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
  - Vava Gligorov & Barbara Storaci (discussion leaders)
  - T. Gershon, V. Gibson, S. Hansmann-Menzemer, U. Uwer, F. Teubert, T. Nakada, A. Shires, S. Wandernoth ...

- This is a school talk, not an overview of the field
  - **the topics presented are a subjective choice, covering fewer topics in more detail**
  - 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/

Contents

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

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

Indirect searches for New Physics

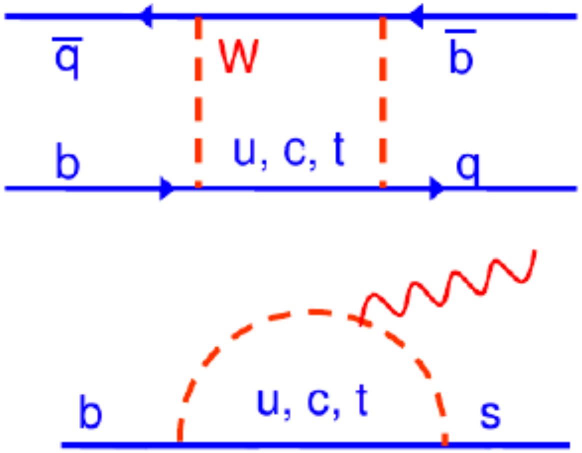
- High **energy**:
  "real" new particles can be produced and discovered via their decays

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

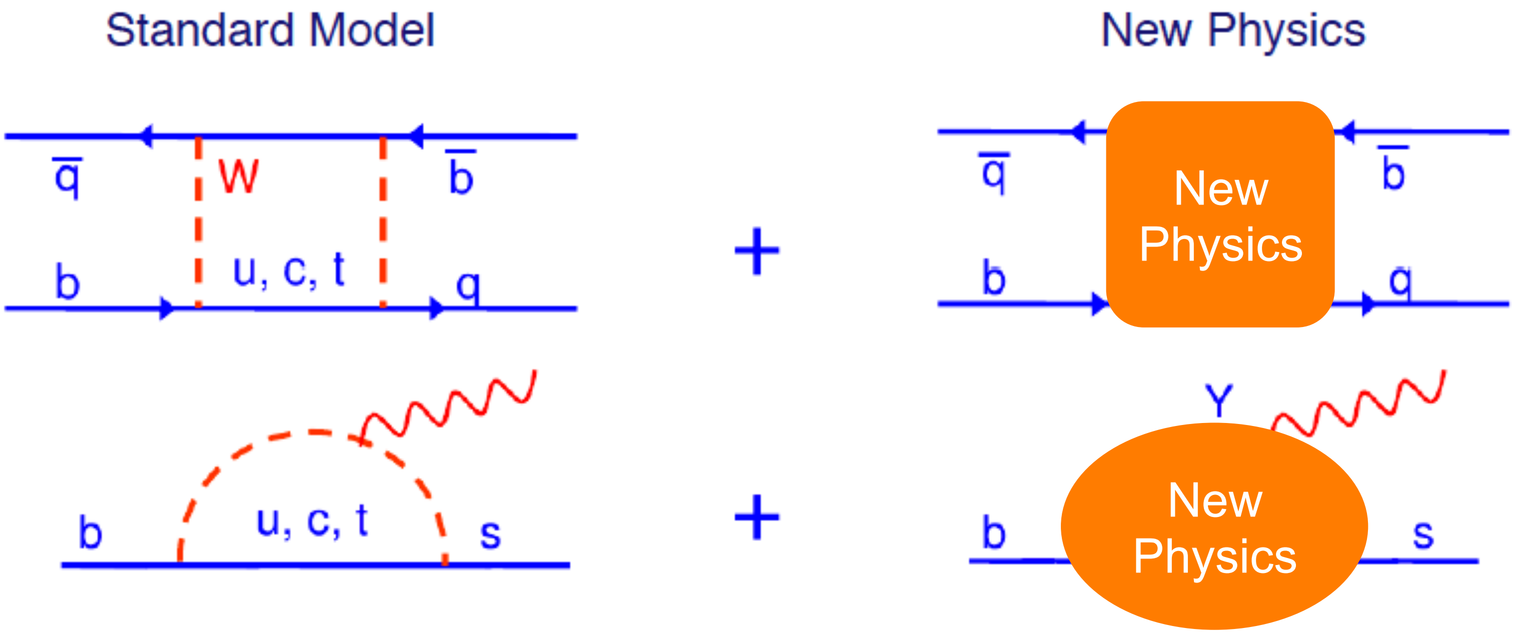
Direct and indirect searches are both needed, both equally important, and complement each other

Contribution of New Physics as correction to the Standard Model

Standard Model



Contribution of New Physics as correction to the Standard Model



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

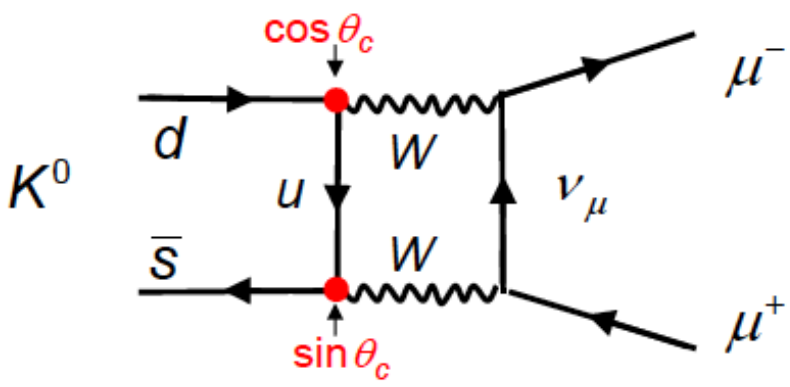
What is the scale of λ_{NP}? What is its coupling C_{NP}?

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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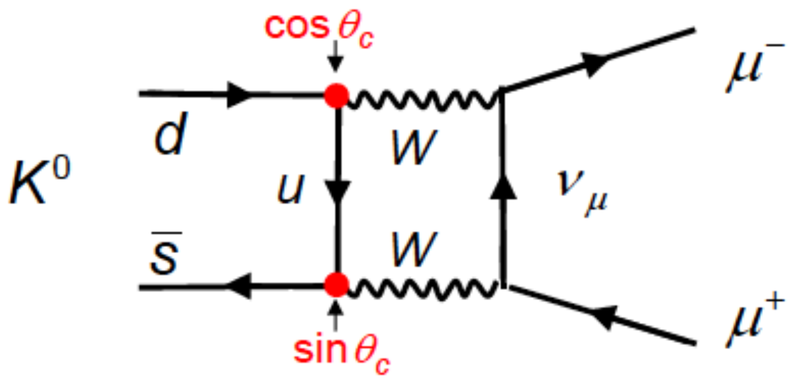
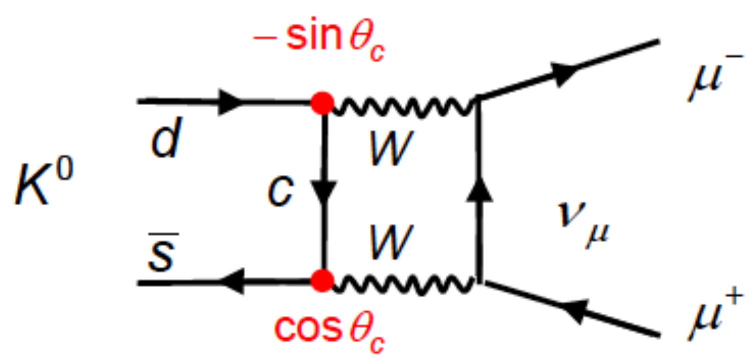
In contradiction with theoretical expectation in the 3-Quark Model

Glashow, Iliopolus, Maiani (1970):

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



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

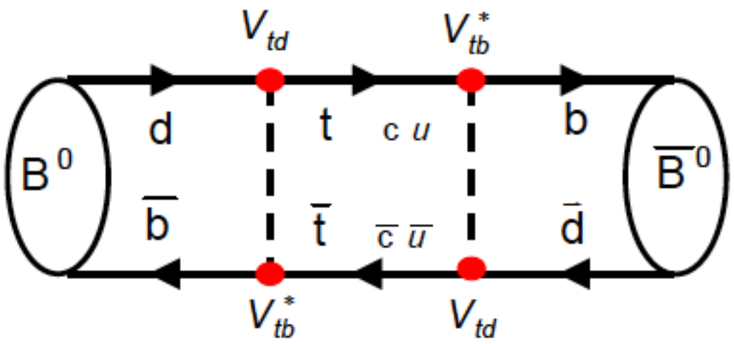


$M \sim -\sin\theta_c \cos\theta_c$

Examples from the past II

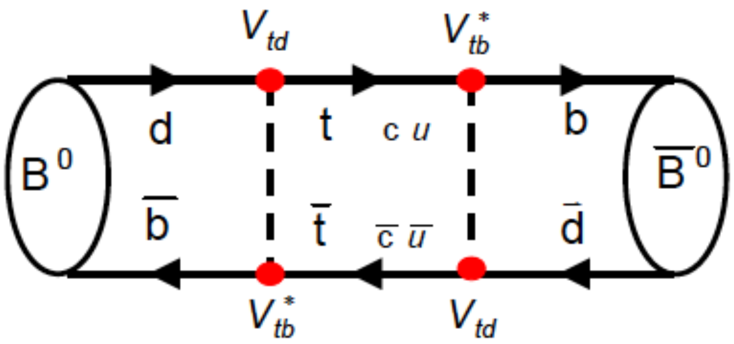
ARGUS Experiment, 1987:

Observation of B^0-B^0 Oscillation ➡ $m_t > 50$ GeV

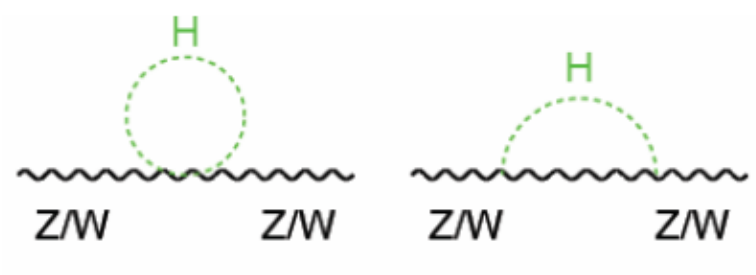


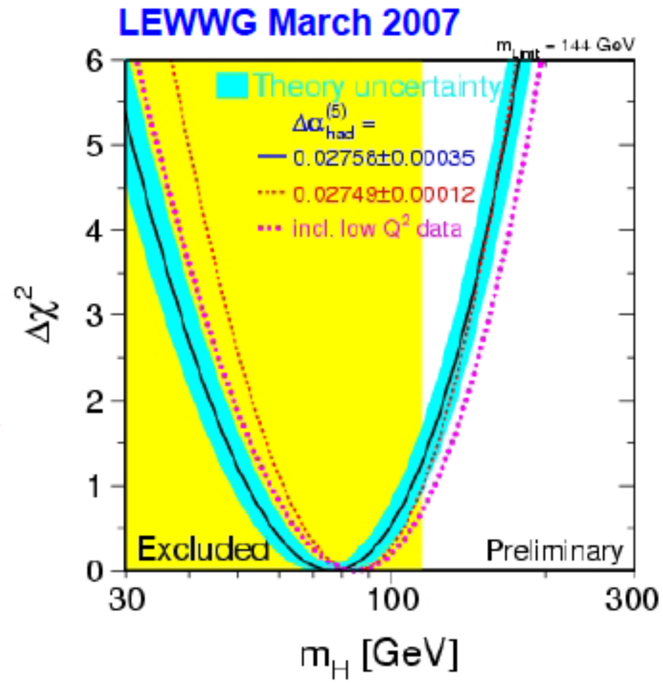
ARGUS Experiment, 1987:

Observation of B^0-B^0 Oscillation → $m_t > 50$ GeV



Precision electro-weak Physics at the Z →





m_H< 144 GeV (95% C.L)

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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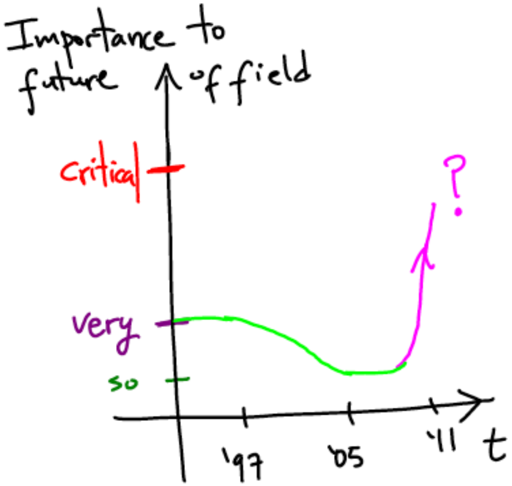
Importance of Flavour



N. Arkani-Hamed
Intensity frontier workshop

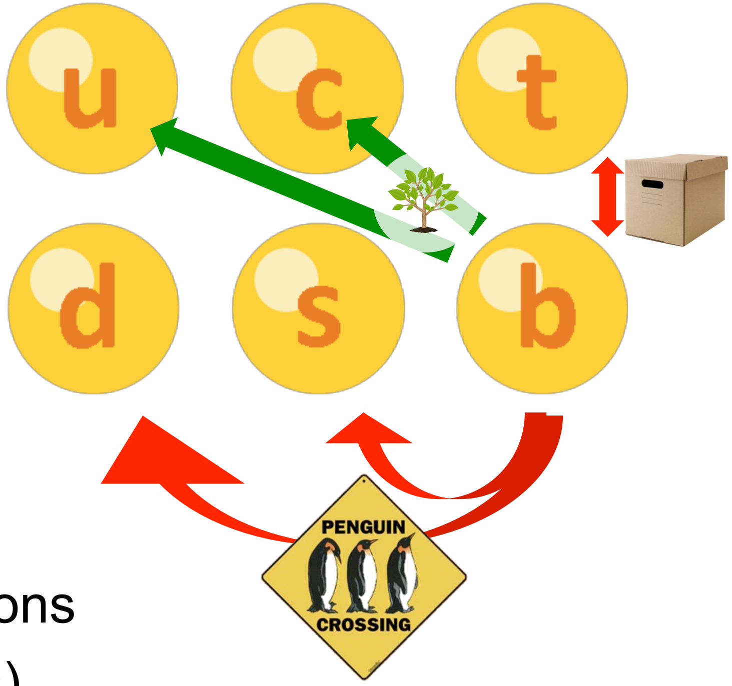
- So far: no significant sign of New Physics
  - The scale for NP get pushed higher
  - NP flavour problem reduced
    → chances to see NP in the flavour sector have increased
    (hypotheses like MFV look less likely)

arXiv:1205.7091, arXiv:1205.2671

- 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

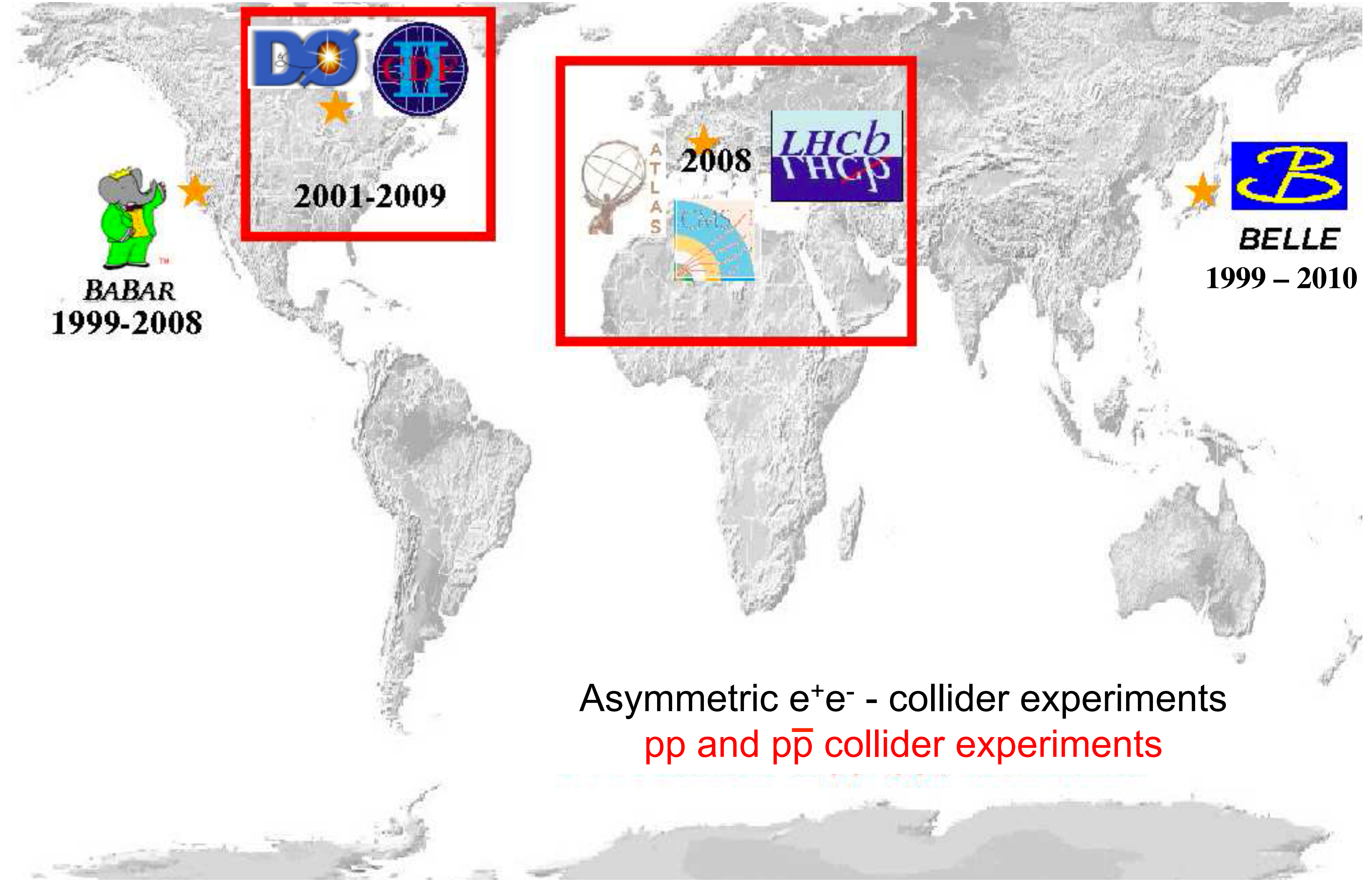
Rich phenomenology with beauty quarks

- 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

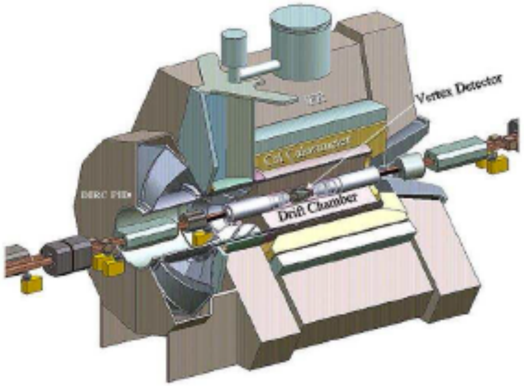
B–Physics Around the World



Asymmetric e^+e^- - collider experiments

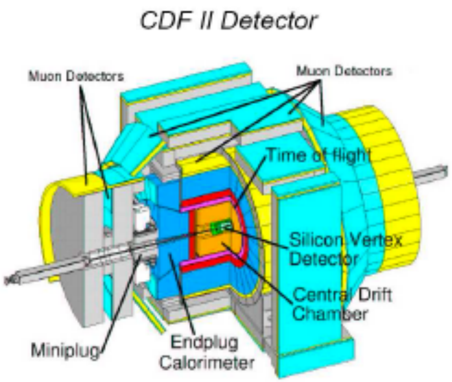
pp and $p\bar{p}$ collider experiments

B-factories (BaBar & Belle)



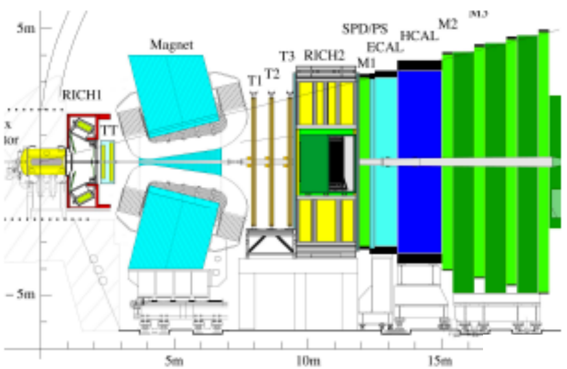
- e^+e^- experiment at SLAC / KEK
- Dedicated B-physics experiment

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^-

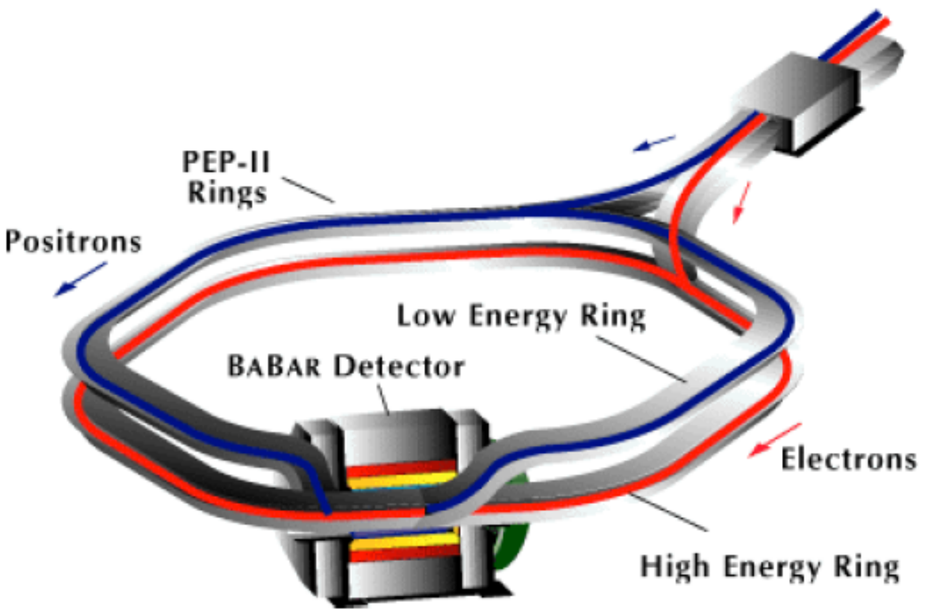
Lepton collider
(collision of pointlike objects)

Hadron collider
(collision of extended objects)

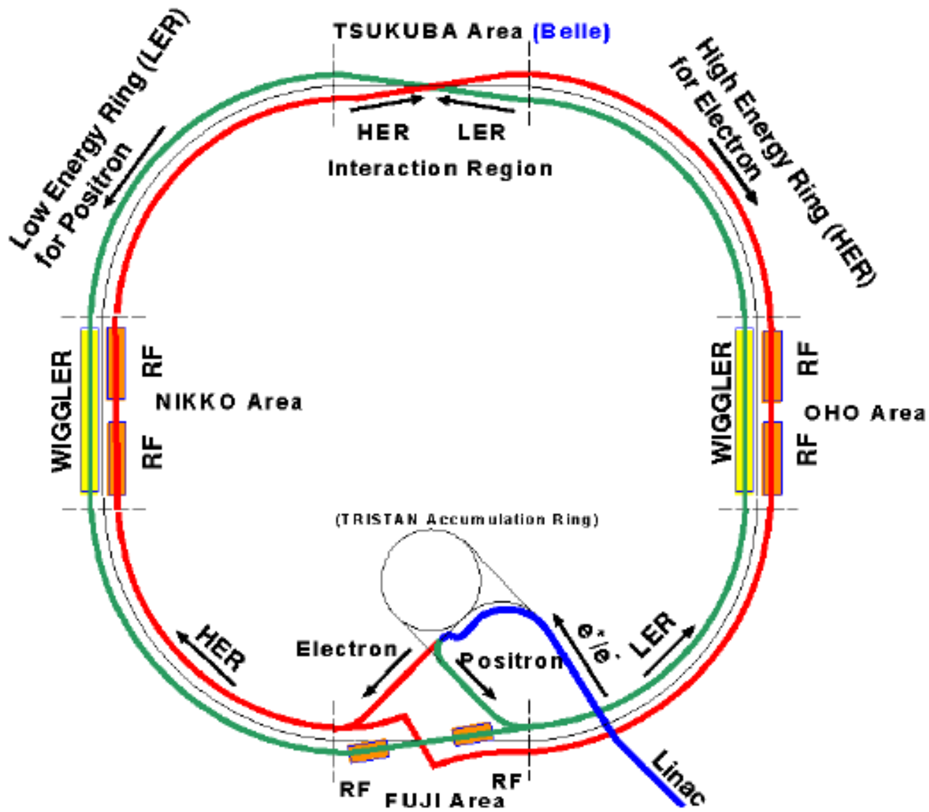
[Karl Jakobs]

e^+e^-: Asymmetric B Factories

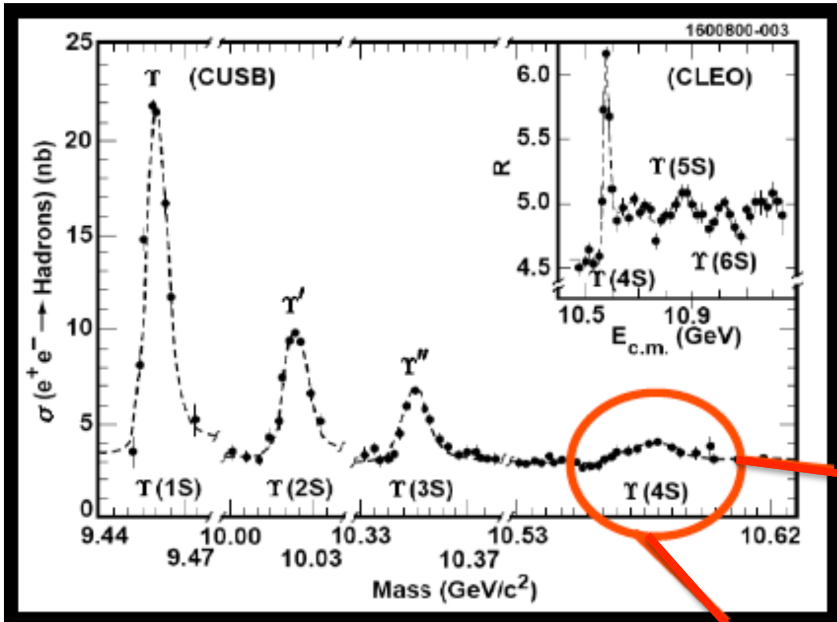
PEPII at SLAC
9.0 GeV e^- on 3.1 GeV e^+



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



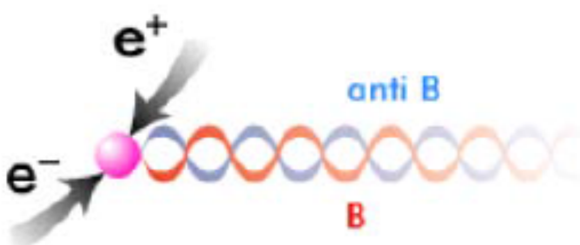
Υ (4S) resonance

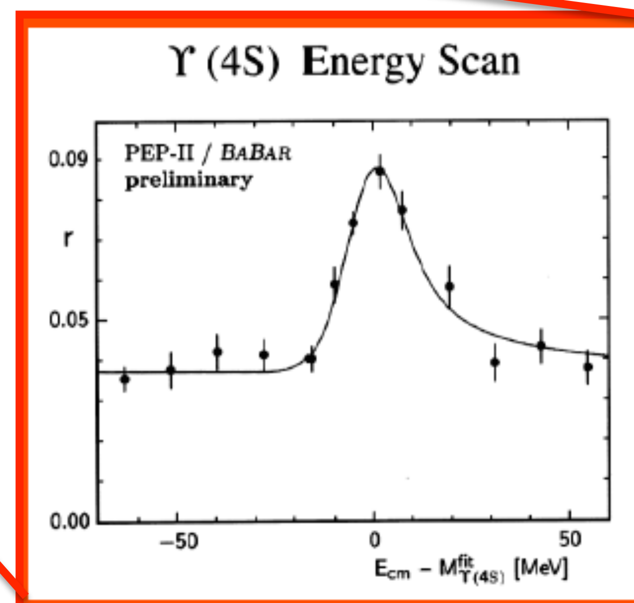


Cleanest way to produce B mesons:
e^+e^- collisions at

$\sqrt{s}$ = 10.58GeV

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





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

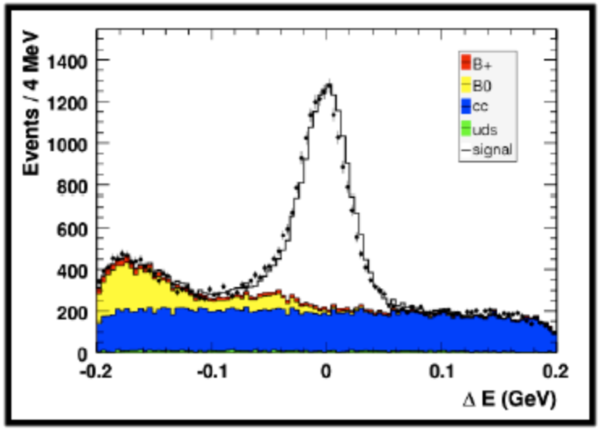
- Asymmetric collider (KEKB, PEPII): with boost $\beta\gamma$ ~ 0.6

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

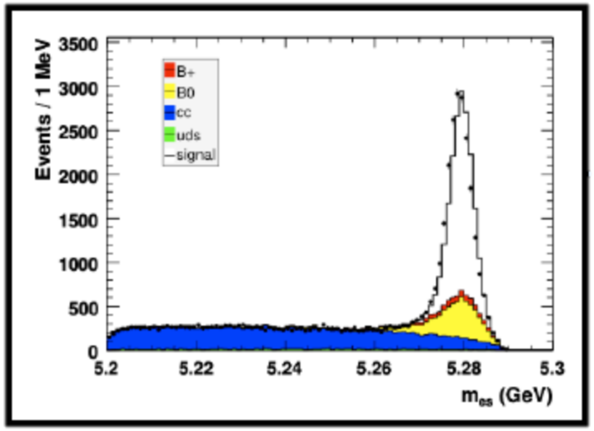
$$\langle |\Delta z| \rangle \approx 200\ \mu\text{m}$$

- 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$\bar{p}$)

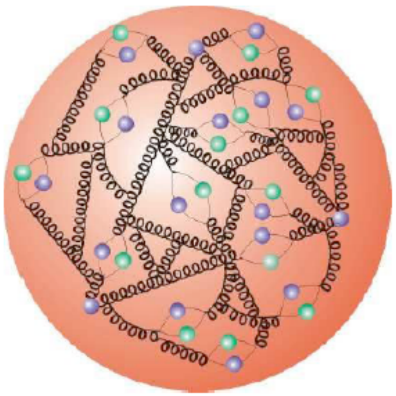
Lepton collider
(collision of pointlike objects)

Hadron collider
(collision of extended objects)

[Karl Jakobs]

Proton Collisions

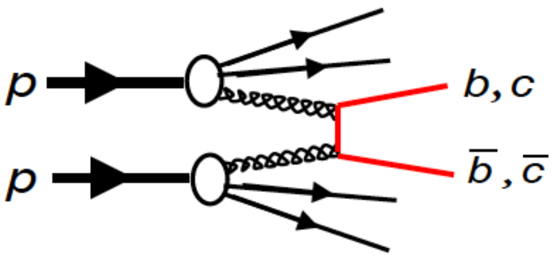
- Protons are complicated objects
  - Valence & sea quarks, gluons



- Available energy of "proton" collision depends on partons

$$\boxed{s' = x_1 \cdot x_2 \cdot s}$$

x_i = Bjorken x (fractional momentum) of parton



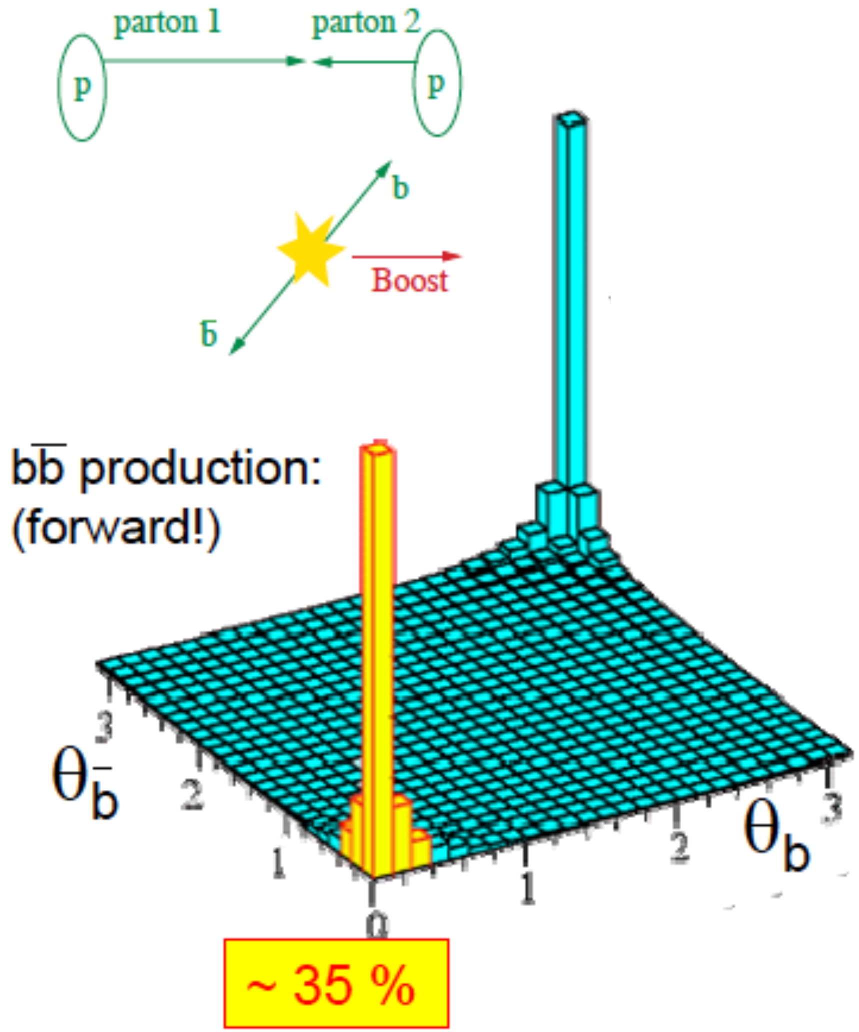
- Energy of particular collision unknown, but distributions known
  - hadron colliders "scan" a wide energy range
  - Average s' ~ 0.1 s
  - Dominant process @ LHC: gluon fusion

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

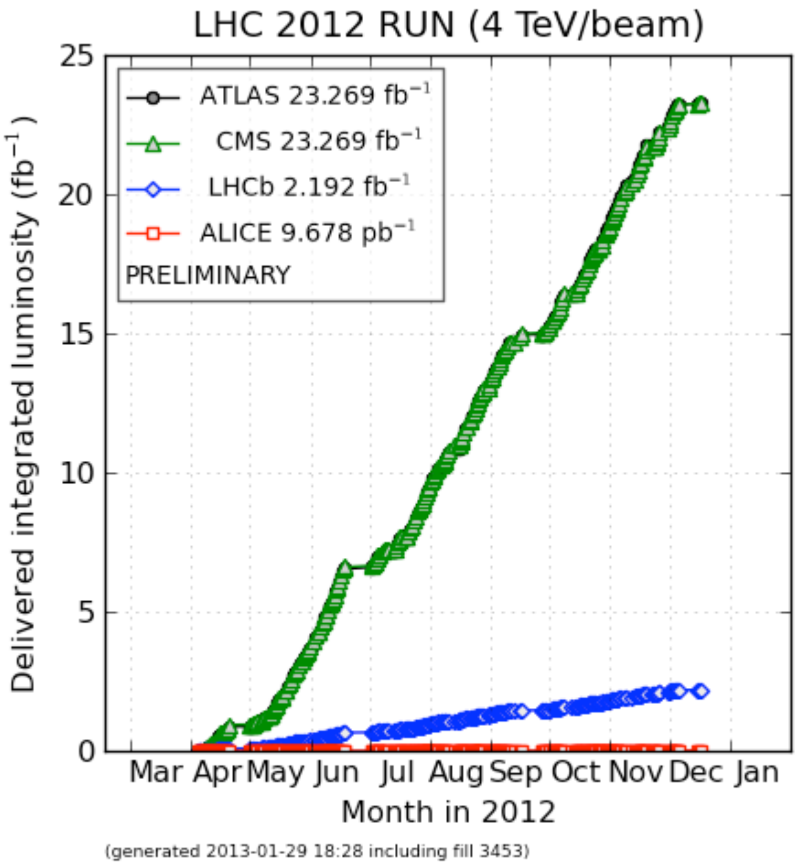
ATLAS / CMS

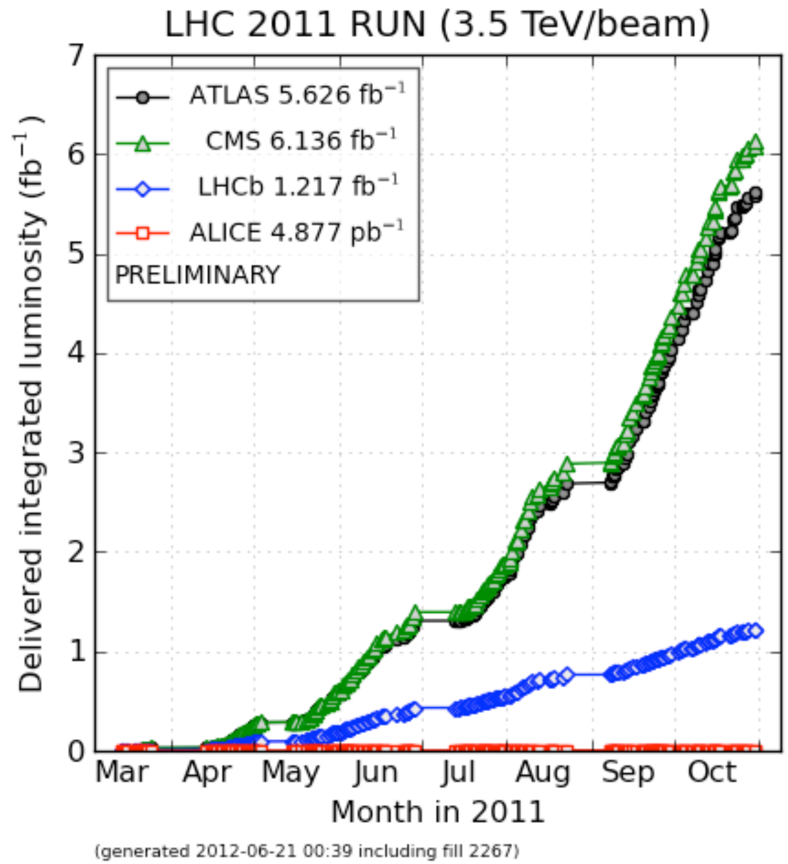
- Central detectors, $|\eta|<2.5$
- **High Luminosity ($>10^{34} cm^{-2}s^{-1}$)**
  → high pileup ~20
- Trigger
  - Relatively low rate (~200-400Hz)
  - High PT muon triggers
- Analysis
  - Mostly modes with dimuons
  - Limited flavour tagging
- Particle identification
  - Excellent muon ID
  - Limited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

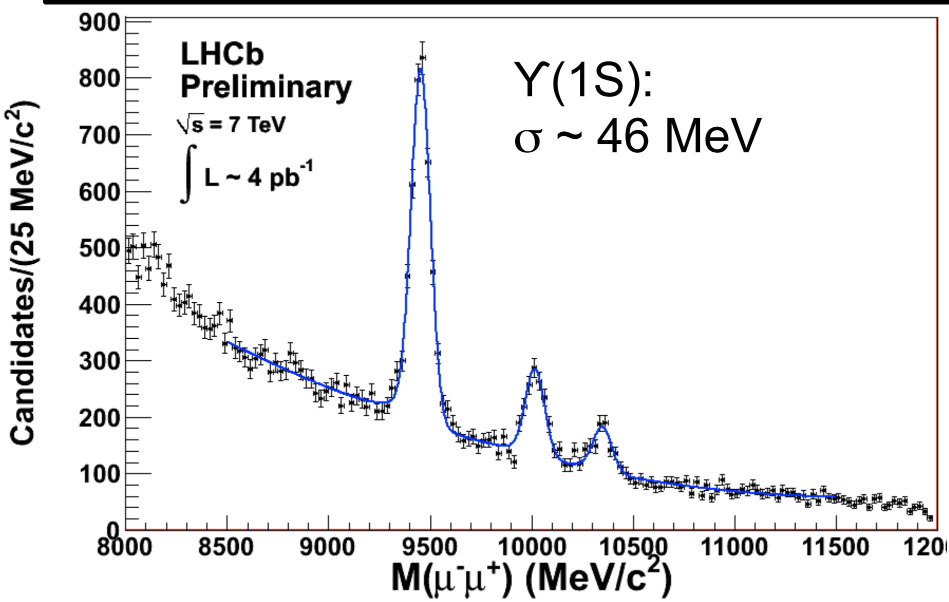


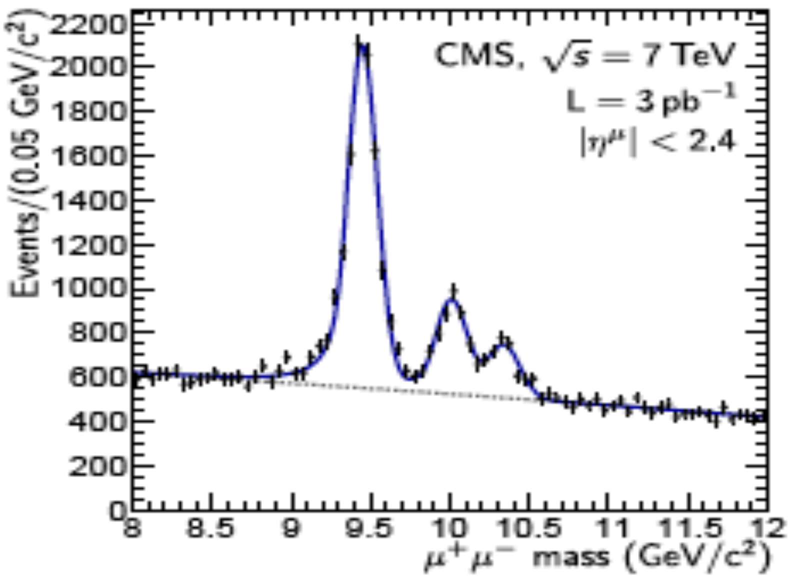


Full dataset: ATLAS = CMS = 10 * LHCb

Keys for b-physics II: mass resolution

Υ(1S), Υ(2S), Υ(3S)





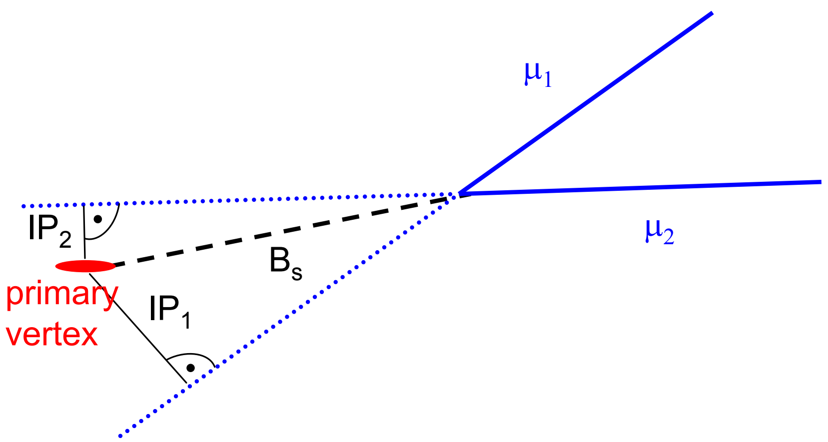
	momentum resolution	mass resolution $J/\psi \rightarrow \mu\mu$
LHCb	$\delta p/p$ = 0.4-0.6 %	13 MeV
CMS	$\delta pt/pt$ = 1-3 %	40 MeV
ATLAS	$\delta pt/pt$ = 5-6 %	71 MeV

Keys for b-physics III: IP and vertex resolution

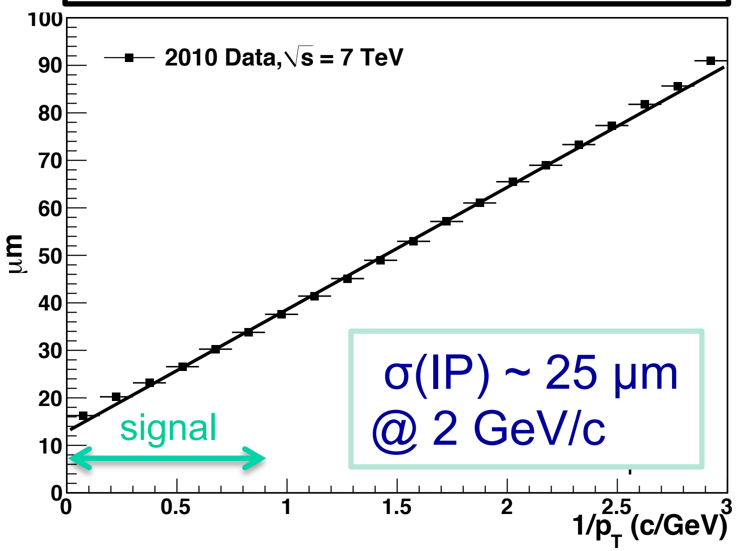
Primary vertex resolutions (25 tracks):

	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

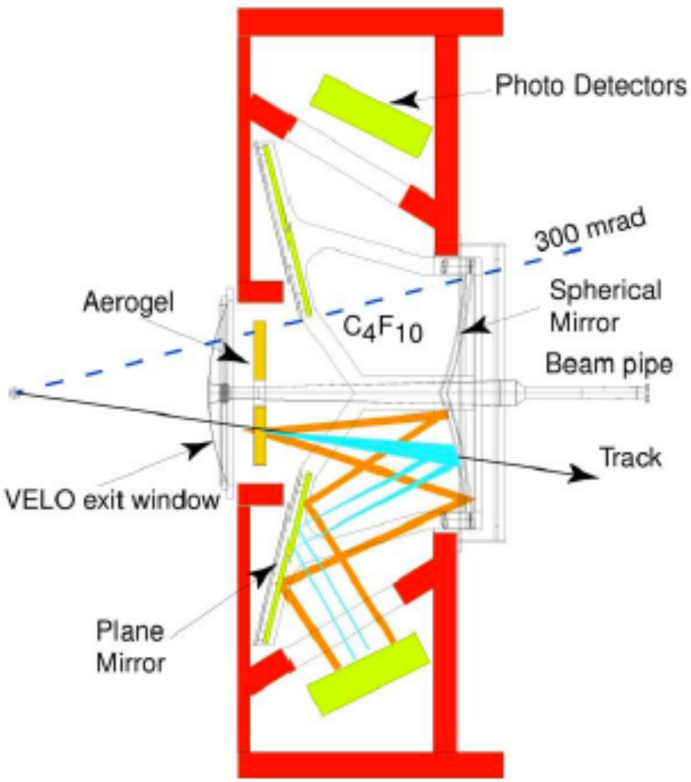
Impact parameter (IP):



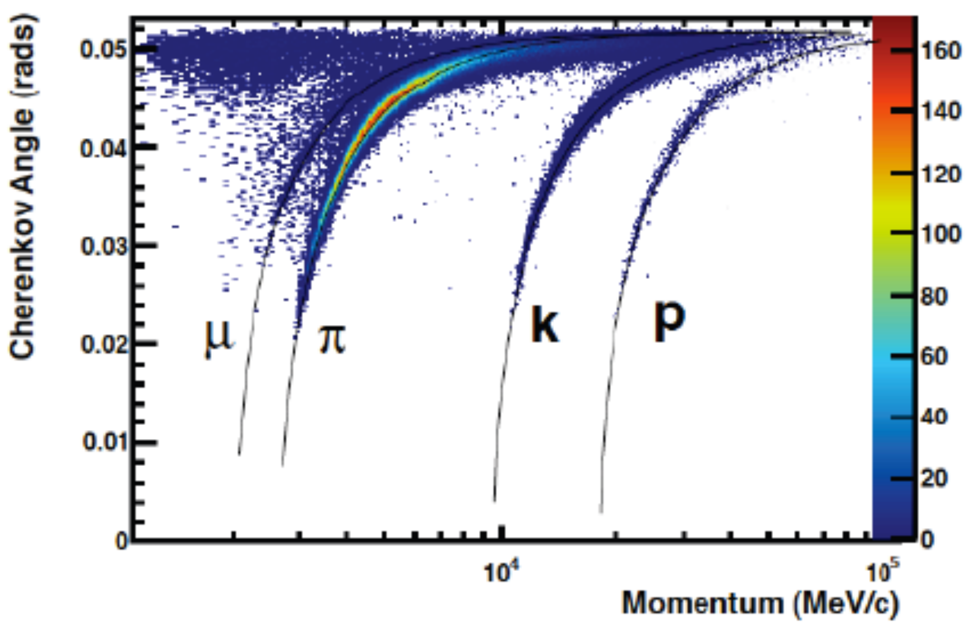
IP resolution vs 1/pT



Keys for b-physics IV: Particle Identification



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



Keys for b-physics IV: Particle Identification

- The LHCb experiment is equipped with two Cherenkov detectors

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

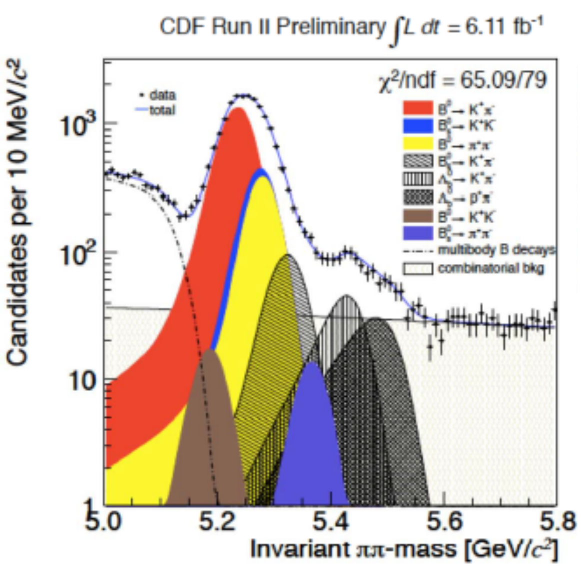
$B \rightarrow h\,h$

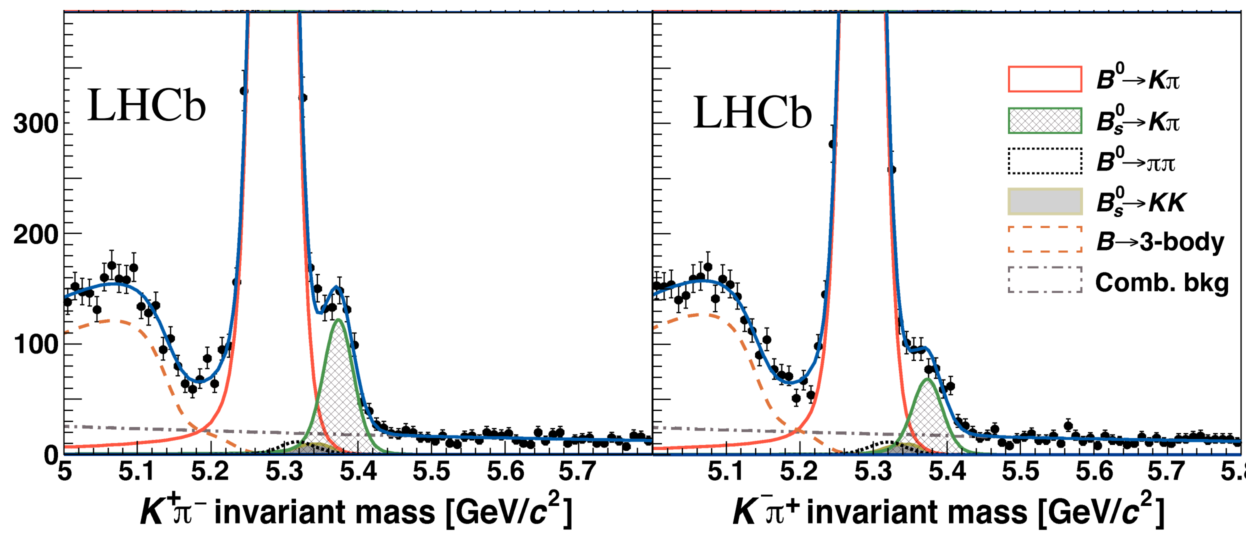
$B^0 \rightarrow K\,\pi$

$B^0 \rightarrow \pi\,\pi$

$B_s \rightarrow K\,K$

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

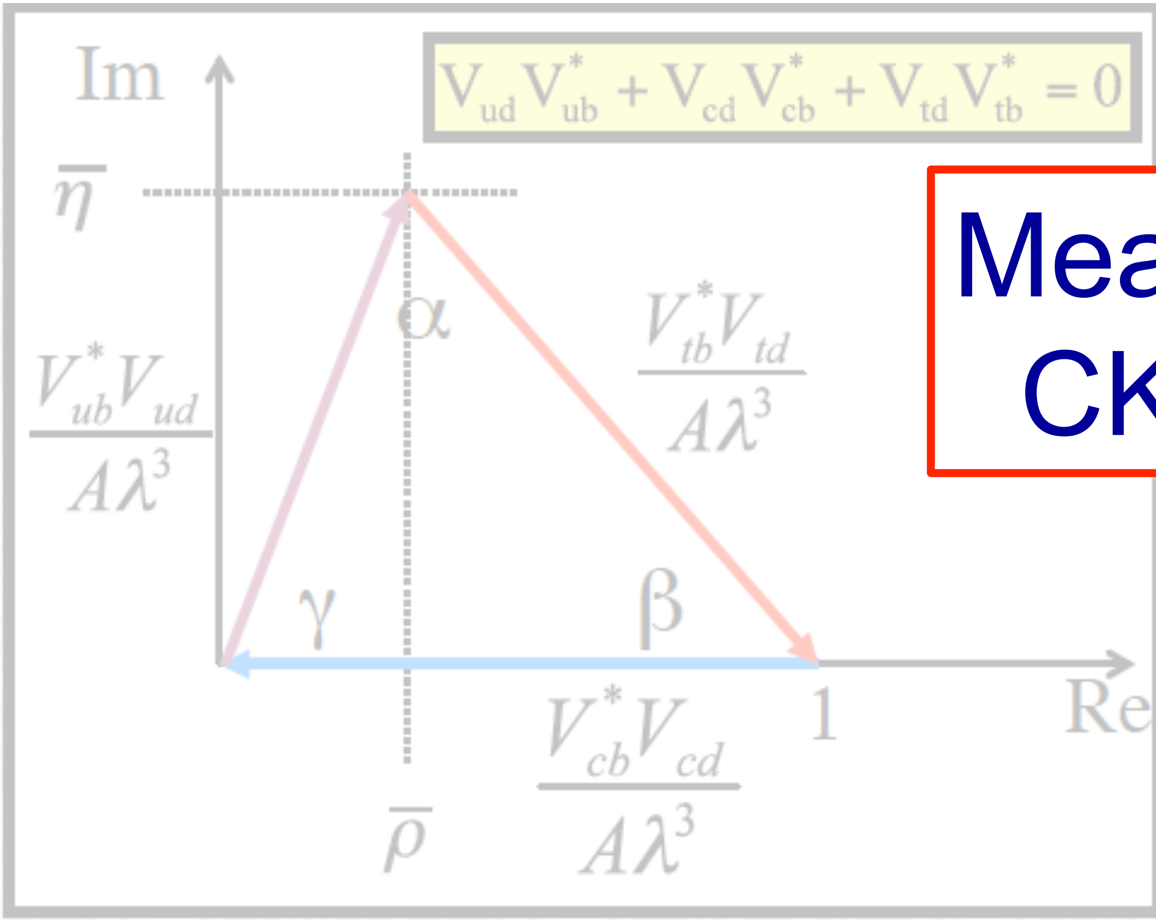




B Production Rates

	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

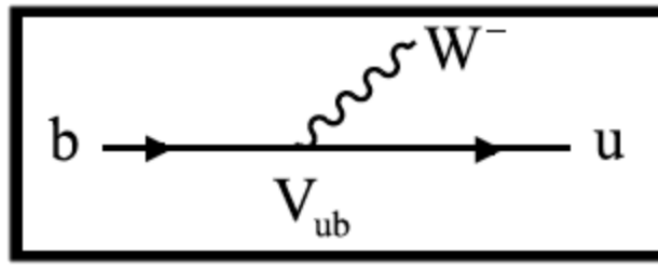
[repetition from detailed discussion from David Straub yesterday]

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

transition amplitude ~ V_{ij}

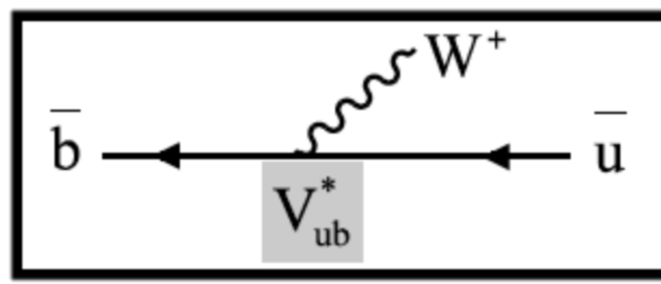
Quarks

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



Antiquarks

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



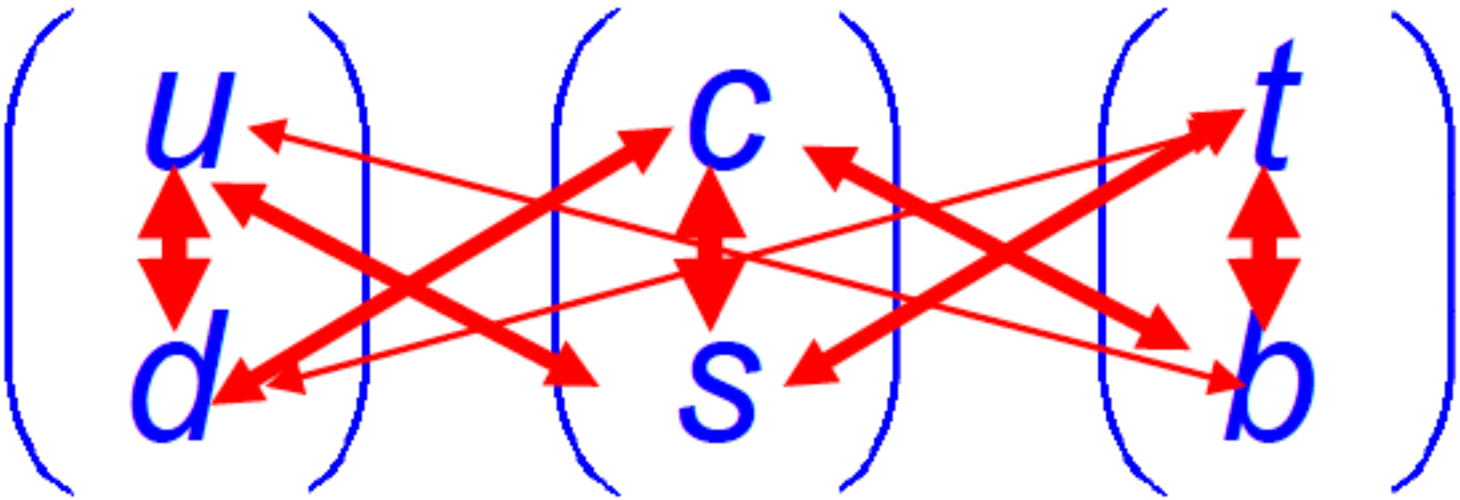
CKM matrix II

[repetition from detailed discussion from David Straub yesterday]

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

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

- Reflects hierarchy of quark transitions



[repetition from detailed discussion from David Straub yesterday]

CKM matrix is unitary:

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

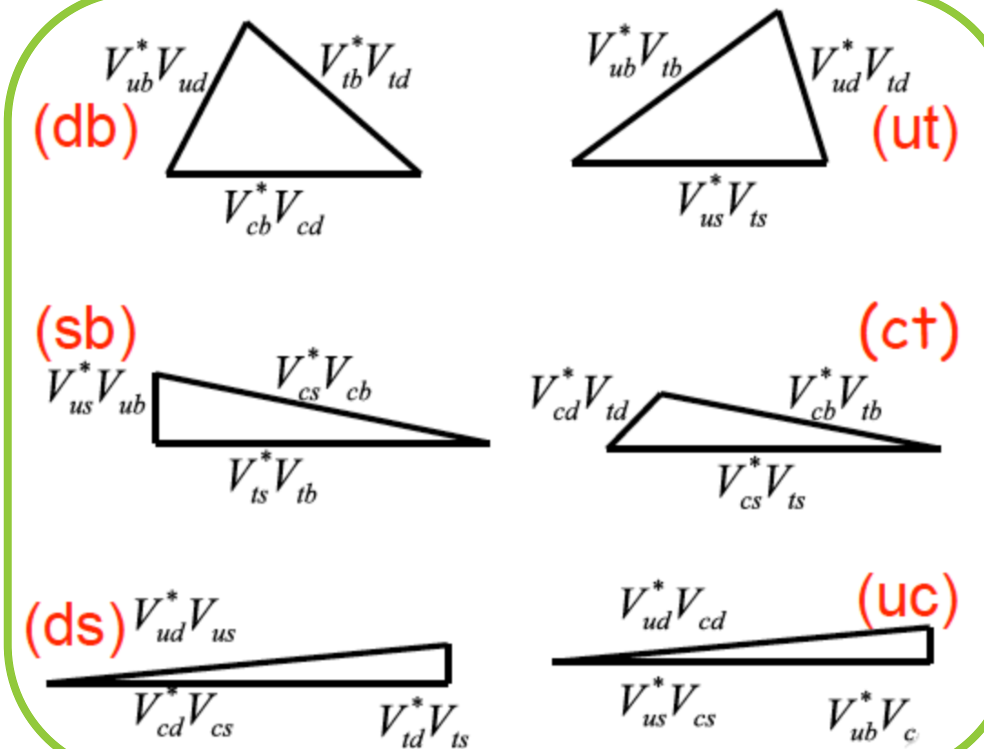
$$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0 \text{ (sb)}$$

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

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

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

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



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

“The” CKM Unitarity Triangle

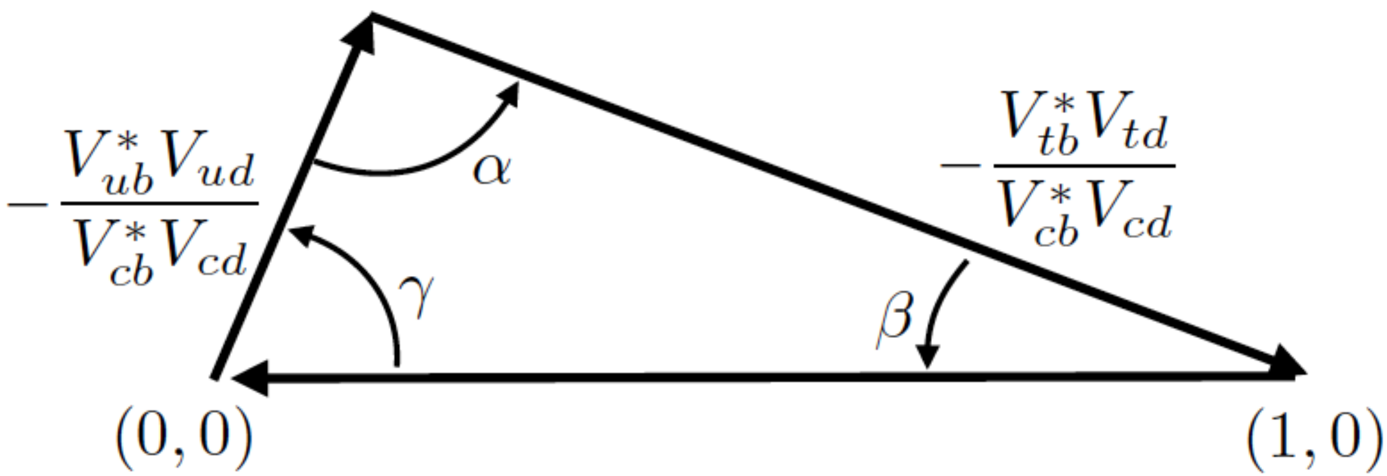
$$V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$$

- 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

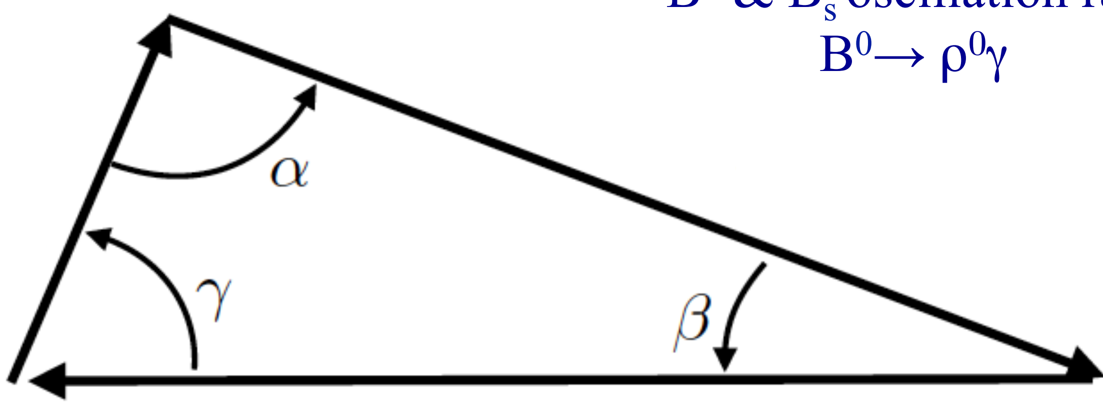
$B^0 \rightarrow \rho^+\rho^-, \rho\pi, \pi^+\pi^-$

B^0 & B_s oscillation rate

$B^0 \rightarrow \rho^0\gamma$

$B \rightarrow X_u\, l\, \nu$

$B \rightarrow \pi\, l\, \nu$



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

$B \rightarrow X_c\, l\, \nu$

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

τ_B

$B^0\ (B^0) \rightarrow cc\ K_s^{\,0}$

$B^0\ (B^0) \rightarrow ss\ K_s^{\,0}$

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

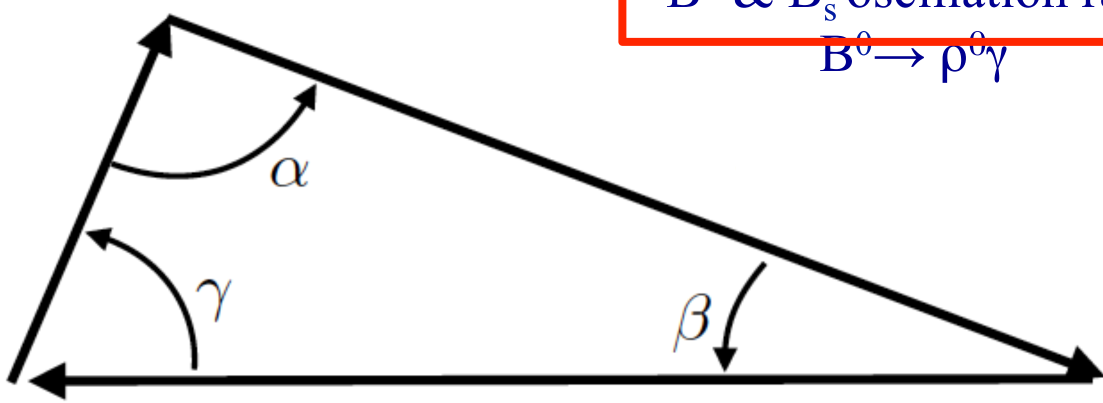
$B^0 \rightarrow \rho^+\rho^-, \rho\pi, \pi^+\pi^-$

B^0 & B_s oscillation rate

$B^0 \rightarrow \rho^0\gamma$

$B \rightarrow X_u \, l \, \nu$

$B \rightarrow \pi \, l \, \nu$



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

$B \rightarrow X_c \, l \, \nu$

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

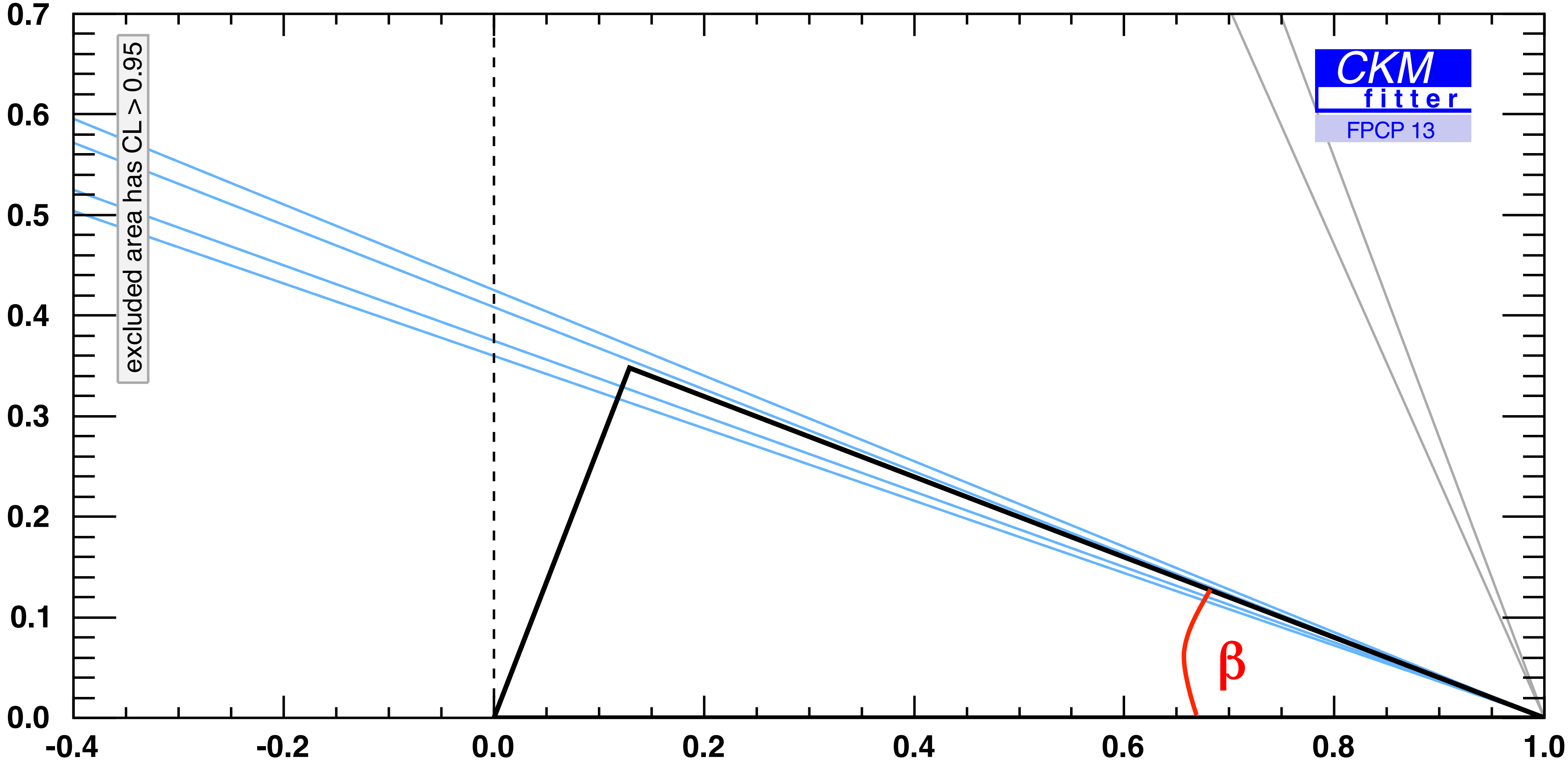
τ_B

$B^0 (B^0) \rightarrow cc \, K_s^0$

$B^0 (B^0) \rightarrow ss \, K_s^0$

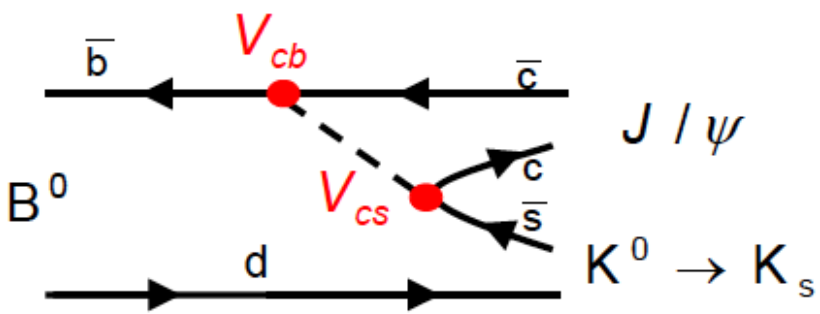
$B^0 (B^0) \rightarrow cc \, dd$

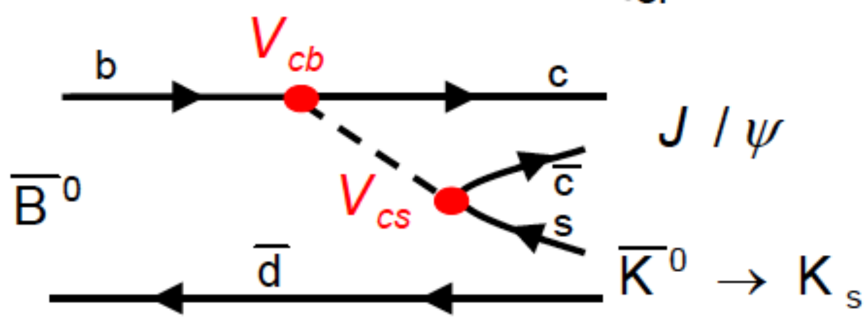
1st CKM measurement: sin 2β

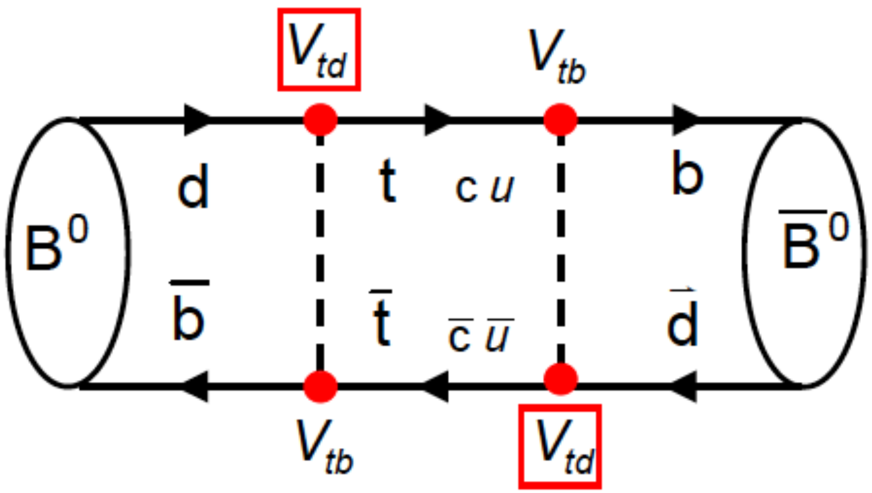


$B^0 \to$ J/ψ K_s $\xrightarrow{CP}$ **$\overline{B}^0 \to$ J/ψ K_s**

η_{CP}=-1





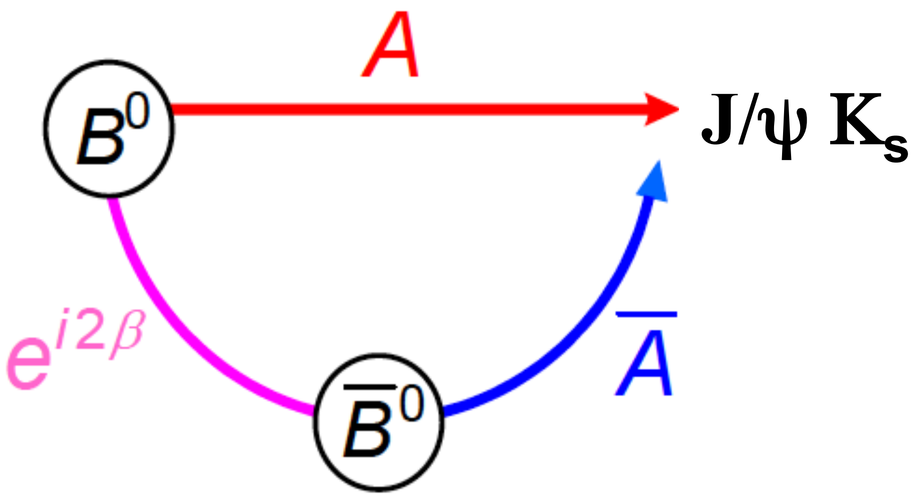


Mixing Phase:

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

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

$\eta_{CP}=-1$



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

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

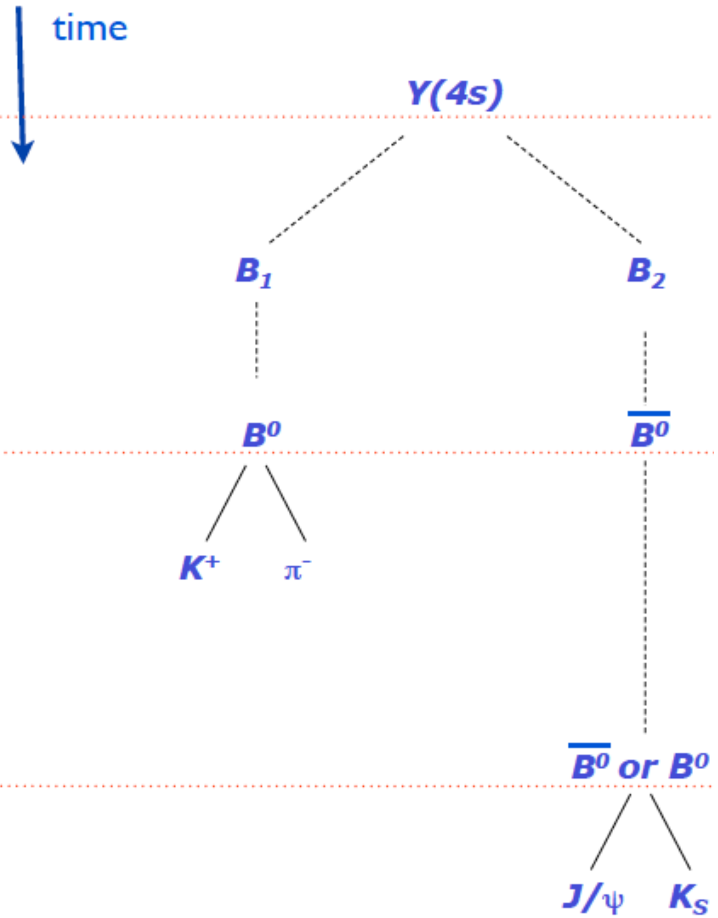
→ Requires knowledge of production flavour of the B

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

Flavour tagging

- 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*!

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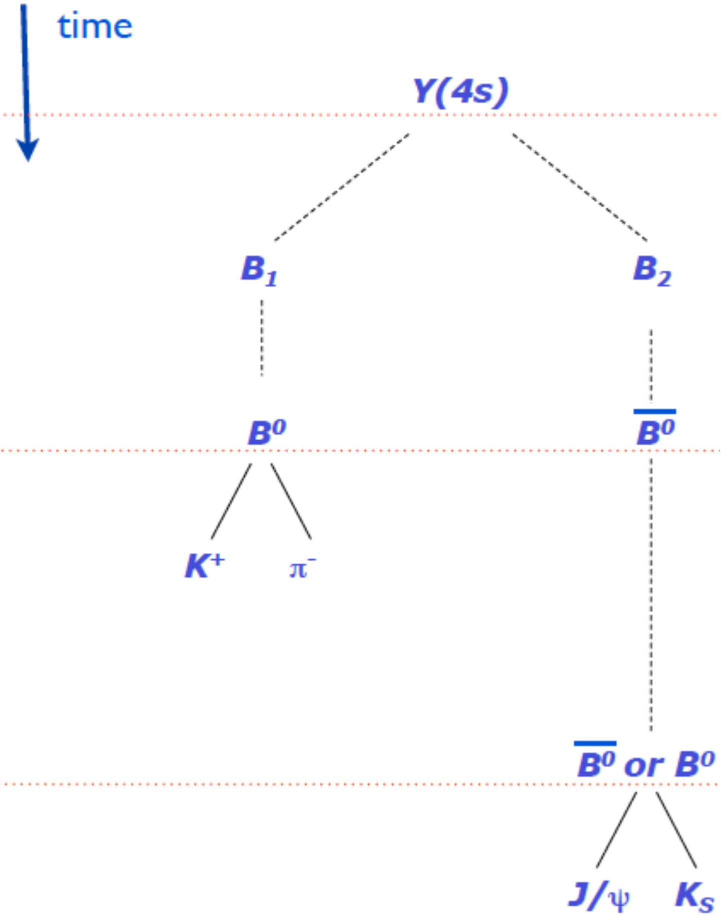
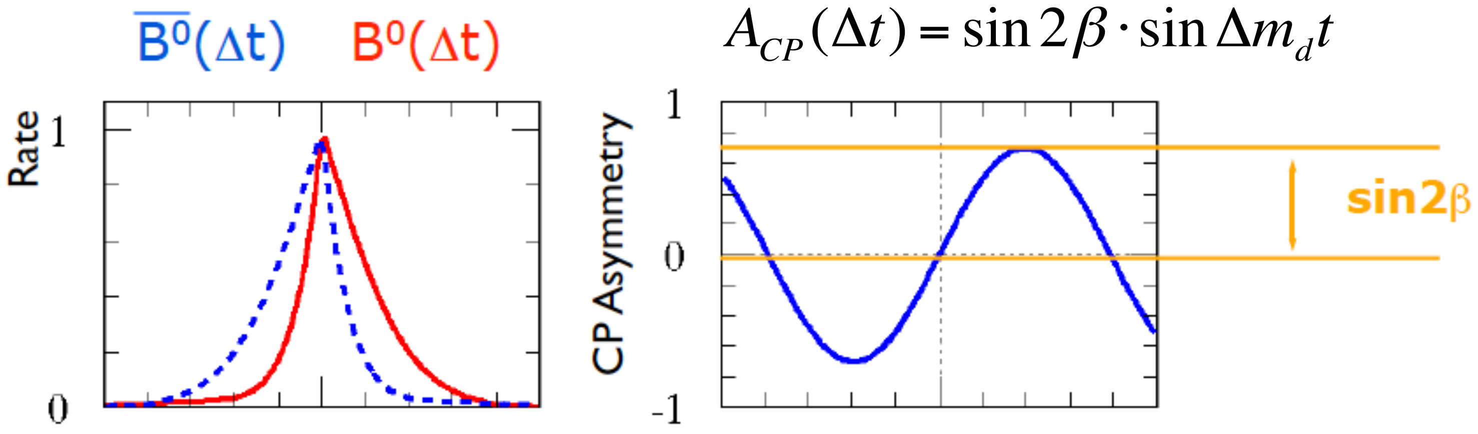


Effective tagging power: εD^2~30% (at B-factories)

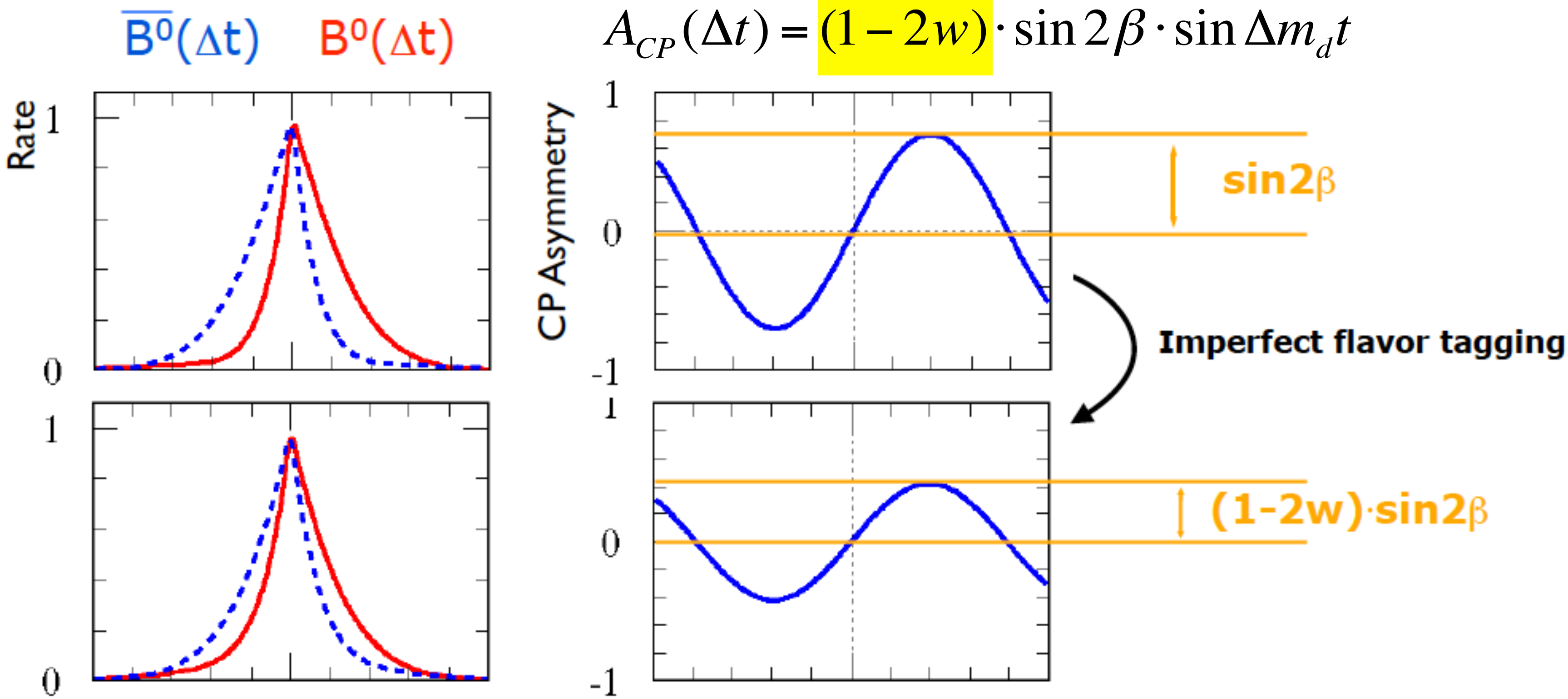
How to extract sin 2β

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



How to extract sin 2β

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



How to extract sin 2β

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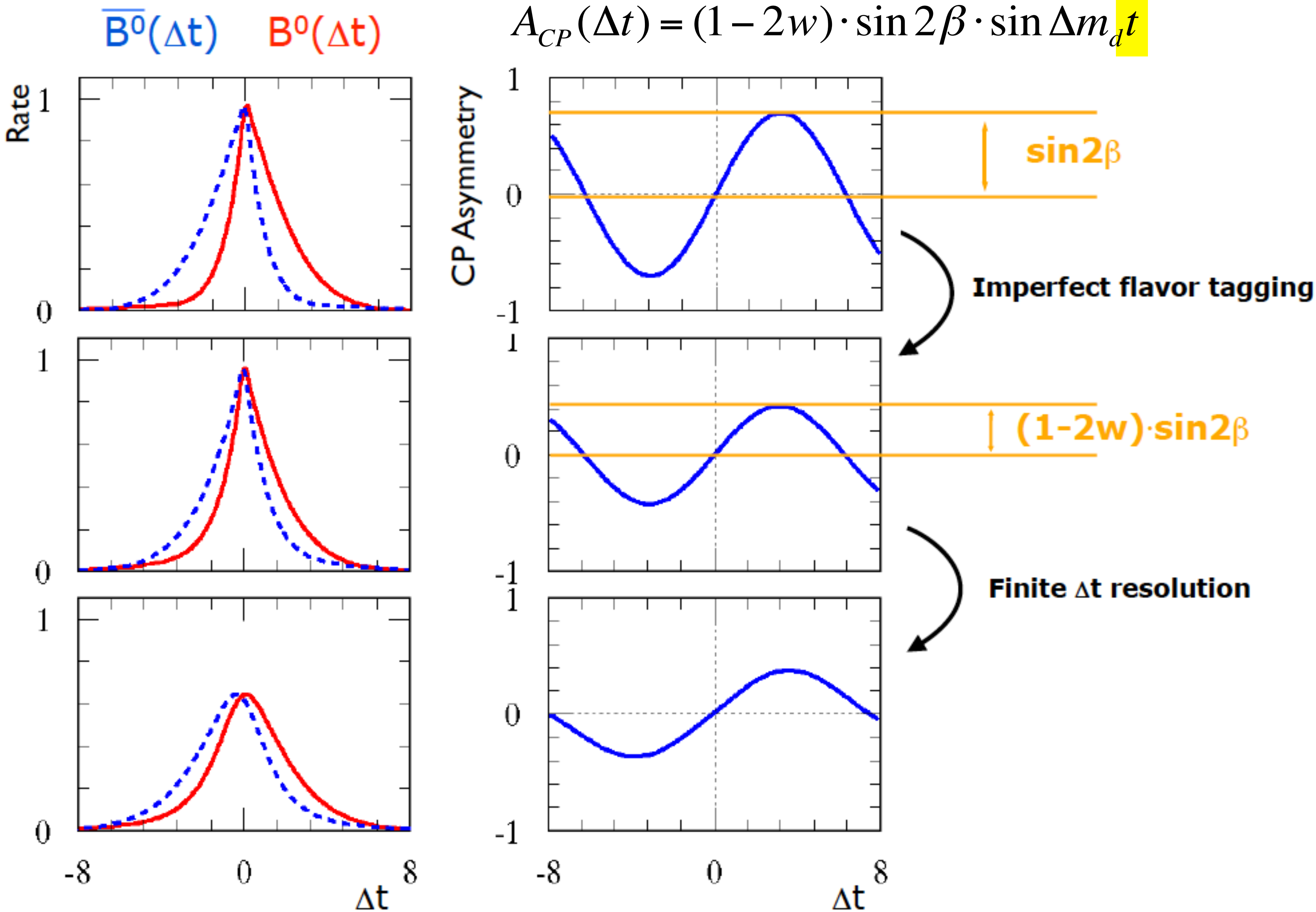
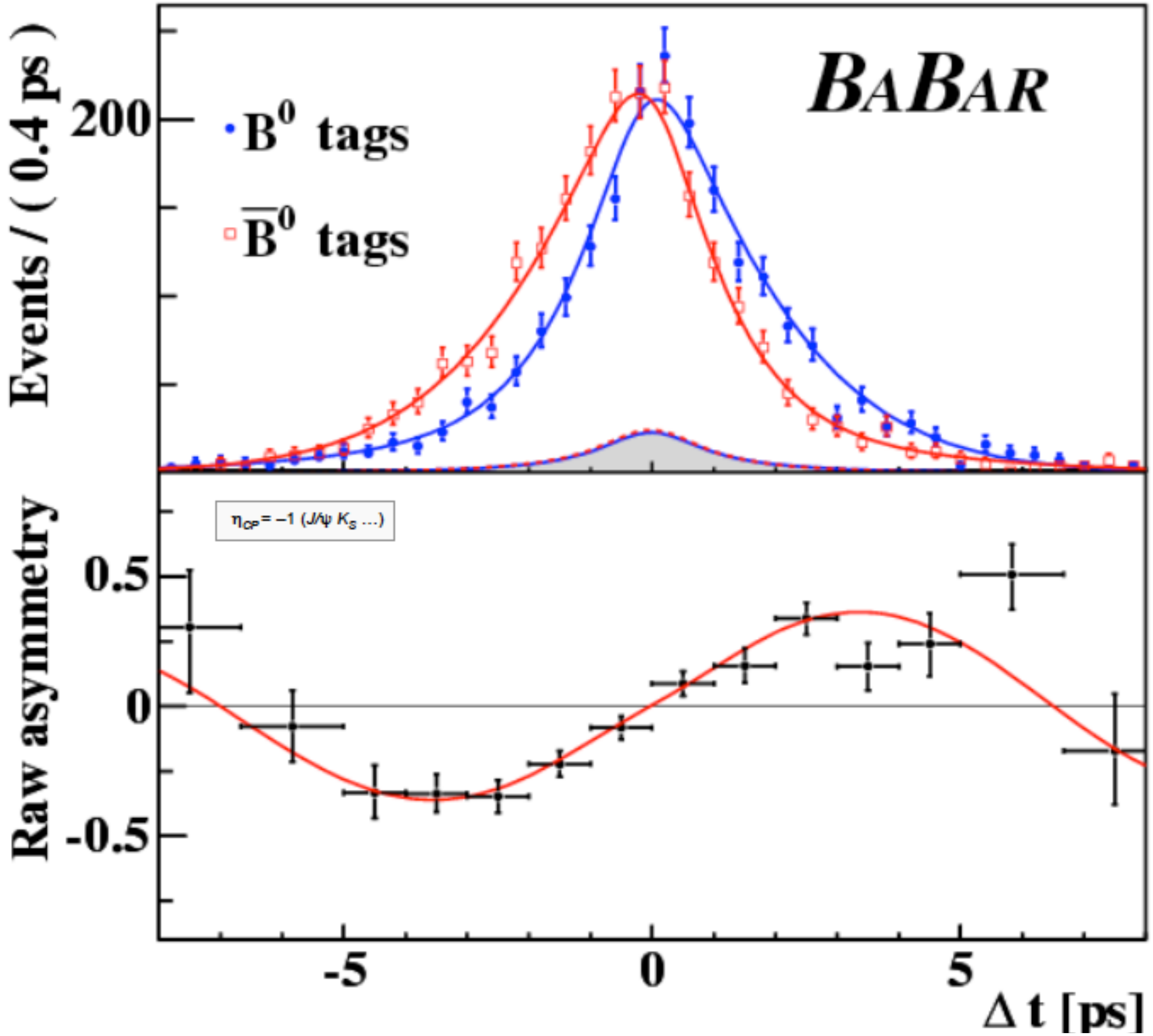


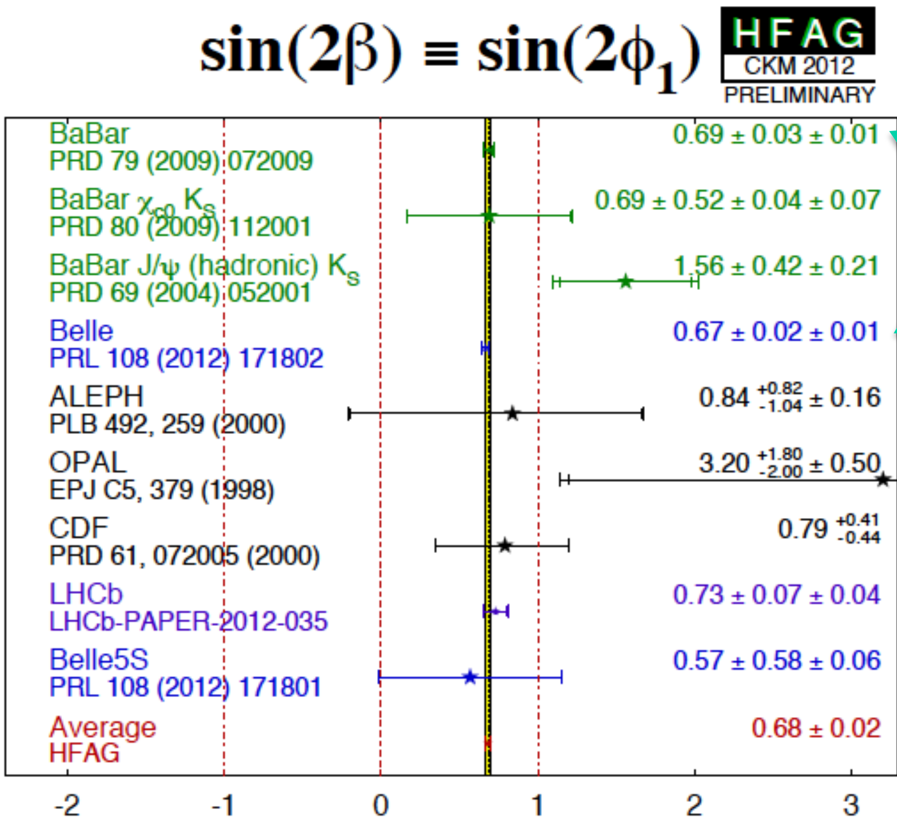
$$e^+e^- \to \Upsilon(4S) \to B_{\text{rec}} B_{\text{tag}}$$

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

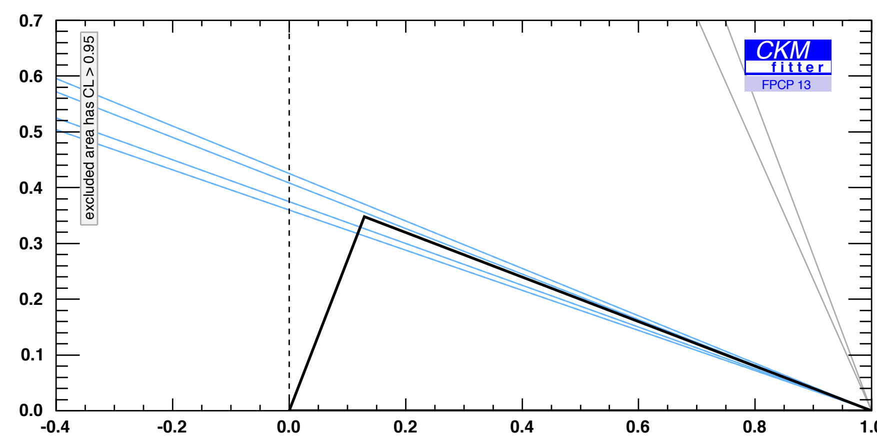
$$B_{\text{tag}} \to \ell^{\pm} X, K^{\pm} X, \pi^{\mp}_{soft}, \pi^{\pm}_{fast} X, \ldots$$



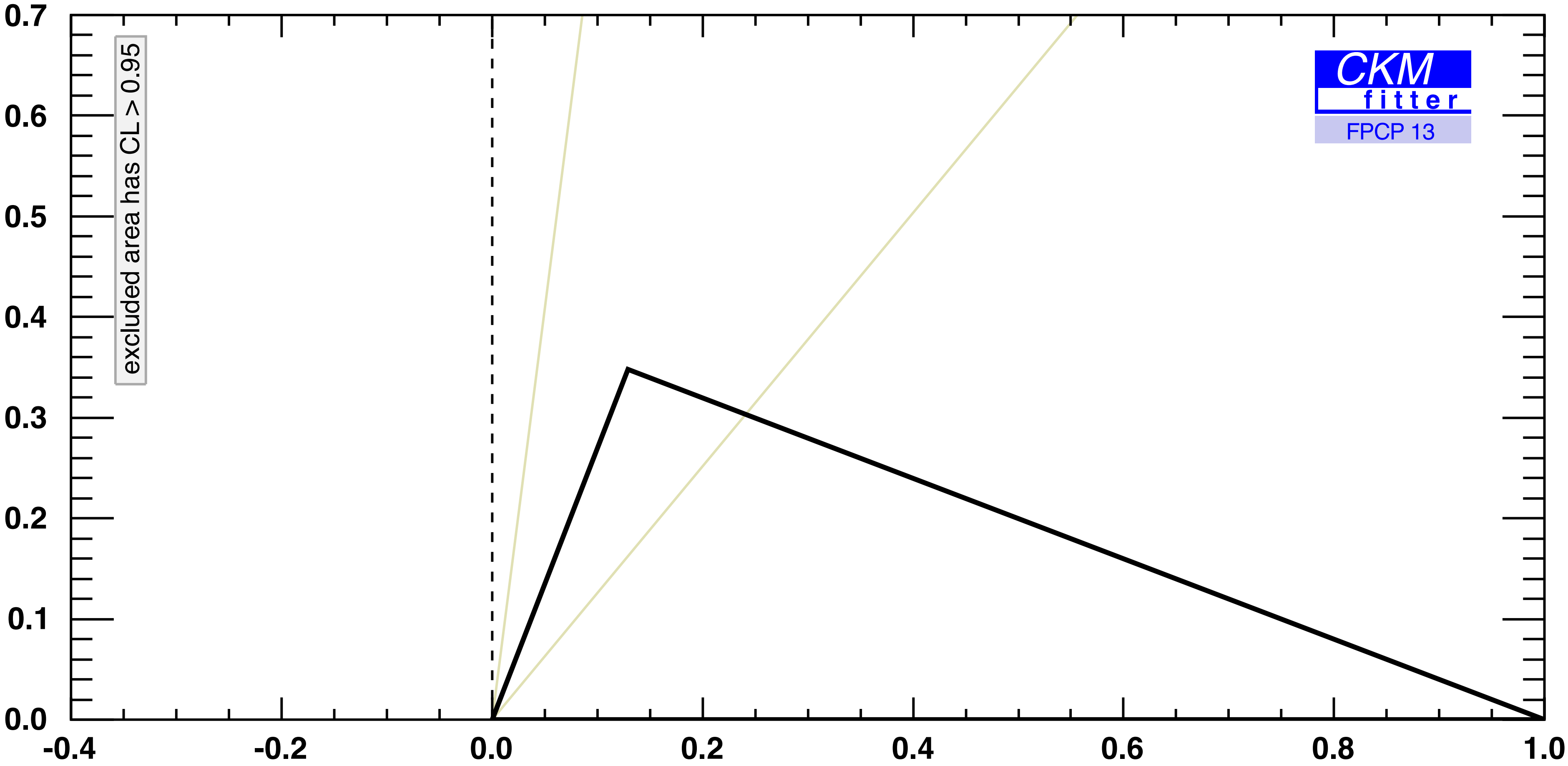
World average of sin 2β



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



2^{nd} CKM measurement: γ

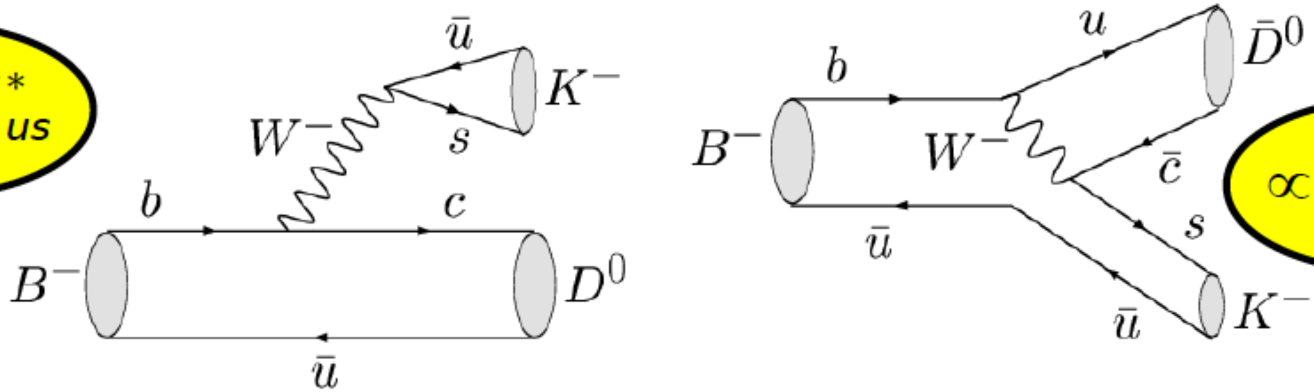


Importance of γ from $B \to D K$

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

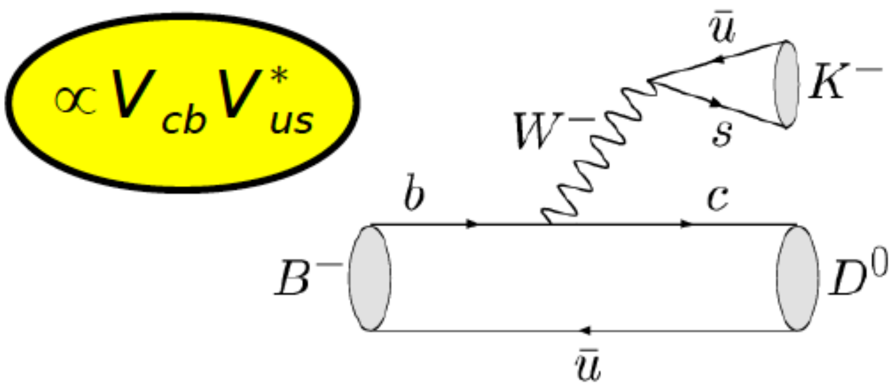
- A benchmark Standard Model reference point
  - Doubly important in case NP is observed

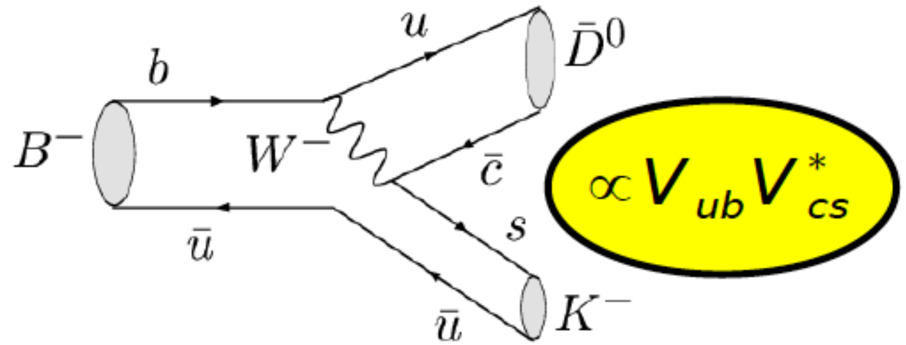
$\propto V_{cb} V_{us}^{*}$



$\propto V_{ub} V_{cs}^{*}$

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





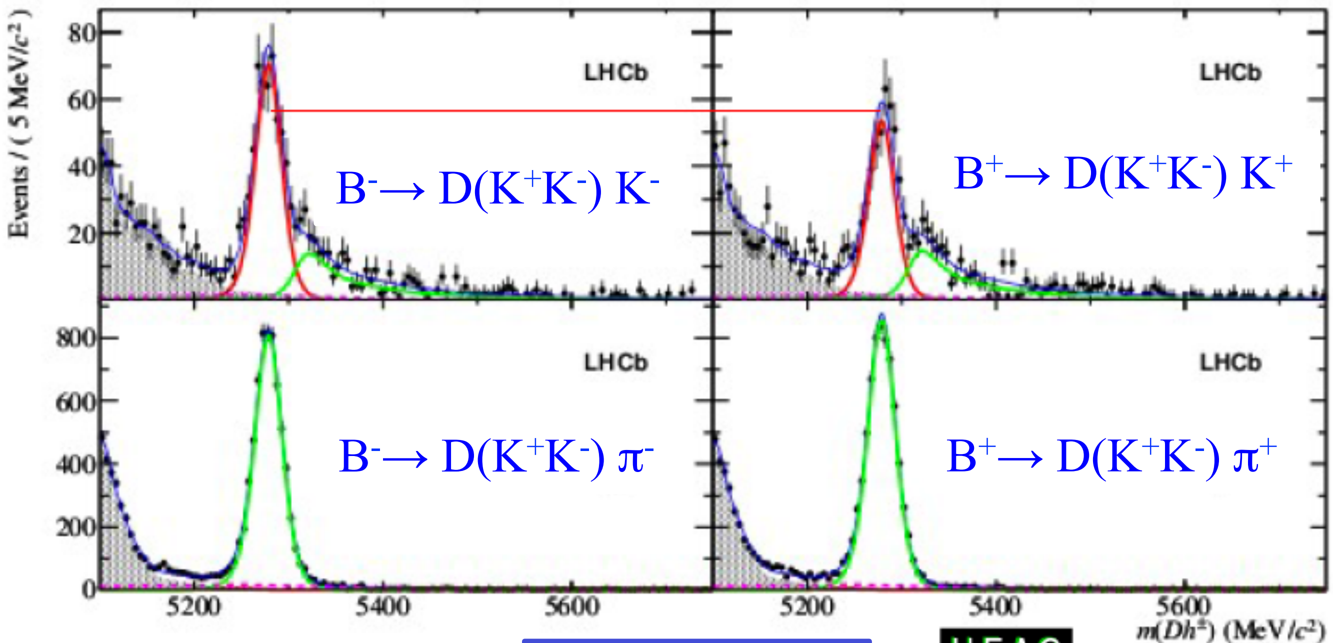
- Theoretical side:
  - Dominant, single tree diagram (suppression of loops)
  - All parameters can be determined from data

- 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

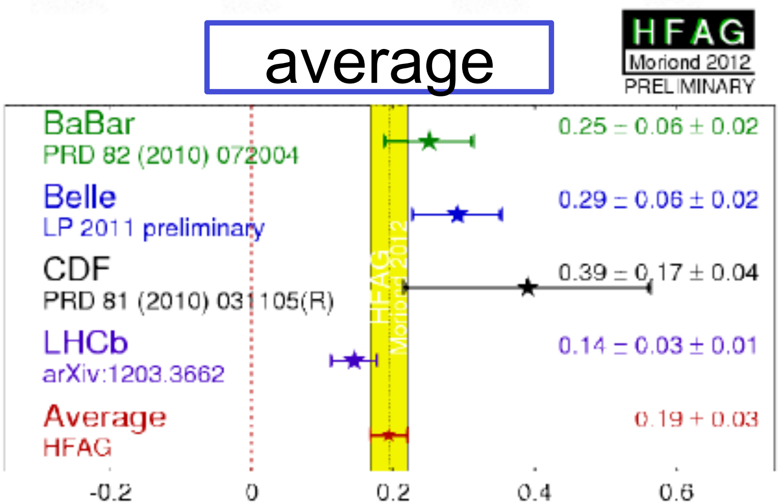
Latest Measurements on B→ D K

Evidence for direct CP violation (y≠0)

PLB 712 (2012) 203



average



Combination of γ measurements

- 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, $R_{K/\pi}$, $r_{K\pi}$, $\delta_{K\pi}$, $A_{CP}^{D\to KK}$, $A_{CP}^{D\to\pi\pi}$
$B^+ \to DK^+$, $D \to K^0_S h^+ h^-$, 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, $\delta_{K\pi}$, $r_{K\pi}$

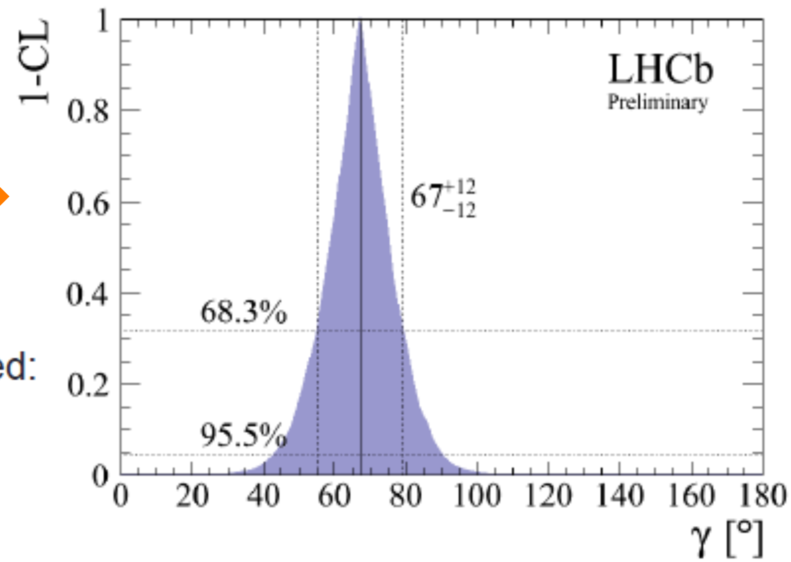
LHCb measurements sensitive to γ

External inputs

- Combine them using a frequentist approach

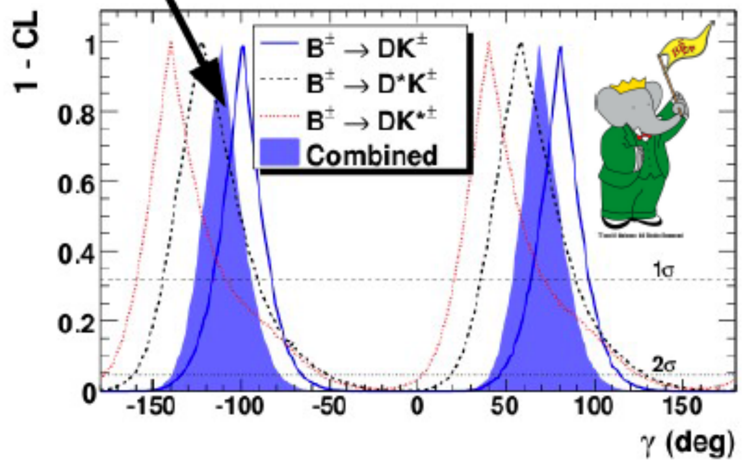
γ from B→DK ADS(1 fb^{-1})/GLW(1 fb^{-1})/GGSZ(3 fb^{-1}) combined:

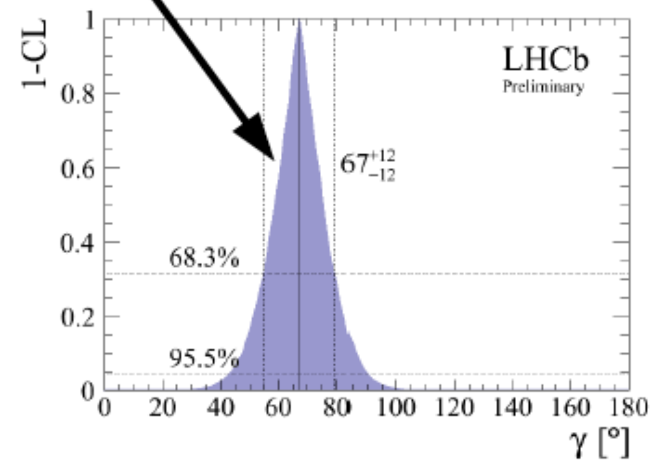
$$\gamma = (67 \pm 12)^\circ$$

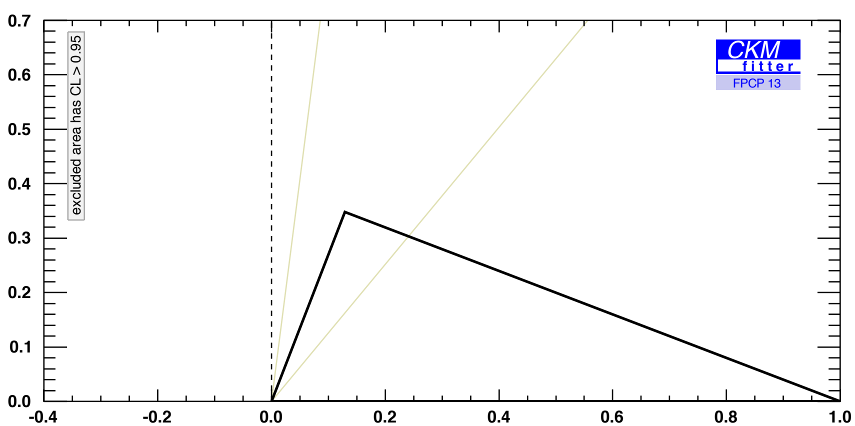


γ only from tree processes

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

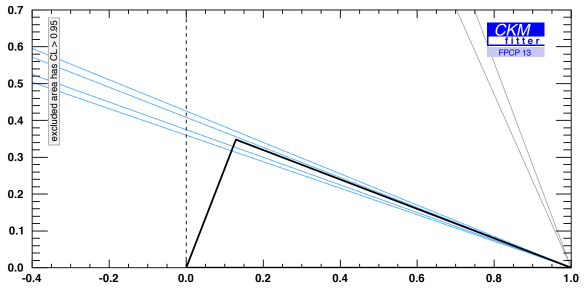




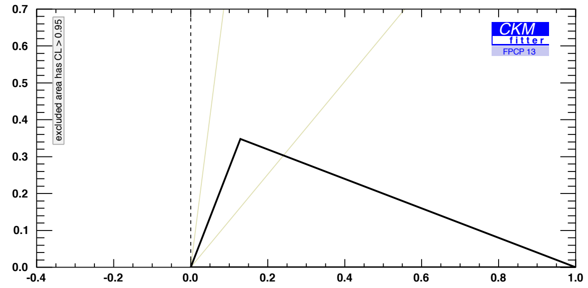


Summary of CKM measurements

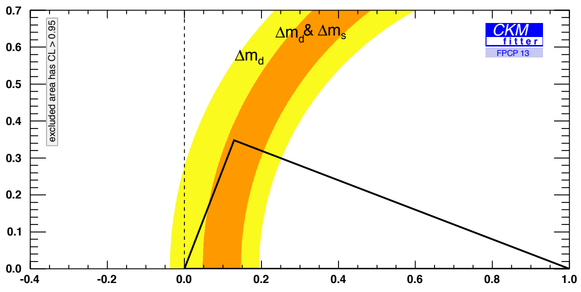
sin 2β



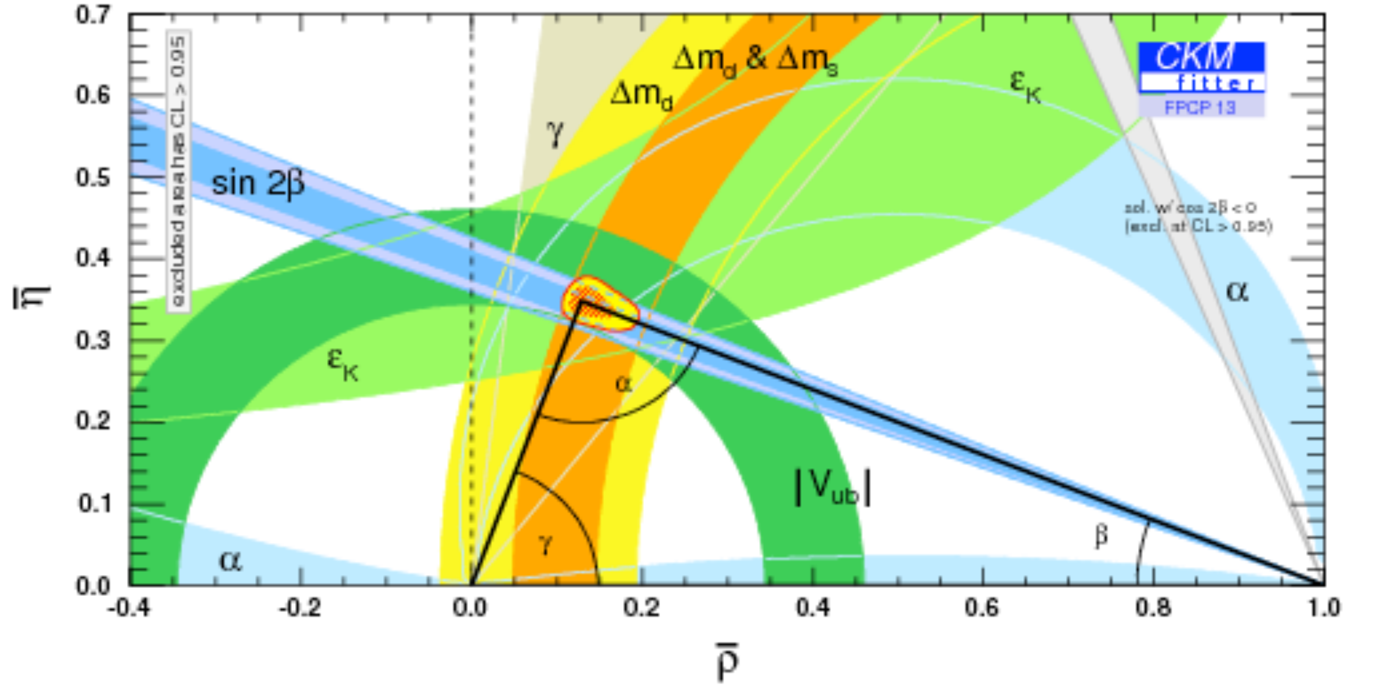
γ



Bs and Bd mixing

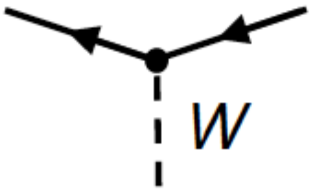


Adding many complimentary measurements



Tree vs loop

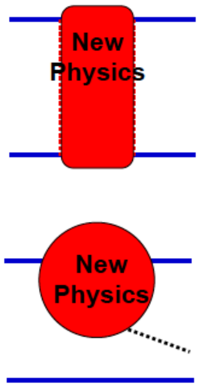
- Tree Processes only



SM dominant
→ no new effects expected

- Loop processes only

New Physics is expected to appear in loops



Tree vs loop

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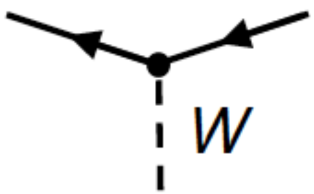
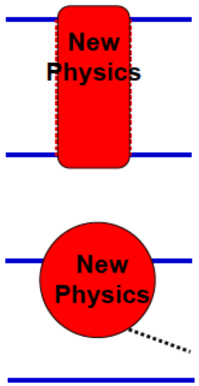


SM dominant
→ no new effects expected

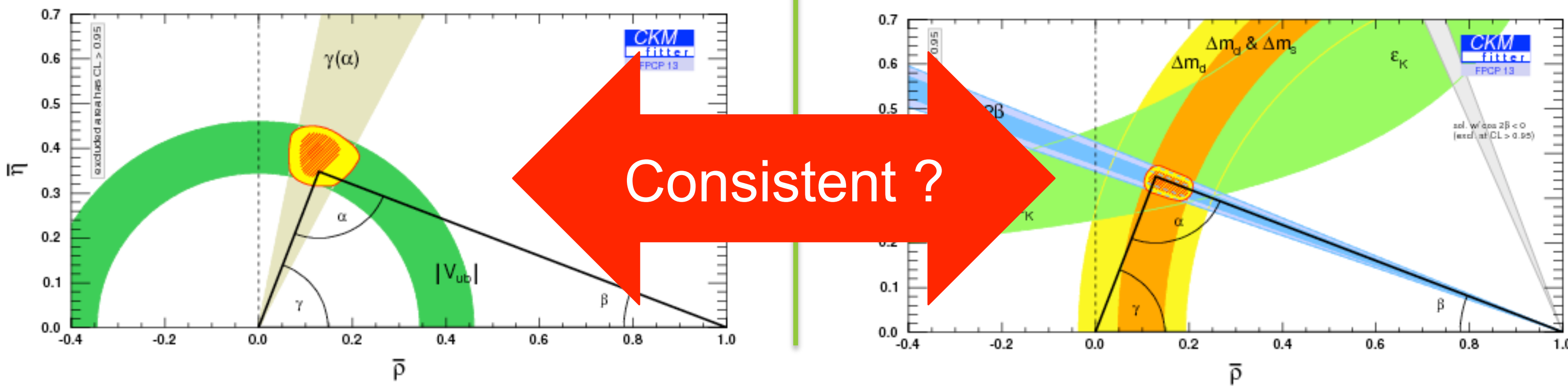
$$\left|V_{ub}/V_{cb}\right|,\ B\to\tau\nu,\ \gamma,\ \pi-\alpha-\beta$$

- Loop processes only

New Physics is expected to appear in loops



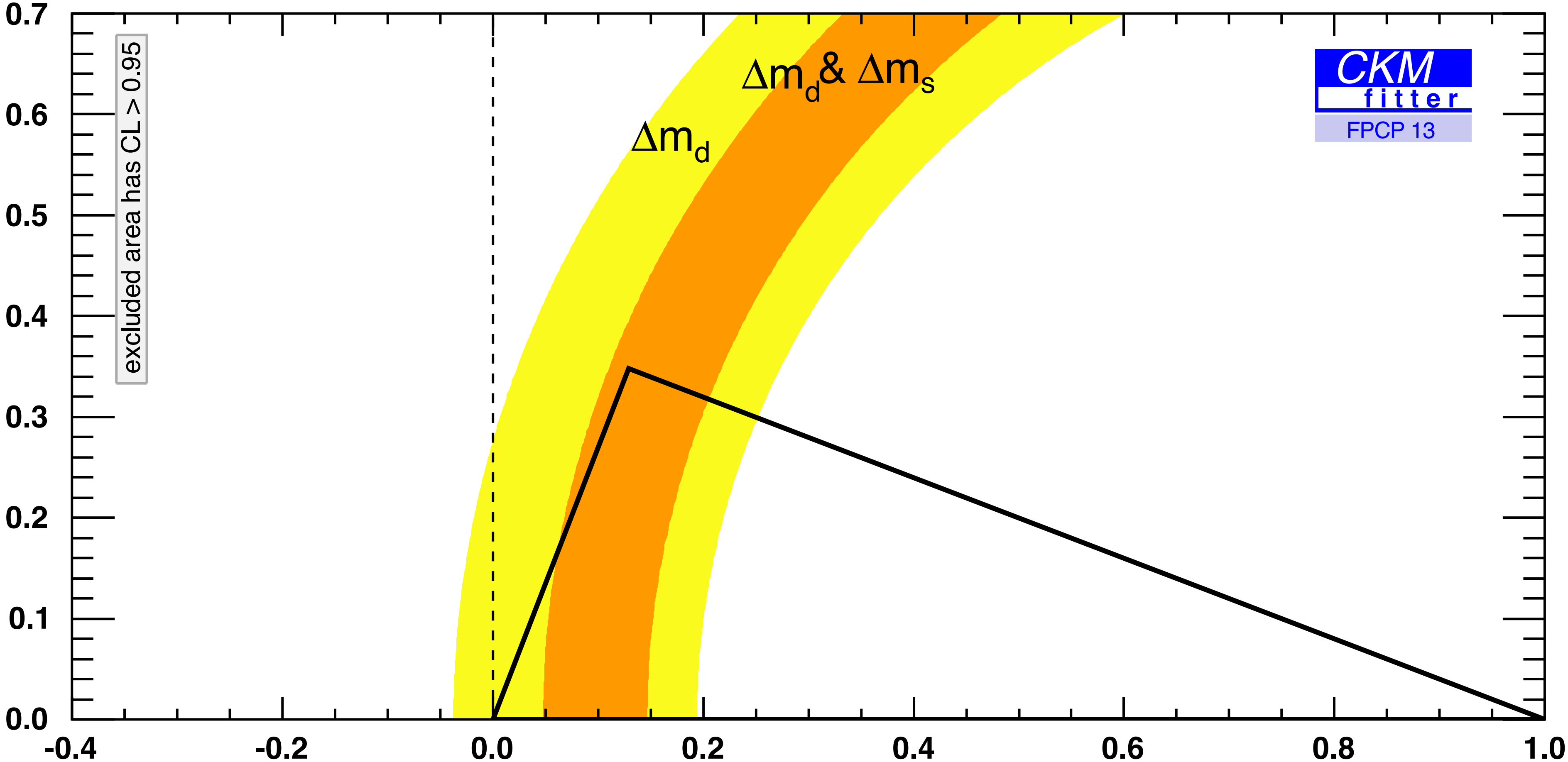
$$\left|\varepsilon_K\right|,\ \sin 2\beta,\ \Delta m_d,\ \Delta m_s$$



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


STOP
AND
THINK

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



Bs mixing

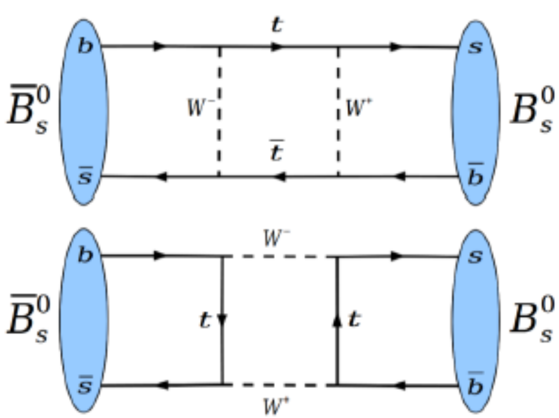
Phenomenological Schroedinger equation describing oscillation and decay

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

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

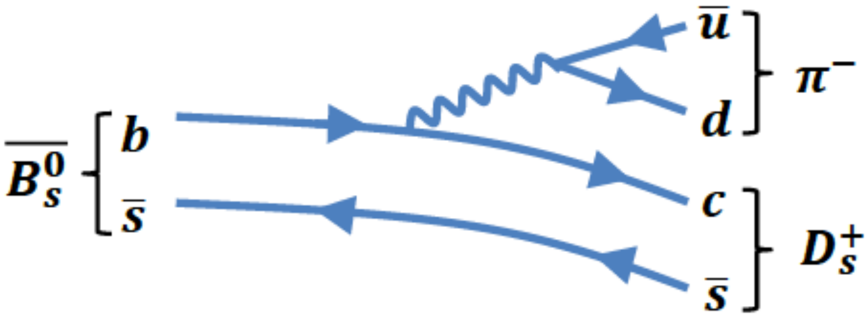
$$B_L\rangle = p|B_s^0\rangle + q|\overline{B_s^0}\rangle$$
$$B_H\rangle = p|B_s^0\rangle - q|\overline{B_s^0}\rangle$$

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



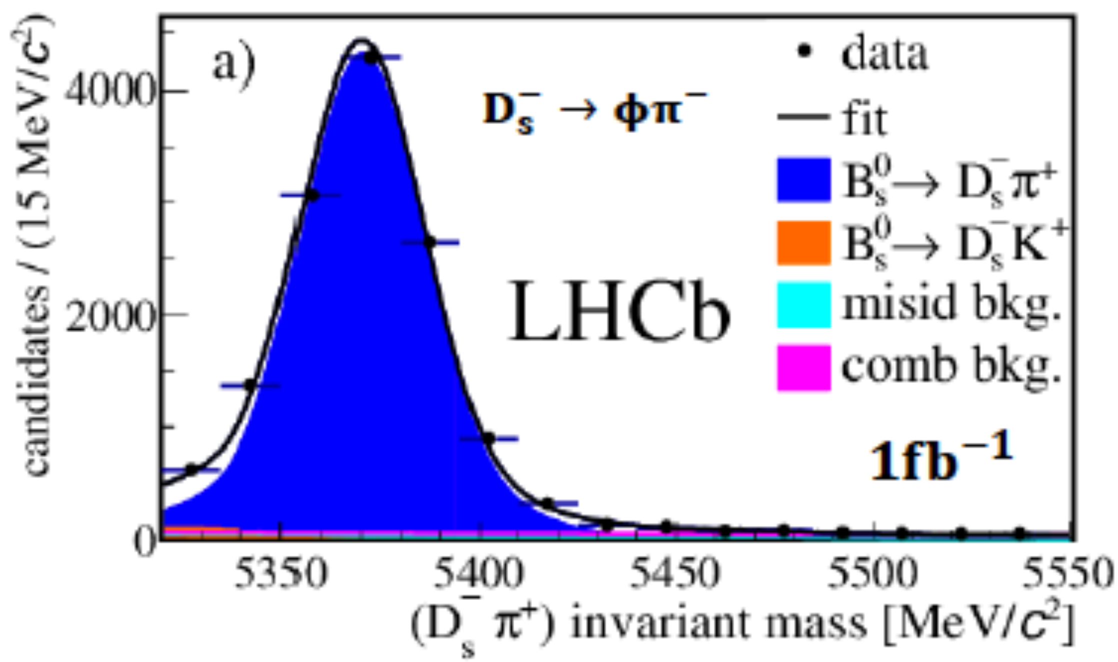
Dominant Feynman diagrams
(Standard Model)

Details in flavour TH lecture by David Straub



New J. Phys. 15 (2013) 053021

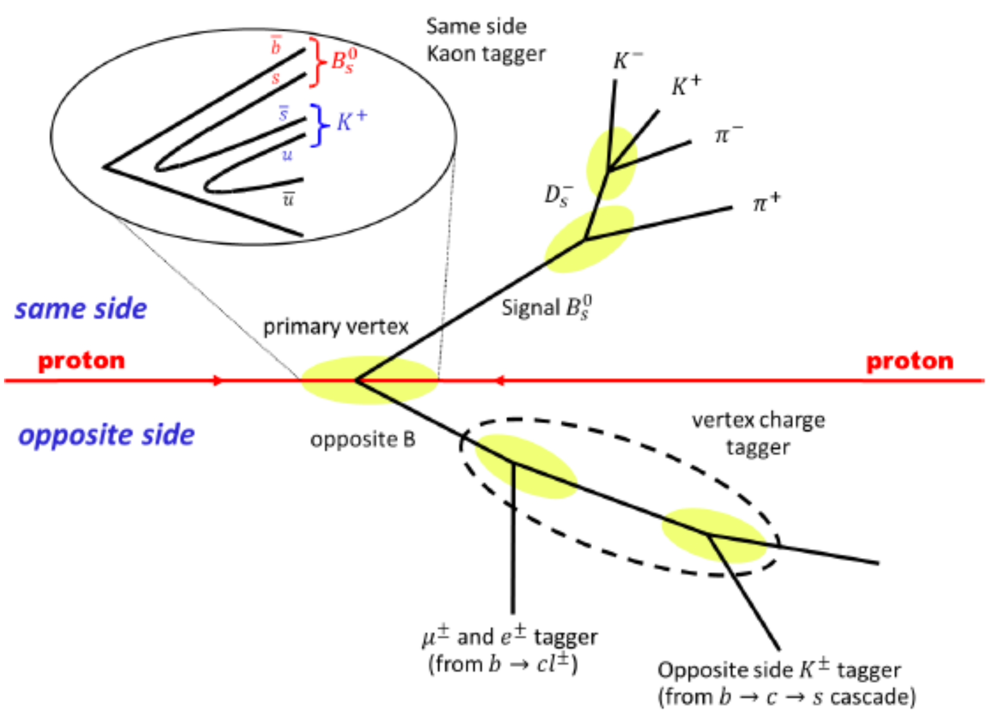
- Very high statistics
- Low background level
- Can resolve B_s mixing frequency due to high boost



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

Flavour tagging at hadron colliders

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



- 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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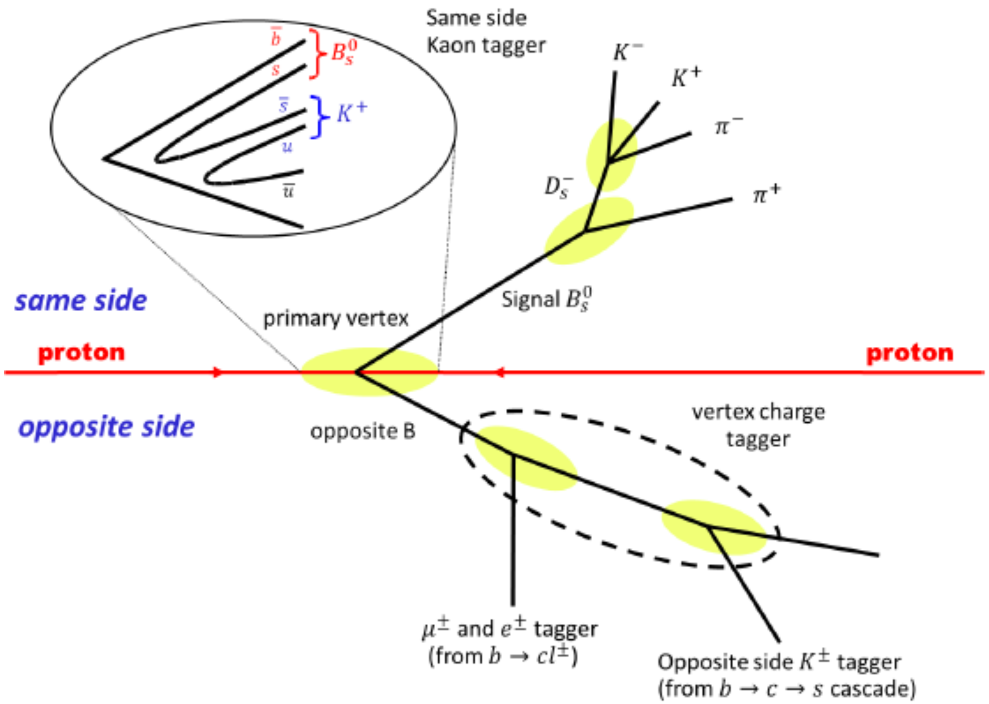

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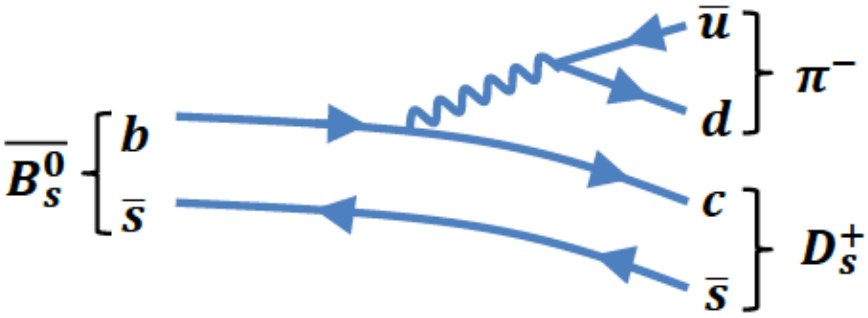
- Combined tagging power (in $B_s^0 \to D_s^- \pi^+$)
  - $\varepsilon D^2 = 3.5 \pm 0.5\%$

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

Δm_s from $B_s \rightarrow D_s \pi^+$



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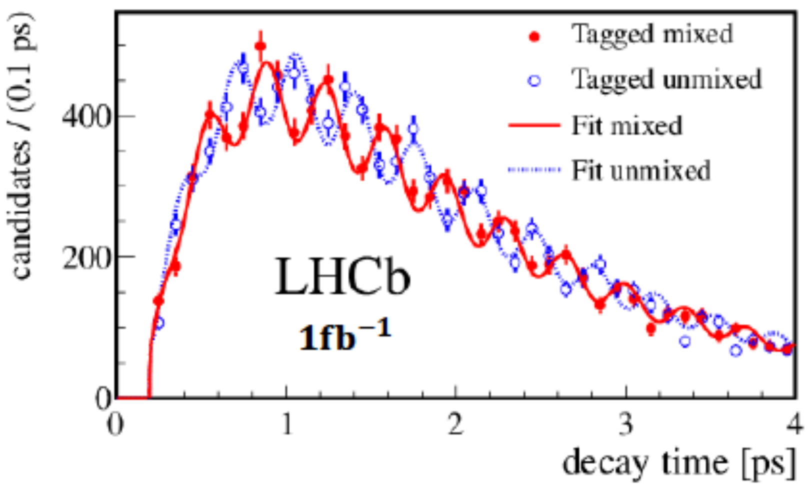

Uses flavour tagging:
opposite side (*Eur.Phys.J. C72(2012) 2022*)
same side (LHCb-CONF-2012-033)

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

$B_{s,d}$ mixing and the CKM matrix

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.