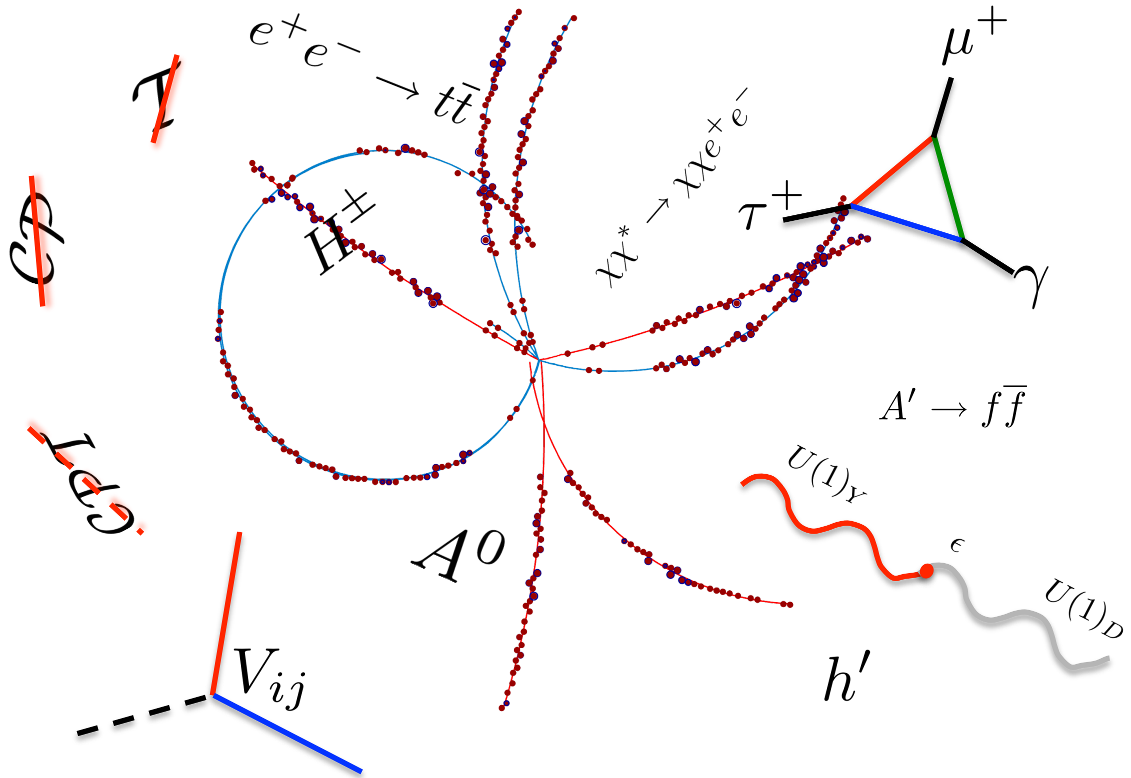
Flavour Physics at e^+e^- machines: Past/Present and Future (Part 2)



Adrian Bevan

IDPASC School, Valencia, May 2013

- There are three files:
  - 1) Introduction and formalism
  - 2) Results and future experiments (this one)
  - 3) Appendices

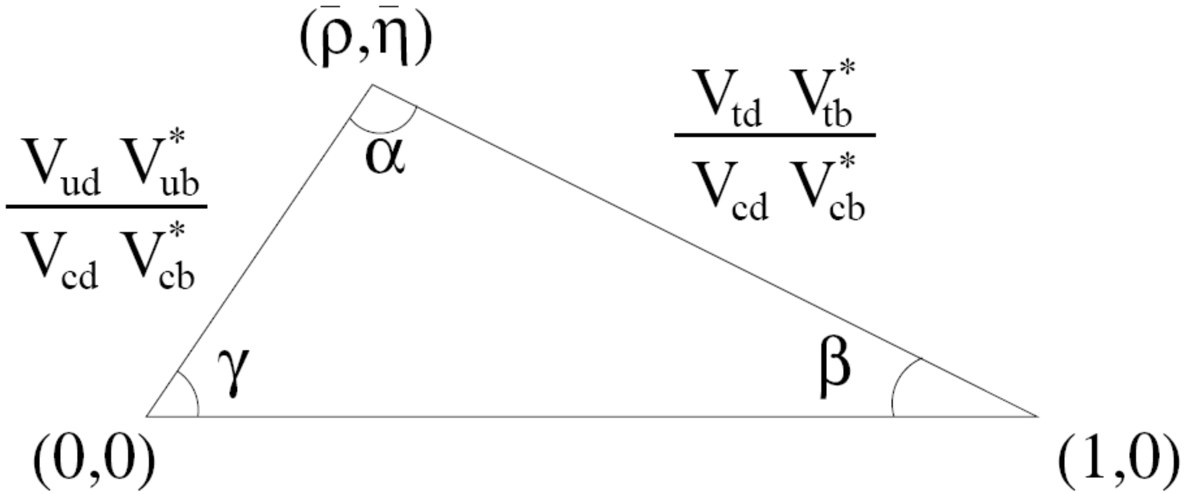
Physics: Quarks

B MESONS

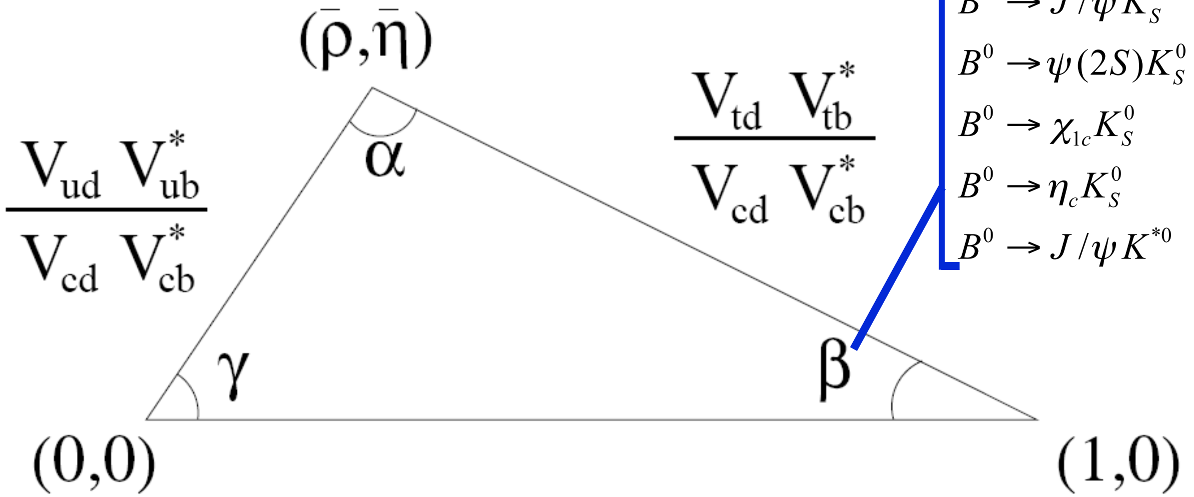
(i) Angles and sides of the Unitarity triangle

(ii) Rare decays

Angles of the Unitarity triangle



Theoretically clean (SM uncertainties ~10^{-2} [data driven method] to 10^{-3} [theoretical calculation]) tree dominated decays to Charmonium + K^0 final states.



$b \to c\bar{c}s$
$B^0 \to J/\psi K_L^0$
$B^0 \to J/\psi K_S^0$
$B^0 \to \psi(2S) K_S^0$
$B^0 \to \chi_{1c} K_S^0$
$B^0 \to \eta_c K_S^0$
$B^0 \to J/\psi K^{*0}$

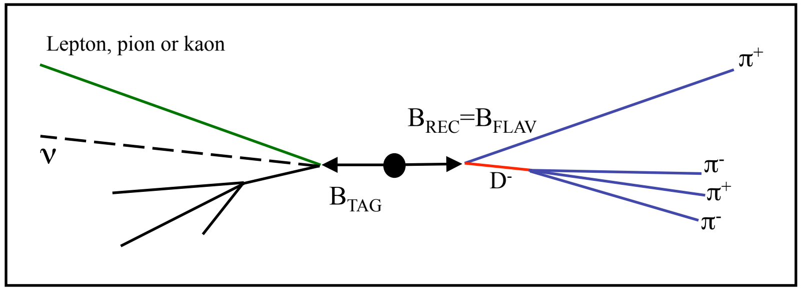
$B \to J/\psi \pi^0$
$B \to D^{(*)+} D^{(*)-}$
$B \to \eta' K^0$
$B \to \rho K^0$
$B \to \omega K^0$
$B \to \pi^0 K^0$
$B \to \phi K^{(*)0}$
$B \to KKK^0$
$B \to f^0(980) K^0$
⋮

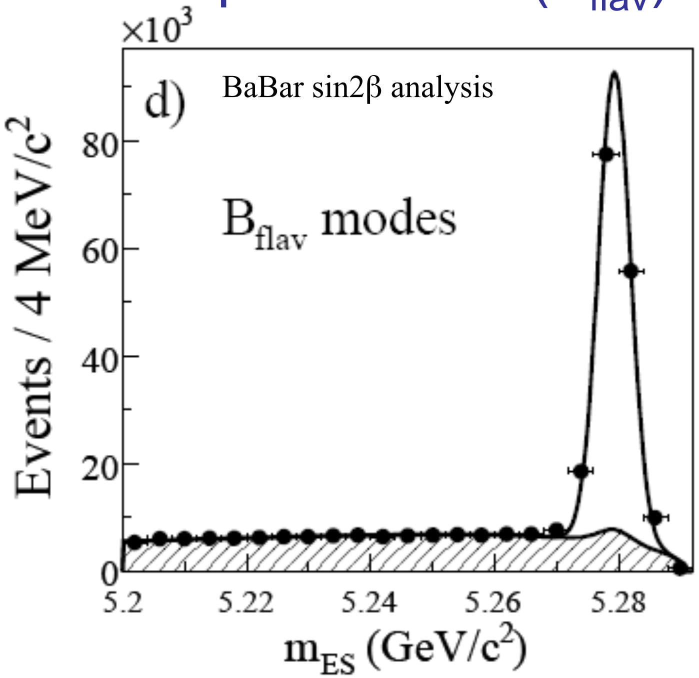
CP violation: β

- Need to determine many parameters before we can extract S and C (and the angles of the triangle):
  - ω, $\Delta\omega$, ε_{TAG}, $\Delta\varepsilon_{TAG}$ for signal and for background.
  - Use a sample of fully reconstructed B decays to flavor specific final states to determine these parameters (B_{flav}).
  - Sample includes:

$$B^0 \to D^{(*)-}\pi^+$$
$$B^0 \to D^{(*)-}\rho^+$$
$$B^0 \to D^{(*)-}a_1^+$$
$$B^0 \to J/\psi K^{*0},\quad K^{*0} \to K^+\pi^-$$

Background





This method to validate the tagging performance is used for all time-dependent CP asymmetry measurements.

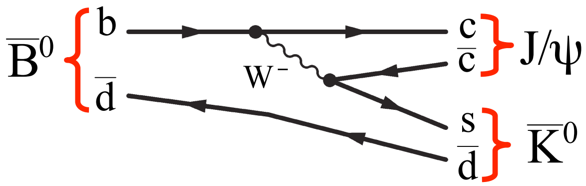
CP violation: β

- Measure S and C in several $b \to c\bar{c}s$ modes.

$$S = \sqrt{1 - C^2}\sin 2\beta$$

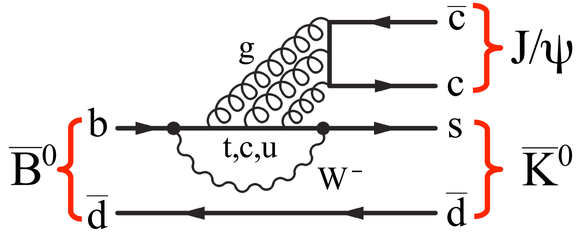
$\eta_f = +1$

- Theoretically clean: Tree level process dominates:



- Gluonic loop (penguin) is small:

$\eta_f = -1$



- Calculations suggest C<10^{-3}.

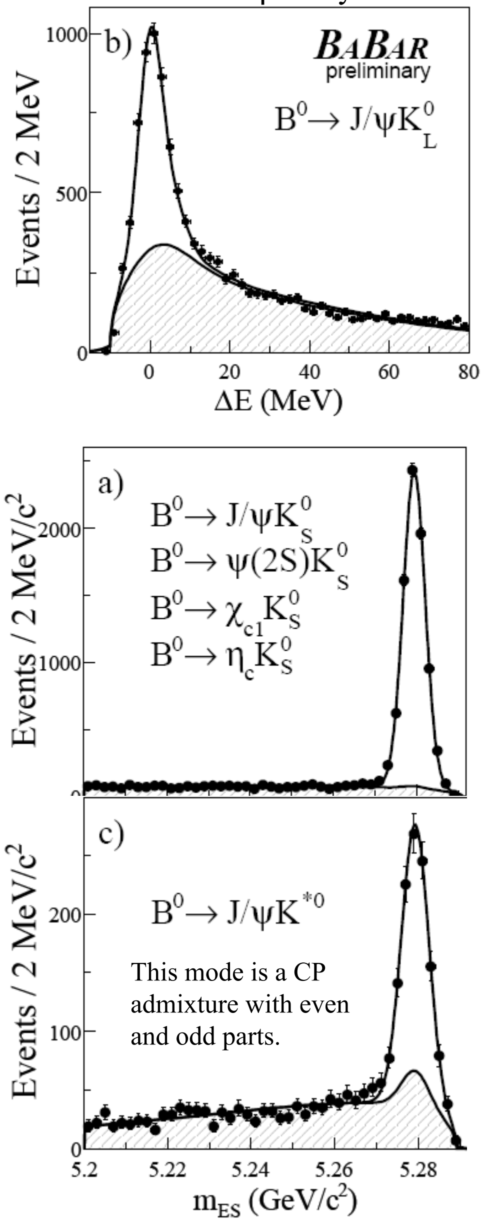
$\eta_f^{eff} \sim 0.5$

H. Li and S. Mishima, hep-ph/0610120.

H. Boos, J. Reuter, and T. Mannel, Phys. Rev. Lett. D **70**, 036006 (2006).

- Data driven methods constrain C<0.012.

BaBar sin2β analysis



CP violation: β

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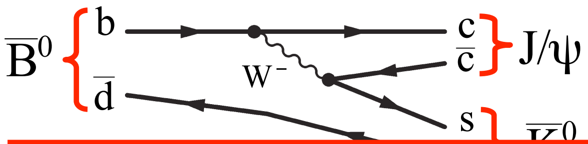

- Gluoni

Penguins are small in charmonium + K0 decays of a B meson, and so hadronic uncertainties from this source are negligible. It is likely for this to remain the case with the next generation of experiments.

- Calculations suggest $C<10^{-3}$. $\eta_f^{eff} \sim 0.5$

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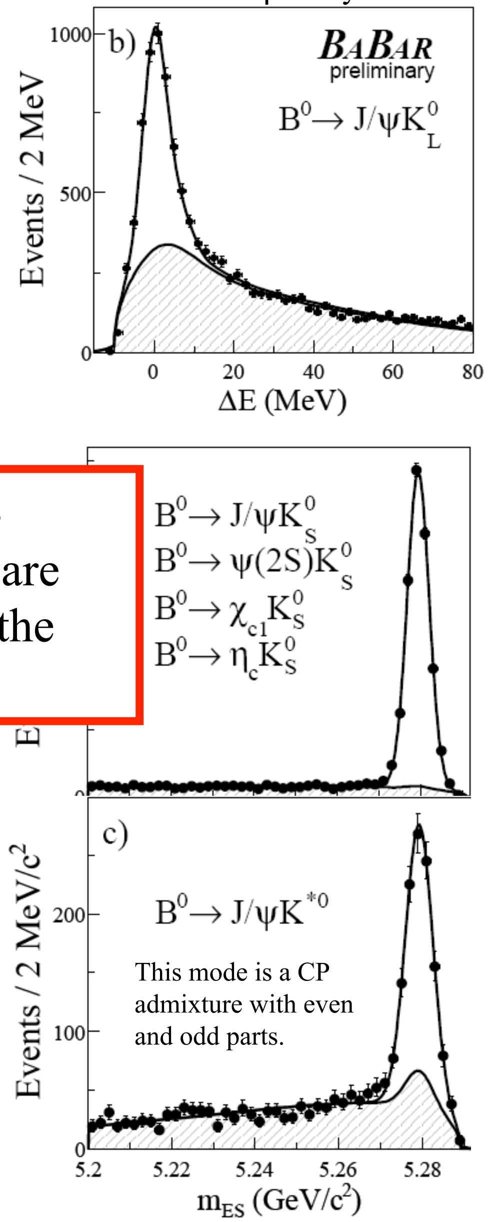
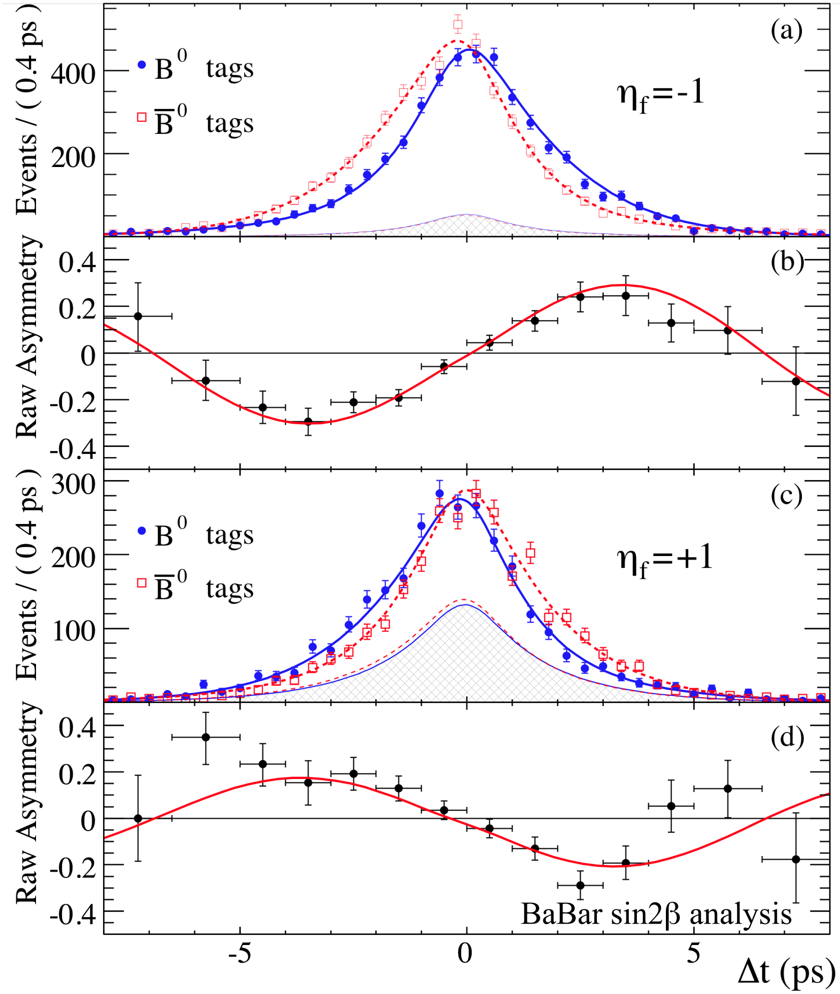


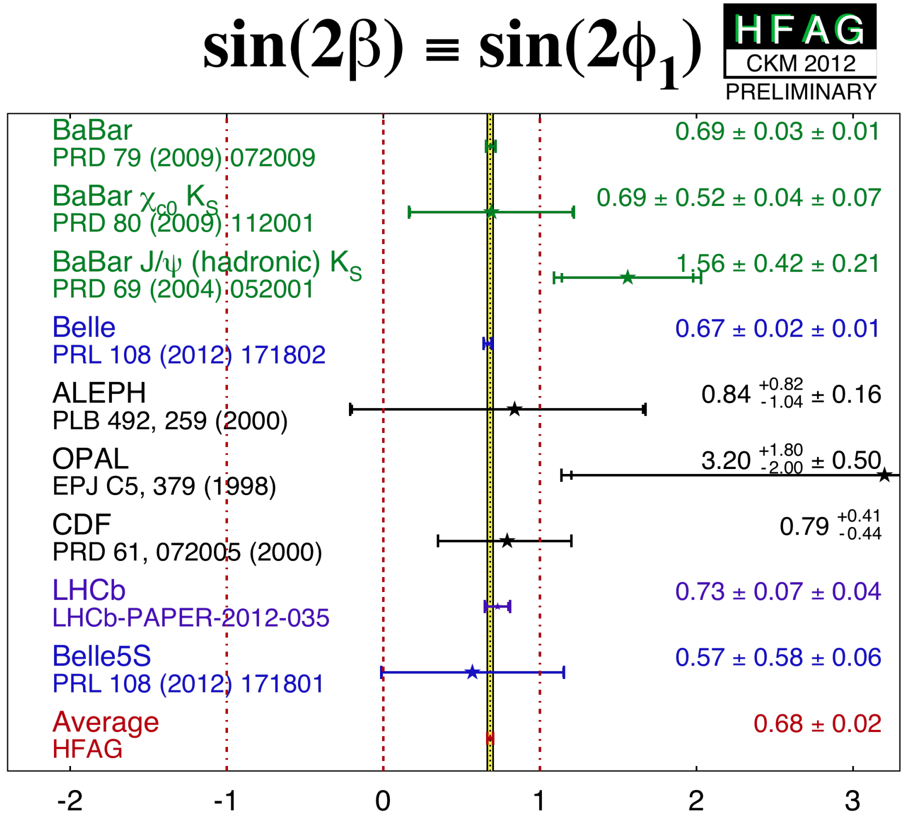
CP violation: β

- CP violating asymmetry is well established in these decays!



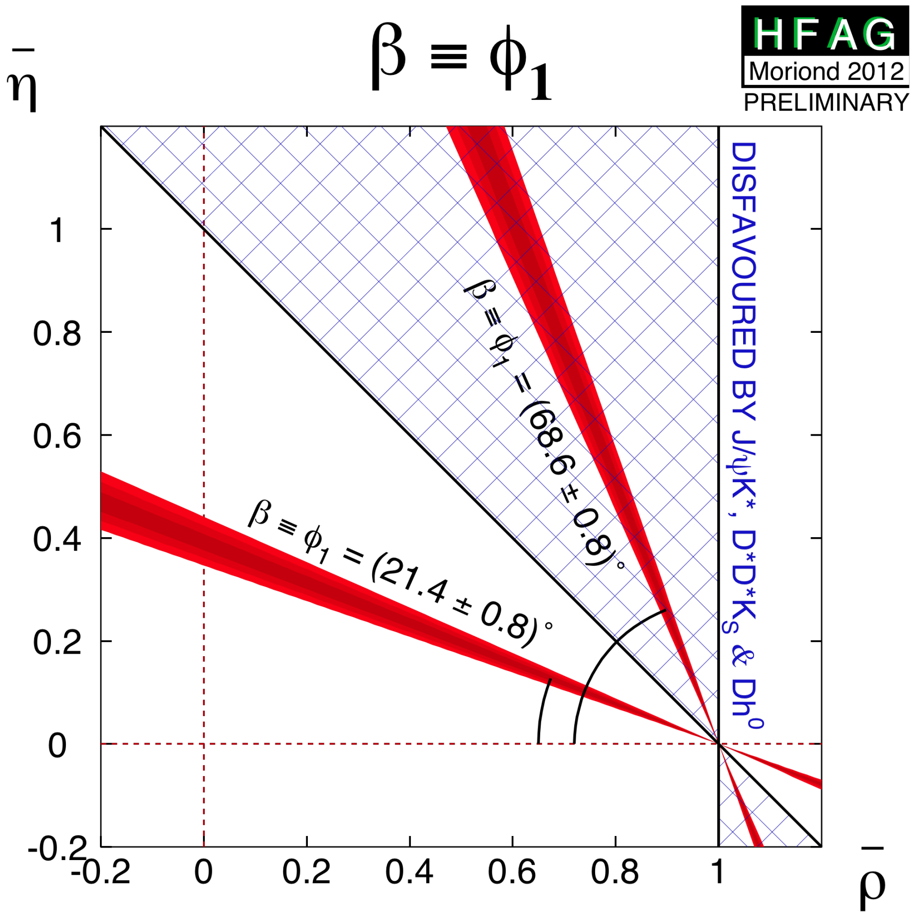
$$\sin 2\beta = (0.677 \pm 0.020)$$
(BaBar + Belle)

$\sin(2\beta) \equiv \sin(2\phi_1)$



BaBar and Belle still dominate the average value of sin2β

CP violation: β



- Four solutions exist in the ρ-η plane as we compute arcsin(2β).
- Additional measurements provide cos(2β) and help to resolve ambiguities.

- Theoretically clean CP violation measurements consistent with the Standard Model for:

$$B^0 \to J/\psi K^0_L$$
$$B^0 \to J/\psi K^0_S$$
$$B^0 \to \psi(2S) K^0_S$$
$$B^0 \to \chi_{1c} K^0_S$$
$$B^0 \to \eta_c K^0_S$$
$$B^0 \to J/\psi K^{*0}$$

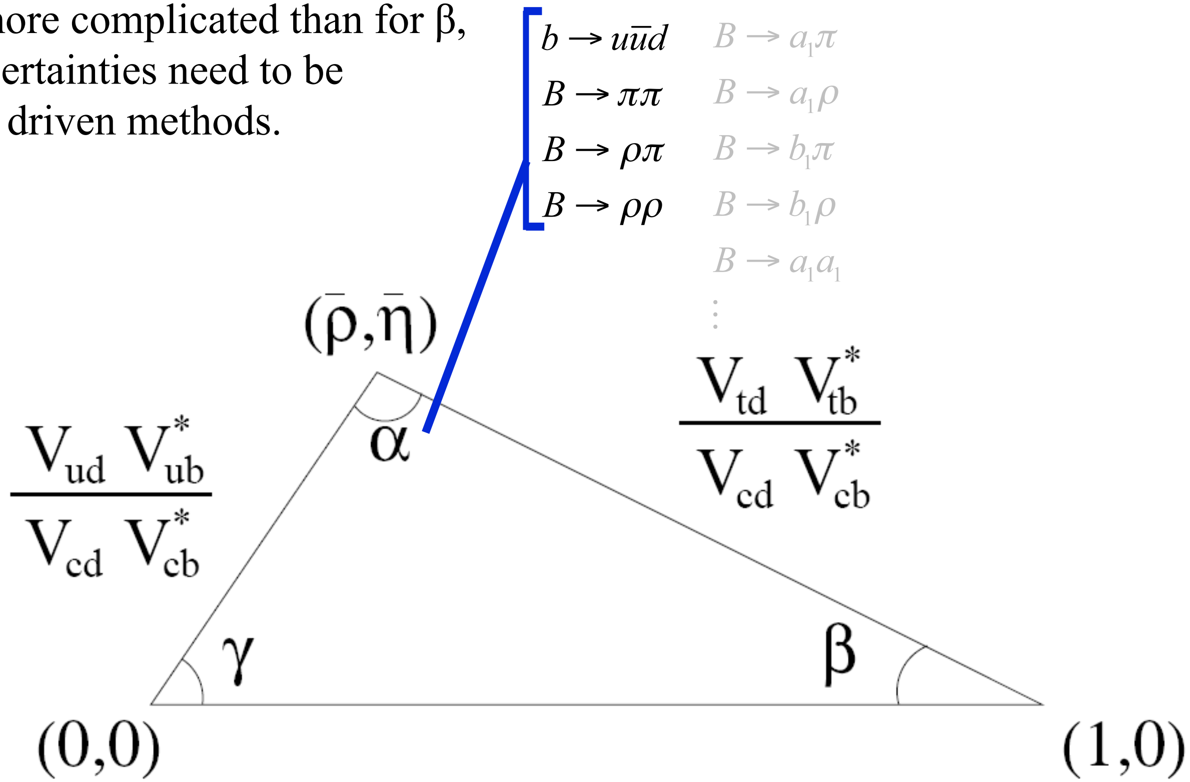
- Established technique for extracting S and C that can be used for other final sates.

- Measured S=sin2 β provides a reference point to search for New Physics (NP).

b→u$\bar{u}$d transitions with possible loop contributions. Extract α using

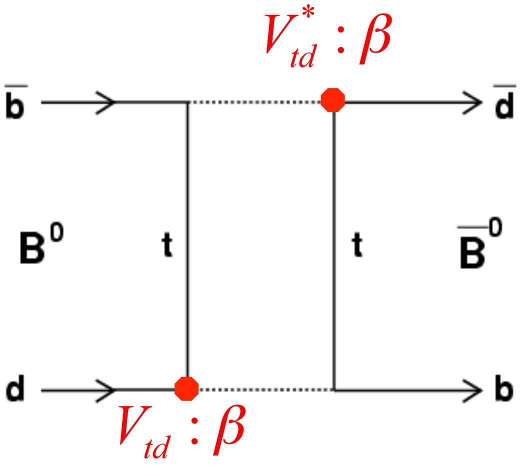
- SU(2) Isospin relations.
- SU(3) flavour related processes.

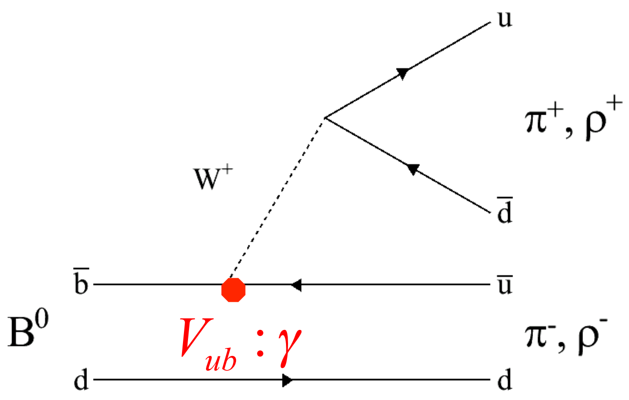
- Interpretation is more complicated than for β, where hadronic uncertainties need to be constrained by data driven methods.



CP violation: α

- Interference between box and tree results in an asymmetry that is sensitive to α in $B \rightarrow hh$ decays: $h = \pi, \rho, \ldots$
- Loop corrections are not negligible for α.





$$C_{hh} = 0$$

$$S_{hh} = \sin(2\alpha)$$

- This scenario is equivalent to the measurement of $\sin 2\beta$ in Charmonium decays … but nature is more complicated than this!

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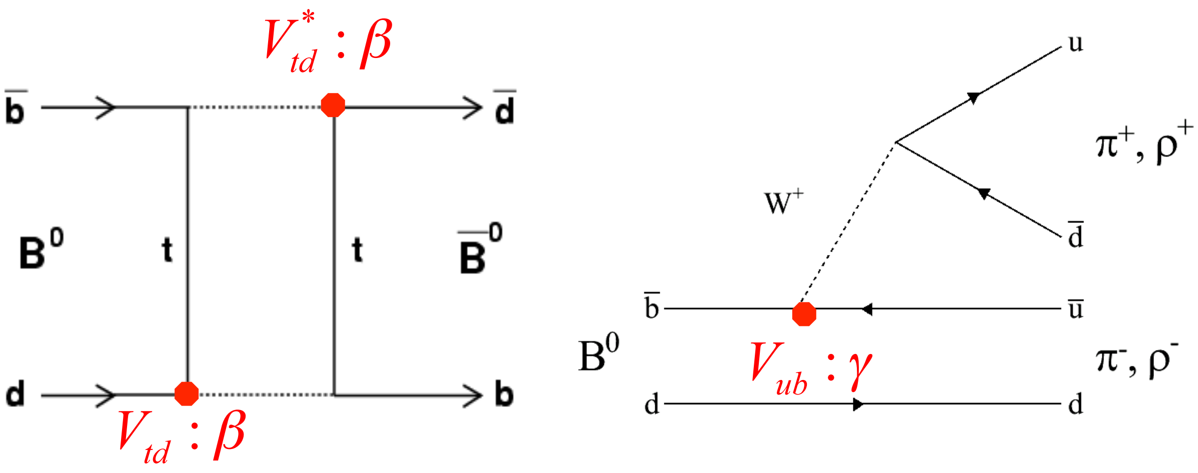
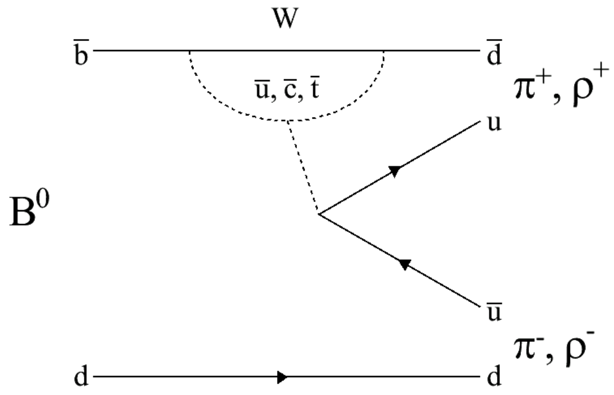
+Loops (penguins)





$$C_{hh} = 0$$

$$S_{hh} = \sin(2\alpha)$$

- This scenario is equivalent to the measurement of sin2β in Charmonium decays … but nature is more complicated than this!

- Measure S $\propto \alpha_{eff}$.
- Need to determine $\delta\alpha=\alpha_{eff}-\alpha$ [P/T is different for each final state]

CP violation: α

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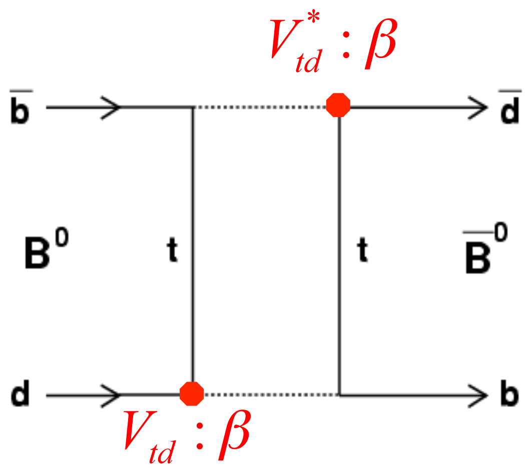

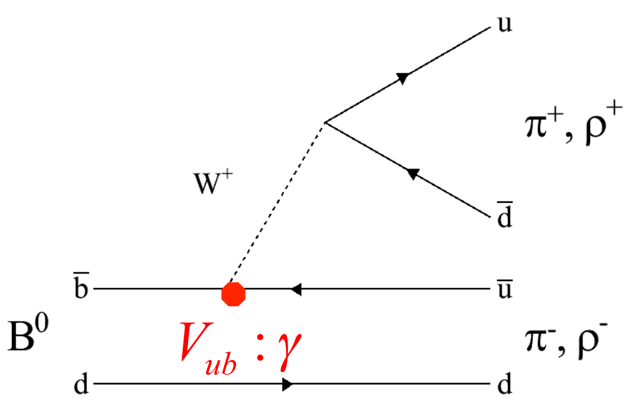

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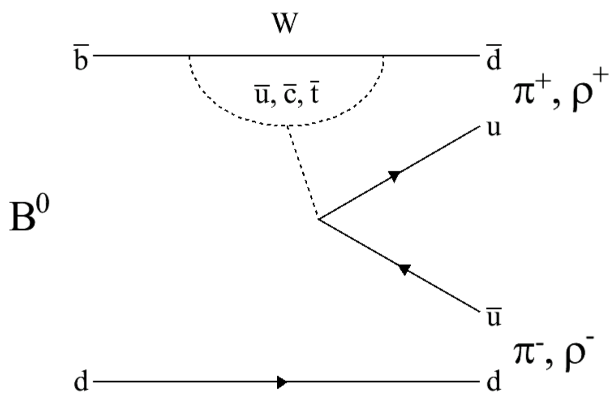

$$C_{hh} = 0$$

$$S_{hh} = \sin(2\alpha)$$

- ΔI =1/2 operators yield penguin and tree amplitudes.
- ΔI = 3/2 operators yield only tree amplitudes.
- Thus isospin is the key to understanding hadronic uncertainties in these decays.

Bounding penguins

- Several recipes describe how to bound penguins and measure alpha.
  - These are based on SU(2) or SU(3) symmetry.

SU(2)
(Isospin analysis)

(i.e. the assumed equivalence of *u* and *d* quark masses)

$\pi^+\pi^-$ and $\rho^+\rho^-$
Gronau-London
Isospin Triangles

- Use charged and neutral B decays to the hh final state to constrain the penguin contribution and measure alpha.

$\pi^{+/-}\rho^{-/+}$
Lipkin (et al.)
Isospin Pentagons

- Use charged and neutral B decays to the $\rho\pi$ final state to constrain the penguin contribution and measure alpha. Remove any overlapping regions in the Dalitz plot.

$\pi^{+/-}\pi^{-/+}\pi^0$
Snider-Quinn (et al.)
Fit Dalitz plot and extract parameters related to α

- Regions of the Dalitz plot with intersecting ρ bands are included in this analysis; this helps resolve ambiguities.

Bounding penguins

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SU(2)

(i.e. the assumed equivalence
sses)

- Focus on extaction of α using these decays, as the 3 π analysis is not numerically robust with existing data samples.

- This robustness issue is discussed in some detail the recent BaBar paper: arXiv: 1304.3503. Some comments are given in Appendix I.

- Final states with neutral pions need to be used to constrain hadronic uncertainties: this angle is only measured (currently) by the B Factories.

$\pi^+\pi^-$ and $\rho^+\rho^-$
Gronau-London
Isospin Triangles

- Use charged and neutral B decays to the hh final state to constrain the penguin contribution and measure alpha.

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SU(3)
flavor analysis

↓

Fit for T and P amplitudes,
as well as phase differences
δ_{TP} in related decays

- Theoretical uncertainties tend to result in weaker constraints than the SU(2) analyses.

- No choice for decays like $B \to a_1\pi$, have to use SU(3) approach

- Exception exists for $B \to \rho^+\rho^-$: Use $K^{*0}\rho^+$ to constrain penguin contribution in $\rho^+\rho^-$ and measure α with better precision than SU(2).

Bounding penguins

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  - These are based on SU(2) or SU(3) symmetry.

SU(3)
flavor analysis

↓

Fit for T and P amplitudes,
as well as phase differences
δ_{TP} in related decays

For brevity, these approaches are not discussed – see the Appendix I.

- Theoretical uncertainties tend to result in weaker constraints than the SU(2) analyses.
- No choice for decays like $B \to a_1 \pi$, have to use SU(3) approach
- Exception exists for $B \to \rho^+\rho^-$: Use $K^{*0}\rho^+$ to constrain penguin contribution in $\rho^+\rho^-$ and measure α with better precision than SU(2).

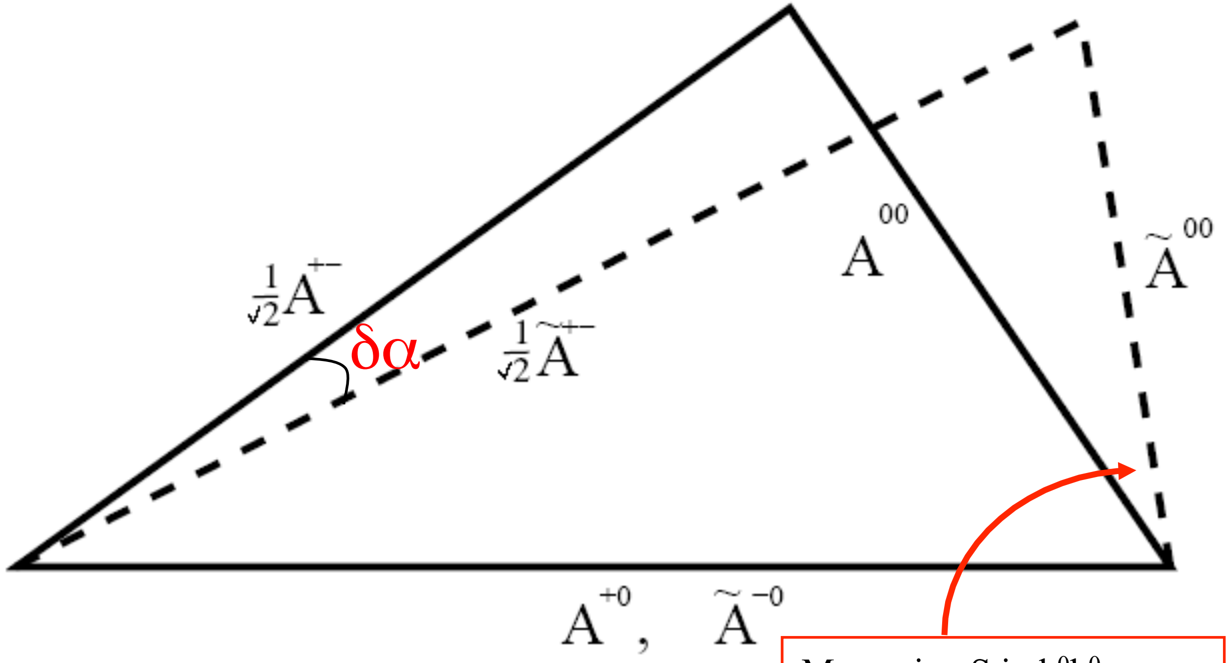
Isospin analysis

- Consider the simplest case: B→ππ / ρρ decays.

$$\frac{1}{\sqrt{2}}A^{+-} + A^{00} = A^{+0}$$

$$\frac{1}{\sqrt{2}}\overline{A}^{+-} + \overline{A}^{00} = \overline{A}^{+0}$$

$\delta\alpha = \alpha_{\mathrm{eff}} - \alpha$



Measuring S in h^0h^0 provides an additional constraint on this angle.

For ππ & ρρ require:

$\mathcal{B}(B^0 \to h^+h^-) + C.C.$

$\mathcal{B}(B^0 \to h^0h^0) + C.C.$

$\mathcal{B}(B^+ \to h^+h^0) + C.C.$

$S_{h^+h^-}$

- There are SU(2) violating corrections to consider, for example electroweak penguins, but these are much smaller than current experimental accuracy and can be incorporated into the Isospin analysis.

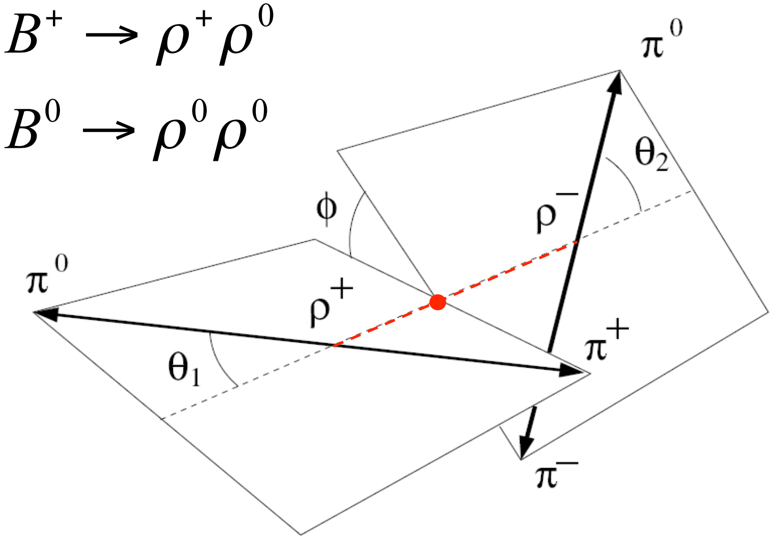
$B \to \rho\rho$

- This is a decay of a B meson to two vector mesons.
- Requires a (simplified) angular analysis.
- Inputs from:

$$B^0 \to \rho^+\rho^-$$

$$B^+ \to \rho^+\rho^0$$

$$B^0 \to \rho^0\rho^0$$



Φ is the angle between the two decay planes. This is integrated over as it plays no role in the angular distribution of the dominant longitudinal contribution.

θ_i are helicity angles: these are the angles between the direction of the π^0 and the direction opposite the B in the ρ rest frame.

- We define the fraction of longitudinally polarised events as:

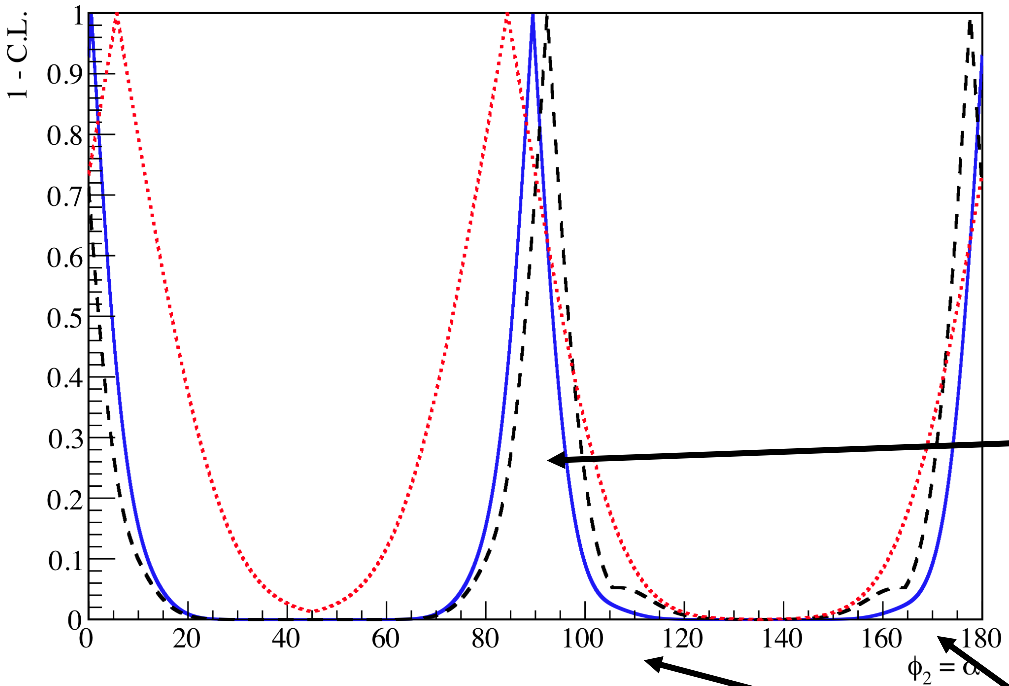
$$\frac{\Gamma_L}{\Gamma} = \frac{|H_0|^2}{|H_0|^2 + |H_{+1}|^2 + |H_{-1}|^2}, \\ = f_L.$$

$$\frac{d^2\Gamma}{\Gamma d\cos\theta_1 d\cos\theta_2} = \frac{9}{4}\left[f_L \cos^2\theta_1 \cos^2\theta_2 + \frac{1}{4}(1-f_L)\sin^2\theta_1 \sin^2\theta_2\right]$$

- $f_L \sim 1$ for $B \to \rho\rho$ decays: this helps simplify extracting α.
- Can measure S^{00} as well as C^{00} to help resolve ambiguities.
- Finite width of the ρ is ignored in the α determination (see Falk et al.)

B→ρρ

- These results dominate our knowledge on α.



- BaBar.
- Belle.
- Combined.

Some features of this result:

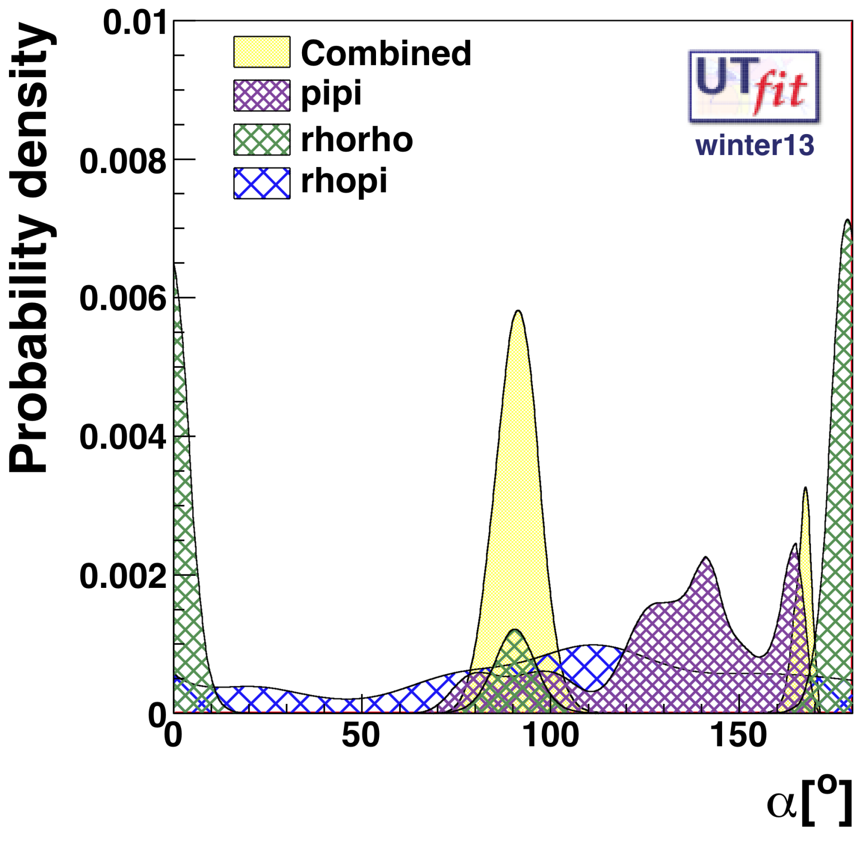
- Two of the solutions overlap near 90° and 180°.
- Ultimately we expect that the time-dependent CP asymmetry parameters measured in the $\rho^0\rho^0$ mode (S^{00} and C^{00}) will help resolve ambiguities. The effect can be seen as the bump at 110° and the mirror ~160°.
- There are two regions for α that are excluded:

$$\alpha \neq 45^\circ$$

$$\alpha \neq 130^\circ$$

CP violation: α

- One set of modes dominate our knowledge of α: B to ρρ decays
  - SU(3) can be used to provide an equivalent measurement with different theoretical uncertainties using B to $\rho^+\rho^-$ and $K^*\rho$.



- Many modes are required to try and measure α precisely. Any deviation in measured values of could indicate new physics.

$$B \to \pi^+\pi^-, \pi^+\pi^0, \pi^0\pi^0$$

$$B \to \rho^+\rho^-, \rho^+\rho^0, \rho^0\rho^0 \Big\}$$

Shown here

$$B \to \pi^+\pi^-\pi^0$$

$$B \to a_1\pi$$

$$B \to a_1\rho$$

...

Not shown: Need more data than currently available, and use SU(3) to extract α from final states with axial-vector mesons. These are related to hh modes above.

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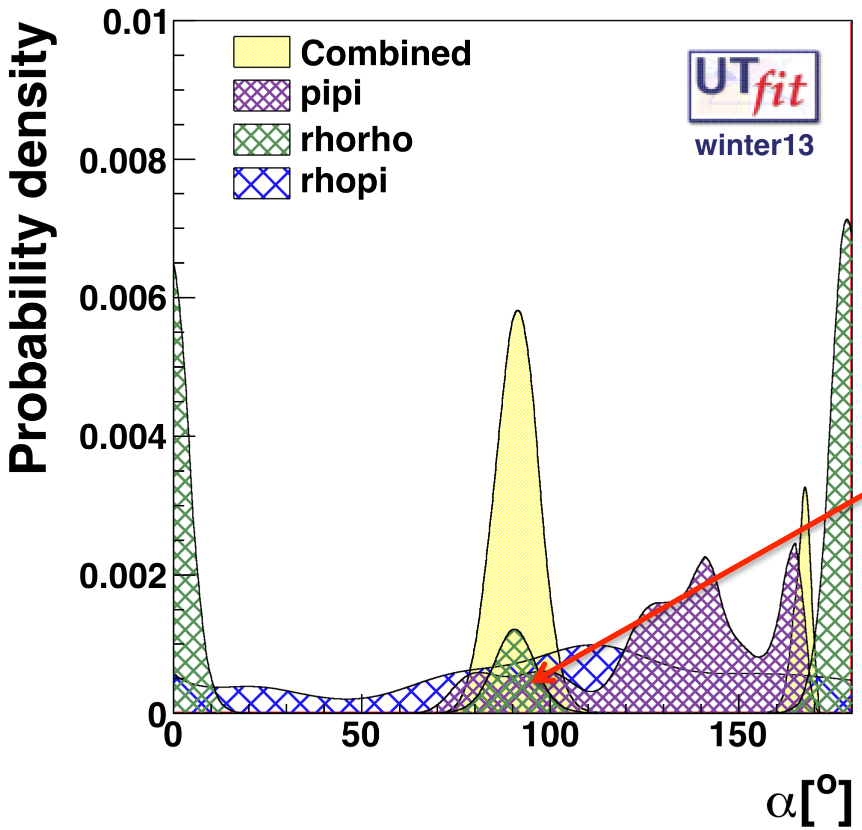

$$\alpha_{BF\ \mathrm{average}} = (88 \pm 5)^\circ$$

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$$B \to \pi^+\pi^-, \pi^+\pi^0, \pi^0\pi^0$$

$$B \to \rho^+\rho^-, \rho^+\rho^0, \rho^0\rho^0 \Big\}$$

Shown here

$$B \to \pi^+\pi^-\pi^0$$

$$B \to a_1\pi$$

$$B \to a_1\rho$$

…

Not shown: Need more data than currently available, and use SU(3) to extract α from final states with axial-vector mesons. These are related to hh modes above.

$b \to c$ interfering with $b \to u$

$B \to D^{(*)} K^{(*)}$

$B^0 \to D^- K^0 \pi^+$

$B^0 \to D^{(*)} \pi$

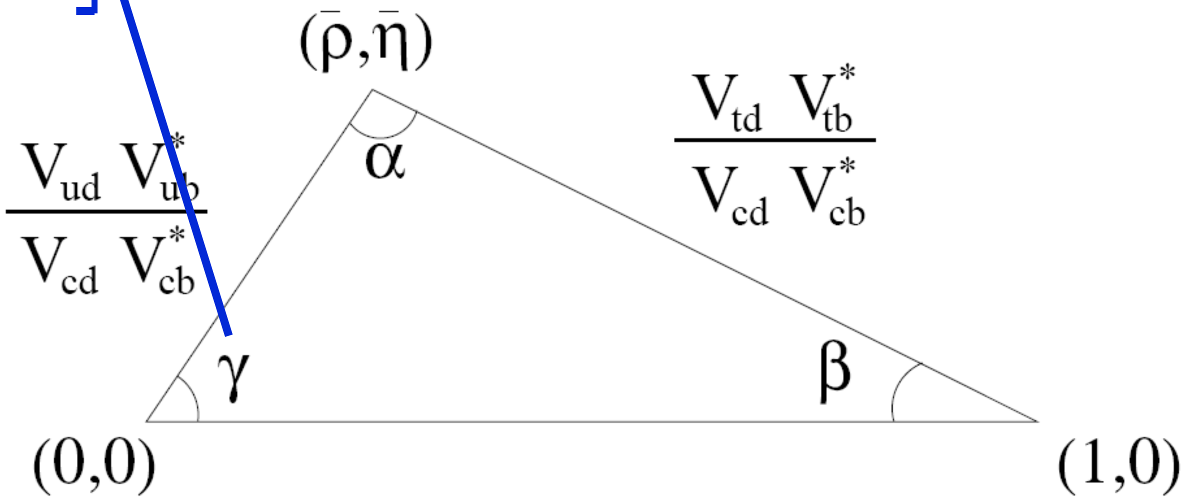
$B^0 \to D^{(*)} \rho$

$+$ *charmless*

Extract γ using $B \to D^{(*)} K^{(*)}$ final states using:

- GLW: Use CP eigen-states of D^0.
- ADS: Interference between doubly suppressed decays.
- GGSZ: Use the Dalitz structure of $D \to K_s h^+ h^-$ decays.

Measurements using neutral D mesons ignore D mixing.



Measuring γ

$\gamma \equiv \arg\left[-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*\right]$

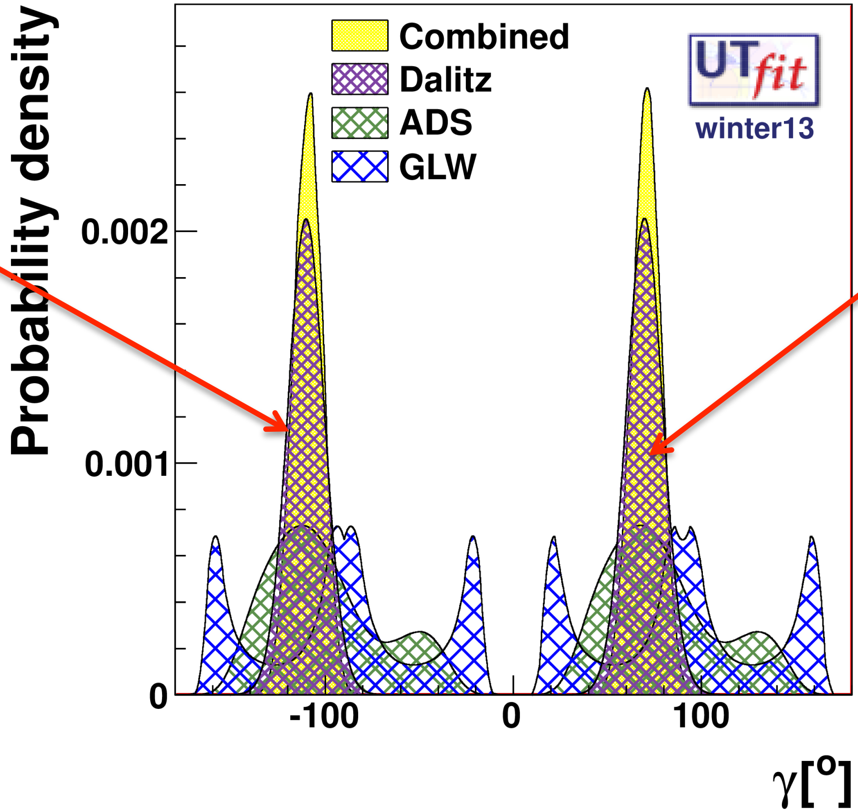
- Conceptually understanding how of the weak phase γ can be accessed in data is similar to α and β.
  - Two interfering amplitudes give rise to a dependence on the weak phase of interest. This is the result of interference between Cabibbo allowed vs Cabibbo suppressed contributions (different orders in λ in the decay amplitudes of interest).
  - One uses B decays to DK final states to extract information about the angle via one of three main methods:
    - ADS
    - GLW
    - GGSZ (or Dalitz method)
  - While it is possible to make theoretically clean measurements of this phase, these result from precision measurements of rare decays and the Dalitz method provides (currently) the best possible precision of all methods.

CP violation: γ

$\gamma \equiv \arg\left[-V_{ud}V_{ub}^{*}/V_{cd}V_{cb}^{*}\right]$

- In the long run the Dalitz method requires a binned measuremet of the strong phase difference in the $D \to K_S\pi^+\pi^-$ Dalitz plot – this is limited currently by CLEO data, however new results from BES III are expected soon.

$\gamma = (-109.0 \pm 7.8)^{\circ}$



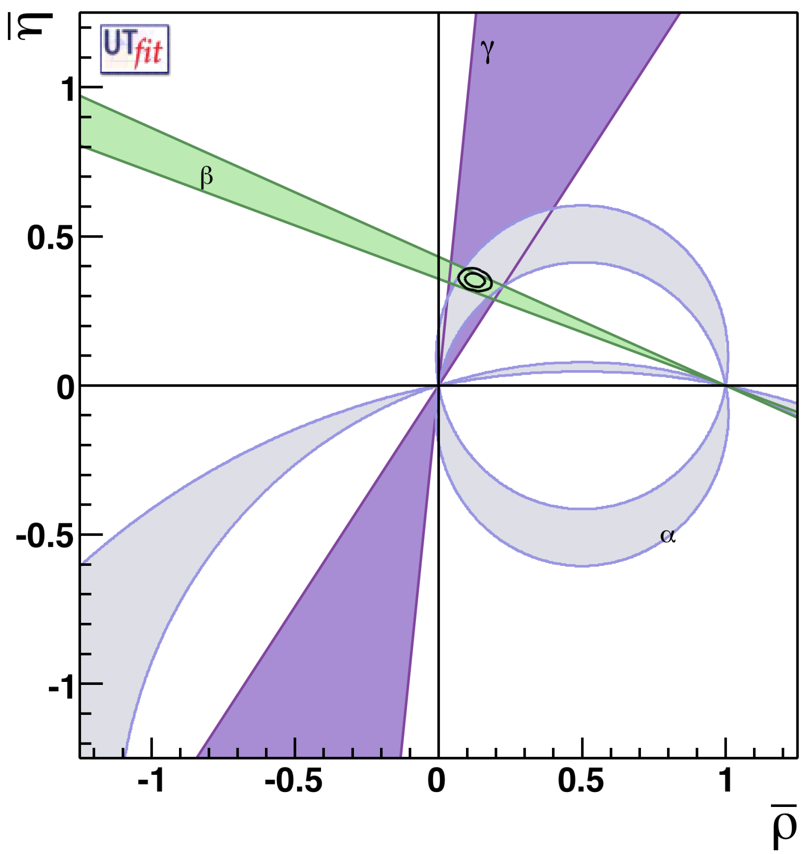
$\gamma = (70.8 \pm 7.8)^{\circ}$

- LHCb are also starting to make significant contriubutions to this measurement.

(Also see Appendix II)

What did we learn about the SM?

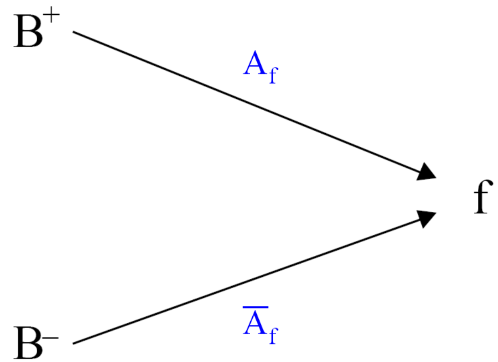
- Consider the angles measurements only (still dominated by the B Factories).



- Measurements of the angles (dominated by the precision on α and β)
  - Converge on a single point as predicted by the CKM matrix.
  - Are consistent with expectations from CPV in the kaon sector.
  - Establish the Kobayashi-Maskawa mechanism as a leading order description of CP violation in the quark sector of the SM.
  - Leave room for new physics to resolve the universal matter-antimatter asymmetry problem.

CP violation: Direct CP violation

- Recap from Introduction:
  - Number counting exercise: $A_{CP} = \frac{\overline{N} - N}{\overline{N} + N}$
  - Requires at least two amplitudes to interfere.
  - Amplitudes have to have different weak and strong phases. $A_{CP} \propto A_1 A_2 \sin(\phi_1 - \phi_2) \sin(\delta_1 - \delta_2)$



  - We are comparing A_f with $\overline{A}_f$.

  - Predictive power will be limited by our knowledge of weak phases and of the strong phase differences.
    - But there are many possible measurements that we can compare!

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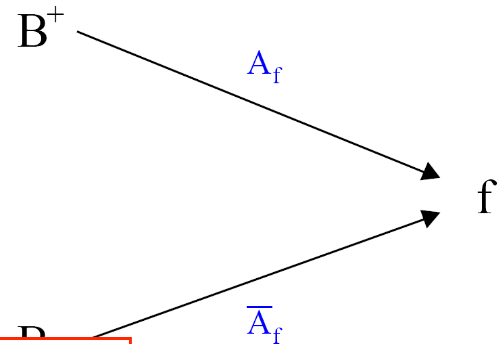

- We are comparing A_f with $\overline{A}_f$.

These are well defined in the SM, come from quartets of CKM matrix elements, thus depend on δ_{KM}.

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  - But there are many possible measurements that we can compare!

CP violation: Direct CP violation

- Recap from Introduction:
  - Number counting exercise: $A_{CP} = \dfrac{\overline{N} - N}{\overline{N} + N}$
  - Requires at least two amplitudes to interfere.
  - Amplitudes have to have different weak and strong phases. $A_{CP} \propto A_1 A_2 \sin(\phi_1 - \phi_2)\sin(\delta_1 - \delta_2)$

These strong phases can not be calculated accurately, and so present a problem when trying to interpret measurements.

  - We are comparing A_f with $\overline{A}_f$.

These are well defined in the SM, come from quartets of CKM matrix elements, thus depend on δ_{KM}.

  - Predictive p… wledge of weak phases and of the strong phase differences.
    - But there are many possible measurements that we can compare!

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  - Number counting exercise: $A_{CP} = \frac{\overline{N} - N}{\overline{N} + N}$
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  - Amplitudes have to have different weak and strong phases. $A_{CP} \propto A_1 A_2 \sin(\phi_1 - \phi_2) \sin(\delta_1 - \delta_2)$

These amplitudes are calculable in an appropriate theoretical framework, for an assumed set of Feynman diagrams (or rather operators in the effective Hamiltonian).

These are well defined in the SM, come from quartets of CKM matrix elements, thus depend on δ_{KM}.

These strong phases can not be calculated accurately, and so present a problem when trying to interpret measurements.

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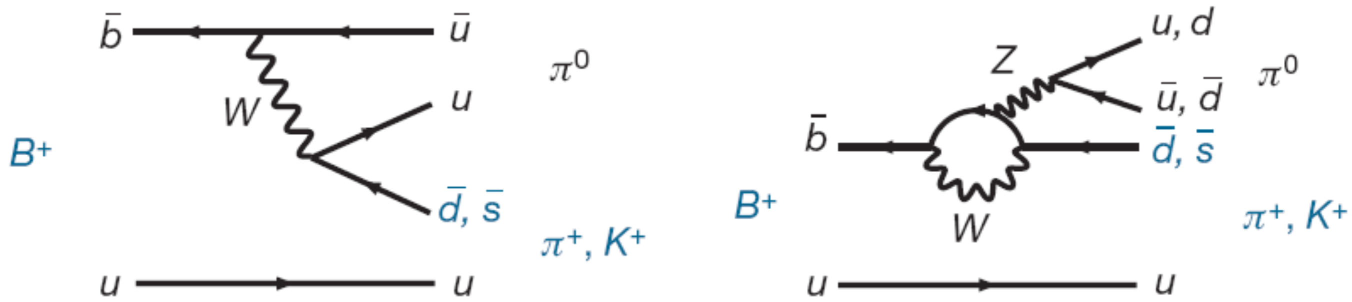
- Predictive p… wledge of weak phases an… es.
  - But there are many possible measurements that we can compare!

CP violation: Direct CP violation

- $B^0 \to K^\pm \pi^\mp$: Tree and gluonic penguin contributions

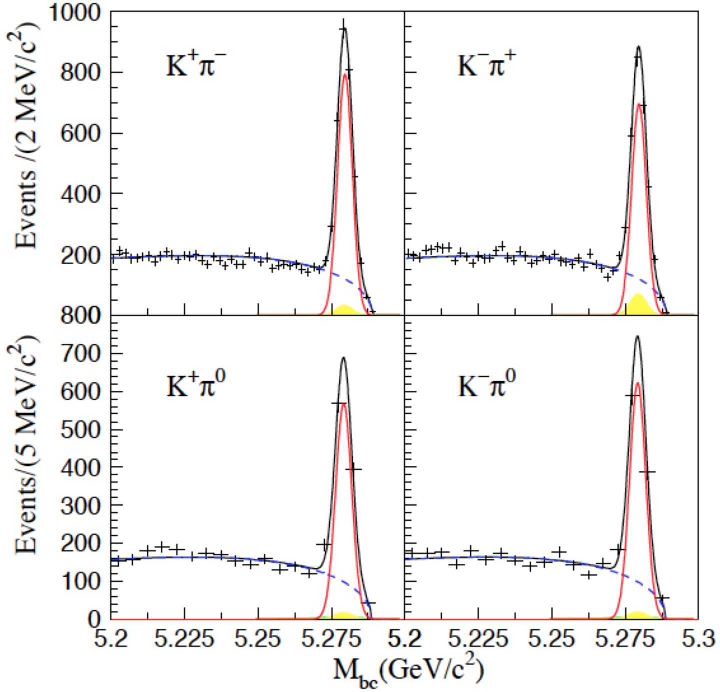


- Compute time integrated asymmetry

$$A_{K^\pm \pi^\mp} = -0.069 \pm 0.014 \pm 0.007$$

- Experimental results from Belle, BaBar, and CDF have significant weight in the world average of this CP violation parameter.
- Direct CP violation present in B decays.
- Unknown strong phase differences between amplitudes, means we can't use this to measure weak phases!

~7500 Kπ events reconstructed.



CP violation: Direct CP violation

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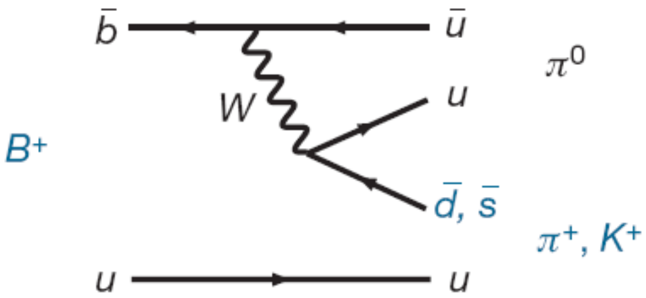

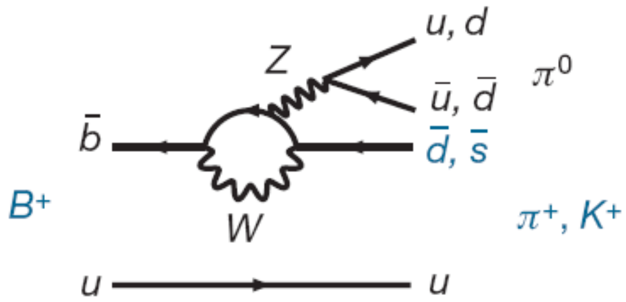

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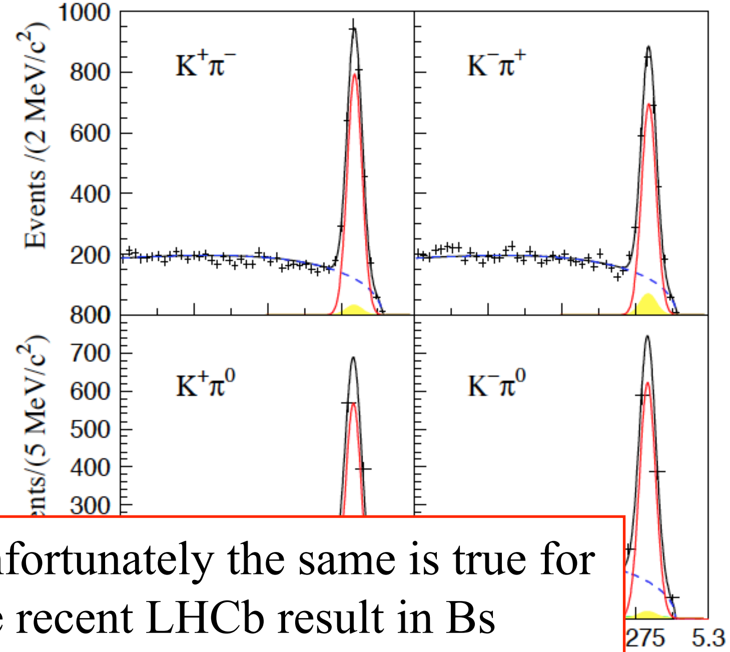

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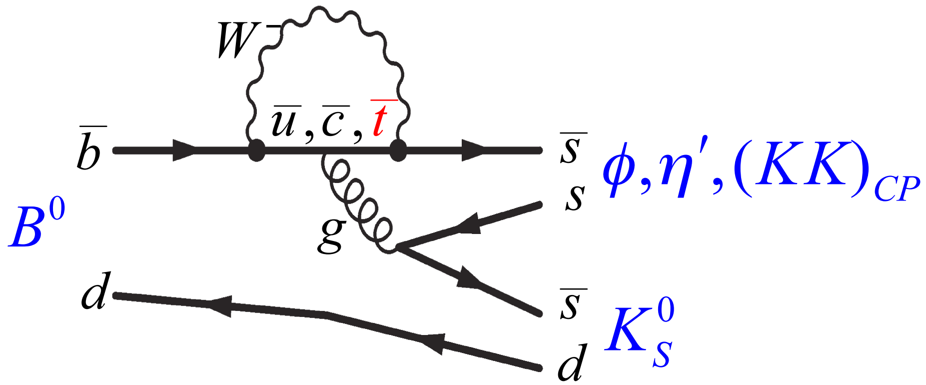
- Direct CP violation present in B decays.
- Unknown strong phase differences between amplitudes, means we can't use this to measure weak phases!

Unfortunately the same is true for the recent LHCb result in Bs decays to the same final state.

CP violation: Searching for new physics

- sin2β has been measured to O(1°) accuracy in $b \to c\bar{c}s$ decays.
- Can use this to search for signs of New Physics (NP) if:
  - Identify a rare decay sensitive to sin2β (loop dominated process).
  - Measure S precisely in that mode (S_{eff}).
  - Control the theoretical uncertainty on the Standard Model 'pollution' (ΔS_{SM}).
  - Compute $\Delta S = S_{meas} - S_{c\bar{c}s} - \delta S_{SM}$
- In the presence of NP: $\Delta S_{NP} \neq 0$



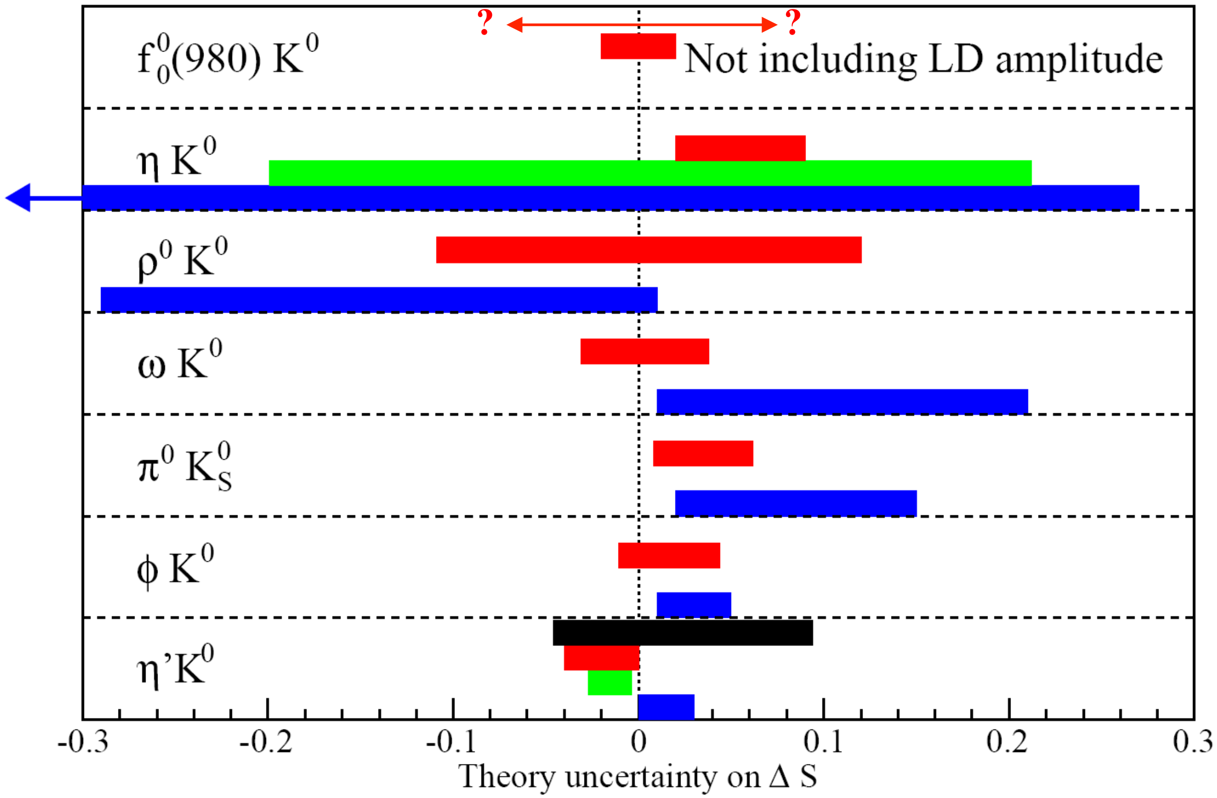
- Many tests have been performed in:
  - B→d processes.
  - B→s processes.

- Unknown heavy particles can introduce new amplitudes that can affect physical observables of loop dominated processes.
- Observables that might be affected include branching fractions, CP asymmetries, forward backward asymmetries … and so on.
- A successful search requires that we understand Standard Model contributions well!

SM uncertainties on ΔS

- To find NP we need to understand the SM contributions to a process.
  - Leading order term is expected to be the same as a SM weak phase.
  - Higher order terms including re-scattering, suppressed amplitudes, final state radiation and so on can modify our expectations.

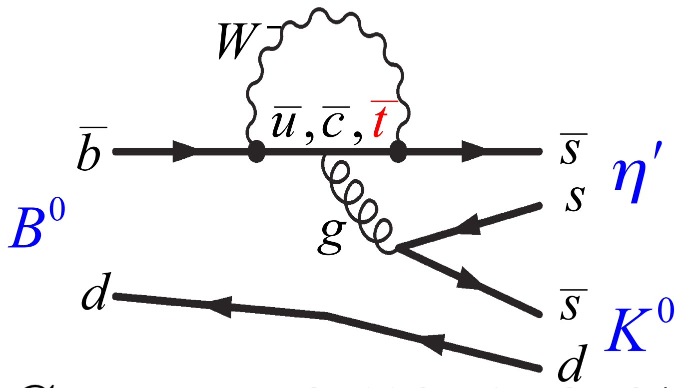
- Some channels are better understood than others.
- Sign of ΔS correction is mode dependent.
- Most precise ΔS correction is for $B^0 \to \eta' K^0$, where $\Delta S_{theory} \sim \pm 0.01$.
- Concentrate efforts on well understood channels.



- QCDF Beneke, PLB**620**, 143 (2005)
- SCET/QCDF, Williamson and Zupan, PRD**74**, 014003 (20
- QCDF Cheng, Chua and Soni, PRD**72**, 014006 (2005)
- SU(3) Gronau, Rosner and Zupan, PRD**74**, 093003 (2006)

$B \to \eta' K^0$

- Loop dominated b→s decay.



$$S = 0.59 \pm 0.07$$

$$C = 0.05 \pm 0.05$$

$$\Delta S = -0.077 \pm 0.075$$

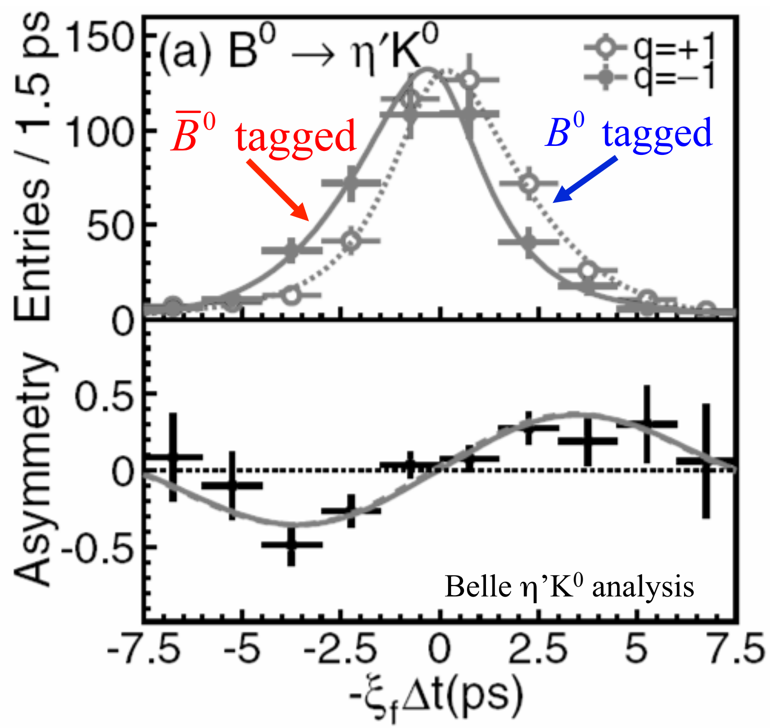
- CP violation has been established in this decay channel by the B factories.
- Need at least 50 ab^{-1} of data to do a precision search for NP at the level of current theoretical uncertainties.

- Possible to measure S and C for both

$$B^0 \to \eta' K^0_S \quad \text{(CP odd)}$$

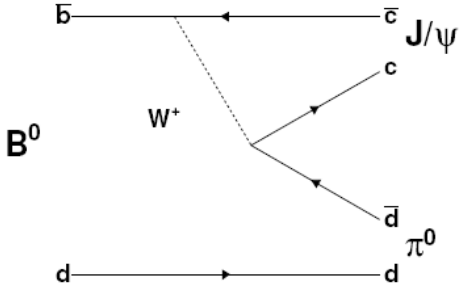
$$B^0 \to \eta' K^0_L \quad \text{(CP even)}$$

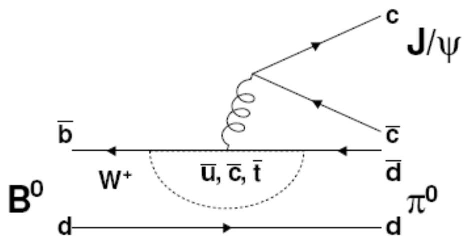
- These asymmetries can be compared with the Charmonium reference measurement to calculate ΔS.



$B^0 \to J/\psi\pi^0$

- Tree and penguin contributions: can be sensitive to NP.
- Alternatively, can be used to constrain SM uncertainties in the Charmonium β measurement.

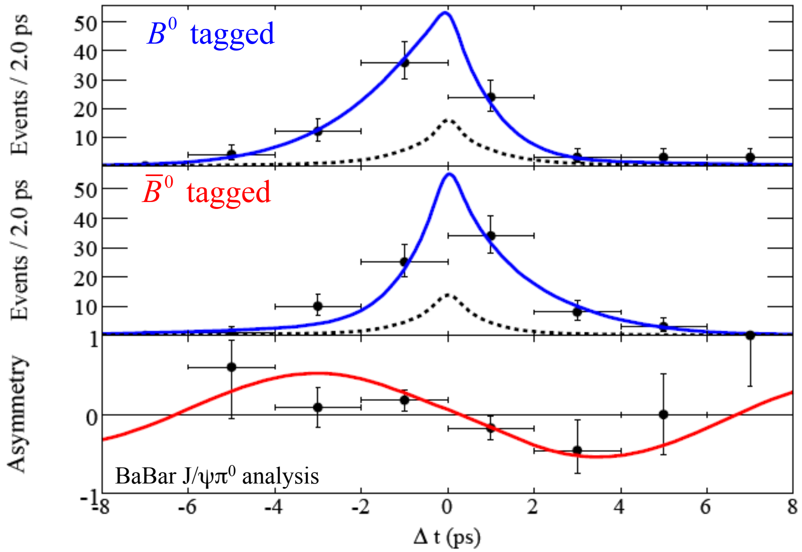




- CP even final state:

$$S^{Tree}_{J/\psi\pi^0} = -S_{c\bar{c}s}$$

- CP violation observed in this decay.



$$S_{J/\psi\pi^0} = -0.93 \pm 0.15$$

$$C_{J/\psi\pi^0} = -0.10 \pm 0.13$$

$$\Delta S_{J/\psi\pi^0} = 0.23 \pm 0.15_{\text{exp}}$$

- Require a dataset of ~220ab^{-1} to make a 1% ΔS measurement in this channel.

Overview of ΔS measurements

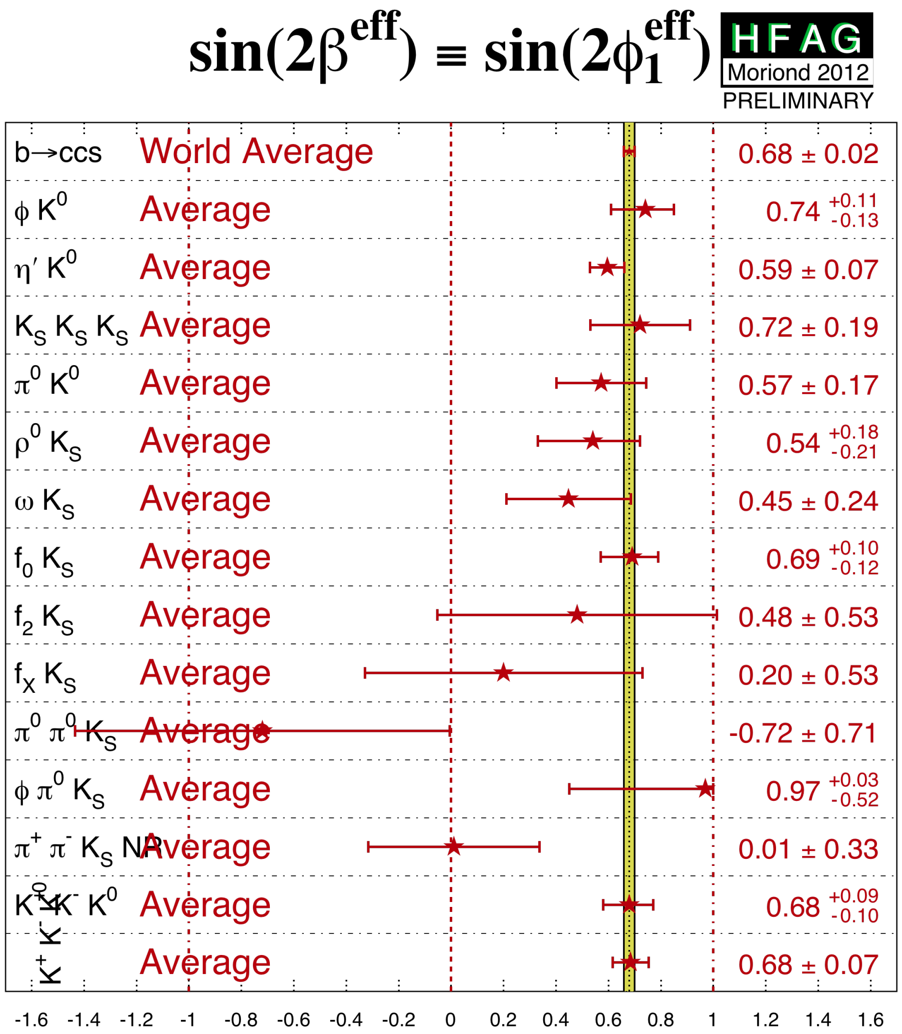
- Comparing sin2β in different physical processes, we see good agreement with the b→ccs reference point.

- Most of the b→s penguin channels have $\sin 2\beta_{eff} < \sin 2\beta$.
  - Could this be an indication of NP?
    - Insufficient statistics to tell.
  - Need to perform a mode-by-mode precision measurement in order to properly decouple Standard Model uncertainties from possible signals of NP.

- We need at least $50ab^{-1}$ to start performing measurements that will have comparable experimental and theoretical uncertainties in b→s penguin processes.

- Need $\sim 220ab^{-1}$ to do the same for b→d.

- Can start to do the same with α and γ once we have a precision measurement from one mode.



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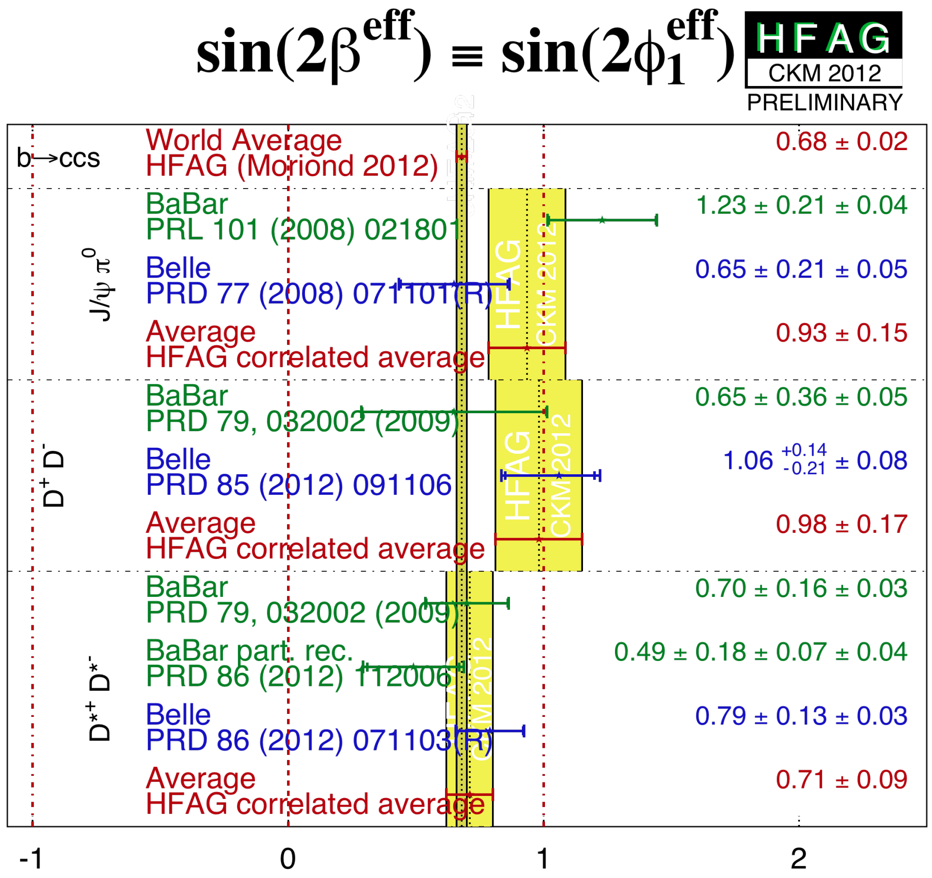


Sides of the Unitarity Triangle

This is a detailed and important topic, however unfortunately there is not time to discuss this in detail.

$b \to u l \nu$

$B \to \pi l \nu$

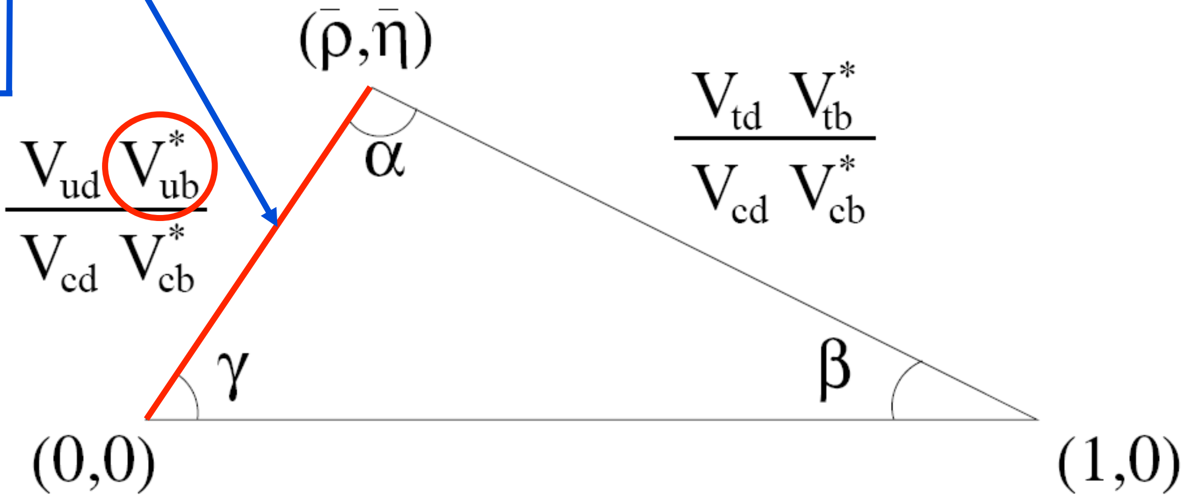
$B \to X_u l \nu$

$B \to \rho l \nu$

$B \to \omega l \nu$

⋮

- Use theory to relate partial branching fractions to V_{ub} for a given region of phase space.
- Several theoretical schemes available.



Sides of the Unitarity Triangle

This is a detailed and important topic, however unfortunately there is not time to discuss this in detail.

- Use theory to relate partial branching fractions to V_{cb} for a given region of phase space.

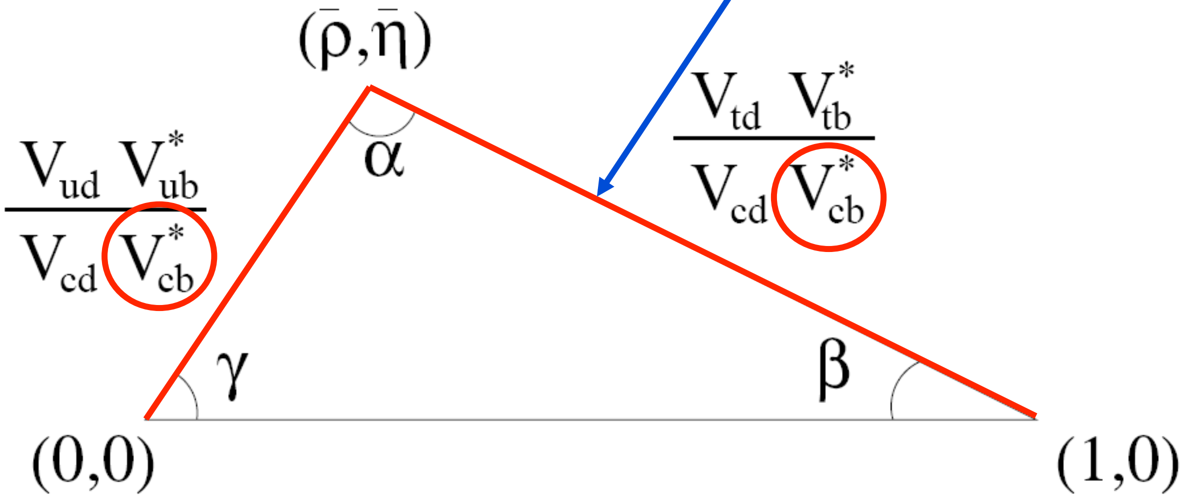
$b \to cl\nu$

$B \to D^{(*)}l\nu$

$B \to DX l\nu$

$B \to D^{**}l\nu$

$\vdots$



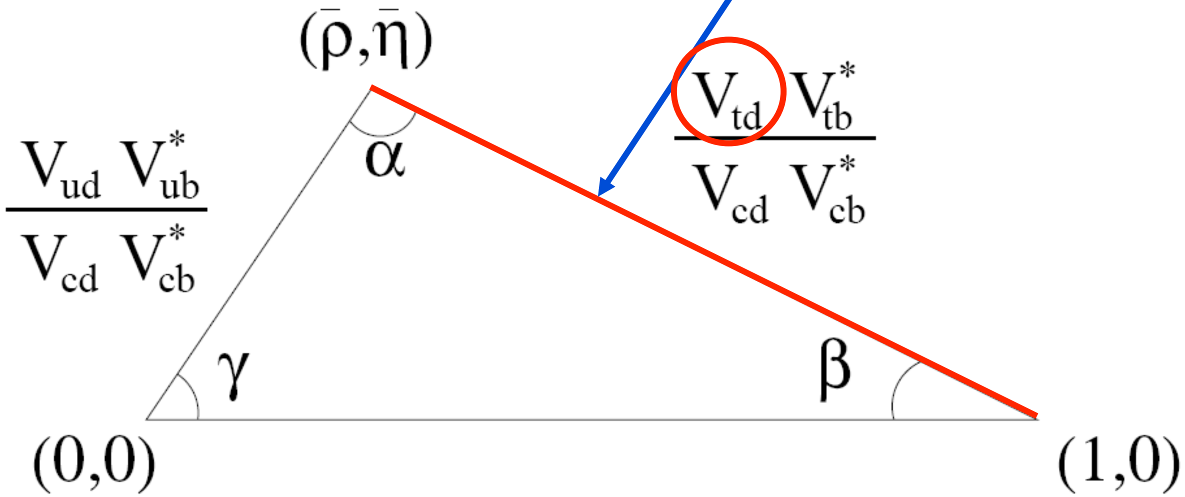
Sides of the Unitarity Triangle

This is a detailed and important topic, however unfortunately there is not time to discuss this in detail.

- Use inclusive measurements of $b \to d\gamma$ and $b \to s\gamma$ to measure the ratio $|V_{td}| / |V_{ts}|$.
- Able to compare results with Bs mixing results from the TeVatron.

$b \to d\gamma$

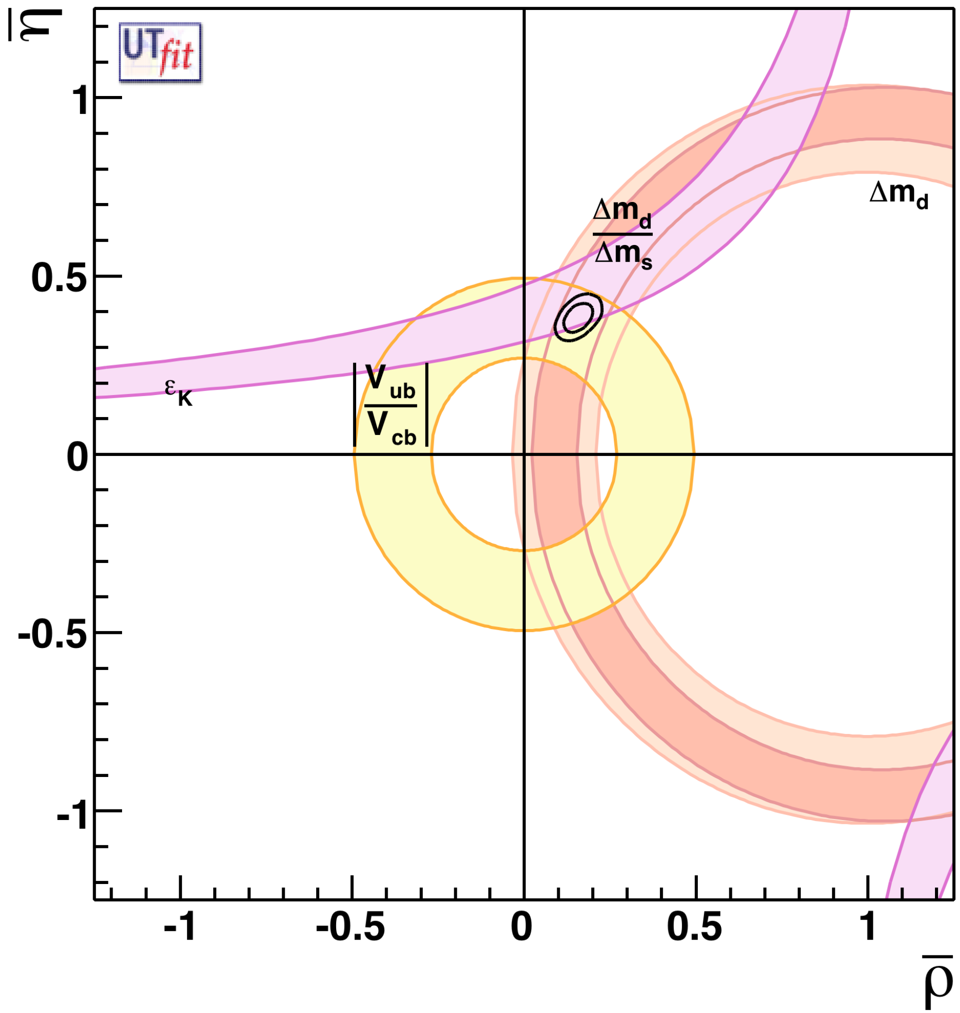
$B \to X_d \gamma$



(Also see Appendix II)

Sides of the Unitarity Triangle

- Annular constraints can be placed on the apex of the triangle

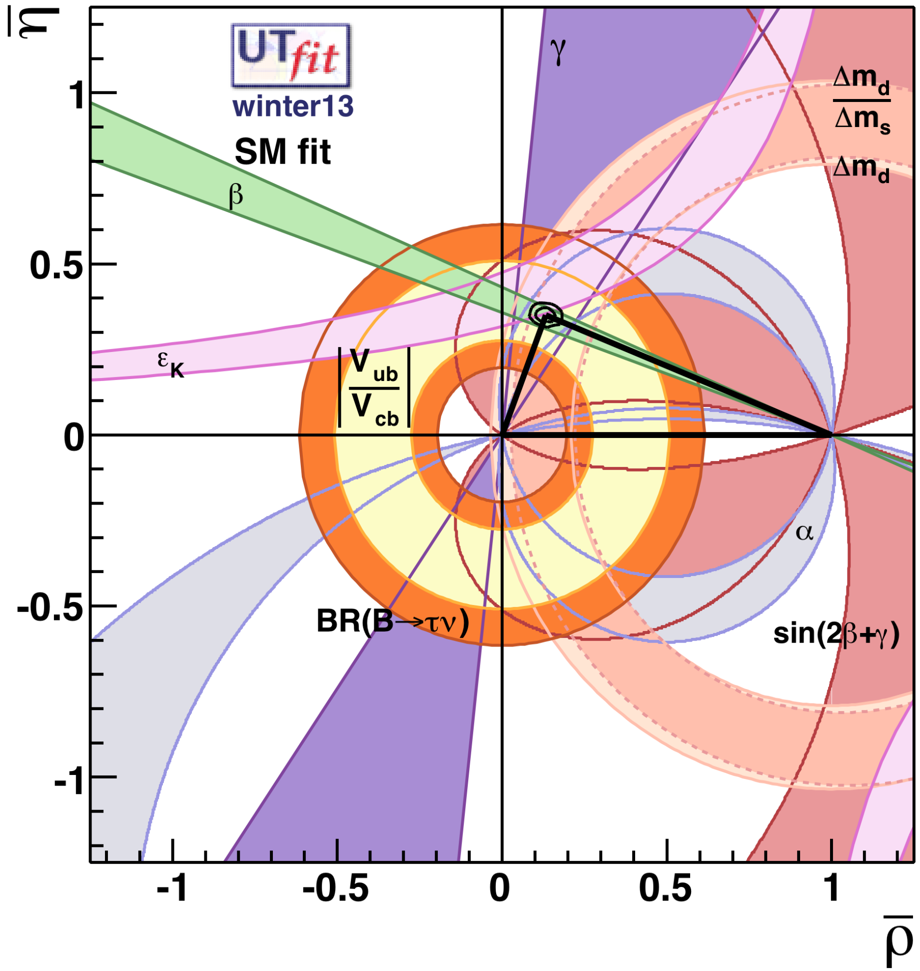


The results on V_{ub} and V_{cb} are compatible with mixing measurements, and CP violation in the kaon sector.

The big picture view

(Also see Appendix II)

- All constraints on the apex of the triangle are compatible.



$$A = 0.827 \pm 0.013$$
$$\lambda = 0.22535 \pm 0.00065$$
$$\rho = 0.136 \pm 0.021$$
$$\eta = 0.359 \pm 0.014$$

Similar results are obtained by other fitter collaborations.

See Appendix II for a brief introduction to how one can constrain a theoretical parameter using experimental observables.

Rare and forbidden B Decays

- These are probes for new physics.

- Different topologies can be used to constrain different features in the Lagrangian of different new physics models.

- In order to be sure that we understand any new physics found in the future, we should ensure that we perform a wide range of tests.
  - *Patterns of deviation from the standard model will tell us something about the detail of new physics, and help us go beyond saying that we have found something unexpected and we don't know what it is.*

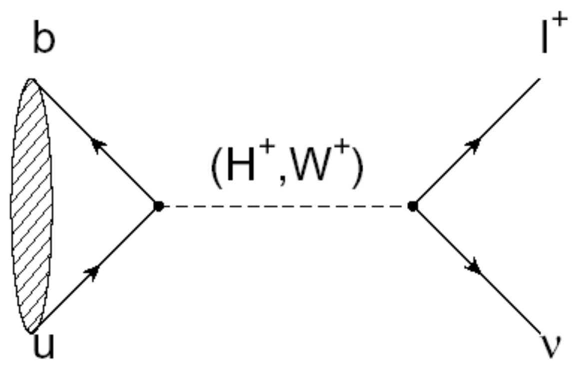
  - *There are many interesting decays, I will just briefly mention B to $\tau\nu$, also see the appendix and the talk by Mary-Helene Schune.*

$B^{\pm} \to \tau^{\pm}\nu$

(Also see Appendix II)

- The decay $B^{\pm} \to \tau^{\pm}\nu$ has been measured, and can be compared with theoretical expectations.
- Measurement: $\mathcal{B}(B^{\pm} \to \tau^{\pm}\nu) = (1.15 \pm 0.23) \times 10^{-4}$
- Standard Model expectation:

$$\mathcal{B}(B^{\pm} \to \tau^{\pm}\nu)_{SM} = (1.01 \pm 0.29) \times 10^{-4}$$



In the Standard Model this channel is mediated by a W boson.

Beyond the Standard Model contributions from a charged Higgs particle can also be relevant.

$B^{\pm} \to \tau^{\pm}\nu$

(Also see Appendix II)

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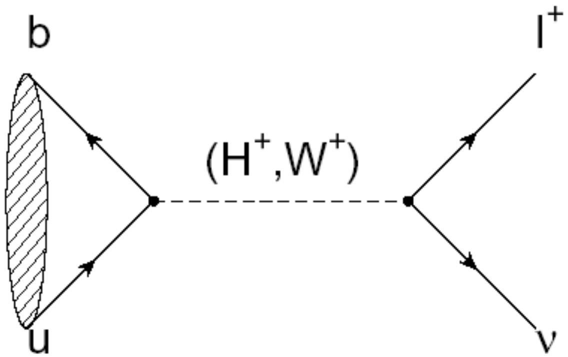
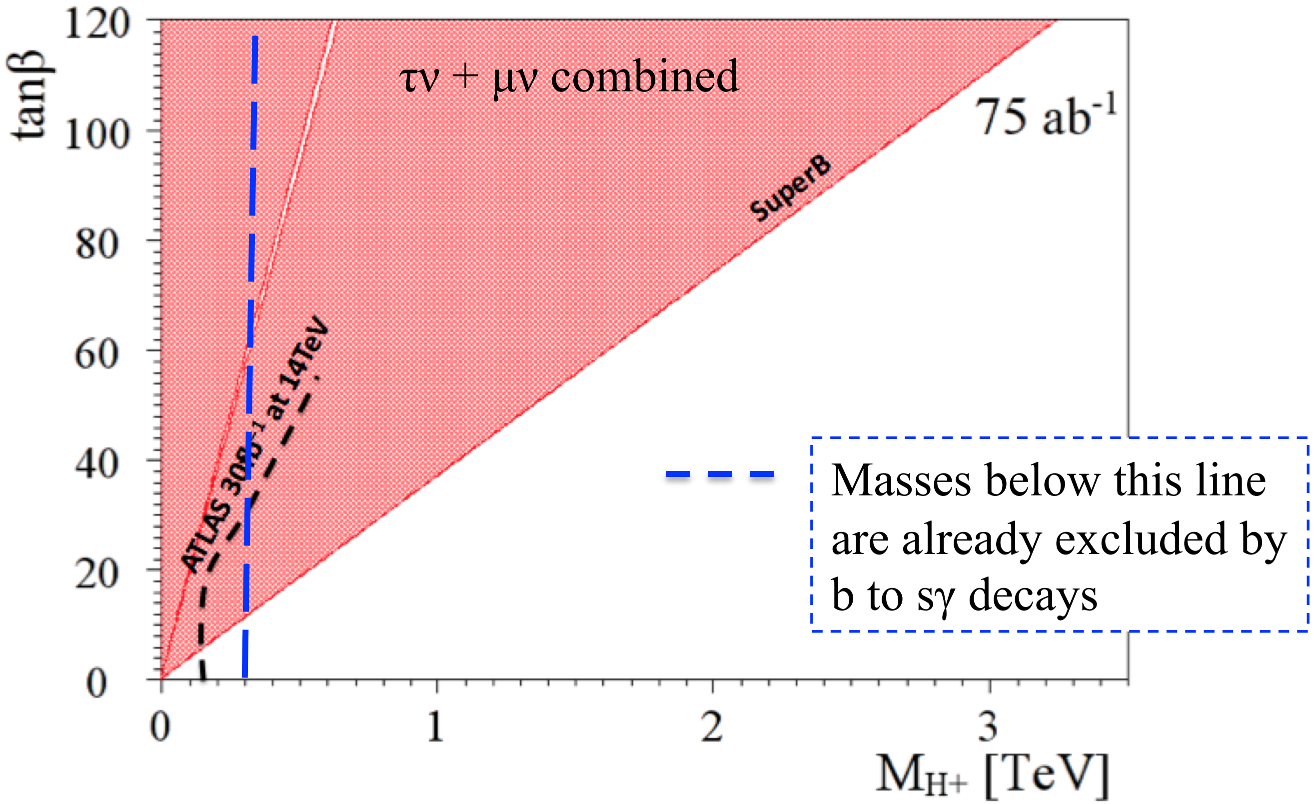


$$r_H = \frac{\mathcal{B}_{SM+NP}}{\mathcal{B}_{SM}}$$

For a simple extension of the Standard Model, called the type II 2 Higgs Doublet Model we know that r_H depends on the mass of a charged Higgs and another parameter, β.

$$r_H = \left(1 - \frac{m_B^2}{m_H^2}\tan^2\beta\right)^2$$

- Looking forward one can estimate the kind of constraint on this model that can be made at Belle II.
  - Assume a measurement compatible with the SM.
  - The constraint for $50ab^{-1}$ is similar to that shown below.



Physics: Quarks

D MESONS

The quest for charm mixing

- Mixing is slow in charm: so instead of Δm and $\Delta\Gamma$, we (usually) describe charm mixing with the parameters x and y, and Taylor expand the usual time-dependent formalism to obtain simplifications relevant for charm.

$$x = \frac{\Delta \mathrm{m}}{\Gamma} \qquad\qquad y = \frac{\Delta\Gamma}{2\Gamma}$$

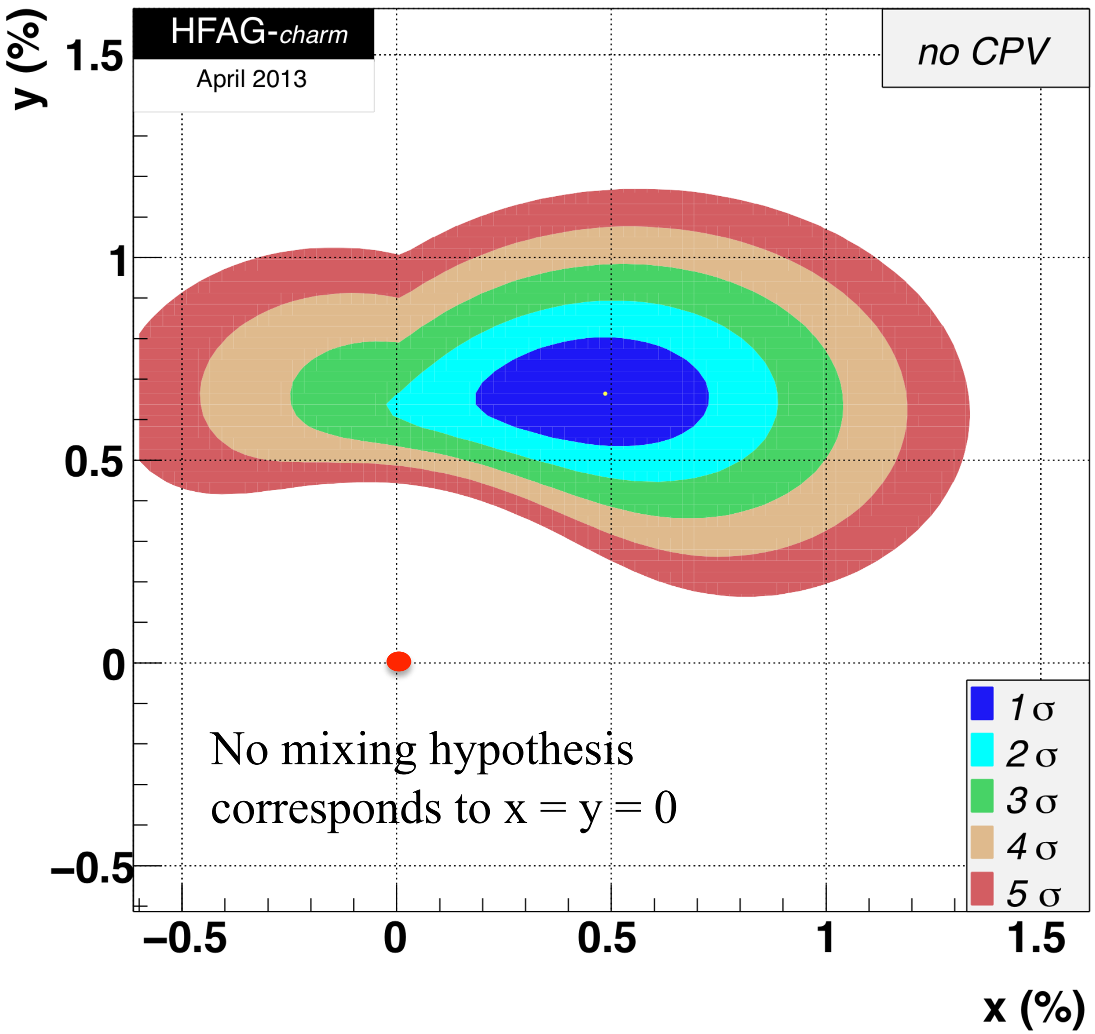
- Different final states can be used to explore mixing, often we study modes which have a strong phase difference that is important in the extraction of mixing parameters. These result in primed variables: x', y' that need to be extracted.

- N.B. While it is clear that the current formalism is good enough, one can expect that future measurements will eventually have sufficient statistics to require a more robust parameterisation.

- BaBar saw oscillations of charm mesons
- The combined BaBar, Belle, CLEO and the Tevatron combined were sufficient to establish charm mixing at the level of 5 sigma, but these results have recently been surpassed by an LHCb result that is the most significant observation of mixing in charm.

Parameter	No CPV	No direct CPV	CPV-allowed	CPV-allowed 95% C.L.
x (%)	$0.49^{+0.17}_{-0.18}$	0.46 ± 0.18	$0.49^{+0.17}_{-0.18}$	[0.10, 0.81]
y (%)	0.66 ± 0.09	0.67 ± 0.09	0.74 ± 0.09	[0.56, 0.92]
δ (°)	$10.8^{+10.3}_{-12.3}$	$11.4^{+10.5}_{-12.7}$	$19.5^{+8.6}_{-11.1}$	[−9.6, 35.4]
R_D (%)	0.347 ± 0.006	0.347 ± 0.006	$0.350^{+0.007}_{-0.006}$	[0.337, 0.362]
A_D (%)	–	–	-2.6 ± 2.2	[−6.9, 1.7]
$\|q/p\|$	–	$1.04^{+0.07}_{-0.06}$	$0.69^{+0.17}_{-0.14}$	[0.44, 1.07]
ϕ (°)	–	$-1.6^{+2.4}_{-2.5}$	$-29.6^{+8.9}_{-7.5}$	[−44.6, −7.5]
$\delta_{K\pi\pi}$ (°)	$21.3^{+23.4}_{-23.8}$	$22.9^{+23.7}_{-24.0}$	$25.1^{+22.3}_{-23.0}$	[−20.6, 69.2]
A_π	–	–	0.16 ± 0.21	[−0.25, 0.57]
A_K	–	–	-0.16 ± 0.20	[−0.56, 0.23]
x_{12} (%)	–	0.46 ± 0.18	–	[0.10, 0.80]
y_{12} (%)	–	0.67 ± 0.09	–	[0.50, 0.85]
ϕ_{12}(°)	–	$4.8^{+9.2}_{-7.4}$	–	[−11.7, 35.9]

Current HFAG results (as of end April 2013)



Mixing in charm is interesting because:

(i) One can have CP violation in mixing.

(ii) One can explore CP violation in the interference between mixing and decay amplitudes.

(iii) There are a number of mixing and CP violation observables that could be affected by physics beyond the standard model.

CP Violation in charm

- The next generation of experiments will yield sufficient statistics to start to constrain time-dependent CP asymmetry parameters in the charm sector.
  - Data samples will be insufficient to measure a non-zero SM effect, but one can perform null tests.
  - Time-dependent measurements result in constraints on $\mathrm{Im}\lambda$ related to the KM phase in the CKM matrix.
  - Hadronic uncertainties will need to be understood.
  - This is an interesting area that is expected to develop in the coming decade.

Many authors have written on this topic in the last few years including AB et al.; Kagan et al. & Zupan et al.; Silvestrini et al; Bigi et al. A lot of the recent focus has been on time-integrated measurements, which in the short term showed promise.

A large number of probes available

- More generally there is a large number of charm decays to study CP violation in.
  - Direct CP violation is a good starting point, but hadronic uncertainties limit what can be learned from such measurements.
  - Time-dependent asymmetries are more interesting as we can constraint the weak phases in the SM.

$$D^0 \to K^+K^-$$
$$D^0 \to K^0_S K^0_S$$
$$D^0 \to \pi^+\pi^-$$
$$D^0 \to \pi^0\pi^0$$
$$D^0 \to \rho^+\rho^-$$
$$D^0 \to \rho^0\rho^0$$
$$D^0 \to \phi\pi^0$$
$$D^0 \to \phi\rho^0$$
$$D^0 \to f^0(980)\pi^0$$
$$D^0 \to \rho^0\pi^0$$
$$D^0 \to a^0\pi^0$$
$$D^0 \to K^0_S K^0_S K^0_S$$
$$D^0 \to K^0_L K^0_S K^0_S$$
$$D^0 \to K^0_L K^0_L K^0_S$$
$$D^0 \to K^0_L K^0_L K^0_L$$

$$D^0 \to K^0_S\pi^0$$
$$D^0 \to K^0_S\omega$$
$$D^0 \to K^0_S\eta$$
$$D^0 \to K^0_S\eta'$$
$$D^0 \to K^0_S\pi^+\pi^- \ \text{(NR)}$$
$$D^0 \to K^0_S\rho^0$$
$$D^0 \to K^0_S K^+K^- \ \text{(NR)}$$
$$D^0 \to K^0_S\phi$$
$$D^0 \to K^0_S f^0$$
$$D^0 \to K^0_S a^0$$

$$D^0 \to K^0_L\pi^0$$
$$D^0 \to K^0_L\omega$$
$$D^0 \to K^0_L\eta$$
$$D^0 \to K^0_L\eta'$$
$$D^0 \to K^0_L\pi^+\pi^- \ \text{(NR)}$$
$$D^0 \to K^0_L\rho^0$$
$$D^0 \to K^0_L K^+K^- \ \text{(NR)}$$
$$D^0 \to K^0_L\phi$$
$$D^0 \to K^0_L f^0$$
$$D^0 \to K^0_L a^0$$

AB, Inguglia, Meadows, PRD **84** 114009 (2011)

BaBar, Belle (II) and the LHC can study CPV via incoherent production.

An asymmetric τ-charm machine would have the benefit of a well defined initial state and high tagging Q.

Ultimately this will be a game of precision.
= systematic control

Physics: Leptons

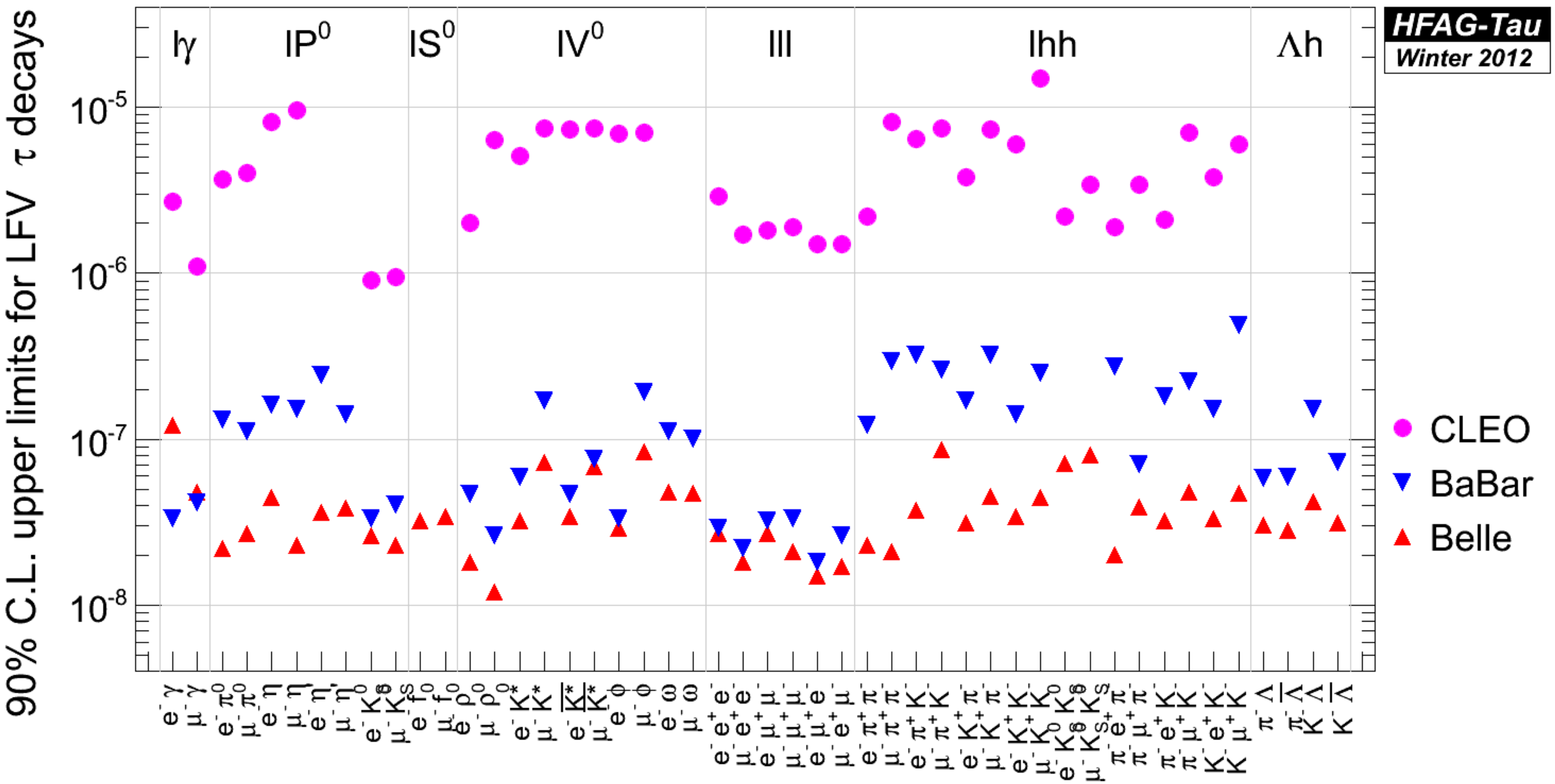
SEE THE LECTURES ON TAU PHYSICS BY J. PORTOLÉS, AND ON LEPTON FLAVOUR VIOLATION BY M. HIRSCH.

- The SM naturally has a low intrinsic level of charged lepton flavour violation (LFV) as a result of neutrino oscillations.
  - Such an effect would be un-observable with current or planned experiments.

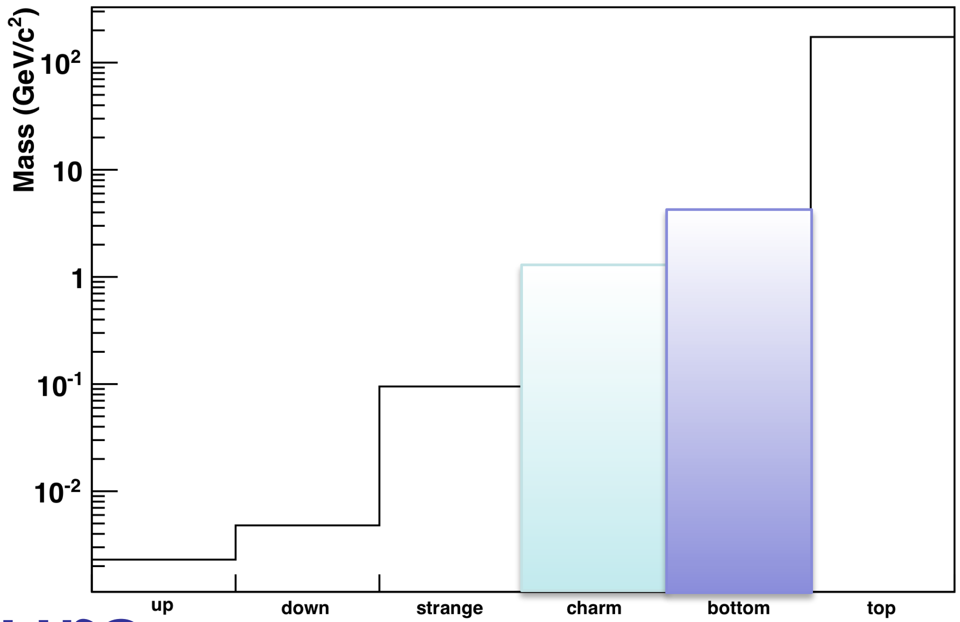
$$\mathcal{B}_{SM}(\tau \to \mu\gamma) \simeq 10^{-54}$$

  - Many new physics scenarios include charged LVF couplings, which are able to enhance the expected level of many branching ratios up to the current experimental limits.
  - Experimentally a large number of potential channels remain background free, and improved sensitivity will scale by 1/N, whereas some modes have backgrounds and the scaling will be with the square root of increase in statistics from present day results.

- Current constraints on charged LFV decays from the B Factories:



- The next generation of B Factories will allow for 1-2 order of magnitude improvements on these limits. for example:
  - Some decays such as $\tau \rightarrow \mu\gamma$ at the Υ(4S) scale with increase in statistics, as there is an irreducible physics background.
  - Some decays such as $\tau \rightarrow \mu\mu\mu$ scale with statistics as these are expected to be background free up to data samples of at least 75–100ab^{-1}.
  - A high-luminosity τ-charm experiment operating just above charm threshold, ψ(3770), would enable a background free measurement of $\tau \rightarrow \mu\gamma$.



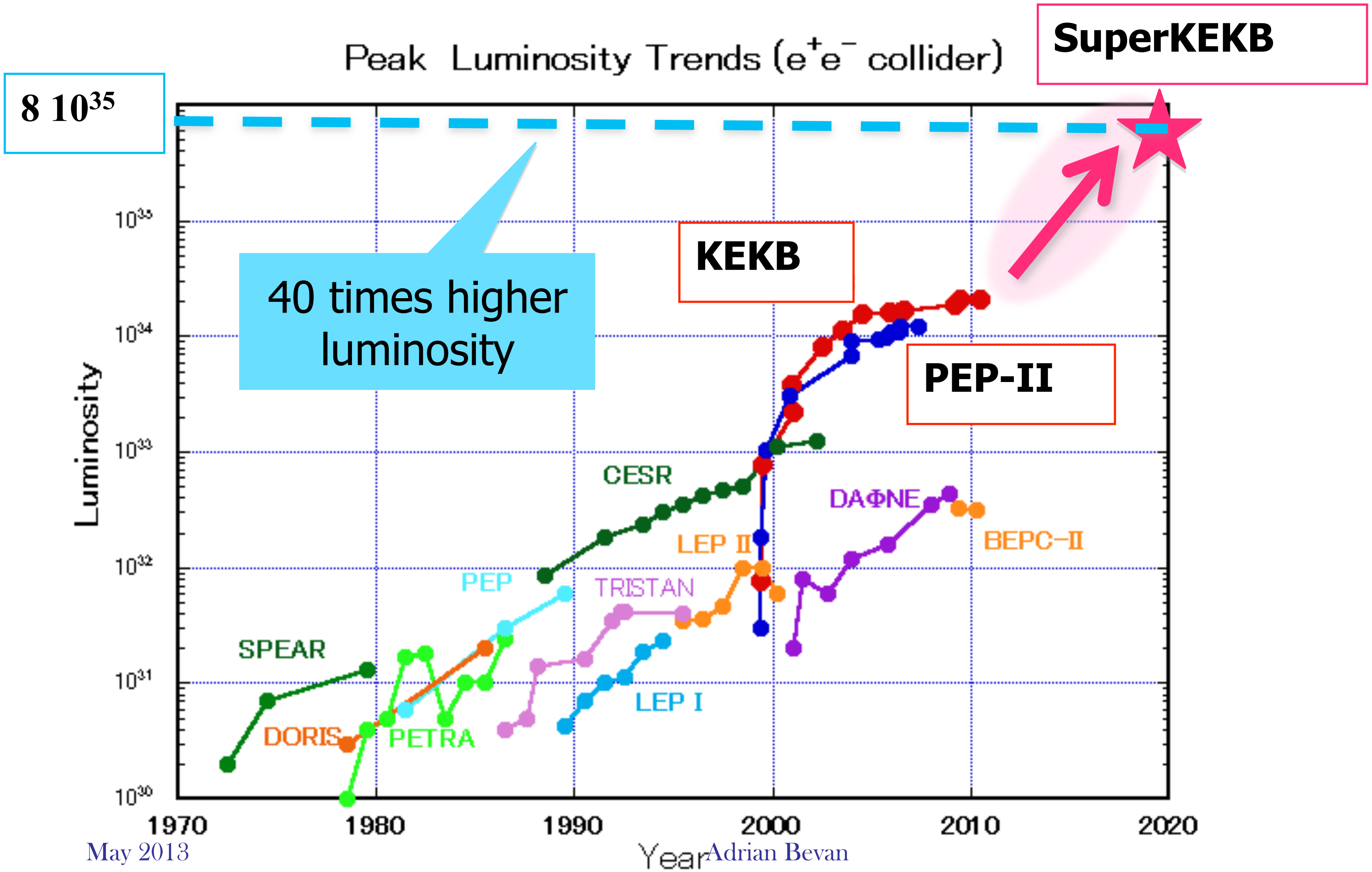
The (near) Future

The future of flavor physics will (in the long term) include precision top physics, studying billions of top quarks collected in hadronic and e^+e^- environments. Until that time, we must be content with studying the heaviest accessible up and down type quarks to learn about the subtleties of their interactions, and laying the groundwork required for precision top physics.

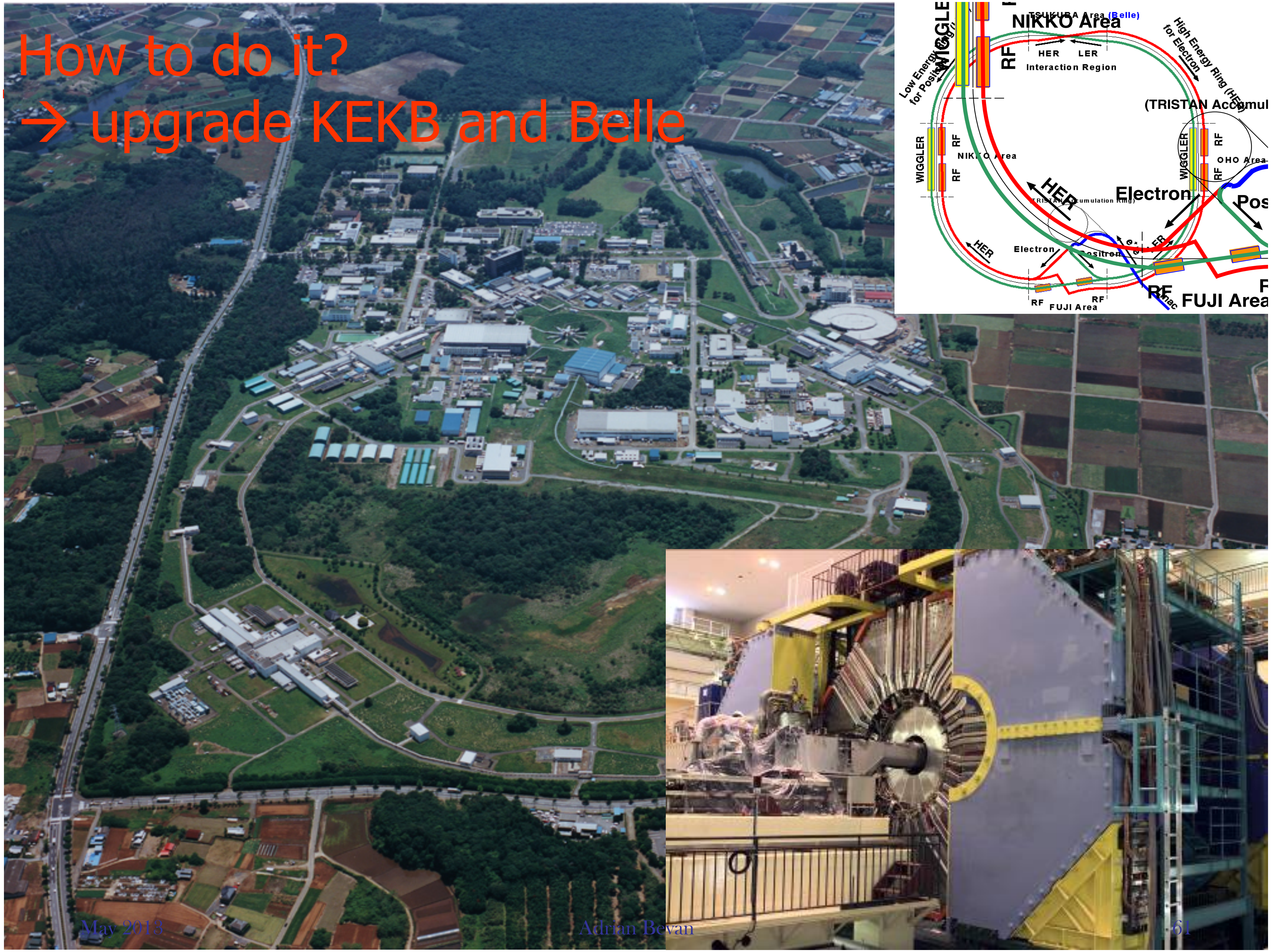
BELLE II AND SUPER KEKB

Thanks to Peter Krizan for up to date slides on the Belle II project.

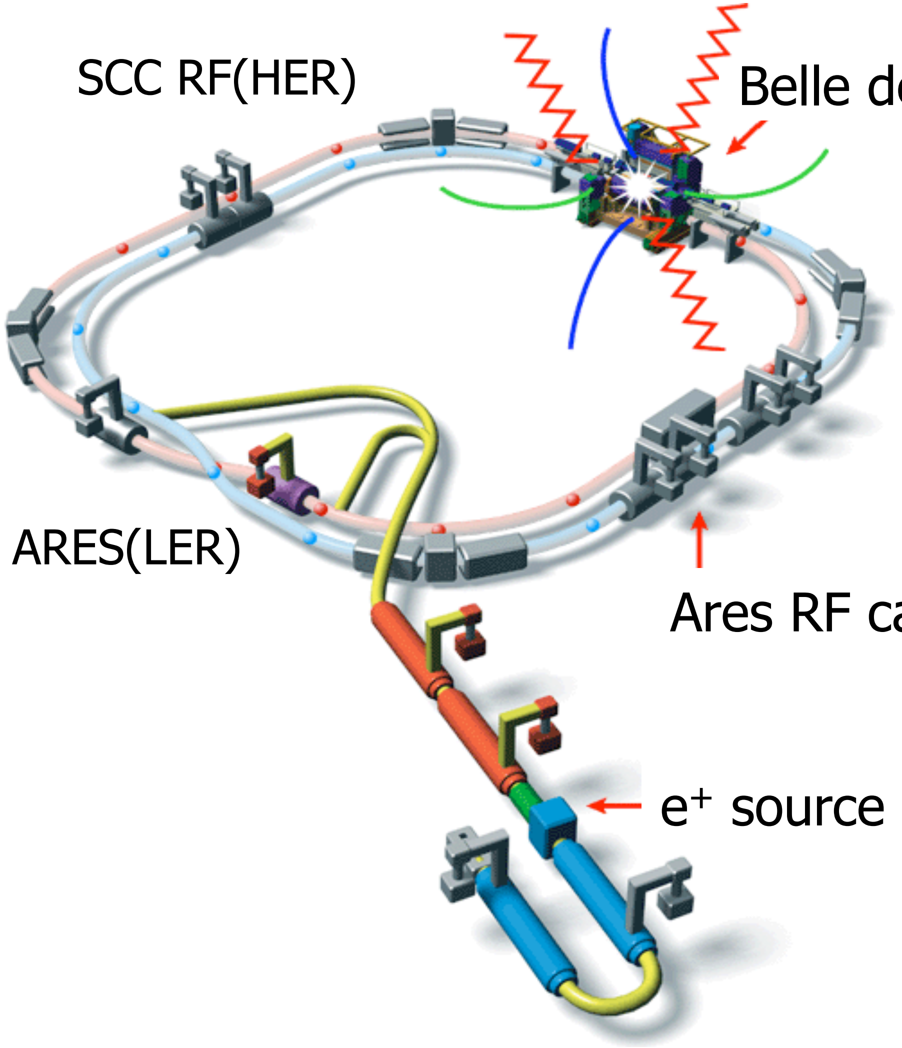
Need 50x more data →Next generation B-Factories



How to do it?
→ upgrade KEKB and Belle



The KEKB Collider & Belle Detector



- e^- (8 GeV) on e^+(3.5 GeV)
  - $\sqrt{s} \approx m_{\Upsilon(4S)}$
  - Lorentz boost: $\beta\gamma$=0.425
- 22 mrad crossing angle
- Operating since 1999

Peak luminosity (WR!) :

2. 1 x 10^{34} $cm^{-2}s^{-1}$

=2x design value

First physics run on June 2, 1999
Last physics run on June 30, 2010
L_{peak} = 2.1x10^{34}/cm^2/s
L > 1ab^{-1}

Strategies for increasing luminosity

Beam-beam parameter

Lorentz factor

Beam current

$$L = \frac{\gamma_{e\pm}}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_{e\pm}\xi_y^{e\pm}}{\beta_y^*}\right)\left(\frac{R_L}{R_{\xi_y}}\right)$$

Lumi. reduction factor (crossing angle)&
Tune shift reduction factor (hour glass effect)
0.8 - 1
(short bunch)

Classical electron radius

Beam size ratio@IP
1 - 2 % (flat beam)

Vertical beta function@IP

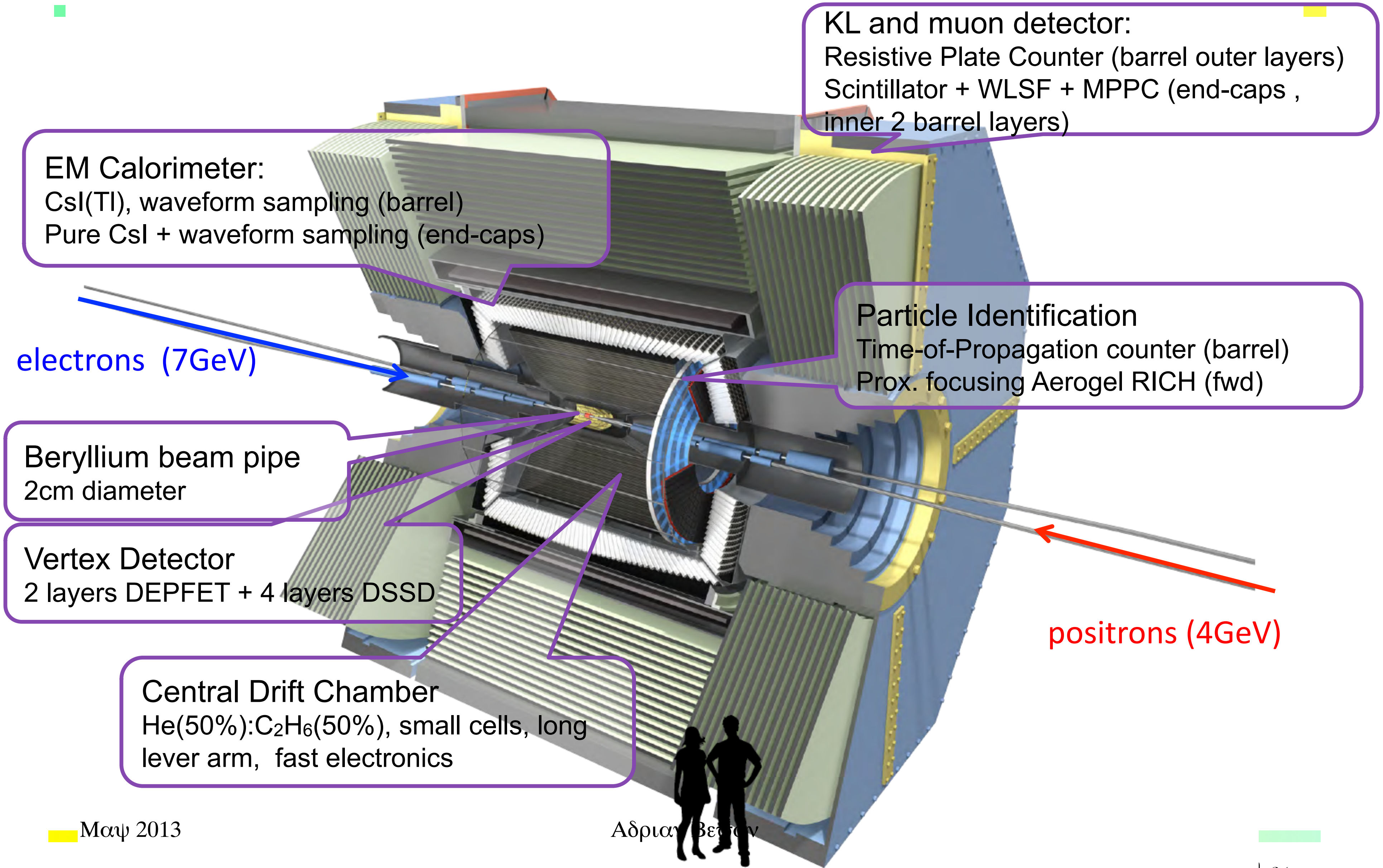
(1) Smaller b_y^*
(2) Increase beam currents
(3) Increase x_y

"Nano-Beam" scheme

Collision with very small spot-size beams

Invented by Pantaleo Raimondi for SuperB

Belle II Detector

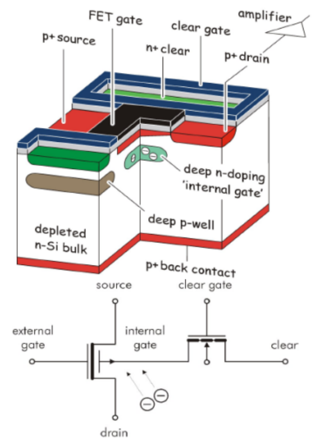


Vertex Detector

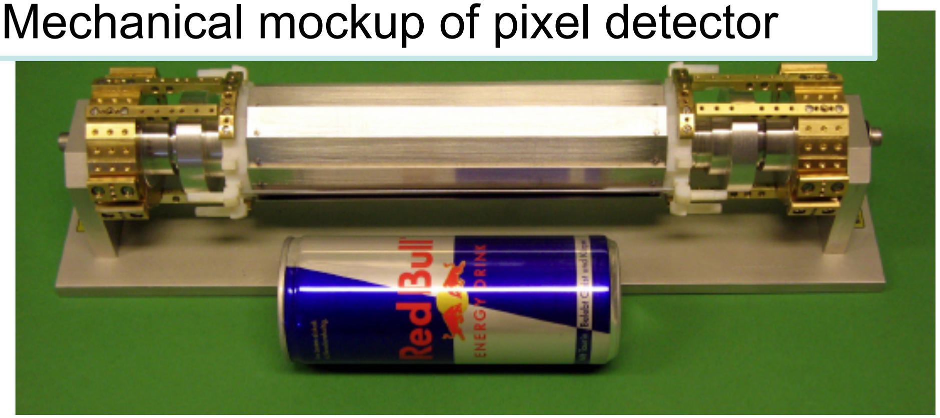
DEPFET:
http://aldebaran.hll.mpg.de/twiki/bin/view/DEPFET/WebHome

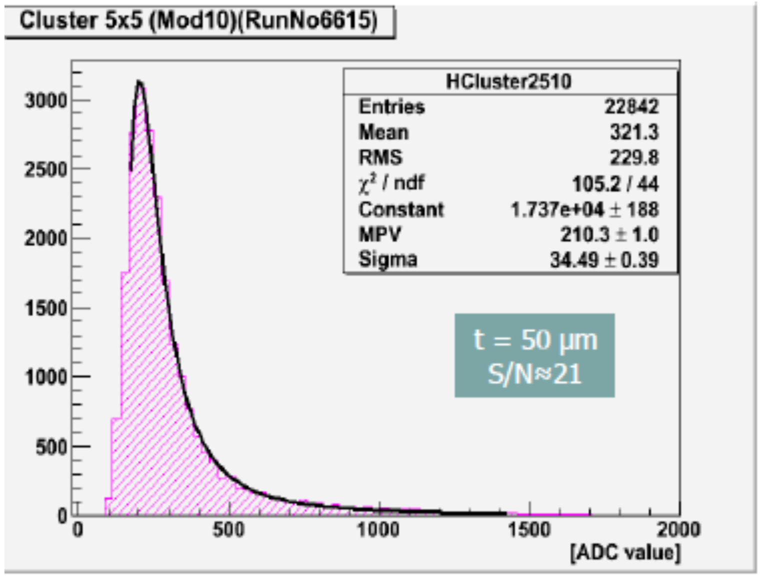
Beam Pipe		**r = 10mm**
DEPFET		
	Layer 1	**r = 14mm**
	Layer 2	**r = 22mm**
DSSD		
	Layer 3	**r = 38mm**
	Layer 4	**r = 80mm**
	Layer 5	**r = 115mm**
	Layer 6	**r = 140mm**

DEpleted P-channel FET



Mechanical mockup of pixel detector





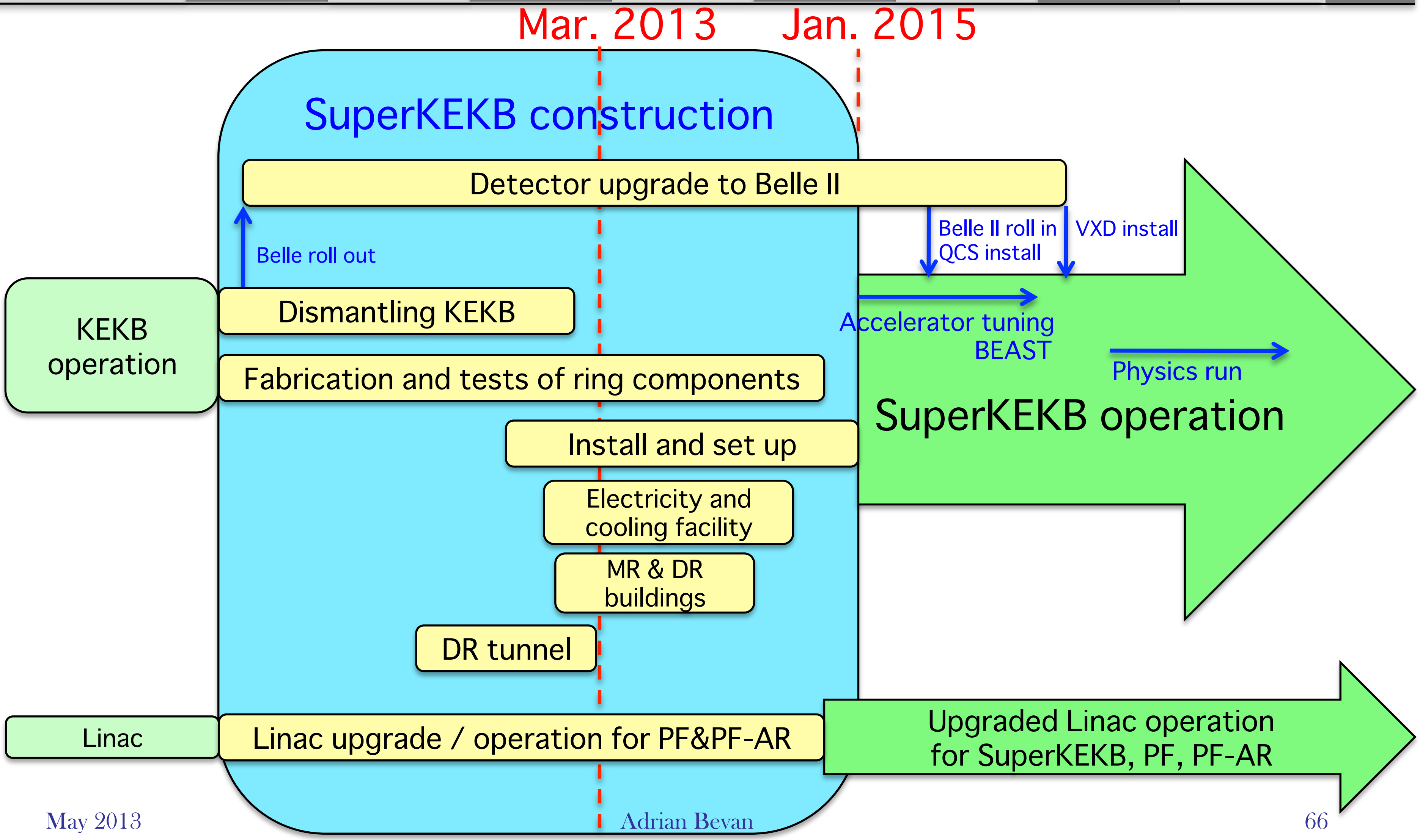
DEPFET pixel sensor

DEPFET sensor: very good S/N

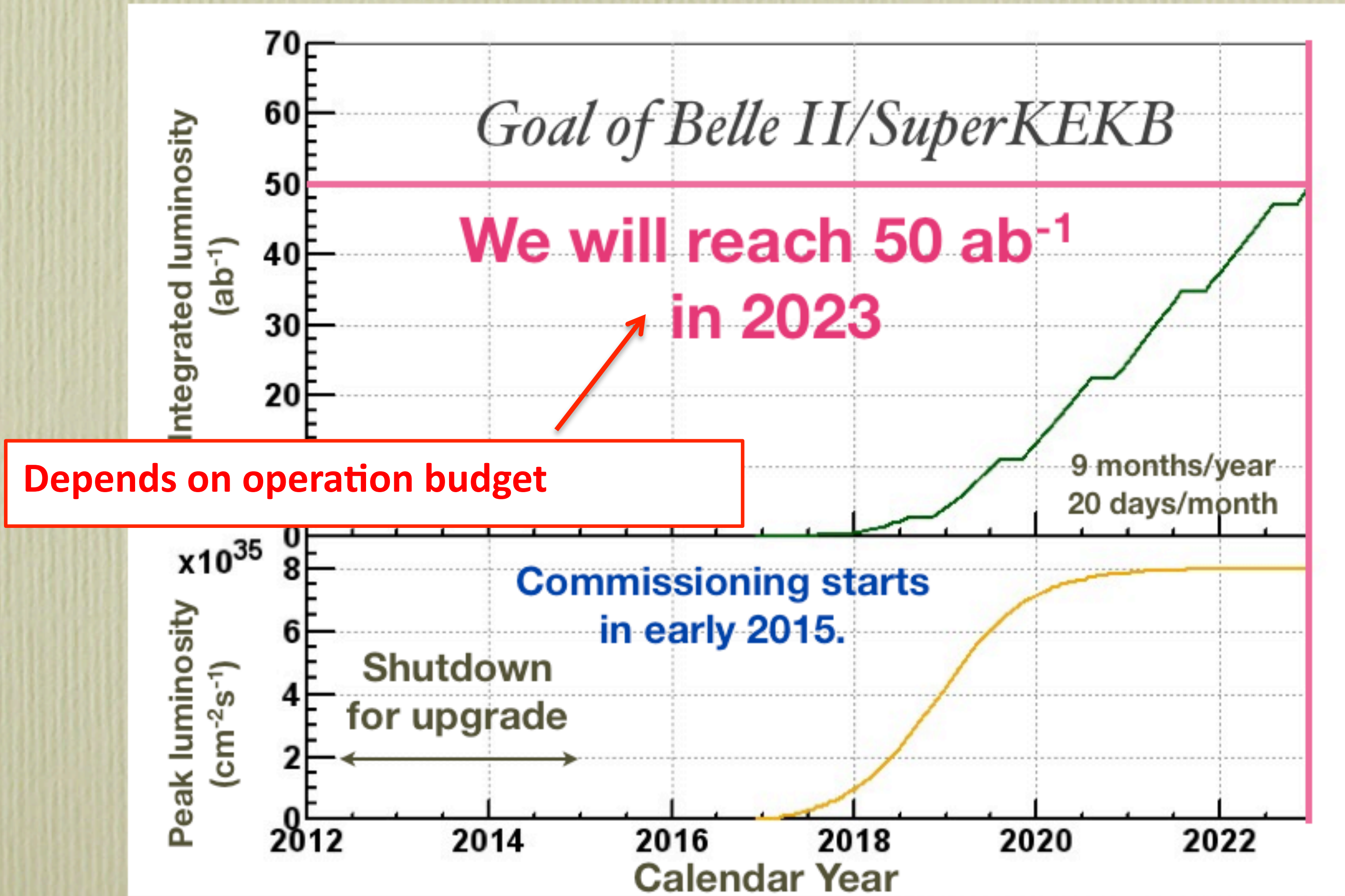
Peter Križan, Ljubljana

SuperKEKB/Belle II schedule

Calendar	2010	2011	2012	2013	2014	2015	2016	2017	...
Japan FY	2010	2011	2012	2013	2014	2015	2016	2017	..



SuperKEKB luminosity projection



C/O Peter Krizan

Physics overview

- Belle II will be able to perform many precision tests, the following are estimates of the sensitivities of key CKM related observables:

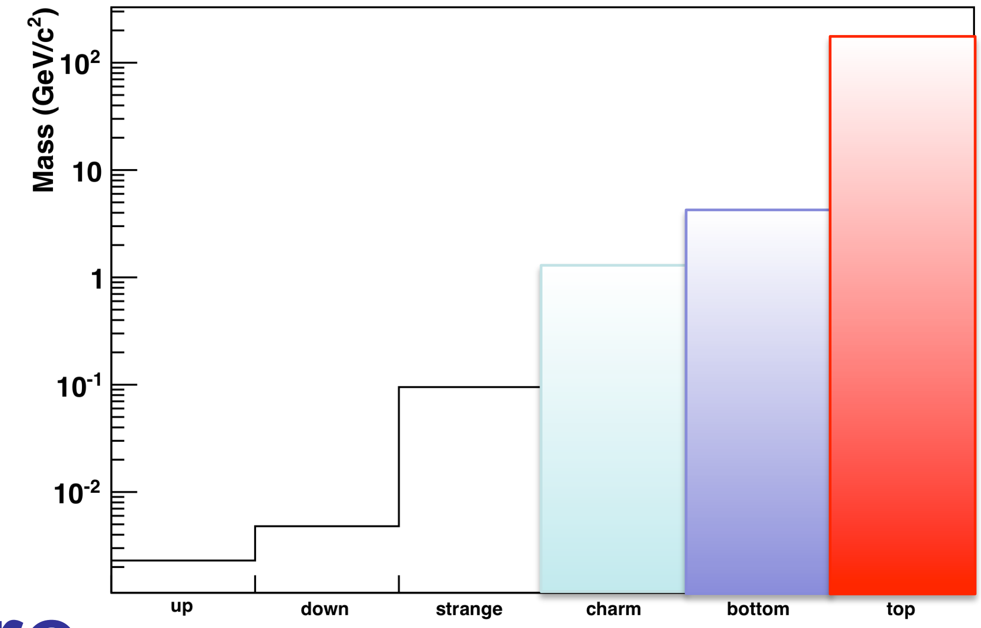
Observable/mode	Current now	Belle II (2023)	theory now
		$50\,\mathrm{ab}^{-1}$	
α from $u\bar{u}d$	6.1°	1°	$1-2^\circ$
β from $c\bar{c}s$ (S)	0.8° (0.020)	0.3° (0.007)	clean
S from $B_d \to J/\psi\pi^0$	0.21	0.021 (est.)	clean
γ from $B \to DK$	11°	1.5°	clean
$\lvert V_{cb}\rvert$ (inclusive) %	1.7	0.6 (est.)	dominant
$\lvert V_{cb}\rvert$ (exclusive) %	2.2	1.2 (est.)	dominant
$\lvert V_{ub}\rvert$ (inclusive) %	4.4	3.0	dominant
$\lvert V_{ub}\rvert$ (exclusive) %	7.0	5.0	dominant

- These results will enable a precision over-constraint of the CKM mechanism early next decade.

Physics overview

- Belle II will be able to perform many precision tests, the following are estimates of the sensitivities of key non-CKM related observables:

Observable/mode	Current B Factory now	Belle II (2023) $50\,\mathrm{ab}^{-1}$	theory now
	τ Decays		
$\tau \to \mu\gamma$ $(\times 10^{-9})$	< 44	< 5.0	
$\tau \to e\gamma$ $(\times 10^{-9})$	< 33	< 3.7 (est.)	
$\tau \to \ell\ell\ell$ $(\times 10^{-10})$	$< 150 - 270$	< 10	
	$B_{u,d}$ Decays		
$\mathrm{BR}(B \to \tau\nu)$ $(\times 10^{-4})$	1.64 ± 0.34	0.04	1.1 ± 0.2
$\mathrm{BR}(B \to \mu\nu)$ $(\times 10^{-6})$	< 1.0	0.03	0.47 ± 0.08
$\mathrm{BR}(B \to K^{*+}\nu\overline{\nu})$ $(\times 10^{-6})$	< 80	2.0	6.8 ± 1.1
$\mathrm{BR}(B \to K^{+}\nu\overline{\nu})$ $(\times 10^{-6})$	< 160	1.6	3.6 ± 0.5
$\mathrm{BR}(B \to X_s\gamma)$ $(\times 10^{-4})$	3.55 ± 0.26	0.13	3.15 ± 0.23
$A_{CP}(B \to X_{(s+d)}\gamma)$	0.060 ± 0.060	0.02	$\sim 10^{-6}$
$B \to K^*\mu^+\mu^-$ (events)	250[a]	7-10k	-
$\mathrm{BR}(B \to K^*\mu^+\mu^-)$ $(\times 10^{-6})$	1.15 ± 0.16	0.07	1.19 ± 0.39
$B \to K^*e^+e^-$ (events)	165	7-10k	-
$\mathrm{BR}(B \to K^*e^+e^-)$ $(\times 10^{-6})$	1.09 ± 0.17	0.07	1.19 ± 0.39
$A_{FB}(B \to K^*\ell^+\ell^-)$	0.27 ± 0.14[b]	0.03	-0.089 ± 0.020
$B \to X_s\ell^+\ell^-$ (events)	280	7,000	-
$\mathrm{BR}(B \to X_s\ell^+\ell^-)$ $(\times 10^{-6})$[c]	3.66 ± 0.77[d]	0.10	1.59 ± 0.11
S in $B \to K_S^0\pi^0\gamma$	-0.15 ± 0.20	0.03	-0.1 to 0.1
S in $B \to \eta' K^0$	0.59 ± 0.07	0.02	± 0.015
S in $B \to \phi K^0$	0.56 ± 0.17	0.03	± 0.02
	B_s^0 Decays		
$\mathrm{BR}(B_s^0 \to \gamma\gamma)$ $(\times 10^{-6})$	< 8.7	$0.2 - 0.3$	0.4 - 1.0
A_{SL}^s $(\times 10^{-3})$	-7.87 ± 1.96[e]	5. (est.)	0.02 ± 0.01
	D Decays		
x	$(0.63 \pm 0.20\%$	0.04%	$\sim 10^{-2}$[f]
y	$(0.75 \pm 0.12)\%$	0.03%	$\sim 10^{-2}$ (see above).
y_{CP}	$(1.11 \pm 0.22)\%$	0.05%	$\sim 10^{-2}$ (see above).
$\|q/p\|$	$(0.91 \pm 0.17)\%$	3.0%	$\sim 10^{-3}$ (see above).
$\arg\{q/p\}$ $(^\circ)$	-10.2 ± 9.2	1.4	$\sim 10^{-3}$ (see above).



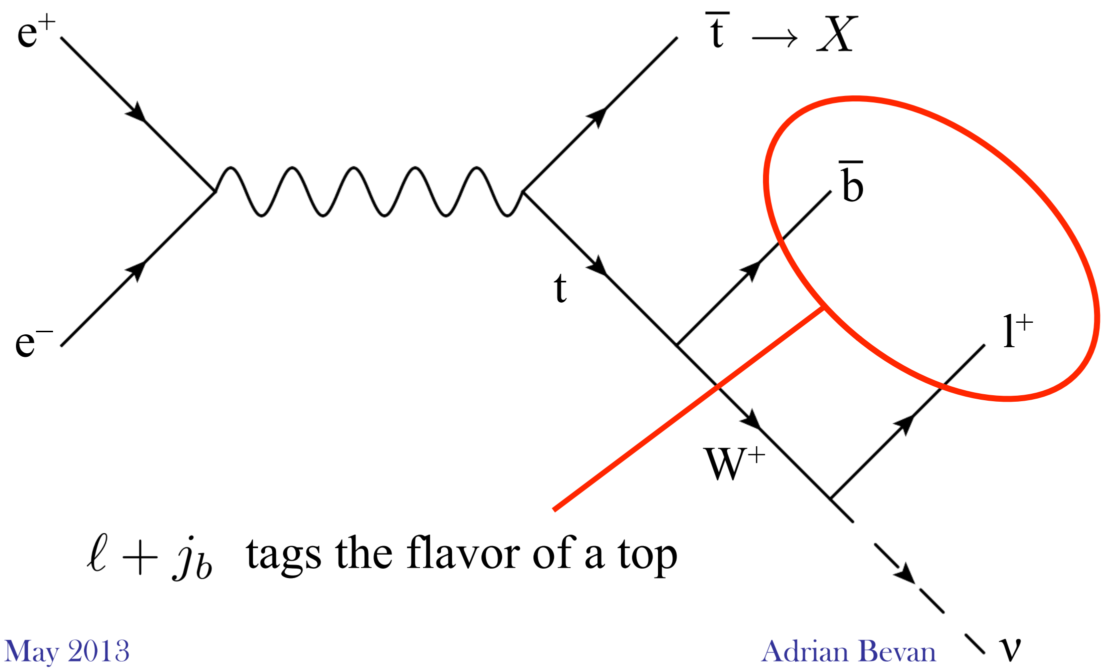
The (far) Future

The future of flavor physics will (in the long term) include precision top physics, studying billions of top quarks collected in hadronic and e^+e^- environments. Until that time, we must be content with studying the heaviest accessible up and down type quarks to learn about the subtleties of their interactions, and laying the groundwork required for precision top physics.

FLAVOUR AT A HIGH ENERGY LINEAR COLLIDER

FLAVOUR AT A HIGH ENERGY LINEAR COLLIDER

- A future linear collider operating at, or above top-pair production threshold has several advantages over the LHC for top physics:
  - Clean production environment
  - top-recoil reconstruction technique:
    - Reconstruct one top decay (e.g. $t \longrightarrow b\ell^+\nu$) and use the rest of the event to constrain the other top in the decay.



Use the charge of the lepton to tag the flavor of the tag top quark.

Infer the flavor of the *other* top.

No mixing to worry about, so flavor analysis of the *other* top decay is well defined. One needs to identify the state X, and accumulate many tops.

FLAVOUR AT A HIGH ENERGY LINEAR COLLIDER

- Precision top physics is motivated by two goals:
  - Understanding the heaviest fermion known to us.
  - Using this as an interferometer to probe for new physics.
    - With large top-pair statistics, in the future one will be able to perform flavour measurements to complement results from kaon, B and D decays.
    - Results from the weak decay of strange quarks hinted at the existence of the c, b and t quarks. The top quark is the heaviest known particle, so precision top physics will play a role in understanding the behaviour of nature at higher scales, and extending our understanding of quark flavor.
    - If the LHC doesn't directly produce new heavy particles in pp collisions, perhaps studying top at a future linear collider will be the only way forward to learn a more complete theory of nature.

FLAVOUR AT A HIGH ENERGY LINEAR COLLIDER

- Will there be a high energy e^+e^- collider? If so what will it be (i.e. what energy range etc.)?
- A CM energy at the $t\bar{t}$ production threshold will provide a clean sample of top quarks to study.
  - With sufficient statistics one can use rare processes to probe for new physics, test the CKM paradigm (unitarity of the CKM matrix etc).
  - Many similarities with the indirect tests being performed at the B Factories and motivating a high luminosity tau -charm factory.
  - However as top doesn't hadronize we can not use mixing to probe dynamics (i.e. there is no mixing as the top decays too quickly and doesn't form a bound meson).
  - Different effects will be important to probe CP violation, and low energy hadronic uncertainties will be replaced by jet fragmentation uncertainties.

Summary

Key Concepts

If you only pay attention to one slide – make sure it is this one.

- The following is true for rare decay searches for new physics AND CP violation:
  - Effects are maximal when amplitudes of similar magnitudes interfere.
  - You want to study experimentally well defined final states.
  - To interpret these one needs to have theoretical control of hadronic uncertainties.
  - A null, or non-null prediction from the standard model can be used to guide expectations.
    - Observed deviations from the standard model are model independent.
      - We don't have any significant guidance from experiment to drive developments in a particular direction.
    - In the absence of a *better idea*, we are left with testing benchmark models. The smallest set of benchmark models is that of the standard model itself.

- Flavour physics has taught us a lot about the fine detail of the Standard Model of particle physics.

- Two paradigms:
  - Study heaviest available quarks and leptons, to use rates and asymmetry observables search for new physics using benchmark models.
  - Place constraints on possible physics beyond the Standard Model via precision tests of SM observables.

- Some observables are able to test fundamental symmetries that may have deeper ramifications for our Universe: CP violation was discussed here, related T and CPT non-conservation tests are also important (see lectures at this school by J. Bernabeu).

- These results can't constrain the energy scale for new physics, but can constrain the ratio of coupling to scale.

- A number of discoveries have been made by the B Factories since 1999: highlights include:
  - CP violation in the interference between mixing and decay amplitudes (indirect CP violation) in B decays.
  - Direct CP violation (CP violation in decay) in B decays.
  - Discovery of new light particles: X(3872), Y(4260), D_{SJ}, etc.
  - Discovery of the ground state of the $b\overline{b}$ system: η_b
  - Evidence for charm mixing.
  - Observation of T-symmetry non-conservation in B decays.
- Conceptual advances include understanding that the CKM matrix provides the leading order description of CP violation in the Standard Model.
  - *This does not rule out possible new physics in CP violating observables.*

- Other notable advances:
  - Indirect constraints on new physics using B decays are (generally) model dependent.
  - The type-II 2HDM is the most recent scenario to be disfavoured at more than 3 σ.
  - Flavour constraints impose strong limits for model builders, in some cases going beyond the energy reach of the LHC.
  - If new physics is found at the LHC, then our experimental understanding of flavour has to come together with our theoretical understanding to explain why hints have not been seen already.
  - If the new physics scale is beyond the energy reach of the LHC, then flavour physics at a B (top) factory may be the best way forward to probe above the EW symmetry breaking scale.
    - One drawback with the last statement: We don't have a high luminosity top factory (yet).

THE END...