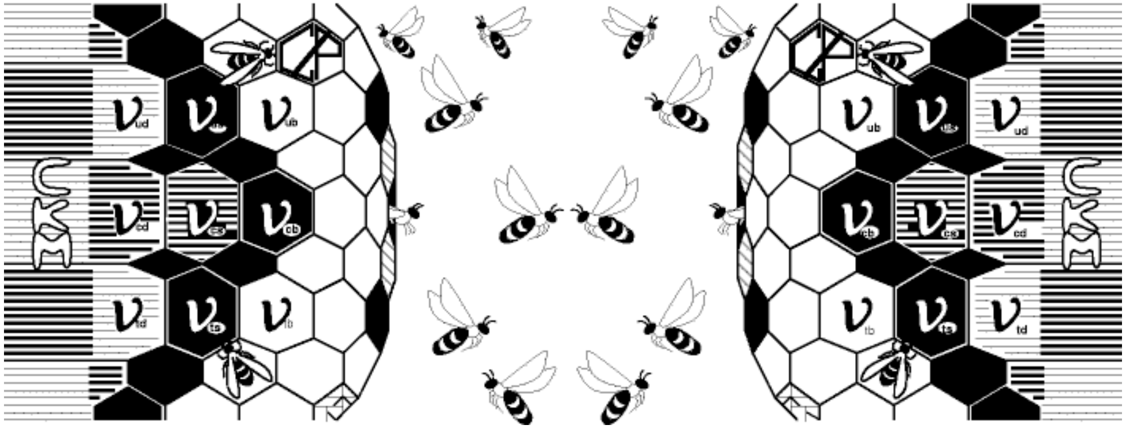
Quark Flavor Physics



February 6, 2018
Yury Kolomensky

CLEO

BABAR

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BELLE

CDF II

LHCb

Contents

- Flavor transitions in quark sector
  - ❑ CKM Matrix
    - ☞ Magnitudes of CKM elements: branching fractions
  - ❑ Phases in CKM matrix
    - ☞ CP violation (mostly B_d and B_s decays)
  - ❑ Rare and forbidden processes: sensitivity to new physics
- Extremely rich and vibrant field
  - ❑ Hundreds of measurements in the PDG booklet
    - ☞ Will only cover key issues today

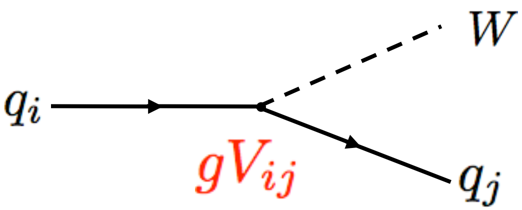
Why Precision Flavor Physics ?

- Core properties of weak interactions
  - ❑ Parameters not predicted within the Standard Model
    - ☞ Mass hierarchy
    - ☞ Mixing between generations
    - ☞ Need measurements !
  - ❑ Rich phenomenology with few parameters
    - ☞ Standard Model measurements: the foundation
    - ☞ Deviations: new physics searches
- LHC era: discoveries (or lack thereof) at the energy frontier
  - ❑ Flavor physics provides important interpretation

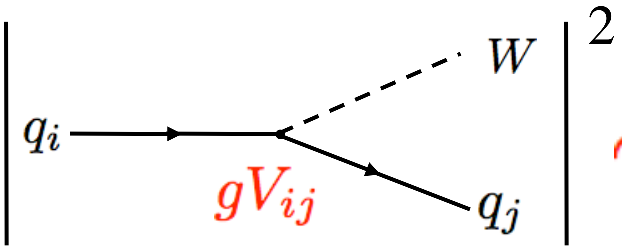
CP Symmetry Violation

- C,P,T: Discrete transformations of the Lagrangian
  - P: parity reversal
  - C: charge conjugation
  - T: time reversal
- Any field theory Lagrangian is invariant under CPT
  - EM and strong interactions conserve all 3 symmetries
  - Weak interactions violate parity, but CP and T are approximately conserved
  - CP symmetry is broken if Lagrangian has complex couplings

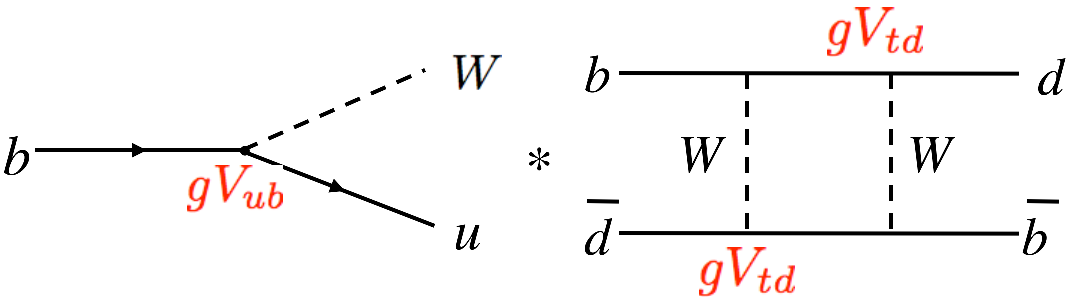
Cabibbo-Kobayashi-Maskawa Matrix



$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{td} \end{pmatrix}$$



$\sim |V_{ij}|^2$ Measure magnitudes from rates:



$\sim e^{i\arg(V_{td}^2 V_{ub})}$

Measure phases through interference: CP violation. Need at least two amplitudes, e.g. 2 decay amplitudes (“direct CPV”), or decay and mixing

CKM Matrix

Unitary mixing matrix: 4 parameters (e.g. 3 angles, 1 phase)
For quarks, conventional Wolferstein parameterization:

$$A,\ \rho,\ \eta \sim \mathcal{O}(1),\ \ \lambda \equiv \sin\theta_c \approx 0.22$$

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

Aside: number of free parameters in a unitary mixing matrix is $(n-1)^2$, so 2-flavor mixing does not have any phases. 3-flavor mixing produces a new phenomenon: CP violation

Nobel Prizes in Physics

Yoichiro
Nambu

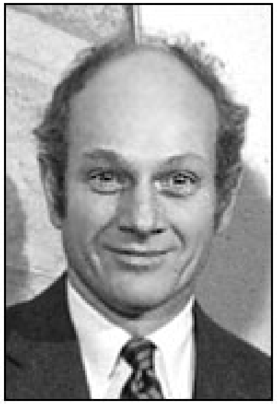
Makoto
Kobayashi

Toshihide
Maskawa

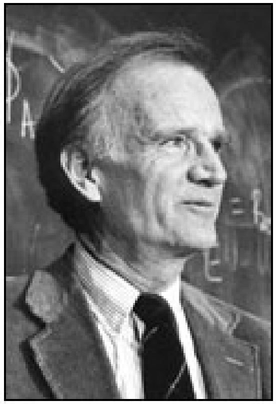
2008: Kobayashi-Maskawa:

"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"

Omitted but not forgotten:
Nicola Cabibbo
(1935-2010)



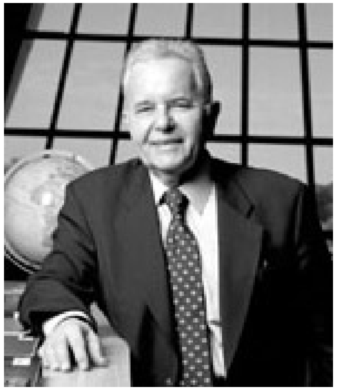
James
Cronin



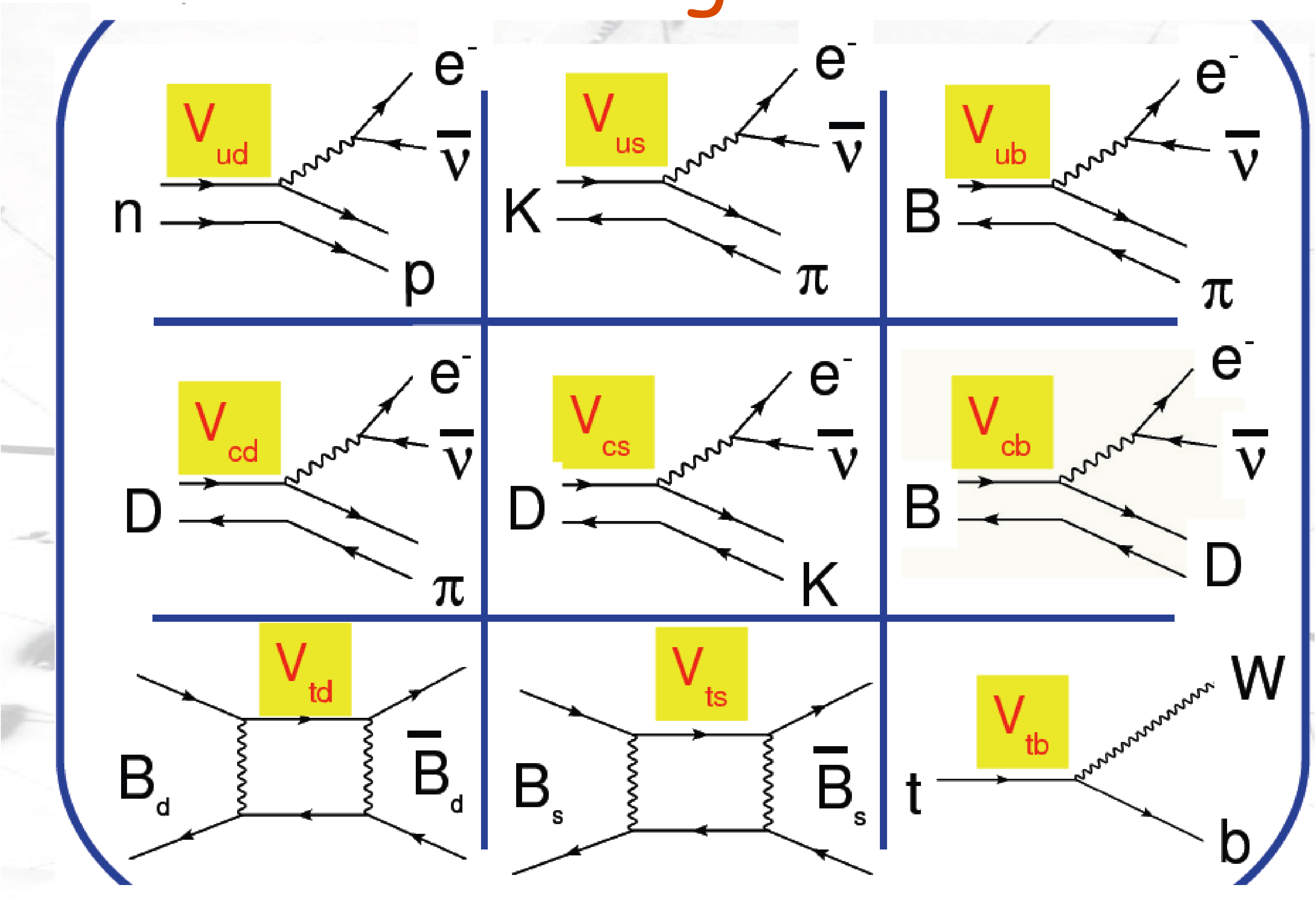
Val
Fitch

1980: Cronin-Fitch

"for the discovery of violations of fundamental symmetry principles in the decay of neutral K-mesons"

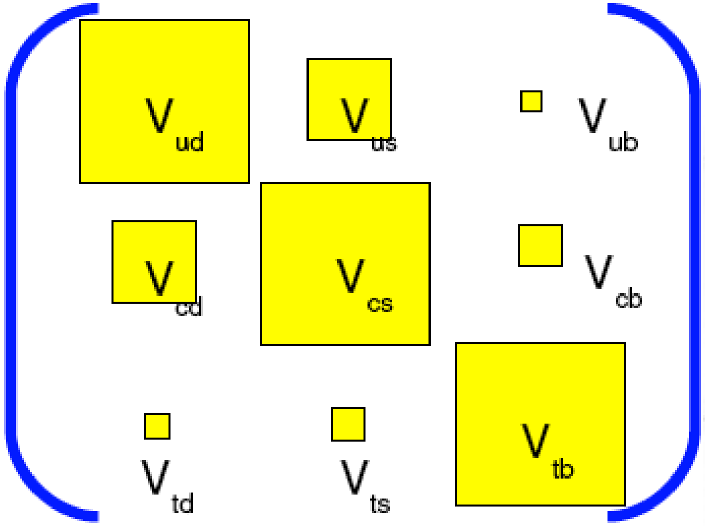


CKM Magnitudes



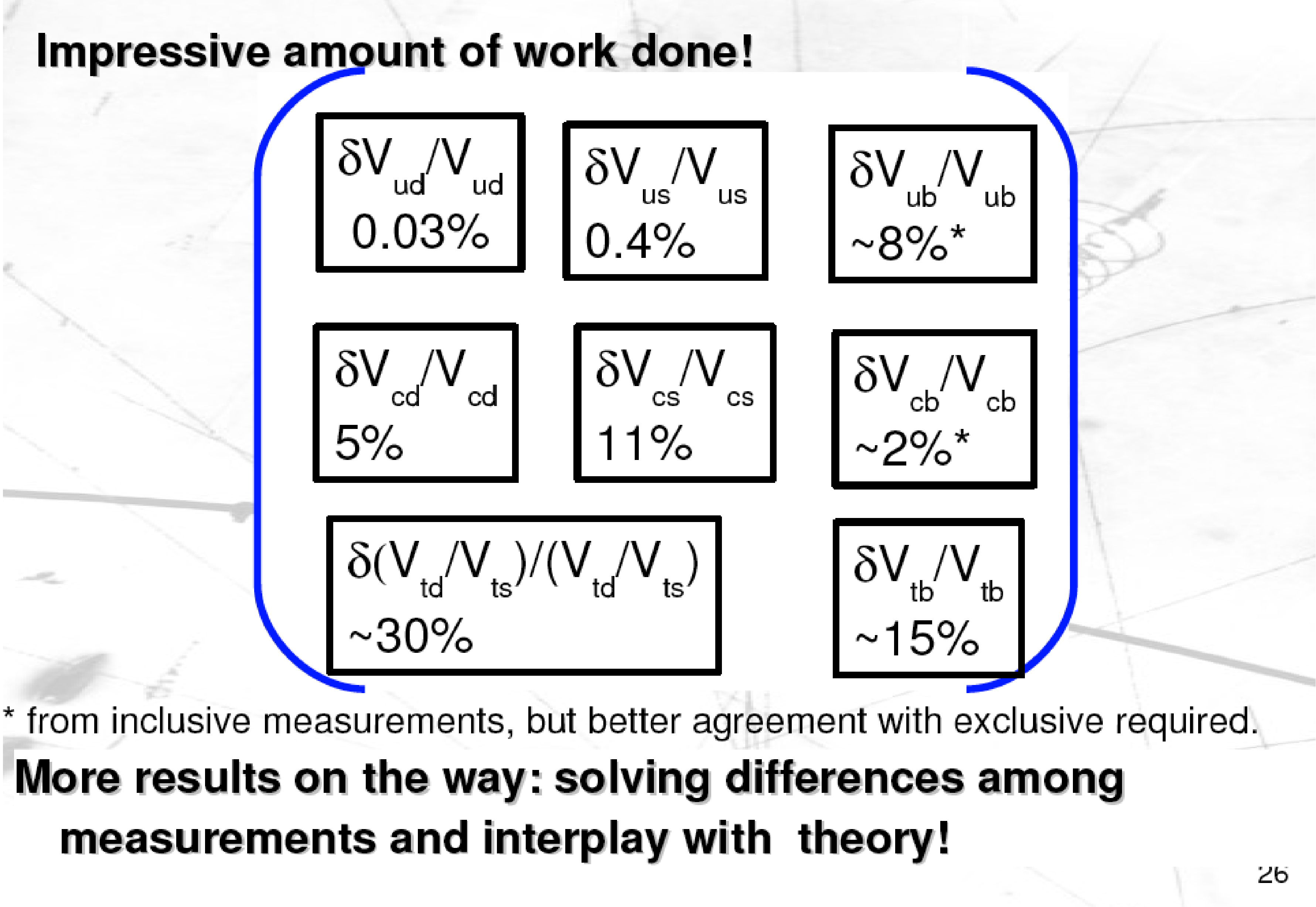
Slides from F. Di Lodovico @ ICHEP2008

Roadmap



- First row
  - $|V_{us}|$
    - Kaon decays (KLOE)
    - τ decays (BaBar, Belle)
  - $|V_{ub}|$ (BaBar, Belle)
- Second row
  - $|V_{cd}|$, $|V_{cs}|$ (CLEO-c)
  - $|V_{cb}|$ (BaBar, Belle)
- Third row
  - $|V_{td}|$, $|V_{ts}|$ (CDF, D0, BaBar, Belle)
  - $|V_{tb}|$ (CDF, D0)

Summary of CKM Magnitudes



Impressive amount of work done!

$\delta V_{ud}/V_{ud}$ 0.03%	$\delta V_{us}/V_{us}$ 0.4%	$\delta V_{ub}/V_{ub}$ ~8%*
$\delta V_{cd}/V_{cd}$ 5%	$\delta V_{cs}/V_{cs}$ 11%	$\delta V_{cb}/V_{cb}$ ~2%*
$\delta(V_{td}/V_{ts})/(V_{td}/V_{ts})$ ~30%		$\delta V_{tb}/V_{tb}$ ~15%

* from inclusive measurements, but better agreement with exclusive required.

More results on the way: solving differences among measurements and interplay with theory!

Matter and Antimatter in the Universe

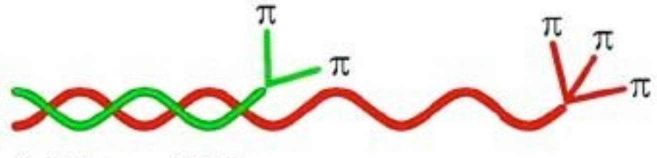
- Matter-antimatter asymmetry is one of the great cosmological puzzles

❑ Need CP violation and baryon number violation to create asymmetry from symmetric early Universe

☞ Standard Model effects do not generate enough matter-antimatter imbalance observed today

☞This is perhaps a hint to search for new physics in CP sector

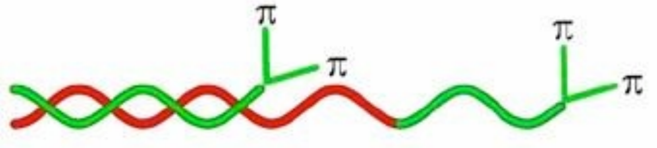
Mixing and CP Violation



(a) Kaon Mixing

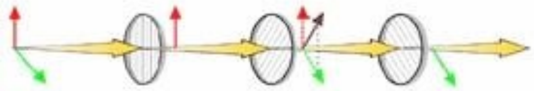
$$|K_S\rangle = p|K^0\rangle + q|\overline{K^0}\rangle$$
$$|K_L\rangle = p|K^0\rangle - q|\overline{K^0}\rangle$$

$$\Rightarrow \quad K^0 \longleftrightarrow \bar{K}^0$$

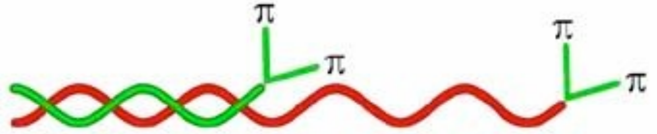


(b) Indirect CP Violation

$$|p/q| \neq 1$$



(c) Polarized Light Analogy



(d) Direct CP Violation

$$|\overline{A}_{\overline{f}_{CP}}/A_{f_{CP}}| \neq 1$$

Interference between mixing and decay:

$$\lambda_{CP} = \eta_{CP}\,\frac{q}{p}\,\frac{\overline{A}_{\overline{f}_{CP}}}{A_{f_{CP}}}$$
$$|\lambda_{CP}| = 1,\; Im\,\lambda_{CP} \neq 0$$

System of Neutral B mesons

- In B system, mass difference between two eigenstates is significant, lifetime difference is not
  - ❑ Define "Light" and "Heavy" states instead of "Long" and "Short"

$$\frac{\Delta m_d}{\Gamma_d} = \frac{M_H - M_L}{\Gamma_d} \equiv x_d = 0.730 \pm 0.029$$

$$\frac{\Delta\Gamma_d}{\Gamma_d} = \mathcal{O}(10^{-2})$$

☞ For B mesons

$$\frac{q}{p} = -\frac{\Delta m_d - i/2\Delta\Gamma_d}{2(M_{12} - i/2\Gamma_{12})}$$ and $|q/p| \sim 1$

- Direct CP violation is predicted to be small, hence

$|\lambda_{CP}| \sim 1$

Unitarity Triangle

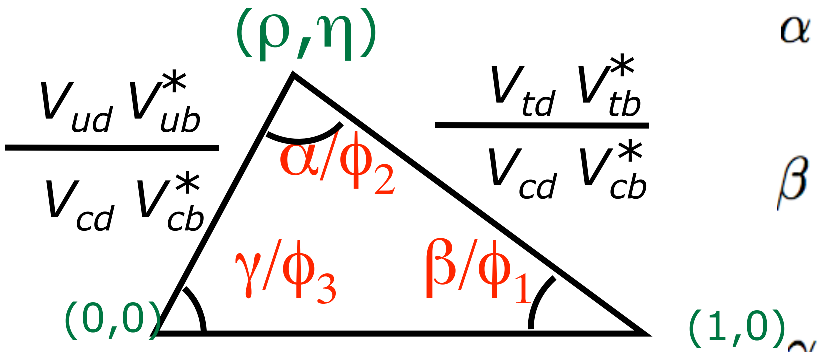
Unitary mixing matrix: 4 parameters (*c.f.* MNSP matrix in neutrinos)

For quarks, conventional Wolferstein parameterization:

$$A,\ \rho,\ \eta \sim \mathcal{O}(1),\ \ \lambda \equiv \sin\theta_c \approx 0.22$$

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

$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$: unitarity relation for B_d decays



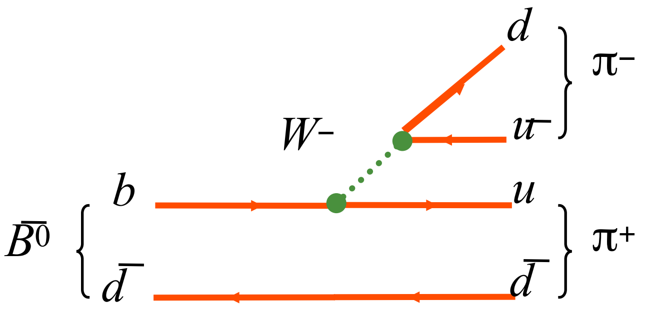
$\alpha \equiv \arg\left[-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right]$: interfere b→u & mixing

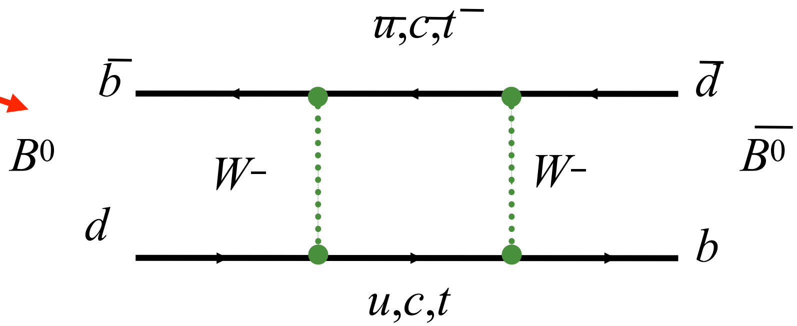
$\beta \equiv \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right]$: interfere b→c & mixing

$\gamma \equiv \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$: interfere b→u & b→c

CP violating observables for B mesons

- Need at least two amplitudes with different phases
- In B decays, we can consider two different types of amplitudes:
  - ❑ Those responsible for **decay**
  - ❑ Those responsible for **mixing**





- This gives rise to three possible manifestations of CP violation:
  - ❑ **Direct *CP* violation**
    - (interference between two decay amplitudes)
  - ❑ **Indirect *CP* violation**
    - (interference between two mixing amplitudes)
  - ❑ ***CP* violation in the interference between mixed and unmixed decays**

Common Definitions

CP violation in interference between decays with and without mixing

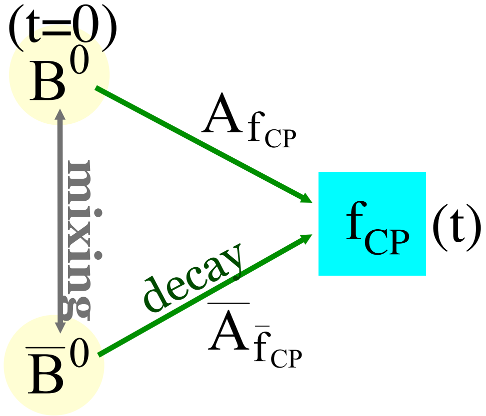
$$\lambda_{f_{CP}} = \eta_{CP}\underbrace{\frac{q}{p}\cdot\frac{\bar{A}_{\bar{f}_{CP}}}{A_{f_{CP}}}}_{\approx e^{-2i\phi_{CP}}}$$

amplitude ratio

CP eigenvalue

CP phase

$\eta_{CP} = \pm 1; \quad \phi_{CP} = \alpha, \beta, \gamma$



Time-dependent *CP* Observable:

$$A_{f_{CP}}(t) = \frac{\Gamma(\bar{B}^0_{phys}(t) \to f_{CP}) - \Gamma(B^0_{phys}(t) \to f_{CP})}{\Gamma(\bar{B}^0_{phys}(t) \to f_{CP}) + \Gamma(B^0_{phys}(t) \to f_{CP})}$$

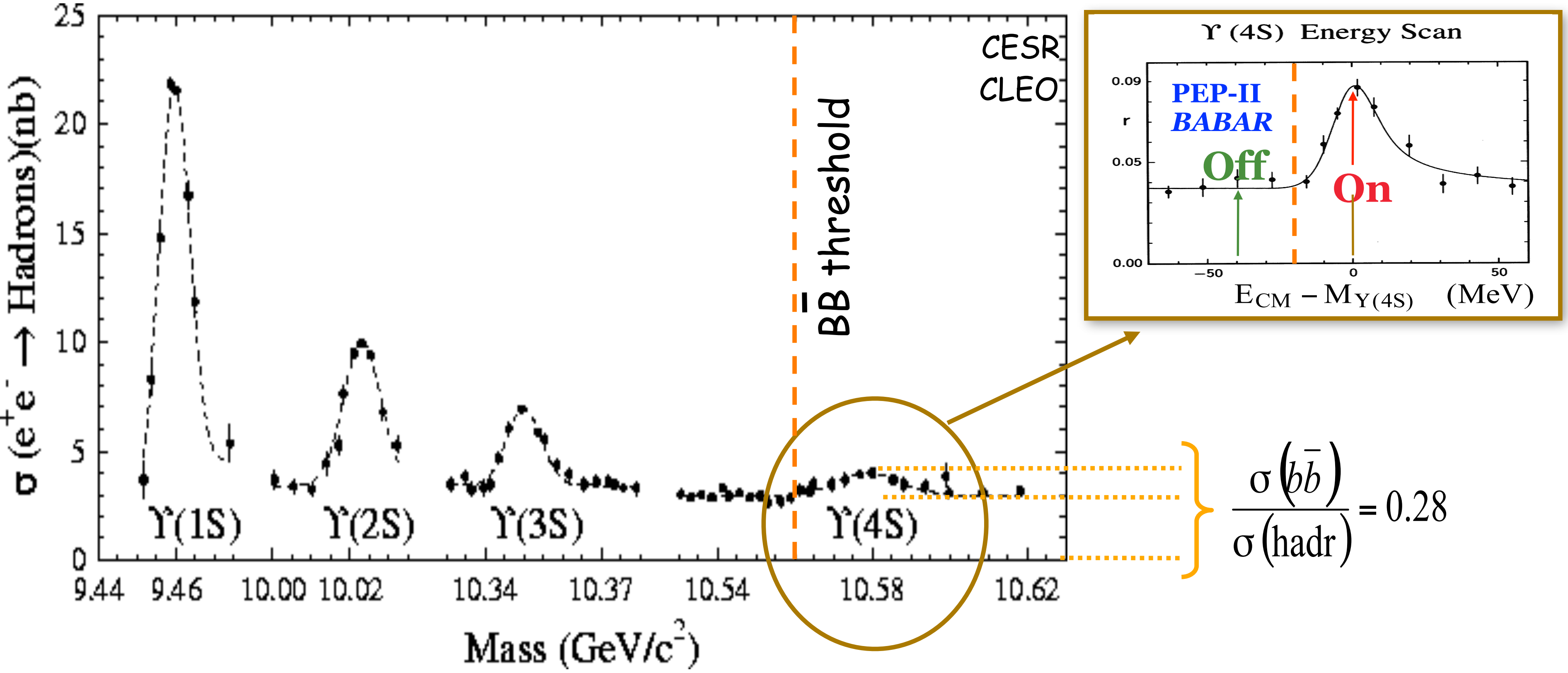
$$= C_{f_{CP}} \cdot \cos(\Delta m_{B_d} t) + S_{f_{CP}} \cdot \sin(\Delta m_{B_d} t)$$

$$\boxed{\begin{aligned} C_{f_{CP}} &= \frac{1 - |\lambda_{f_{CP}}|^2}{1 + |\lambda_{f_{CP}}|^2} \\ S_{f_{CP}} &= \frac{-2\,\mathrm{Im}\lambda_{f_{CP}}}{1 + |\lambda_{f_{CP}}|^2} \end{aligned}}$$

B Meson Production

- Electron-Positron collider: $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B^0\bar{B}^0$
  - ❑ Only 4s resonance can produce B meson pair
  - ❑ B^0 production cross-section: ~1 nb (1 fb^{-1} ~ 1M B^0 decays)
  - ❑ Clean environment, *coherent* B^0B^0 production

B-Factory approach



$$\frac{\sigma(b\bar{b})}{\sigma(hadr)} = 0.28$$

Υ(4S): Coherent $B^0\overline{B}{}^0$ production

- $B^0\overline{B}{}^0$ system evolves coherently until one of them decays
  - ❑ *CP*/Mixing oscillation clock only starts ticking at the time of the first decay, relevant time parameter Δt:

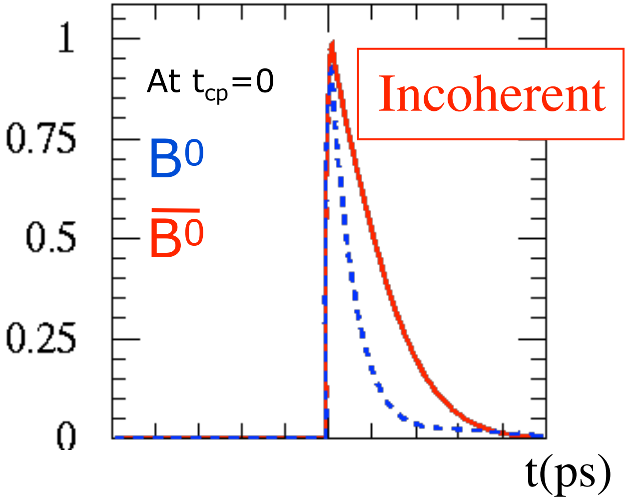
$$\Delta t = t_{CP} - t_{\mathrm{OtherB}}$$

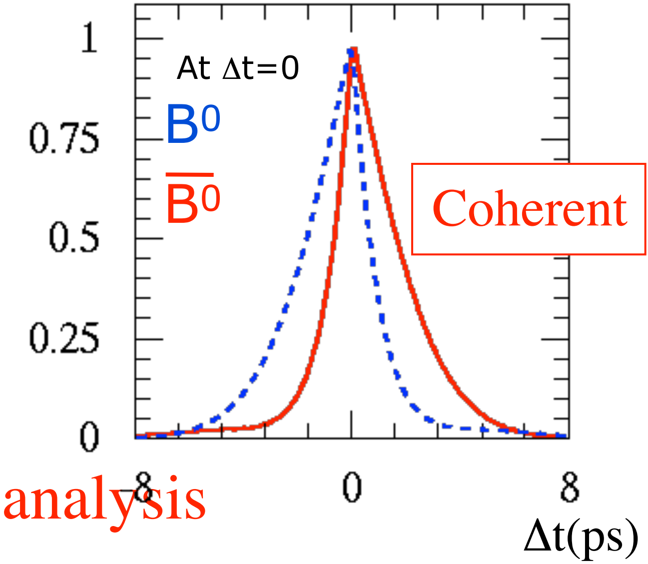
☞ B mesons have opposite flavor at time Δt=0

☞ Half of the time *CP* B decays first (Δt<0)

- Integrated CP asymmetry is 0:

$$\int_{-\infty}^{+\infty} F(t)\ dt = \int_{-\infty}^{+\infty} \overline{F}(t)\ dt$$



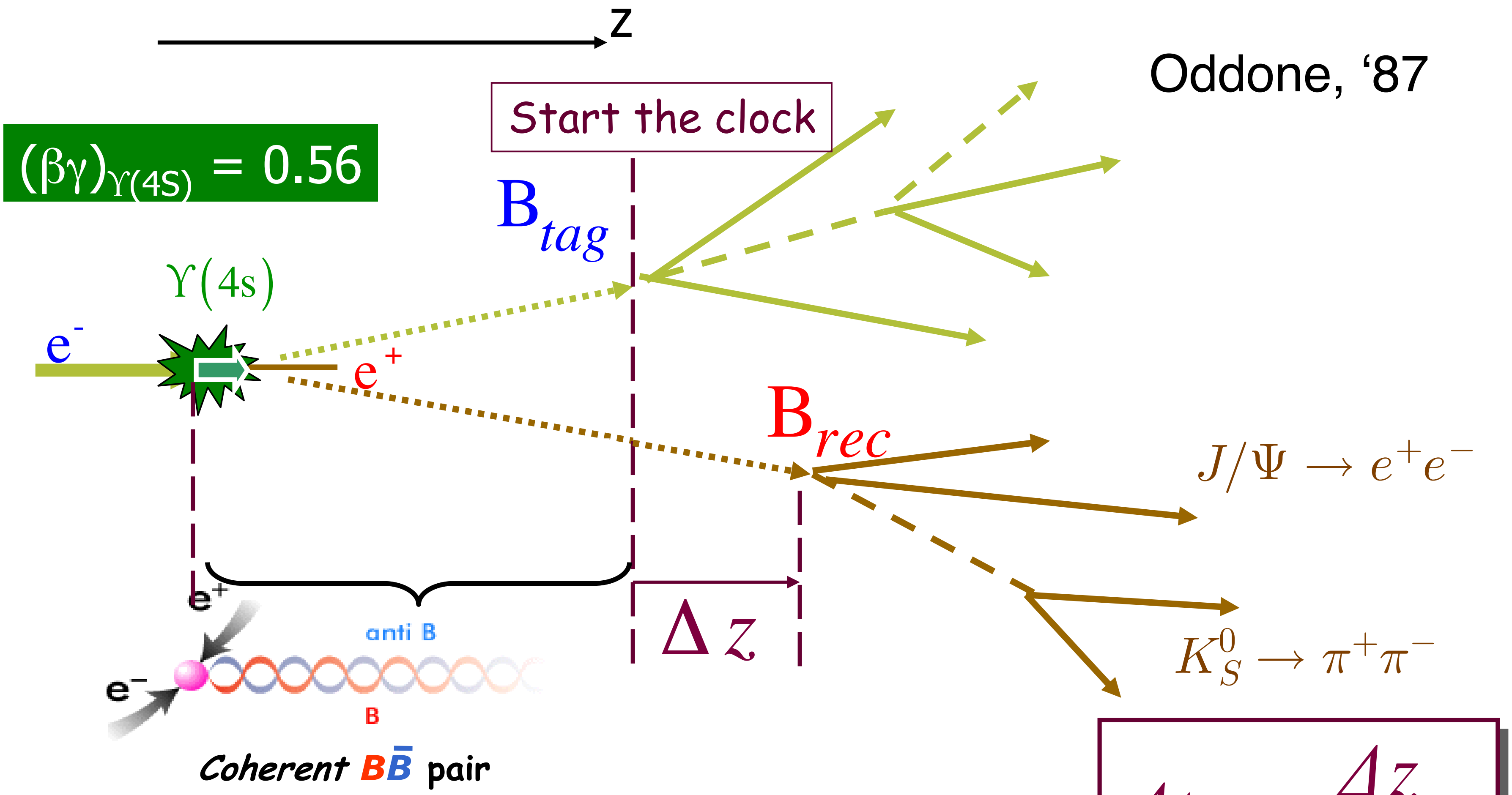


→ Coherent production *requires* time-dependent analysis

The Asymmetric B Factory Concept

Oddone, '87

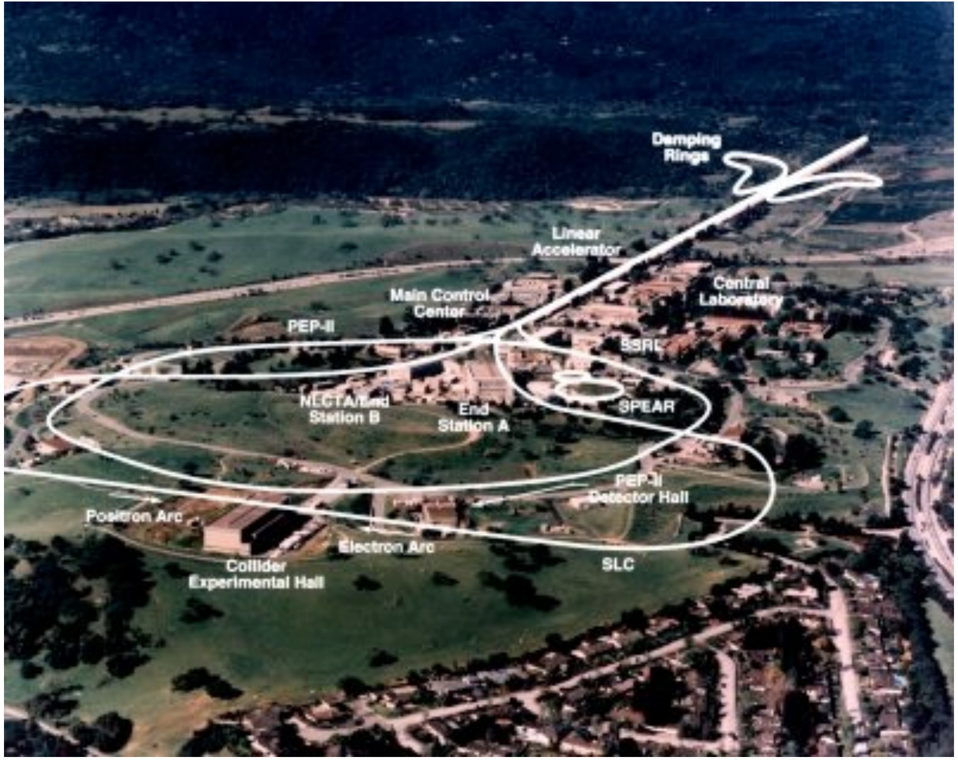
$(\beta\gamma)_{\Upsilon(4S)} = 0.56$



$$\langle|\Delta z|\rangle \approx \beta\gamma c\tau_B = 260\mu\text{m}$$

$$\boxed{\Delta t \approx \frac{\Delta z}{<\beta\gamma>c}}$$

PEP-II Asymmetric B Factory @ SLAC

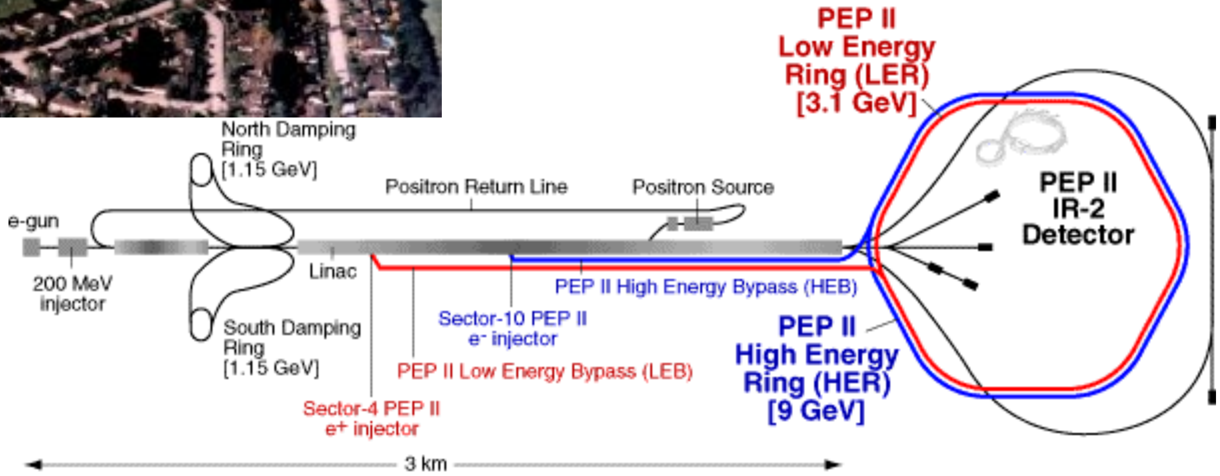


9GeV e^- on 3.1GeV e^+ :

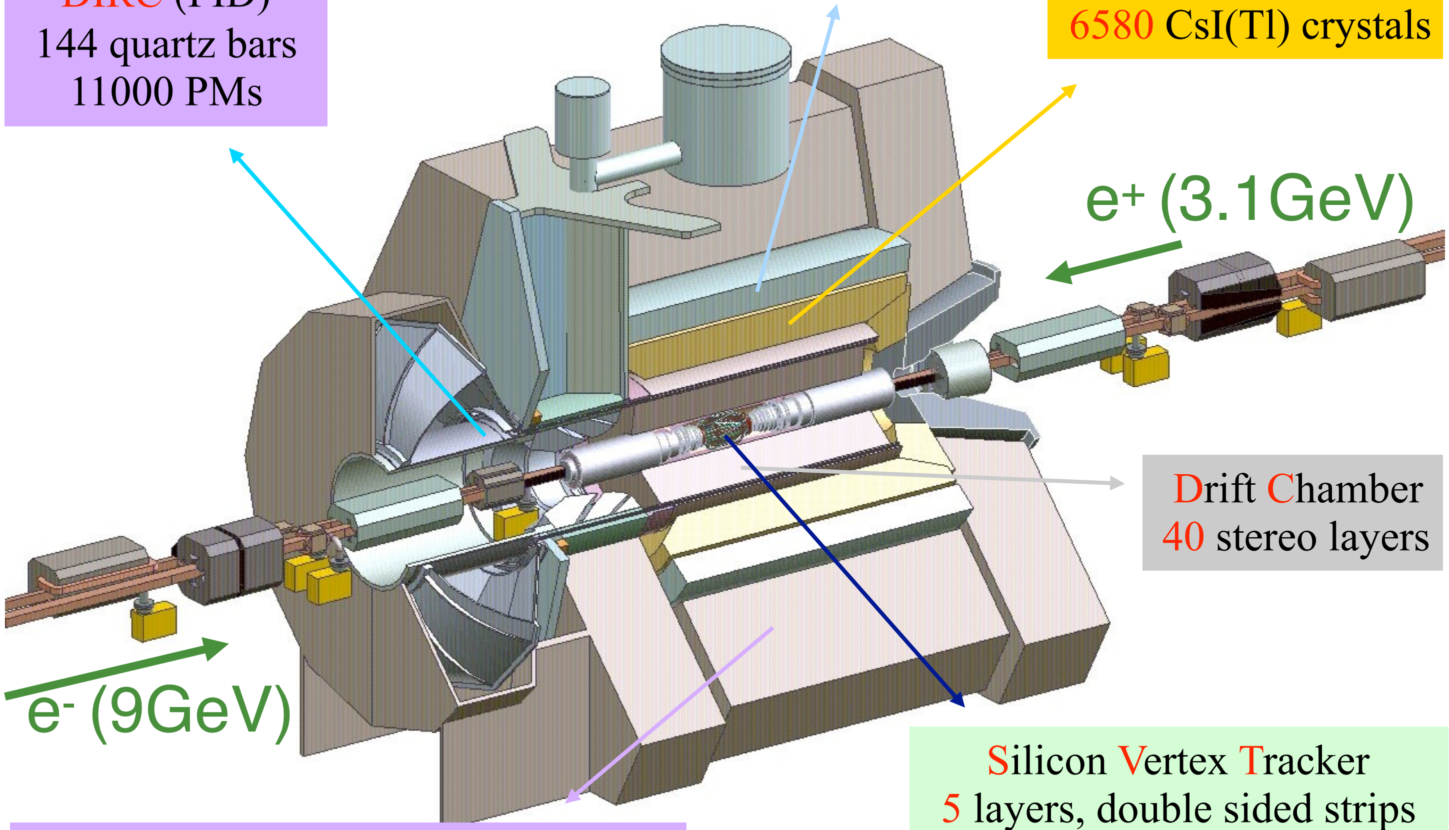
$$e^+e^- \to \Upsilon(4S) \to B^0\overline{B^0}$$

- **boost of Y(4S)**

in lab frame : $\beta\gamma=0.56$



BaBar Detector



DIRC (PID)
144 quartz bars
11000 PMs

1.5T solenoid

EMC
6580 CsI(Tl) crystals

e^+ (3.1GeV)

Drift Chamber
40 stereo layers

e^- (9GeV)

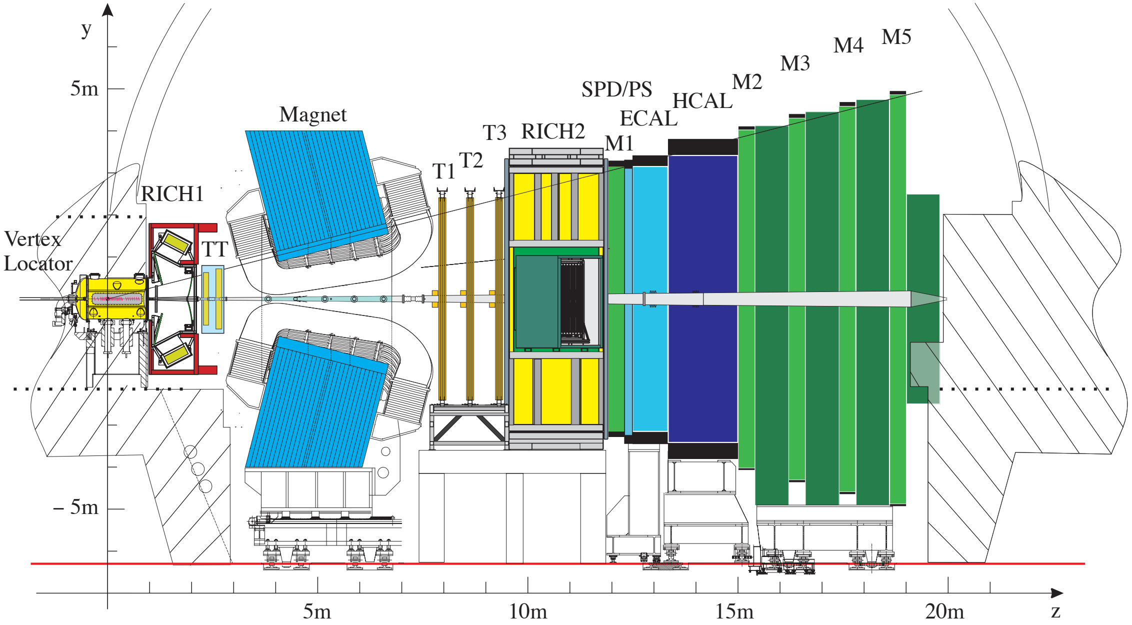
Silicon Vertex Tracker
5 layers, double sided strips

Instrumented Flux Return
iron / RPCs (muon / neutral hadrons)

LHCb Detector

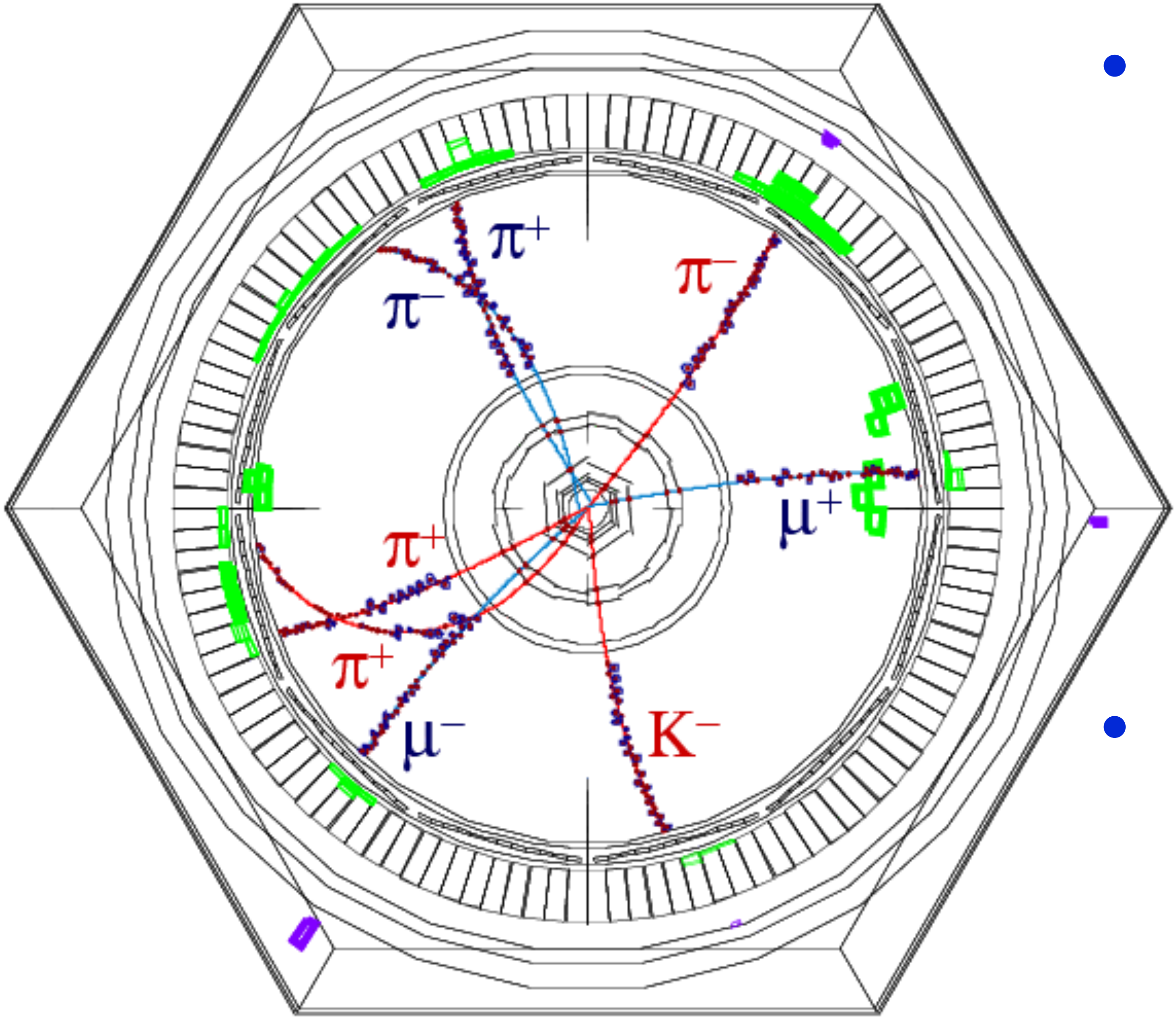
[JINST 3 (2008) S08005]

- Acceptance 2<η<5, with excellent vertexing, tracking, PID
- $\mathcal{L}_{\rm int} = 1\ \mathrm{fb}^{-1}$ @ 7 TeV in 2011, & 2 fb^{-1} @ 8 TeV in 2012



Vertex Locator	$\sigma_{\rm PV,x/y} \sim 10\ \mu$m, $\sigma_{\rm PV,z} \sim 60\ \mu$m
Tracking (TT, T1-T3)	$\Delta p/p$: 0.4% at 5 GeV/c, to 0.6% at 100 GeV/c
RICHs	$\varepsilon(K \to K) \sim 95\%$, mis-ID rate $(\pi \to K) \sim 5\%$
Muon system (M1-M5)	$\varepsilon(\mu \to \mu) \sim 97\%$, mis-ID rate $(\pi \to \mu) = 1-3\%$
ECAL	$\sigma_E/E \sim 10\%/\sqrt{E} \oplus 1\%$ (E in GeV)
HCAL	$\sigma_E/E \sim 70\%/\sqrt{E} \oplus 10\%$ (E in GeV)

Example of a Fully Reconstructed Event



- $B^0 \to \psi(2S)\ \ K_s$

  ↳ $\mu^+\mu^-$ ↳ $\pi^+\pi^-$

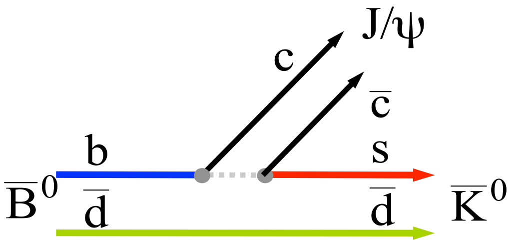
One of ~500 million recorded decays

- $\bar{B}^0 \to D^{*+}\pi^-$

  ↳ $D\pi^+$

  ↳ $K^-\pi^+$

Angle β/ϕ_1 : "Golden" Channel $b\to c\bar{c}s$



S=sin2β

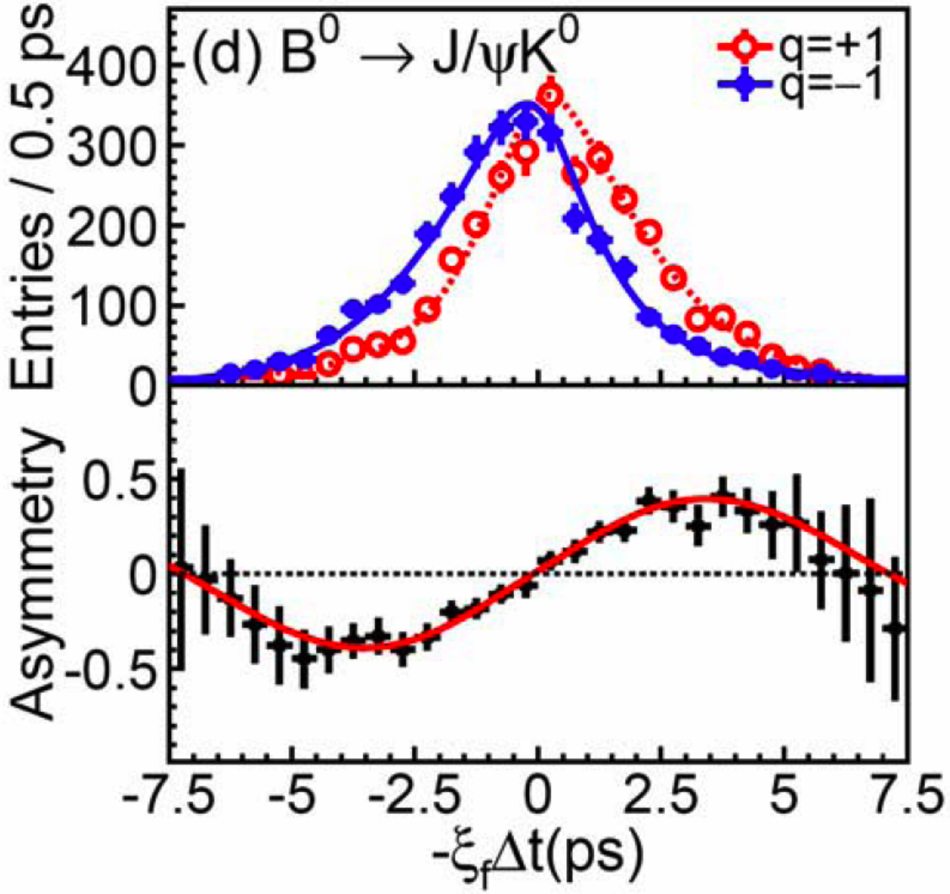
C=0

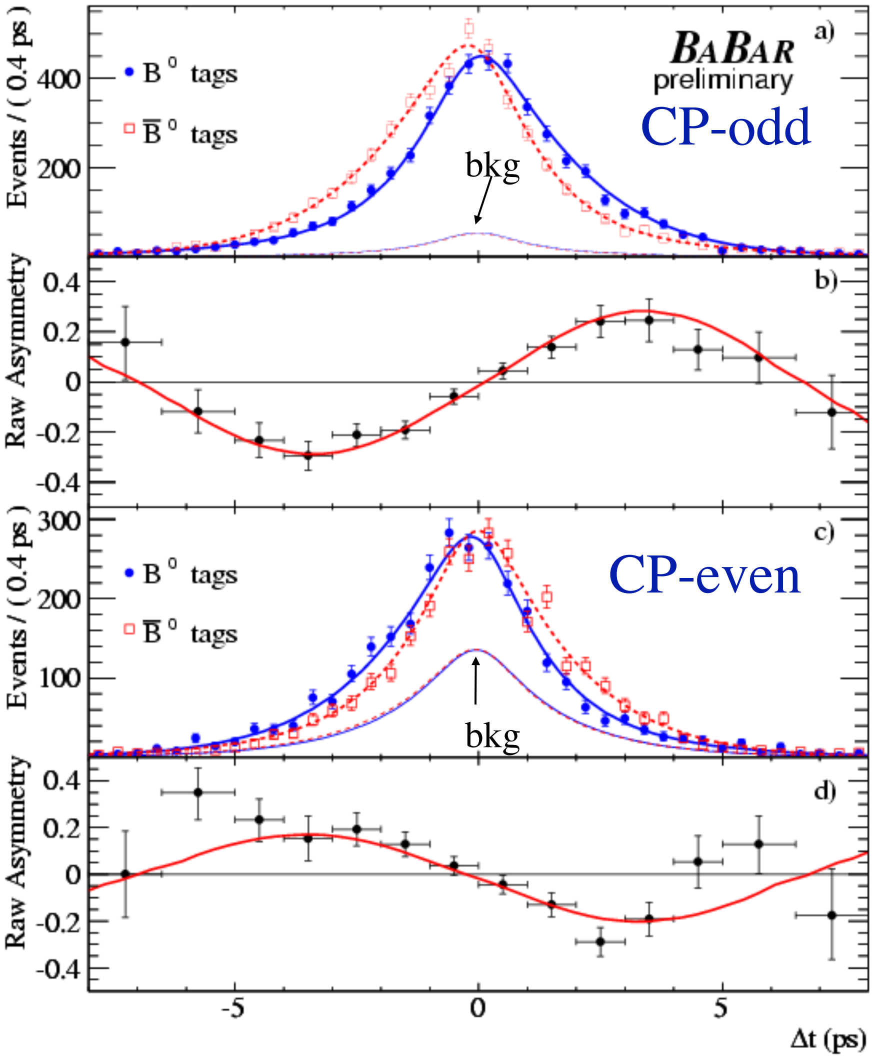
C. Chen

ICHEP-2008

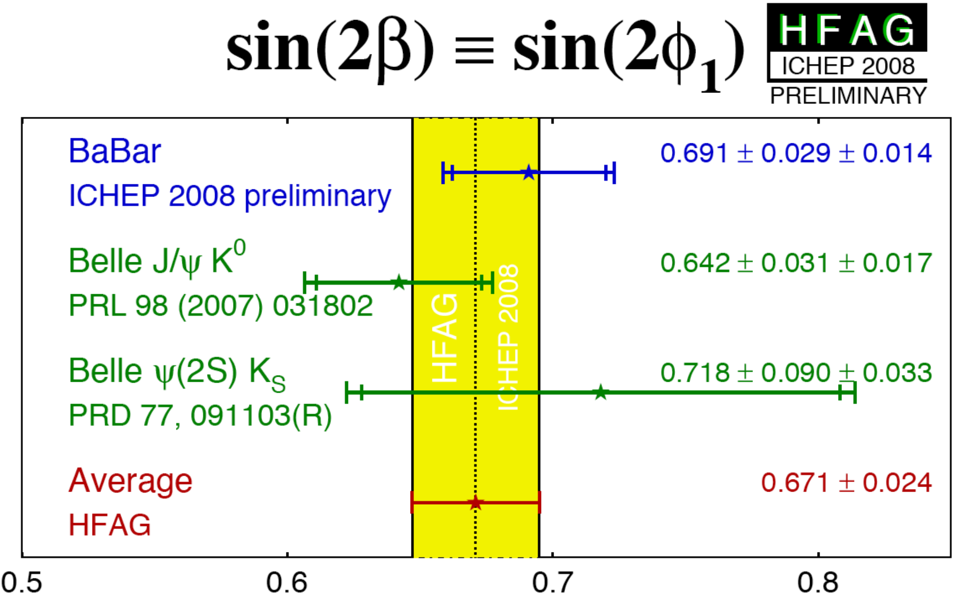
Belle: PRL**98**, 031802 (2007)

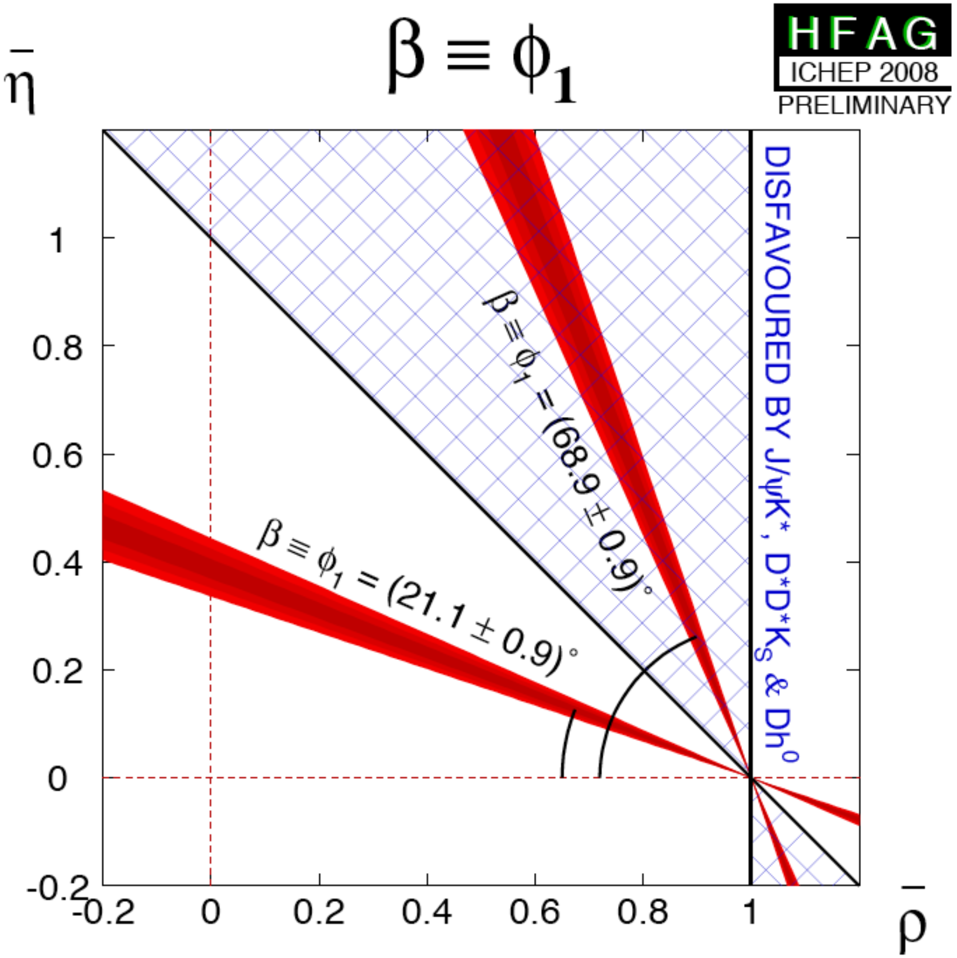
K. Vervink





Angle β/ϕ_1 : “Golden” Channel $b\to c\bar{c}s$





Most precise measurements of CPV in B decays to date

BaBar results for the final dataset

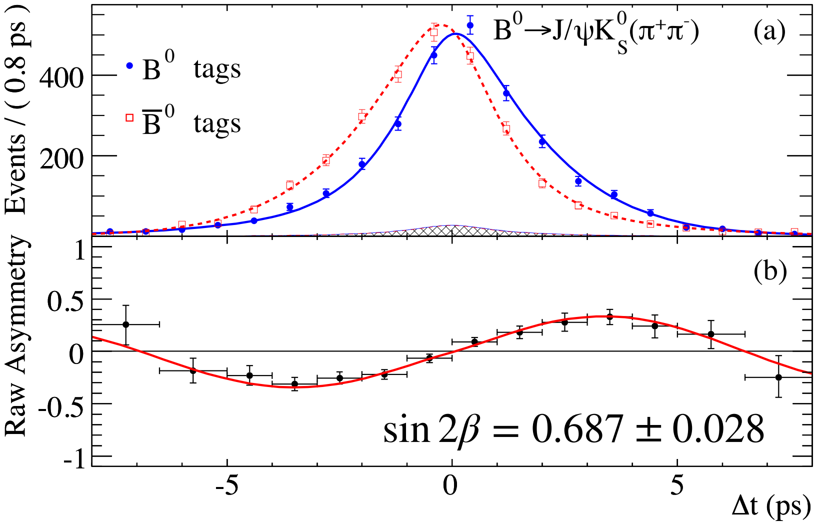
Still statistically-limited measurements

Theoretical uncertainty for sin2β from charmonium modes below 0.01:

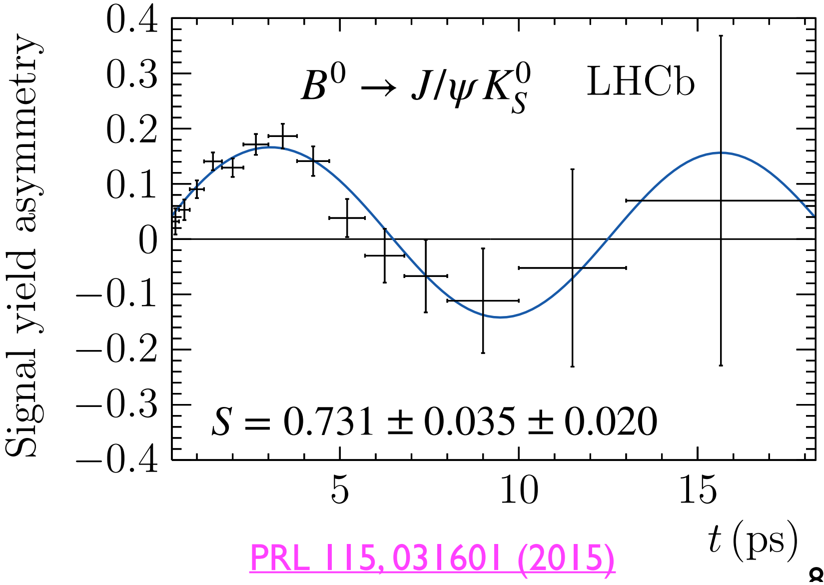
further improvements from LHCb and Super B factories

B-Factories vs LHC-B

BaBar, PRD79:072009,2009



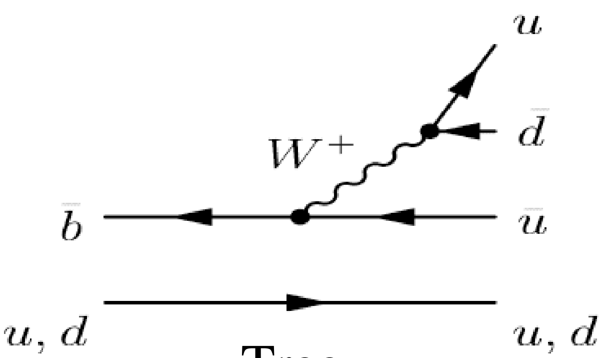
$\sin(2\beta)$



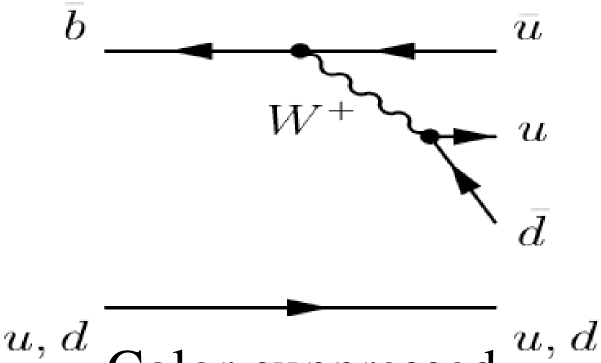
PRL 115, 031601 (2015)

Mat Charles

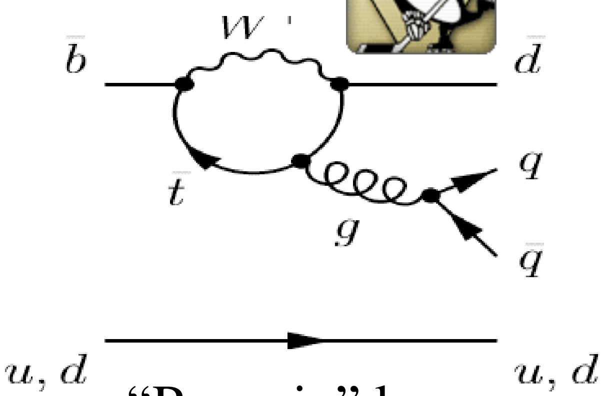
Angle α/ϕ_2



Tree

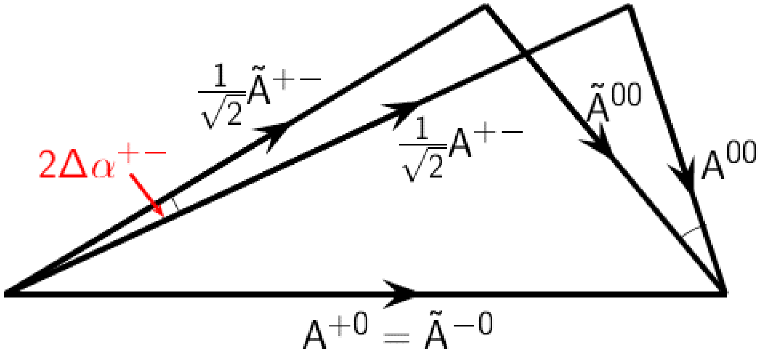


Color-suppressed



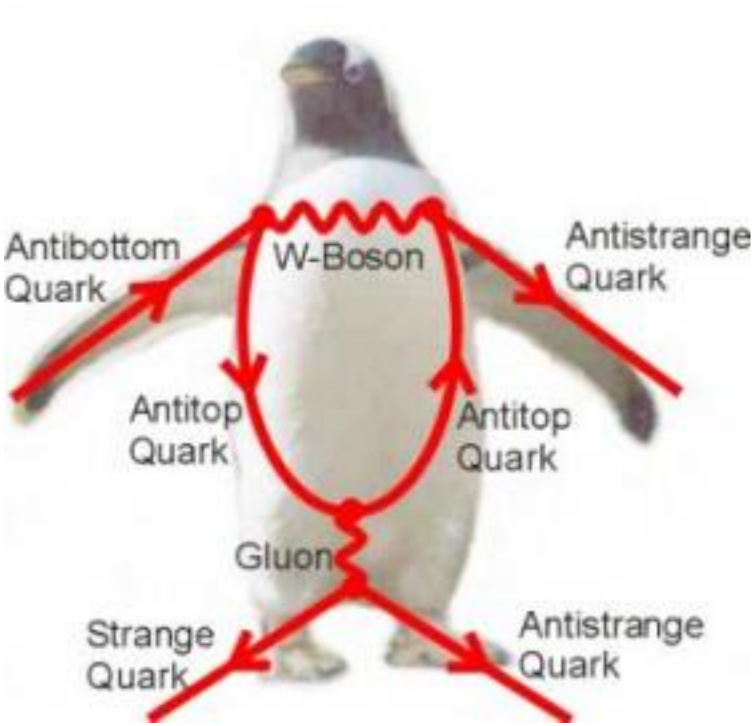
"Penguin" loop

- Time-dependent CPV in b→u transitions
- Problem: 2-3 amplitudes, additional interference
  - ☞ "Penguin" pollution: $S_{\text{eff}} = \sqrt{1-C^2} \times \sin(2\alpha - 2\Delta\alpha)$
- Isospin analysis to measure $\Delta\alpha$
  - ☞ 4-fold ambiguity in $\Delta\alpha$
  - ☞ Small branching fractions
- Most useful modes:
  - ☞ $B \to \rho\rho$, $\pi\pi$, $\rho\pi$



Gronau, London, PRL**65**, 3381 (1990)

Penguin Diagrams

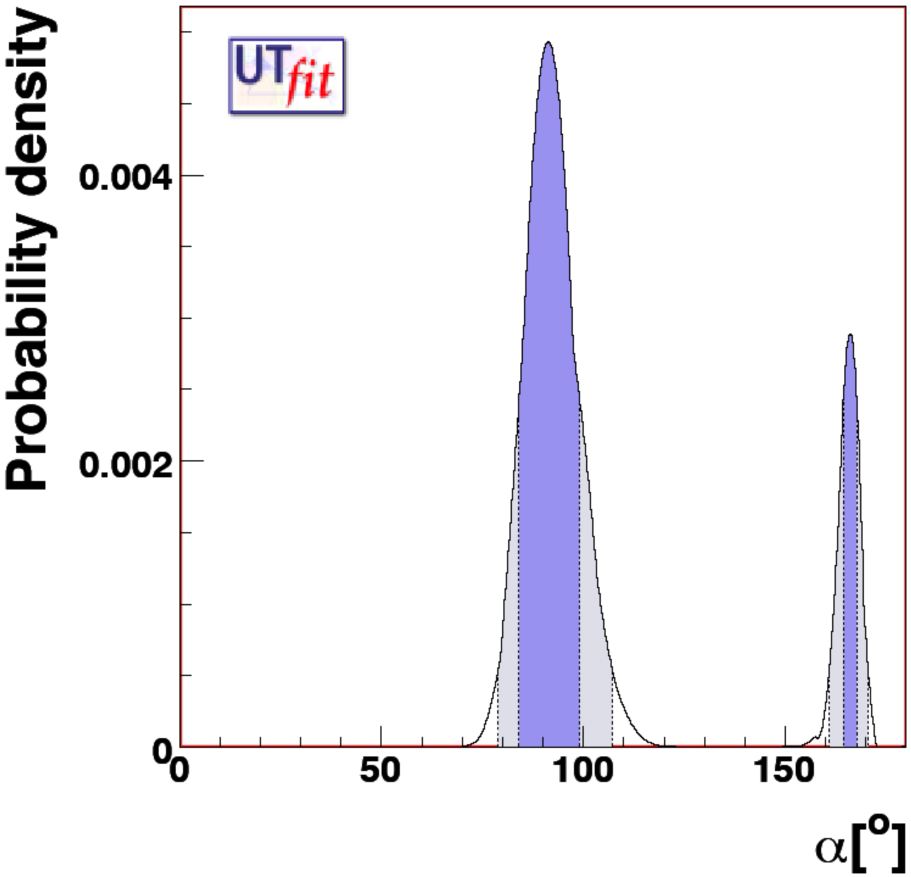


R. Ellis, M.-K. Gaillard, D. Nanopoulos

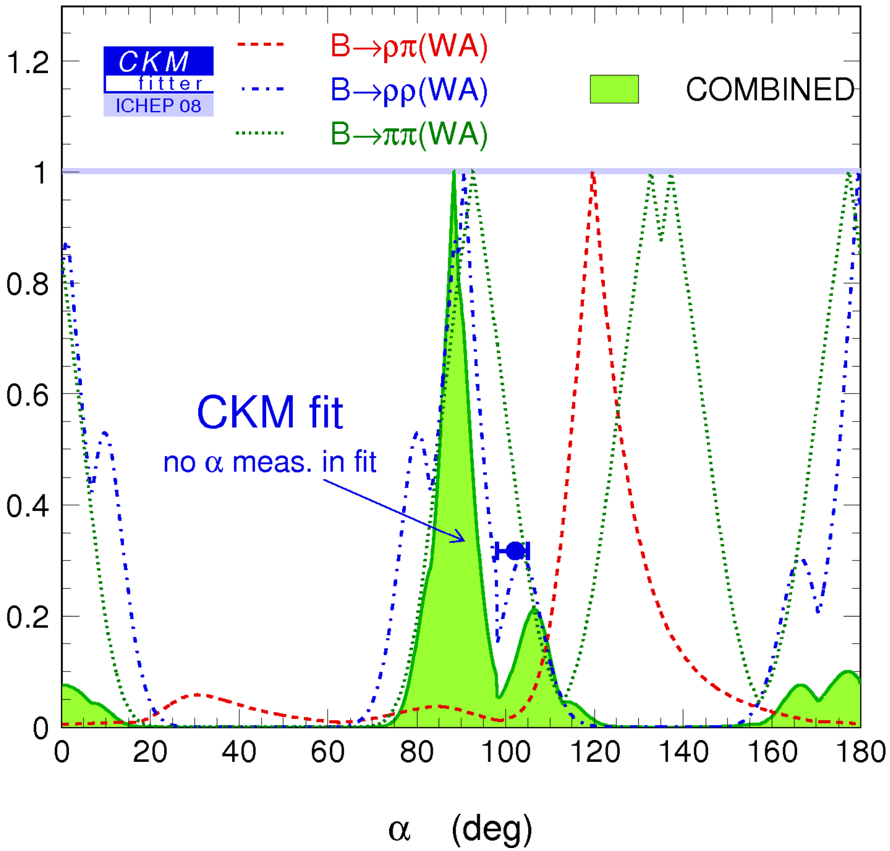
M. Pierini

O. Deschamps

Summary of α/ϕ_2



SM solution: $\alpha=(91\pm8)^{o}$



$\alpha \in [83.5\ ;\ 94.0]^{o}$ @ 68% CL

Angle γ/ϕ_3

- Hardest angle of all to tackle
  - ☞ $\gamma = -\arg(V_{ub})$, and V_{ub} is small
- Direct CPV in $B \to D^{(*)0} K^{(*)}$ decays
  - ❑ 3-body Dalitz Decays (Giri,Grossman,Soffer,Zupan)
    - ☞ $D^0 \to K_s \pi^+ \pi^-$
  - ❑ CP eigenstates (Gronau,London,Wyler)
    - ☞ $D^0 \to \pi\pi, KK, \ldots$
  - ❑ Doubly Cabibbo-suppressed (Atwood,Dunietz,Soni)
    - ☞ $D^0 \to K^+\pi^-$ vs $D^0 \to K^-\pi^+$
- Several complementary techniques
  - ❑ Time-dependent CPV in $B0 \to D^{(*)}\pi$, $D^{(*)}\rho$
    - ☞ Measures $\sin(2\beta+\gamma)$
- Key parameter: r_B, ratio of $|\mathcal{A}(b \to u)/\mathcal{A}(b \to c)|$

Dalitz method for γ/ϕ_3

S. Bahinipati
G. Marchiori
P. Naik

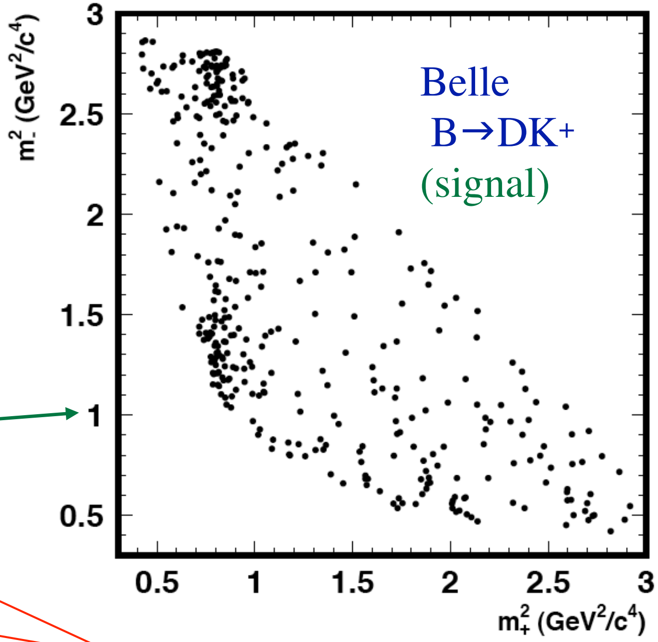
- Most precise method to this point
  - ☞ Direct CPV in $B \to [K_S\pi^+\pi^-]_{D(*)0}K^{(*)}$
  - ☞ Self-tagging: charge ($B^\pm$) or K^* flavor (for B^0 decays)
- Measure interference across Dalitz plot

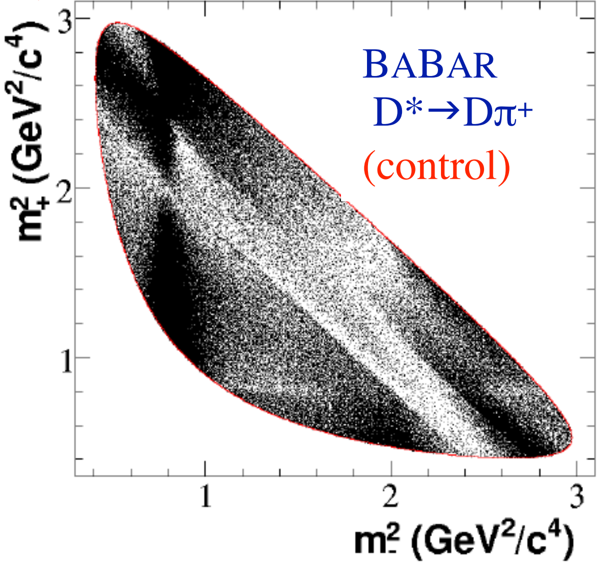
$$A_\pm = f(m_+^2, m_-^2) + \boxed{r_B e^{\pm i\gamma} e^{i\delta_B}} f(m_-^2, m_+^2)$$

$$m_\pm^2 = m^2(K_s\pi^\pm)$$

- Main challenge: D^0 decay model
  - ☞ 18 quasi-twobody states: fit $D^{*+} \to D^0\pi$
  - ☞ Measure at CLEO-c or BES in $\psi(3770) \to D\overline{D}$ to reduce model uncertainty

P. Naik, D.Asner

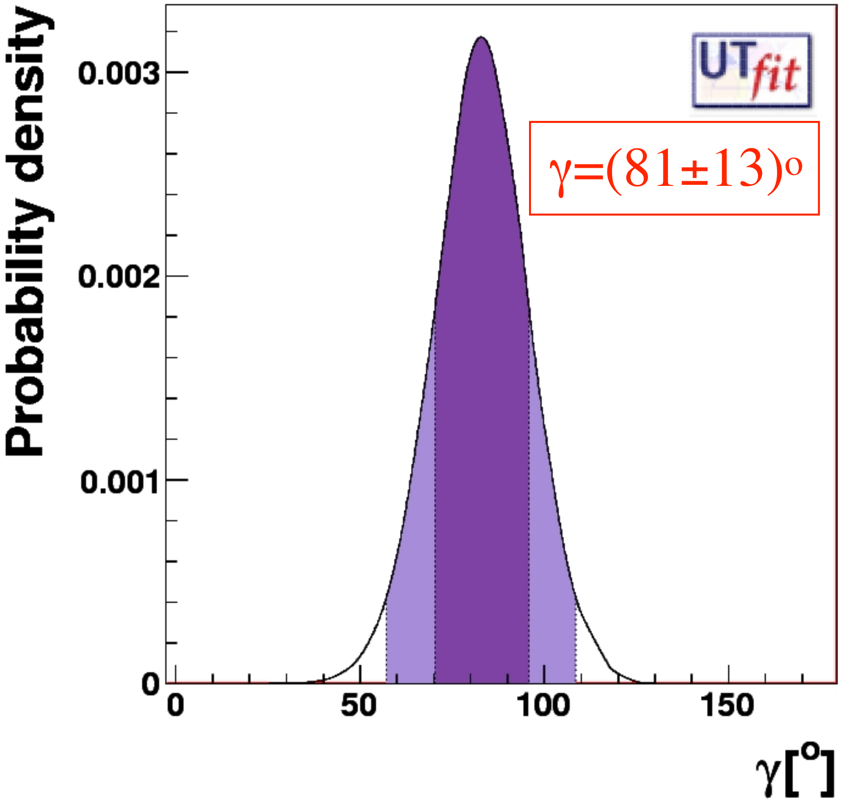

Belle
B→DK+
(signal)


BABAR
D*→Dπ+
(control)

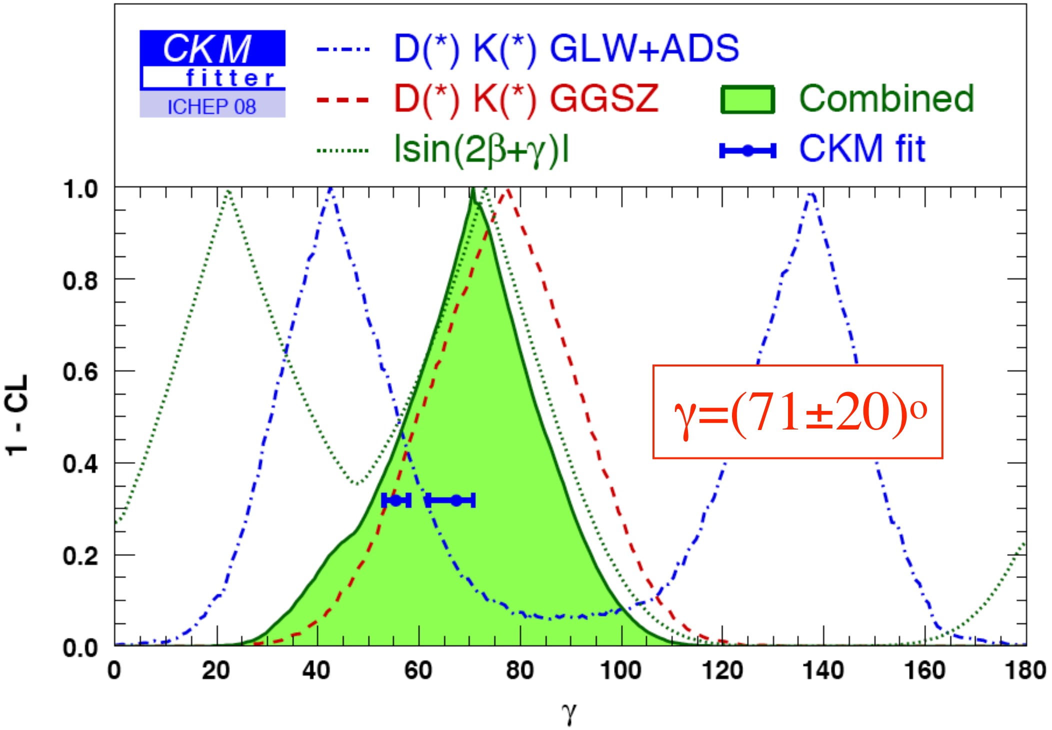
M. Pierini

O. Deschamps

Summary of γ/ϕ_3



$\gamma=(81\pm13)^o$



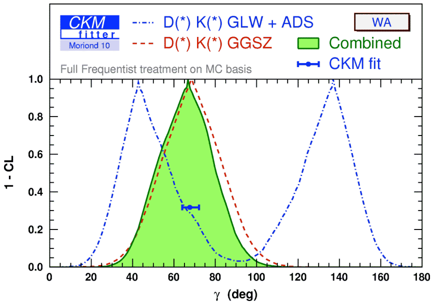
$\gamma=(71\pm20)^o$

Difficult, statistics-limited measurements ! Combination of constraints: uncertainty of ~20^o . Larger statistics needed (LHCb, SuperBelle)

Current Precision

Frequentist interpretation

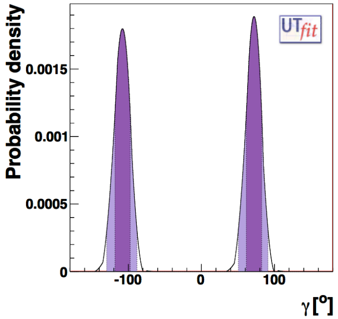
http://ckmfitter.in2p3.fr



$$\gamma = (69\ ^{+19}_{-21})^\circ$$

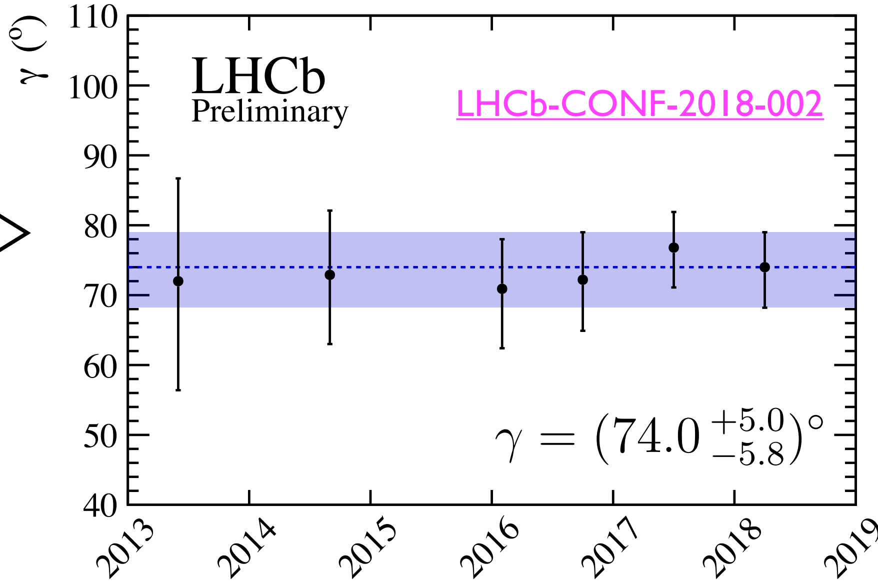
Bayesian interpretation

http://www.utfit.org



$$\gamma = (72 \pm 11)^\circ$$

γ



LHCb-CONF-2018-002

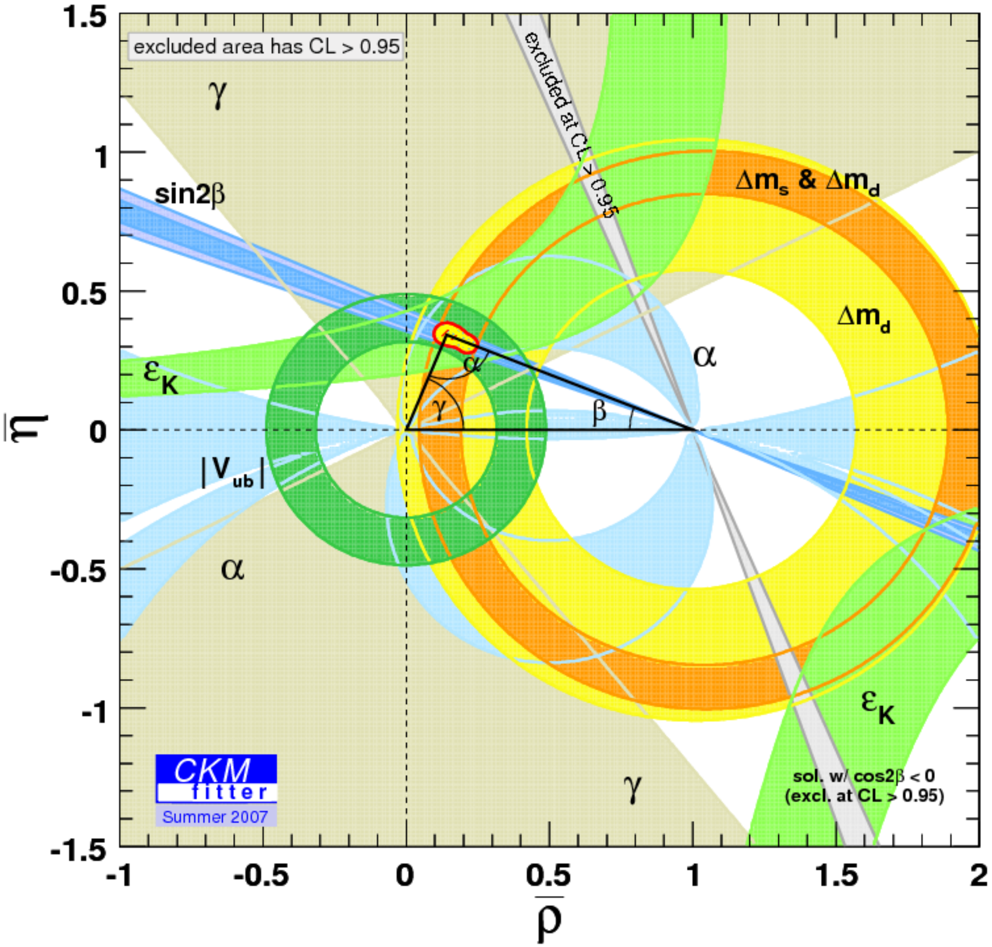
$$\gamma = (74.0\ ^{+5.0}_{-5.8})^\circ$$

Slides by Owen Long, Moriond EW 2010

Mat Charles

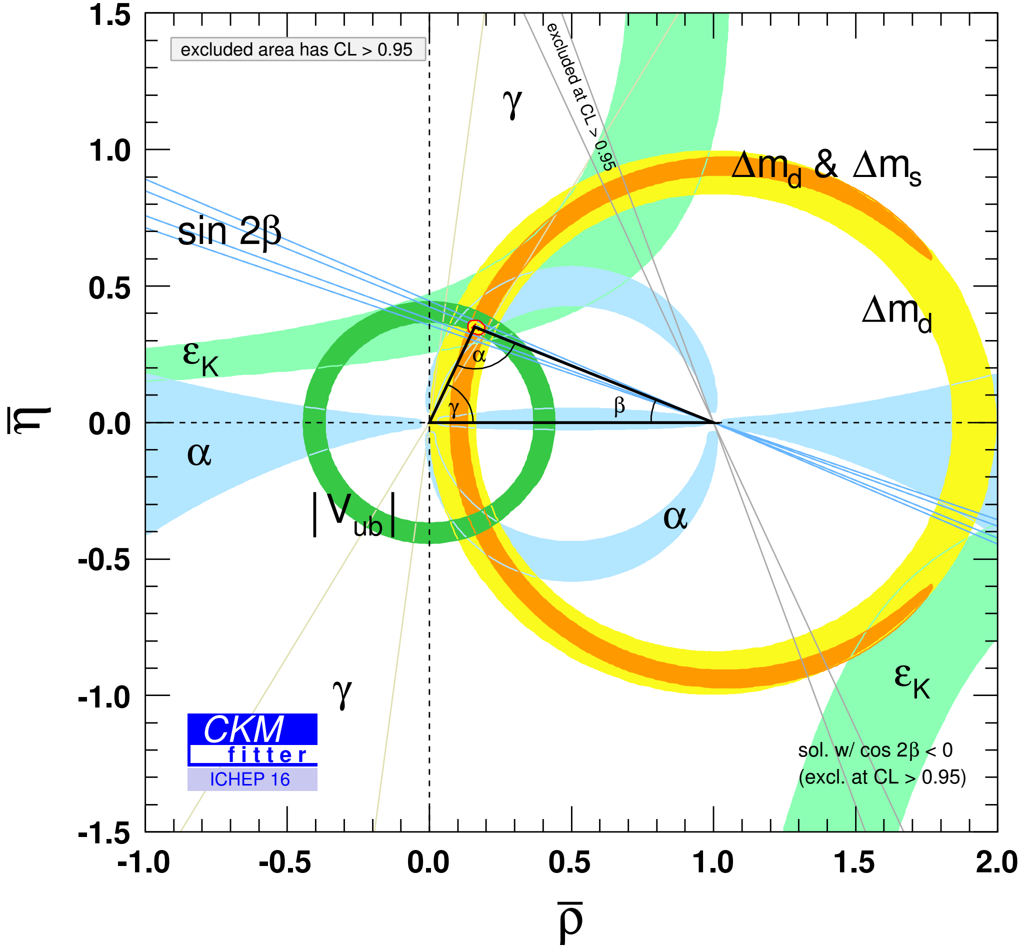
UT Constraints

Circa 2007

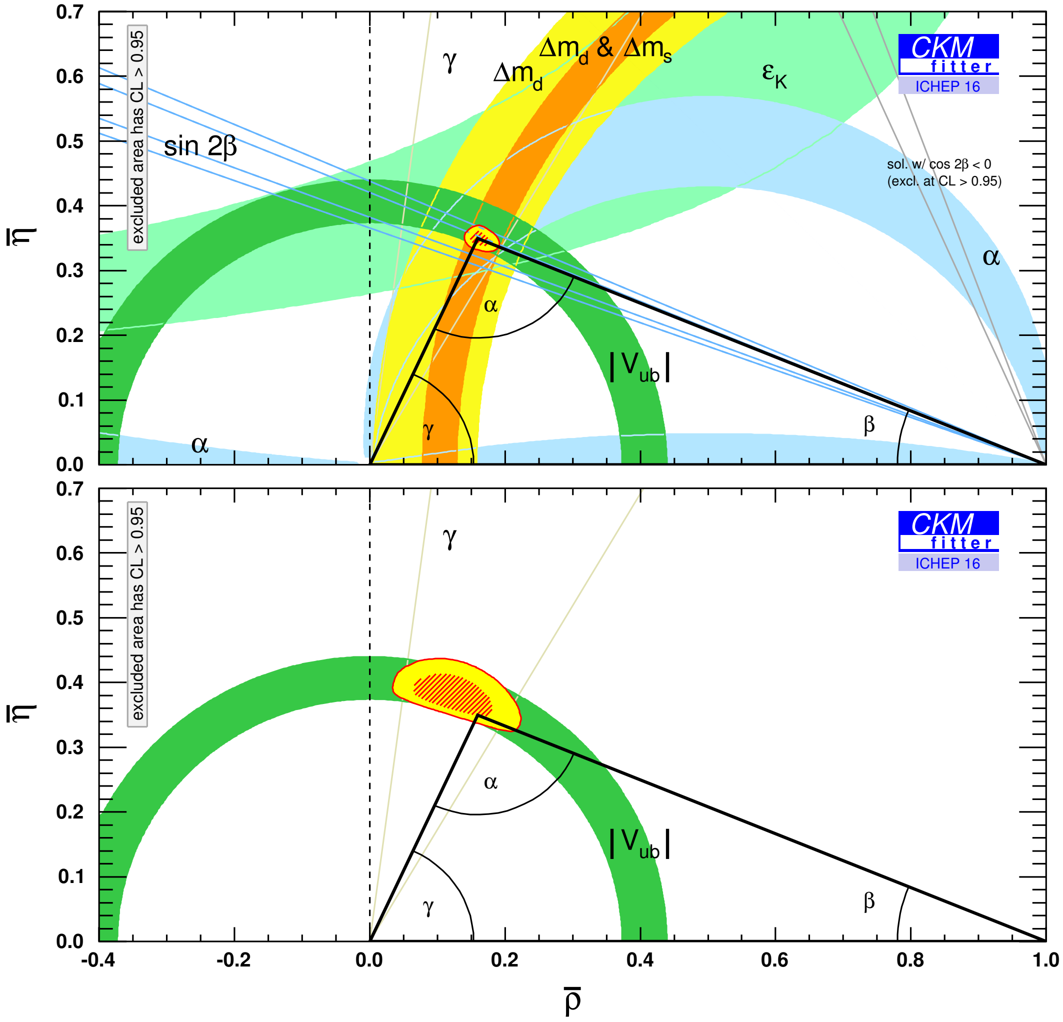


UT Constraints

Circa 2016



UT Constraints



Loop observables

Tree observables

CPV in B_s Decays

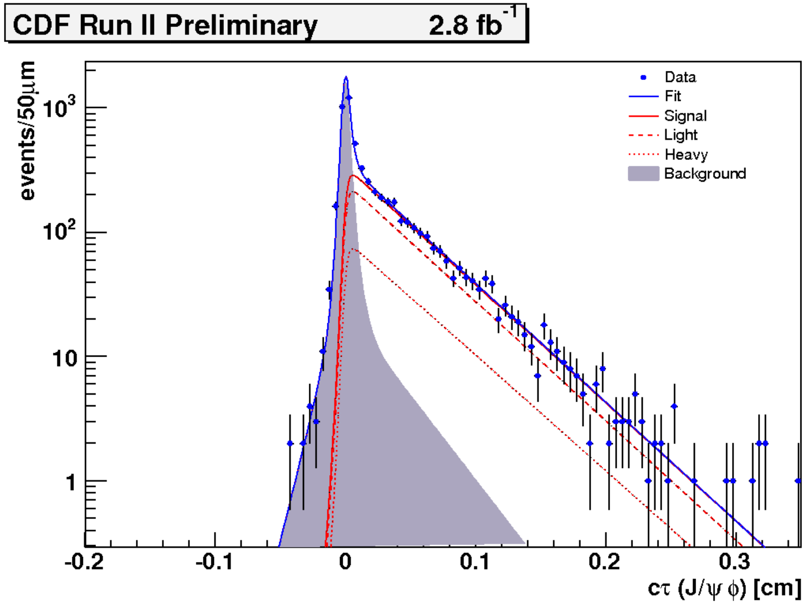
- CPV in $B_s \rightarrow J/\Psi\phi$ measures the phase of B_s mixing amplitude

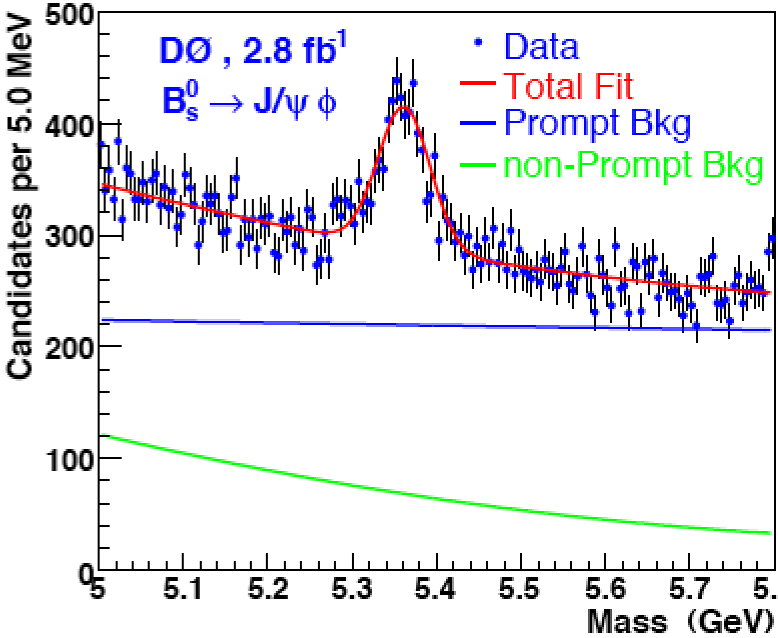
$$\beta_s \equiv \arg\left[-(V_{ts}V_{tb}^*)/(V_{cs}V_{cb}^*)\right]$$

☞ Predicted to be nearly zero in the Standard Model

☞ New Physics may enter through mixing box

☞ Angular analysis determines fractions of CP-odd and CP-even eigenstates; simultaneous fit for $\Delta\Gamma_s$





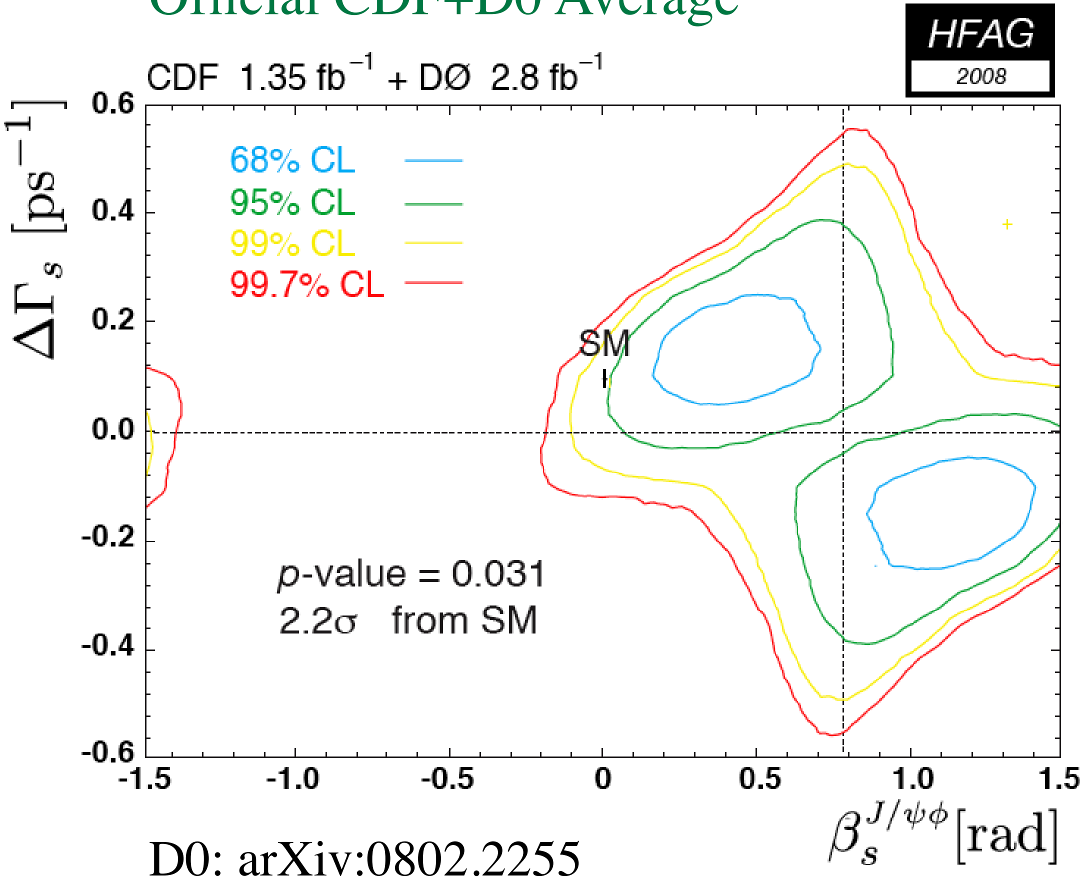
D. Tonelli

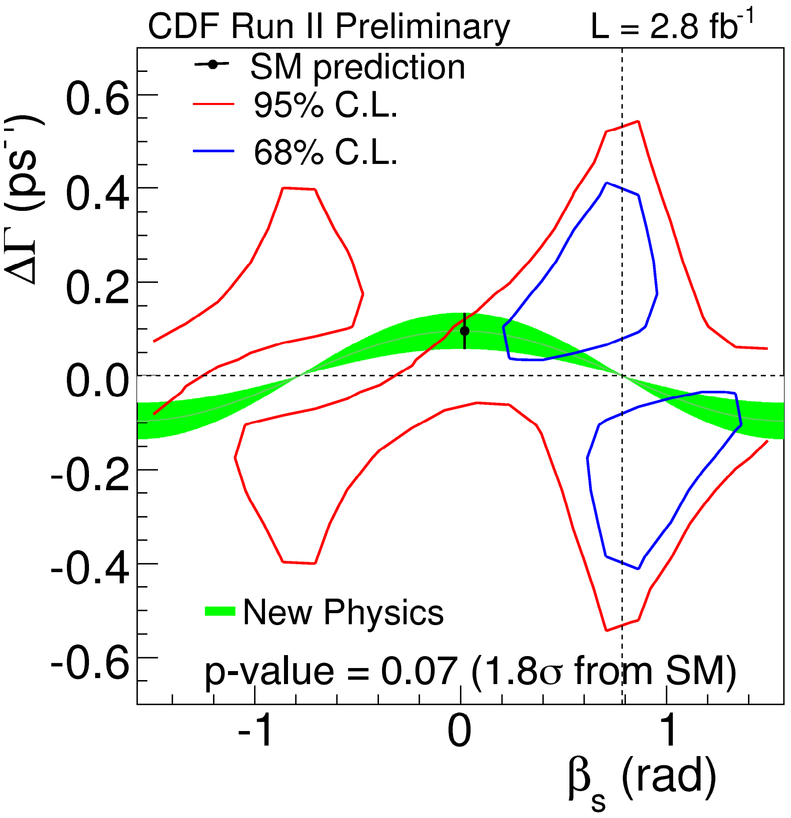
J. Ellison

β_s Results from 2008

Official CDF+D0 Average

➔ New CDF results



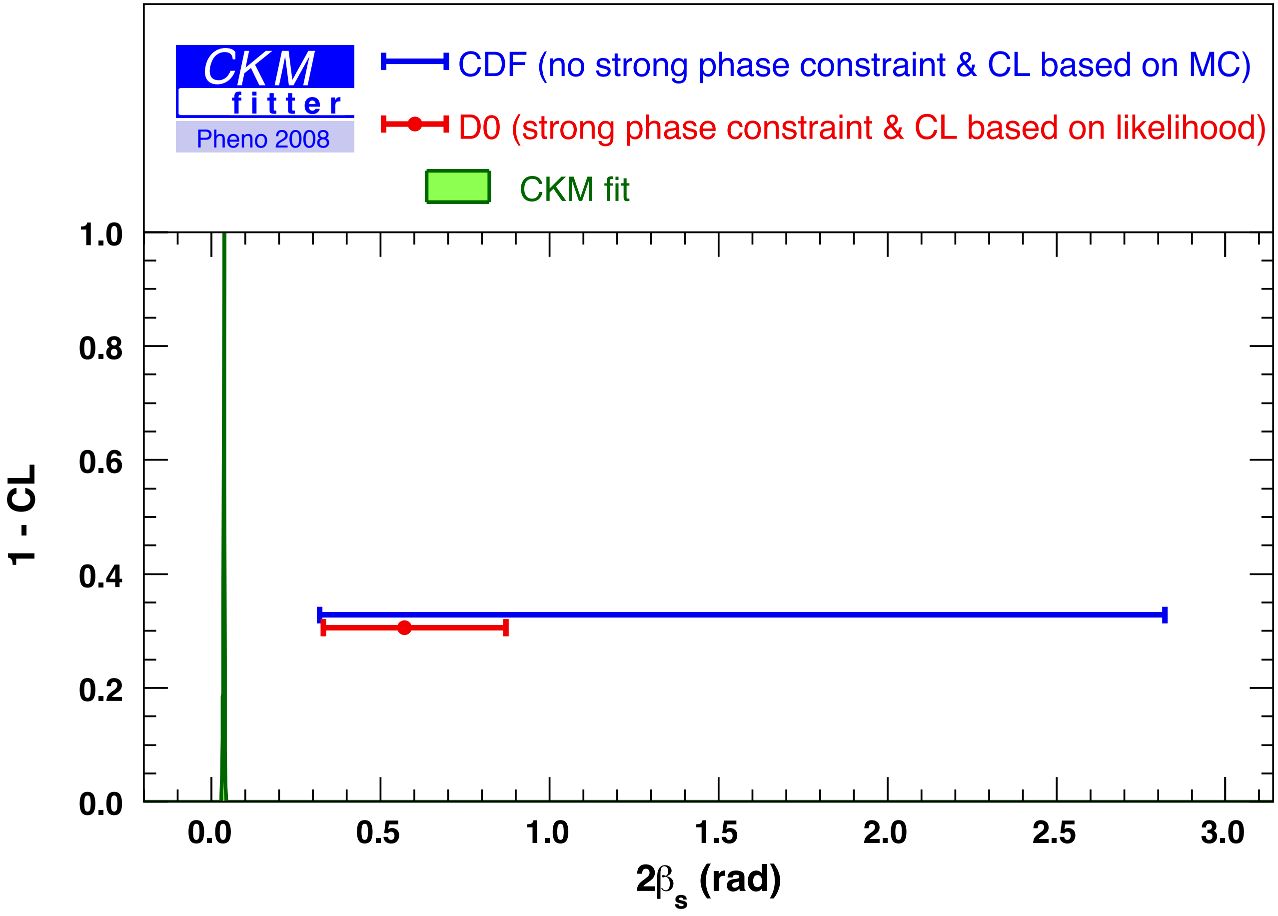


D0: arXiv:0802.2255

CDF: PRL**100**, 161802 (2008)

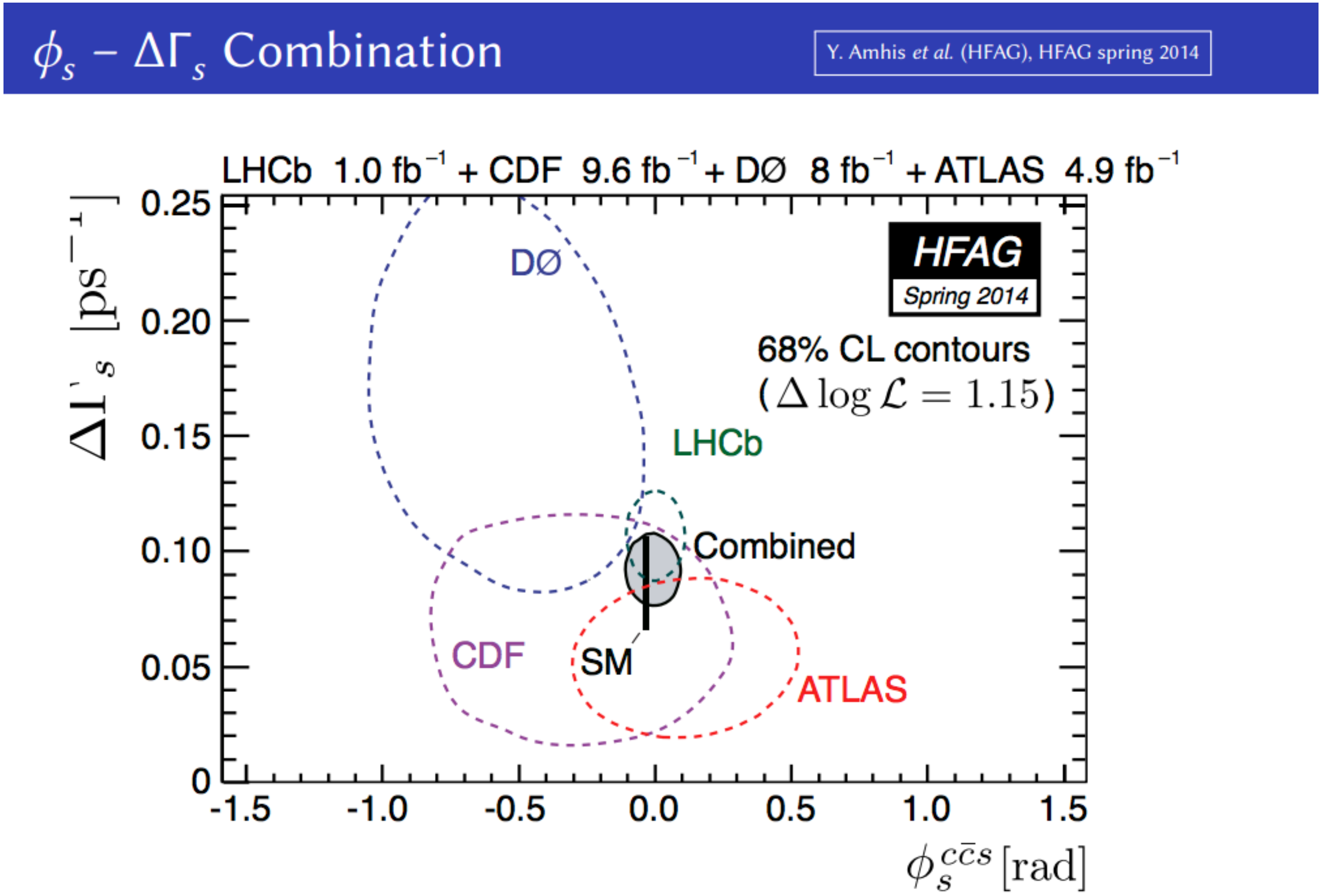
Hint of new physics in B_s mixing ?

β_s Results from 2008



β_s anomaly ? New Physics ???

β_s Results from 2014



$\phi_s - \Delta\Gamma_s$ Combination

Y. Amhis *et al.* (HFAG), HFAG spring 2014

Consistent with the Standard Model.

Rare Decays

- Look for processes suppressed in SM
    - ☞ Deviations are signatures of new physics
  - ❑ Rare or forbidden decays
    - ☞ Forbidden by symmetry in SM
    - ☞ Symmetry can be badly broken for NP: enhancement
  - ❑ Interference effects: P, CP violation, angular distribution
    - ☞ Interference between SM and NP can enhance NP

$B_{(s,d)}\to\mu^+\mu^-$

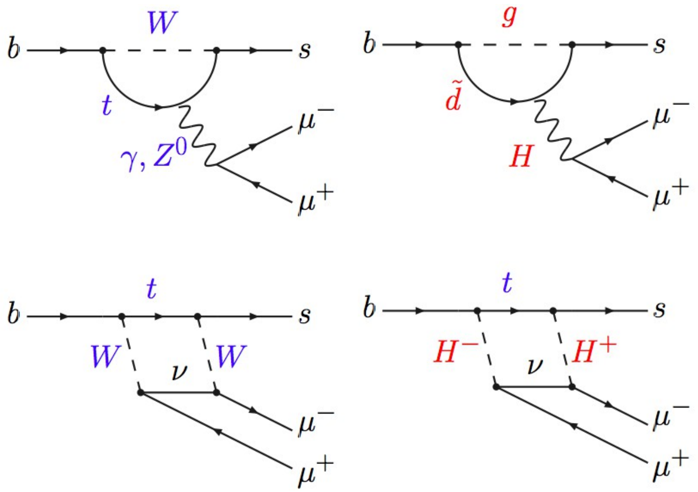
Branching fractions well predicted in the SM: [Eur. Phys. J. C72 (2012) 2172]

$$\begin{aligned}\mathcal{B}(B_s^0\to\mu^+\mu^-)^{CP} &= (3.34\pm0.27)\cdot10^{-9}\\ \mathcal{B}(B^0\to\mu^+\mu^-)^{CP} &= (1.07\pm0.05)\cdot10^{-10}\end{aligned}$$

Due the finite width of the $B^0{}_s$ system the time integrated BF is:

$$\mathcal{B}(B^0\to\mu^+\mu^-)^{\langle t\rangle} = (3.56\pm0.30)\cdot10^{-9}$$ [arXiv:1207.1158]

Probe for models with an extended Higgs sector



Experimental Status

LHCb reported the first evidence of $B_s\to\mu^+\mu^-$ decay with a 3.5 σ significance:

$$\mathcal{B}(B_s^0\to\mu^+\mu^-) = (3.2^{+1.4}_{-1.2}(\text{stat})^{+0.5}_{-0.3}(\text{syst}))\times10^{-9}$$

[PRL 110, 021801 (2013)]

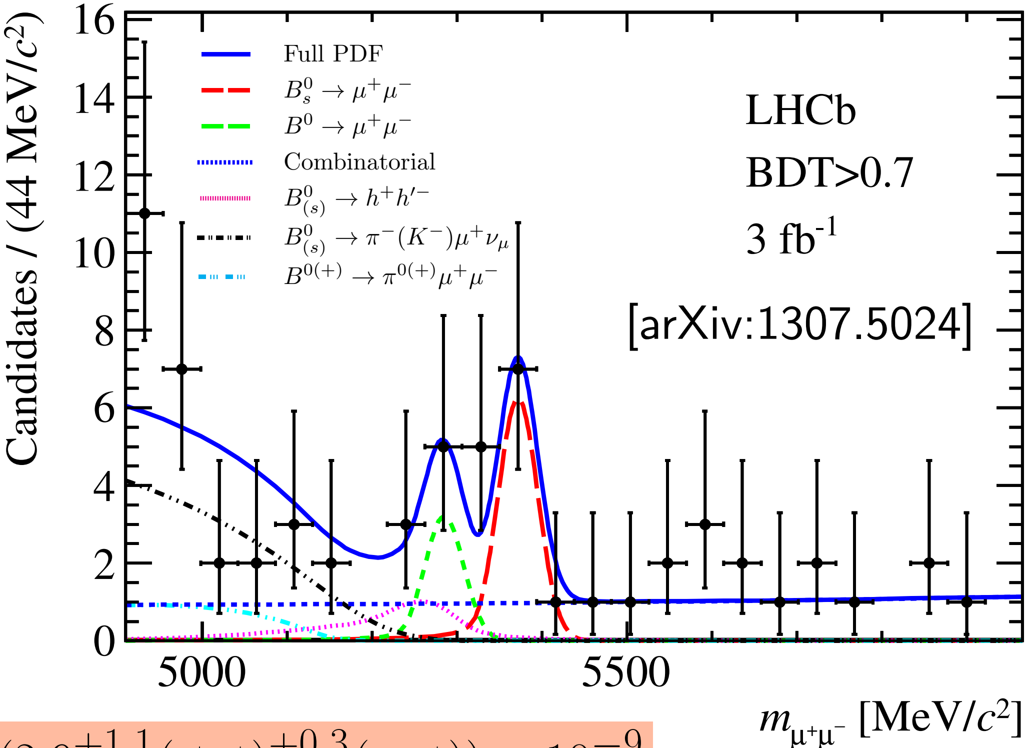
best upper limit on $B^0\to\mu^+\mu^-$ (ATLAS+CMS+LHCb):

$\mathcal{B}(B^0\to\mu^+\mu^-) < 8.4\cdot10^{-10}$ @ 95% CL

[LHCb-CONF-2012-017]

$B_{(s,d)} \to \mu^+\mu^-$

- A simultaneous unbinned likelihood fit to the mass spectra is performed on 8 BDT bins
- Combinatorial bkg, B_s and B^0 yields free
- yield and PDFs of exclusive backgrounds constrained to their expectations.



- For the B_s we obtain:

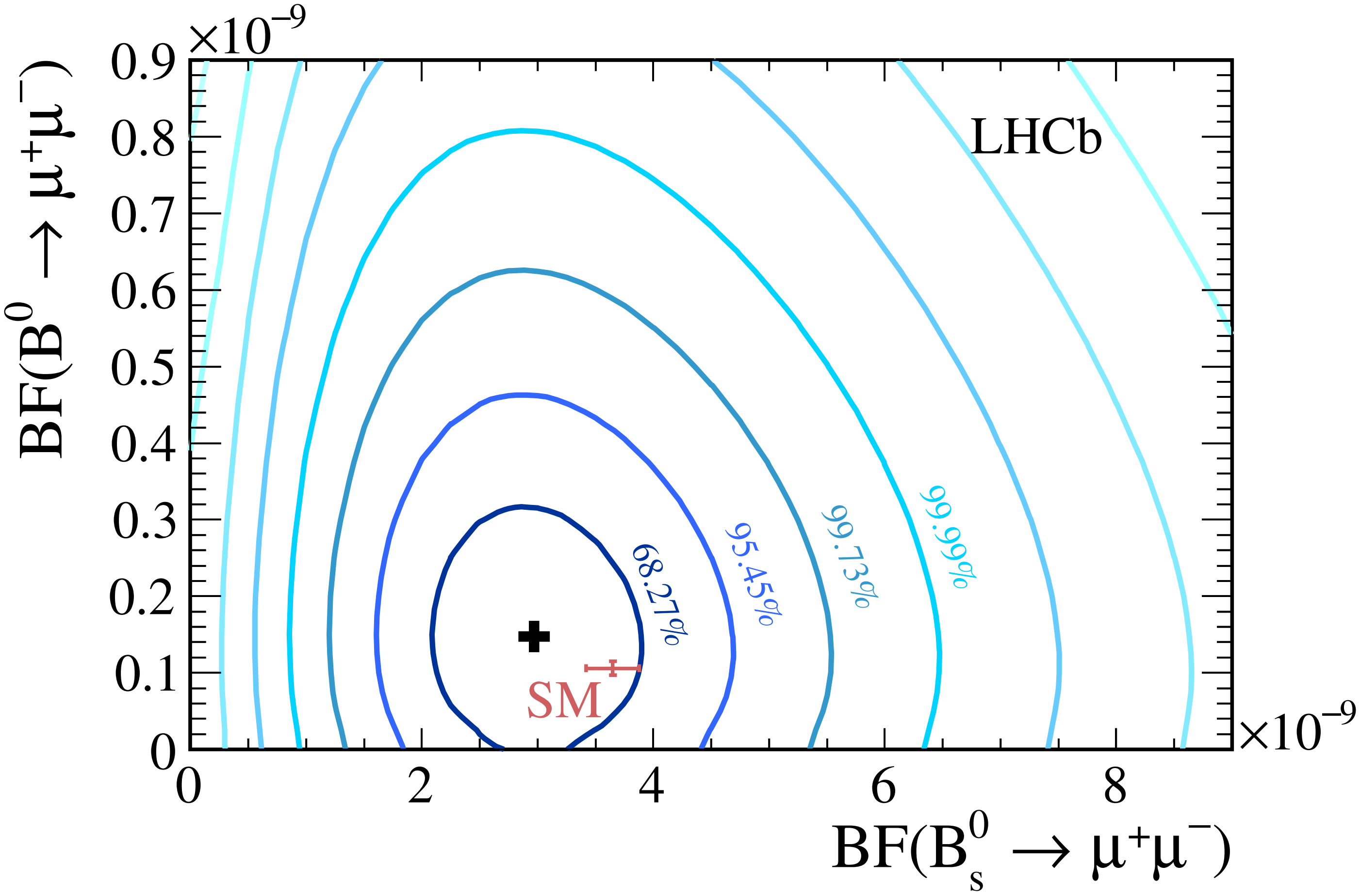
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.9^{+1.1}_{-1.0}(\mathrm{stat})^{+0.3}_{-0.1}(\mathrm{syst})) \times 10^{-9}$$

- with a significance of **4.0 σ**
- For the B^0:

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.7^{+2.4}_{-2.1}(\mathrm{stat})^{+0.6}_{-0.4}(\mathrm{syst})) \times 10^{-10}$$

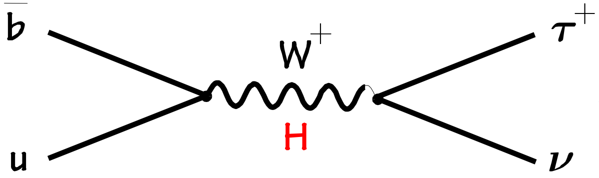
- with a significance of 2.0 σ

Current Status



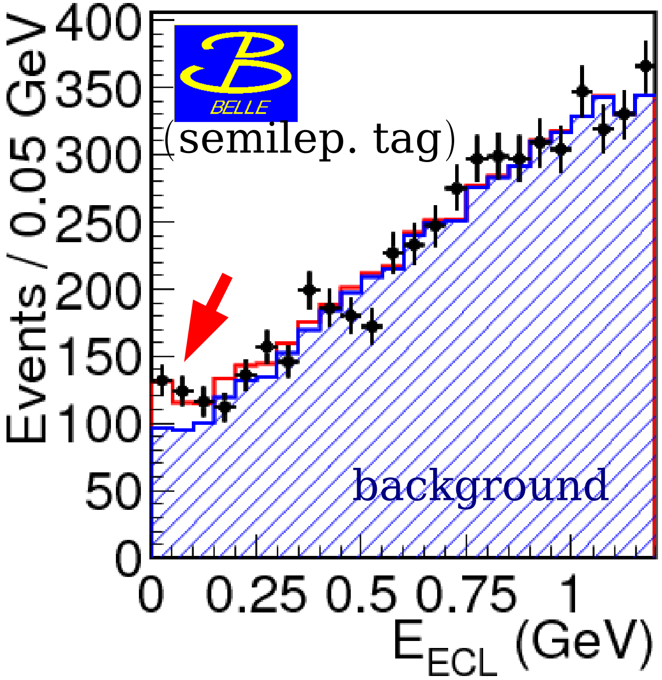
Improvements with HL-LHC data, may start to get interesting

Leptonic Decays: B→τν



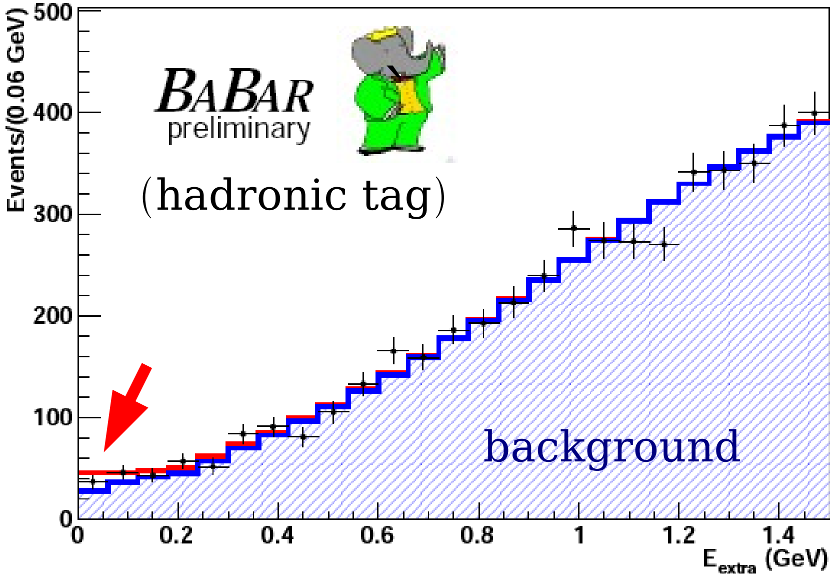
$$\mathcal{B}_{SM}(B^+\to\tau^+\nu) = \frac{G_F^2 m_B m_\tau^2}{8\pi}\left(1-\frac{m_\tau^2}{m_B^2}\right) f_B^2 |V_{ub}|^2 \tau_B$$

$$\text{2HDM (type II)}: \mathcal{B}(B^+\to\tau^+\nu) = \mathcal{B}_{SM}\times\left(1-\frac{m_B^2}{m_{H^+}^2}\tan^2\beta\right)^2$$



(semilep. tag)

background



(hadronic tag)

background

Extra calorimeter energy: $E_{ECL/extra}$ (GeV)

$B^+ \to \tau^+ \nu$ results

World average: $\mathcal{B}(B^+ \to \tau^+ \nu) = (1.68 \pm 0.31) \times 10^{-4}$

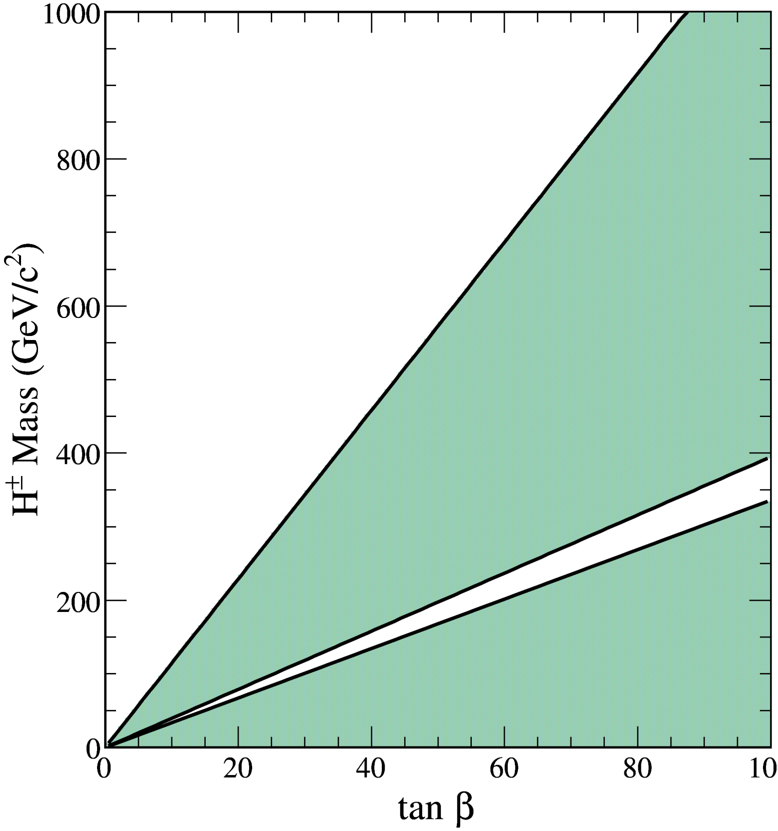
$\mathcal{B}_{SM}(B^+ \to \tau^+ \nu) = (1.20 \pm 0.25) \times 10^{-4}$
using f_B (HPQCD), $|V_{ub}|$ (HFAG)

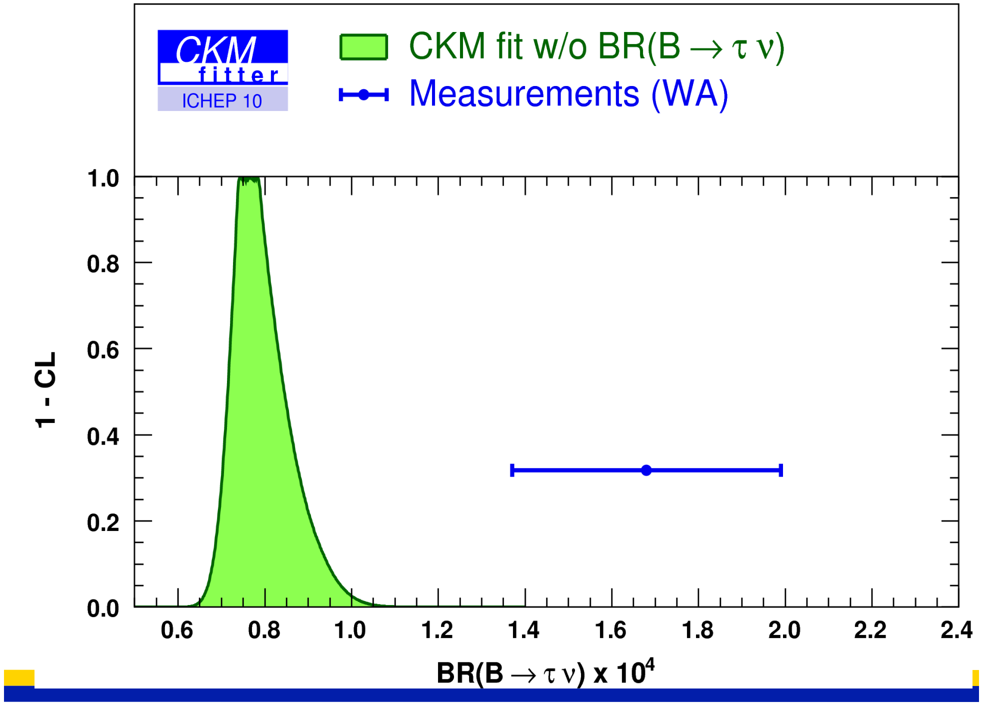
2HDM (type II):

$$\mathcal{B}(B^+ \to \tau^+ \nu) = \mathcal{B}_{SM} \times \left(1 - \frac{m_B^2}{m_{H^+}^2} \tan^2\beta\right)^2$$

CKMfitter: $\mathcal{B}_{SM}(B^+ \to \tau^+ \nu) = (0.763^{+0.114}_{-0.061}) \times 10^{-4}$

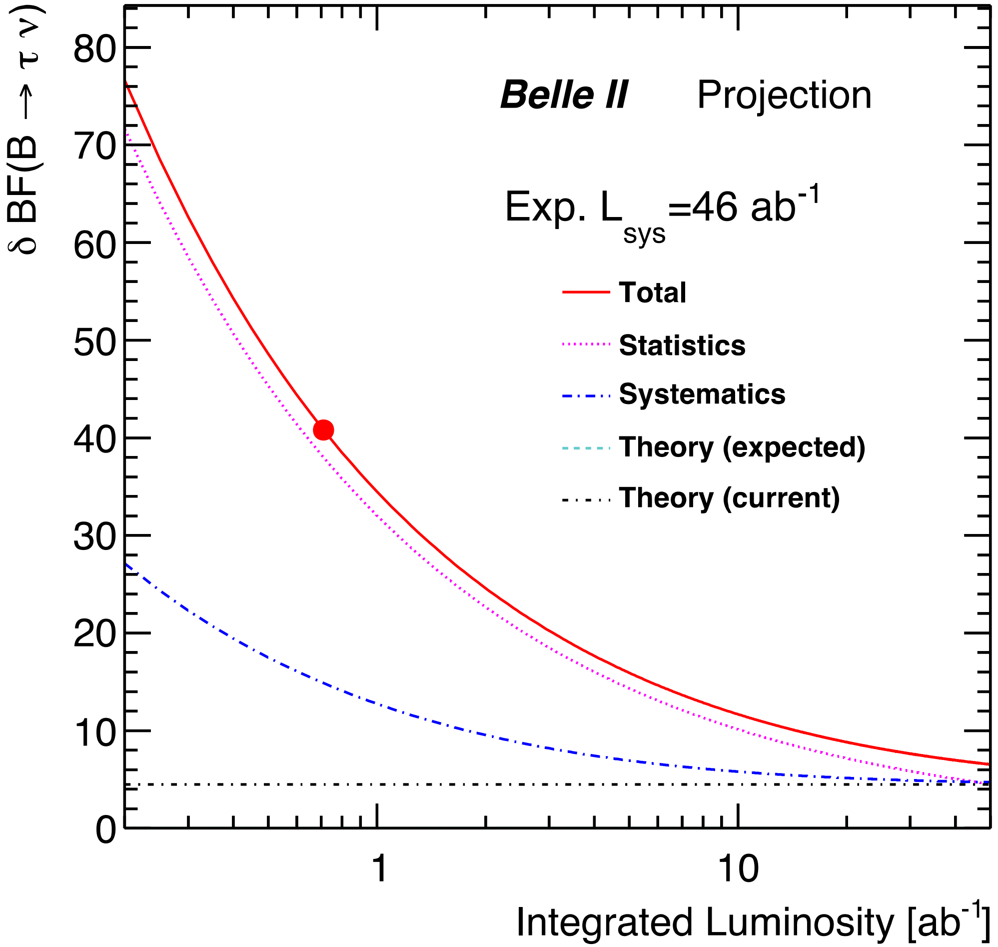
2.8σ difference





see Stephane T'Jampens and Cecilia Tarantino's talks

Future Prospects



Lepton Universality

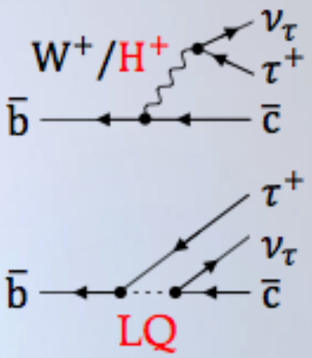
F. Forti

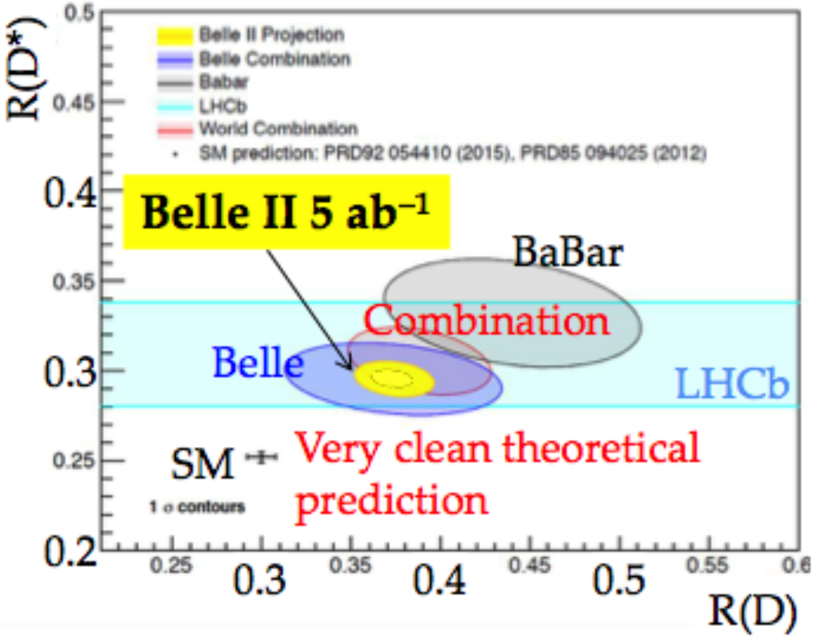
$$R(D^{(*)}) = \frac{\Gamma(B \to D^{(*)}\tau\nu)}{\Gamma(B \to D^{(*)}\ell\nu)} \quad (\ell = \text{e or } \mu)$$

- Partial cancellation of theoretical uncertainties related to hadronic effects and measurement systematics.

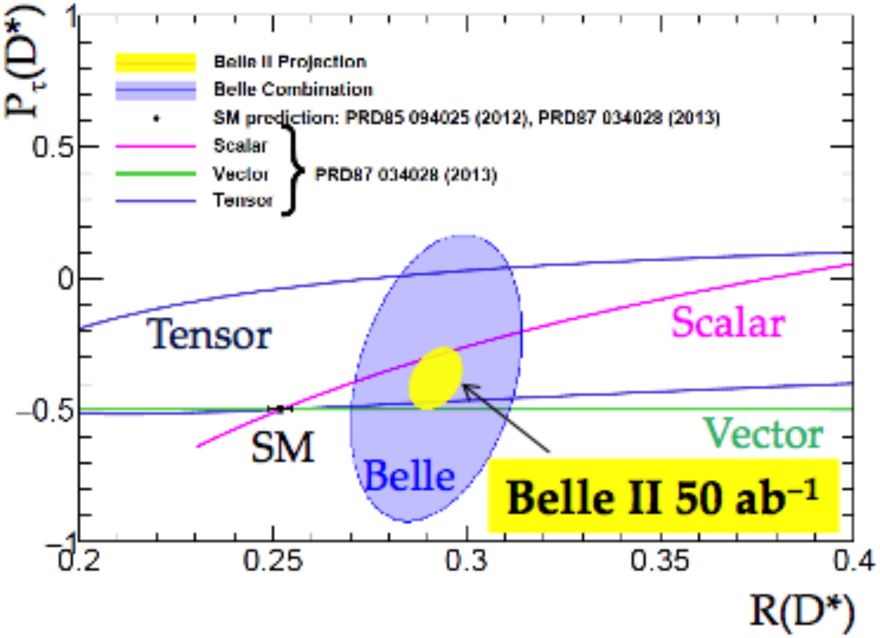
$$P_\tau(D^*) = \frac{\Gamma^+ - \Gamma^-}{\Gamma^+ + \Gamma^-} \quad (\Gamma^\pm\text{: decay rate of } \pm\,\tau\text{-helicity})$$

- Another probe of New Physics





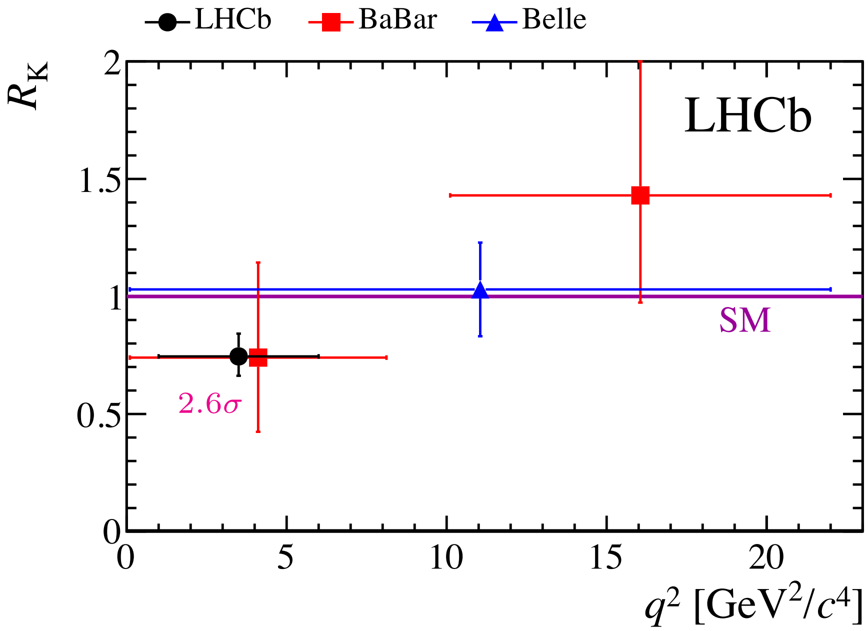
Very clean theoretical prediction

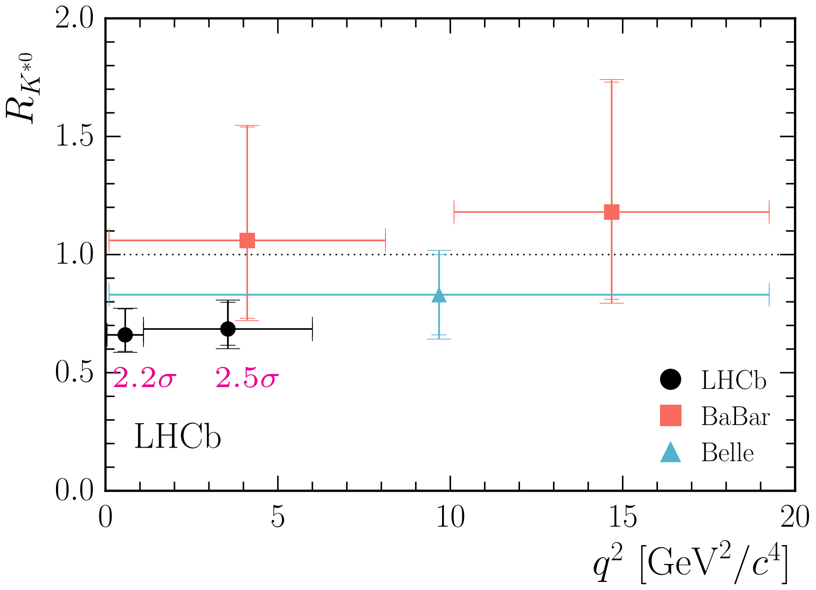


Lepton Universality

Z. Ligeti

- LHCb: $R_{K^{(*)}} = \dfrac{B \to K^{(*)}\mu^+\mu^-}{B \to K^{(*)}e^+e^-} < 1$ both ratios over 2.5σ from lepton universality





Summary

- High-precision measurements from the B-factories, Tevatron, and LHC
  - ❑ Overall, excellent agreement between sides and angles of the Unitarity Triangle
    - ☞ But a few tantalizing discrepancies, e.g. in rare decays
  - ❑ Nontrivial constraints on the flavor of new physics
- Still statistics limited
    - ☞ More data from LHC and Belle-II
- Measurements in the quark flavor sector will continue to provide important insights and constraints on the flavor structure of physics within and beyond the Standard Model