B physics experiments

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15th August 2019

SSI 1999

CP VIOLATION
IN AND BEYOND
THE STANDARD MODEL

B physics colliders/experiments

e^+e^- colliders

- Exploit resonant enhancement for $e^+e^- \to \Upsilon(4S) \to B\bar{B}$
- Produce only $B\bar{B}$ pair in quantum-entangled state
  - CESR/CLEO 1979-2001
  - PEP-II/BaBar 1999-2008
  - KEKB/Belle 1999-2010
  - SuperKEKB/Belle2 2019-

$\Big\}$ asymmetric

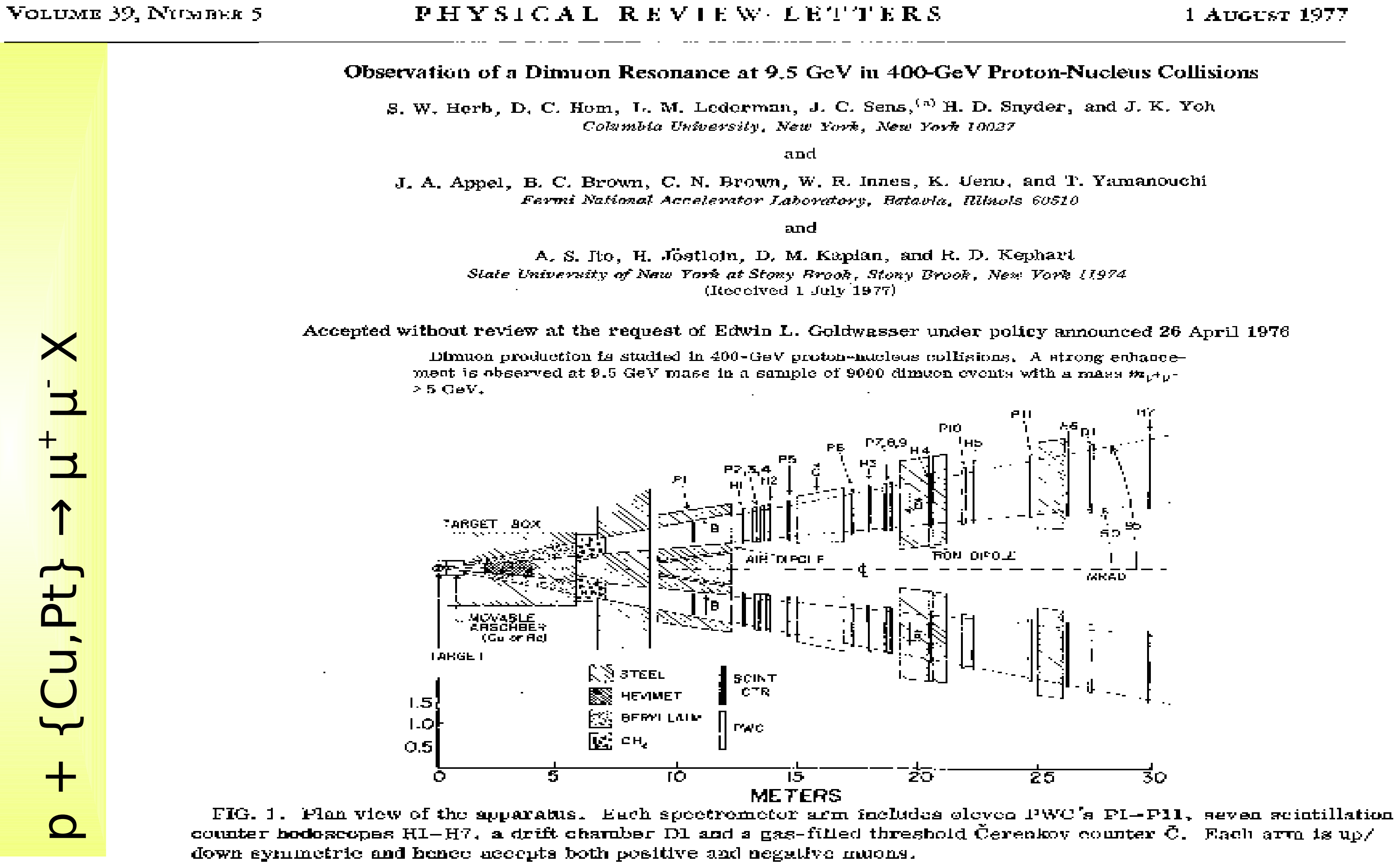
- [$e^+e^- \to Z \to b\bar{b}$ also interesting but will not be discussed here]

Hadron colliders

- Exploit large production cross-sections at high energy
  - Gain for colliders vs. fixed target
- Produce all species of b hadrons, incoherently
- Many additional particles in $pp \to b\bar{b}X$: challenges to record data
  - Tevatron ($p\bar{p}$)/CDF+D0 2001-2011
  - LHC (pp)/ATLAS+CMS+LHCb 2009-
  - HL-LHC (pp)/LHCb upgrades 202X-

Discovery of bottomonium (Υ)

$p + \{Cu,Pt\} \rightarrow \mu^+ \mu^- X$



VOLUME 39, NUMBER 5 PHYSICAL REVIEW LETTERS 1 AUGUST 1977

Observation of a Dimuon Resonance at 9.5 GeV in 400-GeV Proton-Nucleus Collisions

S. W. Herb, D. C. Hom, L. M. Lederman, J. C. Sens,[a] H. D. Snyder, and J. K. Yoh
Columbia University, New York, New York 10027

and

J. A. Appel, B. C. Brown, C. N. Brown, W. R. Innes, K. Ueno, and T. Yamanouchi
Fermi National Accelerator Laboratory, Batavia, Illinois 60510

and

A. S. Ito, H. Jöstlein, D. M. Kaplan, and R. D. Kephart
State University of New York at Stony Brook, Stony Brook, New York 11974

(Received 1 July 1977)

Accepted without review at the request of Edwin L. Goldwasser under policy announced 26 April 1976

Dimuon production is studied in 400-GeV proton-nucleus collisions. A strong enhancement is observed at 9.5 GeV mass in a sample of 9000 dimuon events with a mass $m_{\mu^+\mu^-} > 5$ GeV.

FIG. 1. Plan view of the apparatus. Each spectrometer arm includes eleven PWC's P1–P11, seven scintillation counter hodoscopes H1–H7, a drift chamber D1 and a gas-filled threshold Čerenkov counter Č. Each arm is up/down symmetric and hence accepts both positive and negative muons.

Discovery of bottomonium (Υ)

$p + \{Cu,Pt\} \rightarrow \mu^+ \mu^- X$

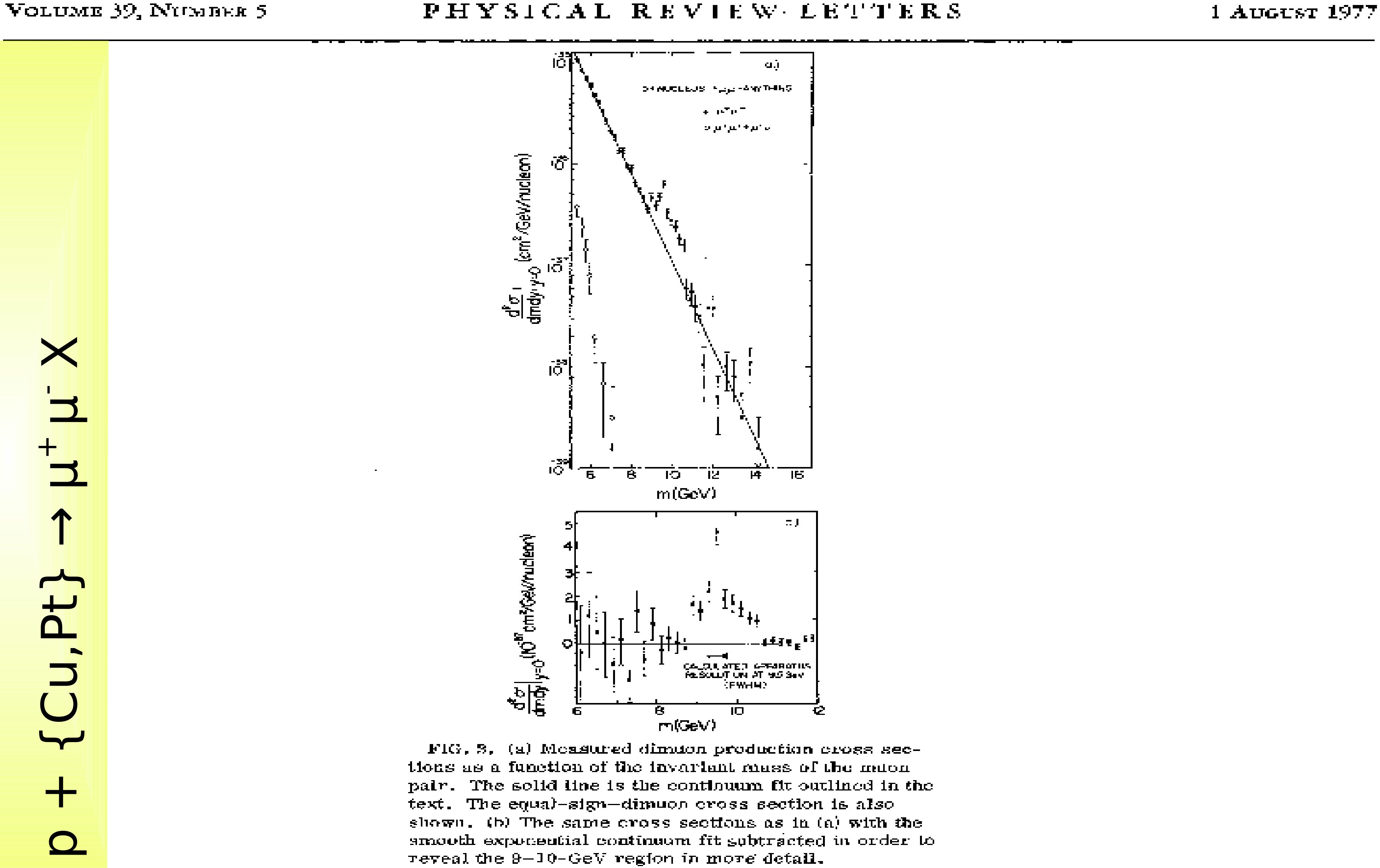


FIG. 3. (a) Measured dimuon production cross sections as a function of the invariant mass of the muon pair. The solid line is the continuum fit outlined in the text. The equal-sign–dimuon cross section is also shown. (b) The same cross sections as in (a) with the smooth exponential continuum fit subtracted in order to reveal the 9–10-GeV region in more detail.

How to discover particles

- The existence of the bottom quark was established in 1977 through the discovery of the Υ state
- The Υ is the vector ($J^{PC} = 1^{--}$) bottomonium ($b\bar{b}$) state
- There is a lighter bottomonia, the η_b ($J^{PC} = 0^{-+}$)
- Hadron colliders produce states with all quantum numbers
  - true for the 1977 FNAL experiment
- … so why was the Υ discovered before the η_b?
  - [the η_b eventually discovered in 2008 by BaBar]

How to discover particles

- … so why was the Υ discovered before the η_b?

- It is not enough to produce particles, you also have to detect them
  - i.e. trigger the event & separate signal from background
- A $pp \rightarrow b\bar{b}X$ event looks very similar to any other QCD $pp \rightarrow q\bar{q}X$ process (q = light quark), except when
  - leptons (especially muons) produced in decay [relevant in 1977 & still now]
  - displaced vertex of b hadrons can be identified [relevant in modern experiments]
- Υ decays to $\mu^+\mu^-$ but η_b does not (highly suppressed in SM)
- [$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$ at threshold and therefore very different to $e^+e^- \rightarrow q\bar{q}$]

Strengths of e^+e^- & hadron colliders

- Sometimes said that hadron colliders are good for discovery, e^+e^- for precision measurements
  - Excessively simplistic
- Or, that e^+e^- provides a clean (low background) environment, while hadron collisions do not
  - Also not true in general for b physics
- Nonetheless, they do have complementary strengths

	$e^+e^- \to \Upsilon(4S) \to B\bar{B}$ PEP-II, KEKB	$p\bar{p} \to b\bar{b}X$ ($\sqrt{s} = 2\,\text{TeV}$) Tevatron	$pp \to b\bar{b}X$ ($\sqrt{s} = 14\,\text{TeV}$) LHC
Production cross-section	1 nb	$\sim 100\,\mu\text{b}$	$\sim 500\,\mu\text{b}$
Typical $b\bar{b}$ rate	10 Hz	$\sim 100\,\text{kHz}$	$\sim 500\,\text{kHz}$
Pile-up	0	1.7	0.5–20
b hadron mixture	B^+B^- (50%), $B^0\bar{B}^0$ (50%)	B^+ (40%), B^0 (40%), B_s^0 (10%), Λ_b^0 (10%), others ($< 1\%$)	
b hadron boost	small ($\beta\gamma \sim 0.5$)	large ($\beta\gamma \sim 100$)	
Underlying event	$B\bar{B}$ pair alone	Many additional particles	
Production vertex	Not reconstructed	Reconstructed from many tracks	
B^0–$\bar{B}^0$ pair production	Coherent (from $\Upsilon(4S)$ decay)	Incoherent	
Flavour tagging power	$\varepsilon D^2 \sim 30\%$	$\varepsilon D^2 \sim 5\%$	

How to design a B physics experiment?

- Depends on exactly what you want to measure
- Easier argument 20+ years ago for BaBar/Belle
  - Single golden mode ($B^0 \rightarrow J/\psi K_S$ to measure $\sin 2\beta$)
- Today there are many observables we want to study
  - e.g. anomalies showing up in places they were not expected
- Fortunately, general features (tracking, calorimetry + vertexing, particle ID) give good sensitivity to most
  - … and also enable a great deal of additional (non-B) physics
  - e.g. B physics experiments are also charm physics experiments

The Cabibbo-Kobayashi-Maskawa Quark Mixing Matrix

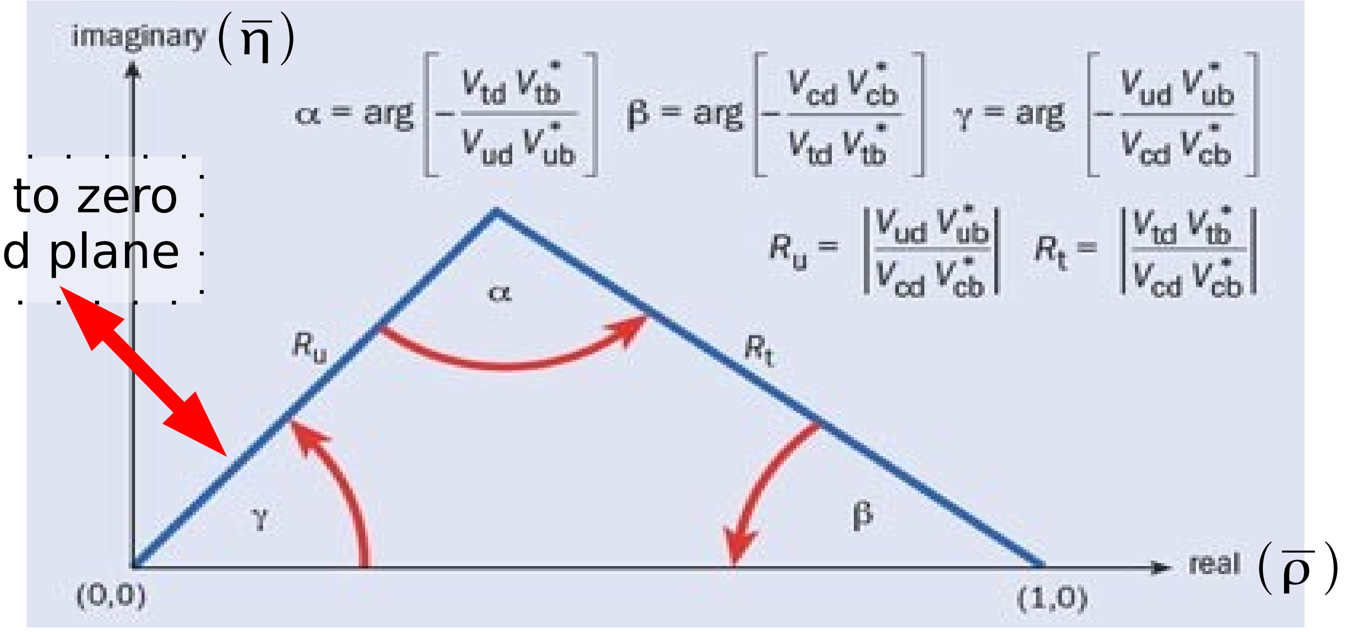
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- A 3x3 unitary matrix
- Described by 4 real parameters – allows CP violation
  - PDG (Chau-Keung) parametrisation: θ_{12}, θ_{23}, θ_{13}, δ
  - Wolfenstein parametrisation: λ, A, ρ, η
- Highly predictive

The Unitarity Triangle

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

Three complex numbers add to zero
⇒ triangle in Argand plane



Axes are $\overline{\rho}$ and $\overline{\eta}$ where

$$\overline{\rho}+i\overline{\eta} \equiv -\frac{V_{ud}V^{*}_{ub}}{V_{cd}V^{*}_{cb}}$$

$$\rho+i\eta = \frac{\sqrt{1-A^2\lambda^4}(\overline{\rho}+i\overline{\eta})}{\sqrt{1-\lambda^2}\left[1-A^2\lambda^4(\overline{\rho}+i\overline{\eta})\right]}$$

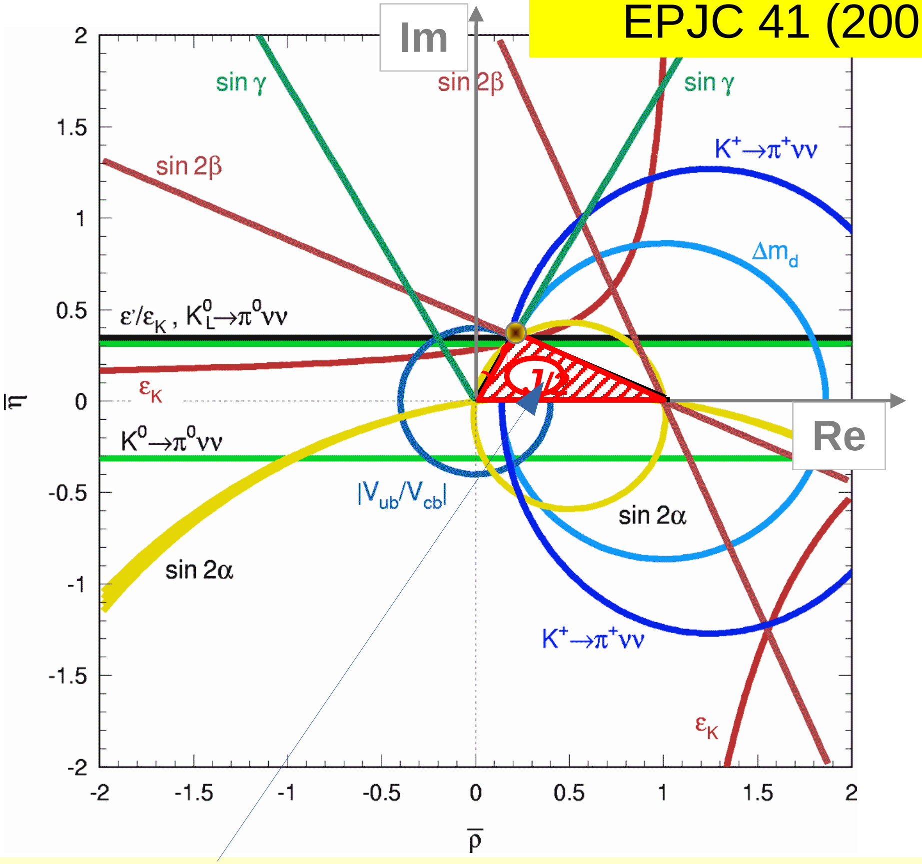
Predictive nature of KM mechanism

In the Standard Model the KM phase is the sole origin of CP violation

Hence:

all measurements must agree on the position of the apex of the Unitarity Triangle

(Illustration shown assumes no experimental or theoretical uncertainties)



EPJC 41 (2005) 1

Area of (all of) the Unitarity Triangle(s) is given by the Jarlskog invariant

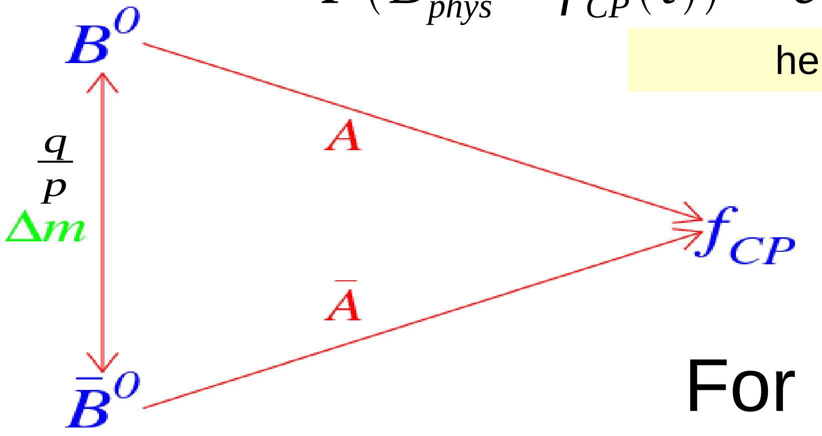
Decay-time-dependent CP violation in the B^0–$\overline{B}^0$ system

- For a B meson known to be 1) B^0 or 2) $\overline{B}^0$ at time t=0, then at later time t:

$$\Gamma\left(B^0_{phys}\rightarrow f_{CP}(t)\right)\propto e^{-\Gamma t}\left(1-\left(S\sin(\Delta m t)-C\cos(\Delta m t)\right)\right)$$

$$\Gamma\left(\overline{B}^0_{phys}\rightarrow f_{CP}(t)\right)\propto e^{-\Gamma t}\left(1+\left(S\sin(\Delta m t)-C\cos(\Delta m t)\right)\right)$$

here assume ΔΓ negligible – will see full expressions later



$$S=\frac{2\Im(\lambda_{CP})}{1+|\lambda^2_{CP}|}\qquad C=\frac{1-|\lambda^2_{CP}|}{1+|\lambda^2_{CP}|}\qquad \lambda_{CP}=\frac{q}{p}\frac{\overline{A}}{A}$$

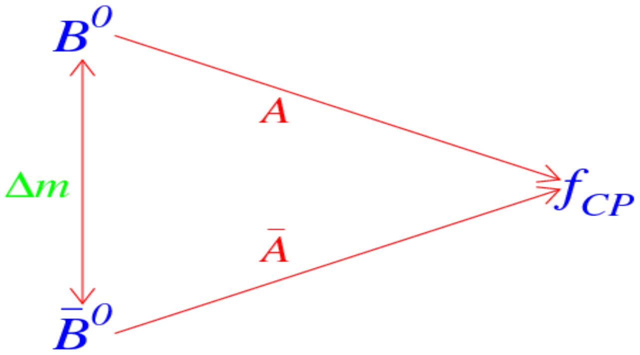
For $B^0\rightarrow J/\psi\, K_S$, $S=\sin(2\beta)$, $C=0$

NPB 193 (1981) 85

Categories of CP violation

- Consider decay of neutral particle to a CP eigenstate

$$\lambda_{CP} = \frac{q}{p}\frac{\overline{A}}{A}$$

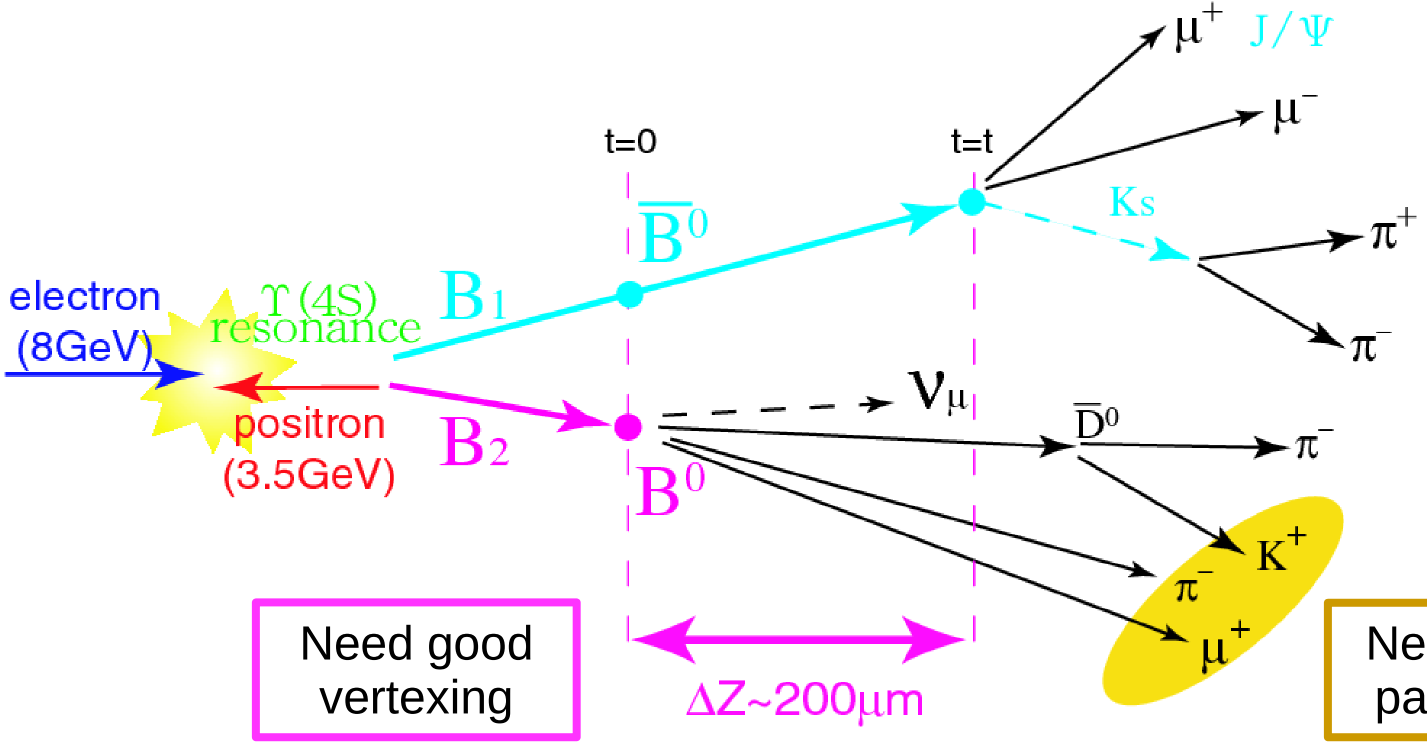


$\left\|\frac{q}{p}\right\| \neq 1$	CP violation in mixing
$\left\|\frac{\overline{A}}{A}\right\| \neq 1$	CP violation in decay
$\Im\left(\frac{q}{p}\frac{\overline{A}}{A}\right) \neq 0$	CP violation in interference between mixing and decay

Asymmetric B factory principle

To measure t require B meson to be moving

→ e^+e^- at threshold with asymmetric collisions (Oddone)



Need good vertexing

Need good particle ID

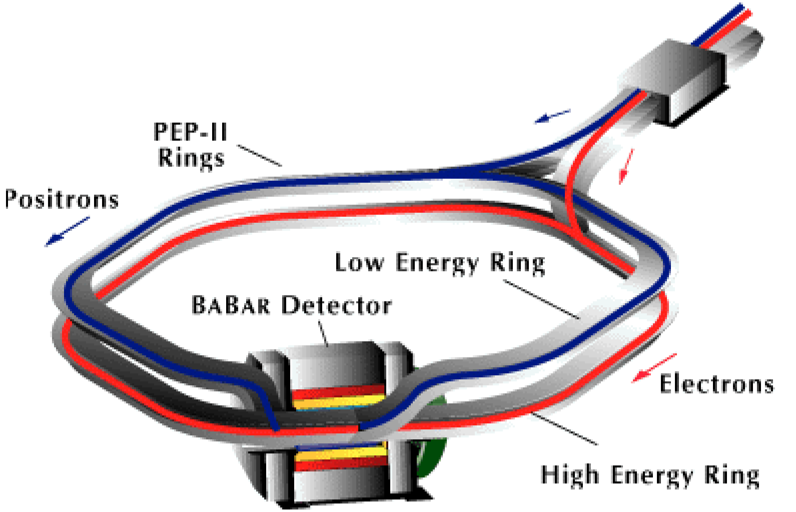
Asymmetric B Factories

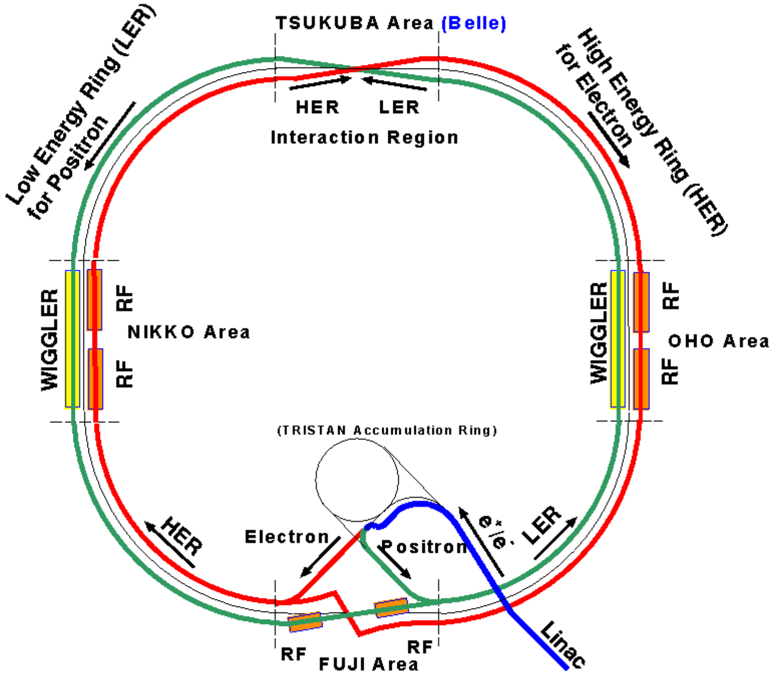
PEPII at SLAC

9.0 GeV e^- on 3.1 GeV e^+

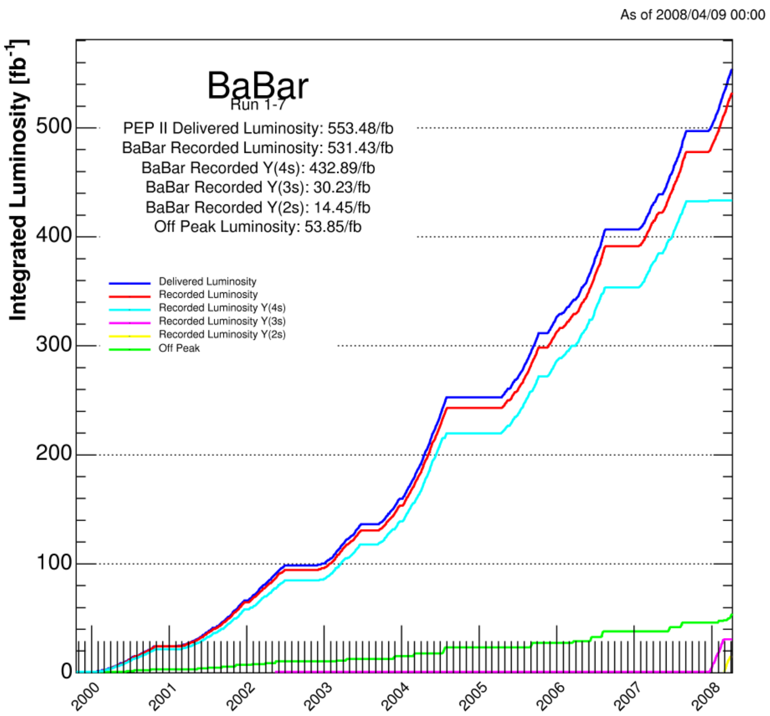
KEKB at KEK

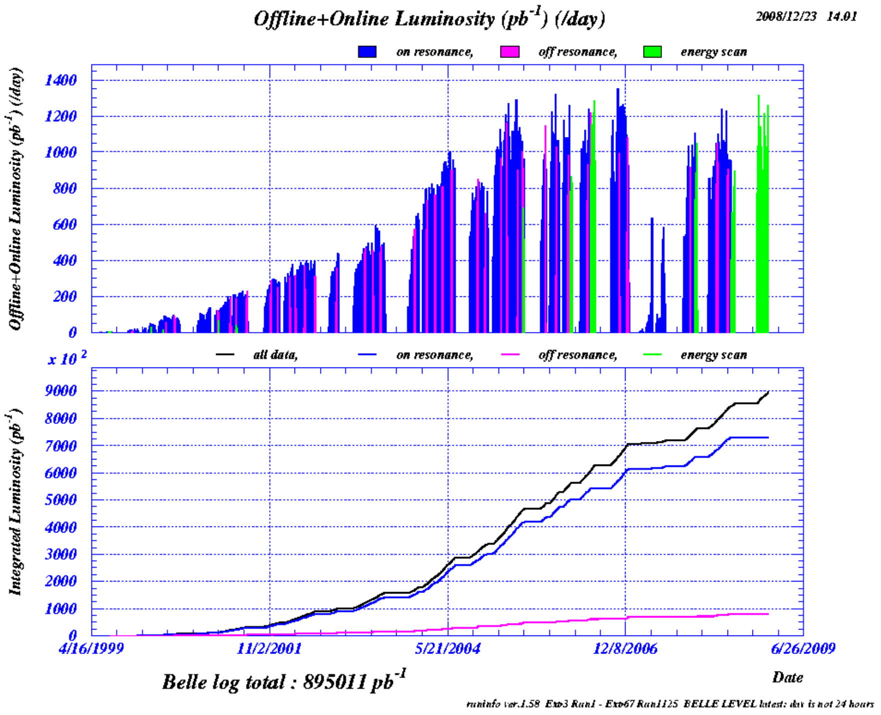
8.0 GeV e^- on 3.5 GeV e^+





B factories – world record luminosities



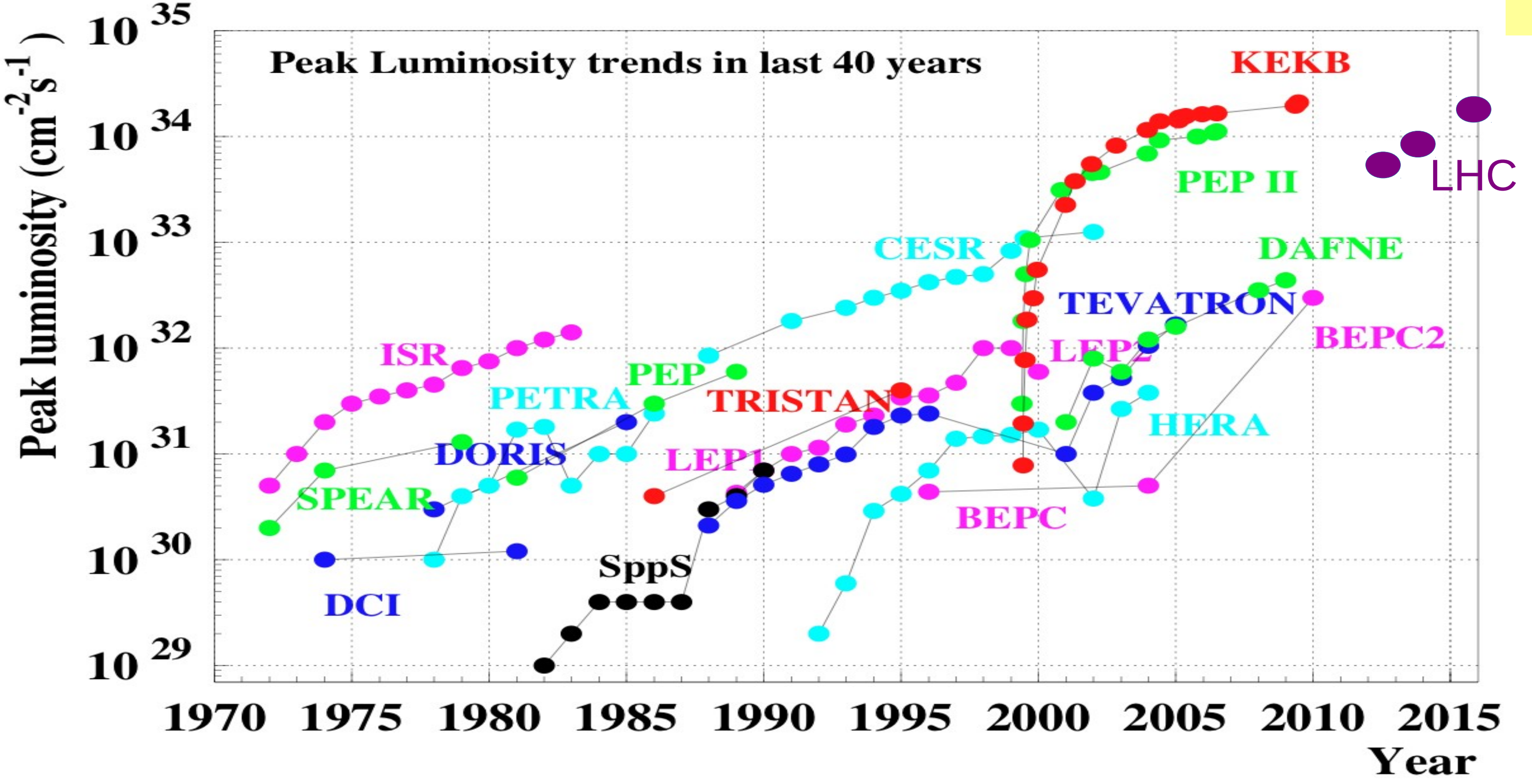


~ 433/fb on Y(4S) **~ 711/fb on Y(4S)**

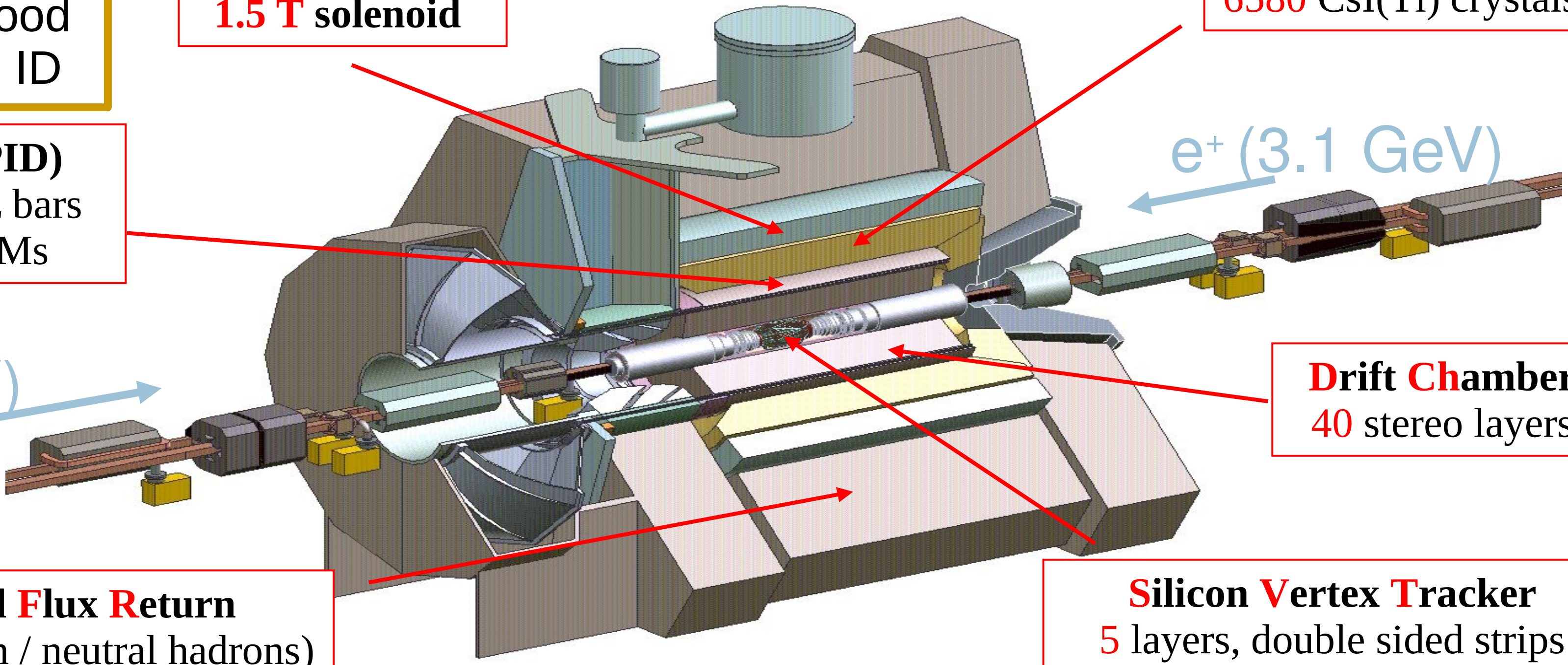
Total over 10^9 $B\bar{B}$ pairs recorded

World record luminosities (2)

SuperKEKB
& HL-LHC



BaBar Detector



Need good particle ID

1.5 T solenoid

EMC
6580 CsI(Tl) crystals

DIRC (PID)
144 quartz bars
11000 PMs

Drift Chamber
40 stereo layers

Instrumented Flux Return
iron / RPCs (muon / neutral hadrons)
2/6 replaced by LST in 2004
Rest of replacement in 2006

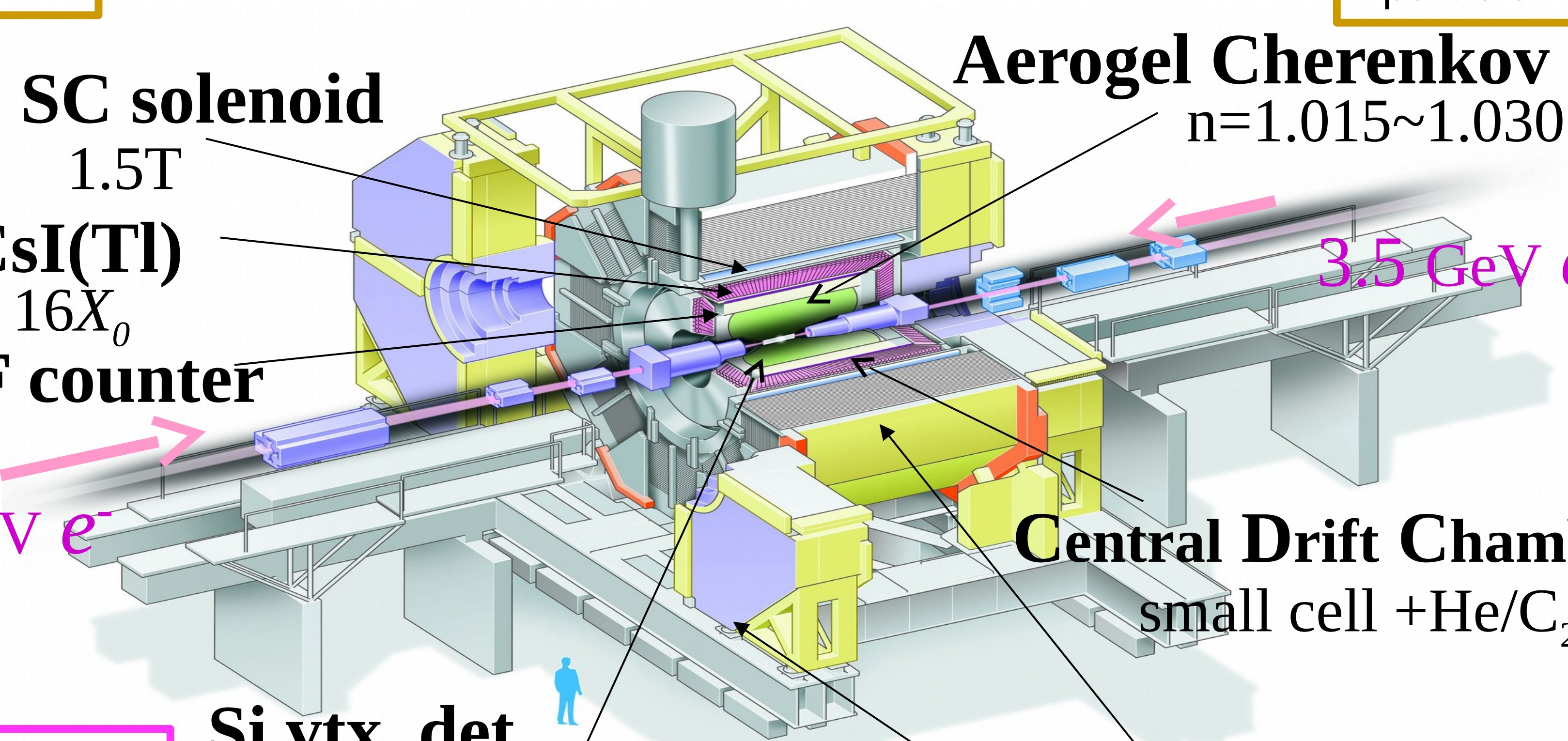
Silicon Vertex Tracker
5 layers, double sided strips

Need good vertexing

Belle Detector

Need good particle ID

Need good particle ID



SC solenoid
1.5T

CsI(Tl)
$16X_0$

TOF counter

Aerogel Cherenkov cnt.
n=1.015~1.030

3.5 GeV e^+

8 GeV e^-

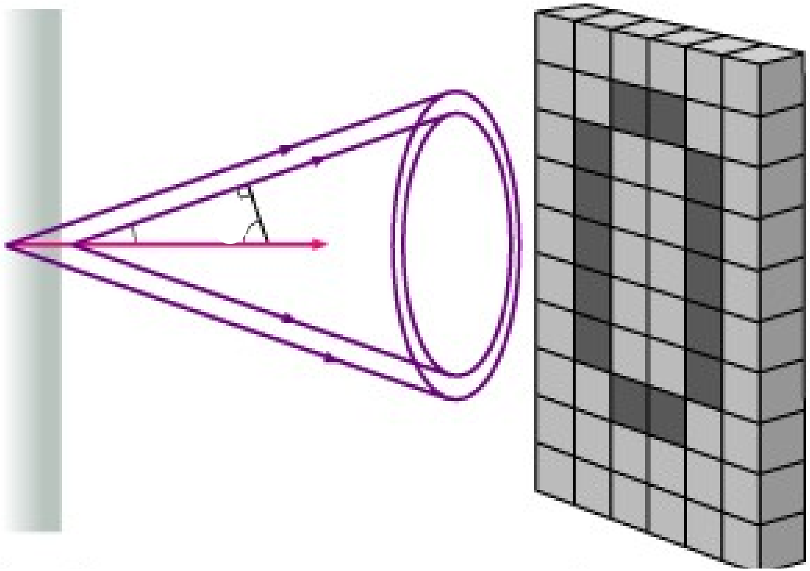
Central Drift Chamber
small cell +He/C$_2$H$_6$

Si vtx. det.
- 3 lyr. DSSD
- 4 lyr. since summer 2003

μ / K_L detection
14/15 lyr. RPC+Fe

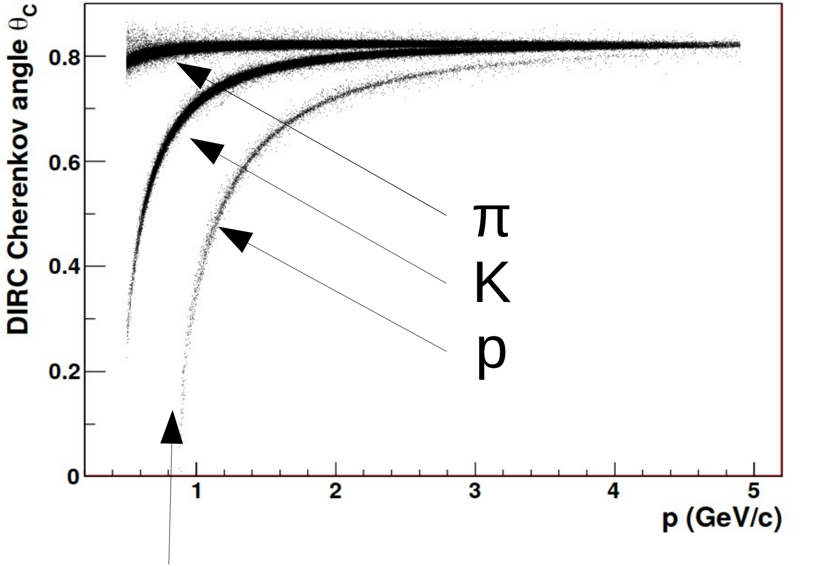
Need good vertexing

Particle ID with Cherenkov radiation



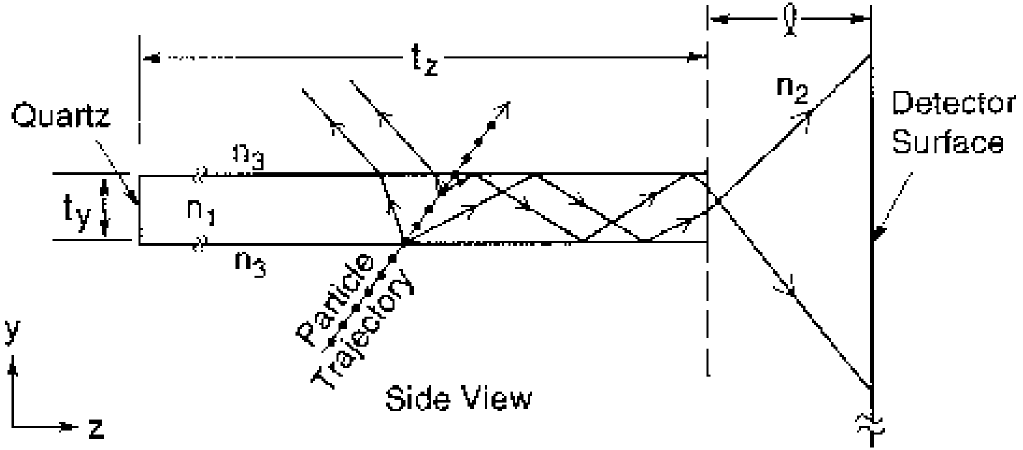
Particle travelling above speed of light in medium (with refractive index n) emits light in cone with opening angle given by
$\cos\theta_c = 1/(\beta n)$

BaBar DIRC: quartz radiator (n = 1.473)



Thresholds also provide separation

Particle ID with Cherenkov radiation



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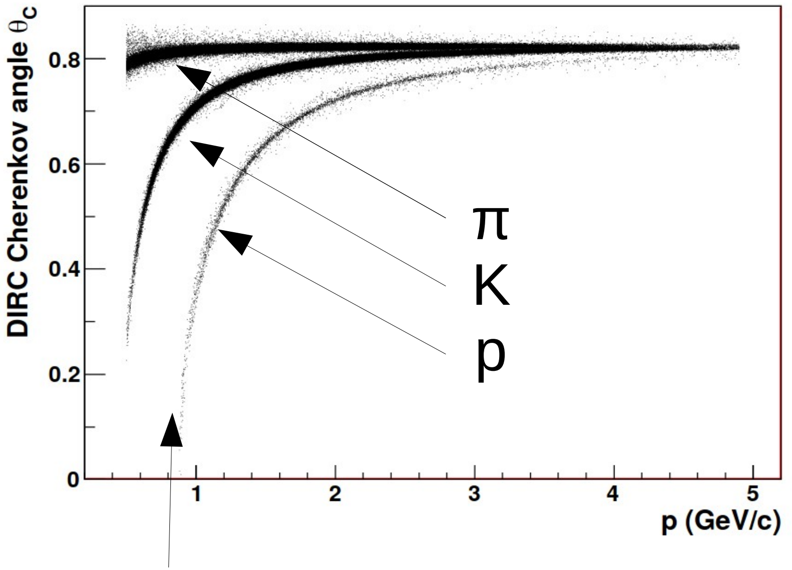


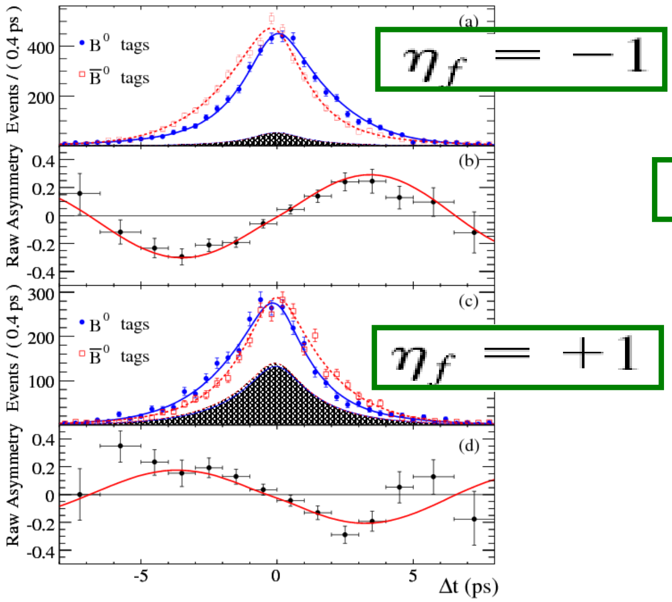
Thresholds also provide separation

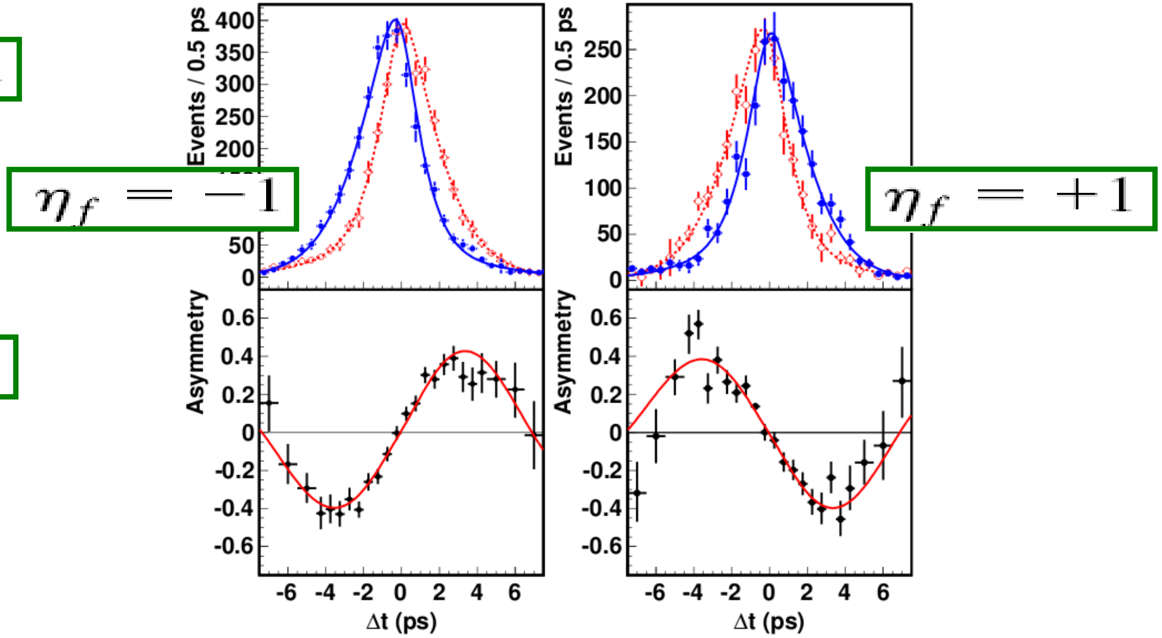
Results for the golden mode

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

BABAR

BELLE





PRD 79 (2009) 072009

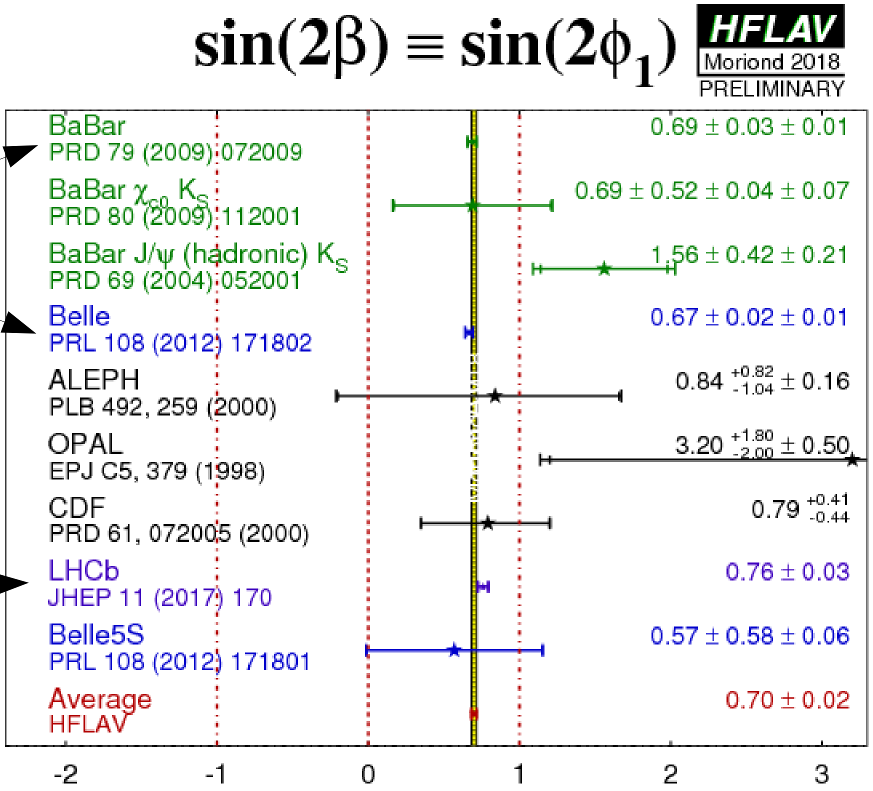
PRL 108 (2012) 171802

Asymmetry ≈ (1–2w) sin(2β) sin(ΔmΔt)

Compilation of results

Results on previous slide

Note LHCb also highly competitive



World average sin(2β) = 0.699 ± 0.017

A brief history of CP violation and Nobel Prizes

- 1964 – Discovery of CP violation in K^0 system

PRL 13 (1964) 138

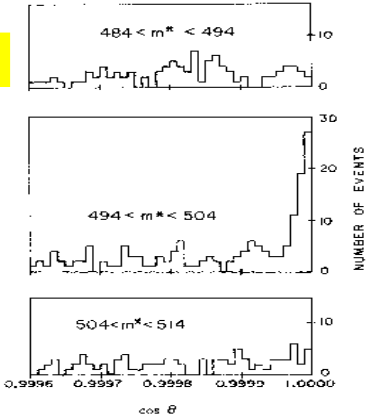


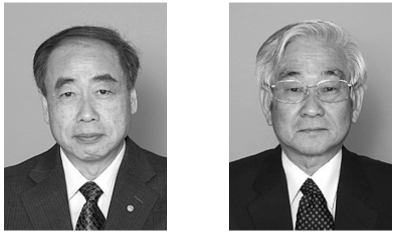
FIG. 3. Angular distribution in three mass ranges for events with cosθ > 0.9995.

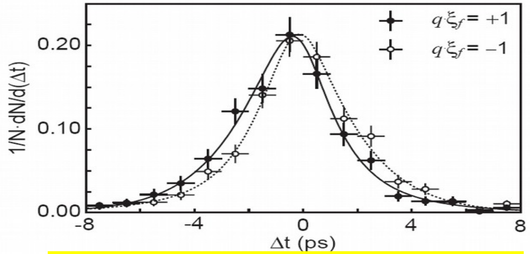
- 1973 – Kobayashi and Maskawa propose 3 generations

Prog.Theor.Phys. 49 (1973) 652

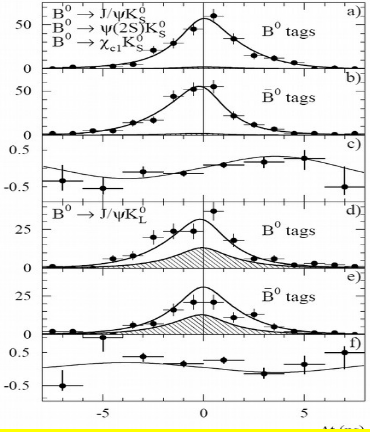
- 1980 – Nobel Prize to Cronin and Fitch

- 2001 – Discovery of CP violation in B_d system
- 2008 – Nobel Prize to Kobayashi and Maskawa



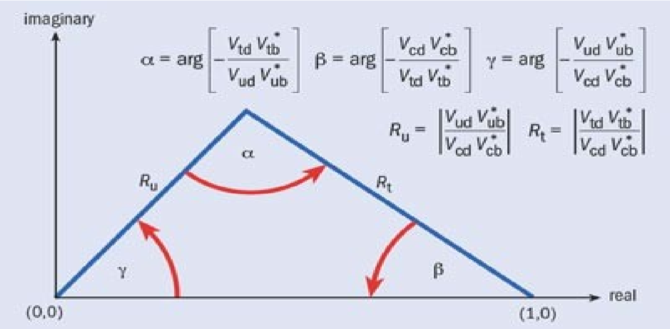


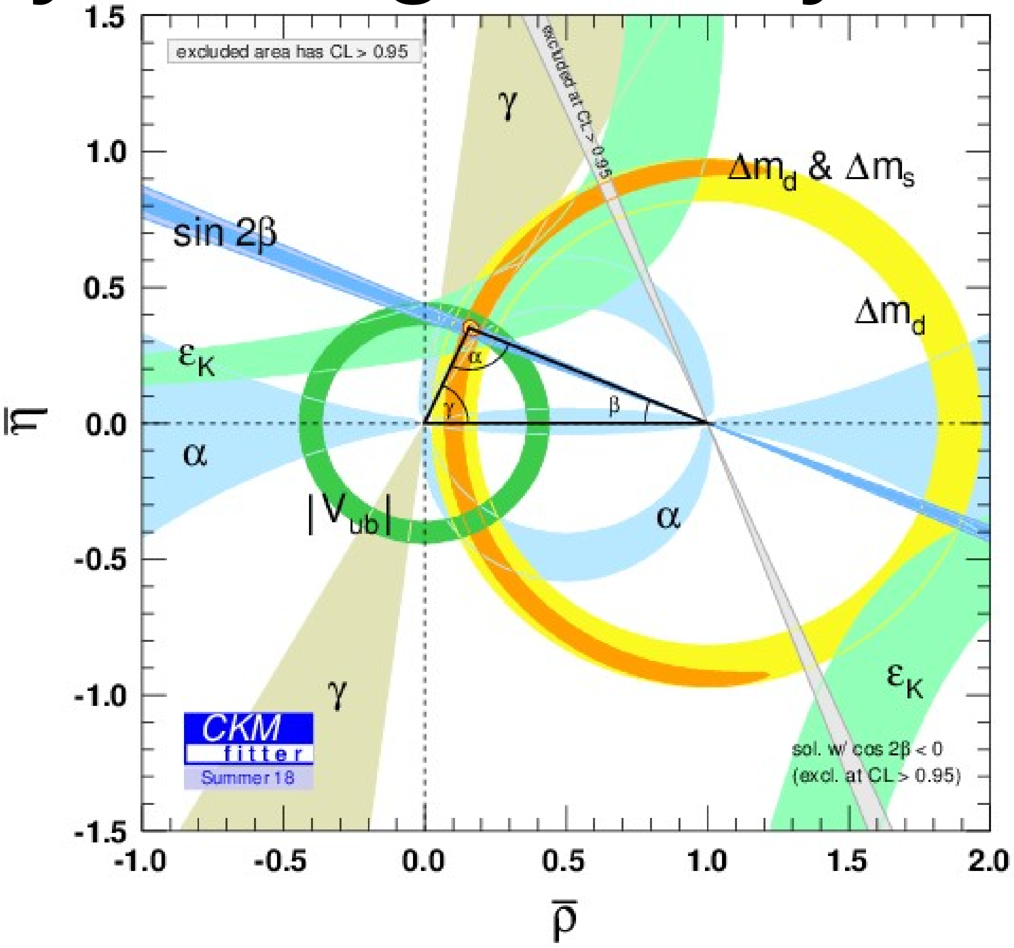
Belle PRL 87 (2001) 091802



BABAR PRL 87 (2001) 091801

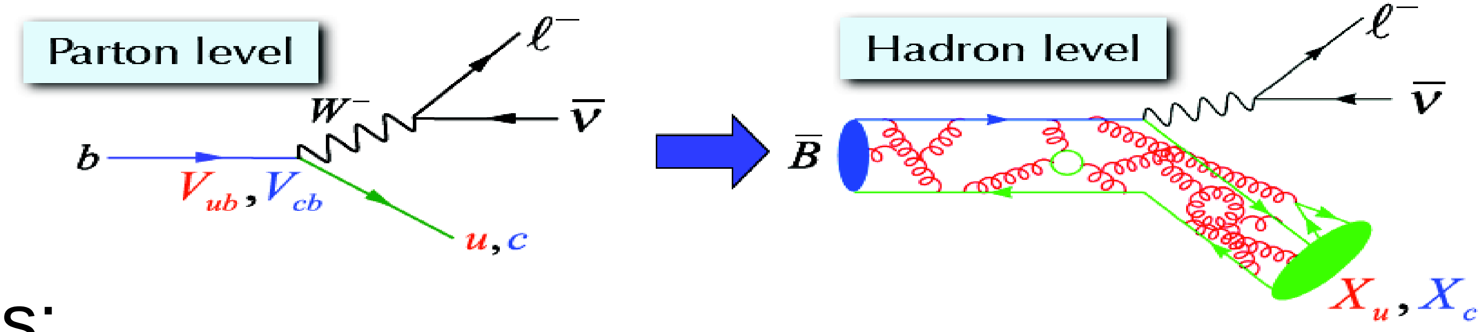
Unitarity Triangle today





R_u side from semileptonic decays

$$R_u = \left| \frac{V_{ud} V_{ub}^*}{V_{cd} V_{cb}^*} \right|$$



- Approaches:
  - exclusive semileptonic B decays, e.g. $B^0 \to \pi^- e^+ \nu$
    - require knowledge of form factors (lattice QCD)
  - inclusive semileptonic B decays, e.g. $B \to X_u e^+ \nu$
    - clean theory in principle
    - but experimentally need to reject b → c background
      - re-introduce theoretical uncertainties

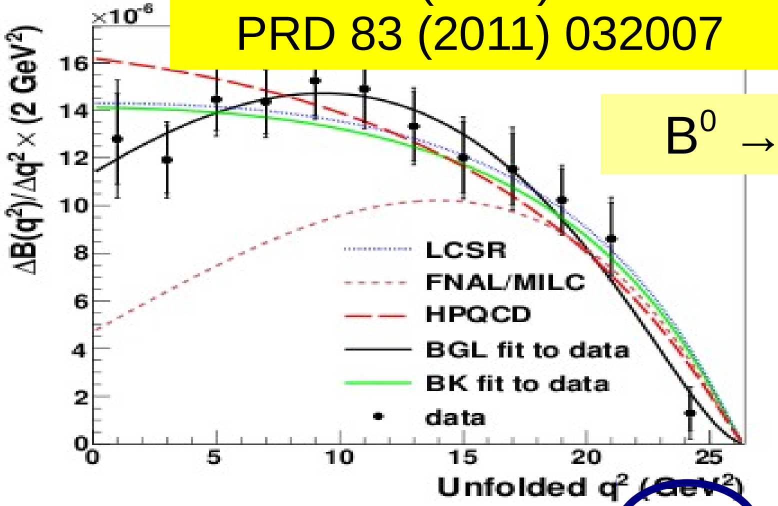
$|V_{ub}|$ from exclusive semileptonic decays

Current best measurements use $B^0 \rightarrow \pi^- l^+ \nu$

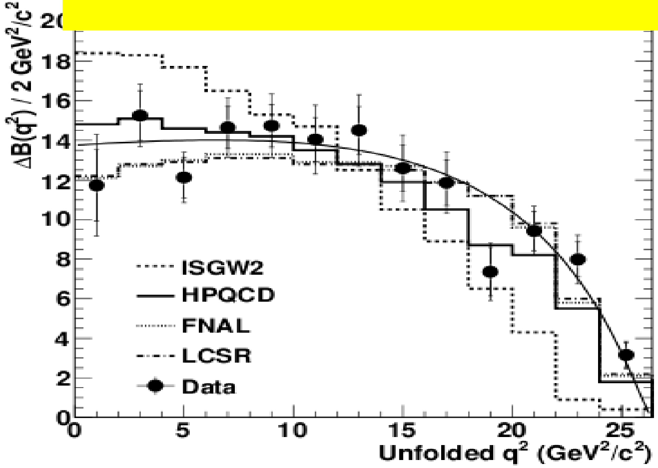
(recent competitive measurement from LHCb with $\Lambda_b \rightarrow p \mu \nu$)

BaBar experiment
PRD 83 (2011) 052011
PRD 83 (2011) 032007

Belle experiment
PRD 83 (2011) 071101(R)



$B^0 \rightarrow \pi^- l \nu$



$$|V_{ub}| = (3.09 \pm 0.08 \pm 0.12 {}^{+0.35}_{-0.29}) \times 10^{-3}$$

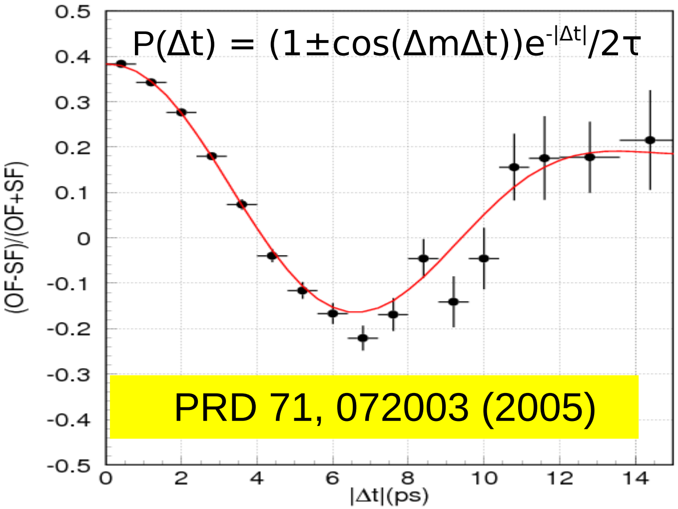
$$|V_{ub}| = (3.43 \pm 0.33) \times 10^{-3}$$

lattice uncertainty

R_t side from B^0–$\overline{B}^0$ mixing

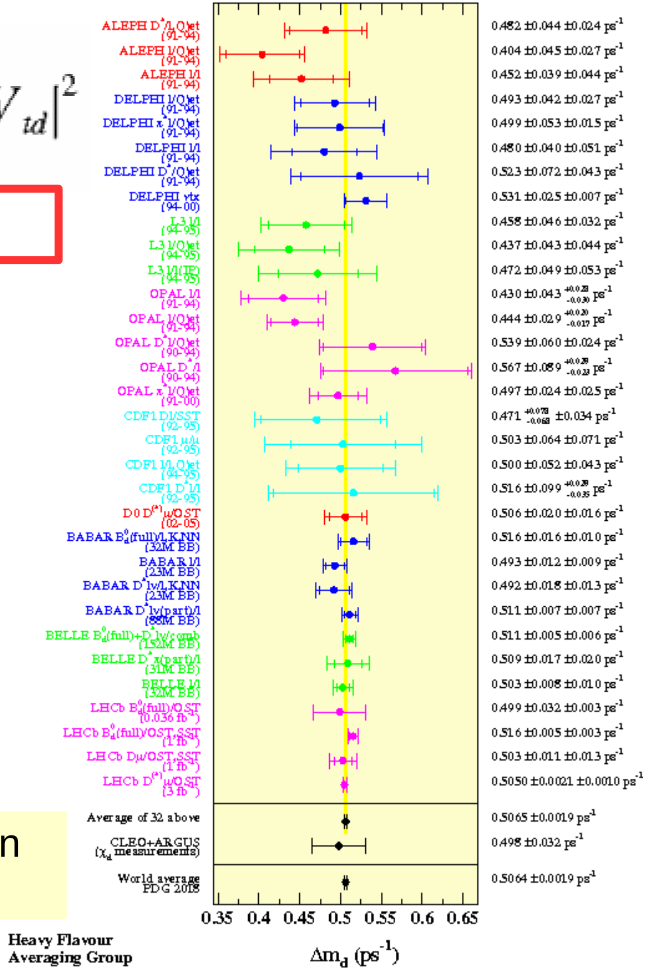
$$R_t = \left| \frac{V_{td} V_{tb}^*}{V_{cd} V_{cb}^*} \right| \quad \& \quad \Delta m_d = \frac{G_F^2}{6\pi^2} m_W^2 \underline{\eta_b S(x_t) m_{B_d} f_{B_d}^2 \hat{B}_{B_d}} |V_{tb}|^2 |V_{td}|^2$$

sources of theory uncertainty



$P(\Delta t) = (1 \pm \cos(\Delta m \Delta t)) e^{-|\Delta t|}/2\tau$

PRD 71, 072003 (2005)

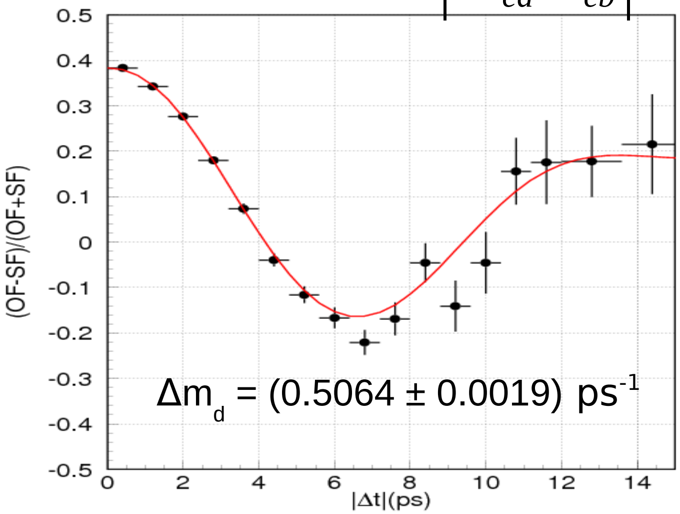


Heavy Flavour
Averaging Group

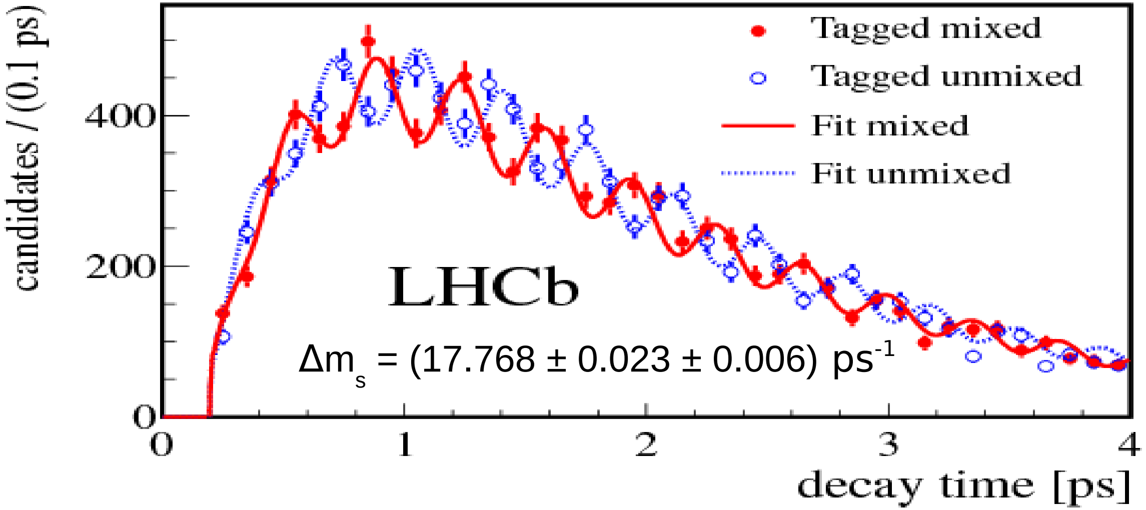
World average based on
many measurements

R_t side from B^0–$\overline{B}^0$ mixing

$$R_t = \left|\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}\right| \quad \& \quad \frac{\Delta m_d}{\Delta m_s} = \frac{m_{B_d} f_{B_d}^2 \hat{B}_{B_d}}{m_{B_s} f_{B_s}^2 \hat{B}_{B_s}} \frac{|V_{td}|^2}{|V_{ts}|^2}$$



$\Delta m_d = (0.5064 \pm 0.0019)\ \text{ps}^{-1}$



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

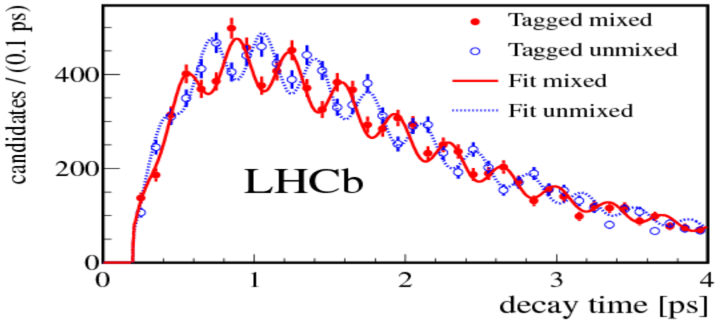
NJP 15 (2013) 053021

$$|V_{td}/V_{ts}| = 0.216 \underset{\substack{\uparrow \\ \text{experimental} \\ \text{uncertainty}}}{\pm 0.001} \underset{\substack{\uparrow \\ \text{theoretical} \\ \text{uncertainty}}}{\pm 0.011}$$

How to measure B_s oscillations?

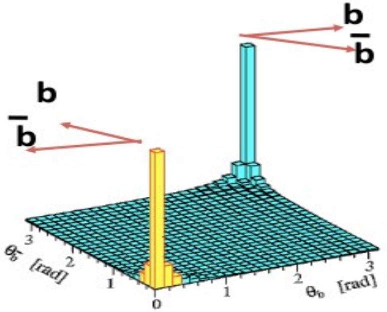
- [First done by CDF, but excelled at by LHCb]

- Produce B_s mesons … with a large boost
  - high-energy hadron collisions
- Measure their flight distance and momentum
  - need excellent vertexing performance
- Measure their flavour at production and decay
  - initial state flavour tagging (particle identification)
  - final state such as $D_s^- \pi^+$ ideal (no leptons!)

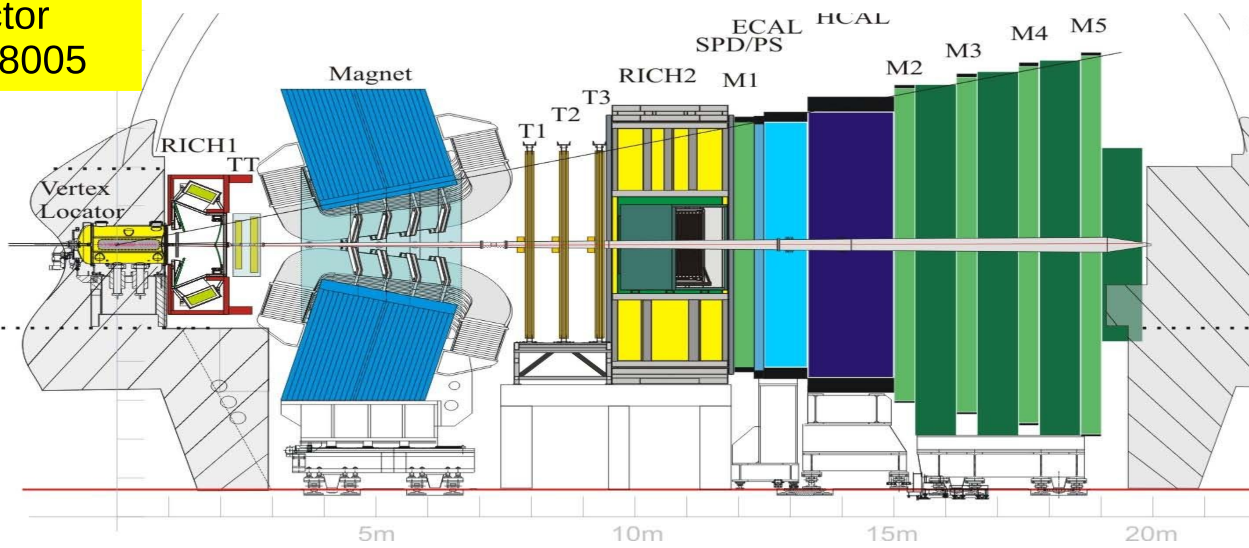


LHCb experiment

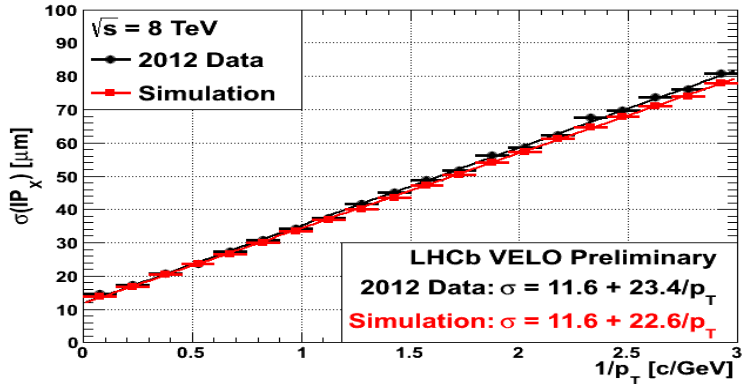
- In high energy collisions, $b\bar{b}$ pairs produced predominantly in forward or backward directions
- LHCb is a forward spectrometer

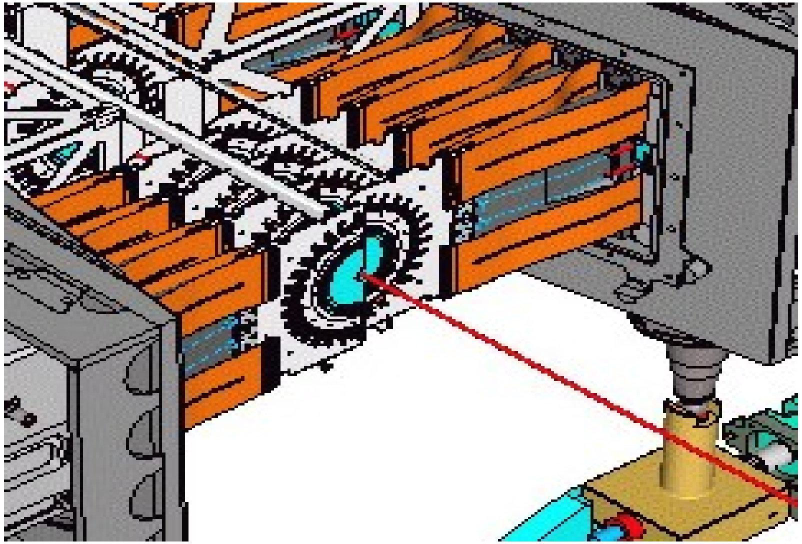


The LHCb Detector
JINST 3 (2008) S08005

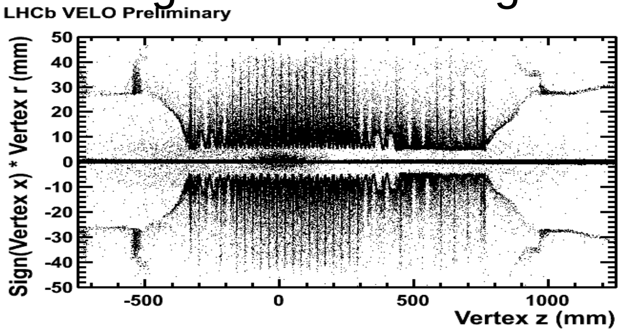


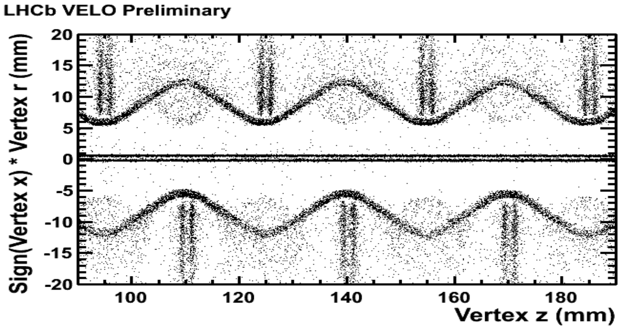
VELO





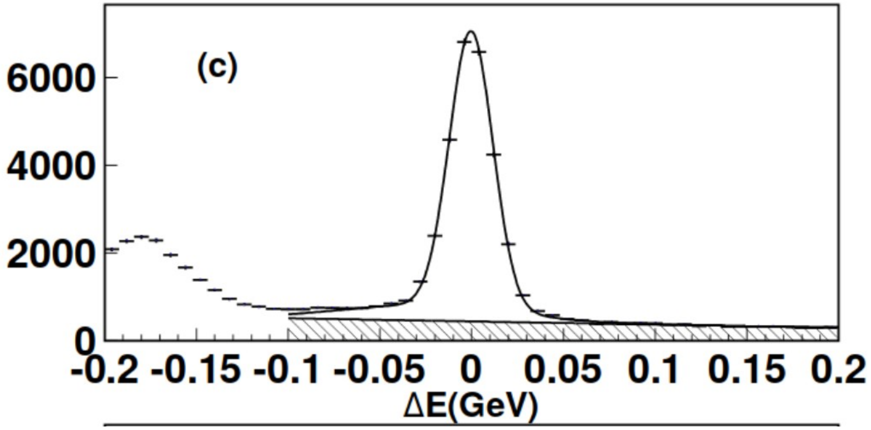
Material imaged used beam gas collisions

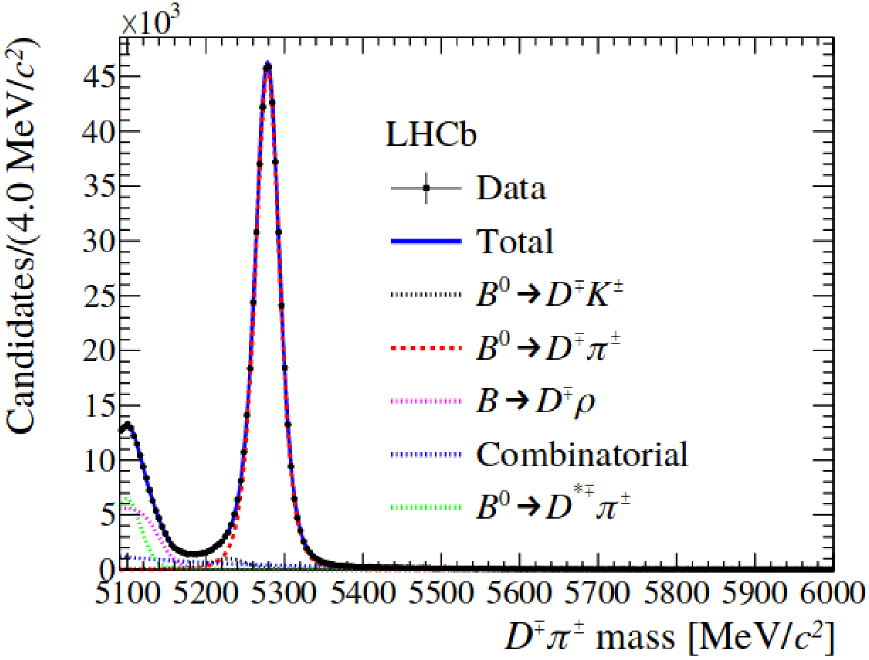


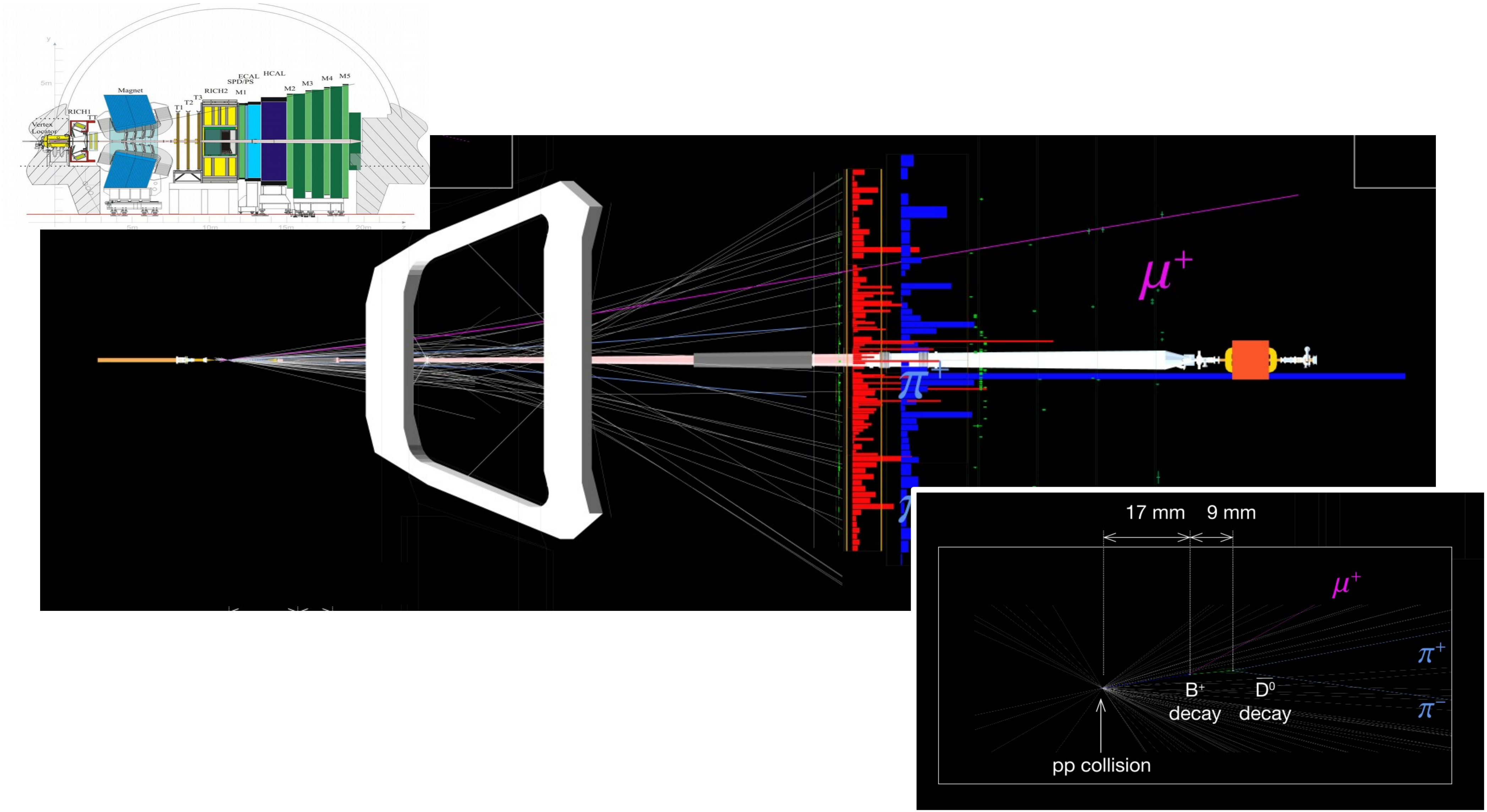


Vertexing kills background

Comparison of (left) Belle and (right) LHCb signals for $B^0 \rightarrow D^- \pi^+$
Which is the “low background” environment?

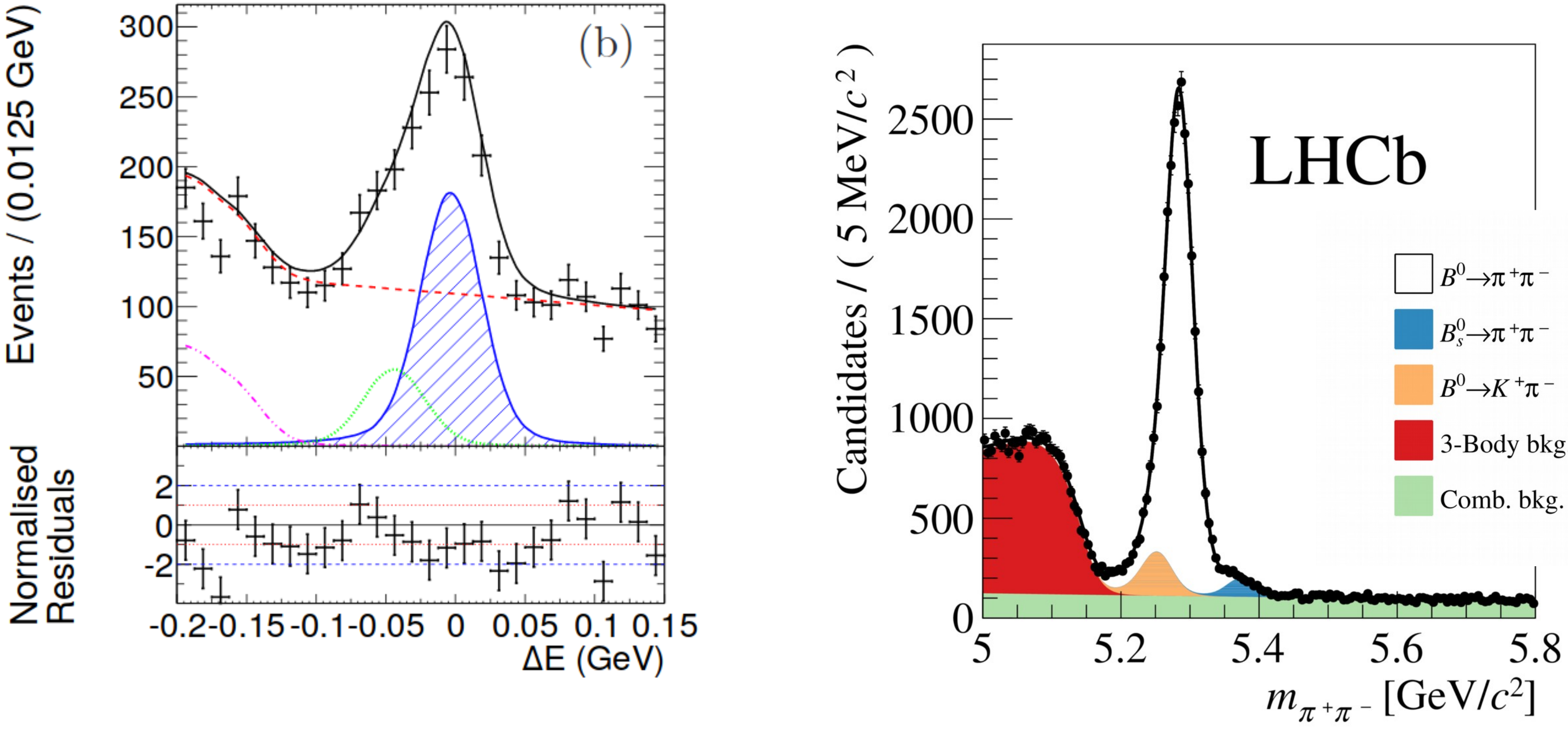





y
5m
Vertex Locator
RICH1
TT
Magnet
T1
T2
T3
RICH2
SPD/PS
ECAL
M1
HCAL
M2
M3
M4
M5
5m
10m
15m
20m
z
μ^+
π^+
17 mm
9 mm
μ^+
π^+
π^-
B^+ decay
$\overline{D}^0$ decay
pp collision

Particle ID kills other backgrounds

Comparison of (left) Belle and (right) LHCb signals for $B^0 \to \pi^- \pi^+$



Tomorrow

- More key observables
  - CP violation in decay: the CKM angle γ
  - CP violation in the B_s system
  - Rare decays: $B_{(s)} \rightarrow \mu^+\mu^-$, $B \rightarrow K^{(*)}l^+l^-$, $B \rightarrow K^{(*)}\nu\bar{\nu}$
- Future B physics experiments
  - Belle II
  - LHCb upgrades