New Physics Belle II Through CP Violation

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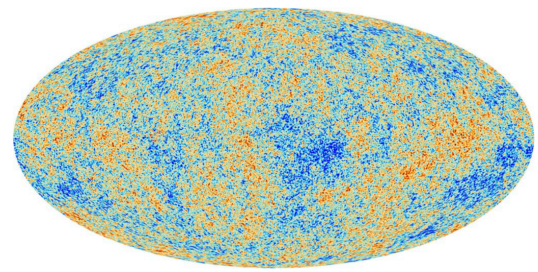
Why New Physics?

- The Standard Model cannot be the complete story of fundamental physics because:
  - Dark Matter

    Strong cosmological evidence for DM

    We don't know what it is

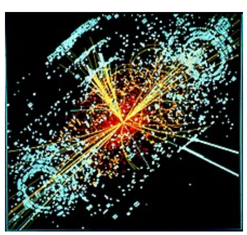


  - Baryon Asymmetry of the universe

    We see mater out there

    But almost no antimatter

  - Hierarchy Problem



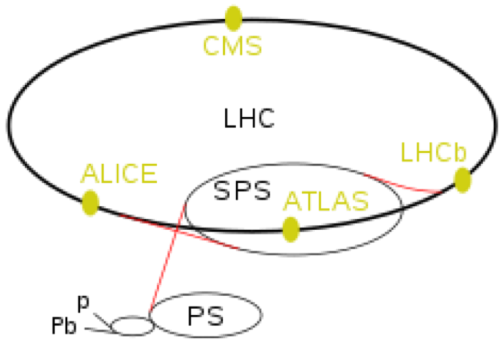
Higgs mass is unstable if there is no new physics by ~10TeV

Frontiers

- How do you get to the bottom of the fundamental laws of physics
  - The obvious approach: go to higher energy and try to produce BSM particles directly:

Energy Frontier

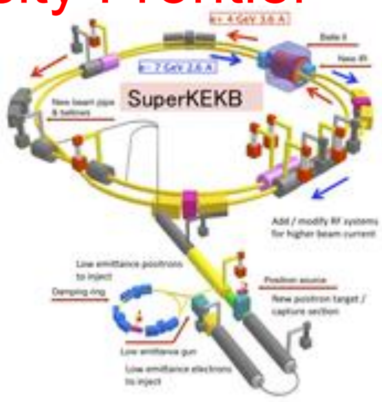
(LHC)

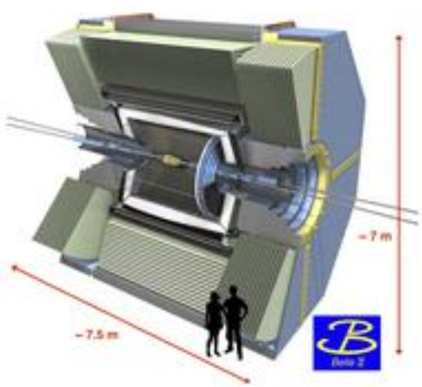


  - The subtle approach: Look for subtle effects of NP at low energy:

The Intensity Frontier

(BELLE II; LHCb)





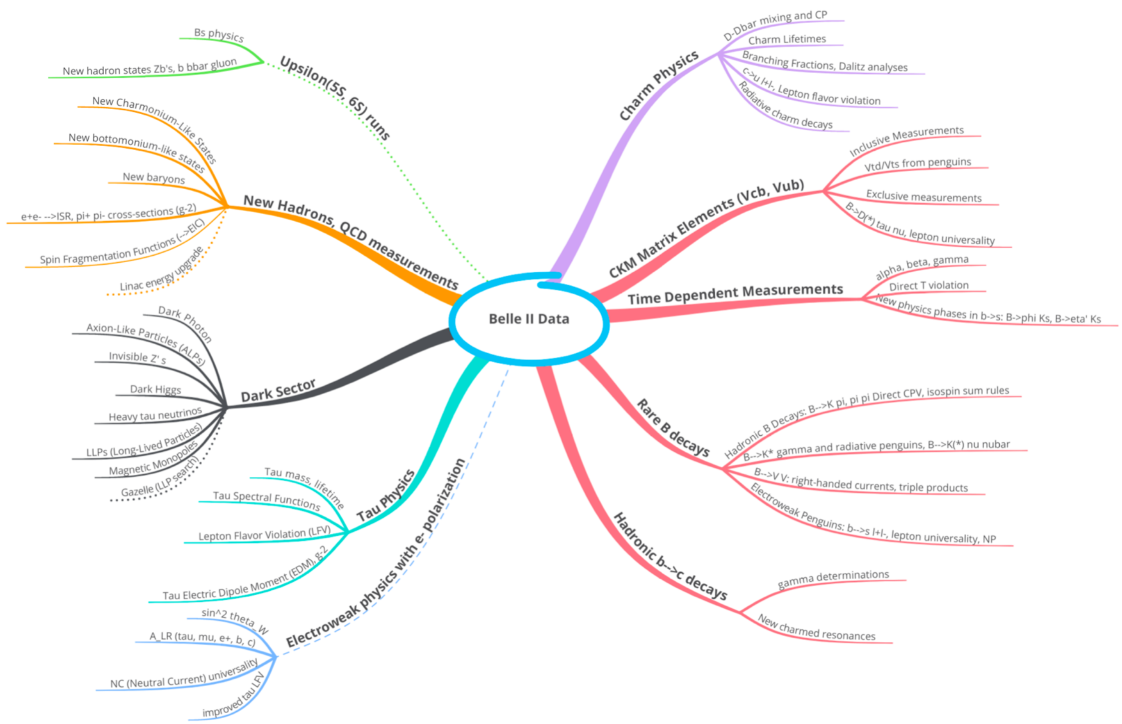
Also Neutrino physics

Intensity Frontier.

- B factories are uniquely able to look for NP because:
  - The weak decay of b-quarks is suppressed because V_{cb} is <1
  - Suppressed decays, perhaps involving NP is therefore more evident
  - We do, however, need to produce a lot of B mesons to take advantage of this.
  - Electron Positron B factories (i.e. Belle) are uniquely clean in that many final states may be reconstructed without overwhelming background allowing more channels to potentially look at.

Mapping out Physics and signals

- The Belle Physics book (PTEP 2019, 123C01 (2019)) contains a comprehensive list of possible new physics signals to be addressed at BELLE II which is nicely illustrated with the “Mind Map”.



- In this talk I would like to stack things up a little differently and then focus on a few of the connections which may be productive (and are interesting to me)… I do suggest everyone read all 600 pages of the physics book

Threading from NP to Experimental Observables

Fundamental NP Model

- SUSY
- Extended Higgs sector
- Vector like fermions
- LR Symmetric models
- Technicolor
- Large Extra Dimensions
- Extended Gauge groups

…and many more

Salient Feature

- Z’
- W’
- Charged Scalars
- Neutral Scalars
- leptoquarks
- Extra Fermions
- Axions

These objects can be
- Produced explicitly
- Appear in tree diagrams
- Appear in loop diagrams (Wilson coefs.)

Type of observable

- Missing Energy (low mass dark particle)
- CP violation
  - –direct
  - –time dependent
- Tauonic decays
  - $B \to \tau\nu$
  - $B \to X_c\tau\nu$
- Precision CKM
- b→sγ & b→s $l^+ l^-$
- Rare hadronic B decays
- b→ γ [γ γ]
- Tau physics
- Charm physics

CP Violation

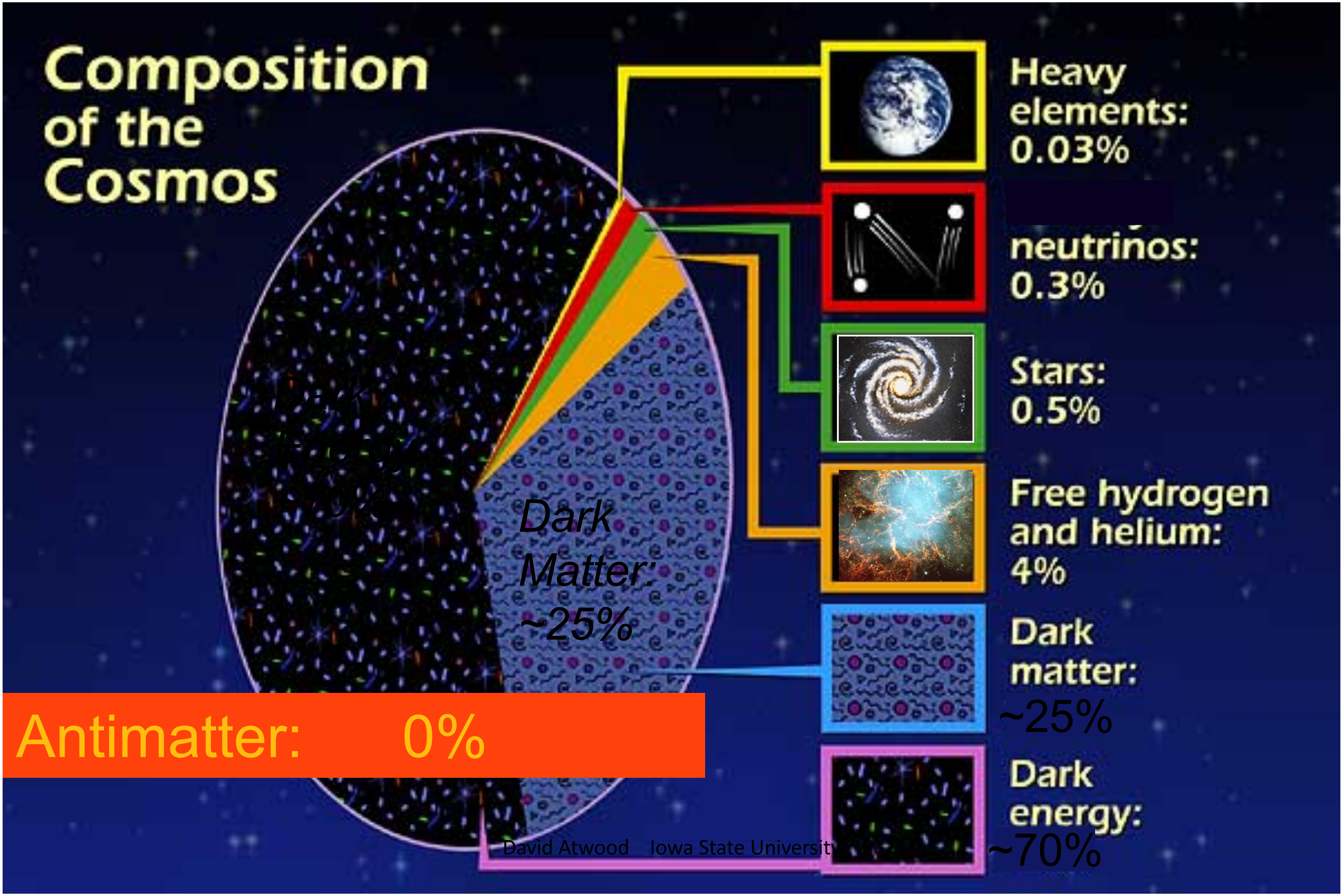
- Why is CP violation Interesting?

- It is small in the SM (but not zero so there is something to see)
  - So in B physics we are looking for a small effect in a meson with unusually suppressed decay rates.
  - "Small in SM" gives an NP opportunity to shine through

- It is almost certain that large CP violation exists at high energy and most likely at the TeV scale

- The goal of CP studies at B factories are twofold:
  1. Refine our knowledge of the CKM matrix so that we know what the SM prediction is (or better yet find a inconsistency)
  2. Look for deviations from the SM.

Energy budget of Universe



How do we know large CP violation is a feature of BSM Physics?

As a general feature, most NP models allow large CP violation baryogensis actually requires it.

Soon after the discovery of CP violation in the Laboratory in 1964, Andrei Sakharov proved in 1967 that some form of CP violation was essential for baryogenesis

<u>Sakharov Theorem</u>

If CPT is true and the universe is created with 0 baryon number, in order to have baryogenesis in the early universe, the following 3 conditions must be satisfied:

1) Baryon Number is violated

   clearly needed to have excess baryons.

2) CP is violated

   Need to tell the baryon violation which way to go otherwise baryon number will be erased

3) The system must depart from thermal equilibrium

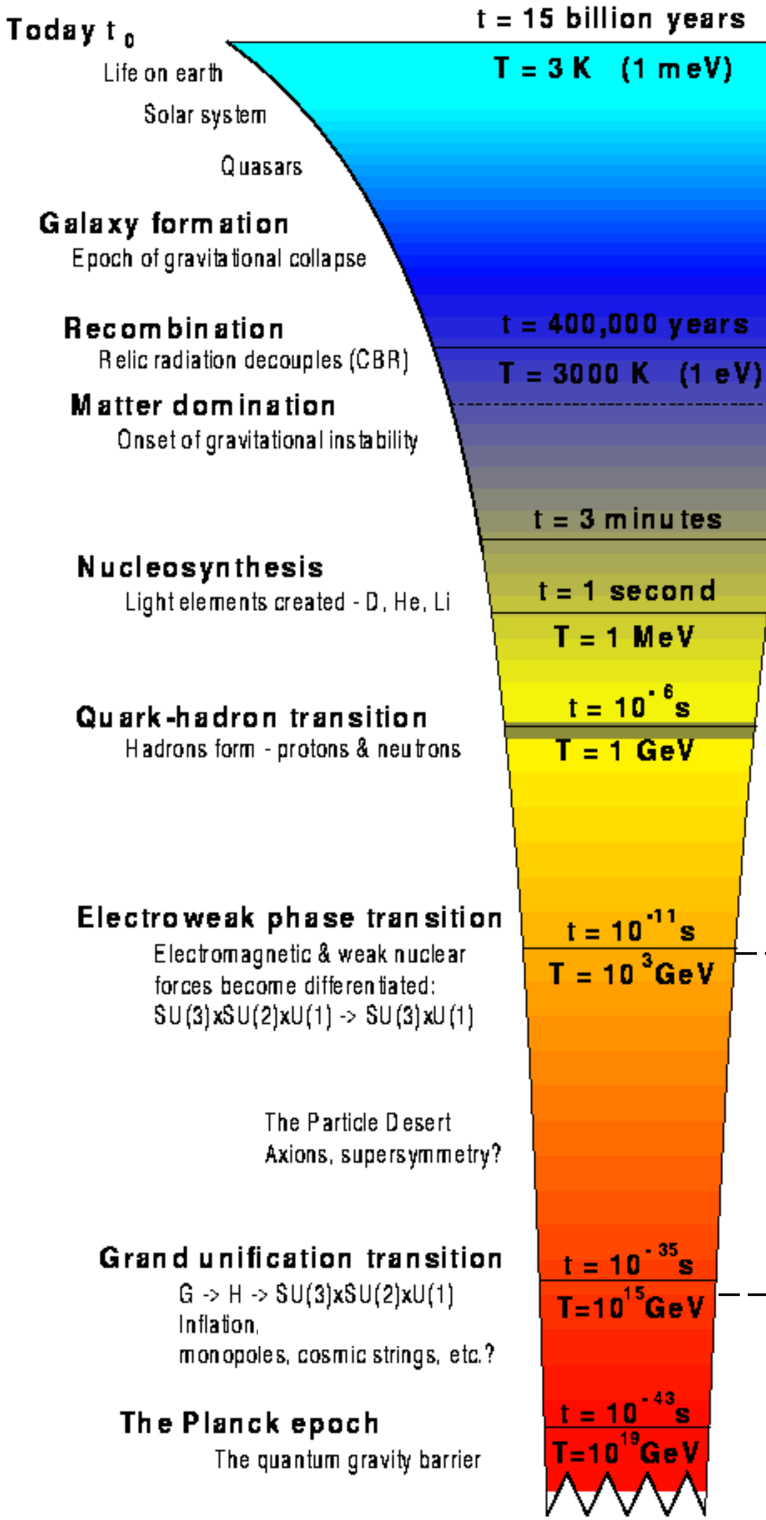
$$< B >= Tr(e^{-\beta H} B) = Tr(e^{-\beta H}[cpt]B[cpt]^{+}) = -< B >$$

Baryogenesis Near EW Transition

- Sakharov #1 Baryon Number is violated
  - OK in SM High temperature Electroweak processes should violate baryon number
  - In fact any previous baryon asymmetry may be erased absent the other two conditions (unless B-L is violated).
- Sakharov #2 CP is violated
  - CP violation is present in the SM
  - However this CP violation is too weak to do the job
- Sakharov #3 The system must depart from thermal equilibrium
  - Phase transition is expected
  - However strong first order phase transition needed in realistic models does not arise in bare SM

➢ To get baryogenesis in the Electroweak era, new physics at the electroweak scale (we can hope to see it in our lifetime) is required.

➢ In addition, new physics must violate CP substantially.



Astronomy

The farthest we can see EM radiation with WMAP

Low Energy Nuclear Physics

QGP: High Energy Nuclear physics

EW phase transition

W Z Fermions massive

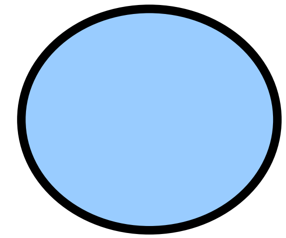
W Z Fermions massless

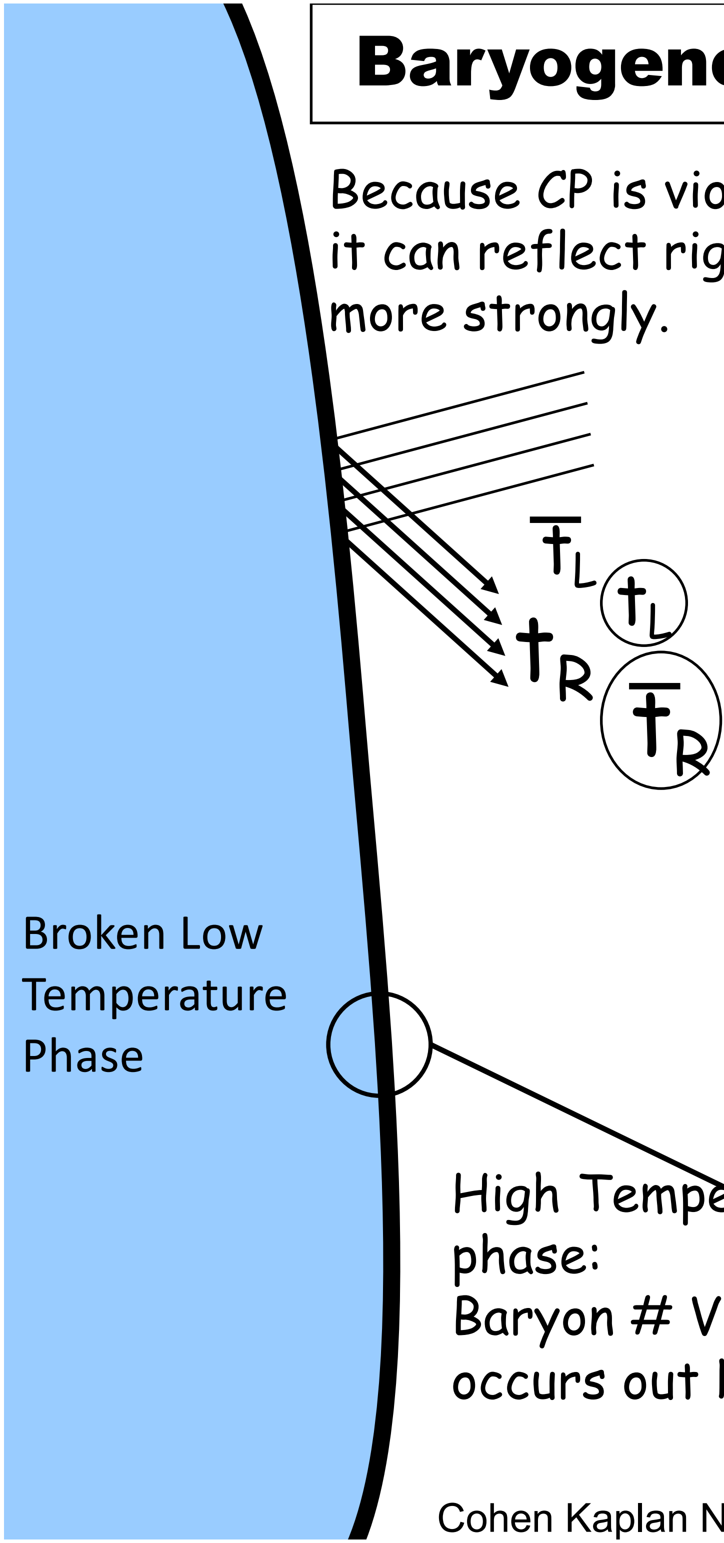
Leptogenesis via Majorana Neutrino mass converts to baryons via SM
⇒violation of B-L

GUT baryogen.

Baryogenesis near the bubble wall

Because CP is violated in the wall of the bubble it can reflect right handed fermions and antifermions more strongly.





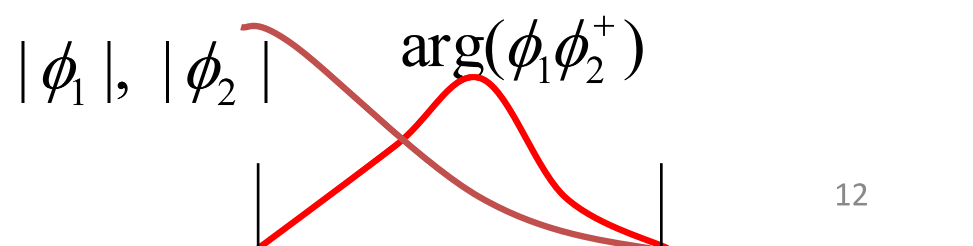
Baryon number violation is CP conserving so (for instance) it destroys t_L at the same rate as $\bar{t}_R$. Combined with the helicity buildup you get net baryon production

High Temperature phase:
Baryon # Violation occurs out here

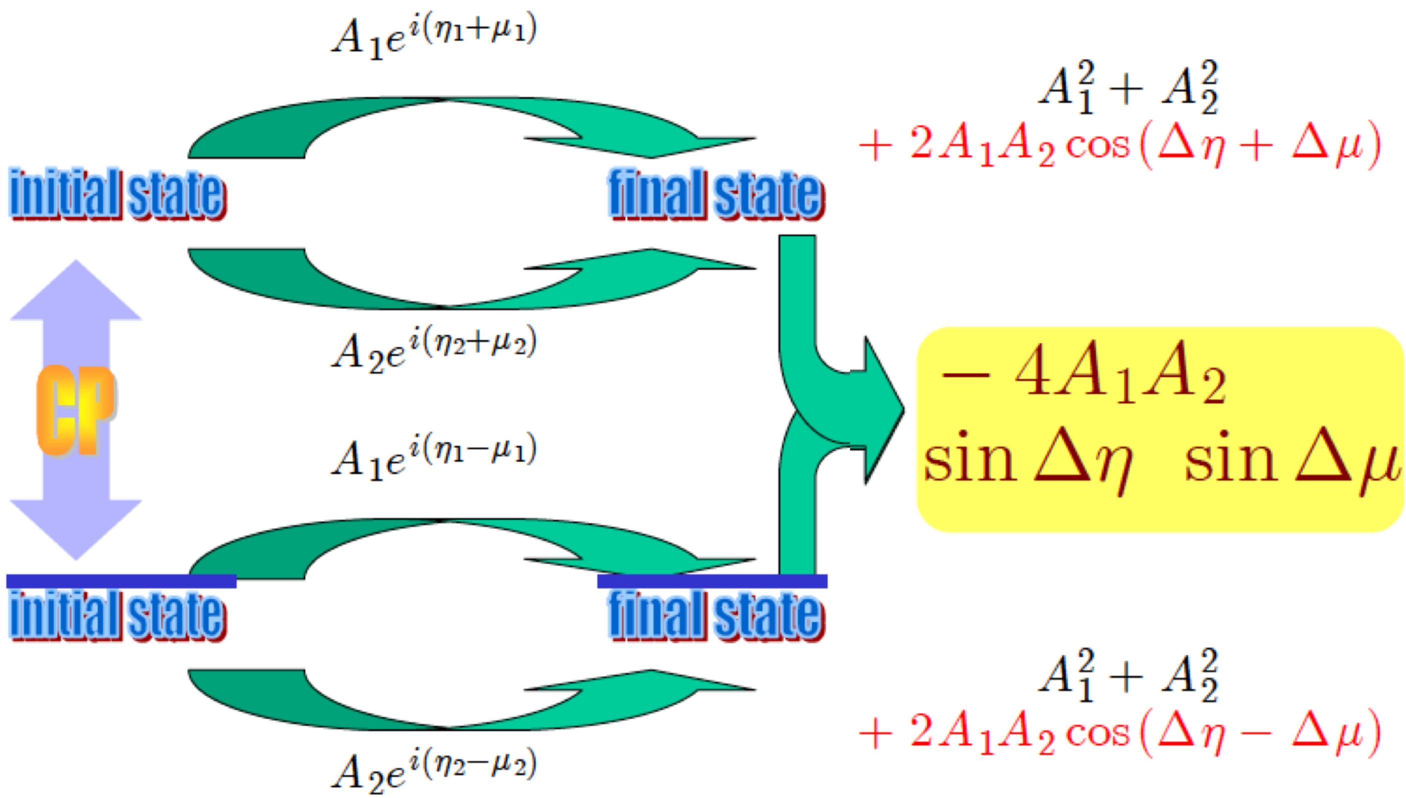
Cohen Kaplan Nelson (94)

What Happens at the Wall?

If there is CP violation in the Higgs sector then the phase will evolve through the bubble wall.



CP Violating Observables



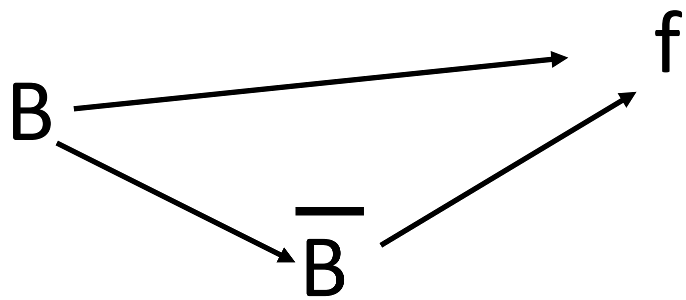
- We want to know $\Delta\mu$, the CP odd phase in the Lagrangian
- To do this however, we need a strong phase $\Delta\eta$

The Strong phase may be due to

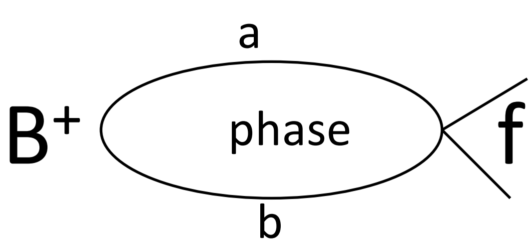
- Rescatering of the final state (direct CP violation)
- Time evolution (e^{iHt}) time dependent CP asymmetry

Source of Strong Phase

- To produce a CP violating signal, we need $\Delta\eta$, the strong phase.
  - Time Evolution e^{iHt}



  - Rescattering



Gold Plated
CP violation in Oscillation to get CKM Phases

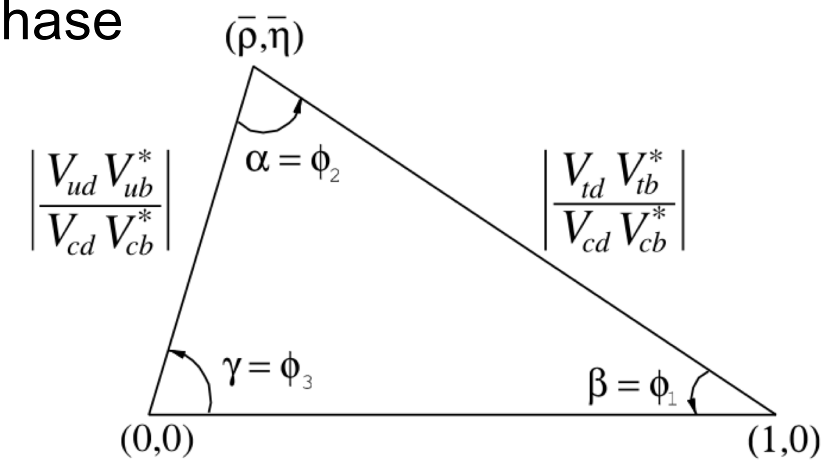
- The CKM Matrix in the Wolfenstein Parameterization is

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

- To lowest order $V_{ub} \propto e^{-i\phi_3}$ and $V_{td} \propto e^{-i\phi_1}$
- Only the 1-3 elements have a phase

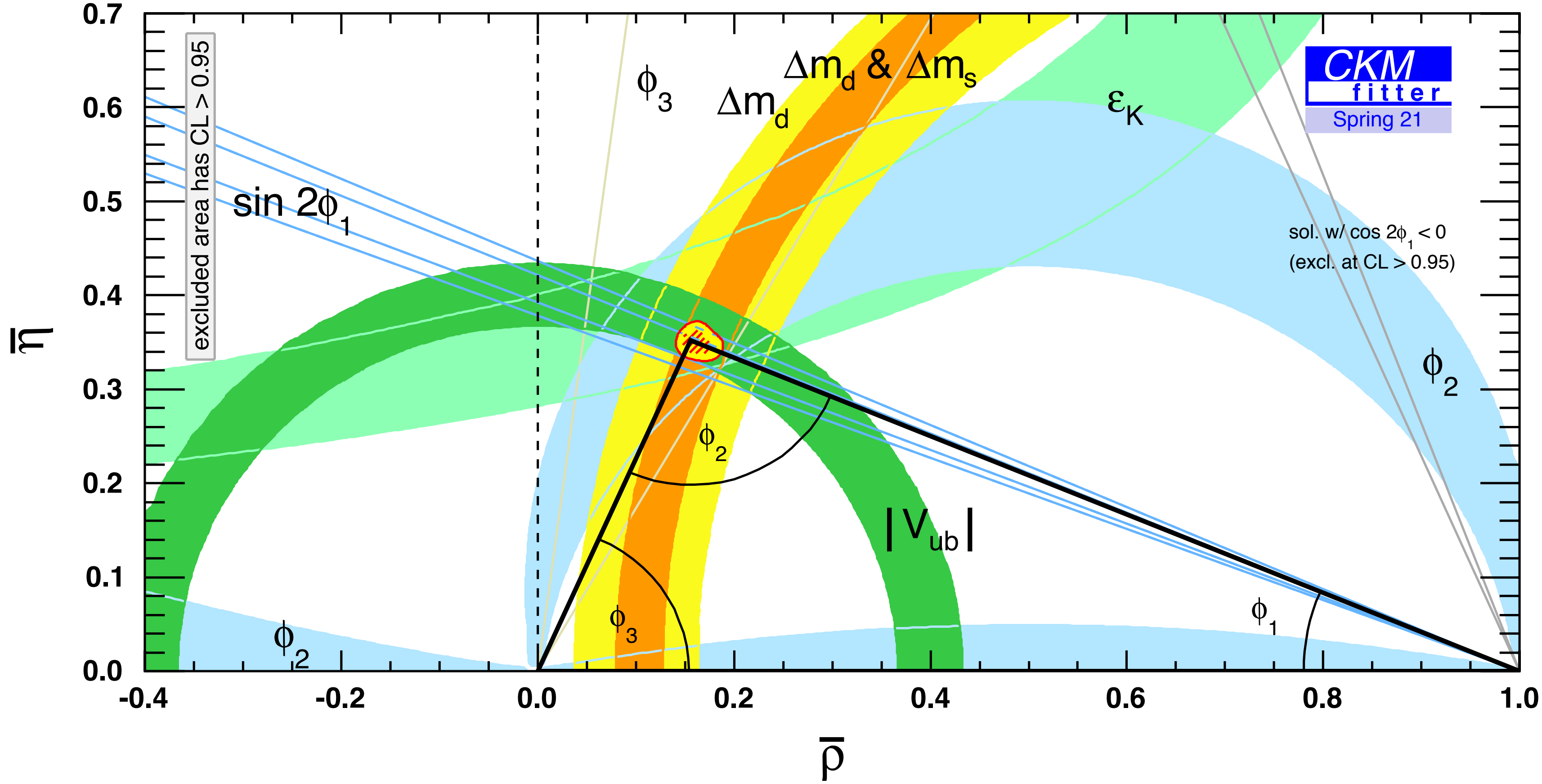
U triangle: take first col and third col conjugate multiply them together they will sum to 0 if CKM matrix is unitary

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

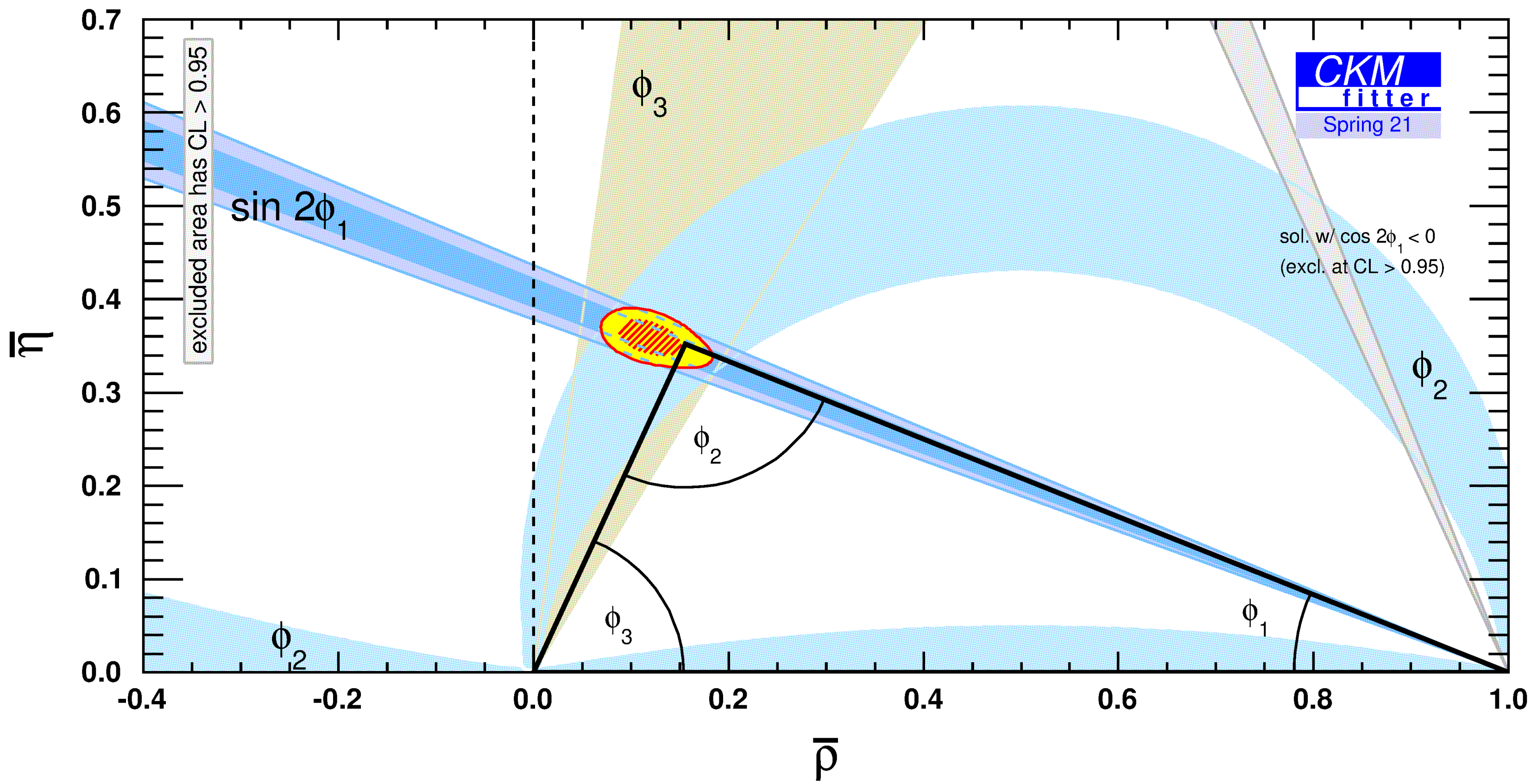


Status of CKM Matrix

CKM Fitter Plots form Moriond 2021

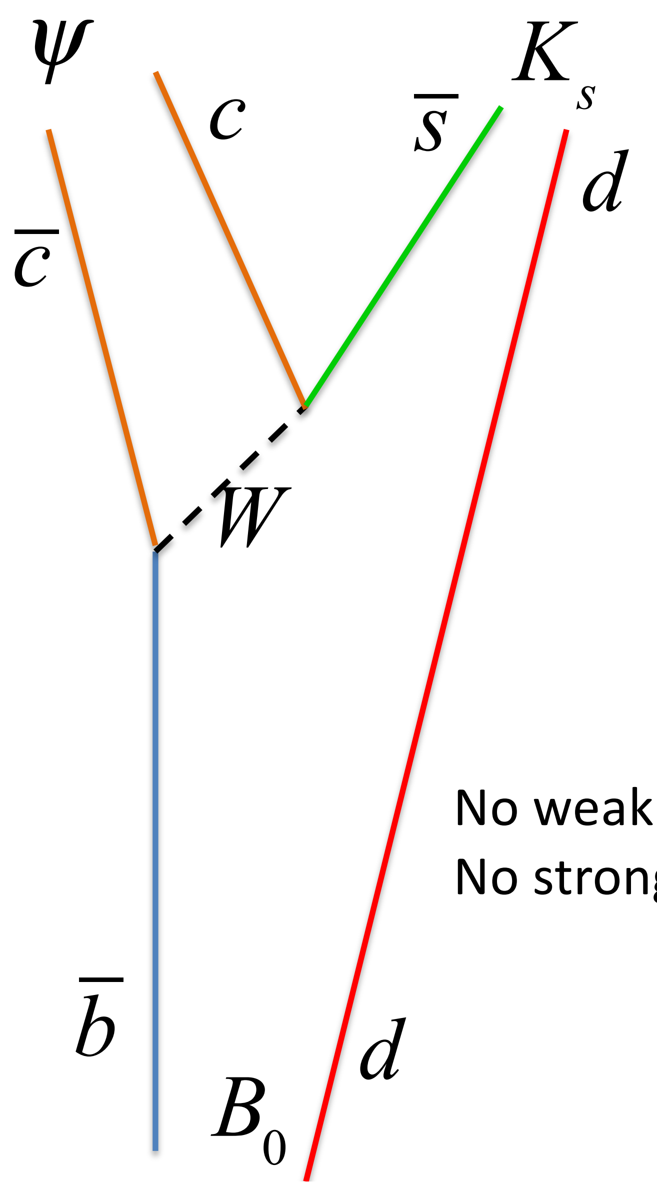


In Fact, just from CP studies



Applied to the gold plated $B \to \psi K_s$

Path 1



No weak phase
No strong phase

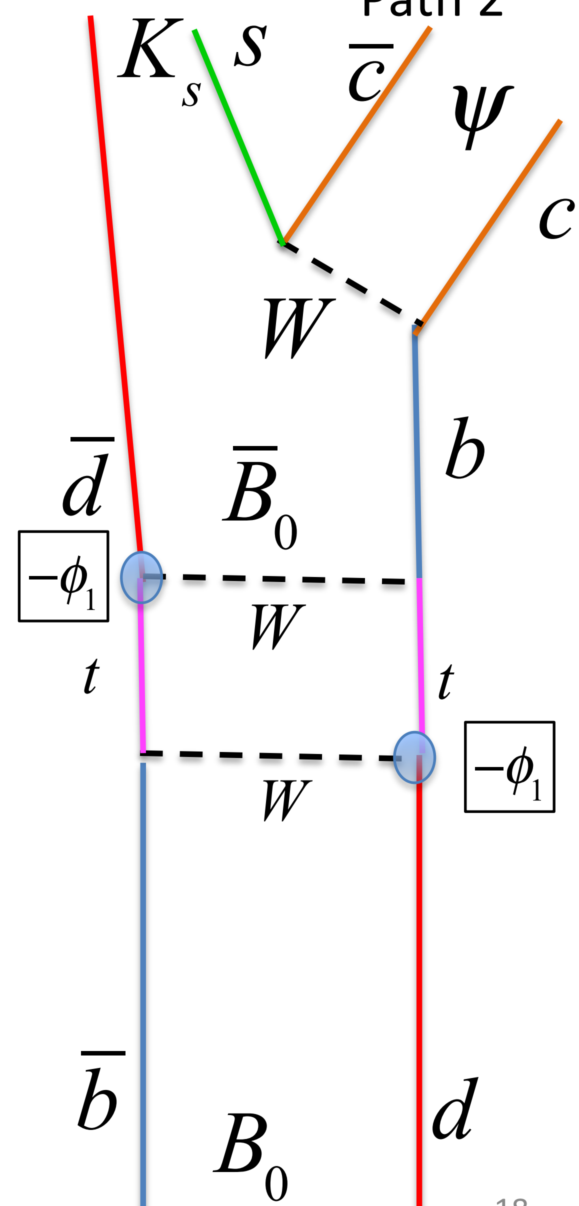
ψK_s

weak phase=$-2\phi_1$

Strong phase:
Time dependent oscillation

B_0

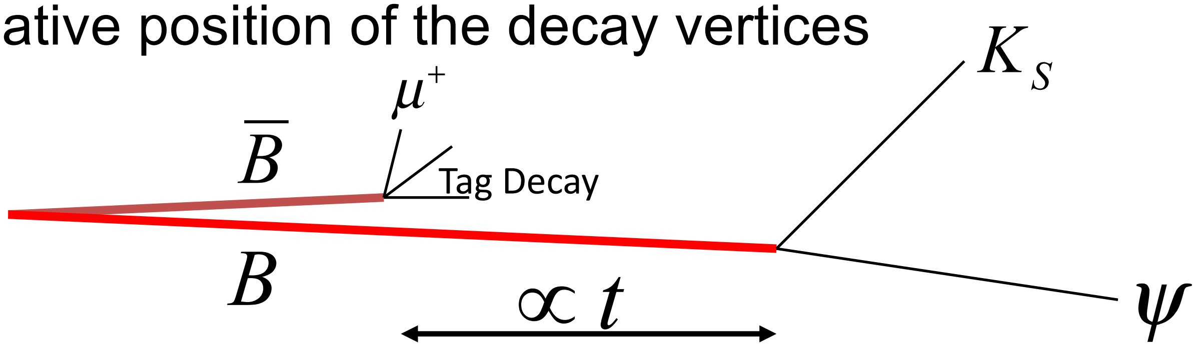
Path 2



The experiment you do

- At B factories running at the 4S, the B meson pair is produced with little relative motion but moving in the lab due to asymmetric beams

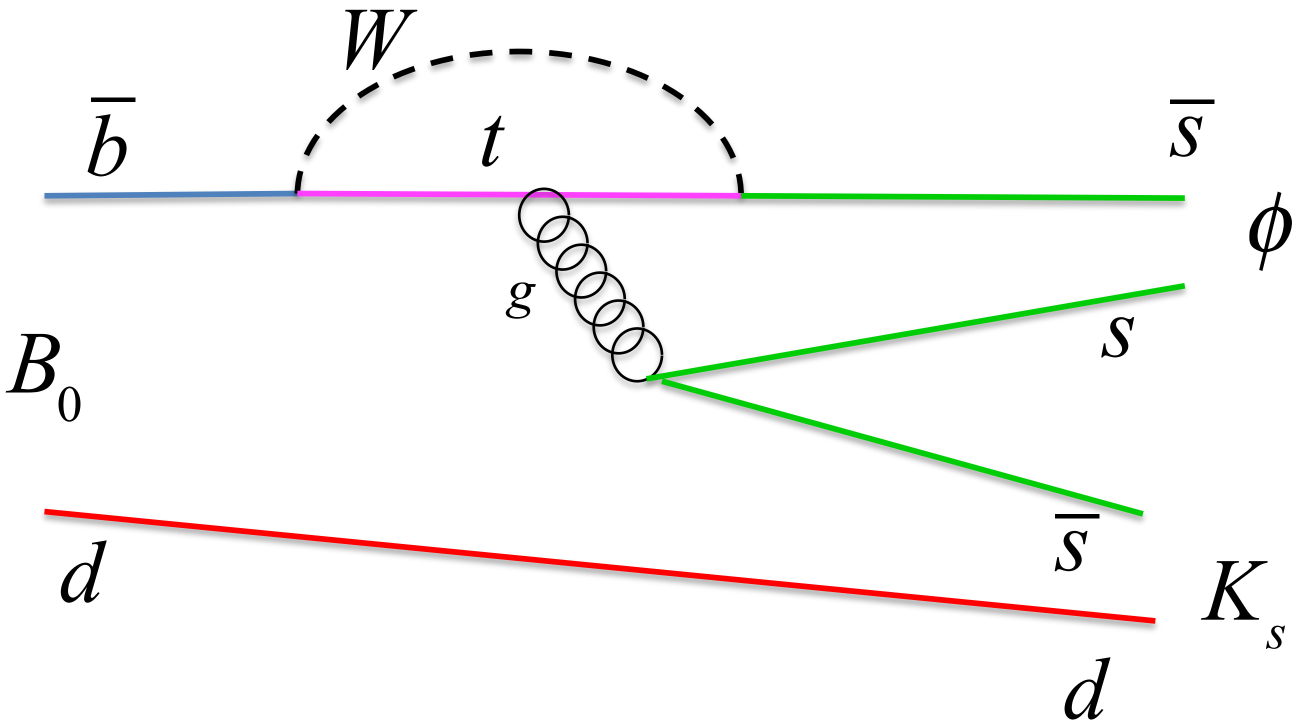
- The time dependence of the decay can thus be observed by looking at the relative position of the decay vertices



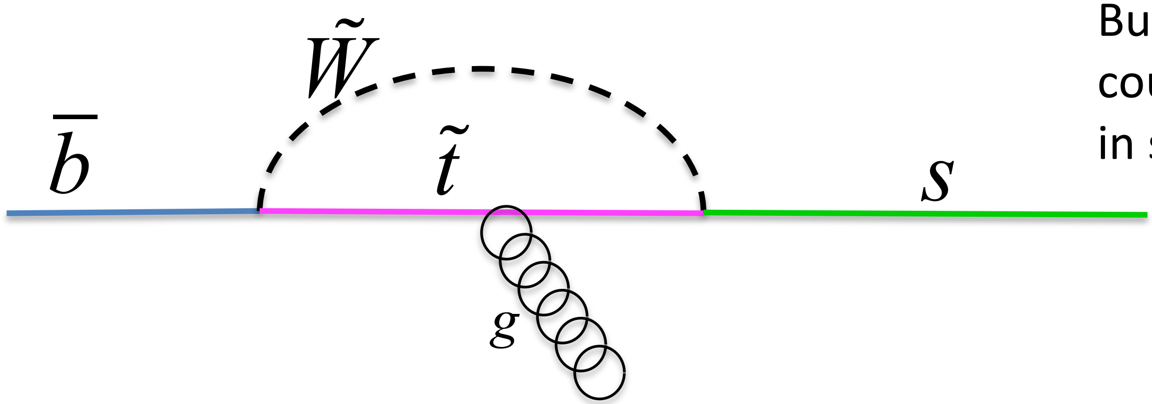
- Of course many other similar modes are sensitive to the same CKM angle $J/\psi K_s$ $J/\psi K^*$ $D^*D^*K_s$ $D\pi^0$

- Some other modes such as ϕK_s are sensitive to the same angle in the SM but proceed through gluonic penguins and therefore could be sensitive to NP which might be revealed by BELLE II.

Gluonic Penguin

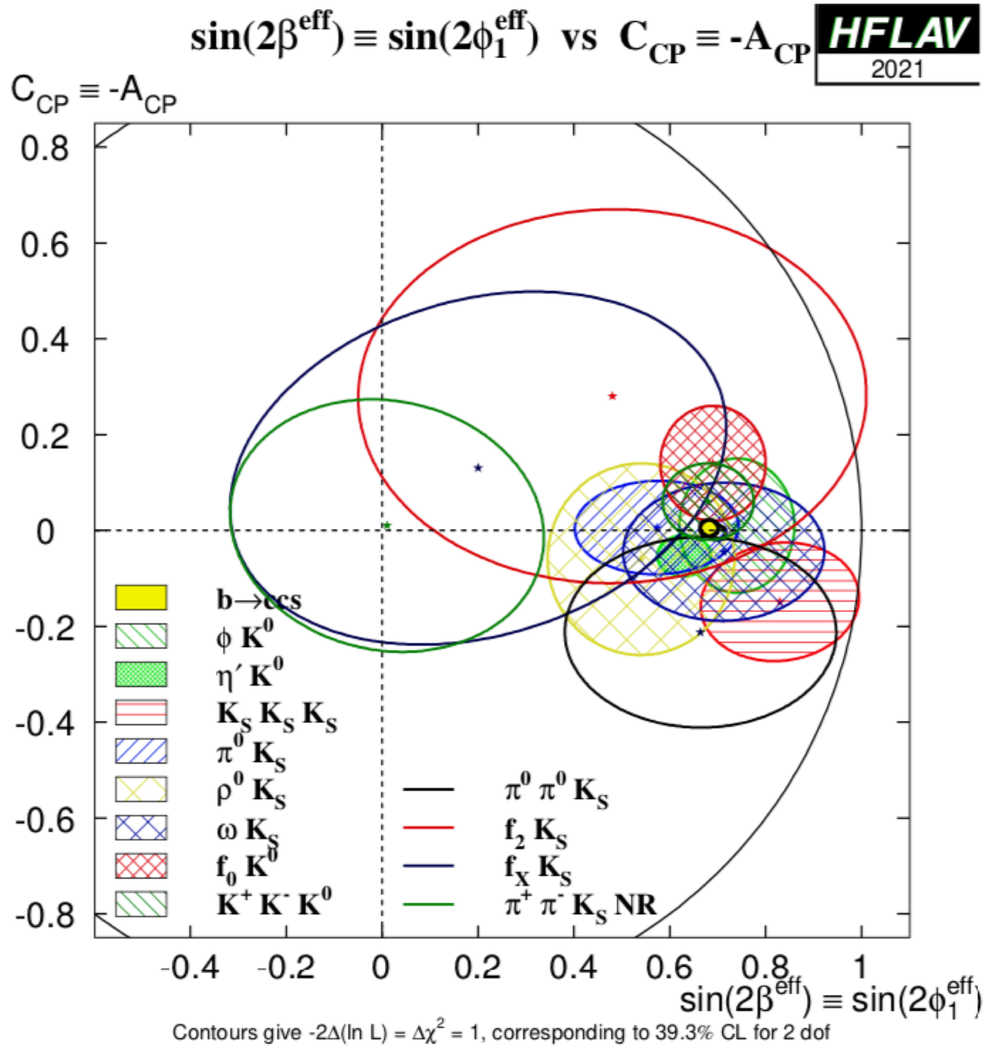


Phase the same as the Previous case



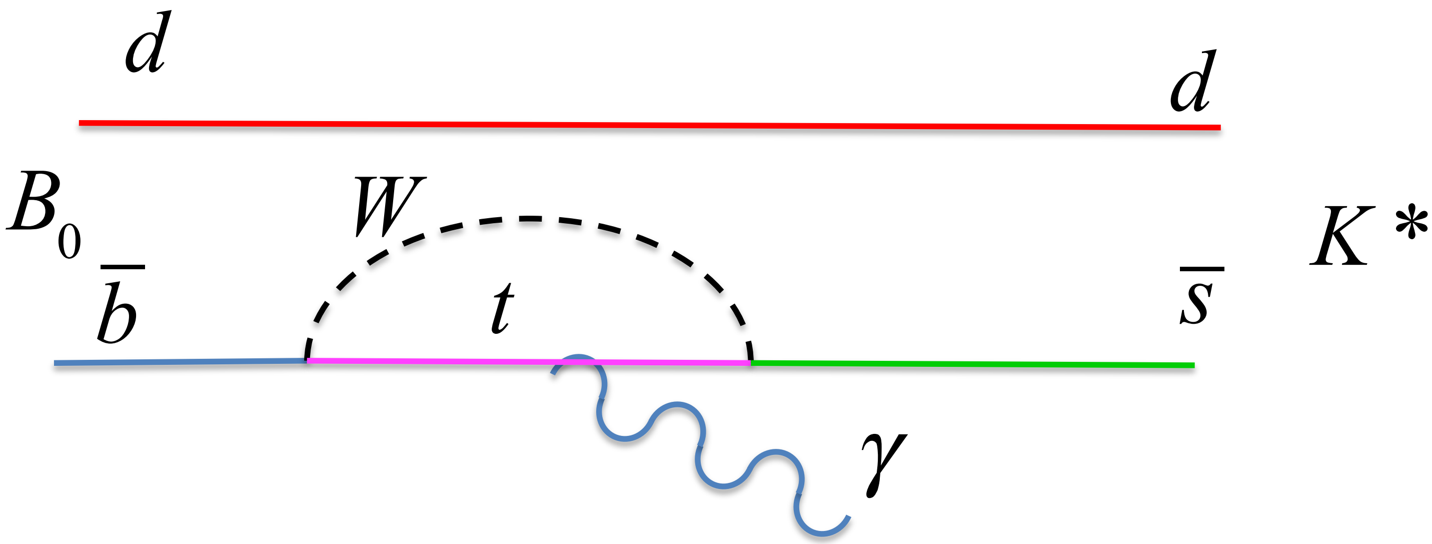
But inside the penguin there could be exotic particles bringing in some NP CP phases

Gluonic $b \to s$ Penguins Results so far



From HFLAG
arXiv:2206.07501

How about Photonic Penguins?



- In the decay $b \to s\gamma$ the photon is (mostly) left handed
- In the decay $\bar{b} \to \bar{s}\gamma$ the photon is (mostly) right handed

deviation $\propto m_s/m_b$ and λ

- Therefore the SM expectation is that the CP violation signal is small because B and $\bar{B}$ decays are now distinguishable
- This is a clean test for NP
- The key thing new physics must do to contribute is generate photons with opposite helicity to the SM (LR symmetric SUSY Extra Higgs)

DA, Gershon, Hazumi, Soni PRD **71**, 076003 (2005)

Such NP has not been discovered yet…

- No signal is seen in this and related modes so far

Mode	Experiment	S_{CP} (b → sγ)	C_{CP} (b → sγ)	Correlation	Reference
$K^*(892)\gamma$	BaBar N(BB)=467M	$-0.03 \pm 0.29 \pm 0.03$	$-0.14 \pm 0.16 \pm 0.03$	0.05 (stat)	PRD 78 (2008) 071102
	Belle N(BB)=535M	$-0.32^{+0.36}_{-0.33} \pm 0.05$	$0.20 \pm 0.24 \pm 0.05$	0.08 (stat)	PRD 74 (2006) 111104
	Average	-0.16 ± 0.22	-0.04 ± 0.14	0.06	HFLAV correlated average $\chi^2 = 1.9/2$ dof (CL=0.40 ⇒ 0.9σ)
$K_S\pi^0\gamma$ (incl. $K^*\gamma$)	BaBar N(BB)=467M	$-0.17 \pm 0.26 \pm 0.03$	$-0.19 \pm 0.14 \pm 0.03$	0.04 (stat)	PRD 78 (2008) 071102
	Belle N(BB)=535M	$-0.10 \pm 0.31 \pm 0.07$	$0.20 \pm 0.20 \pm 0.06$	0.08 (stat)	PRD 74 (2006) 111104(R)
	Average	-0.15 ± 0.20	-0.07 ± 0.12	0.05	HFLAV correlated average $\chi^2 = 2.4/2$ dof (CL=0.30 ⇒ 1.0σ)
$K_S\,\eta\,\gamma$	BaBar N(BB)=465M	$-0.18^{+0.49}_{-0.46} \pm 0.12$	$-0.32^{+0.40}_{-0.39} \pm 0.07$	−0.17 (stat)	PRD 79 (2009) 011102
	Belle N(BB)=772M	$-1.32 \pm 0.77 \pm 0.36$	$0.48 \pm 0.41 \pm 0.07$	−0.15 (stat)	PR D97 (2018) 092003
	Average	-0.49 ± 0.42	0.06 ± 0.29	−0.15	HFLAV correlated average $\chi^2 = 2.9/2$ dof (CL=0.24 ⇒ 1.2σ)
$K_S\,\rho^0\,\gamma$ (*)	BaBar N(BB)=471M	$-0.18 \pm 0.32^{+0.06}_{-0.05}$	$-0.39 \pm 0.20^{+0.03}_{-0.02}$	−0.09 (stat)	PRD 93 (2016) 052013
	Belle N(BB)=657M	$0.11 \pm 0.33^{+0.05}_{-0.09}$	$-0.05 \pm 0.18 \pm 0.06$	0.04 (stat)	PRL 101 (2008) 251601
	Average(*)	-0.06 ± 0.23	-0.22 ± 0.14	−0.02	HFLAV correlated average $\chi^2 = 1.9/2$ dof (CL=0.38 ⇒ 0.9σ)
$K_S\,\phi\,\gamma$	Belle N(BB)=772M	$0.74^{+0.72}_{-1.05}{}^{+0.10}_{-0.24}$	$-0.35 \pm 0.58^{+0.10}_{-0.23}$	-	PRD 84 (2011) 071101

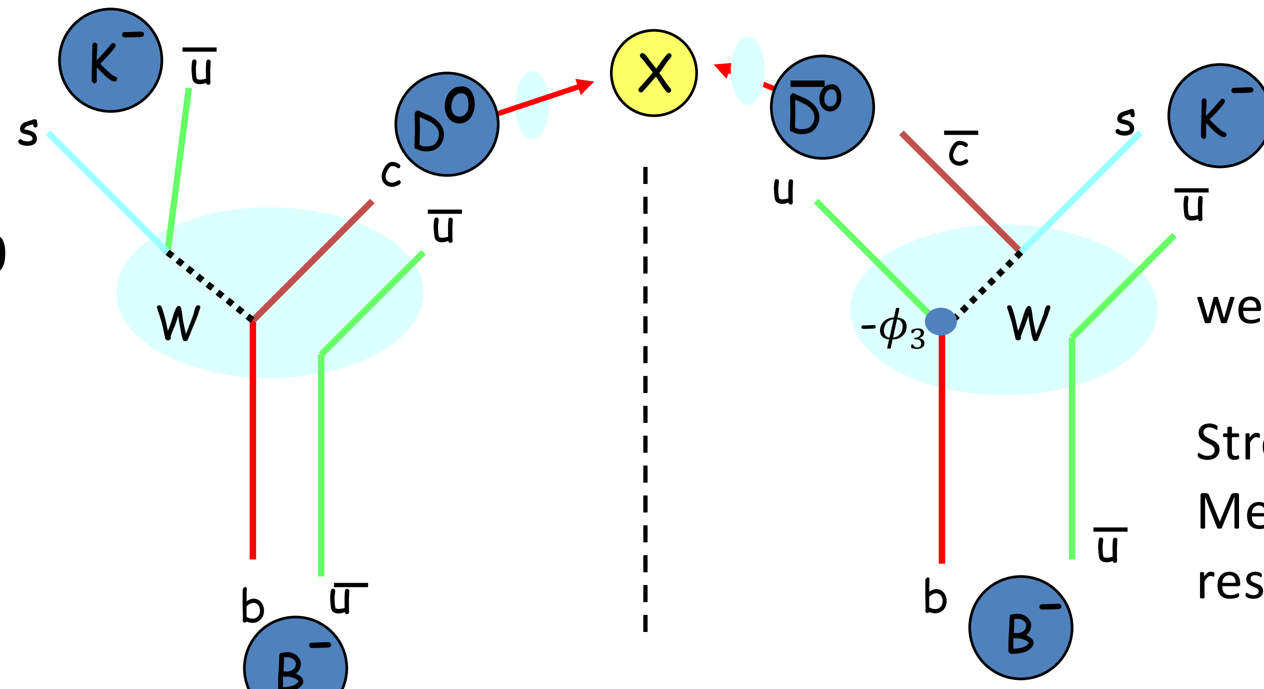
Mode	Experiment	S_{CP} (b → dγ)	C_{CP} (b → dγ)	Correlation	Reference
$\rho^0\gamma$	Belle N(BB)=657M	$-0.83 \pm 0.65 \pm 0.18$	$0.44 \pm 0.49 \pm 0.14$	−0.08 (stat)	PRL 100 (2008) 021602

From HFLAG
arXiv:2206.07501

Time independent CP Violation to determine ϕ_3

weak phase=0

Strong phase:
Meson
rescattering



weak phase=$-\phi_3$

Strong phase:
Meson
rescattering

- The basic B decay looks like it will not work since the final states are different.
- However if the D_0 and $\overline{D}_0$ decay to the same final state, X, the two amplitudes will interfere.
- There are a couple of choices you can make for X
  - X is a CP eigenstate such as $\pi^+\pi^-$ or K^+K^- (GLW method)
  - X is not a CP eigenstate such as $K^+\pi^-$ (ADS method)
  - Three body final generalizations of the above (each dalitz point is a separate final state) (GGSC method)

Gronau, Wyler Phys.Lett.B 265 (1991); Gronau London *Phys.Lett.B* 253 (1991); DA, Dunietz Soni PRL 78 3257 (97); Giri et al PRD68, 054018 (2003); Grossman et. al PRD67, 071301 (2003).

Prospect for ϕ_3

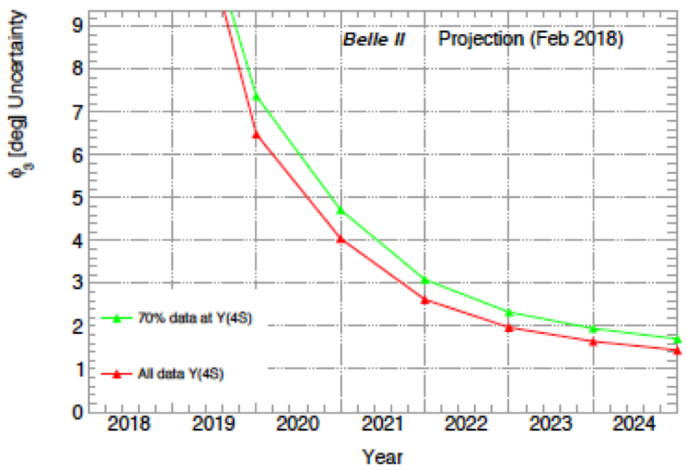


Fig. 130: The future prospect of Belle II sensitivity

Belle Physics book

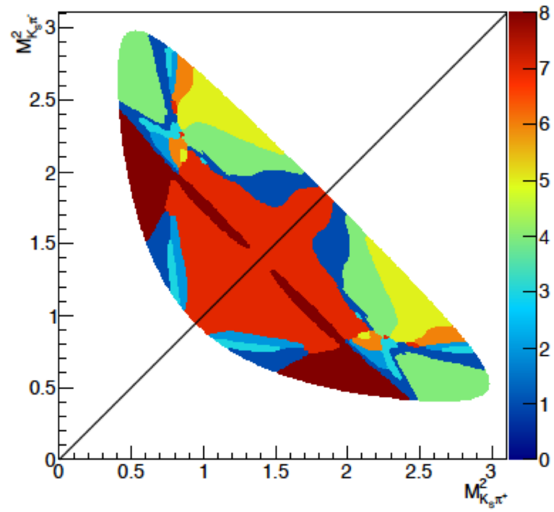


Fig. 124: Dalitz binning used for the $D \to K_S^0\pi^+\pi^-$ analyses.

Belle Physics book

- Gold plated mode for Belle II is thought to be $D \to K_S\pi^+\pi^-$ with Dalitz binning

Conclusions

- There must be physics beyond the SM; energy or intensity frontiers are where to look for it.
- There are a multitude of signals to look for at B factories
- CP violation is promising because we know there must be CP violation beyond the SM
- CP violating observables can either be time dependent or time independent depending on the source of the strong phase.
- Particular signals either check CKM unitarity directly or are sensitive to non-SM CP violation. BELLE II should allow meaningful probing of many such modes.