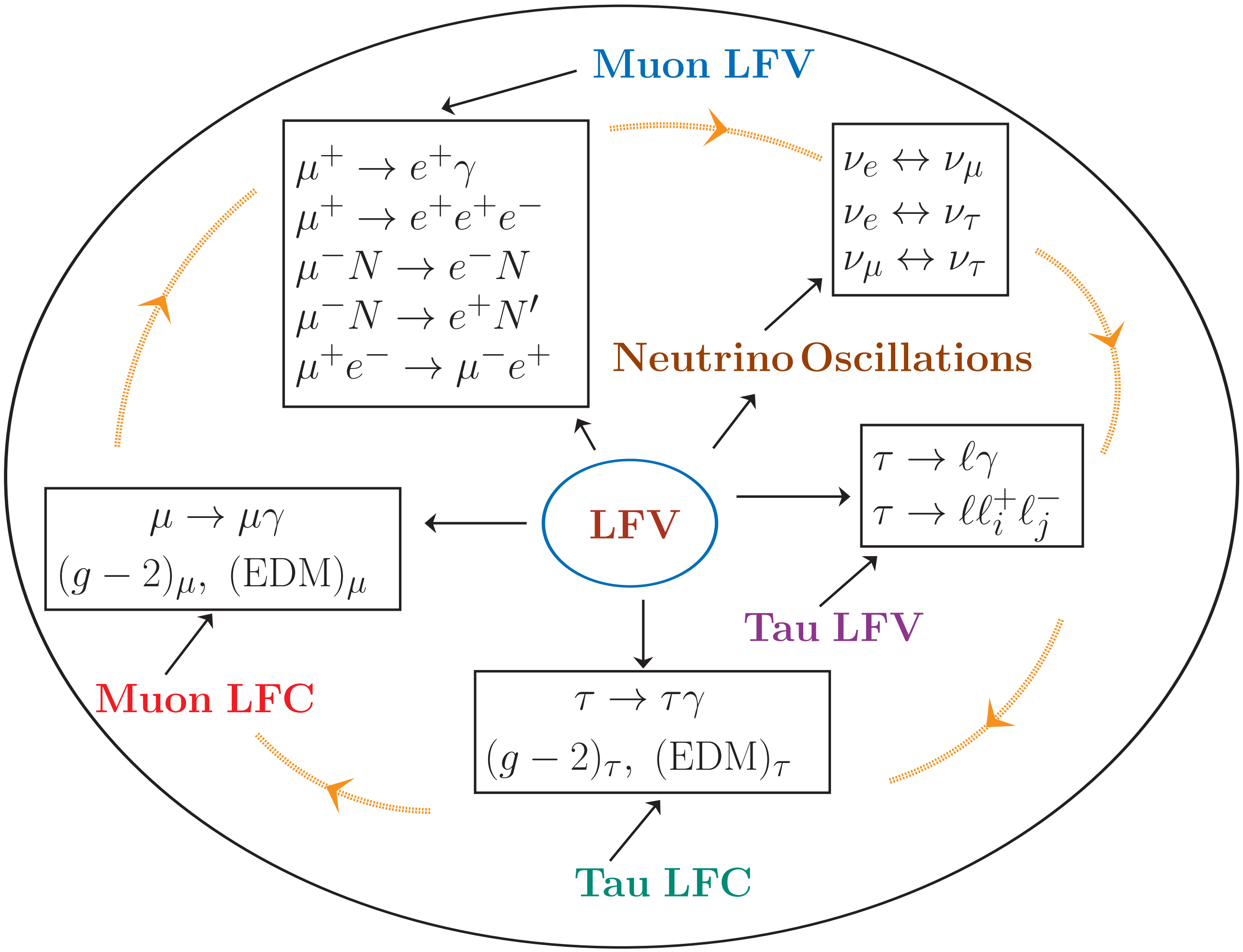
  $\mu \to e\gamma,\ \ \mu \to eee,\ \ \mu + N \to e + N,\ \ \mu + N \to e + N',\ \ \mu^+e^- \to \mu^-e^+$

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

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

- In next 10–20 years, sensitivities can improve by 2–5 orders of magnitude

Rich field, many experiments and processes



- Observation of a BSM signal would trigger explosion of many new experiments

Charged lepton flavor violation

- $\mu \to e\gamma$ vs. $\mu \to eee$?

- Which gives the better sensitivity? — depends on NP model, consider operators:

$$\frac{C_1}{\Lambda_1^2}\, m_\mu\, \bar{\mu}_R \sigma_{\alpha\beta} F^{\alpha\beta} e_L + \frac{C_2}{\Lambda_2^2}\, (\bar{\mu}_L \gamma^\alpha e_L)(\bar{e}_L \gamma_\alpha e_L)$$

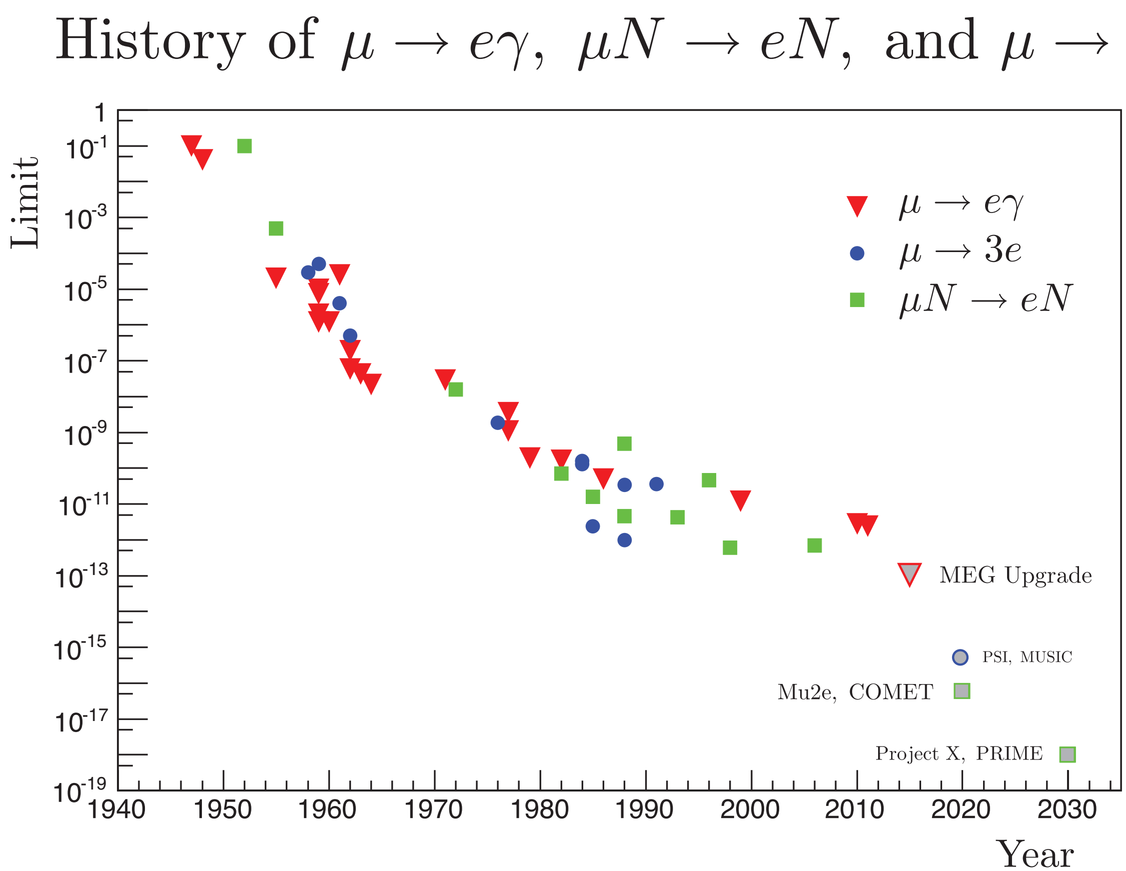
First term mediates $\mu \to e\gamma$, and at order α generates $\mu \to eee$

Second term mediates $\mu \to eee$, and at order α generates $\mu \to e\gamma$

- Flavor: $\mu \to e\gamma$ and $(g-2)_\mu$ operators very similar: $\dfrac{m_\mu}{\Lambda^2}\, \bar{\mu}\sigma_{\alpha\beta}F^{\alpha\beta} e\,, \quad \dfrac{m_\mu}{\Lambda^2}\, \bar{\mu}\sigma_{\alpha\beta}F^{\alpha\beta}\mu$

If NP is seen, pattern tells us about underlying structure

CLFV history



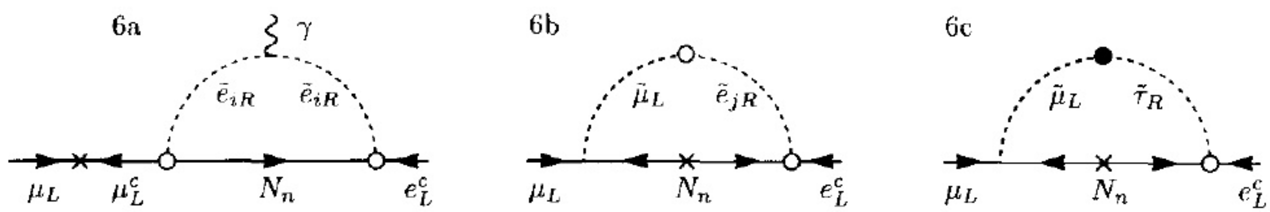
[arXiv:1307.5787]

- Mu2e: improve bound $R_{\mu e} = \dfrac{\Gamma[\mu^- N(A,Z) \to e^- N(A,Z)]}{\Gamma[\mu^- N(A,Z) \to \nu N(A,Z-1)]} < 7 \times 10^{-13}$ by 10^4
- An order of magnitude increase in the NP scale probed

CLFV in τ decays

- $\mu \to e\gamma, eee$ vs. $\tau \to \mu\gamma, \mu\mu\mu$

  Either can win, very large model dependence: $\mathcal{B}(\tau \to \mu\gamma)/\mathcal{B}(\mu \to e\gamma) \sim 10^{4\pm 3}$



- Belle II and LHCb will improve current bounds by an order of magnitude

sensitivity with $75\,\mathrm{ab}^{-1}$ e^+e^- data

Process	Sensitivity
$\mathcal{B}(\tau \to \mu\,\gamma)$	2×10^{-9}
$\mathcal{B}(\tau \to e\,\gamma)$	2×10^{-9}
$\mathcal{B}(\tau \to \mu\,\mu\,\mu)$	2×10^{-10}
$\mathcal{B}(\tau \to eee)$	2×10^{-10}

- If a positive signal is seen $\Rightarrow$ trigger broad program to map out other operators

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Kaon physics

Precision CKM tests with kaons

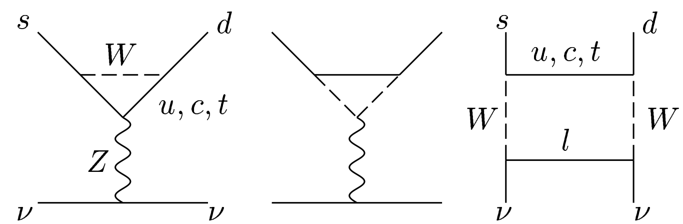
- CPV in K system is at the right level (ϵ_K accommodated with $\mathcal{O}(1)$ KM phase)
- Hadronic uncertainties precluded precision tests (ϵ'_K notoriously hard to calculate)

  (N.B.: bad luck in part — heavy m_t enhanced hadronic uncertainties, but helps for B physics)

  Lattice QCD improvements: ϵ_K has become more sensitive, hopes for ϵ'/ϵ

- $K \to \pi\nu\bar{\nu}$: Theory error $\sim$ few %, but very small rates $10^{-10}\,(K^\pm)$, $10^{-11}\,(K_L)$

$$\mathcal{A} \propto \begin{cases} (\lambda^5\, m_t^2) + i(\lambda^5\, m_t^2) & t: \text{CKM suppressed} \\ (\lambda\, m_c^2) + i(\lambda^5\, m_c^2) & c: \text{GIM suppressed} \\ (\lambda\, \Lambda_{\rm QCD}^2) & u: \text{GIM suppressed} \end{cases}$$



  So far $\mathcal{O}(1)$ uncertainty in $K^+ \to \pi^+\nu\bar{\nu}$, and $\mathcal{O}(10^3)$ in $K_L \to \pi^0\nu\bar{\nu}$

- Much higher statistics needed to achieve ultimate sensitivity

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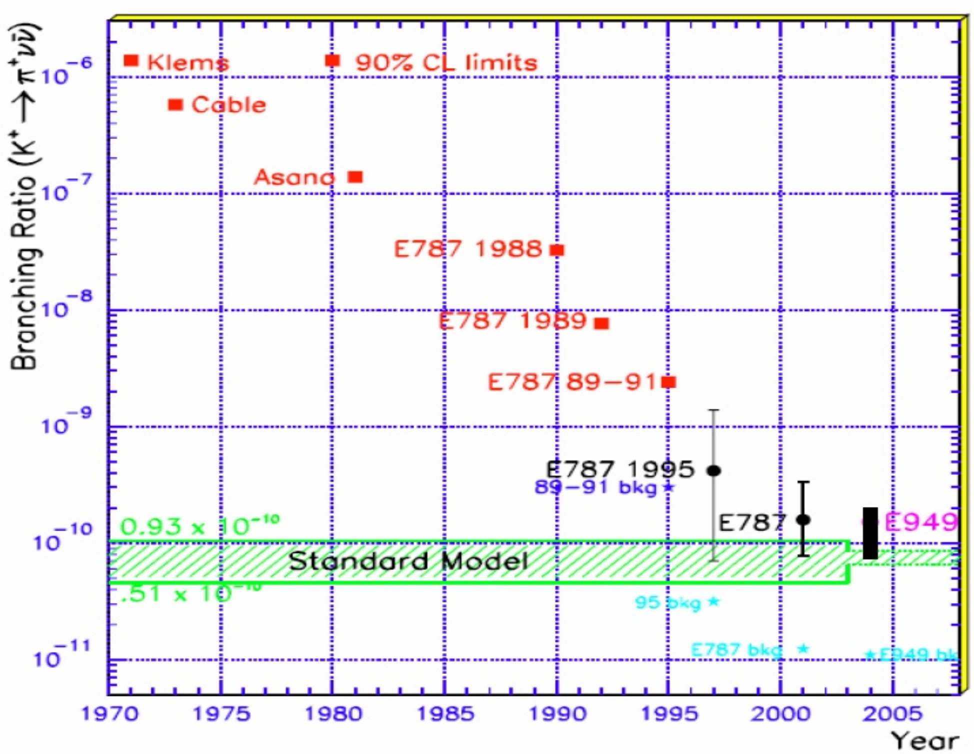
The holy grail: $K \to \pi\nu\bar{\nu}$

- Long history of ingenious experimental progress

E787/E949, 7 events: $\mathcal{B}(K \to \pi^+\nu\bar{\nu}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$

SM: $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (0.78 \pm 0.08) \times 10^{-10}$, $\mathcal{B}(K_L^0 \to \pi^0\nu\bar{\nu}) = (0.24 \pm 0.04) \times 10^{-10}$



CERN NA62: expect to get ~ 100 $K^+ \to \pi^+\nu\bar{\nu}$ events

FNAL ORKA proposal: ~ 1000 $K^+ \to \pi^+\nu\bar{\nu}$ events [Stage-1 approval]

J-PARC KOTO: observe $K_L^0 \to \pi^0\nu\bar{\nu}$ at SM level

FNAL w/ project-X: proposal for ~ 1000 event $K_L^0 \to \pi^0\nu\bar{\nu}$

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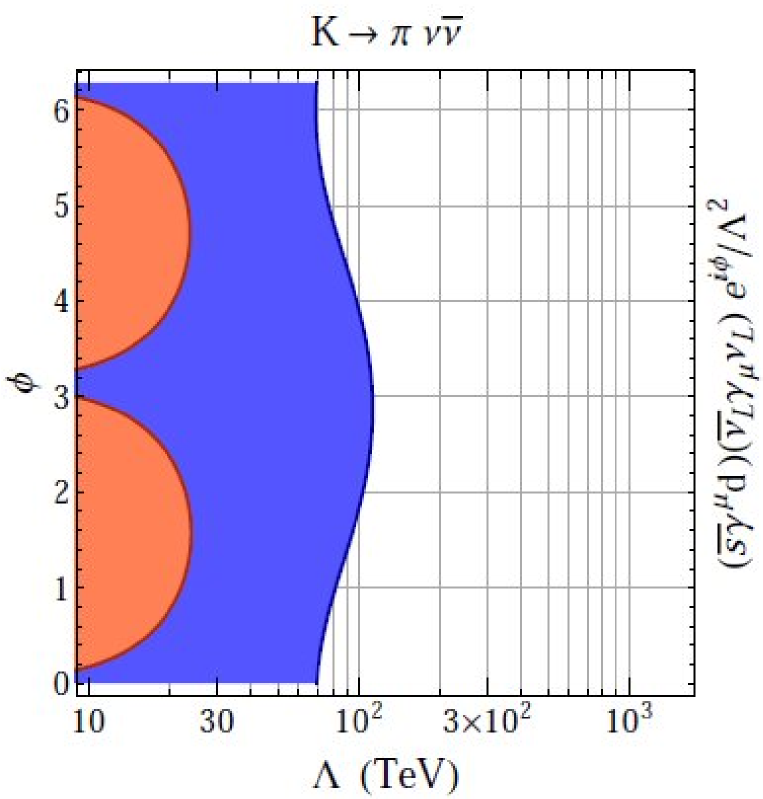
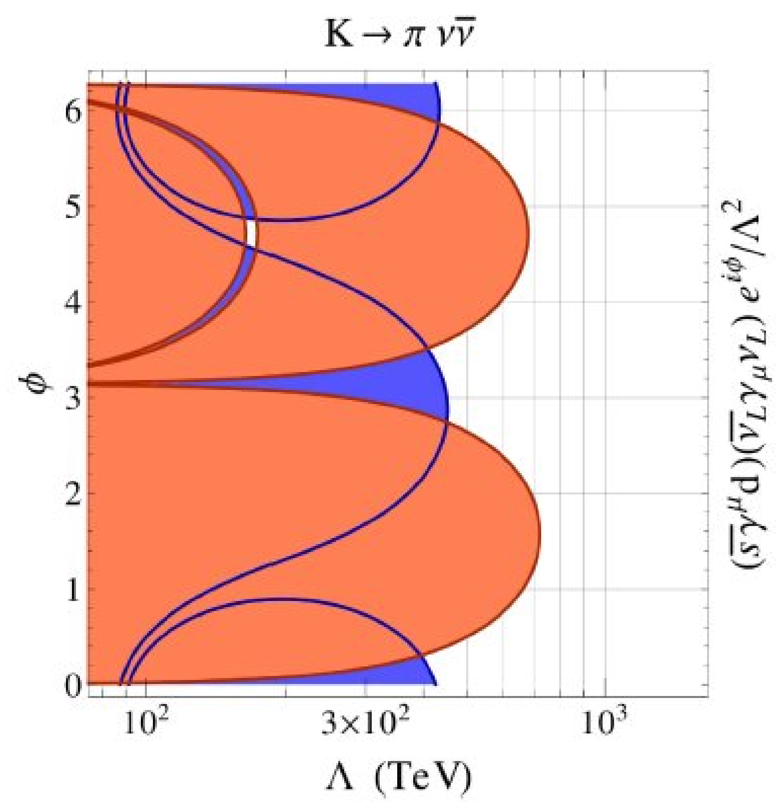
Scales probed by $K \to \pi\nu\bar{\nu}$

- $K^+ \to \pi^+\nu\bar{\nu}$ already constrains $\sim 100\,\text{TeV}$ scale [Altmannshofer @ ANL IF workshop]

current situation



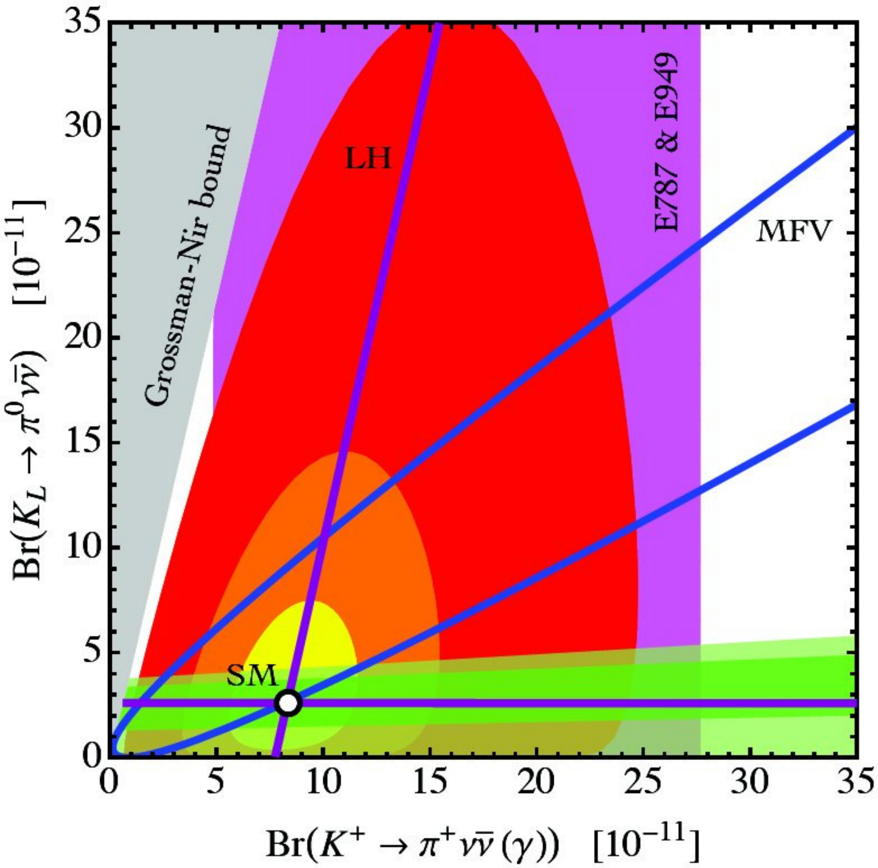
assuming 5% measurements of both modes

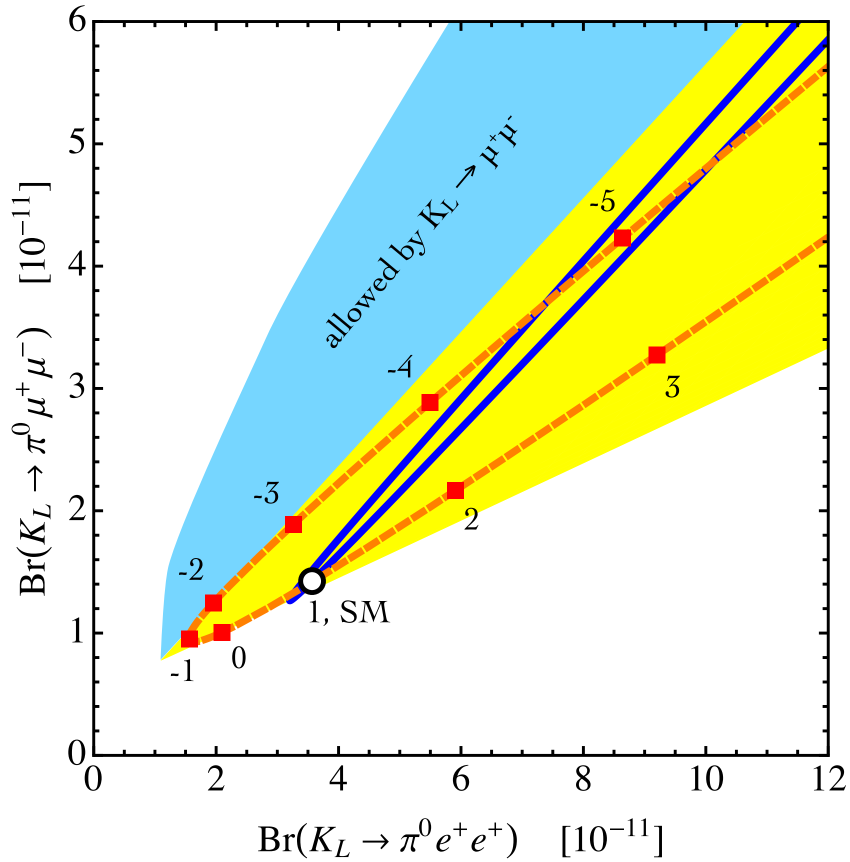


- Factor 10–20 in precision $\to$ factor 3–4 in NP scale

Predictions near current bounds

- Large variety of models in which deviations from SM will be detectable





Many interesting measurements

Observable	SM Theory	Current Status	Future Experiments
$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$	$7.81(75)(29) \times 10^{-11}$	$1.73^{+1.15}_{-1.05} \times 10^{-10}$ E787/E949	$\sim$10% at NA62 $\sim$5% at ORKA $\sim$2% at Project-X
$\mathcal{B}(K_L^0 \to \pi^0\nu\bar{\nu})$	$2.43(39)(6) \times 10^{-11}$	$< 2.6 \times 10^{-8}$ E391a	1^{st} observation at KOTO $\sim$5% at Project-X
$\mathcal{B}(K_L^0 \to \pi^0 e^+ e^-)$	$(3.23^{+0.91}_{-0.79}) \times 10^{-11}$	$< 2.8 \times 10^{-10}$ KTeV	$\sim$10% at Project-X
$\mathcal{B}(K_L^0 \to \pi^0 \mu^+ \mu^-)$	$(1.29^{+0.24}_{-0.23}) \times 10^{-11}$	$< 3.8 \times 10^{-10}$ KTeV	$\sim$10% at Project-X
$\lvert P_T \rvert$ in $K^+ \to \pi^0 \mu^+ \nu$	$\sim 10^{-7}$	< 0.0050	< 0.0003 at TREK < 0.0001 at Project-X
$\Gamma(K_{e2})/\Gamma(K_{\mu 2})$	$2.477(1) \times 10^{-5}$	$2.488(12) \times 10^{-5}$ (NA62, KLOE)	$\pm 0.0054 \times 10^{-5}$ at TREK $\pm 0.0025 \times 10^{-5}$ at Project-X
$\mathcal{B}(K_L^0 \to \mu^\pm e^\mp)$	$< 10^{-25}$	$< 4.7 \times 10^{-12}$	$< 2 \times 10^{-13}$ at Project-X

- Many interesting measurements, not just the $K \to \pi\nu\bar{\nu}$ rates
- ORKA is a unique opportunity for US to have world-leading kaon program

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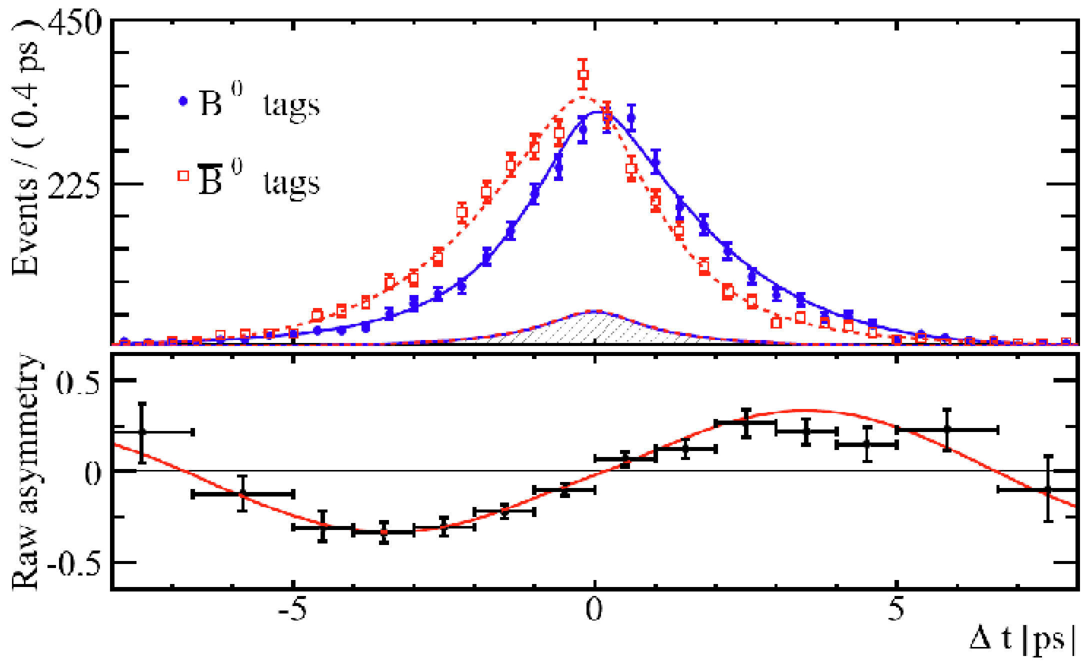
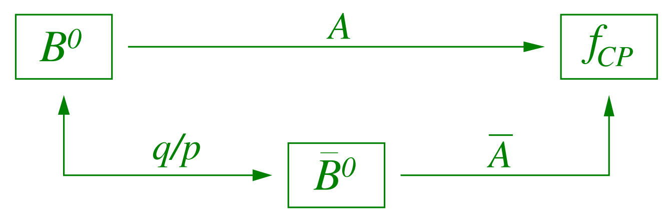
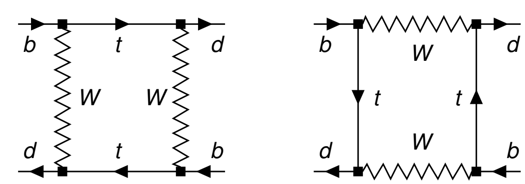
B and D: LHCb and Belle II

One of the cleanest cases: CPV in $B \to \psi K_S$

- CP violation is an $\mathcal{O}(1)$ effect: $\sin 2\beta = 0.677 \pm 0.020$ — not small in general







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

- Measurements in many other modes will get to a similar level in the future

A Belle II & LHCb "best buy" list

- Breadth: many measurements can improve by (nearly) an order of magnitude
  - The CP asymmetry, $S_{B_s \to \psi\phi}$
  - γ from CP asymmetries in tree-level decays vs. γ from $S_{\psi K_S}$ and $\Delta m_d / \Delta m_s$
  - Difference of CP asymmetries: $S_{\psi K_S} - S_{\phi K_S}$, $S_{\psi K_S} - S_{\eta' K_S}$, $S_{B_s \to \psi\phi} - S_{B_s \to \phi\phi}$
  - Search for charged lepton flavor violation, $\tau \to \mu\gamma$, $\tau \to 3\mu$, and similar modes
  - Search for CP violation in $D^0 - \overline{D}{}^0$ mixing
  - Rare decays: $B_{d,s} \to \mu^+\mu^-$, $B \to \tau\bar{\nu}$, $B \to \mu\bar{\nu}$, $b \to s\nu\bar{\nu}$, etc.
  - Search for CP violation in mixing, $A_{\mathrm{SL}}^{d,s}$
  - CP asymmetry in the radiative decay, $S_{K_S \pi^0 \gamma}$
  - Inclusive rates, magnitudes of CKM elements (needed as inputs)
- Large BSM discovery potential — complementarity between Belle II and LHCb
- Any one of these measurements has the potential to establish new physics

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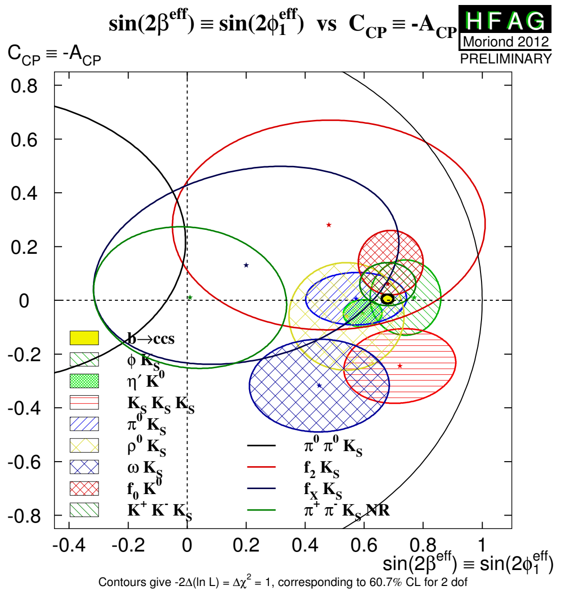
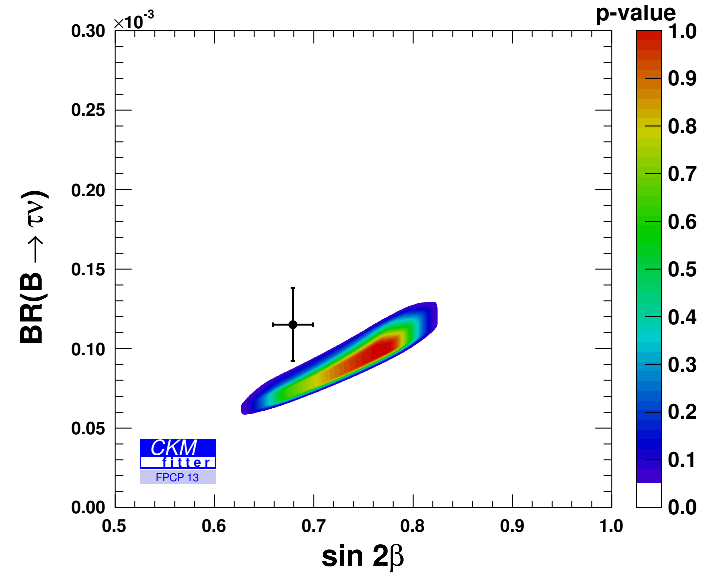
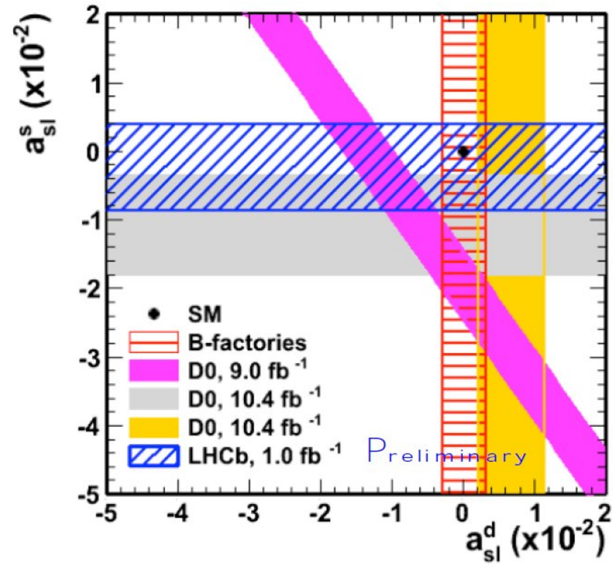
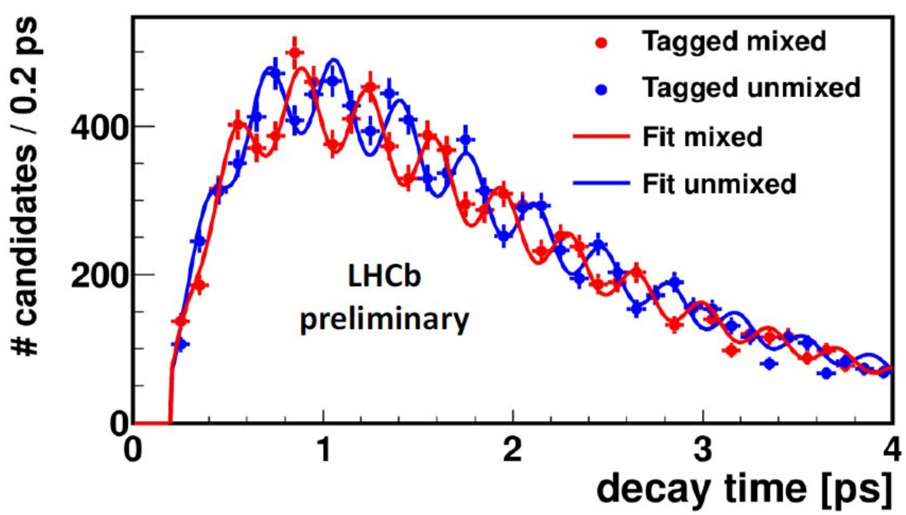
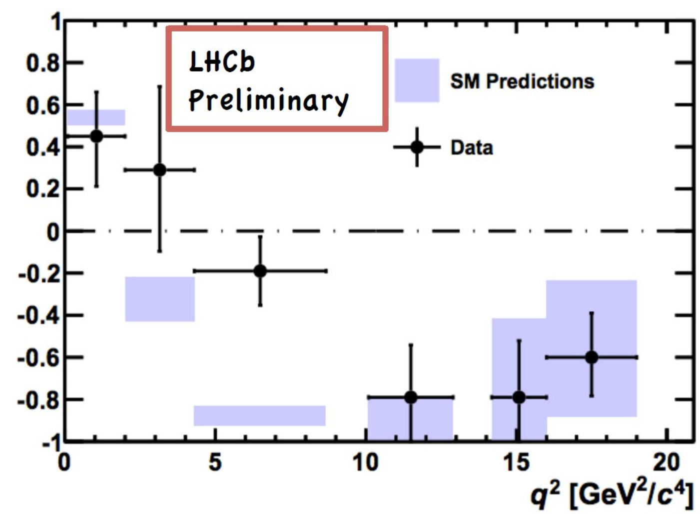
Can’t explain them all...











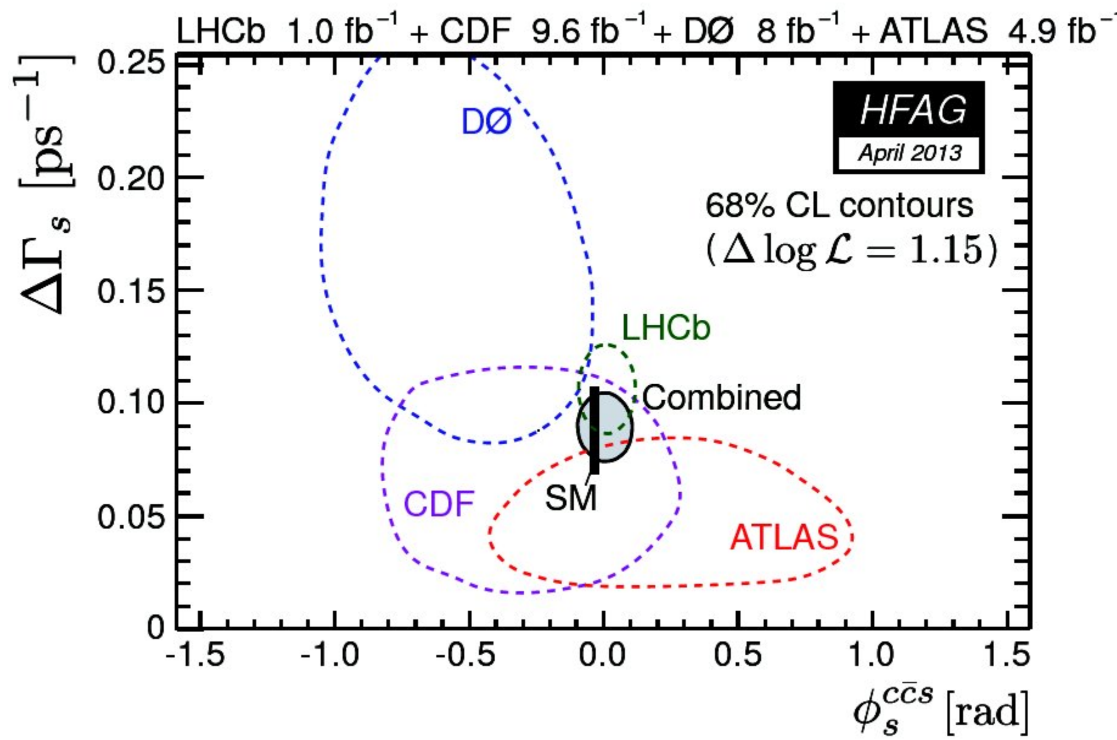
CP violation in $B_s \to \psi\phi$

- Time dependent $B_s \to \psi\phi$ CP asymmetry (analog of $B \to \psi K$ + angular anal.)

  In SM: $\beta_s = \arg(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*) = 0.019 \pm 0.002$ (λ^2 suppressed compared to β)

- LHCb: $\phi_s \equiv -2\beta_s = 0.01 \pm 0.07$

  Uncertainly will decrease by almost an order of magnitude



- Uncertainty of the SM prediction $\ll$ current experimental error ($\Rightarrow$ LHCb upgrade)

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$B_{s,d} \to \mu^+\mu^-$ and other rare decays

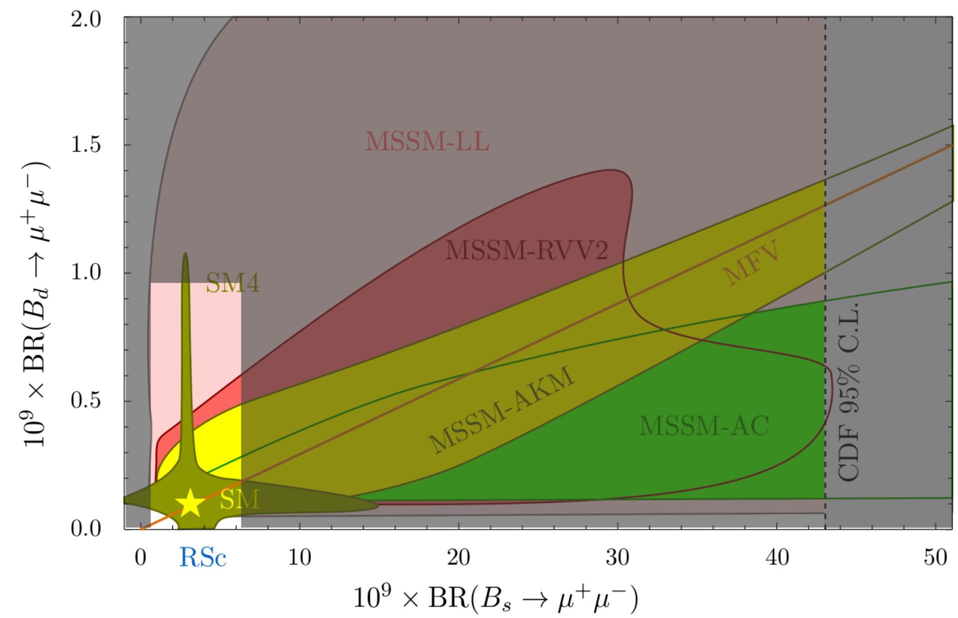
- Shrinking room for NP comparable to SM

  LHCb – CMS combination:

  $\mathcal{B}(B_s \to \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9}$

  $\mathcal{B}(B_d \to \mu^+\mu^-) = (3.6^{+1.6}_{-1.4}) \times 10^{-10}$

- Experimental uncertainty will decrease a lot, interpretation not theory limited



- Many other rare decays, $b \to q\ell^+\ell^-$, $b \to q\nu\bar{\nu}$, with much improved sensitivity

  [LHCb @ EPS: $\sim 4\sigma$ difference from a SM expectation in $B \to K^*\mu^+\mu^-$ angular distribution]

- In some decay modes, even in 2025 we'll have (Exp. bound)/SM $\gtrsim 10^3$

  [E.g.: $B_{(s)} \to \tau^+\tau^-,\ e^+e^-$, can build many models...]

IF 23: CPV in up sector, D mixing

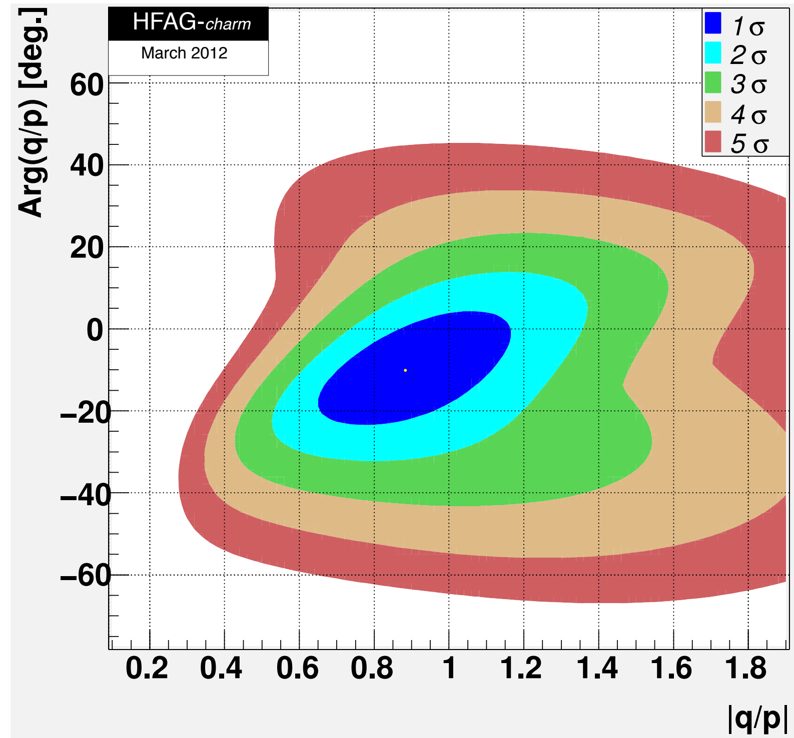
- Mass eigenstates: $|D_{H,L}\rangle = p|D^0\rangle \mp q|\overline{D}^0\rangle$ — CP is conserved iff $|q/p| = 1$

  CPV iff: (mass eigenstates) $\neq$ (CP eigenstates)

- Only meson mixing generated by down-type quarks — in SUSY by up-type squarks

  Mixing observed only in 2007

  Bound on CPV in mixing is 1–2 orders of magnitude weaker than in $B_{d,s}$ and K mixing



Uncertainty of $|q/p|$ is ~ 0.2 !

- Far from hitting the “theory wall”

- Possible connections to FCNC top decays

- Complementary to K, B — interplay in SUSY between Δm_D & Δm_K constraints

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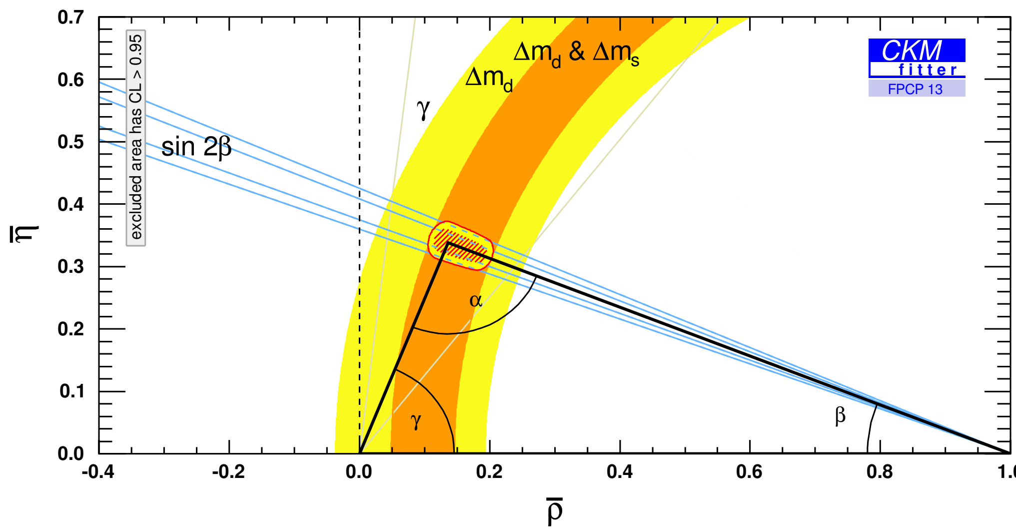
IF 22: γ, $\sin 2\beta$, and $B_{d,s}$ mixing

- Tree level measurement

  (interference of $b \to c\bar{u}s$ and $b \to u\bar{c}s$)

  Together with $|V_{ub}|$ give "reference" CKM, insensitive to NP

  Especially simple to see, as $\alpha \sim 90^\circ$



- Now $\sigma(\gamma) = 11^\circ$, future: $\sim 1^\circ$ (LHCb and Belle II) — $\Delta m_{B_d}/\Delta m_{B_s}$: lattice QCD

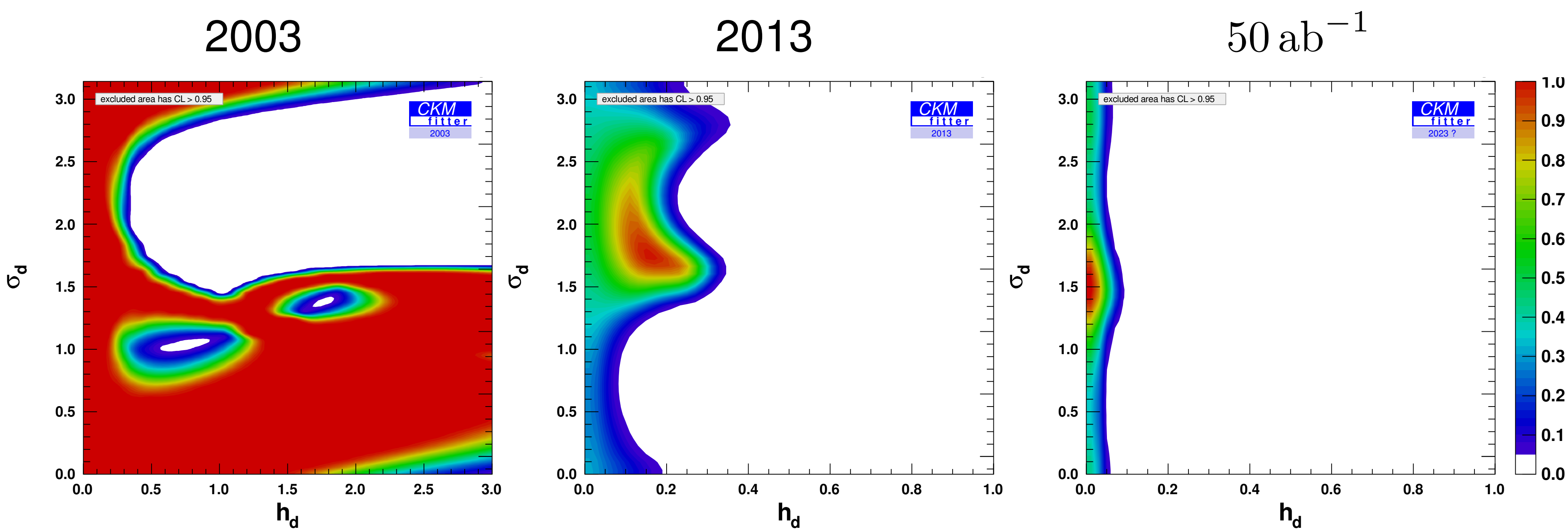
- Order of magnitude improvement in this comparison possible

  (Measurement of γ will not be theory limited at any future experiment)

IF 22: NP in B_d^0 mixing — preliminary

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

$M_{12} = M_{12}^{\rm SM} \times \left(1 + h\, e^{2i\sigma}\right)$ — mature topic, conservative picture of future progress



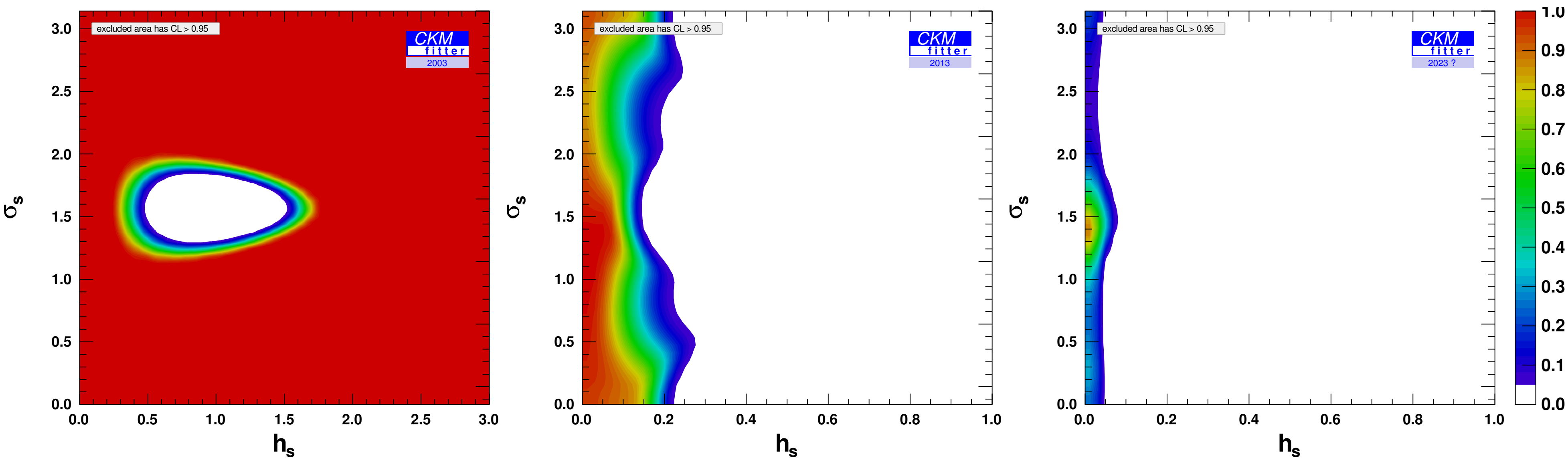
[Charles, Descotes-Genon, ZL, Monteil, Papucci, Trabelsi]

- 95% CL: NP $\lesssim$ (many $\times$ SM) $\to$ NP $\lesssim (0.3 \times$ SM) $\to$ NP $\lesssim (0.05 \times$ SM)

IF 22': NP in B_s^0 mixing — preliminary

- Bounds have caught up with those in B_d — assuming that NP has same CKM factors: $h_q \sim (|C_q|/|V_{tb}V_{tq}|)^2\,(4.2\,\mathrm{TeV}/\Lambda)^2 \;\Rightarrow\; \Lambda \sim 20\,\mathrm{TeV}$ (tree), $\Lambda \sim 2\,\mathrm{TeV}$ (loop)

2003 | 2013 | $50\,\mathrm{fb}^{-1}$



[Charles, Descotes-Genon, ZL, Monteil, Papucci, Trabelsi]

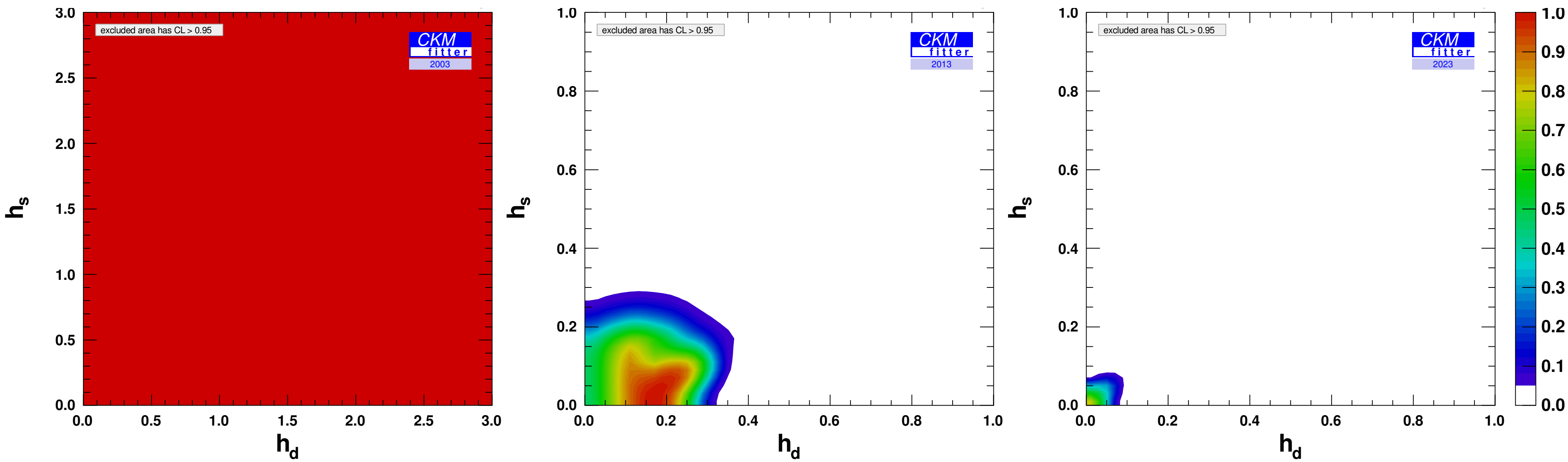
- 95% CL: NP $\lesssim$ (many $\times$ SM) $\;\rightarrow\;$ NP $\lesssim (0.2\,\times$ SM) $\;\rightarrow\;$ NP $< (0.05\,\times$ SM)

IF 22”: NP in $B_{d,s}$ mixing — preliminary

- Looking at $B_{d,s}$ mixing simultaneously:

  (Connections to K mixing in $U(2)^3$ flavor models)

2003 | 2013 | $50\,\mathrm{ab}^{-1}\,B_d + 50\,\mathrm{fb}^{-1}\,B_s$



[Charles, Descotes-Genon, ZL, Monteil, Papucci, Trabelsi]

- 95% CL: NP $\lesssim$ (many $\times$ SM) $\rightarrow$ NP $\lesssim (0.3 \times$ SM) $\rightarrow$ NP $< (0.05 \times$ SM)

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Look for "surprises" — cannot predict the future

- Many interesting searches can be done a lot better at Belle II & LHCb:

  $B \to (\gamma +)\,\text{invisible}$

  $B \to X_s + \text{invisible}$

  $\Upsilon(1S) \to \text{invisible}$

  $\Upsilon(nS) \to \gamma + \text{invisible}$

  $e^+e^- \to (\gamma +)\,\text{invisible}$

  Also: "invisible" replaced by a new resonance; may decay to $\ell^+\ell^-$, etc.

- Synergies with "New light, weakly coupled particles" (Essig, Jaros, Wester)
- Searches for (almost) forbidden processes (e.g., $B_s \to \mu^+ e^-$ probes $100\,\text{TeV}$ LQ, etc.)
- Obvious! most cited Belle paper: $X(3872)$, most cited BaBar paper: $D_{s0}^*(2317)$

Aside: CP violation was a surprise...

PROPOSAL FOR K^o_2 DECAY AND INTERACTION EXPERIMENT

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

(April 10, 1963)

I. INTRODUCTION

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

II. EXPERIMENTAL APPARATUS

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

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

III. COUNTING RATES

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

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

IV. POWER REQUIREMENTS

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

$\Rightarrow$ Cronin & Fitch, Nobel Prize, 1980

$\Rightarrow$ 3 generations, Kobayashi & Maskawa, Nobel Prize, 2008

Final comments

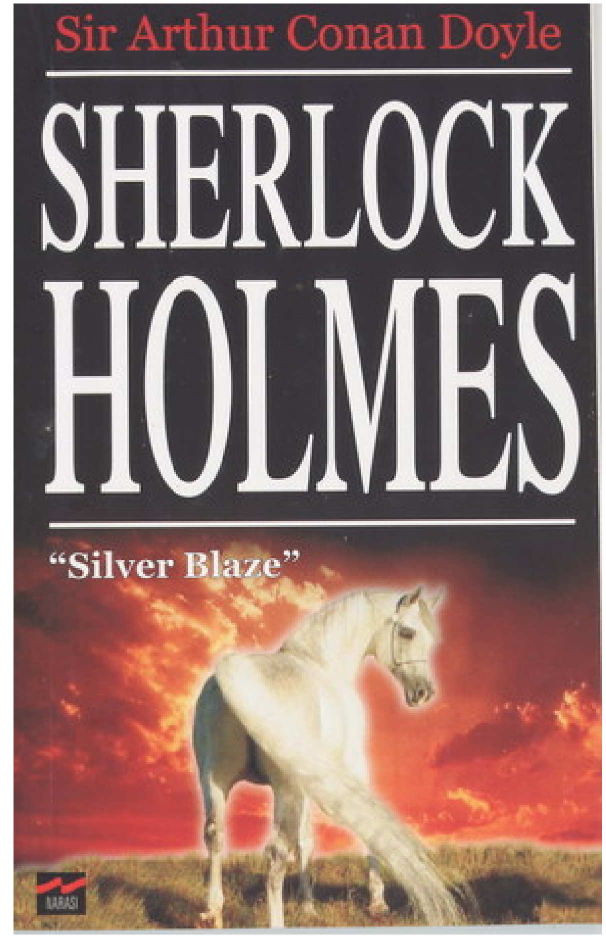
Puzzles solved by lack of signals

- 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.”



- Lack of signals can be critical (even when the solution to a puzzle is in sight)

Summary

- Flavor physics probes scales $\gg 1\,\mathrm{TeV};$ sensitivity limited by statistics, not theory
- New physics in most FCNC processes may still be $\sim 20\%$ of the SM or more
- Flavor physics data are essential, whether LHC discovers BSM or not
  - Synergies with TeV-scale BSM searches, and to interpret signals
  - Probes above the reach of LHC and other foreseeable colliders
- Possible convergence between (s)quark and (s)lepton flavor physics
- Theory, including lattice QCD, is important to interpret data

  Progress, and interplay with measurements, will enhance sensitivity to NP
- Flavor measurements will improve a lot in next decade, by 10–10^4 in many modes

  Exploring NP requires CLFV (Mu2e), kaon (ORKA), LHCb upgrade, Belle II, EDM

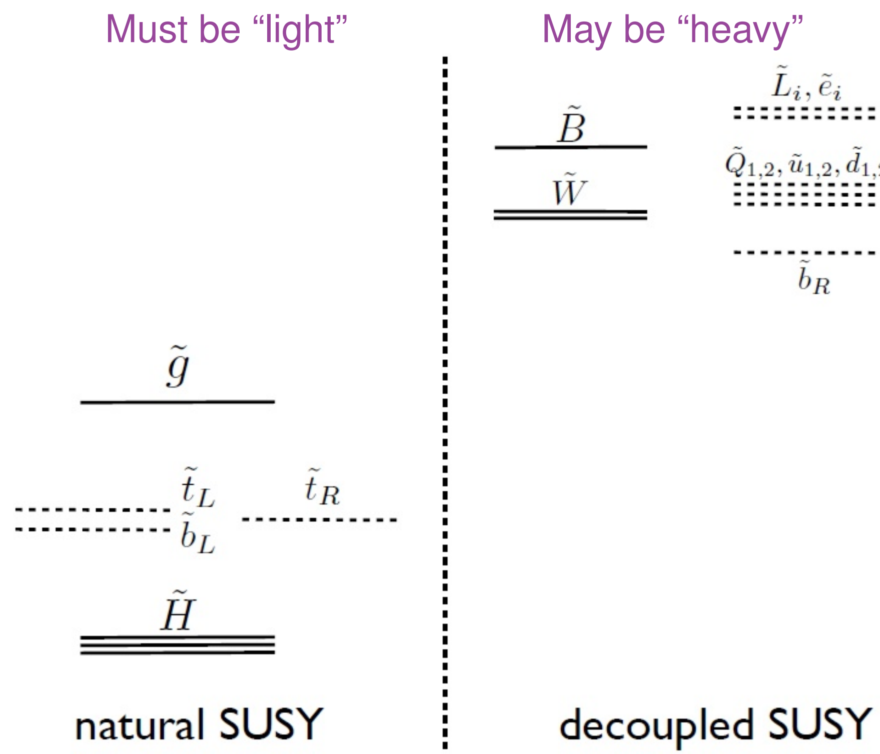
Backup slides

Hope to maintain naturalness

- Naturalness has been main motivation for TeV-scale NP — leave no stone unturned!
- No observation of other heavy particles yet

  Simplest bottom-up approach:

  Light $\tilde{t}$, 1st & 2nd generation (a lot) heavier



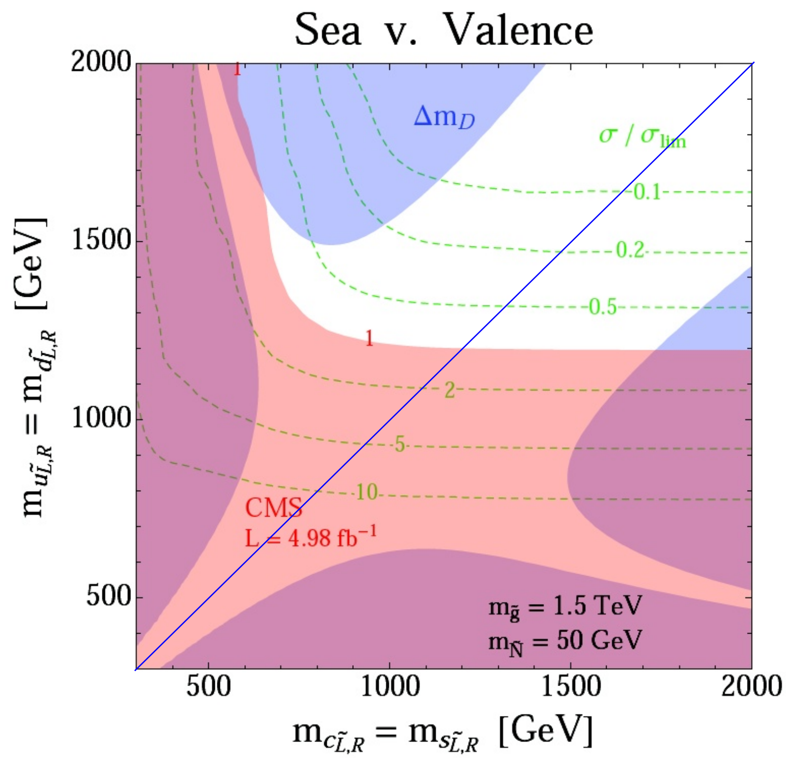
- Can have SUSY GIM, (approximate) MFV, etc., but with larger mass splittings expect larger flavor non-universality and more flavor signals
- Typically, expect increasing synergy of high-p_T searches and flavor

Hide LHC signals ⇔ hide flavor signals

- If 4 pairs of u, d, s, c squarks not degenerate, lot weaker LHC bounds: $1.2\,\text{TeV} \;\Rightarrow \sim 0.5\,\text{TeV}$

  E.g., assume that 4–4 squarks (1st and 2nd generation, but not all 8) are degenerate

  Unshaded region still allowed [arXiv:1212.3328]



- Modify search strategies to improve coverage

- Ways for naturalness to survive — can give up many assumptions before abandoning key principles (many new LHC studies are yet to be devised and done)

  We're still at the early stages of learning as much as we can from the LHC

Flavor and CP violation in SUSY

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

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

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

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

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

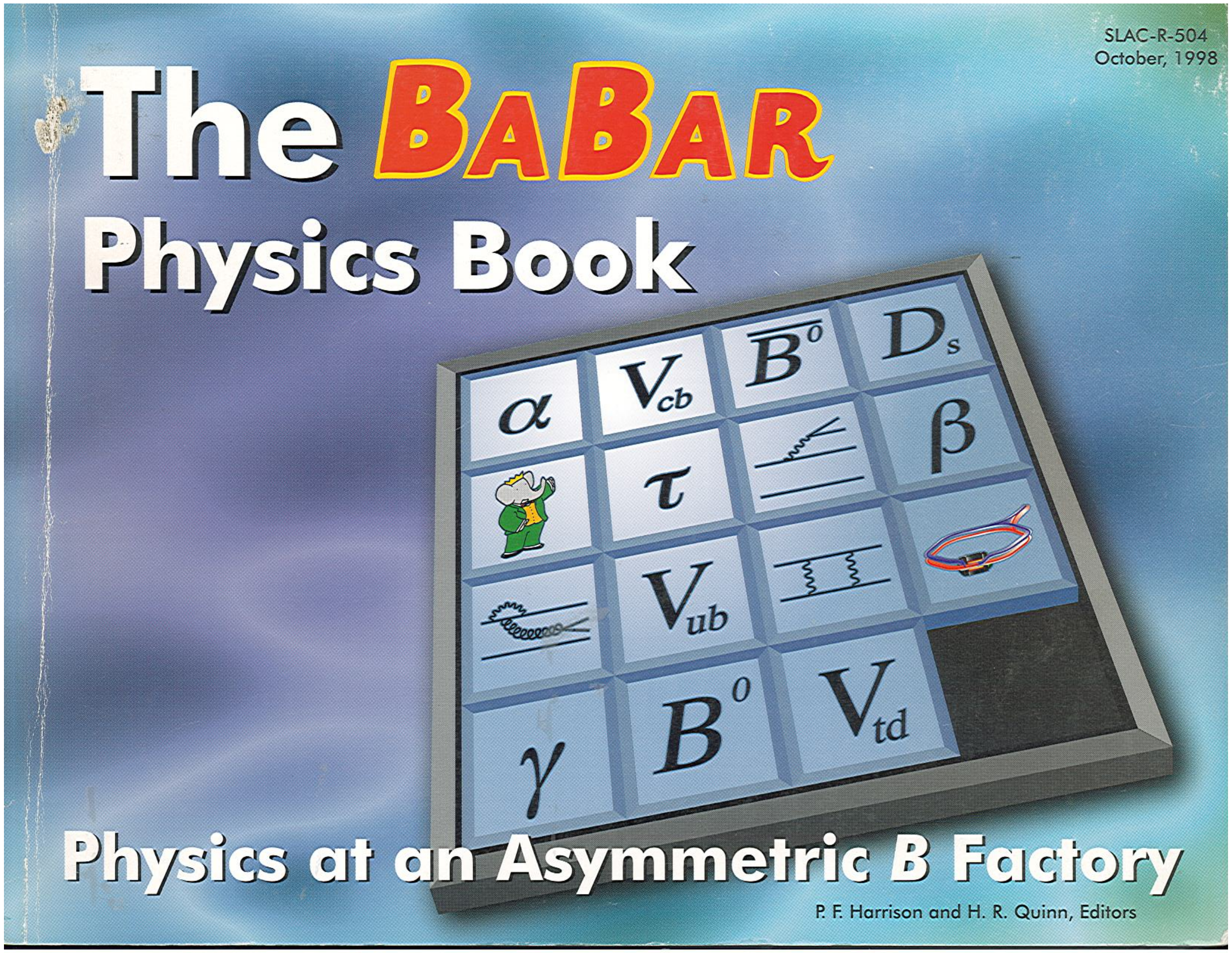
$5\ m^2_S$ hermitian sfermion mass-squared matrices — $5\times(6$ real $+\ 3$ imag.) param's

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

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

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

“Killer apps” in BaBar Physics Book?



- There was no executive summary... Neither a list of gold-plated measurements...

Substantial discovery potential: Belle II

Observable	SM theory	Current measurement (early 2013)	Belle II ($50\,\mathrm{ab}^{-1}$)
$S(B \to \phi K^0)$	0.68	0.56 ± 0.17	± 0.03
$S(B \to \eta' K^0)$	0.68	0.59 ± 0.07	± 0.02
α from $B \to \pi\pi,\ \rho\rho$		$\pm 5.4^\circ$	$\pm 1.5^\circ$
γ from $B \to DK$		$\pm 11^\circ$	$\pm 1.5^\circ$
$S(B \to K_S \pi^0 \gamma)$	< 0.05	-0.15 ± 0.20	± 0.03
$S(B \to \rho\gamma)$	< 0.05	-0.83 ± 0.65	± 0.15
$A_{\mathrm{CP}}(B \to X_{s+d}\,\gamma)$	< 0.005	0.06 ± 0.06	± 0.02
A_{SL}^d	-5×10^{-4}	-0.0049 ± 0.0038	± 0.001
$\mathcal{B}(B \to \tau\nu)$	1.1×10^{-4}	$(1.64 \pm 0.34) \times 10^{-4}$	$\pm 0.05 \times 10^{-4}$
$\mathcal{B}(B \to \mu\nu)$	4.7×10^{-7}	$< 1.0 \times 10^{-6}$	$\pm 0.2 \times 10^{-7}$
$\mathcal{B}(B \to X_s\gamma)$	3.15×10^{-4}	$(3.55 \pm 0.26) \times 10^{-4}$	$\pm 0.13 \times 10^{-4}$
$\mathcal{B}(B \to X_s \ell^+\ell^-)$	1.6×10^{-6}	$(3.66 \pm 0.77) \times 10^{-6}$	$\pm 0.10 \times 10^{-6}$
$\mathcal{B}(B \to K\nu\overline{\nu})$	3.6×10^{-6}	$< 1.3 \times 10^{-5}$	$\pm 1.0 \times 10^{-6}$
$A_{\mathrm{FB}}(B \to K^*\ell^+\ell^-)_{q^2 < 4.3\,\mathrm{GeV}^2}$	-0.09	0.27 ± 0.14	± 0.04
$s_0\ A_{\mathrm{FB}}(B^0 \to K^{*0}\ell^+\ell^-)$	0.16	0.029	0.008
$\lvert V_{ub}\rvert$ from $B \to \pi\ell^+\nu$ ($q^2 > 16$ GeV^2)	$9\% \to 2\%$	11%	2.1%

- Some of the theoretically cleanest modes (ν, τ, inclusive) only possible at e^+e^-

Substantial discovery potential: LHCb

Observable	SM theory uncertainty	Precision as of 2013	LHCb (6.5 fb^{-1})	LHCb Upgrade (50 fb^{-1})
$2\beta_s(B_s \to J/\psi\phi)$	~ 0.003	0.09	0.025	0.008
$\gamma(B \to D^{(*)}K^{(*)})$	$< 1^\circ$	8°	4°	0.9°
$\gamma(B_s \to D_s K)$	$< 1^\circ$	—	$\sim 11^\circ$	2°
$\beta(B^0 \to J/\psi K^0_S)$	small	0.8°	0.6°	0.2°
$2\beta_s^{\rm eff}(B_s \to \phi\phi)$	0.02	1.6	0.17	0.03
$2\beta_s^{\rm eff}(B_s \to K^{*0}\bar{K}^{*0})$	< 0.02	—	0.13	0.02
$2\beta_s^{\rm eff}(B_s \to \phi\gamma)$	0.2%	—	0.09	0.02
$2\beta^{\rm eff}(B^0 \to \phi K^0_S)$	0.02	0.17	0.30	0.05
$A^s_{\rm SL}$	0.03×10^{-3}	6×10^{-3}	1×10^{-3}	0.25×10^{-3}
$\mathcal{B}(B_s \to \mu^+\mu^-)$	8%	42%	15%	5%
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s \to \mu^+\mu^-)$	5%	—	$\sim 100\%$	$\sim 35\%$
$s_0\, A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$	7%	18%	6%	2%

- Many modes first seen at Belle II or LHCb; complementarity between them
- In some decay modes, even in 2025 we'll have (Exp. bound)$/$SM $\gtrsim 10^3$

  E.g.: $B_{(s)} \to \tau^+\tau^-,\ e^+e^-$, can build many models...

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 are smaller than the expected sensitivity of future experiments.

- What to expect in terms of experimental precision?

  Useful data sets will increase by $\sim 10^{2\pm1}$, and will probe fairly generic BSM predictions

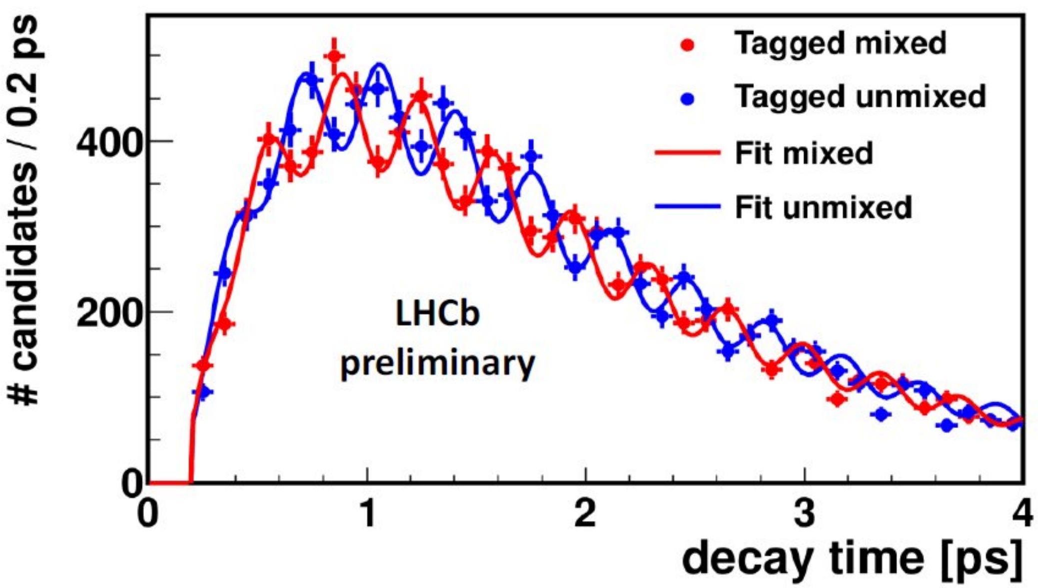
- What will the measurements teach us if deviations from the SM are [not] seen?

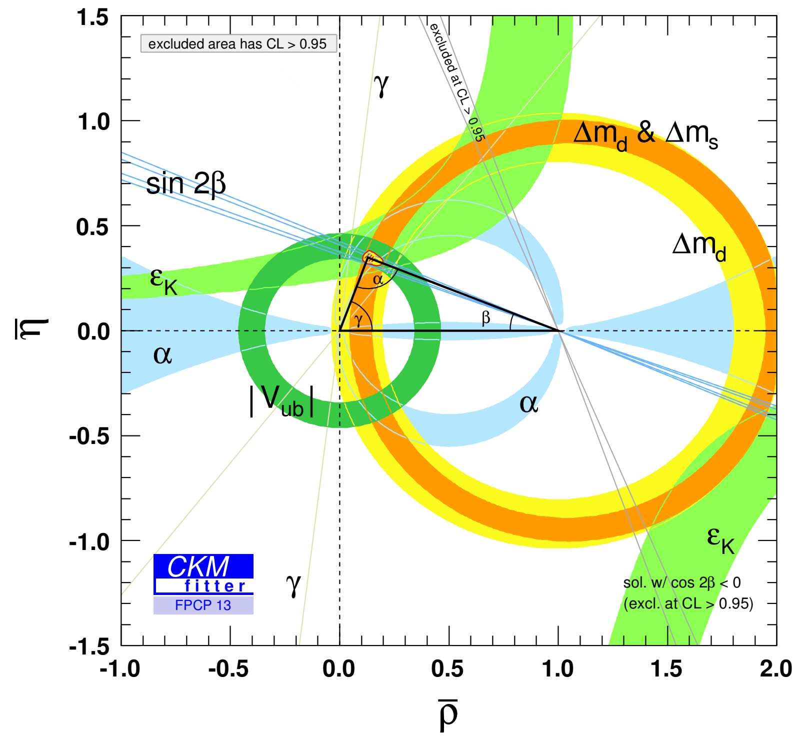
  The new flavor physics data will be complementary with the high-p_T part of the LHC program. The synergy of measurements can teach us about what the new physics at the TeV scale is [not].

Berkeley Lab

B_s^0 mixing and $|V_{td}/V_{ts}|$

- $B_s^0 - \overline{B}_s^0$ oscillate ~ 25 times before they decay (first measured by CDF in 2007)





$$\Delta m_s = (17.768 \pm 0.024)\,\mathrm{ps}^{-1}$$

- Uncertainty $\sigma(\Delta m_s) = 0.13\%$ is much smaller than $\sigma(\Delta m_d) = 0.8\%$

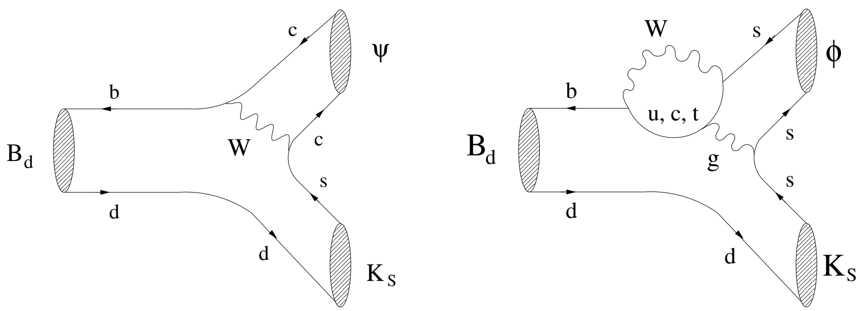
Largest uncertainty: $\xi = \dfrac{f_{B_s}\sqrt{B_s}}{f_{B_d}\sqrt{B_d}}$

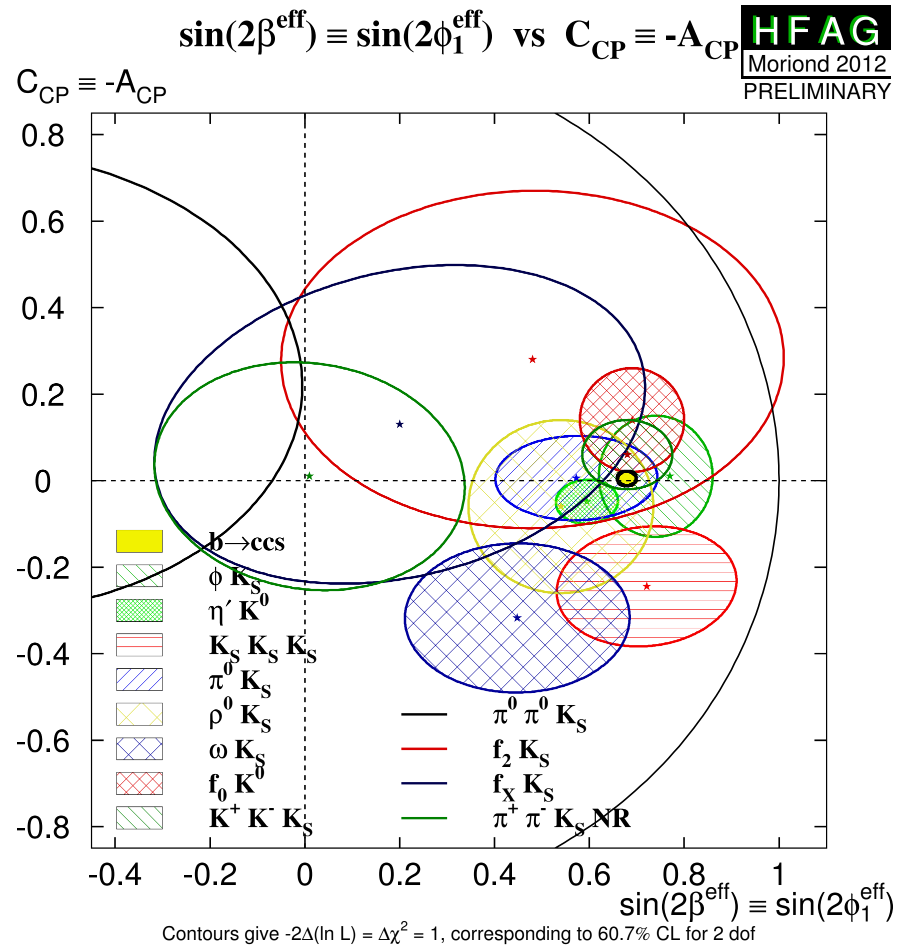
Lattice QCD: $\xi = 1.24 \pm 0.03 \pm 0.02$

$\sin 2\beta$ in tree vs. penguin-dominated modes

- Compare: $B \to \psi K$ and $B \to \phi K$, etc.

  $B_s \to \psi\phi$ and $B_s \to \phi\phi$, etc.



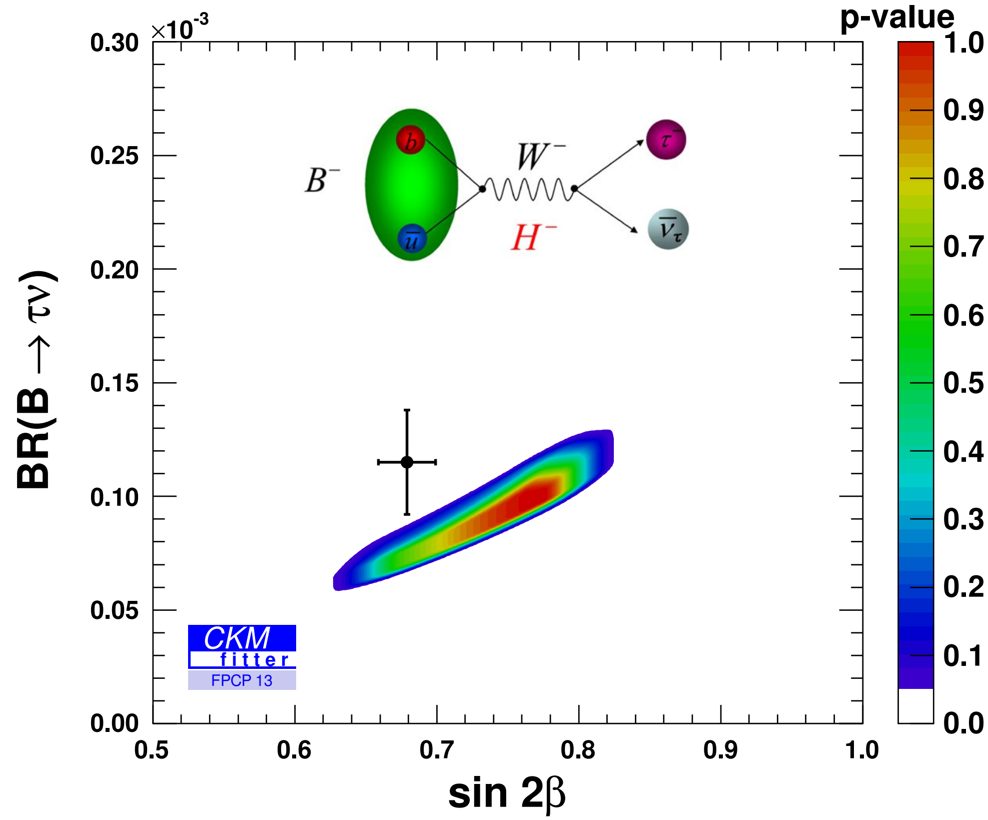


- Some penguin-dominated modes will get as precise as $B \to \psi K$ is now
- In several cases:
  theory uncertainty $\ll$ exp uncertainty
- A lot can be learned from reducing these experimental uncertainties

$B \to \tau\nu$ and $\mu\nu$

- Past hint of a (3σ) tension reduced
- Measurement can improve a lot:

  Uncertainty: $20\% \to 3-4\%$
- Lattice QCD crucial: need f_B only



- Belle II: also measure $\mathcal{B}(B \to \mu\nu)$ with $< 5\%$ uncertainty — complementary
- Increase NP sensitivity $+$ independent determinations of $|V_{ub}|$ (both exp & theo)

BERKELEY LAB

$A_{\rm SL}$ — CP violation in mixing

- Mass eigenstates: $|B_{H,L}\rangle = p|B^0\rangle \mp q|\overline{B}^0\rangle$ — if CP is conserved then $|q/p| = 1$

  CP violated iff: (mass eigenstates) $\neq$ (CP eigenstates)

- The measurements: “dilepton” asymmetry

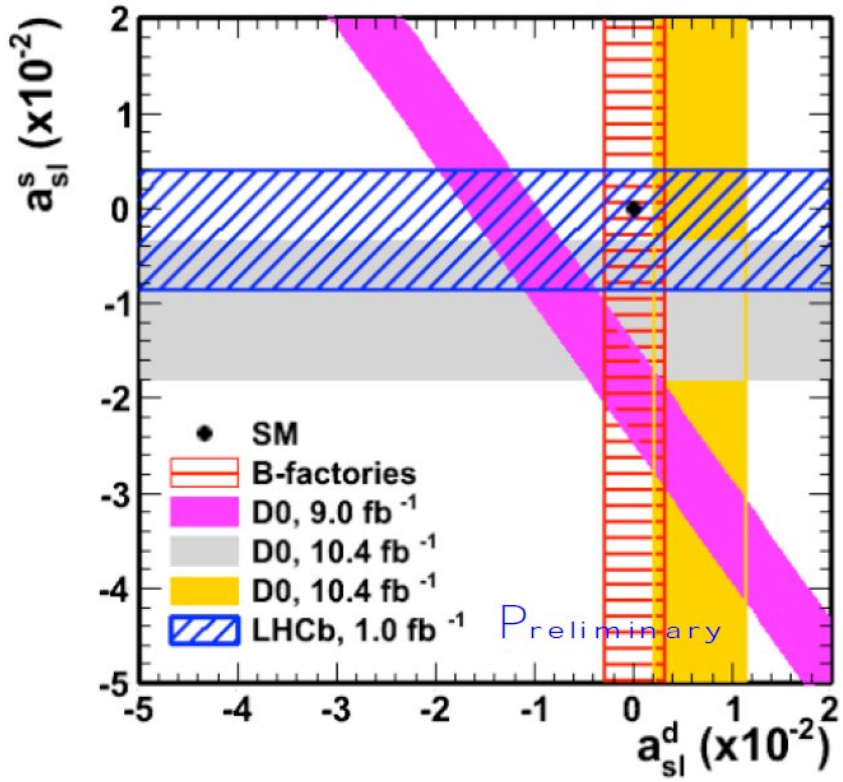
$$a_{\rm SL} = \frac{\Gamma[\overline{B}^0(t) \to \ell^+ X] - \Gamma[B^0(t) \to \ell^- X]}{\Gamma[\overline{B}^0(t) \to \ell^+ X] + \Gamma[B^0(t) \to \ell^- X]} = \frac{1 - |q/p|^4}{1 + |q/p|^4}$$

- Hint of a 4σ effect from DØ — magenta band

  SM prediction tested for K: $4\,{\rm Re}\,\epsilon_K$ [CPLEAR]

  SM predictions: $a^d_{\rm SL} \simeq -5 \times 10^{-4}$

  $a^s_{\rm SL} \simeq 2 \times 10^{-5}$



- Order of magnitude experimental improvement will still be far from theory uncert.