Heavy Flavour Experiment
Lecture 1

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Acknowledgements & 1st Introduction

- I have taken inspiration from many recent results and conference talks

- Many thanks to those who (un)knowingly helped me
  - T. Gershon, V. Gibson, S. Hansmann-Menzemer, U. Uwer, F. Teubert, T. Nakada, A. Shires, S. Wandernoth ...

- This is a talk for students, not an overview of the field
  - For complete overviews, look at recent conferences, e.g.
    EPS13: https://indico.cern.ch/getFile.py/access?contribId=864&sessionId=28&resId=1&materialId=slides&confId=218030
    LHCC: http://indico.cern.ch/categoryDisplay.py?categId=3427
    FPCP: http://fpcp2013.if.ufrj.br/fpcp-2013/

- Please interrupt me at any time

Contents

- Lecture 1:
  - Introduction to “heavy flavour physics”
  - The Experiments:
    Flavour physics at e^+e^- and at hadron colliders
  - CKM matrix and types of CP violation
  - Precision measurements of the quark mixing matrix

- Lecture 2:
  - “Golden modes for New physics searches” – loop zoology

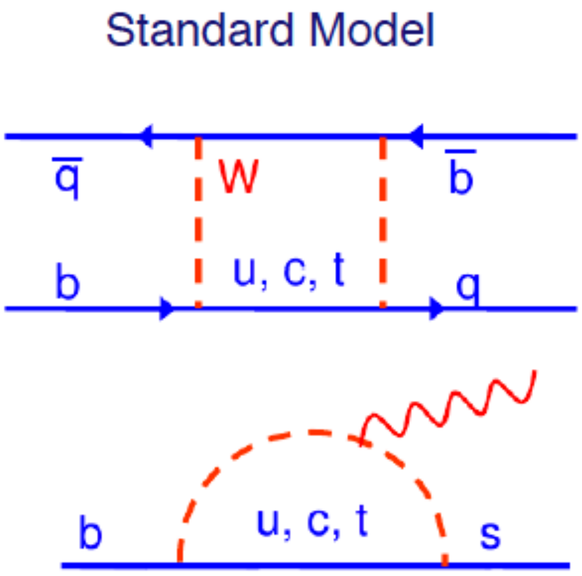
Indirect searches for New Physics

- High **energy**:
  "real" new particles can be produced and discovered via their decays

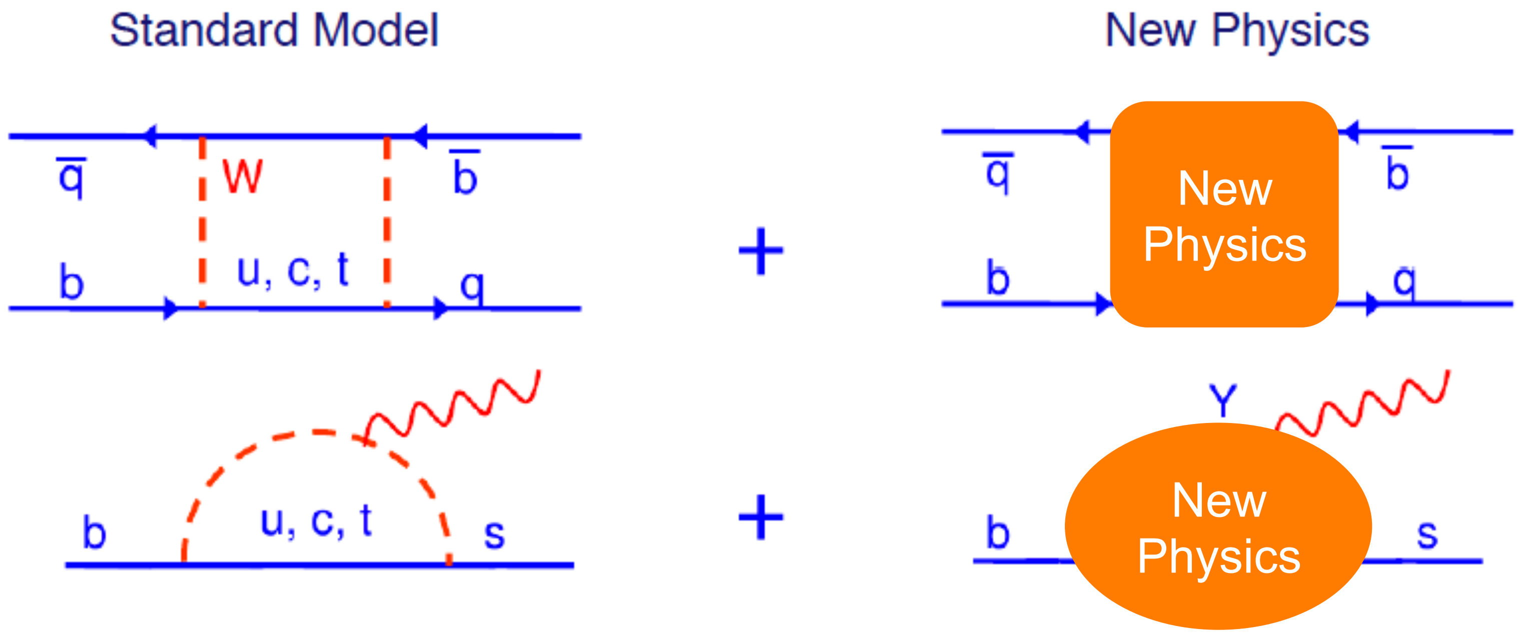
- High **precision**:
  "virtual" new particles can be discovered in loop processes

**Direct and indirect searches are both needed,
both equally important,
and complement each other**

Contribution of New Physics as correction to the Standard Model



Contribution of New Physics as correction to the Standard Model



$$\mathcal{A}_{BSM} = \mathcal{A}_0 \left(\frac{c_{SM}}{m_W^2} + \boxed{\frac{c_{NP}}{\Lambda^2}} \right)$$

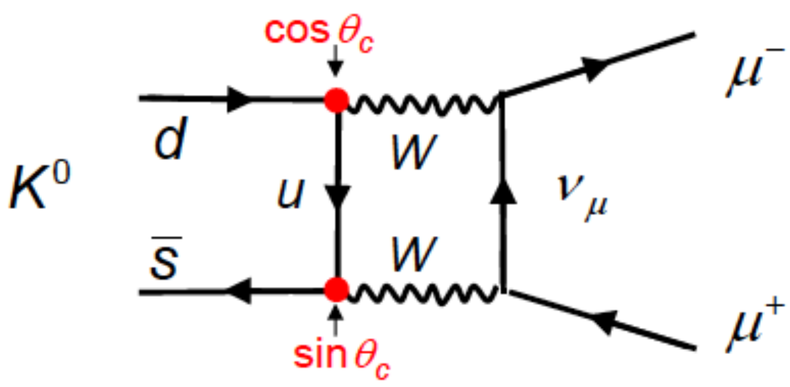
What is the scale of λ_{NP}? What is its coupling C_{NP}?

GIM Mechanism

Observed branching ratio $K^0 \to \mu\mu$

$$\frac{BR(K_L \to \mu^+\mu^-)}{BR(K_L \to all)} = (7.2 \pm 0.5) \cdot 10^{-9}$$

In contradiction with theoretical expectation in the 3-Quark Model



$M \sim \sin\theta_c \cos\theta_c$

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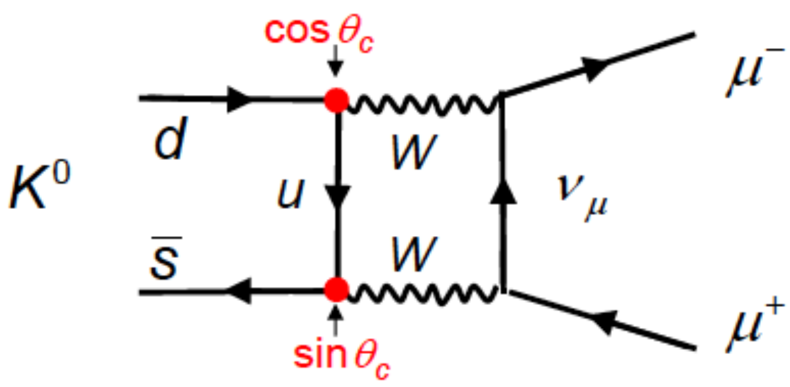
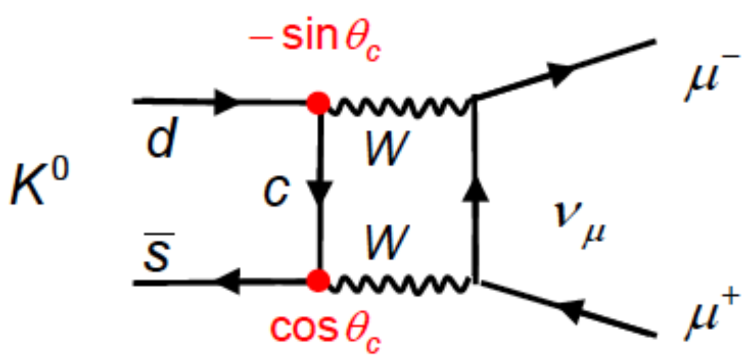
In contradiction with theoretical expectation in the 3-Quark Model

Glashow, Iliopolus, Maiani (1970):

Prediction of a 2nd up-type quark, additional Feynman graph cancels the "u box graph".



$M \sim \sin\theta_c \cos\theta_c$



$M \sim -\sin\theta_c \cos\theta_c$

Status of searches for NP

- Before the LHC, λ_{NP}~1TeV was expected
  - Fine tuning at EW scale reduced
  - But: NP effects expected in flavour physics → NP flavour problem
    → Ad-hoc solution: introduce Minimal Flavour Violation
    to avoid fine tuning in the flavour sector
  - After Higgs discovery: scale of New Physics fully unclear

Status of searches for NP

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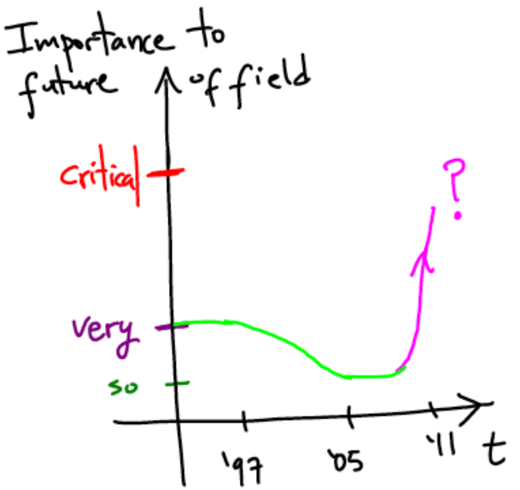
Importance of Flavour



N. Arkani-Hamed
Intensity frontier workshop

- So far: no significant sign of New Physics
  - The scale for NP get pushed higher
  - NP flavour problem reduced
    → chances to see NP in the flavour sector have increased
    (hypotheses like MFV look less likely)

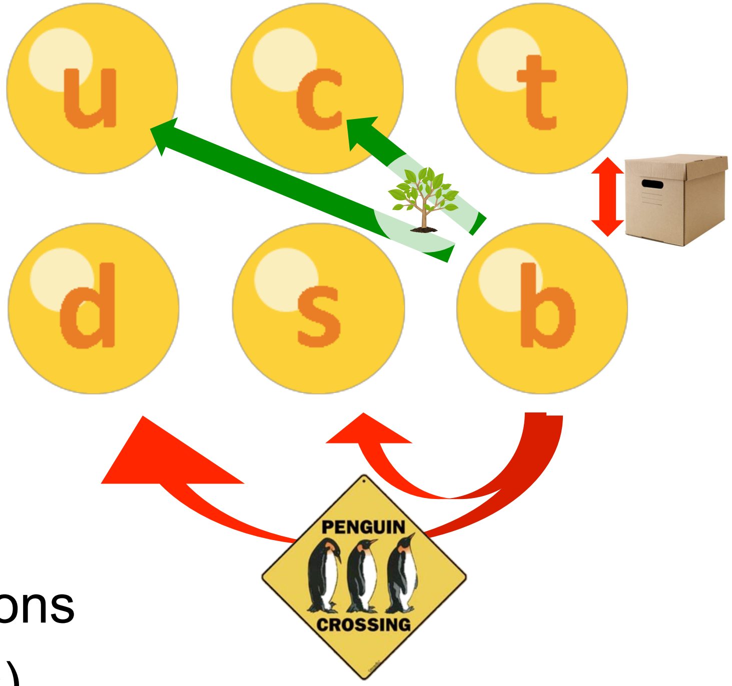
arXiv:1205.7091, arXiv:1205.2671

Heavy Quark Flavour Physics

- Focus in these lectures will be on
  - Flavour changing interactions of charm and **beauty quarks**
- But quarks feel the strong interaction and hadronize
  - Various different beauty hadrons
  - Many, many possible decays to different final states
    → Hadronization introduces great complications,
    BUT also increases the observability of CP violation effects
- Many aspects of flavour physics left out in this lecture
  - Neutrino physics: have own phenomenology
  - Light quark flavour physics
  - Charged lepton physics
  - Top-flavour physics: different, as the top does not hadronize

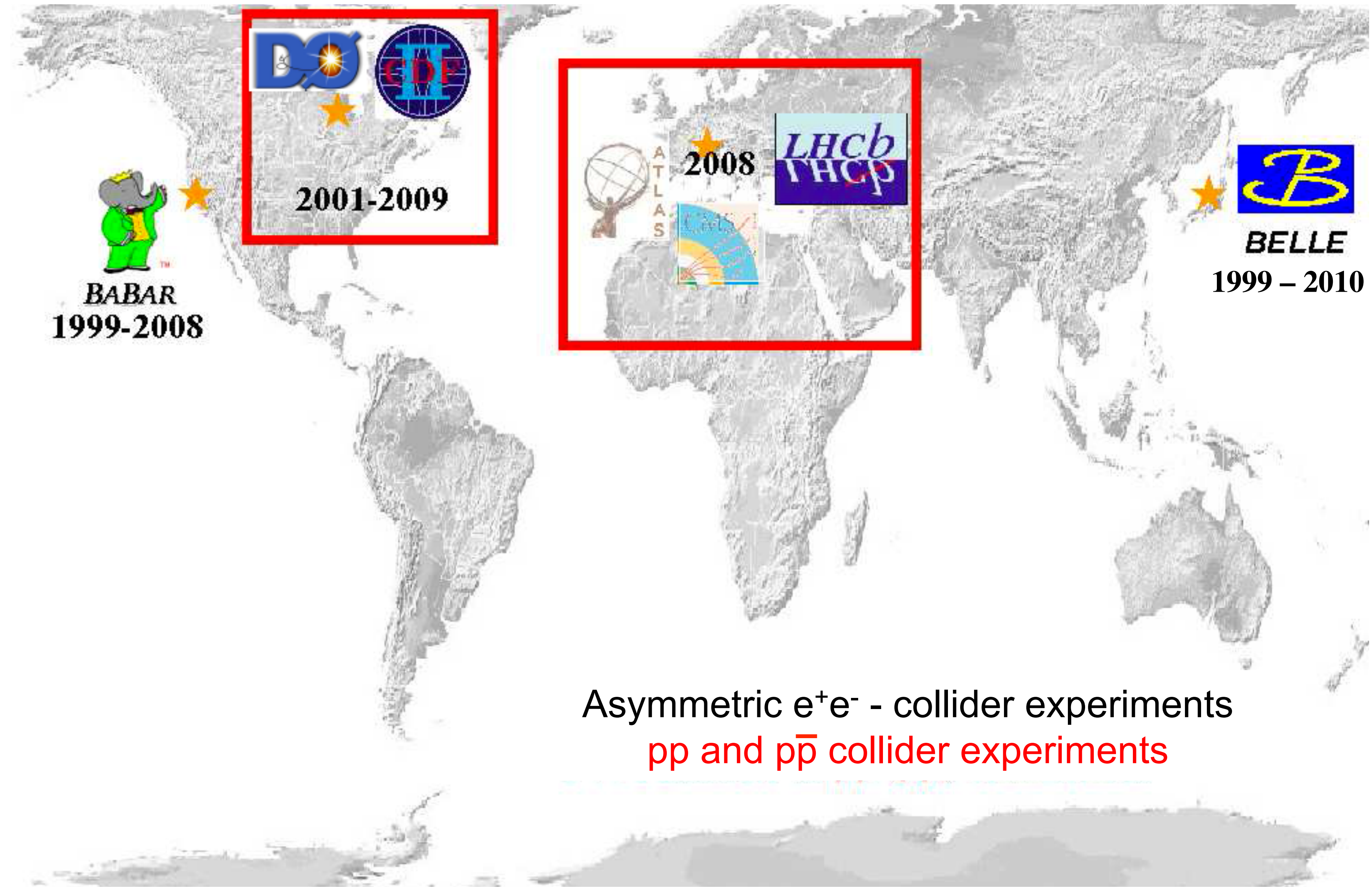
Rich phenomenology with beauty quarks

- The beauty quark …
  - Is the heaviest quark that forms hadronic bound states
    → high mass: many accessible final states
  - Must decay outside the 3rd family
    - All decays are CKM suppressed
    - Long lifetime (~1.6ps)



- Beauty-decays:
  - Dominant decay process: "tree" b→c transition
  - Very suppressed "tree" b→u transition
  - FCNC "penguin" b-> s and b→ d transitions
  - Flavour oscillations (b→t "box" diagrams)
  - CP violation – expect large CP asymmetries in some B decays

B–Physics Around the World

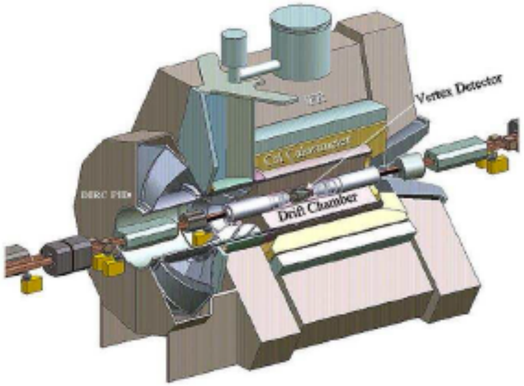


Asymmetric e^+e^- - collider experiments

pp and $p\bar{p}$ collider experiments

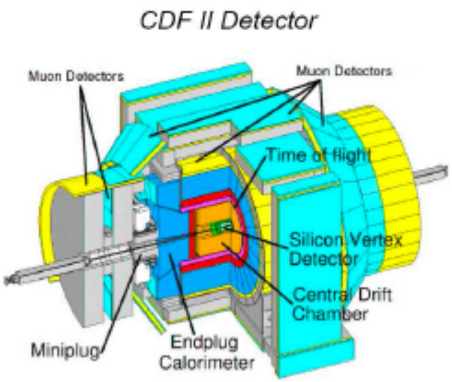
B-factories (BaBar & Belle)

- e^+e^- experiment at SLAC / KEK
- Dedicated B-physics experiment



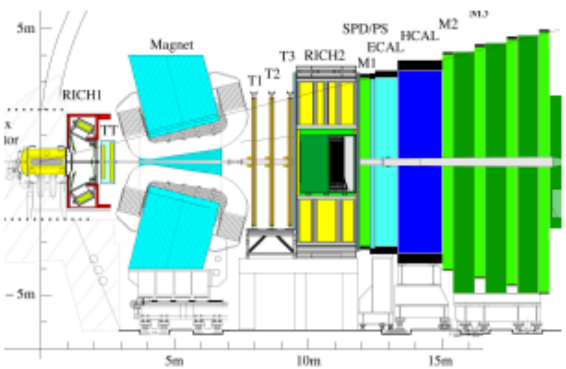
General purpose detectors (ATLAS, CMS, CDF, D0)

- Proton colliders @ CERN / Tevatron
- 4π multi purpose detectors



LHCb

- Proton colliders @ CERN
- Dedicated B-physics experiment



Experimental environment: e^+e^-

Lepton collider
(collision of pointlike objects)

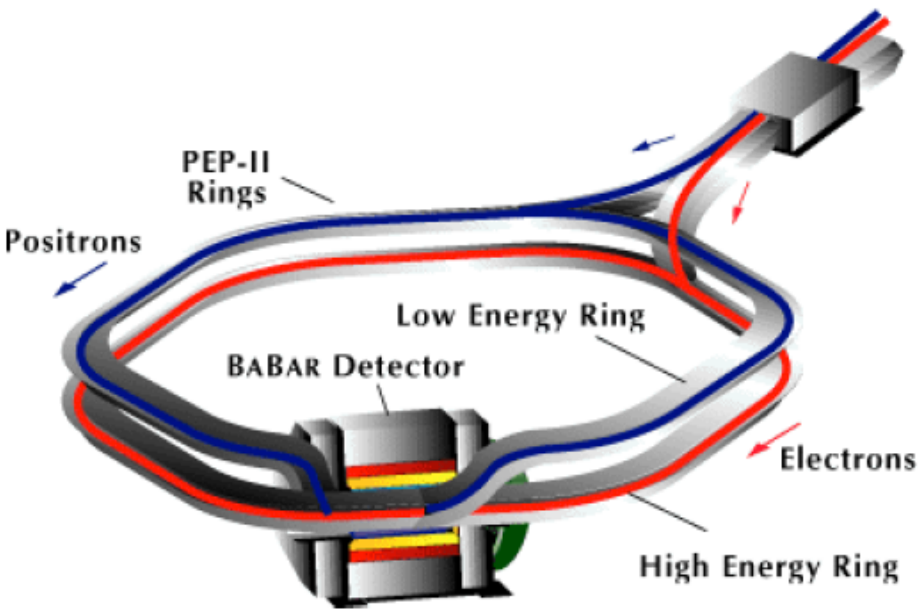
Hadron collider
(collision of extended objects)

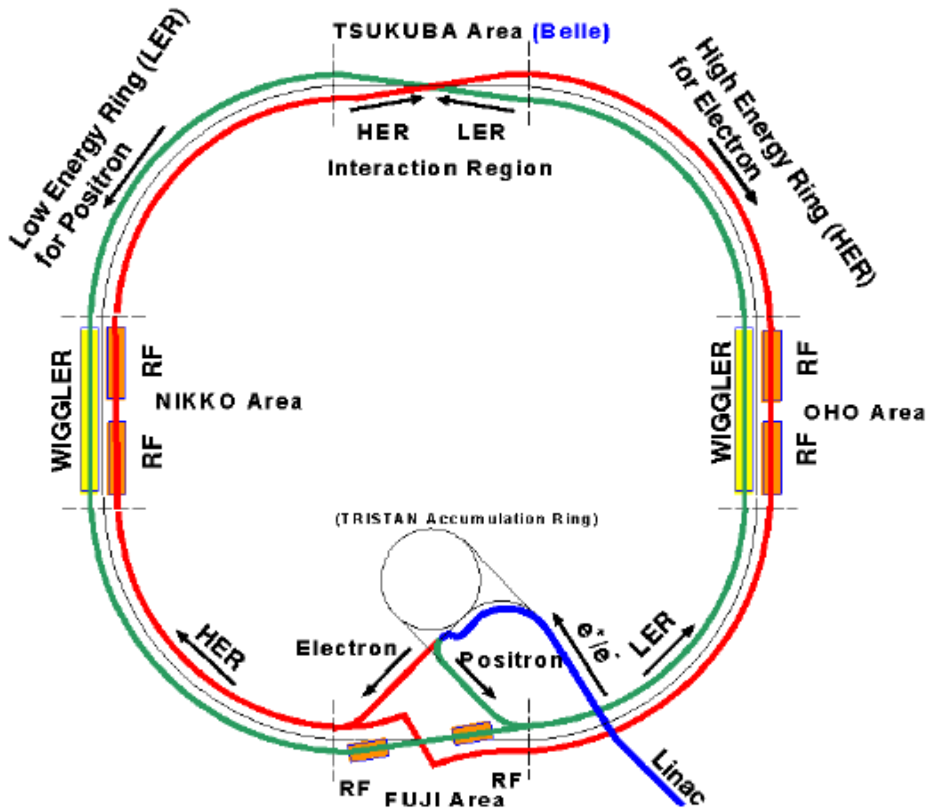
[Karl Jakobs]

e^+e^-: Asymmetric B Factories

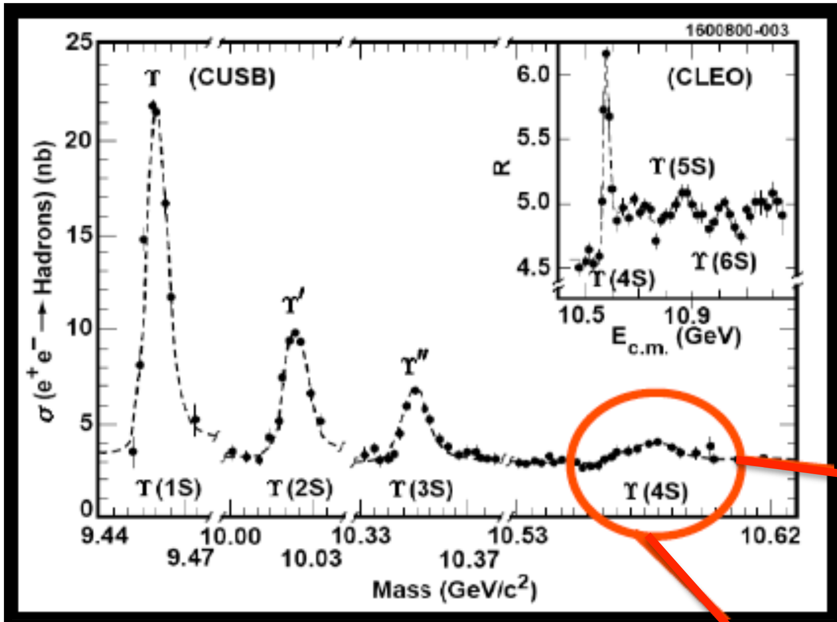
PEPII at SLAC
9.0 GeV e^- on 3.1 GeV e^+

KEKB at KEK
8.0 GeV e^- on 3.5 GeV e^+





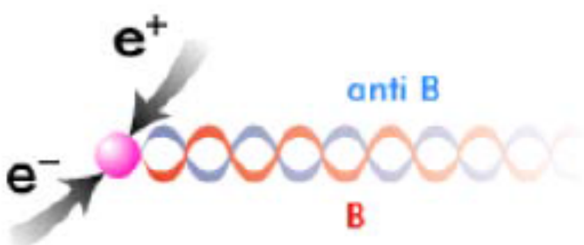
Υ (4S) resonance

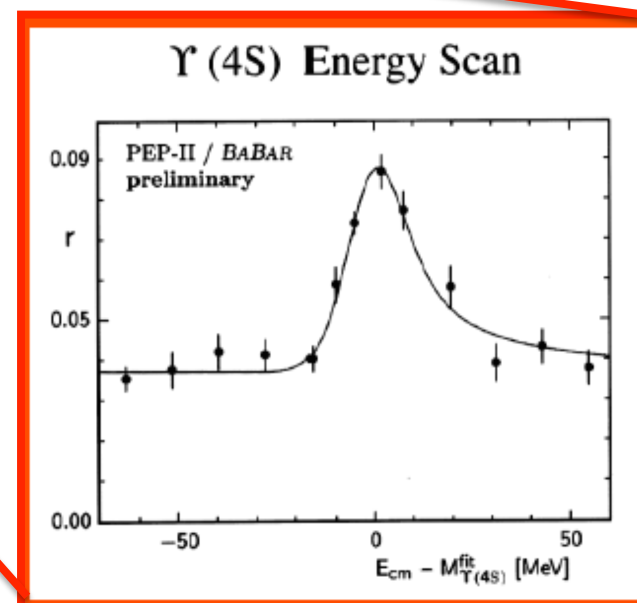


Cleanest way to produce B mesons:
e^+e^- collisions at

$\sqrt{s}$ = 10.58GeV

~1.1M BB pairs per fb^{-1}
$\sigma_{bb} / \sigma_{continuum}$ ~ 1/3





BB pair is produced in a coherent state
→ two B mesons evolve until one decays

Kinematics at e^+e^- Colliders

- Symmetric collider: B-mesons produced ~ at rest
  - Short lifetime make flight distance unmeasurably small

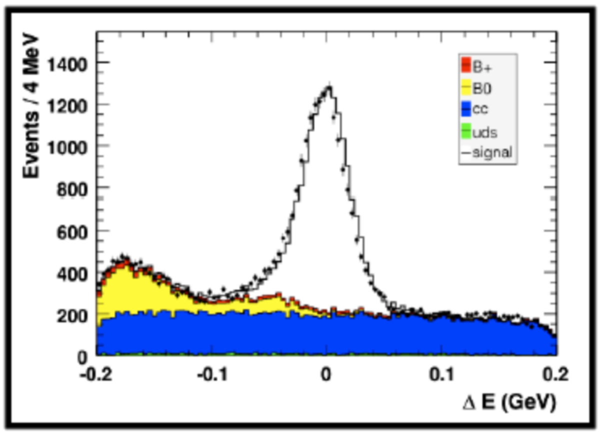
- Asymmetric collider (KEKB, PEPII): with boost $\beta\gamma$ ~ 0.6

$$\Delta t \approx \frac{\Delta z}{\langle \beta\gamma \rangle c}$$

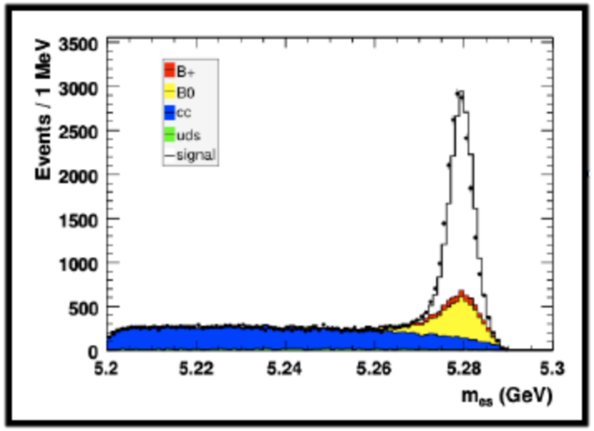
$$\langle |\Delta z| \rangle \approx 200\ \mu m$$

- Beam energy precisely known → constrain B kinematics

$$\Delta E \equiv E_B^* - E_{beam}^*$$



$$m_{ES} \equiv \sqrt{E_{beam}^{*\,2} - p_B^{*\,2}}$$



Experimental environment: pp (or $p\bar{p}$)

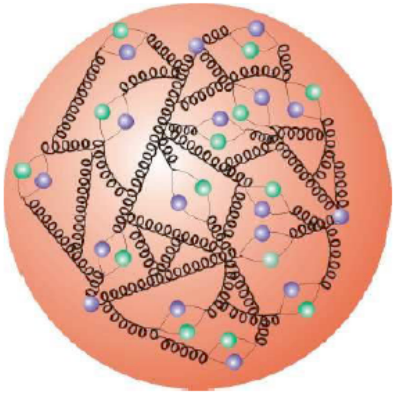
Lepton collider
(collision of pointlike objects)

Hadron collider
(collision of extended objects)

[Karl Jakobs]

Proton Collisions

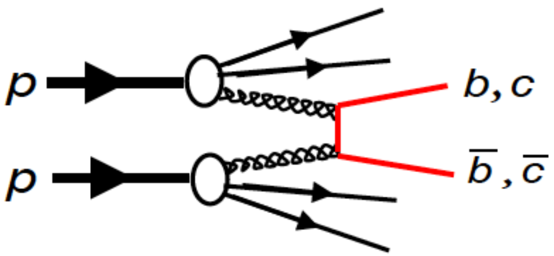
- Protons are complicated objects
  - Valence & sea quarks, gluons



- Available energy of "proton" collision depends on partons

$$s' = x_1 \cdot x_2 \cdot s$$

x_i = Bjorken x (fractional momentum) of parton



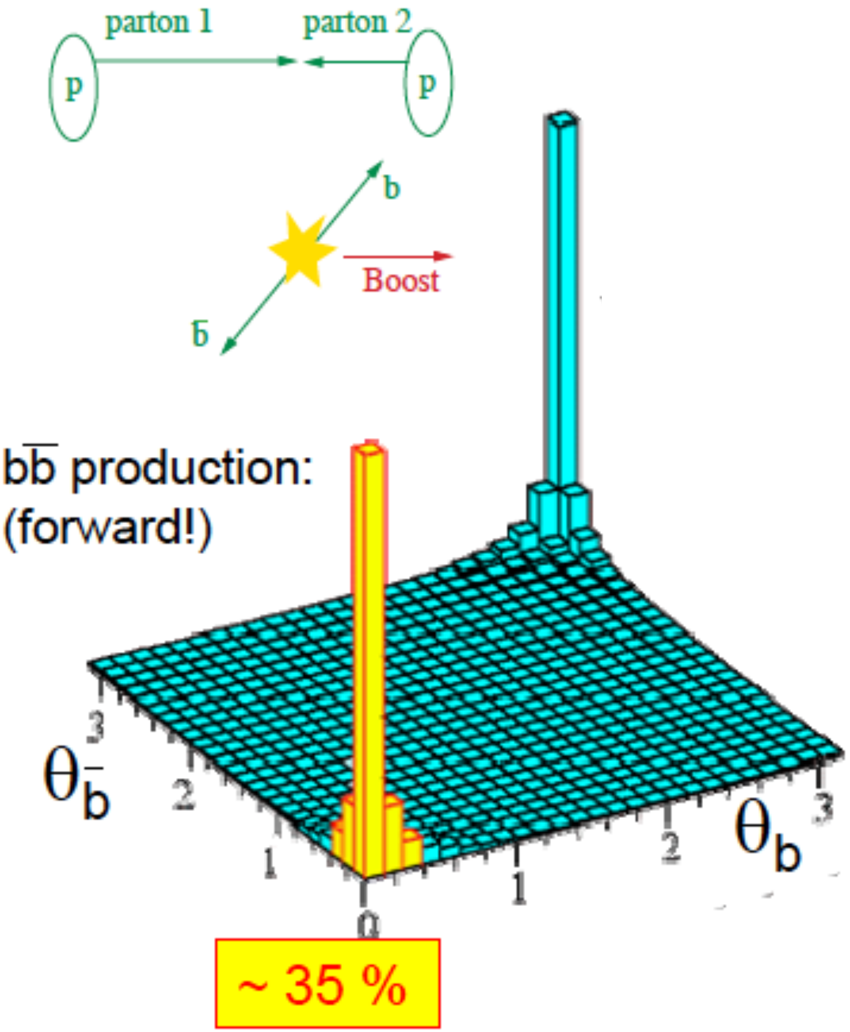
- Energy of particular collision unknown, but distributions known
  - hadron colliders "scan" a wide energy range
  - Average s' ~ 0.1 s
  - Dominant process @ LHC: gluon fusion

Event kinematics

- B hadron mass ~ 5 GeV
  - asymmetric x-values
  - strongly boosted ($\beta\gamma$~100)
  - average flight length ~ 7mm

- Boost allows time dependent analyses of fast B_s mixing

- B hadron admixture:
  - 40% B^0
  - 40% B^+
  - 10% B_s
  - 10% Λ_b
  - <1% others (B_c, B*, B**, ..)



LHC Flavour Physics Programme

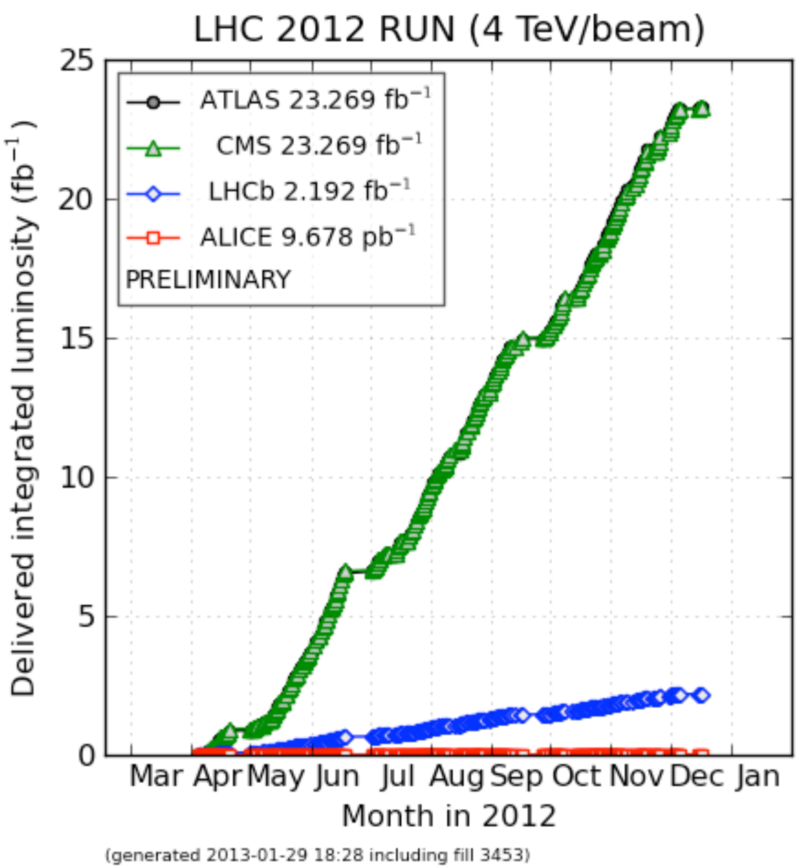
ATLAS / CMS

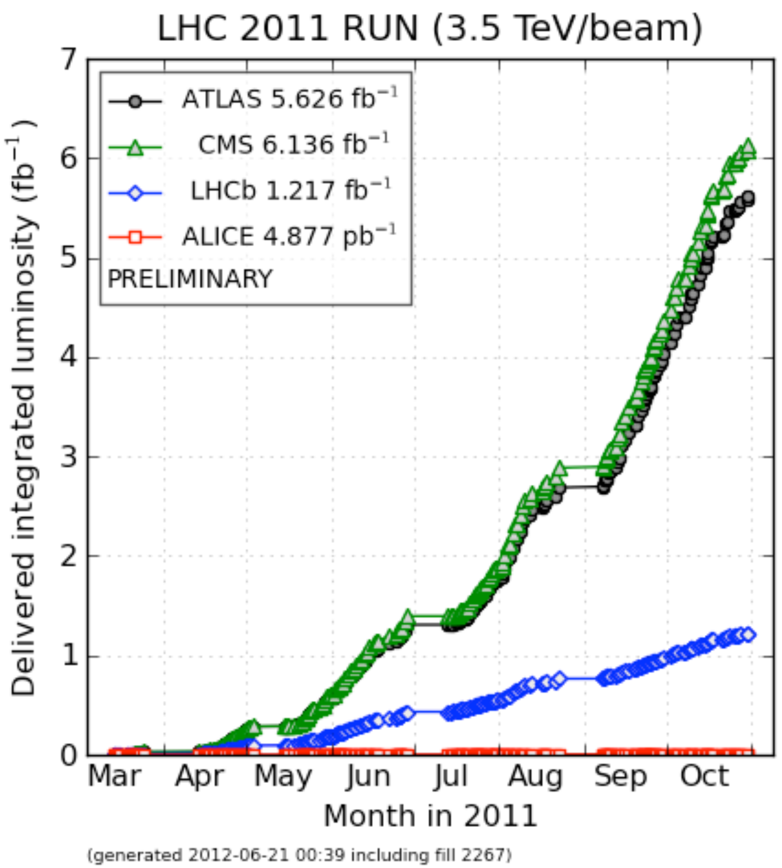
- Central detectors, $|\eta|<2.5$
- **High Luminosity ($>10^{34} cm^{-2} s^{-1}$)**
  → high pileup ~20
- Trigger
  - Relatively low rate (~200-400Hz)
  - High PT muon triggers
- Analysis
  - Mostly modes with dimuons
  - Limited flavour tagging
- Particle identification
  - Excellent muon ID
  - Limited K / π separation

LHCb

- Forward spectrometer, $1.9< \eta < 5$
- Lower Luminosity ($4x10^{32} cm^{-2} s^{-1}$)
  → pileup ~1.5
- Trigger
  - **High trigger rate** (~5kHz)
  - Muon & hadron triggers, softer thresholds
  - **Large bandwidth for charm**
- Analysis
  - Hadronic and low M modes accessible
  - Excellent flavour tagging & σ_t
- Particle identification
  - Excellent muon ID
  - Dedicated RICH PID (K / π)

Keys for b-physics I: Data

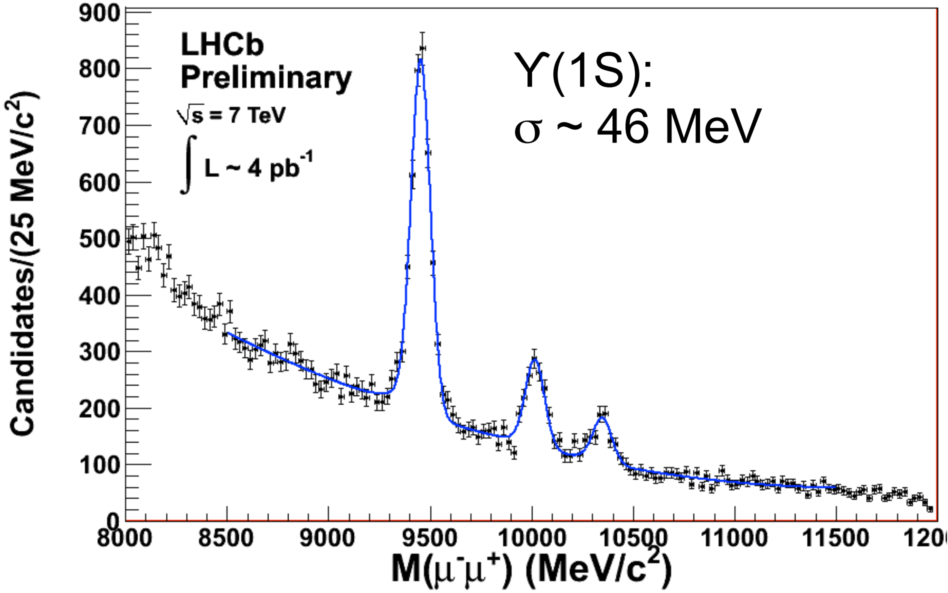


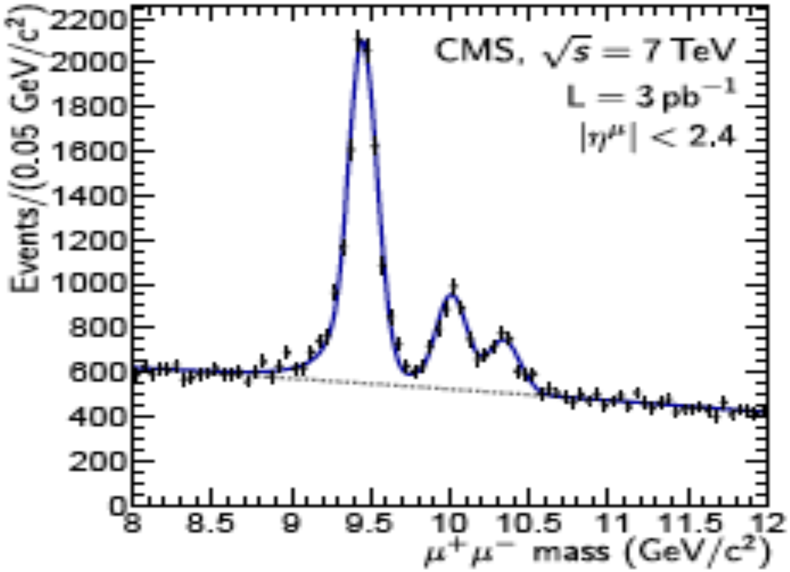


Full dataset: ATLAS = CMS = 10 * LHCb

Keys for b-physics II: mass resolution

ϒ(1S), ϒ(2S), ϒ(3S)



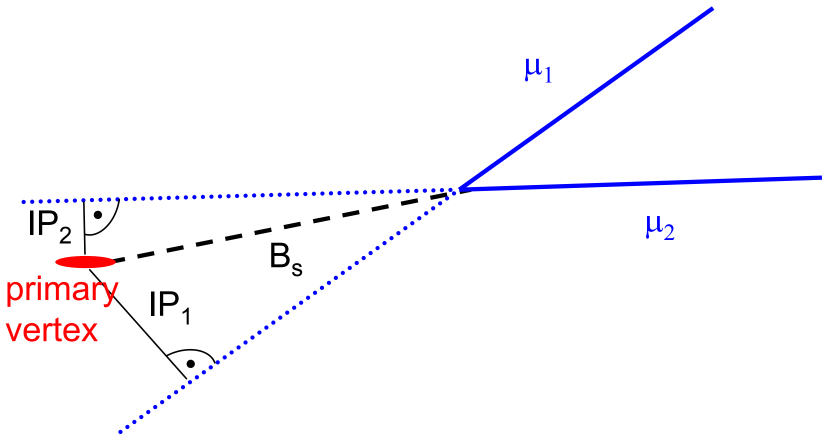


	momentum resolution	mass resolution $J/\psi \rightarrow \mu\mu$
LHCb	$\delta p/p$ = 0.4-0.6 %	13 MeV
CMS	$\delta pt/pt$ = 1-3 %	40 MeV
ATLAS	$\delta pt/pt$ = 5-6 %	71 MeV

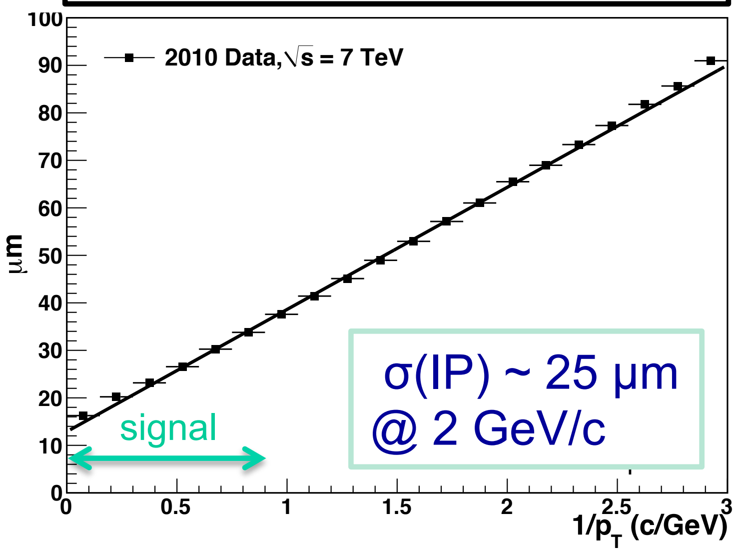
Primary vertex resolutions (25 tracks):

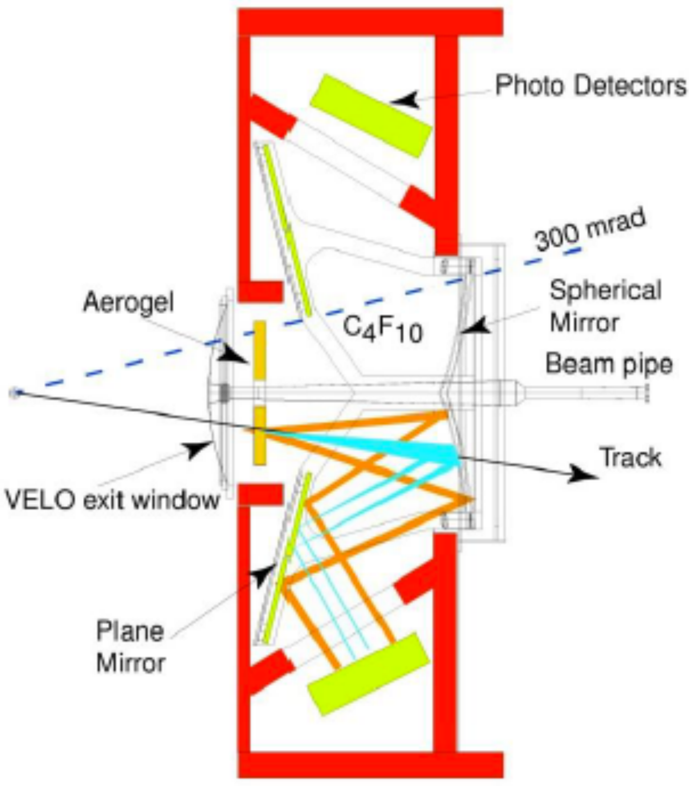
	LHCb [μm]	ATLAS [μm]	CMS [μm]
σ(x)	15.8	60	20-40
σ(y)	15.2	60	20-40
σ(z)	76	100	40-60

Impact parameter (IP):

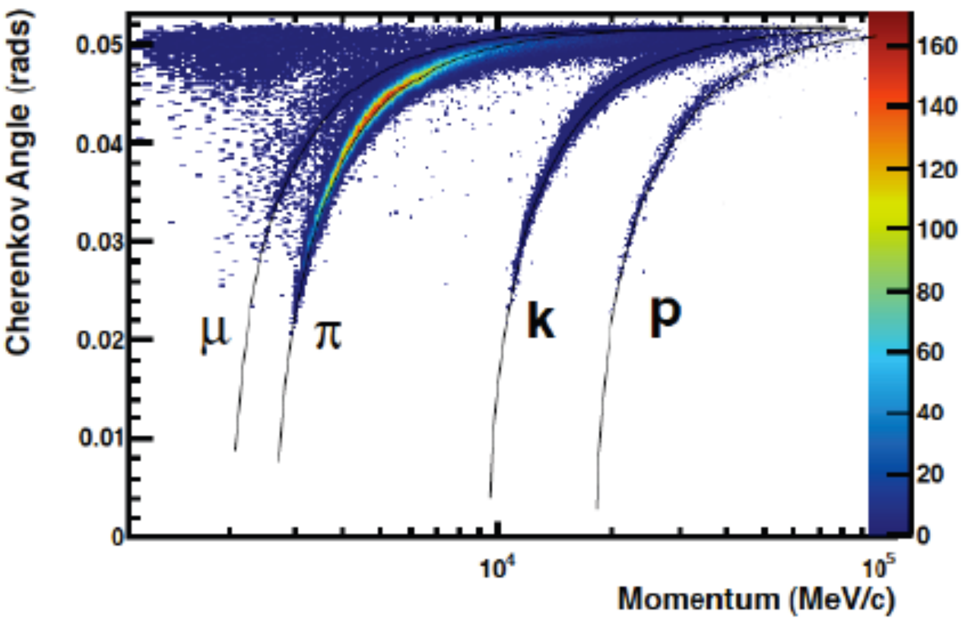


IP resolution vs 1/pT





$$\cos\theta_c = \frac{1}{\beta n}$$



Keys for b-physics IV: Particle Identification

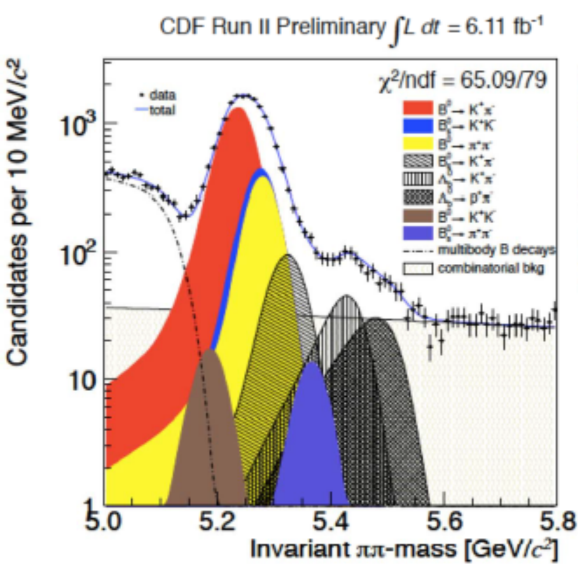
- The LHCb experiment is equipped with two Cherenkov detectors

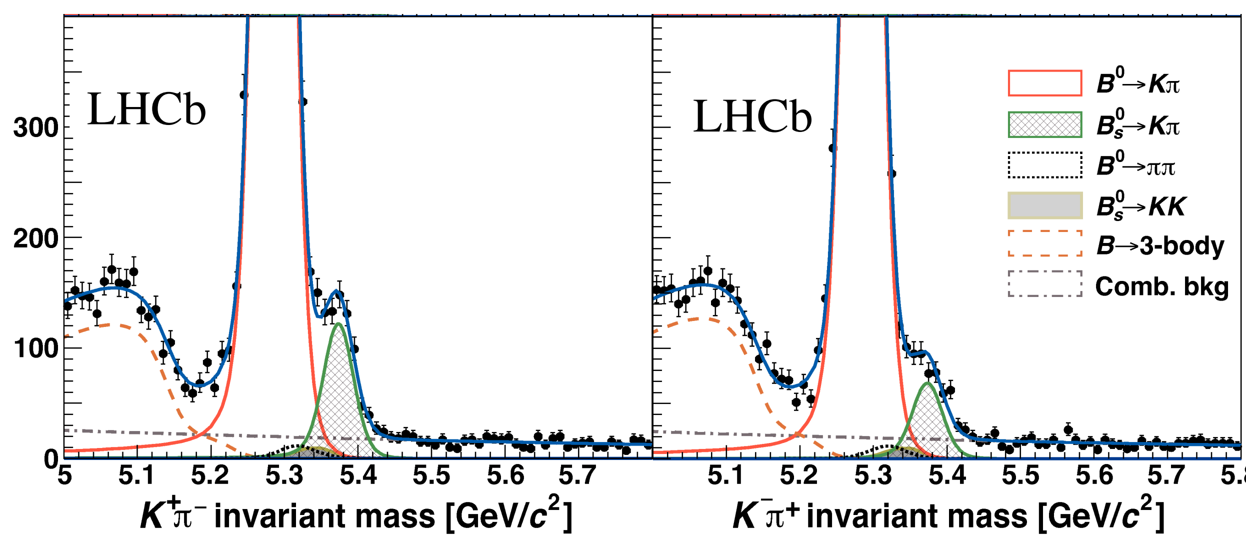
Kaon identification: $K \to K$: 95.5% $\pi \to K$: 7.1%

⇒

$B \to h\, h$
$B^0 \to K\, \pi$
$B^0 \to \pi\, \pi$
$B_s \to K\, K$

$B \to h^+h^-$ without and with RICH Particle ID



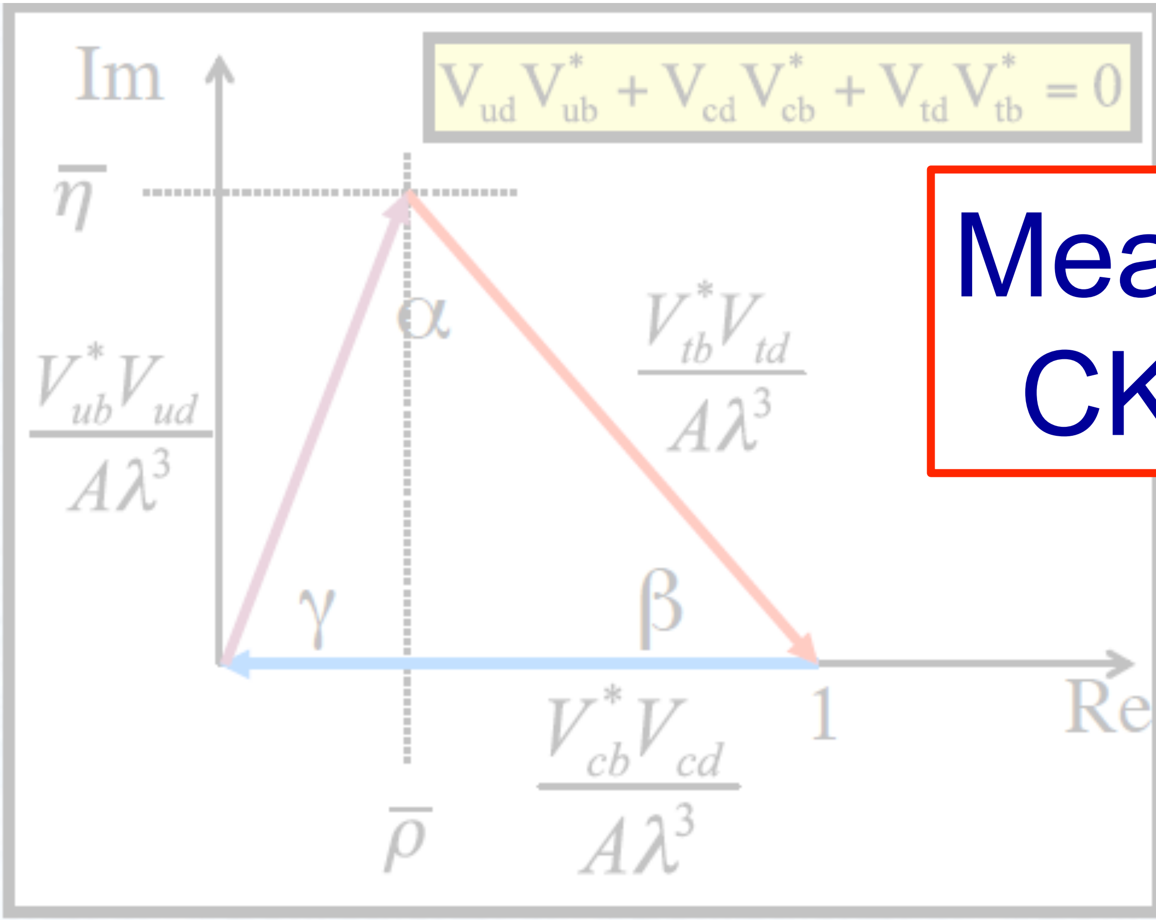


B Production Rates

	BaBar / Belle (ee)	CDF / D0 (pp)	ATLAS / CMS (pp)	LHCb (pp)
$\sqrt{s}$ [GeV]	10.58 (Y(4S))	1980	7000 / 8000	7000 / 8000
BB production	coherent BB state	Incoherent BB state		
σ_{bb} [μb] in acceptance	0.0011	6.3	75	94
L [fb^{-1}]	550 / ~1000	~10	~30	3
bb pairs in acceptance [10^{11}]	0.01	0.6	22	3

What does 1/ab mean?

N(bb) = Lumi * x-section



Measuring the CKM Matrix

Pick 3 measurements/quantities:

- CKM angle sin 2β
- CKM angle γ
- B_s mixing frequency: Δm_s

CKM matrix I

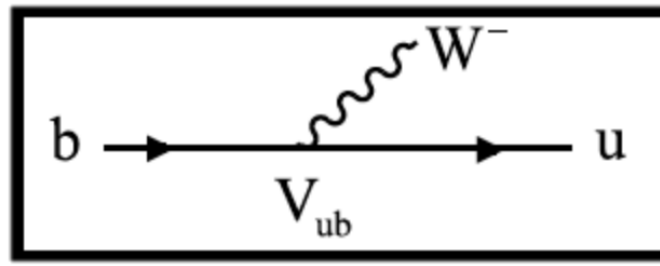
[I assume everyone in the room has seen the CKM matrix before]

V_{CKM} describes the rotation between weak (d’, s’, b’) and mass eigenstates (d, s, b)

transition amplitude ~ V_{ij}

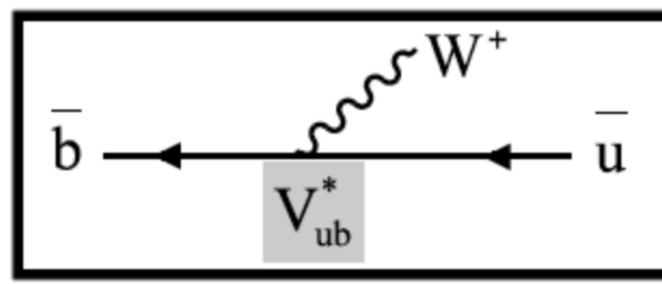
Quarks

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$



Antiquarks

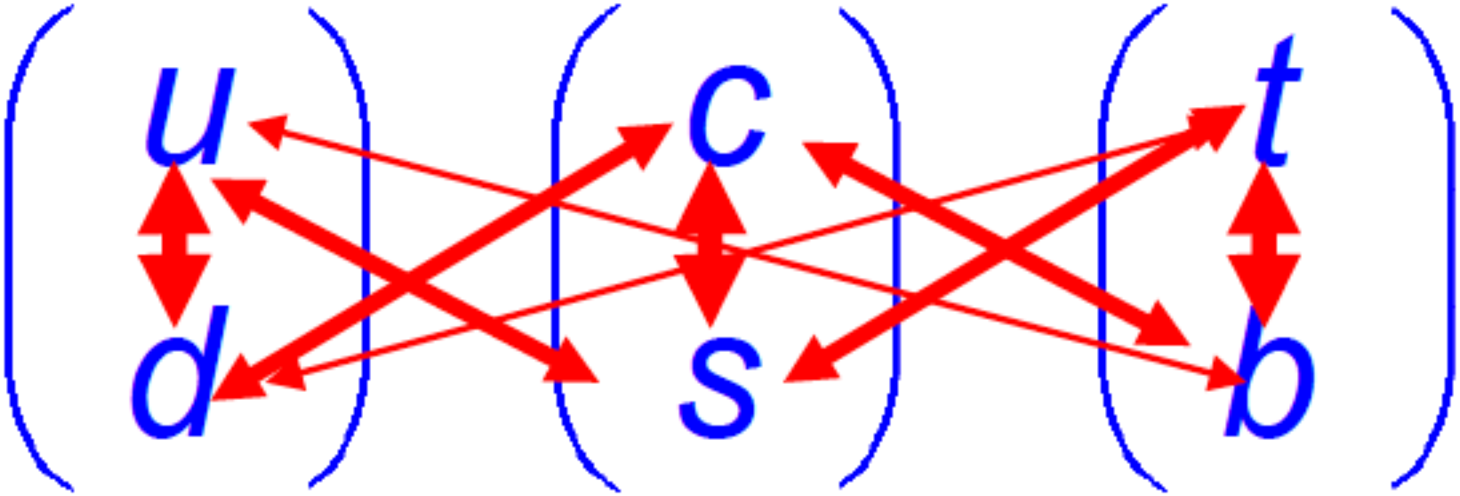
$$\begin{pmatrix} \bar{d}' \\ \bar{s}' \\ \bar{b}' \end{pmatrix} = \begin{pmatrix} V_{ud}^* & V_{us}^* & V_{ub}^* \\ V_{cd}^* & V_{cs}^* & V_{cb}^* \\ V_{td}^* & V_{ts}^* & V_{tb}^* \end{pmatrix} \begin{pmatrix} \bar{d} \\ \bar{s} \\ \bar{b} \end{pmatrix}$$



- CKM matrix is complex and unitary
- Four independent parameters
  - Fundamental constants of nature that must be measured

$$\hat{V}^{+}_{CKM}\hat{V}_{CKM} = 1$$

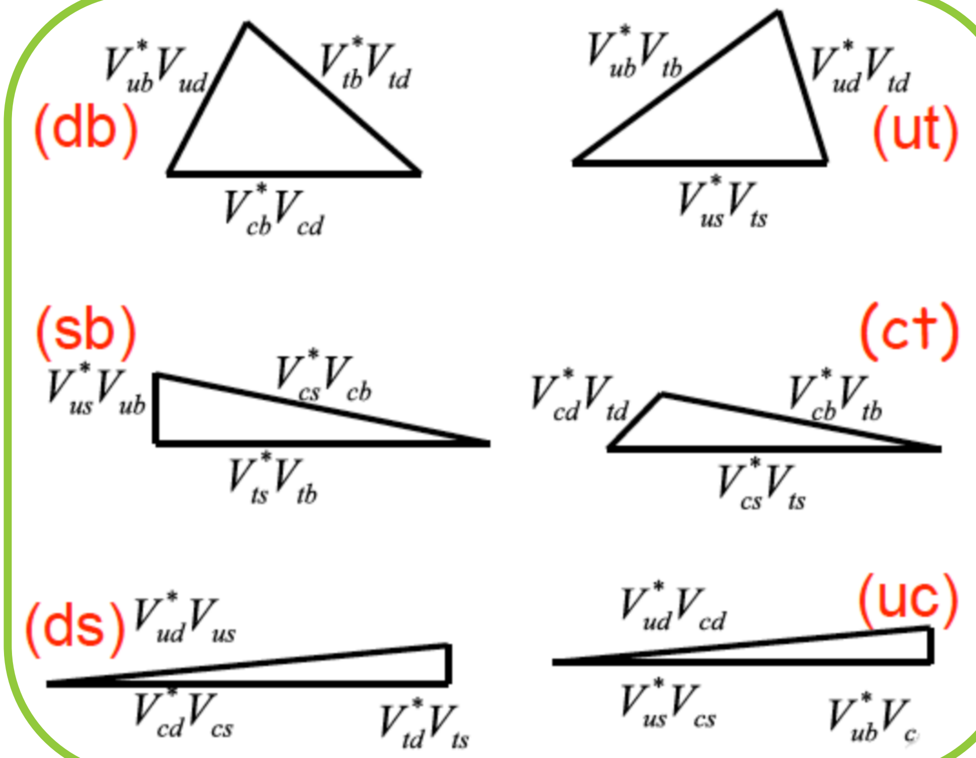
- Reflects hierarchy of quark transitions



CKM matrix is unitary:

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0 \text{ (db)}$$
$$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0 \text{ (sb)}$$
$$V_{ud}V_{us}^* + V_{cd}V_{cs}^* + V_{td}V_{ts}^* = 0 \text{ (ds)}$$

$$V_{ud}V_{td}^* + V_{us}V_{ts}^* + V_{ub}V_{tb}^* = 0 \text{ (ut)}$$
$$V_{cd}V_{td}^* + V_{cs}V_{ts}^* + V_{cb}V_{tb}^* = 0 \text{ (ct)}$$
$$V_{ud}V_{cd}^* + V_{us}V_{cs}^* + V_{ub}V_{cb}^* = 0 \text{ (uc)}$$



All 6 triangles have the same area, a measure of CPV in the SM

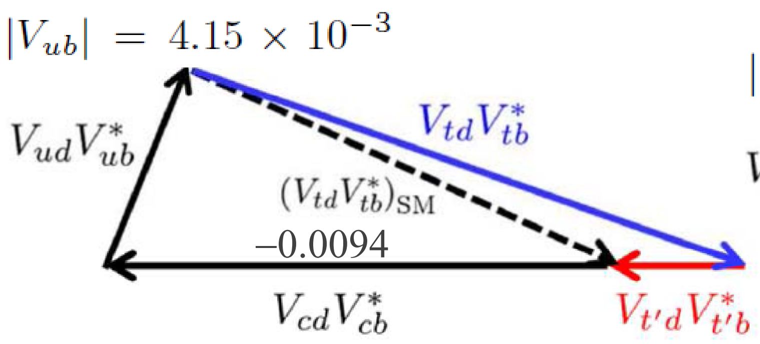
What could a non-uniform CKM matrix mean?

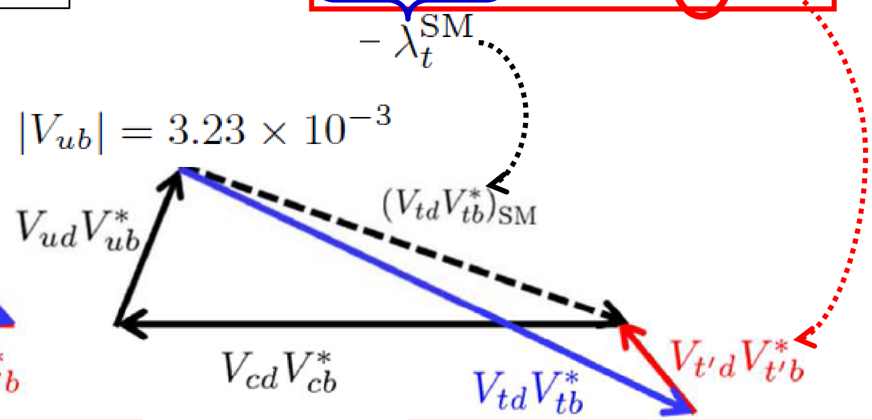
Discussion on CKM4

CPV4BAU?

- b → d quadrangle in our lap!

$$\underbrace{\lambda_u + \lambda_c}_{-\lambda_t^{\rm SM}} + \lambda_t + \lambda_{t'} = 0$$





from: Region A $V_{t'd}^*V_{t'b} = 0.0025\, e^{i180^\circ}$ A′ $V_{t'd}^*V_{t'b} = 0.0023\, e^{i230^\circ}$

- The above CKM4 values are quite large. [$V_{t'b}$ < 0.1 necessary] WSH & Ma, PRD'11

  If we learn from $\sin\phi_s$ experience [CKM hierarchy seem upheld], then $B_d \to \mu^+\mu^-$ > 4x SM is possible, but not particularly likely.

  Heavier t′ could still do it with more "naturally" small CKM4.

“The” CKM Unitarity Triangle

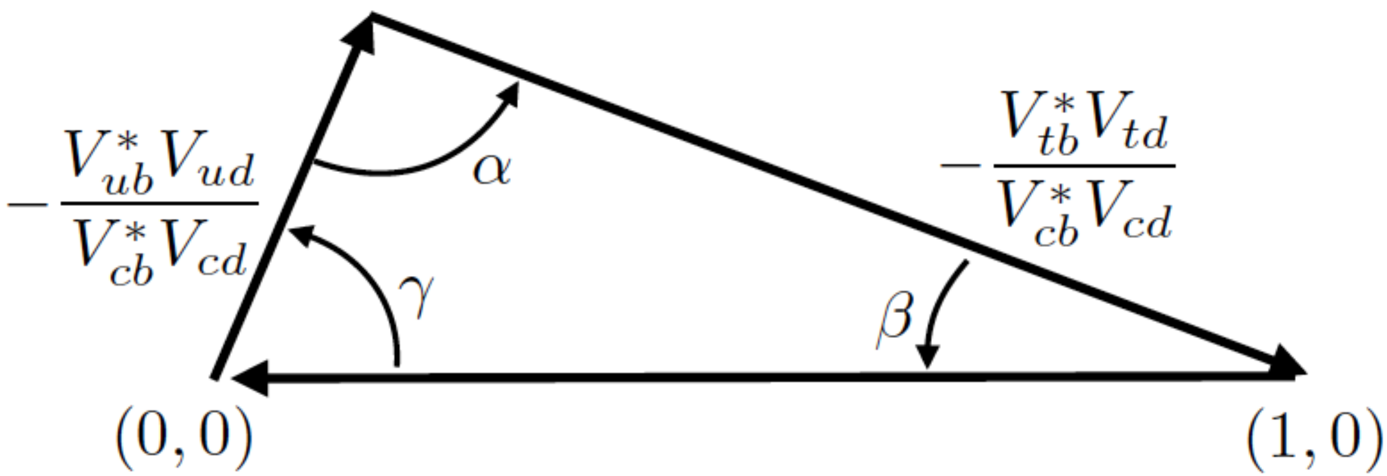
$$V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$$

- Pick a quark phase convention such that $V_{cb}^* V_{cd}$ is real
- Normalize all sides by $-V_{cb}^* V_{cd}$

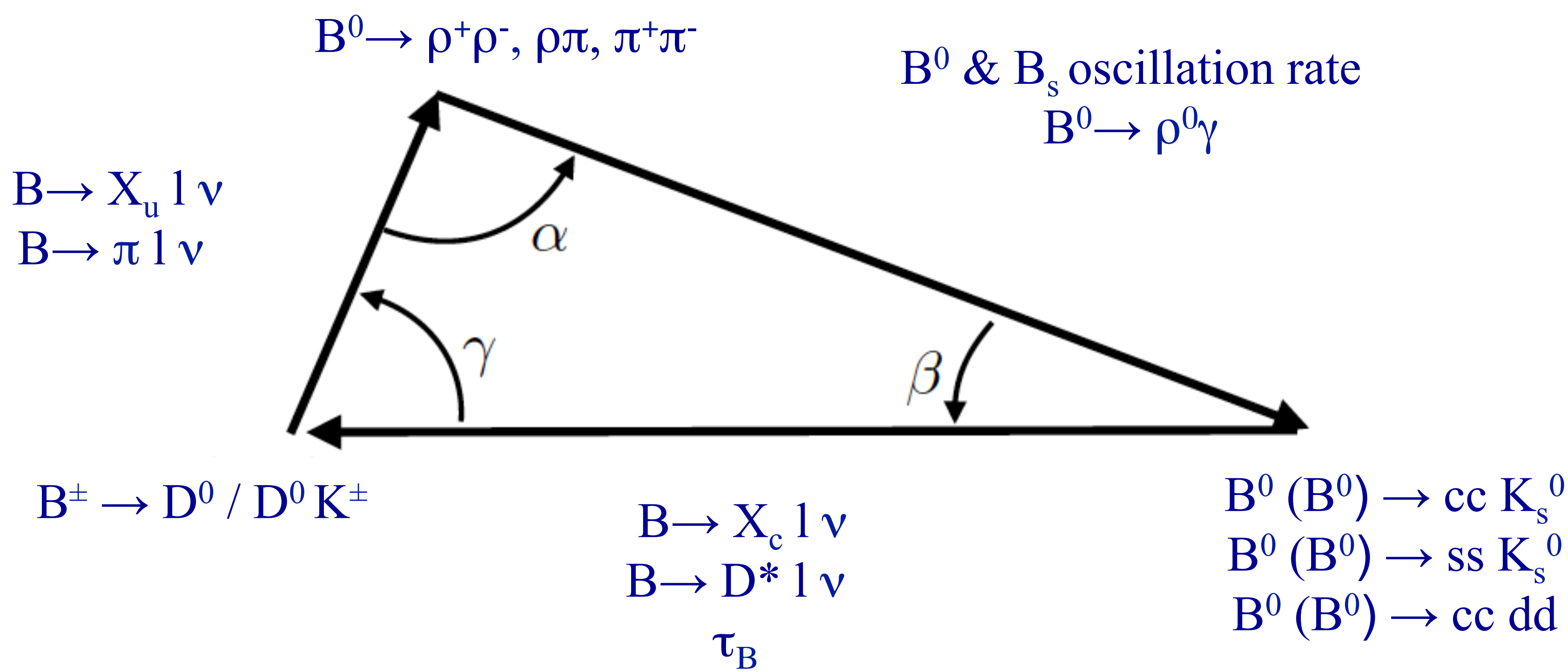
$$\alpha = \arg\left(-\frac{V_{tb}^* V_{td}}{V_{ub}^* V_{ud}}\right)$$

$$\gamma = \arg\left(-\frac{V_{ub}^* V_{ud}}{V_{cb}^* V_{cd}}\right)$$

$$\beta = \arg\left(-\frac{V_{cb}^* V_{cd}}{V_{tb}^* V_{td}}\right)$$



Over-constraining the Unitarity Triangle



Over-constraining the Unitarity Triangle

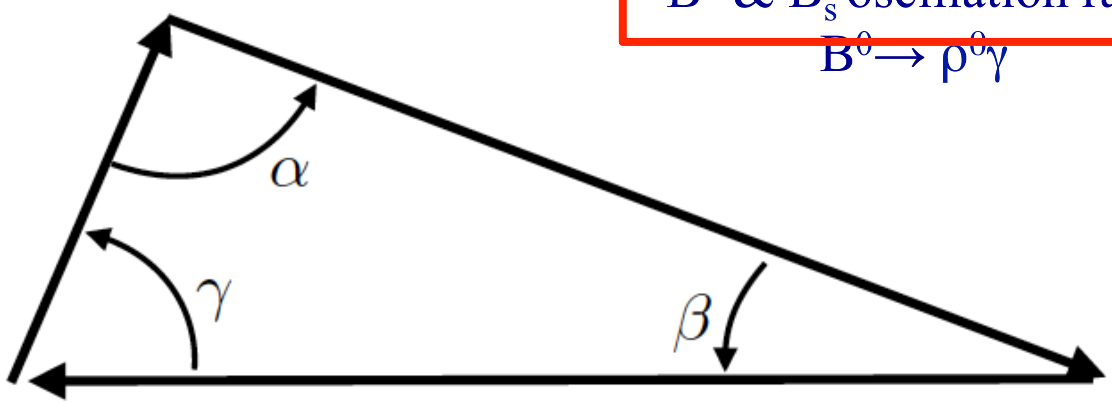
$B^0 \to \rho^+\rho^-, \rho\pi, \pi^+\pi^-$

B^0 & B_s oscillation rate

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

$B \to X_u\, l\, \nu$

$B \to \pi\, l\, \nu$



$B^\pm \to D^0 / D^0 K^\pm$

$B \to X_c\, l\, \nu$

$B \to D^*\, l\, \nu$

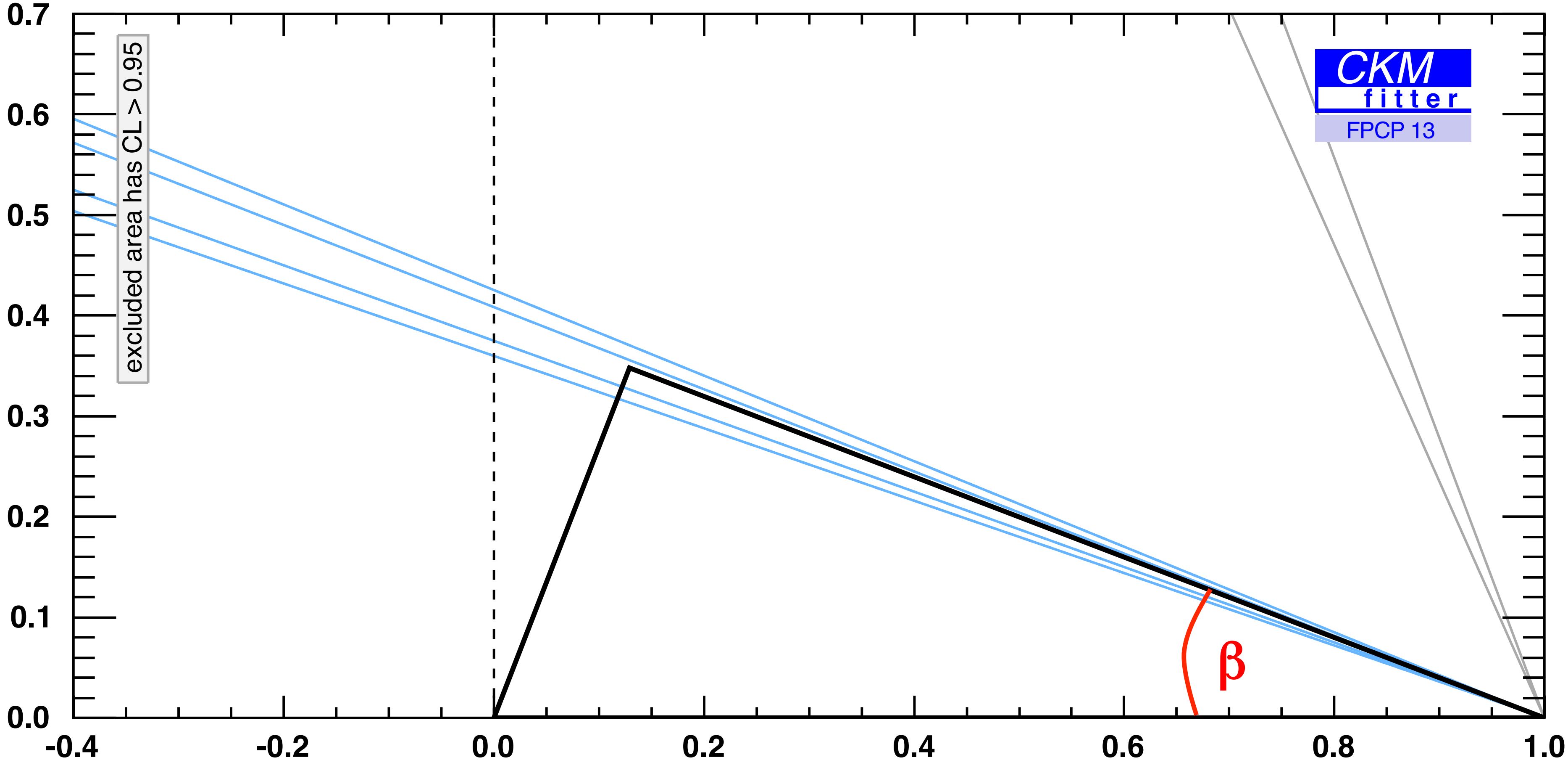
τ_B

$B^0\ (B^0) \to cc\ K_s^0$

$B^0\ (B^0) \to ss\ K_s^0$

$B^0\ (B^0) \to cc\ dd$

1st CKM measurement: sin 2β



sin 2β: Golden decay $B^0 \rightarrow J/\psi\ K_s$

$B^0 \rightarrow J/\psi\ K_s$ —CP→ $\overline{B}^0 \rightarrow J/\psi\ K_s$

$\eta_{CP} = -1$

Interlude CP violation

Phases and CP-Violation

CP violation: $|\mathcal{A}(B \to f)|^2 \neq |\mathcal{A}(\bar{B} \to \bar{f})|^2$

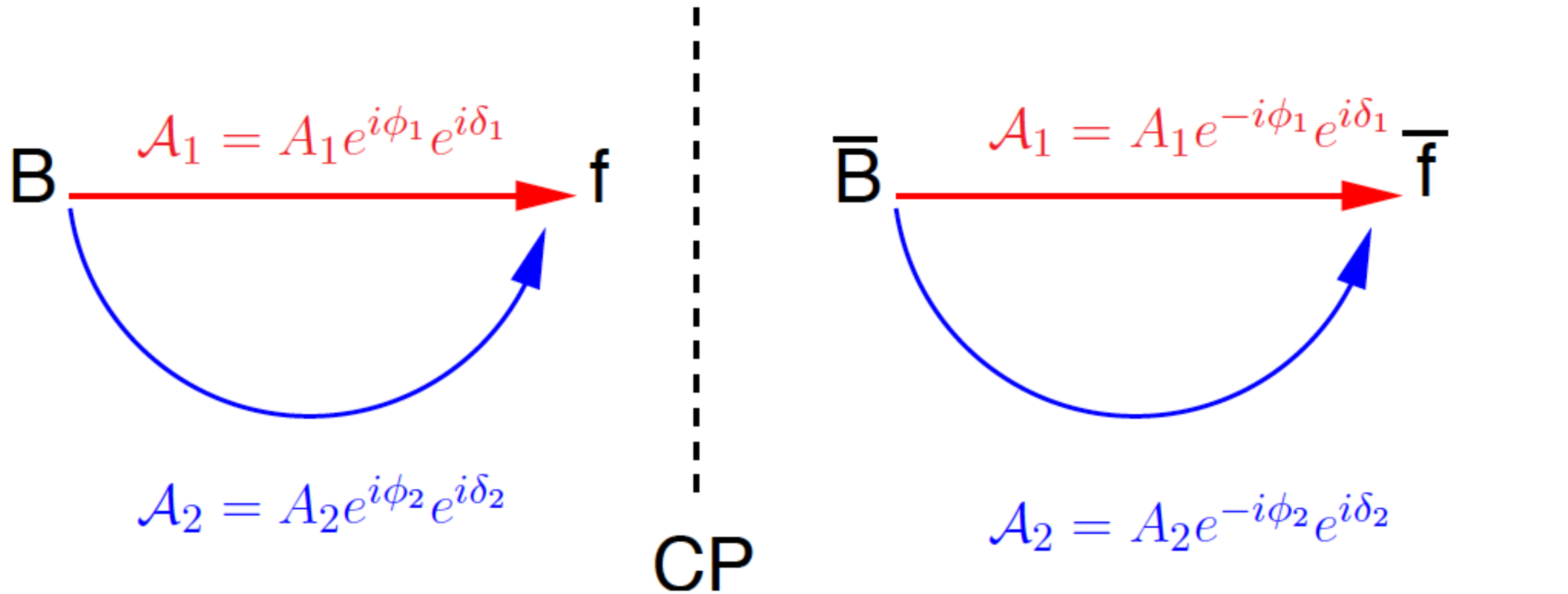
Within weak interaction, moving from particle to antiparticle, system amplitudes are complex conjugated.

No CP violation if:

- There is only one amplitude contributing to the decay:
  $|\mathcal{A}|^2 = |\mathcal{A}^*|^2$
- The sum of two amplitudes, where both are complex conjugated by moving from particle to antiparticle system:
  $|\mathcal{A}_1 + \mathcal{A}_2|^2 = (\mathcal{A}_1 + \mathcal{A}_2)(\mathcal{A}_1^* + \mathcal{A}_2^*) = |\mathcal{A}_1^* + \mathcal{A}_2^*|^2$

For CP violation one needs two complex amplitudes, where one of them is complex conjugated and one not by moving from particle to antiparticle system.

Phases and CP-Violation

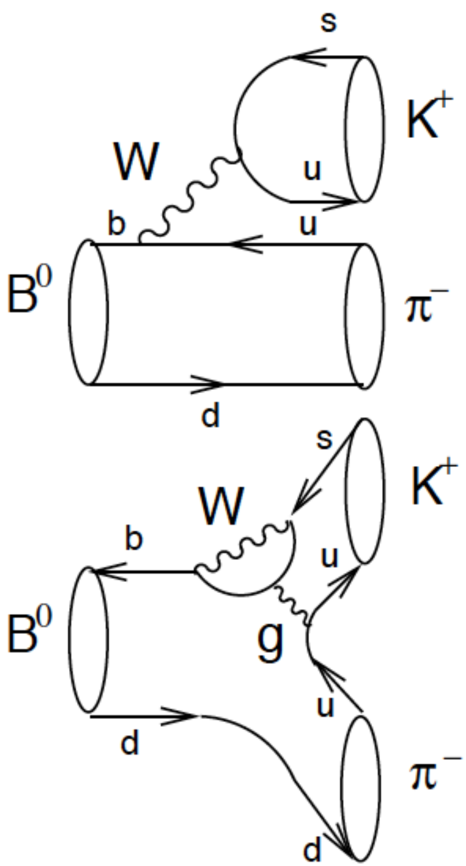


$$|\mathcal{A}|^2 = A_1^2 + A_2^2 + 2A_1A_2\cos(\Delta\phi + \Delta\delta)$$

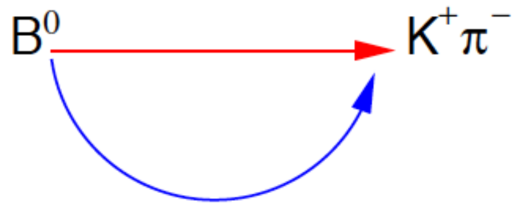
$$|\mathcal{A}|^2 = A_1^2 + A_2^2 + 2A_1A_2\cos(\Delta\phi - \Delta\delta)$$

$\mathcal{A}_1$ and $\mathcal{A}_2$ need to have different weak phases ϕ and different (e.g. strong) phases δ.

1) Direct CP violation:



$\mathcal{A}_1 e^{i*arg(V_{ub}^* V_{us})} e^{i\delta_1}$



$\mathcal{A}_2 e^{i*arg(V_{tb}^* V_{ts})} e^{i\delta_2}$

CP Asymmetrie:

$$|\bar{\mathcal{A}}|^2 - |\mathcal{A}|^2 = 2|A_1||A_2|[\cos(arg(V_{tb}^* V_{ts} + \delta)) - \cos(arg(V_{tb}^* V_{ts} - \Delta\delta))]$$

2) CP violation in mixing

CP eigenstates $\neq$ mass eigenstates ($|\frac{q}{p}| \neq 0$)
$\rightarrow CP$ violation in mixing.

Model independent: CP Violation in mixing $< \mathcal{O}(\frac{\Delta\Gamma}{\Delta m})$

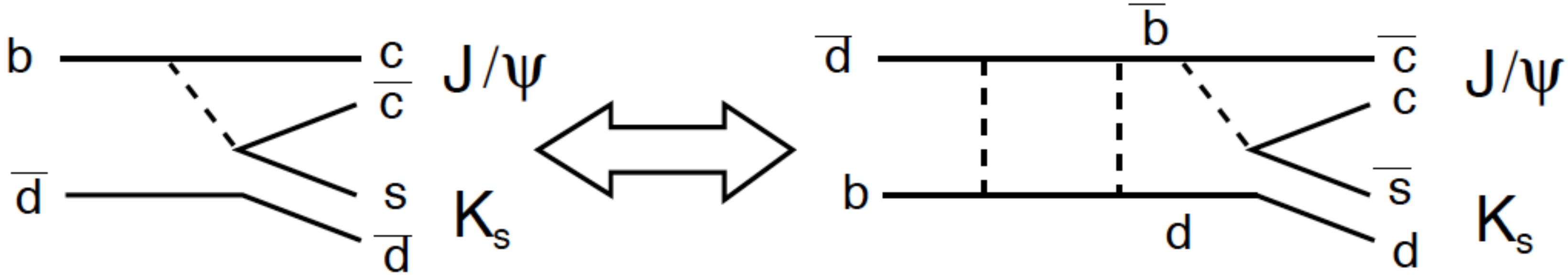
	B_d	B_s
$\Delta m = m_H - m_L$	0.5 ps^{-1}	17.8 ps^{-1}
$\Delta\Gamma/\Gamma = (\Gamma_L - \Gamma_H)/\Gamma$	$\mathcal{O}$(0.01)	$\mathcal{O}$(0.1)
$\tau = 1/\Gamma$	1.5 ps	1.5 ps
$\rightarrow$ CP in mixing	$\mathcal{O}$(0.01)	$\mathcal{O}$(0.01)

In first order, CP violation in mixing negligible in B system, however

it is important in the kaon system

3) CP violation in interference between mixing and decay

Same final state through decay & mixing + decay



$$\begin{aligned} \mathcal{A}_1 &= \mathcal{A}_{mix}(B^0 \to B^0) * \mathcal{A}_{decay}(B^0 \to J/\Psi K_s) \\ &= \cos(\frac{\Delta m t}{2}) * A * e^{i\omega} \\ \mathcal{A}_2 &= \mathcal{A}_{mix}(B^0 \to \bar{B}^0) * \mathcal{A}_{decay}(\bar{B}^0 \to J/\Psi K_s) \\ &= i \sin(\frac{\Delta m t}{2}) * e^{+i\phi} * A * e^{-i\omega} \end{aligned}$$

$\Delta\phi = \phi - 2\omega$ (assume no CP violation in mixing and in decay)

$\Delta\delta = \pi/2 \Leftarrow$ mixing introduce second phase difference

CPV in B_d and B_s

No CP violation in $B_{d/s}$ mixing.

No CP violation in decay $B_d \rightarrow J/\psi K_s$, $B_s \rightarrow J/\psi\phi$

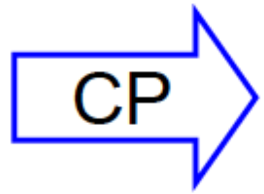
Sensitivity to $\phi_{d/s} = 2\beta_{d/s}$ via CP violation in interference of mixing & decay.

	$B_d \rightarrow J/\psi K_s$	$B_s \rightarrow J/\psi\phi$
CP	CP odd eigenstate	comb. of even/odd eigen states $\longrightarrow$ angular analysis
$\Delta\Gamma$	too small, no sensitivity	$\Delta\Gamma$ measurable
$\phi\,(=\ 2\beta)$	only tagged analyses	in untagged analysis due to large $\Delta\Gamma_s$; higher sensitivity in tagged analyses

End interlude CP vioaltion

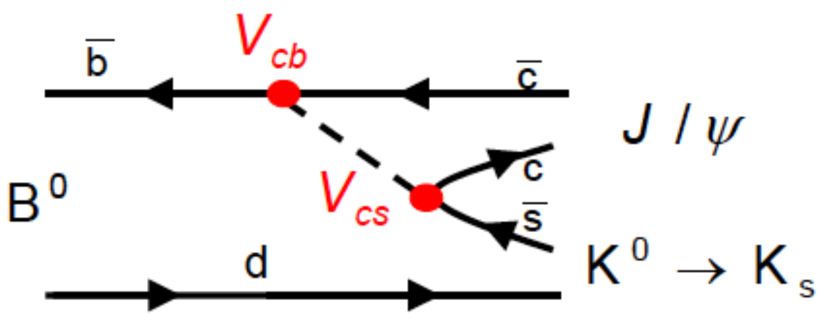
sin 2β: Golden decay $B^0 \to J/\psi\ K_s$

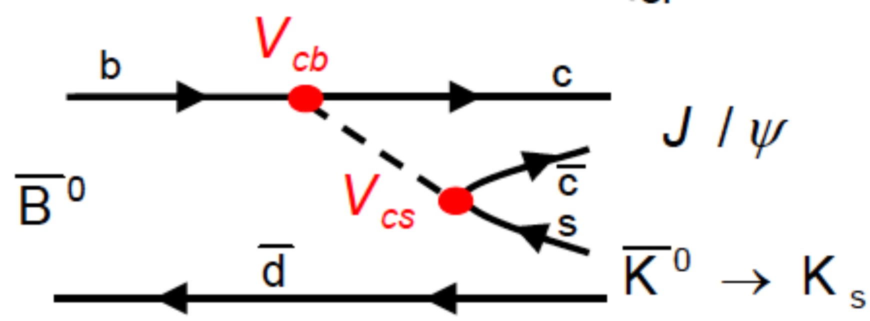
$B^0 \to J/\psi\ K_s$

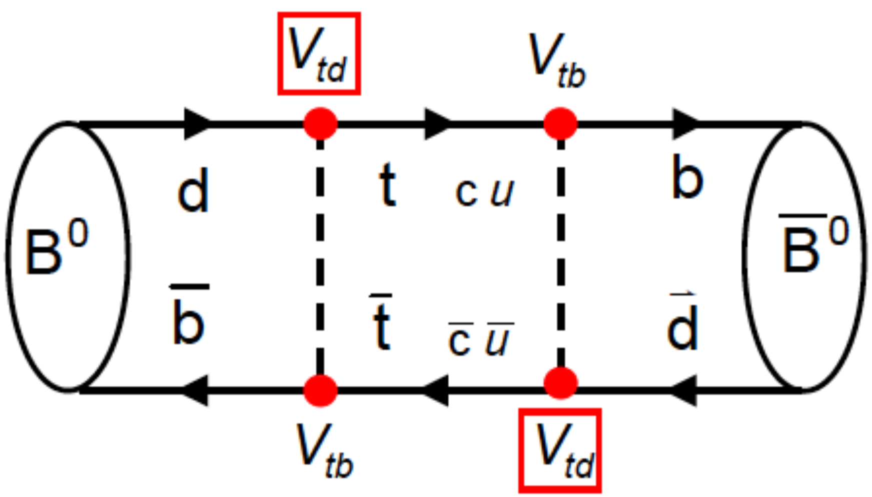


$\overline{B}^0 \to J/\psi\ K_s$

η_{CP}=-1







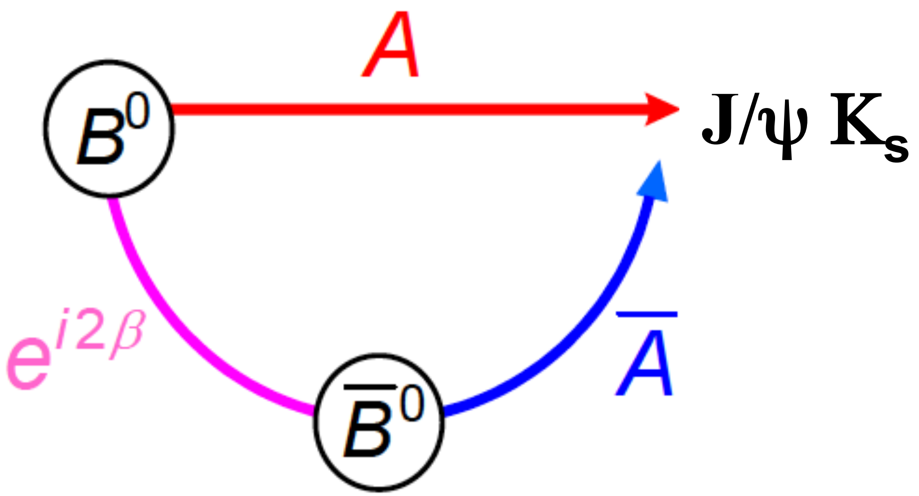
Mixing Phase:

$$e^{i\phi_d} = e^{i2\beta}$$

sin 2β: Golden decay $B^0 \rightarrow J/\psi\, K_s$

$B^0 \rightarrow J/\psi\, K_s$ CP $\overline{B}^0 \rightarrow J/\psi\, K_s$

$\eta_{CP} = -1$



$$\Gamma(B^0 \rightarrow J/\psi\, K_s)(t) \neq \Gamma(\overline{B}^0 \rightarrow J/\psi\, K_s)(t)$$

$$\mathcal{A}_{CP} = \frac{\Gamma(\overline{B^0} \rightarrow J/\psi K_S) - \Gamma(B^0 \rightarrow J/\psi K_S)}{\Gamma(\overline{B^0} \rightarrow J/\psi K_S) + \Gamma(B^0 \rightarrow J/\psi K_S)} = \sin(2\beta)\sin(\Delta m t)$$

→ Requires knowledge of production flavour of the B

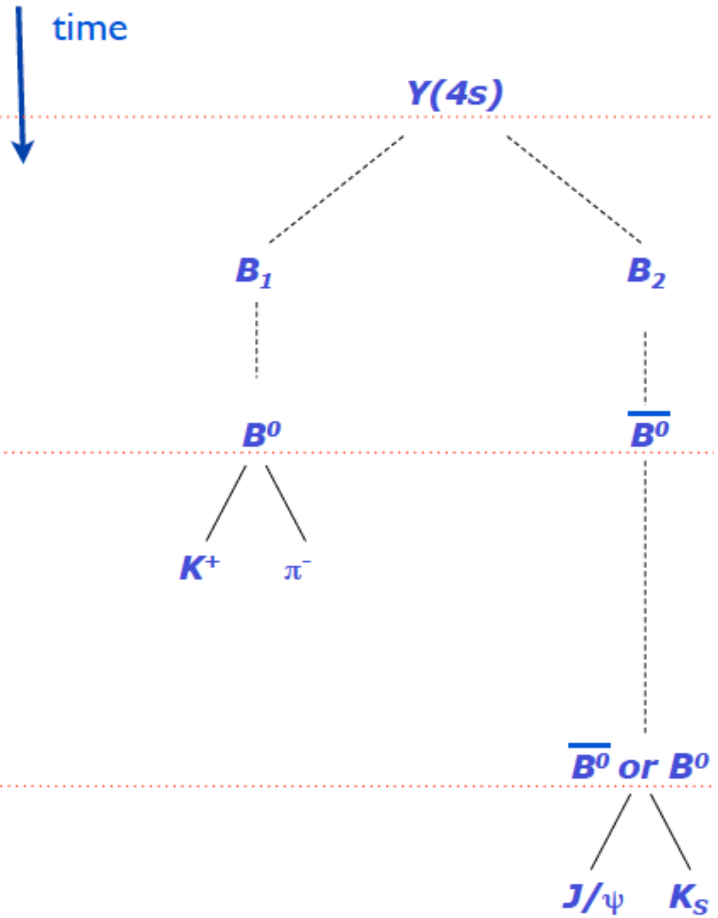
Flavour tagging – B-factories

- Time evolution of Υ(4s) decay
  - t=0: Decay of Υ(4s) into 2 B mesons

    Neither B is in a specific eigenstate, *but* B_1B_2 system evolves *coherently*, i.e. flavor *anti*-correlation preserved during evolution
  - $t=t_{tag}$ One of the two mesons (B_1) decays.

    If it decays into a flavor eigenstate, flavor conservation in the coherent B_1B_2 system requires that also B_2 *goes into a flavor eigenstate, even though it has not decayed yet!*
  - $t=t_{CP}$ The other B meson decays

    mixing took place *between* t_{CP} and t_{tag}.



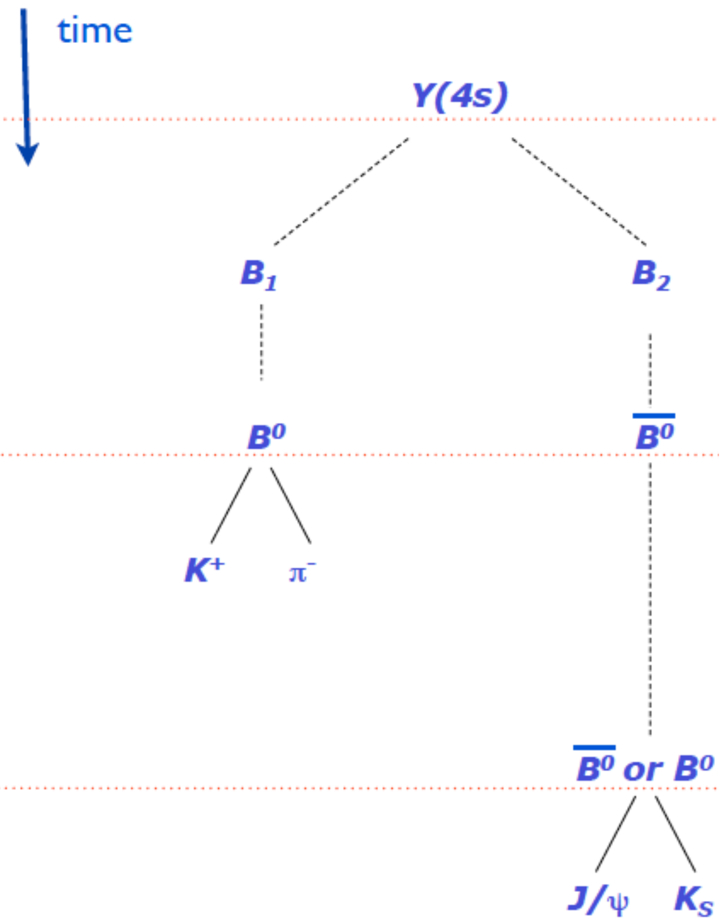
Tagging efficiency	Mistag probability	Dilution
$\varepsilon = \frac{\#\,tagged\ candidates}{\#\,all\ candidates}$	$\omega = \frac{\#\,tagged\ wrong}{\#\,tagged}$	$D = (1 - 2\omega)$

- Time evolution of $\Upsilon(4s)$ decay
  - t=0: Decay of $\Upsilon(4s)$ into 2 B mesons

    Neither B is in a specific eigenstate, *but* B_1B_2 system evolves *coherently*, i.e. flavor *anti*-correlation preserved during evolution
  - $t=t_{tag}$ One of the two mesons (B_1) decays.

    If it decays into a flavor eigenstate, flavor conservation in the coherent B_1B_2 system requires that also B_2 *goes into a flavor eigenstate, even though it has not decayed yet!*
  - $t=t_{CP}$ The other B meson decays

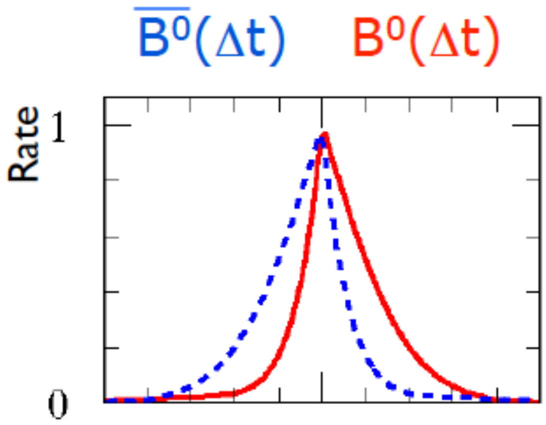
    mixing took place *between* t_{CP} and t_{tag}.

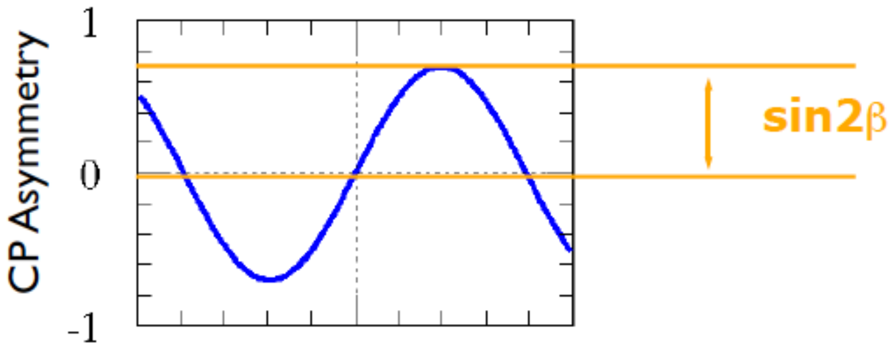


Effective tagging power: εD^2~30% (at B-factories)

How to extract sin 2β

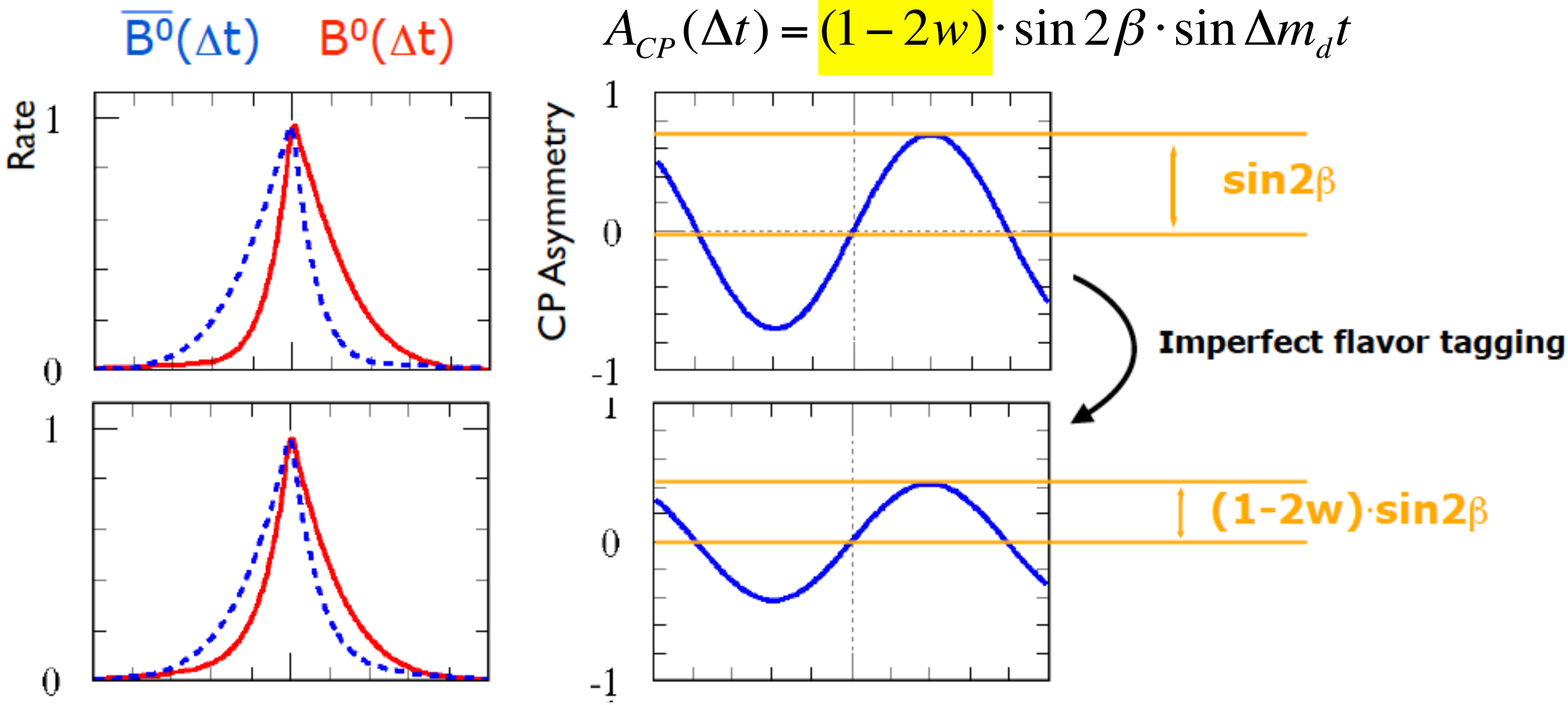
$$A_{CP}(\Delta t) = \sin 2\beta \cdot \sin \Delta m_d t$$





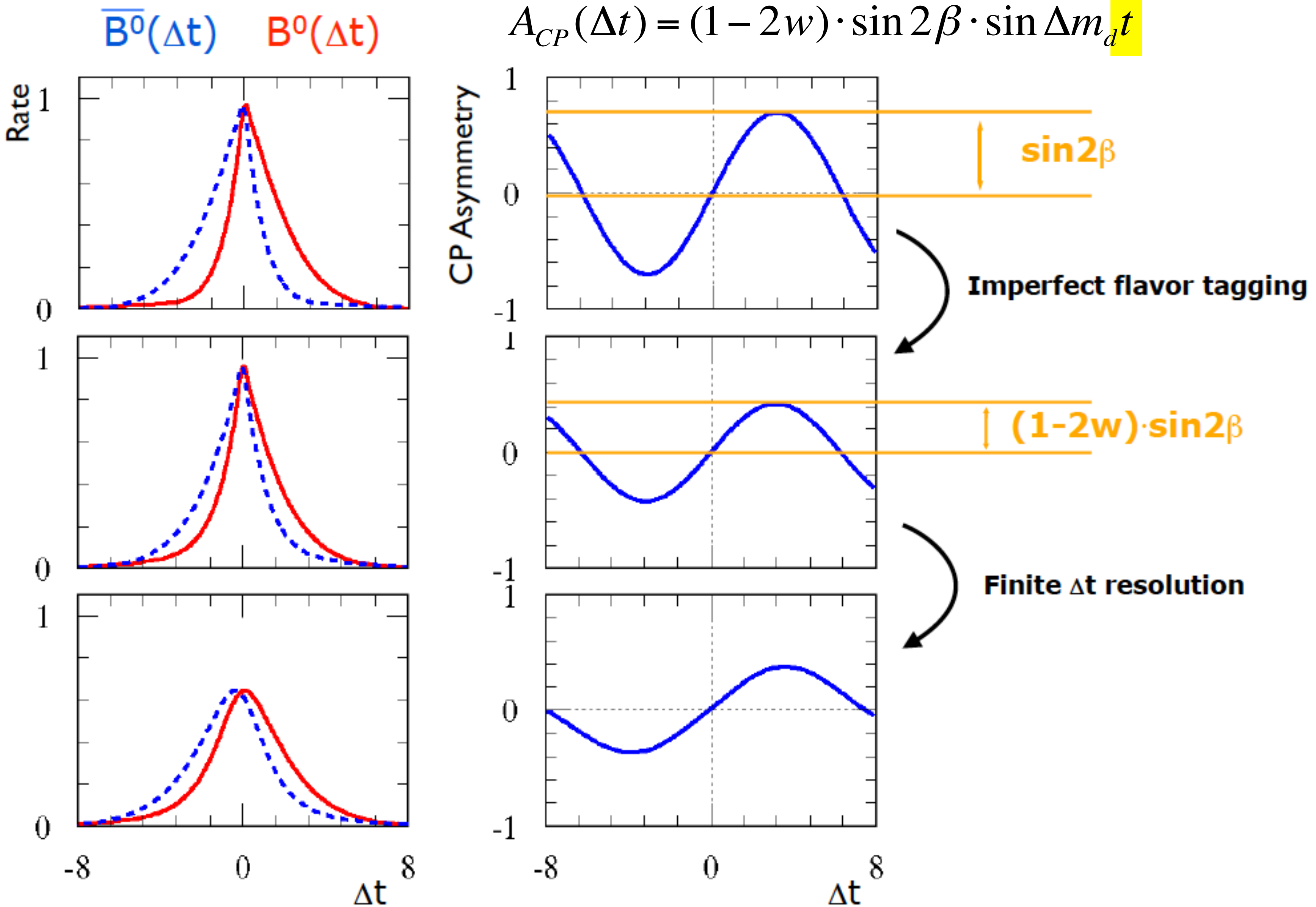
How to extract sin 2β

$$A_{CP}(\Delta t) = (1-2w)\cdot \sin 2\beta \cdot \sin \Delta m_d t$$



How to extract sin 2β

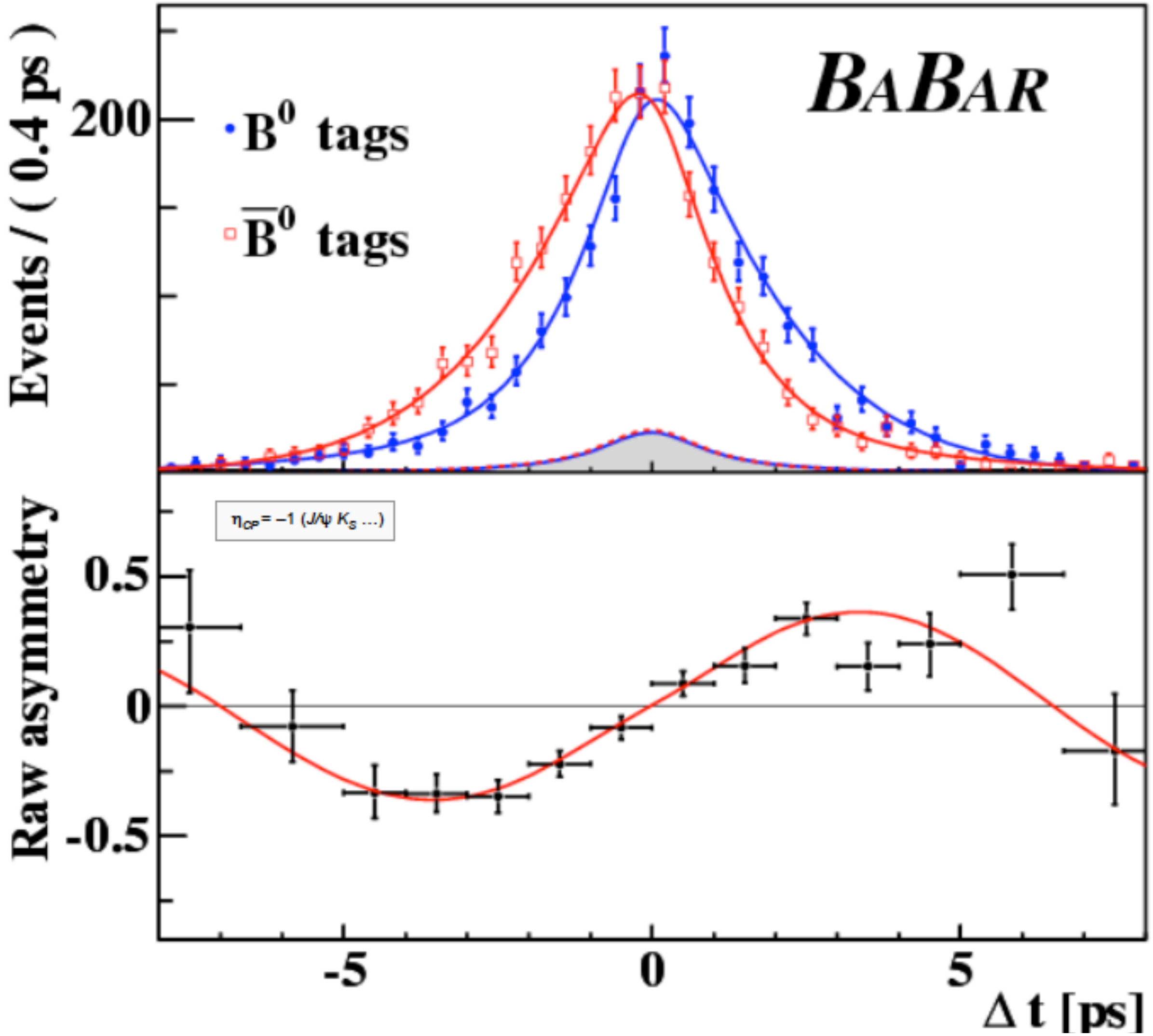
$$A_{CP}(\Delta t) = (1-2w)\cdot \sin 2\beta \cdot \sin \Delta m_d t$$

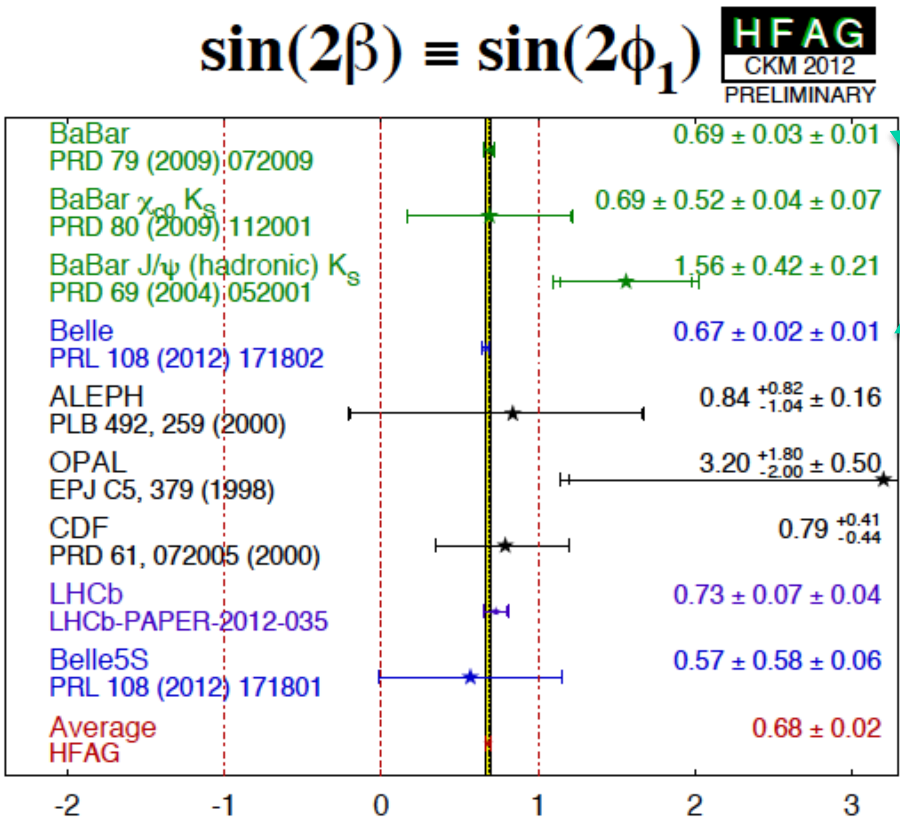


$$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B_{\text{rec}}B_{\text{tag}}$$

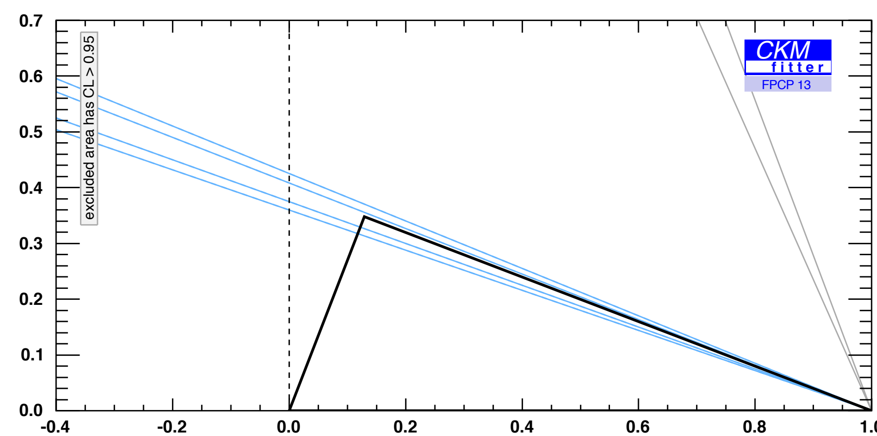
$$B_{\text{rec}} \rightarrow J/\psi K_S$$

$$B_{\text{tag}} \rightarrow \ell^\pm X, K^\pm X, \pi^\mp_{soft}, \pi^\pm_{fast}X, \ldots$$



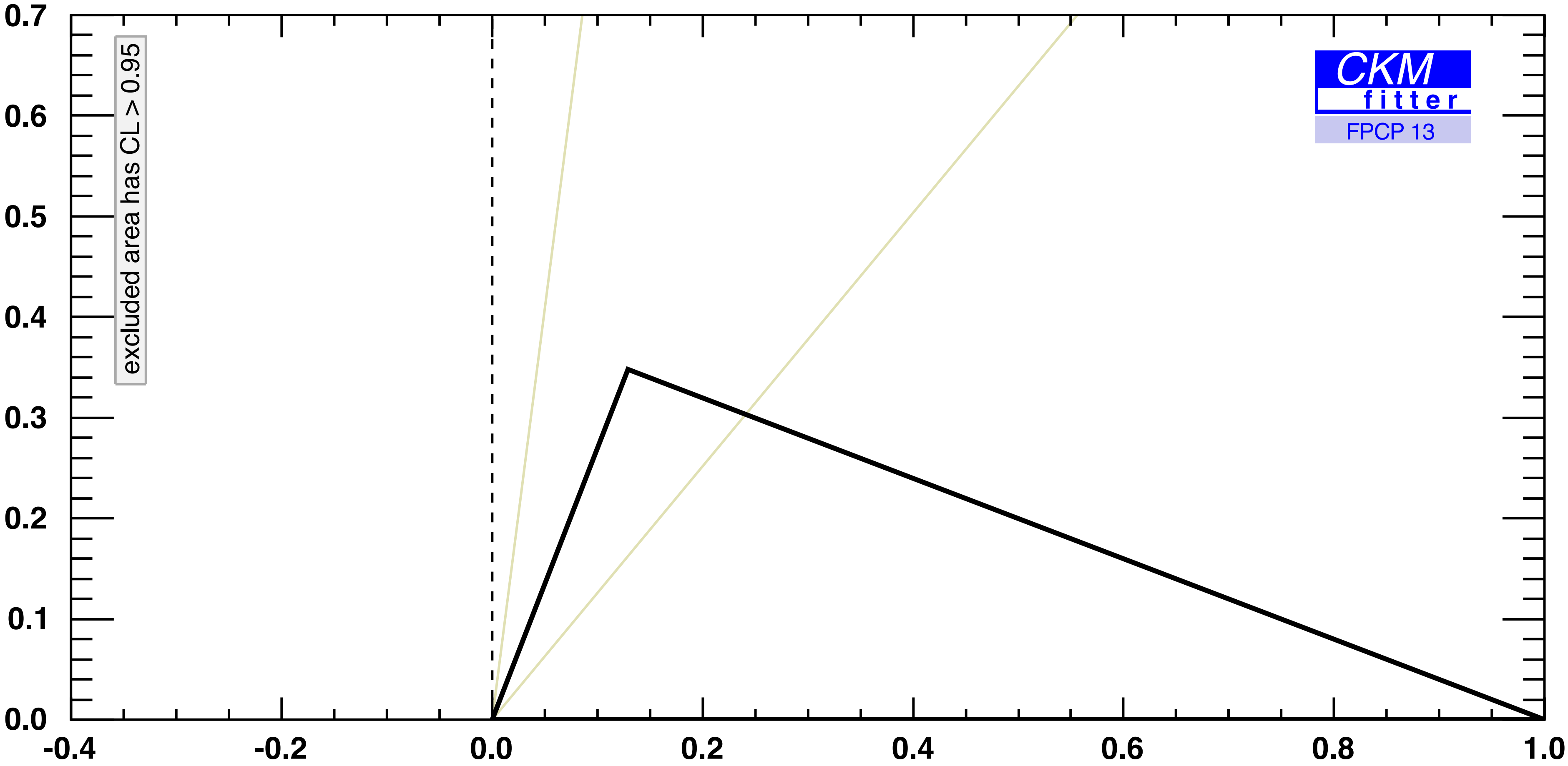


$B^0 \rightarrow c\bar{c}\, K^{(*)0}$



There is some chance that LHCb overtakes the BaBar measurement with 3/fb

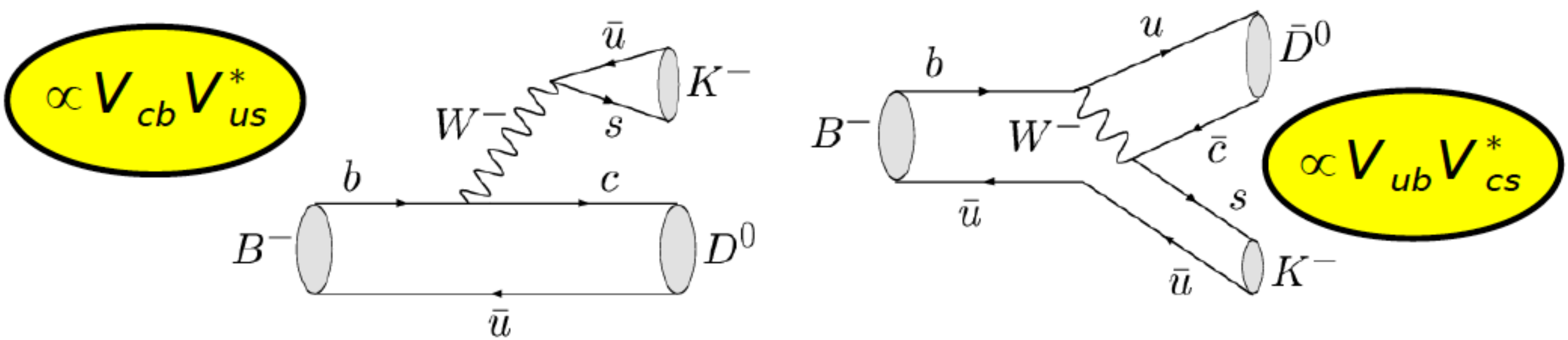
2nd CKM measurement: γ



Importance of γ from B→ D K

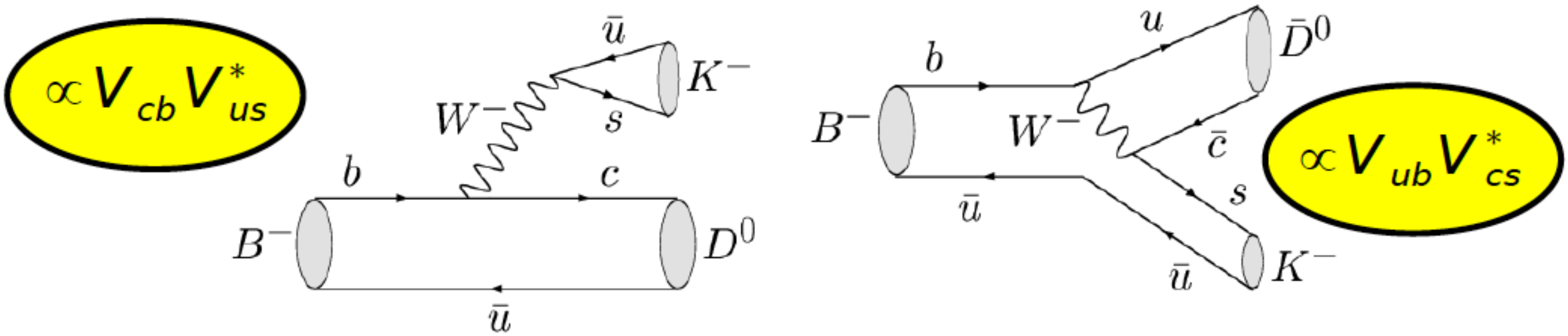
- The CKM angle γ plays a unique role in flavour physics
  - CP violating parameter that can be measured through tree decays

- A benchmark Standard Model reference point
  - Doubly important in case NP is observed



Variants use different B or D decays
→ require final state common to D^0 and $\bar{D}^0$

Importance of γ from B→ D K



- Theoretical side:
  - Dominant, single tree diagram (suppression of loops)
  - All parameters can be determined from data

- Experimental side:
  - Many different final states → different observables
  - All parameters can be determined from data
    - CKM angle γ
    - δ_B: weak & strong phase differences
    - r_B : ratio of amplitudes

Latest Measurements on B→ D K

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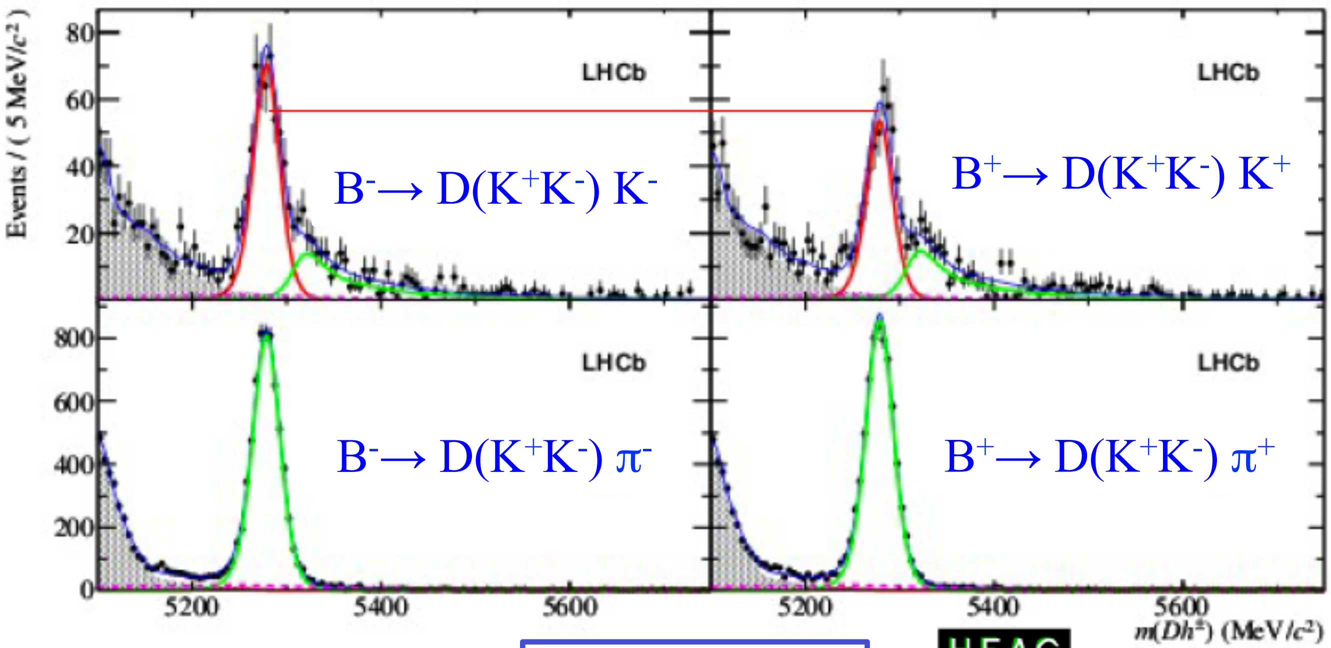
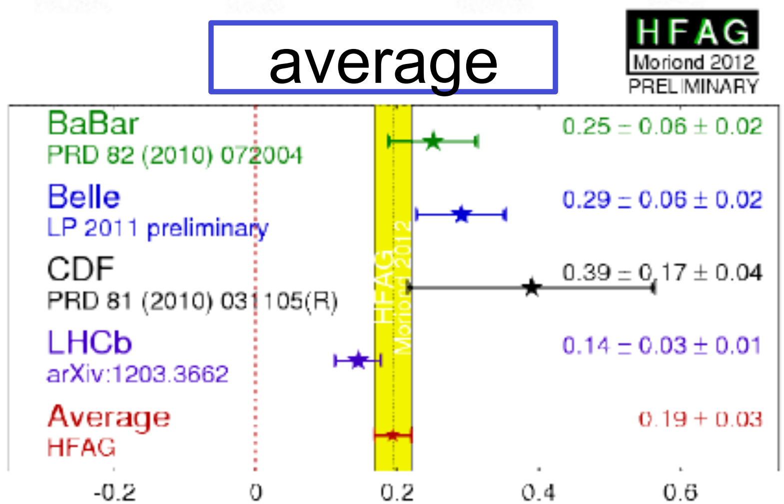
Evidence for direct CP violation (y≠0)



average



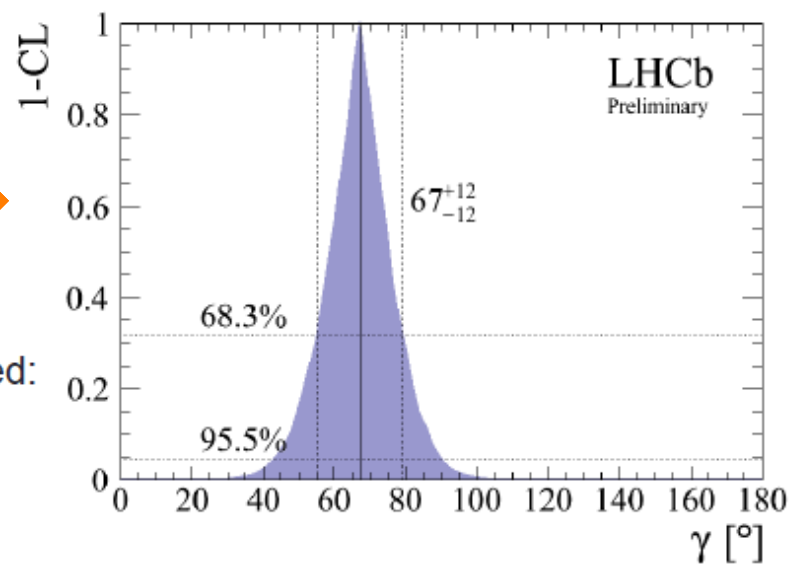
- Several different modes with each limited sensitivity on γ

Analysis	N_{obs}	Parameters
$B^+ \to Dh^+$, $D \to hh$, GLW/ADS	13	γ, r_B, δ_B, r_B^π, δ_B^π, $R_{K/\pi}$, $r_{K\pi}$, $\delta_{K\pi}$, $A_{CP}^{D\to KK}$, $A_{CP}^{D\to\pi\pi}$
$B^+ \to DK^+$, $D \to K_S^0 h^+ h^-$, GGSZ	4	γ, r_B, δ_B
$B^+ \to Dh^+$, $D \to K\pi\pi\pi$, ADS	7	γ, r_B, δ_B, r_B^π, δ_B^π, $R_{K/\pi}$, $r_{K3\pi}$, $\delta_{K3\pi}$, $\kappa_{K3\pi}$
CLEO $D^0 \to K\pi$, $D^0 \to K\pi\pi\pi$	9	x_D, y_D, $\delta_{K\pi}$, $\delta_{K3\pi}$, $\kappa_{K3\pi}$, $r_{K\pi}$, $r_{K3\pi}$, $\mathcal{B}(K\pi)$, $\mathcal{B}(K\pi\pi\pi)$
CP violation in the charm system	2	$A_{CP}^{D\to KK}$, $A_{CP}^{D\to\pi\pi}$
charm mixing	3	x_D, y_D, $\delta_{K\pi}$, $r_{K\pi}$

LHCb measurements sensitive to γ

External inputs

- **Combine them using a frequentist approach**

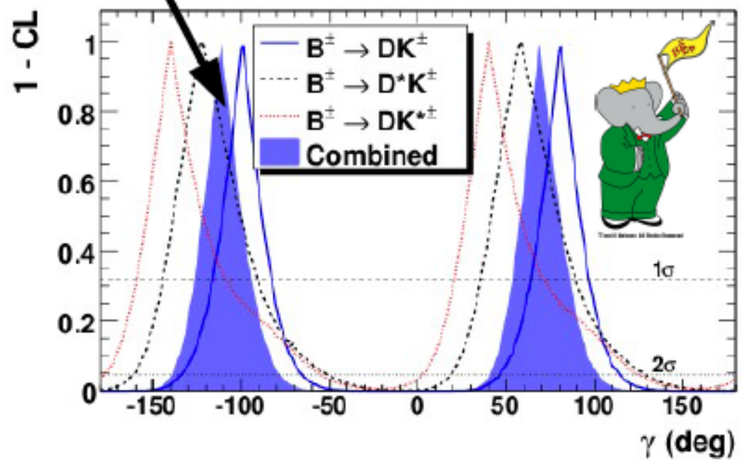


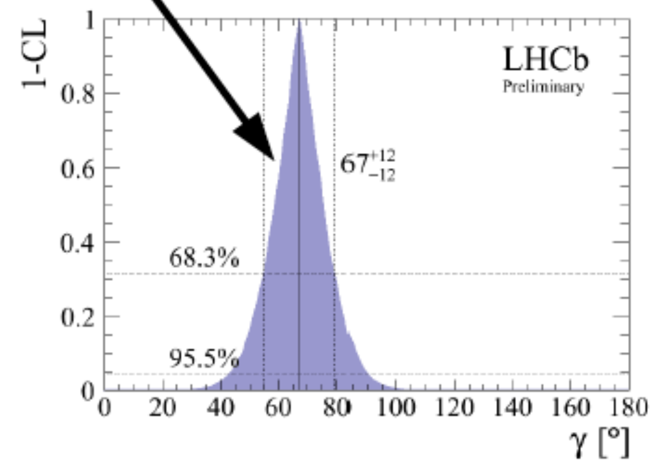
γ from B→DK ADS(1 fb^{-1})/GLW(1 fb^{-1})/GGSZ(3 fb^{-1}) combined:

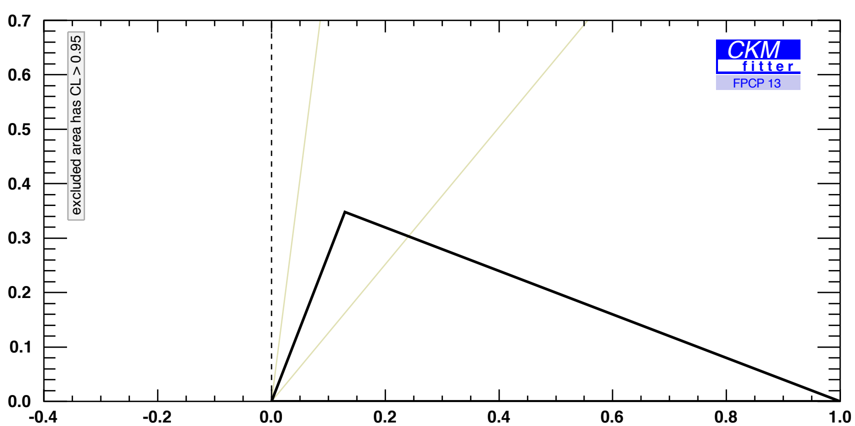
$$\gamma = (67 \pm 12)^\circ$$

γ only from tree processes

- Sensitivity: BaBar & Belle each ~16°; latest LHCb ~12°

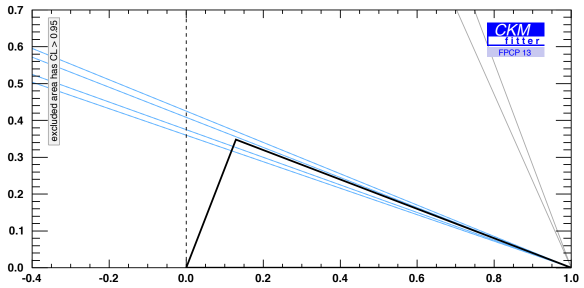




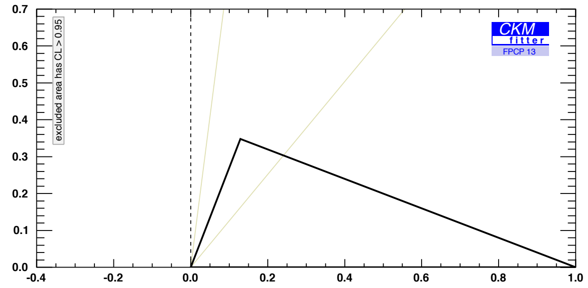


Summary of CKM measurements

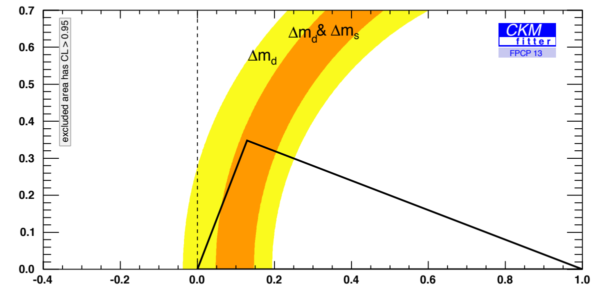
sin 2β



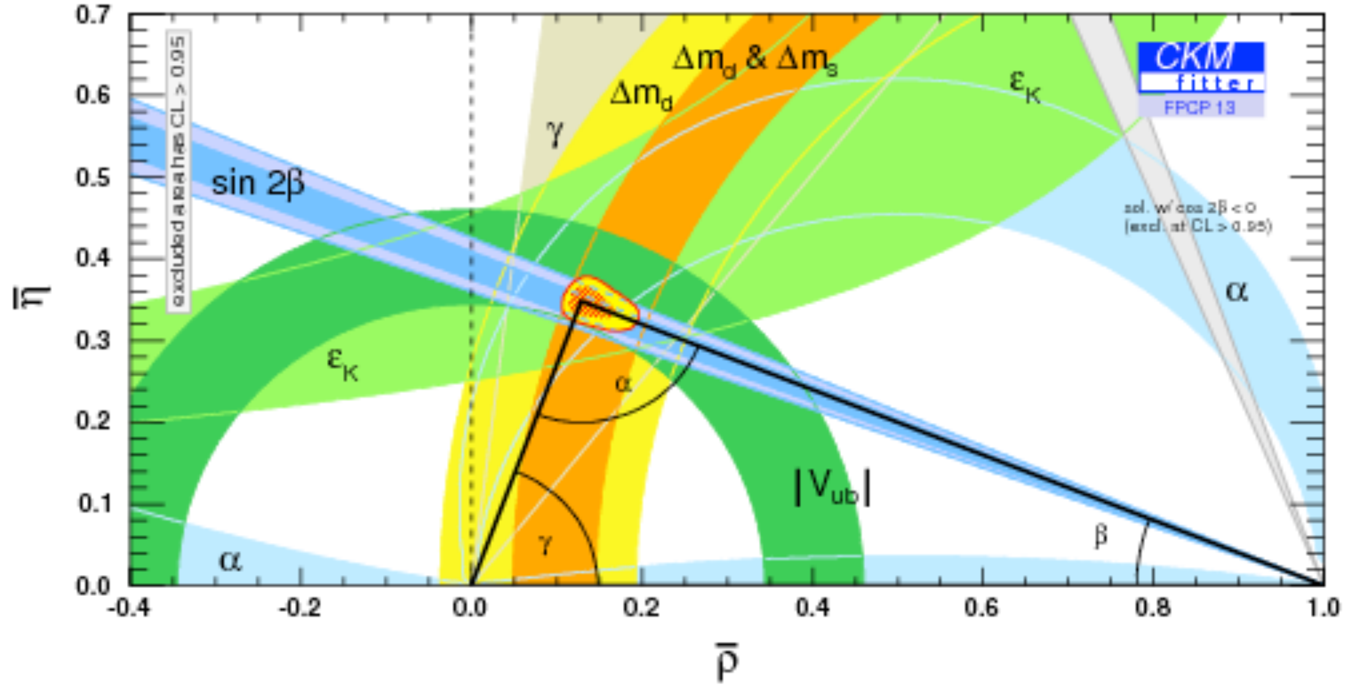
γ



Bs and Bd mixing

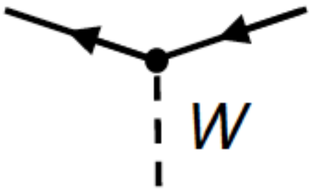


Adding many complimentary measurements



Tree vs loop

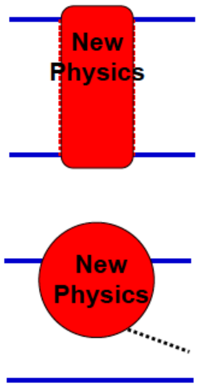
- Tree Processes only



SM dominant
→ no new effects expected

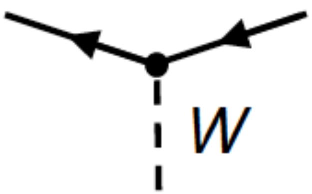
- Loop processes only

New Physics is expected to appear in loops



Tree vs loop

- Tree Processes only

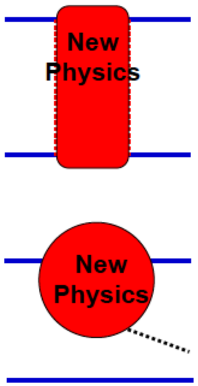


SM dominant
→ no new effects expected

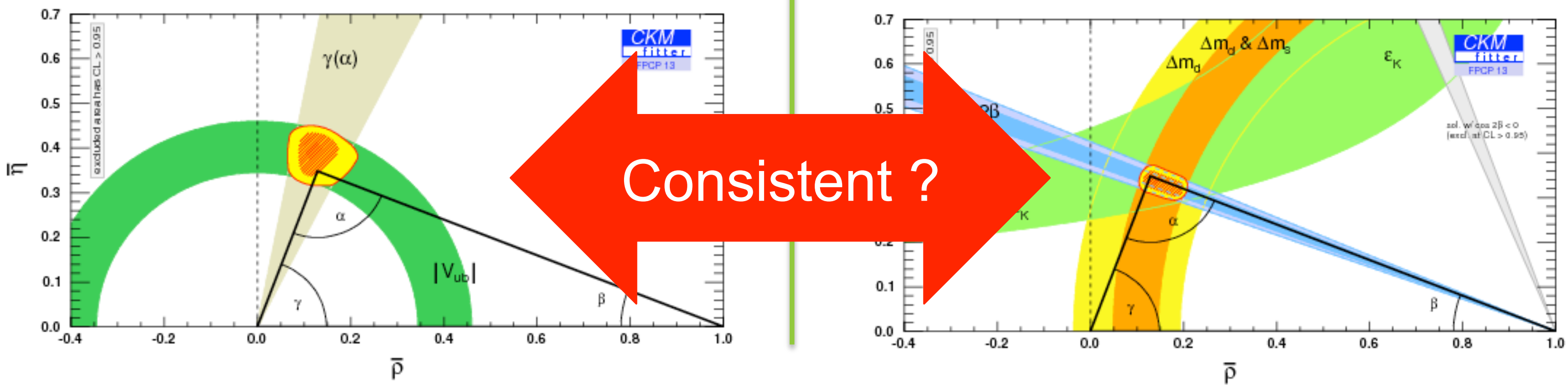
$|V_{ub}/V_{cb}|,\ B\to\tau\nu,\ \gamma,\ \pi-\alpha-\beta$

- Loop processes only

New Physics is expected to appear in loops



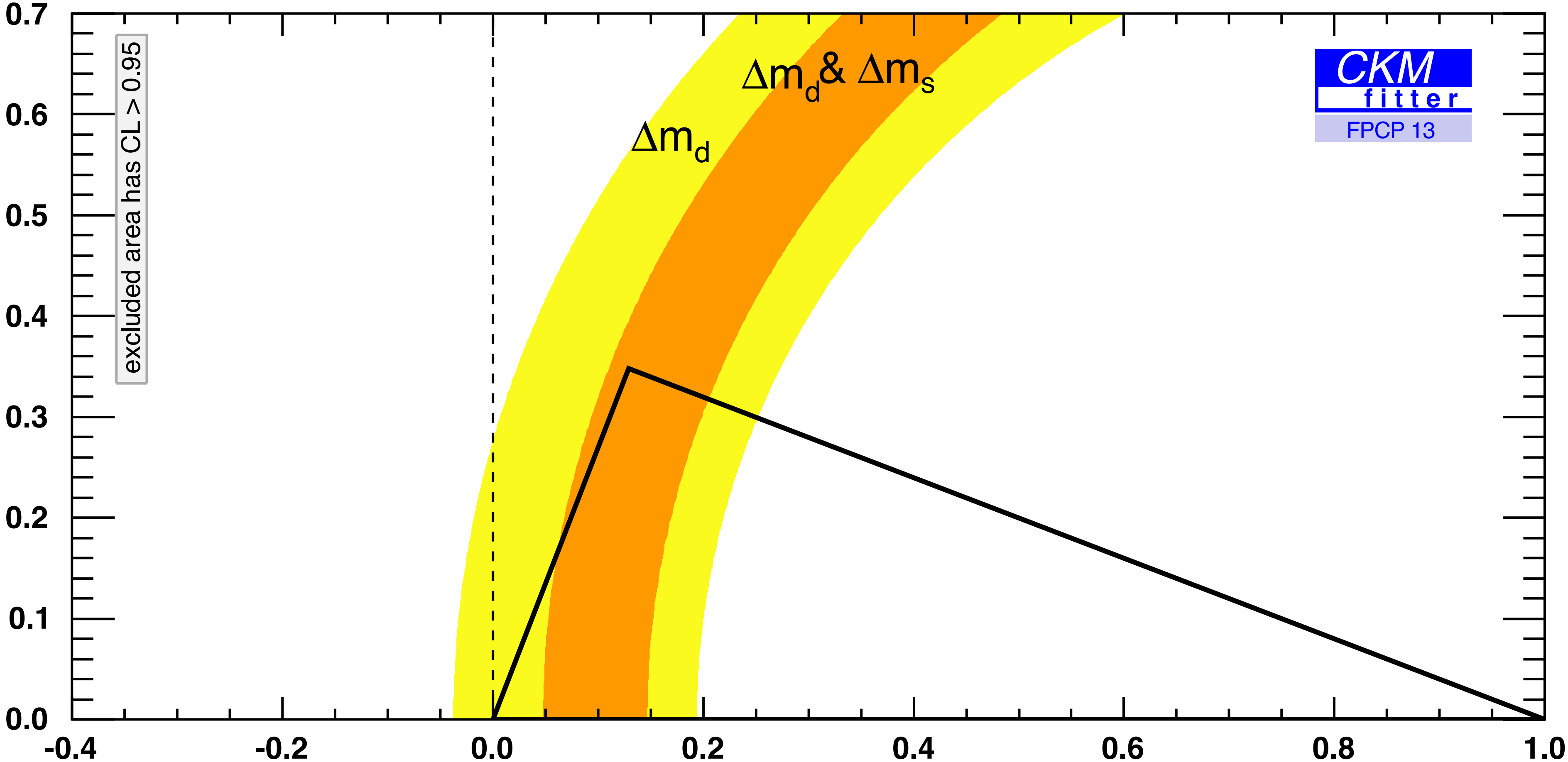
$|\varepsilon_K|,\ \sin 2\beta,\ \Delta m_d,\ \Delta m_s$



Apex known with 10-20%, aim at <1%


STOP
AND
THINK

3^{rd} CKM measurement: $B_{s,d}$ mixing frequency



Bs mixing

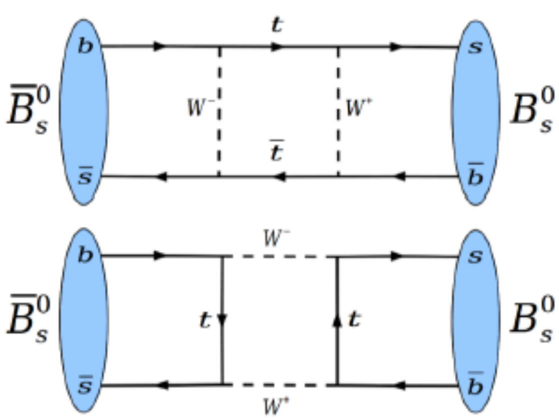
Phenomenological Schroedinger equation describing oscillation and decay

$$i\frac{d}{dt}\begin{pmatrix} B_s^0 \\ \overline{B_s^0} \end{pmatrix} = \left(M - \frac{i}{2}\Gamma\right)\begin{pmatrix} B_s^0 \\ \overline{B_s^0} \end{pmatrix} \qquad \mathrm{M} = \begin{pmatrix} M_{11} & M_{12} \\ M_{12}^* & M_{22} \end{pmatrix}; \Gamma = \begin{pmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma_{22} \end{pmatrix}$$

Mass eigenstates ≠ flavour eigenstates → mass difference ∝ osc. frequency

$$B_L\rangle = p|B_s^0\rangle + q|\overline{B_s^0}\rangle$$
$$B_H\rangle = p|B_s^0\rangle - q|\overline{B_s^0}\rangle$$

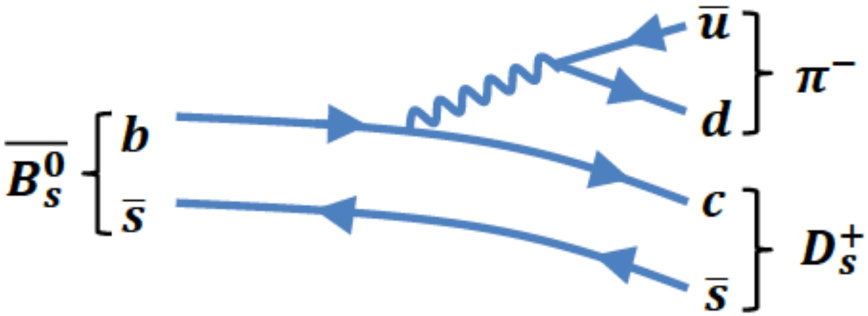
$$\Delta m_s = m_H - m_L = 2|M_{12}|$$
$$\Delta\Gamma_s = \Gamma_L - \Gamma_H$$
$$\phi_M = \arg(M_{12})$$



Dominant Feynman diagrams (Standard Model)

Details in flavour TH lecture by David Straub

Δm_s from $B_s \to D_s \pi^+$



- Very high statistics
- Low background level
- Can resolve B_s mixing frequency due to high boost

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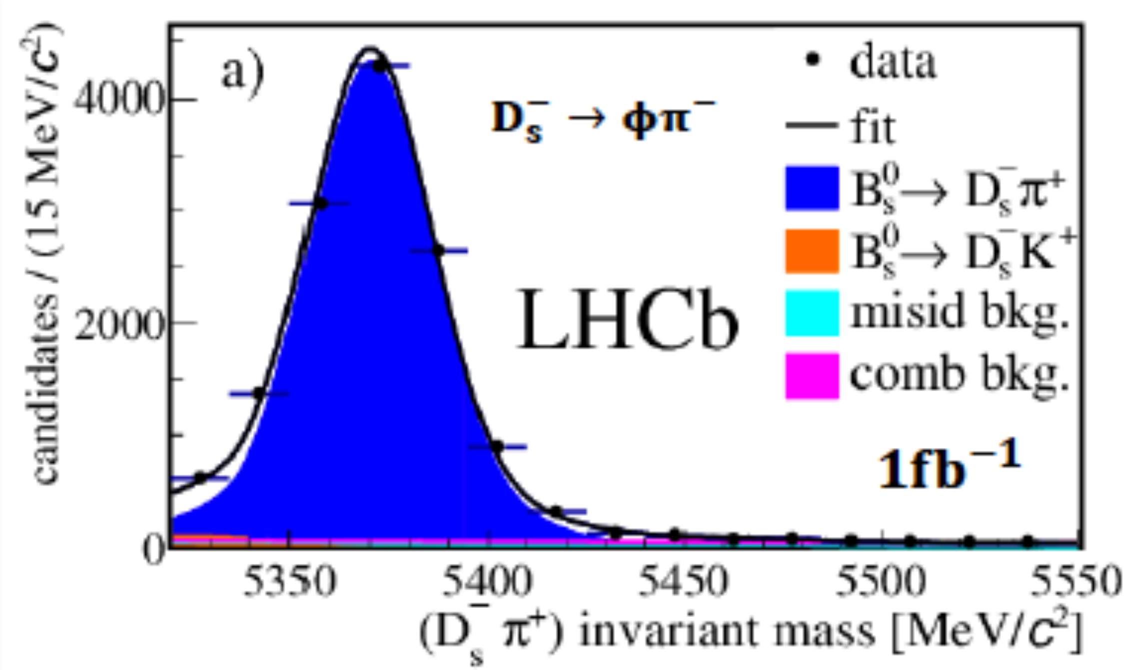
Use flavour tagging to determine flavour at production,
pion charge for flavour at decay



Flavour tagging at hadron colliders

Tagging efficiency

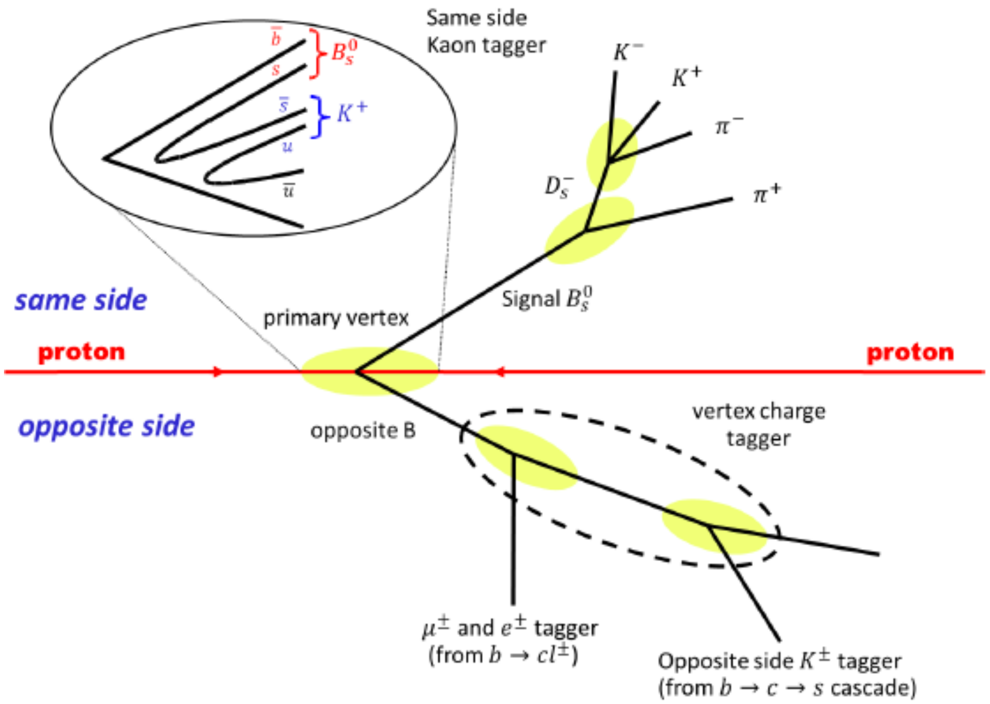
$$\varepsilon = \frac{\#\, tagged\ candidates}{\#\, all\ candidates}$$

Mistag probability

$$\omega = \frac{\#\, tagged\ wrong}{\#\, tagged}$$

Dilution

$$D = (1 - 2\omega)$$



- Opposite side taggers
  - exploits $b\bar{b}$ pair production by partially reconstructing the second B-hadron in the event
- Same side kaon tagger
  - exploits hadronization of signal B_s-meson
- Combined tagging power (in $B_s^0 \to D_s^- \pi^+$)
  - $\varepsilon D^2 = 3.5 \pm 0.5\%$

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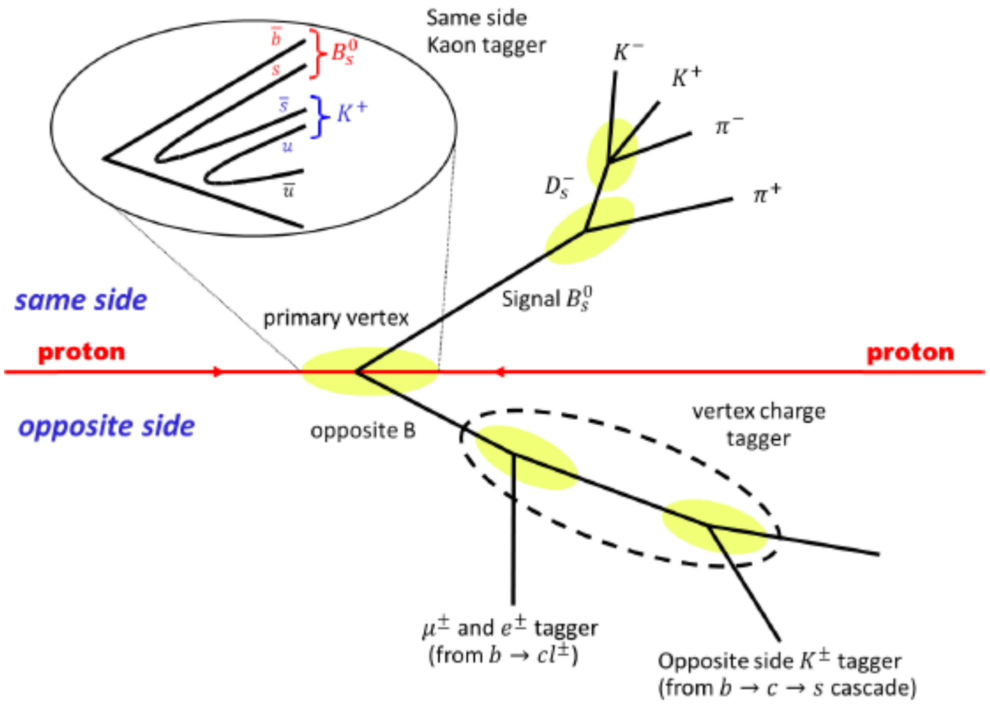

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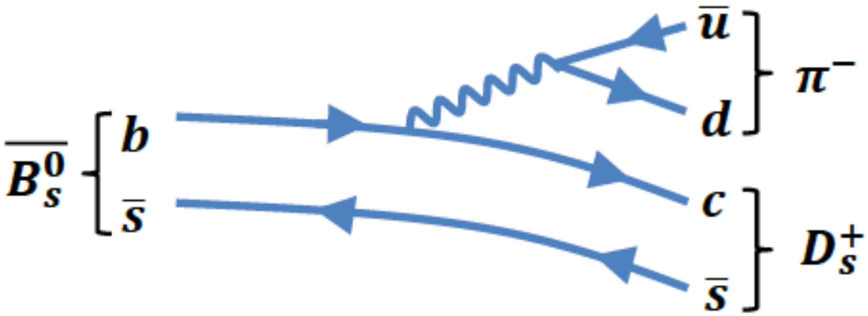
Compare this to e$^+$e$^-$ colliders:
$\varepsilon D^2 \sim 30\%$

Δm_s from $B_s \rightarrow D_s \pi^+$



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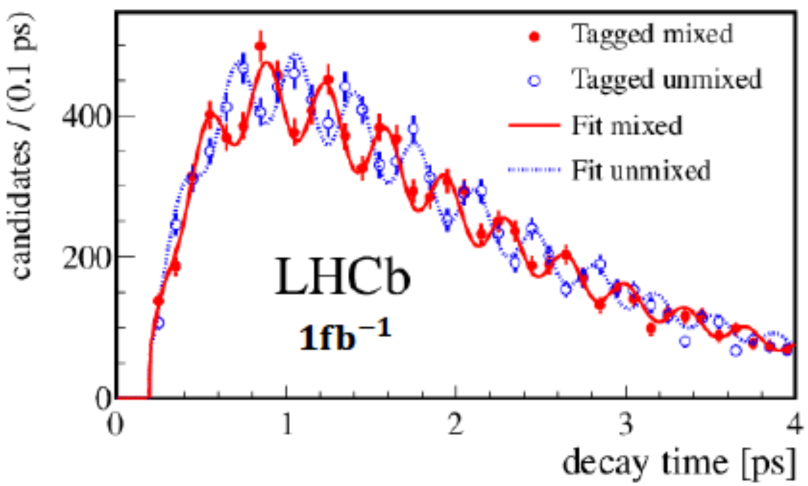

Uses flavour tagging:
opposite side (*Eur.Phys.J. C72(2012) 2022*)
same side (LHCb-CONF-2012-033)

$$\Delta m_s = 17.768 \pm 0.023(stat) \pm 0.006(syst)\ ps^{-1}$$

Slide shown by D. Straub, flavour theory lecture I

Our final result reads

$$A(B^0 \to \bar{B}^0) = \frac{G_F^2}{6\pi^2} m_W^2 m_B \left(V_{tb}^* V_{td}\right)^2 S_0(x_t)\, \hat{\eta}_B\, f_B^2 \hat{B}$$

and we needed

- CKM elements,
- short-distance contributions (box diagram!),
- QCD corrections, and
- input from the lattice.

Importance of Flavour Physics

- Many open questions in the flavour sector of the SM
  - Are there only 3 Generations? And why?
  - What determines the strong hierarchy of fermion masses?
  - What determines the structure of the CKM matrix?
  - What is the origin of CP violation?

- Progress in flavour physics may help to understand open questions in cosmology
  - SM insufficient to explain matter dominance in the universe
  - No candidate for dark matter known

- **Precise studies of flavour observables are a proven tool of discovery**

Parameters of the Standard Model

- The Standard Model of particle physics has 25 free parameters:
  - 3 gauge couplings
  - 2 Higgs parameters
  - 6 quark masses
  - 3 quark mixing angles + 1 phase
  - 3 + 3 lepton masses
  - 3 lepton mixing angles + 1 phase

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Flavour parameters