Flavour Physics in the LHC Era
Lecture 2 of 3

Tim Gershon
University of Warwick & CERN

HCPSS 2015
2 July 2015

Contents

- Part 1
  - Why is flavour physics interesting?
- Part 2
  - What do we know from previous experiments?
- Part 3
  - What do we hope to learn from current and future heavy flavour experiments?

Today hope to cover Part 2 & start Part 3

(but let's see how we go)

What do we know about heavy quark flavour physics as of today?

CKM Matrix : parametrizations

- Many different possible choices of 4 parameters
- PDG: 3 mixing angles and 1 phase

PRL 53 (1984) 1802

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

- Apparent hierarchy: $s_{12} \sim 0.2$, $s_{23} \sim 0.04$, $s_{13} \sim 0.004$
  - Wolfenstein parametrization (expansion parameter $\lambda \sim \sin\theta_c \sim 0.22$)

PRL 51 (1983) 1945

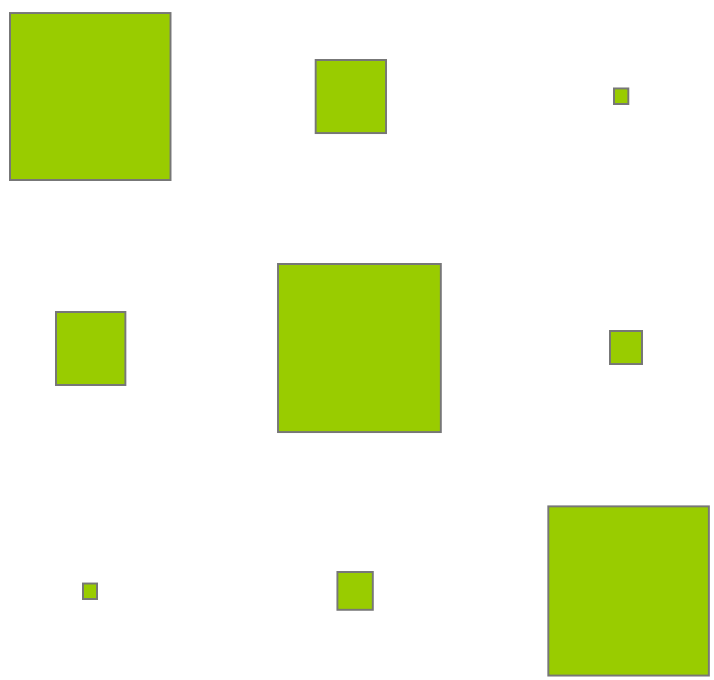
$$V = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}\left(\lambda^4\right)$$

- Other choices, eg. based on CP violating phases

PLB 680 (2009) 328

Hierarchy in quark mixing

$$V = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}\left(\lambda^4\right)$$



Very suggestive pattern

No known underlying reason

Situation for leptons (νs) is completely different

CKM matrix to O(λ^5)

$$V_{\rm CKM} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda+\frac{1}{2}A^2\lambda^5[1-2(\rho+i\eta)] & 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4(1+4A^2) & A\lambda^2 \\ A\lambda^3[1-(1-\frac{1}{2}\lambda^2)(\rho+i\eta)] & -A\lambda^2+\frac{1}{2}A\lambda^4[1-2(\rho+i\eta)] & 1-\frac{1}{2}A^2\lambda^4 \end{pmatrix}$$

imaginary part at O(λ^3)

imaginary part at O(λ^4)

imaginary part at O(λ^5)

Remember – only *relative* phases are observable

Unitarity Tests

- The CKM matrix must be unitary

$$V_{CKM}^{+} V_{CKM} = V_{CKM} V_{CKM}^{+} = 1$$

- Provides numerous tests of constraints between independent observables, such as

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$
$$V_{ud} V_{ub}^{*} + V_{cd} V_{cb}^{*} + V_{td} V_{tb}^{*} = 0$$

CKM Matrix – Magnitudes

PDG 2014

$$\begin{pmatrix} 0.97425 \pm 0.00022 & 0.2253 \pm 0.0008 & (4.13 \pm 0.49) \times 10^{-3} \\ 0.225 \pm 0.008 & 0.986 \pm 0.016 & (41.1 \pm 1.3) \times 10^{-3} \\ (8.4 \pm 0.6) \times 10^{-3} & (40.0 \pm 2.7) \times 10^{-3} & 1.021 \pm 0.032 \end{pmatrix}$$

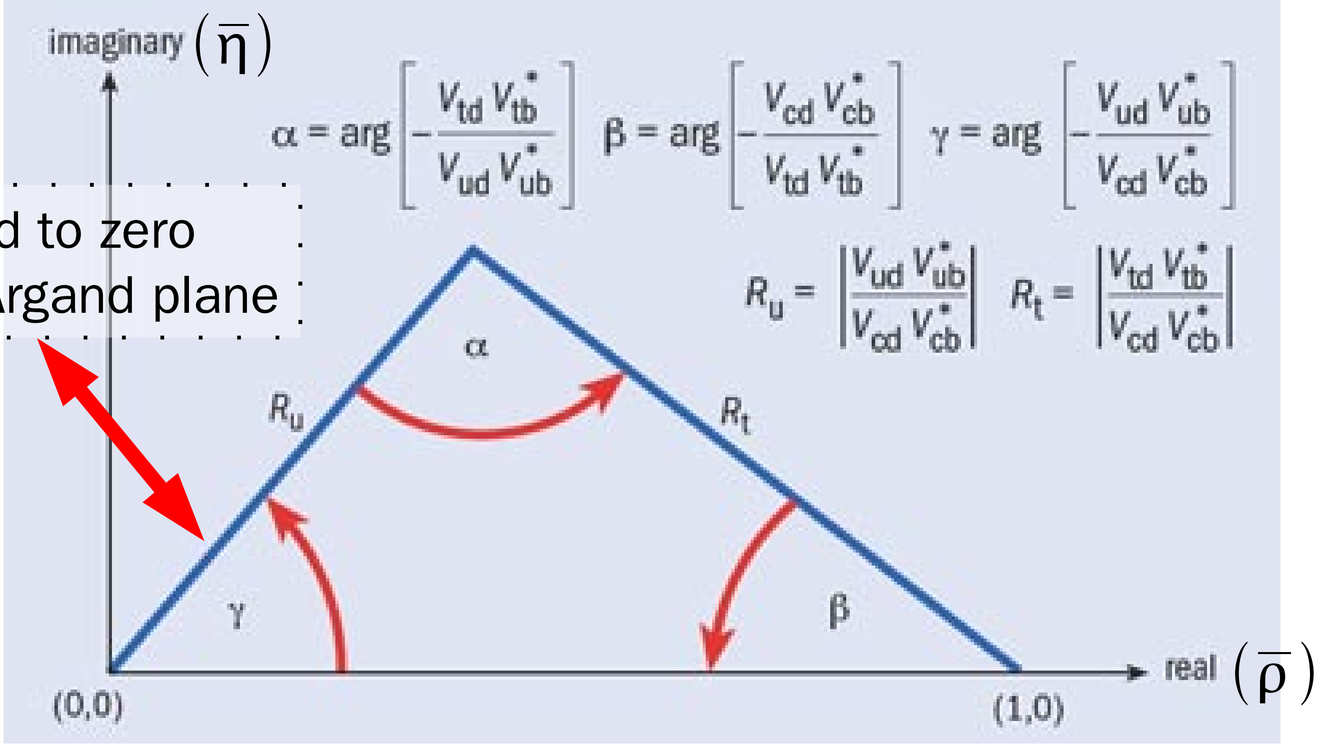
- superallowed $0^+ \rightarrow 0^+$ β decays (V_{ud})
- semileptonic / leptonic kaon decays, hadronic tau decays (V_{us})
- semileptonic / leptonic B decays (V_{ub})
- semileptonic charm decays, charm production in neutrino beams (V_{cd})
- semileptonic / leptonic charm decays (V_{cs})
- semileptonic B decays (V_{cb})
- B_d oscillations (V_{td})
- B_s oscillations (V_{ts})
- single top production (V_{tb})

theory inputs (eg., lattice calculations) required

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

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

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

Predictive nature of KM mechanism

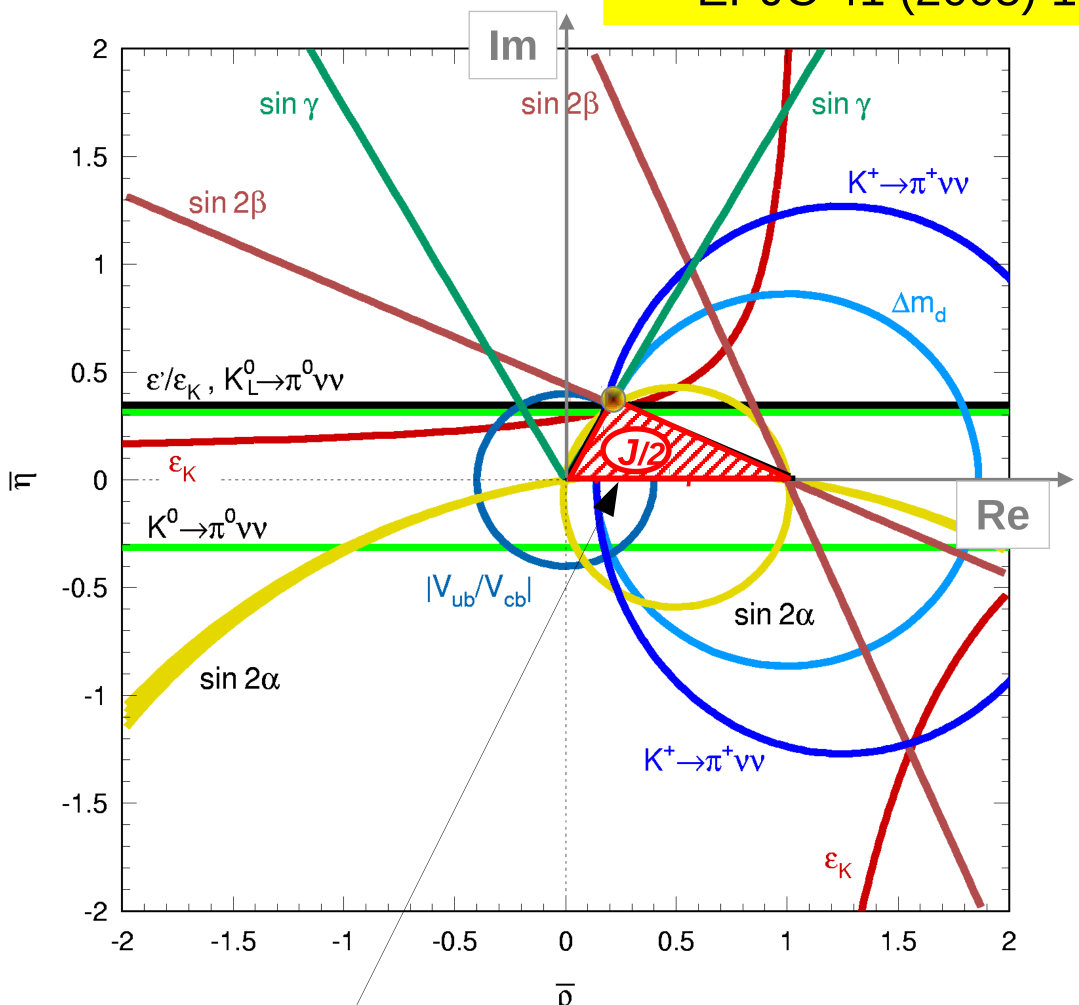
EPJC 41 (2005) 1

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)

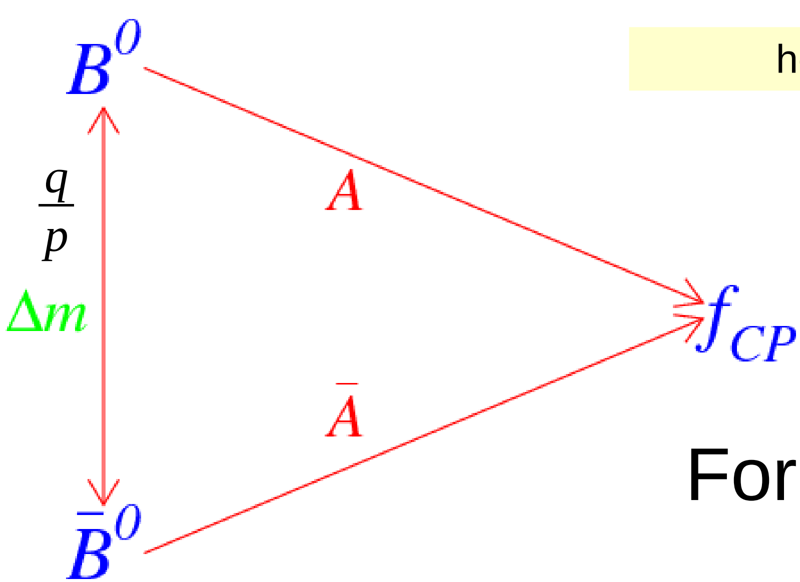


Area of (all of) the Unitarity Triangle(s) is given by the Jarlskog invariant

Time-Dependent CP Violation in the B^0–$\bar{B}^0$ System

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

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



here assume ΔΓ negligible – will see full expressions later

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

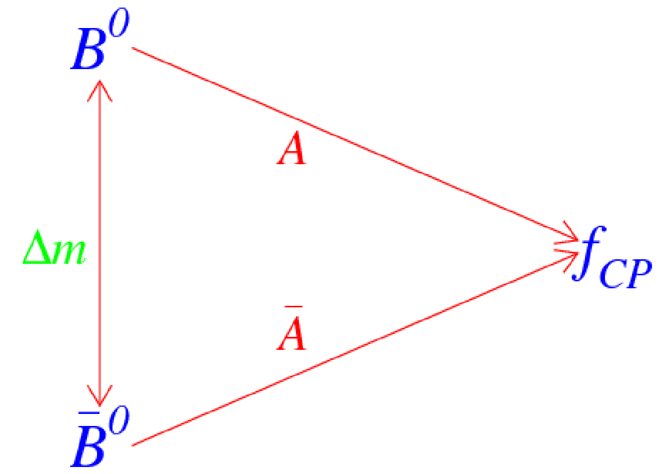
For $B^0 \to J/\psi\, K_S$, $S = \sin(2\beta)$, $C=0$

NPB 193 (1981) 85

Categories of CP violation

- Consider decay of neutral particle to a CP eigenstate

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



$$\left|\frac{q}{p}\right| \neq 1$$

CP violation in mixing

$$\left|\frac{\bar{A}}{A}\right| \neq 1$$

CP violation in decay

$$\Im\left(\frac{q}{p}\frac{\bar{A}}{A}\right) \neq 0$$

CP violation in interference between mixing and decay

Asymmetric B factory principle

To measure t require B meson to be moving

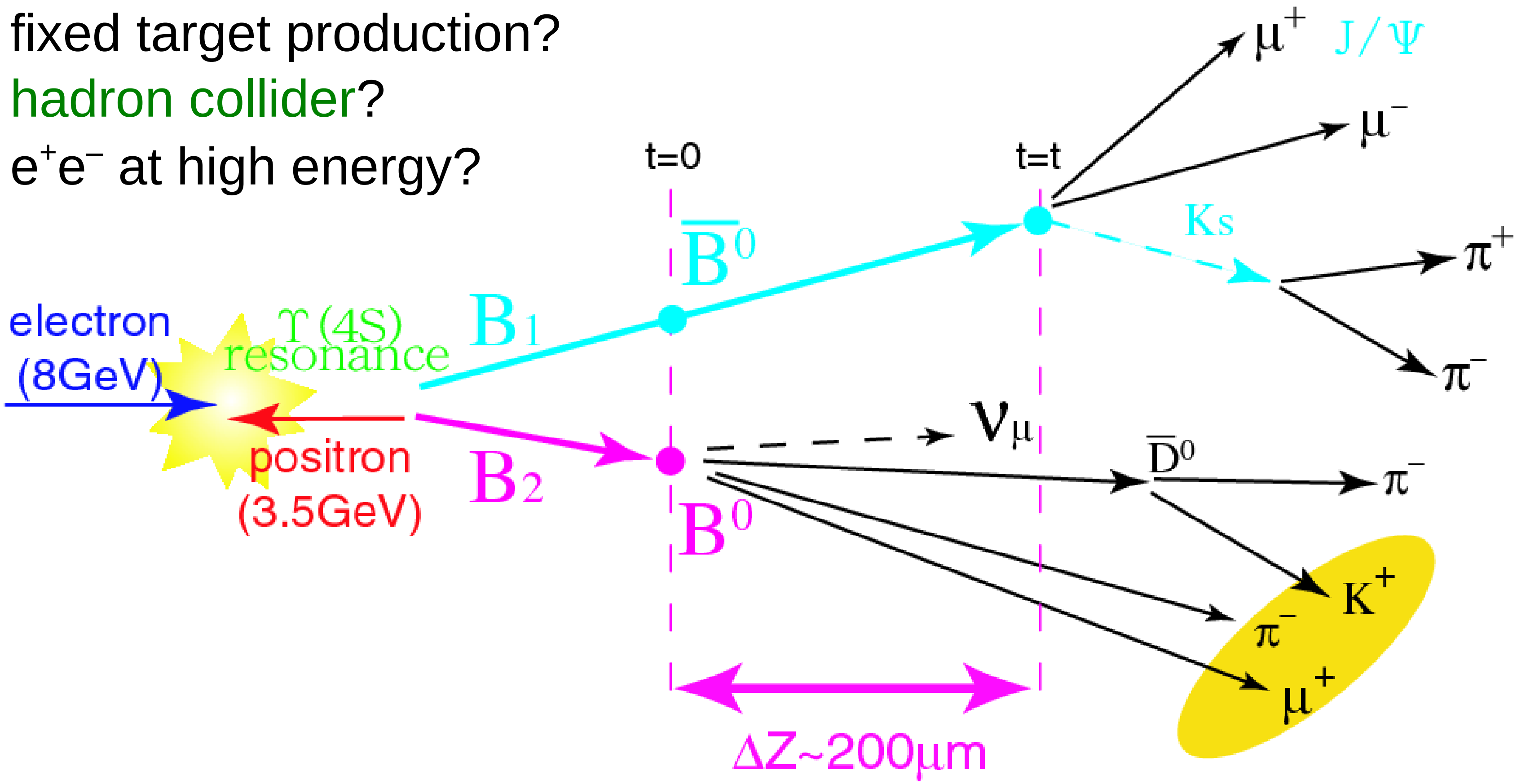
→ e^+e^- at threshold with asymmetric collisions (Oddone)

Other possibilities considered

→ fixed target production?

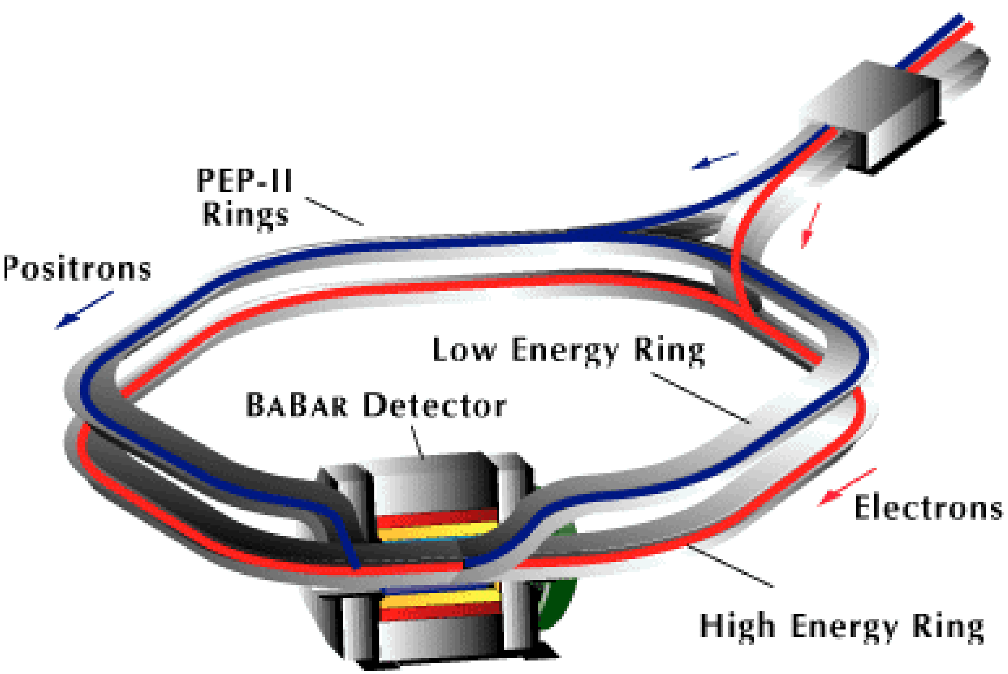
→ hadron collider?

→ e^+e^- at high energy?

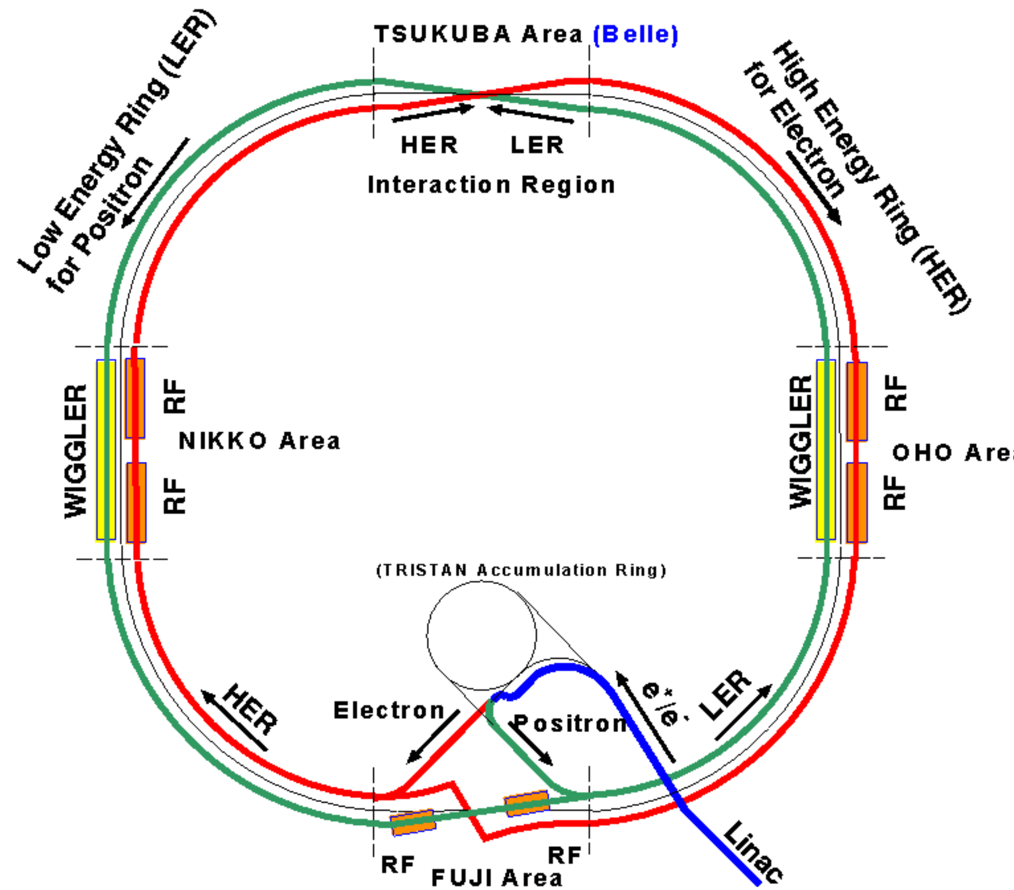


Asymmetric B Factories

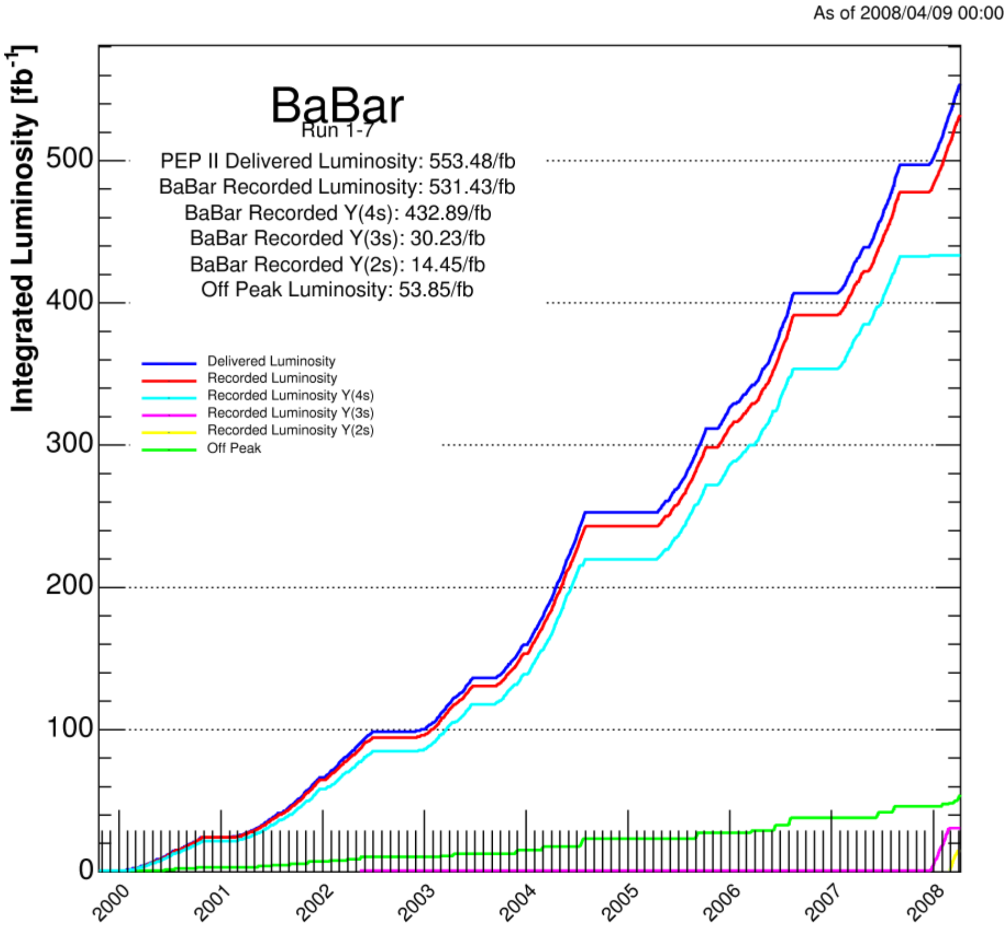
PEPII at SLAC
9.0 GeV e^- on 3.1 GeV e^+

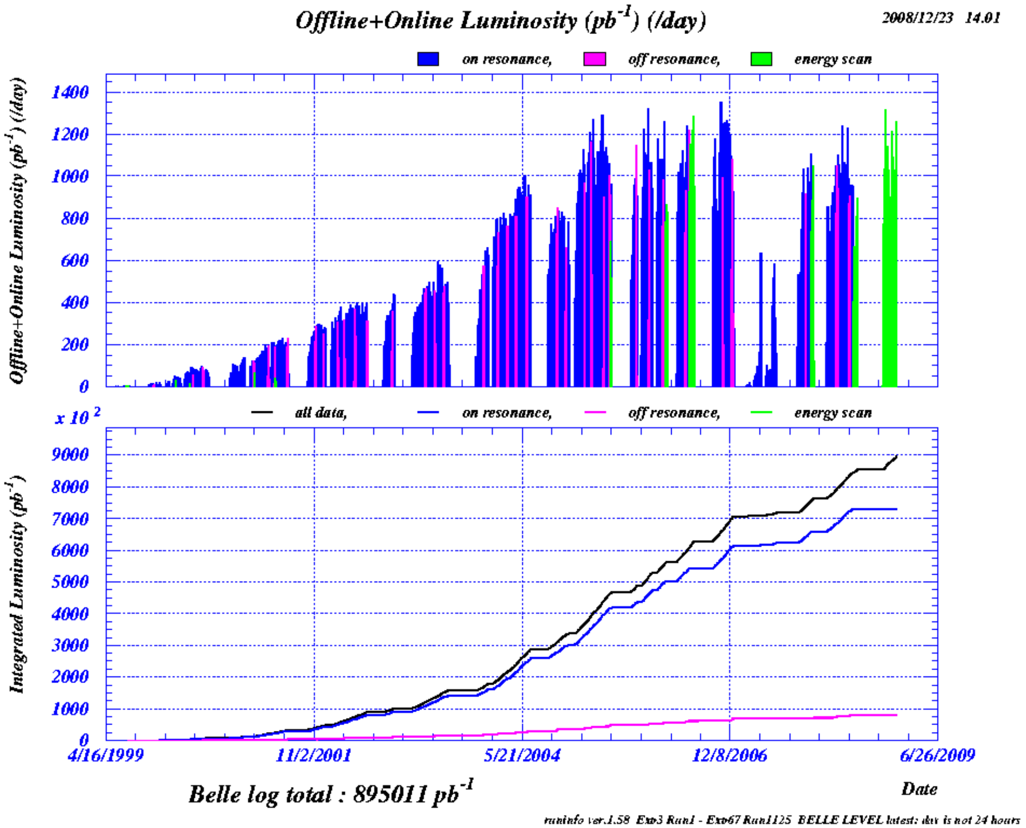


KEKB at KEK
8.0 GeV e^- on 3.5 GeV e^+



B factories – world record luminosities



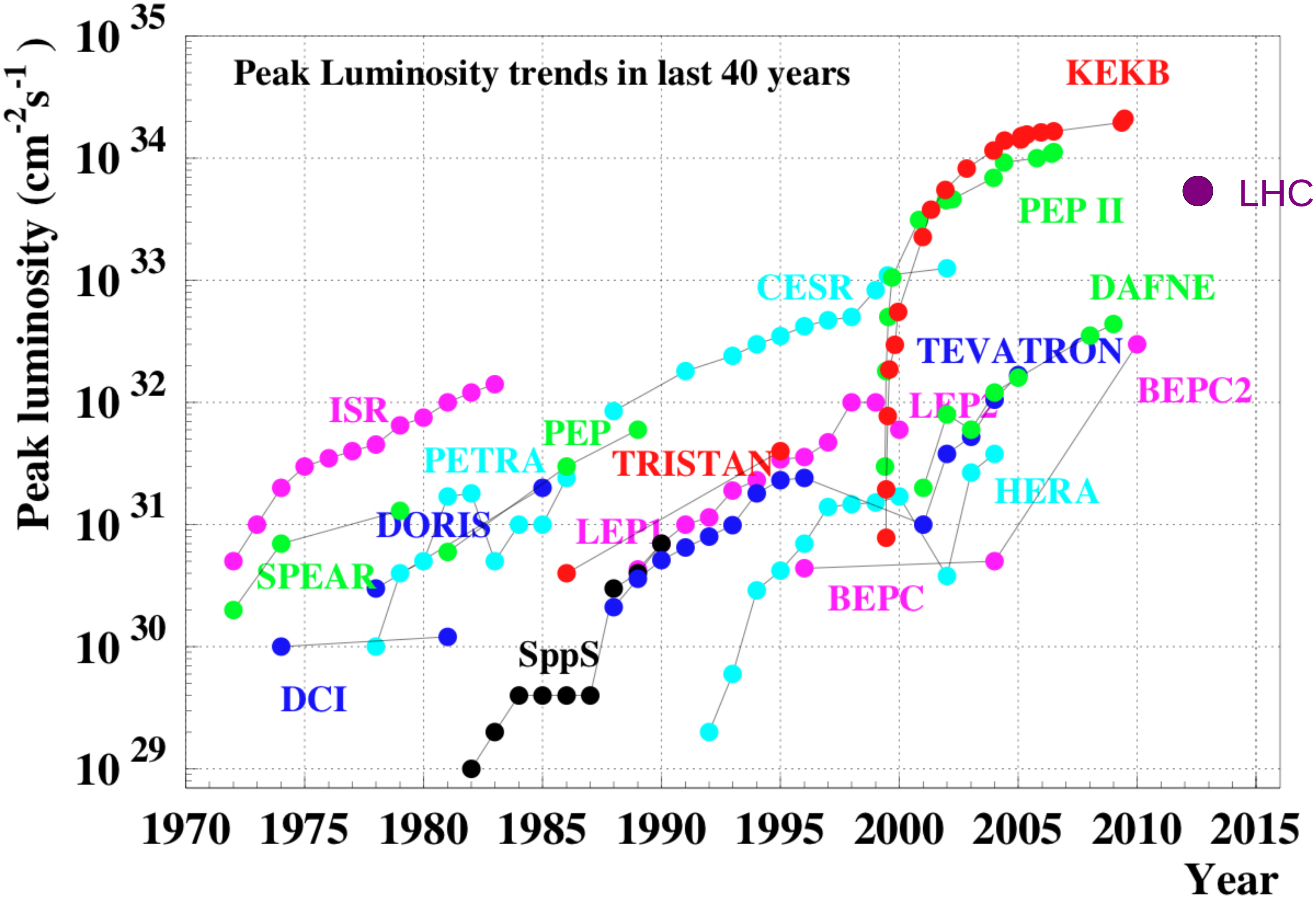


~ 433/fb on Y(4S)

~ 711/fb on Y(4S)

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

World record luminosities (2)

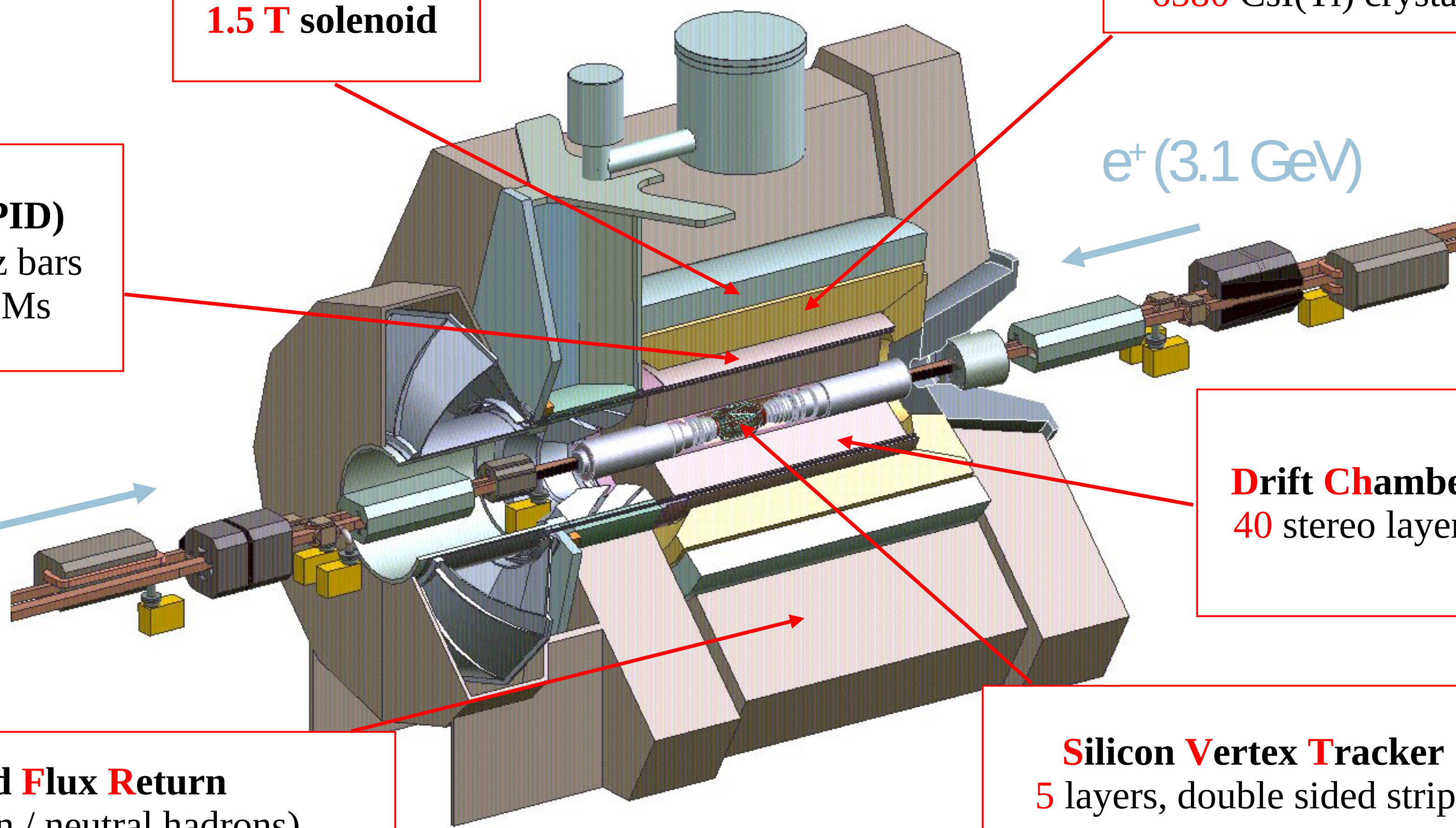


BaBar Detector

EMC
6580 CsI(Tl) crystals

1.5 T solenoid

DIRC (PID)
144 quartz bars
11000 PMs

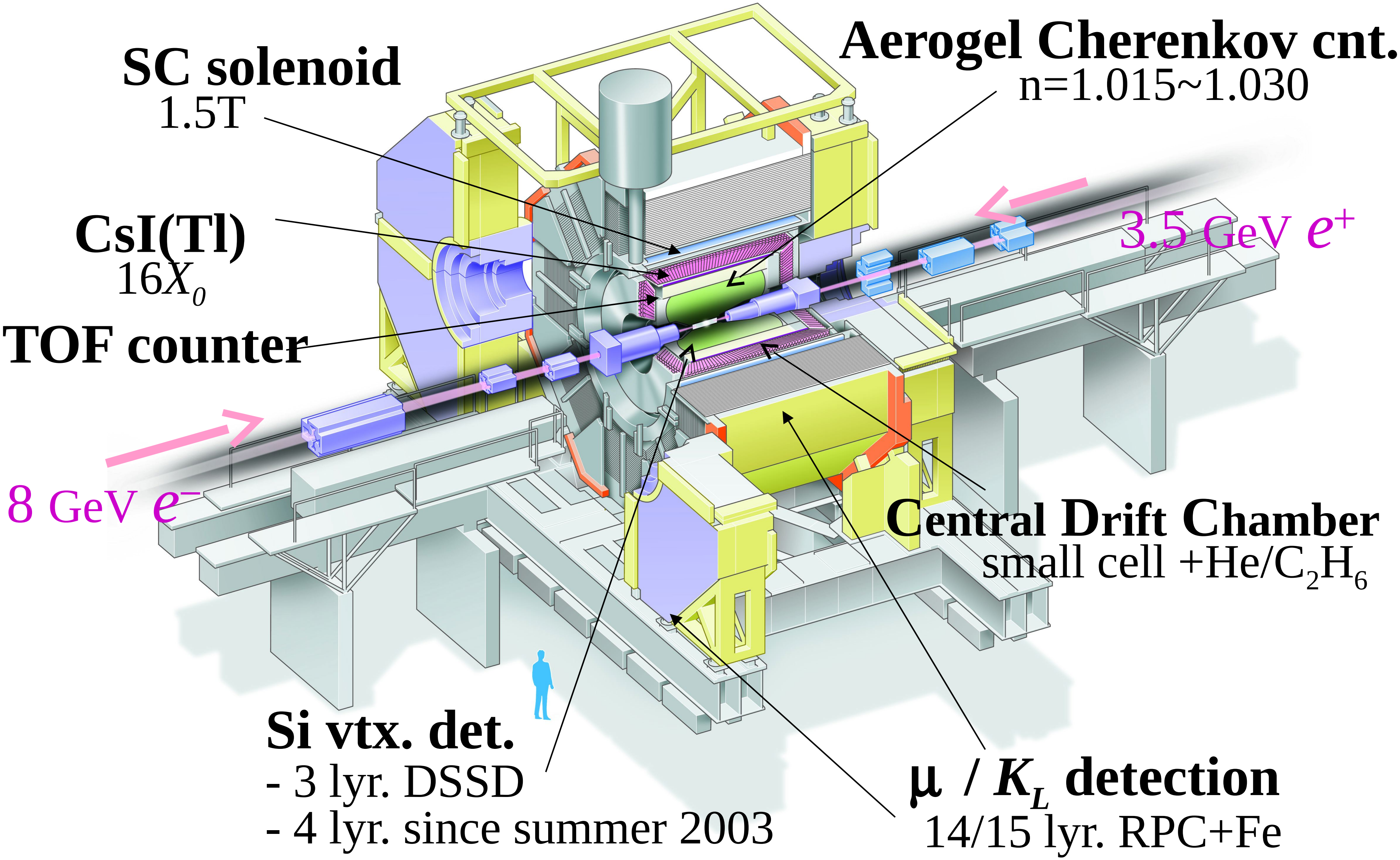


Drift Chamber
40 stereo layers

Silicon Vertex Tracker
5 layers, double sided strips

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

Belle Detector

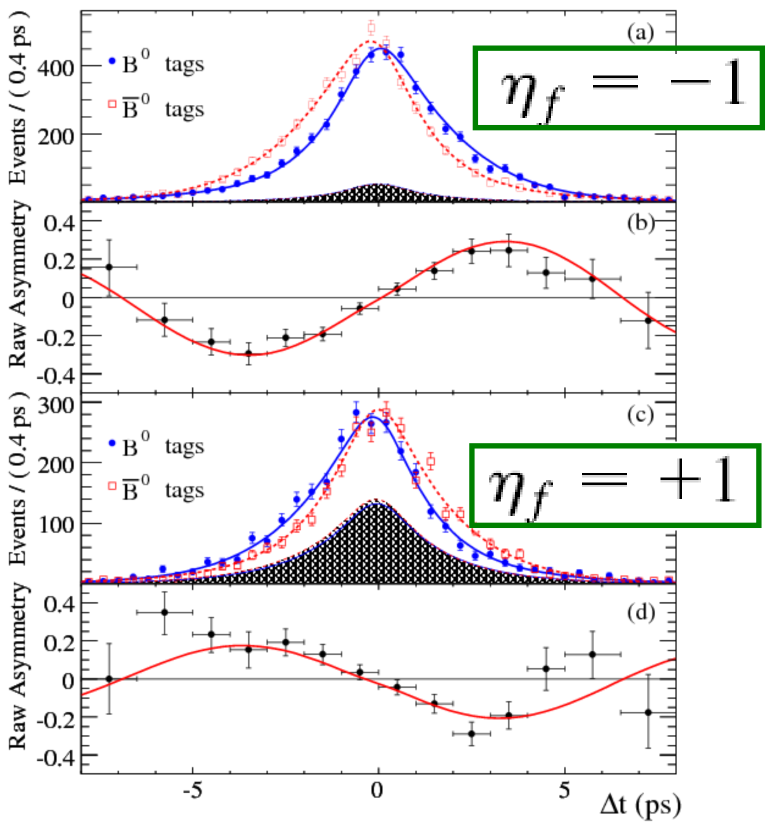


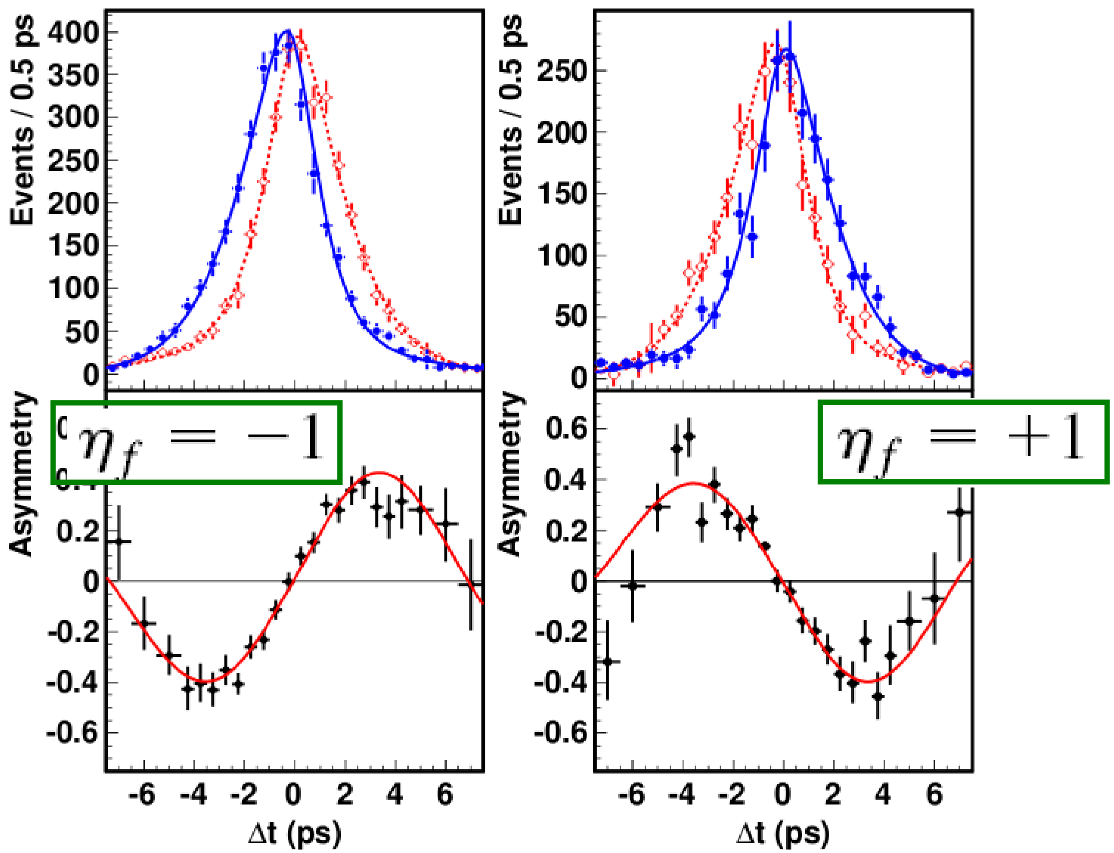
Results for the golden mode

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

BABAR

BELLE





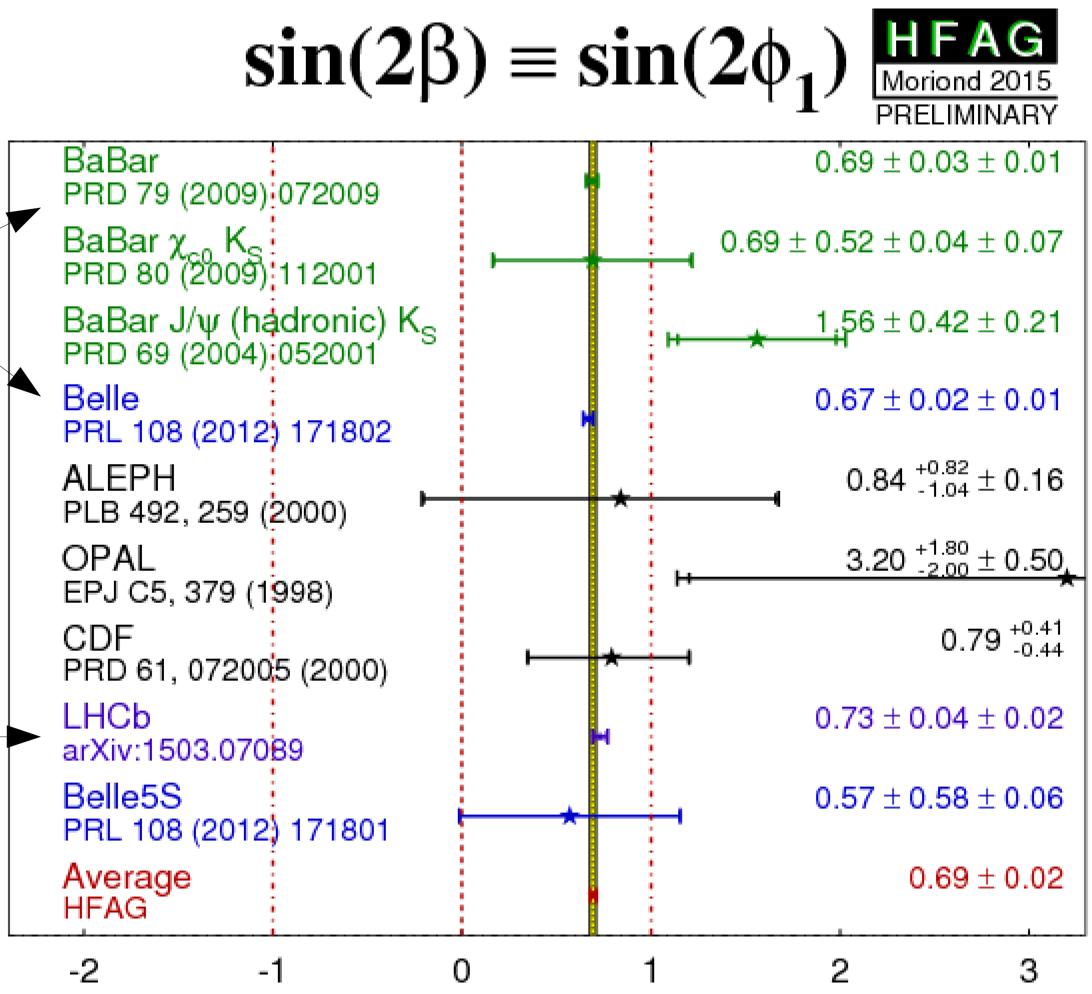
PRD 79 (2009) 072009

PRL 108 (2012) 171802

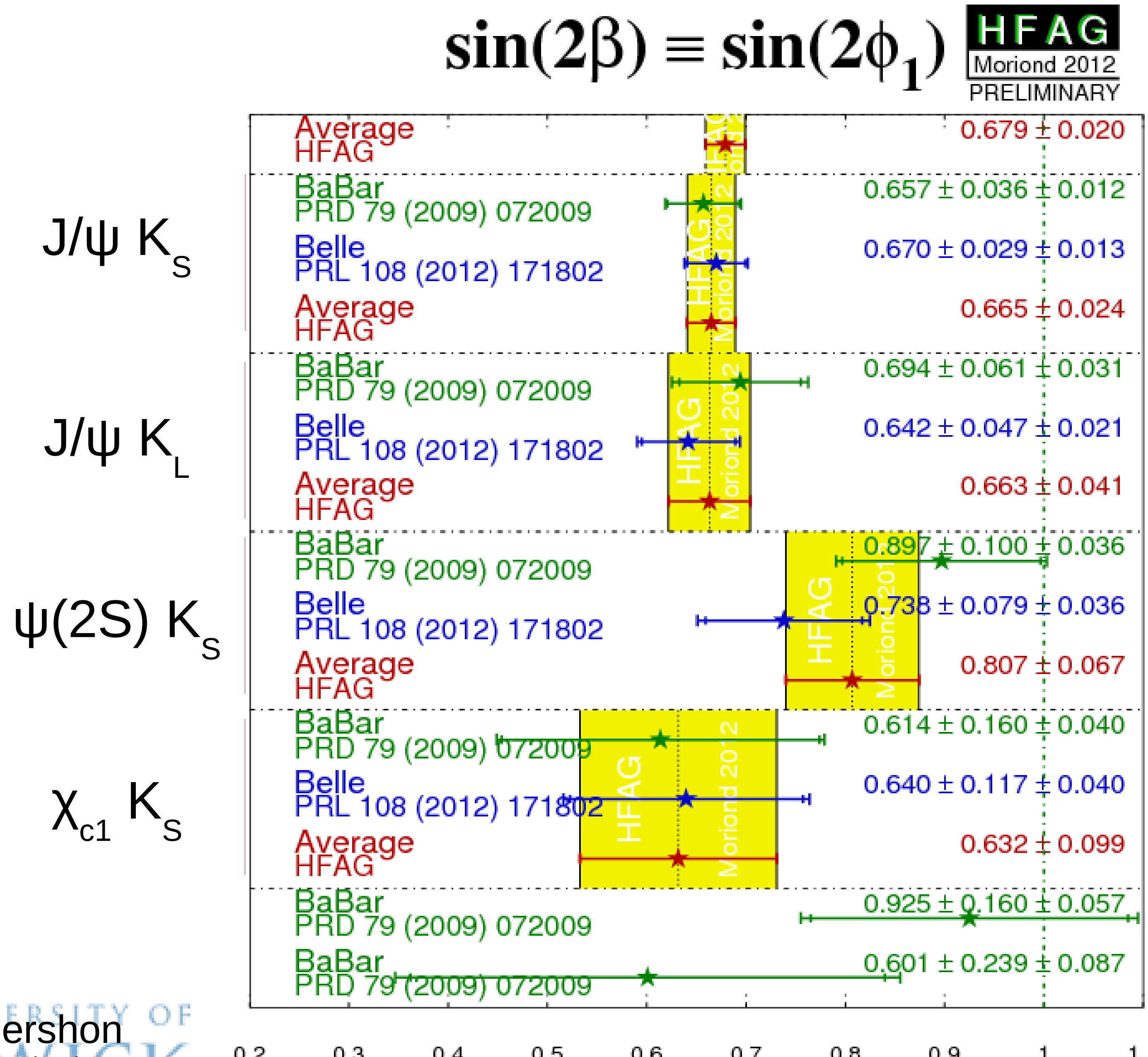
Compilation of results

Results on previous slide

Note LHCb also highly competitive



Compilation of B factory results

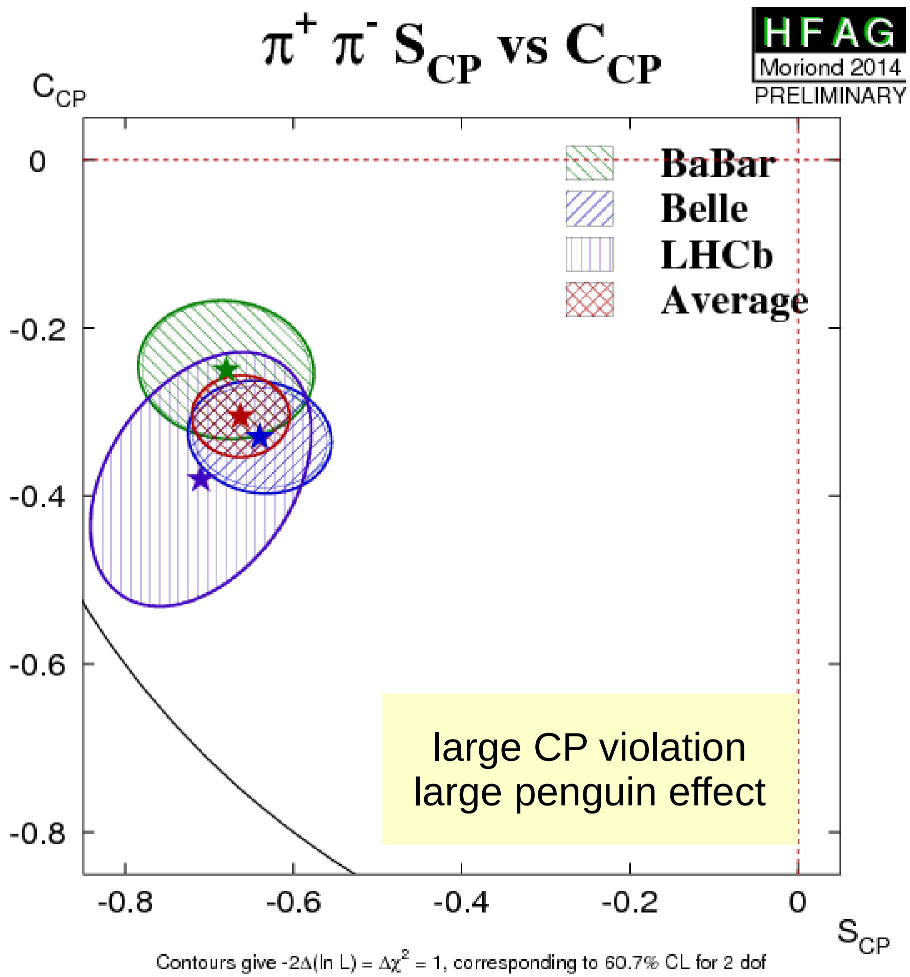


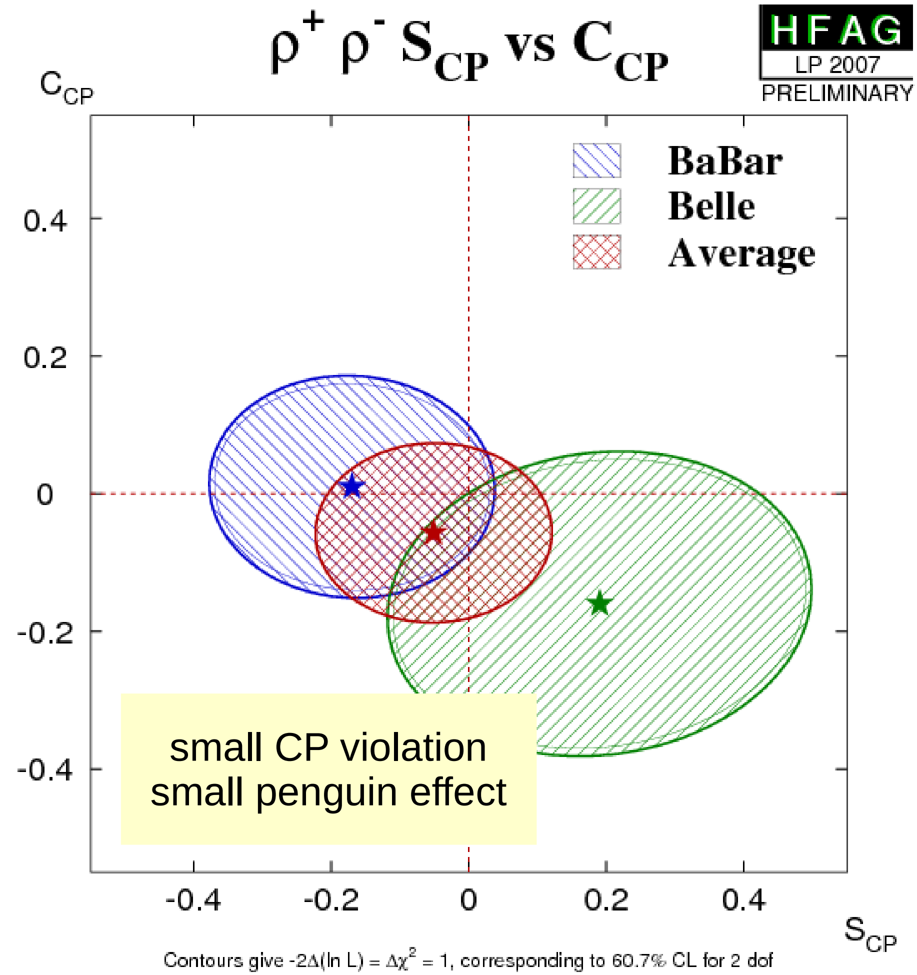
Measurement of α

- Similar analysis using $b \to u\bar{u}d$ decays (e.g. $B_d^0 \to \pi^+\pi^-$) probes $\pi-(\beta+\gamma) = \alpha$
  - but $b \to d\bar{u}u$ penguin transitions contribute to same final states ⇒ "penguin pollution"
  - $C \neq 0 \Leftrightarrow$ CP violation in decay can occur
  - $S \neq +\eta_{CP} \sin(2\alpha)$
- Two approaches (optimal approach combines both)
  - try to use modes with small penguin contribution
  - correct for penguin effect (isospin analysis)

PRL 65 (1990) 3381

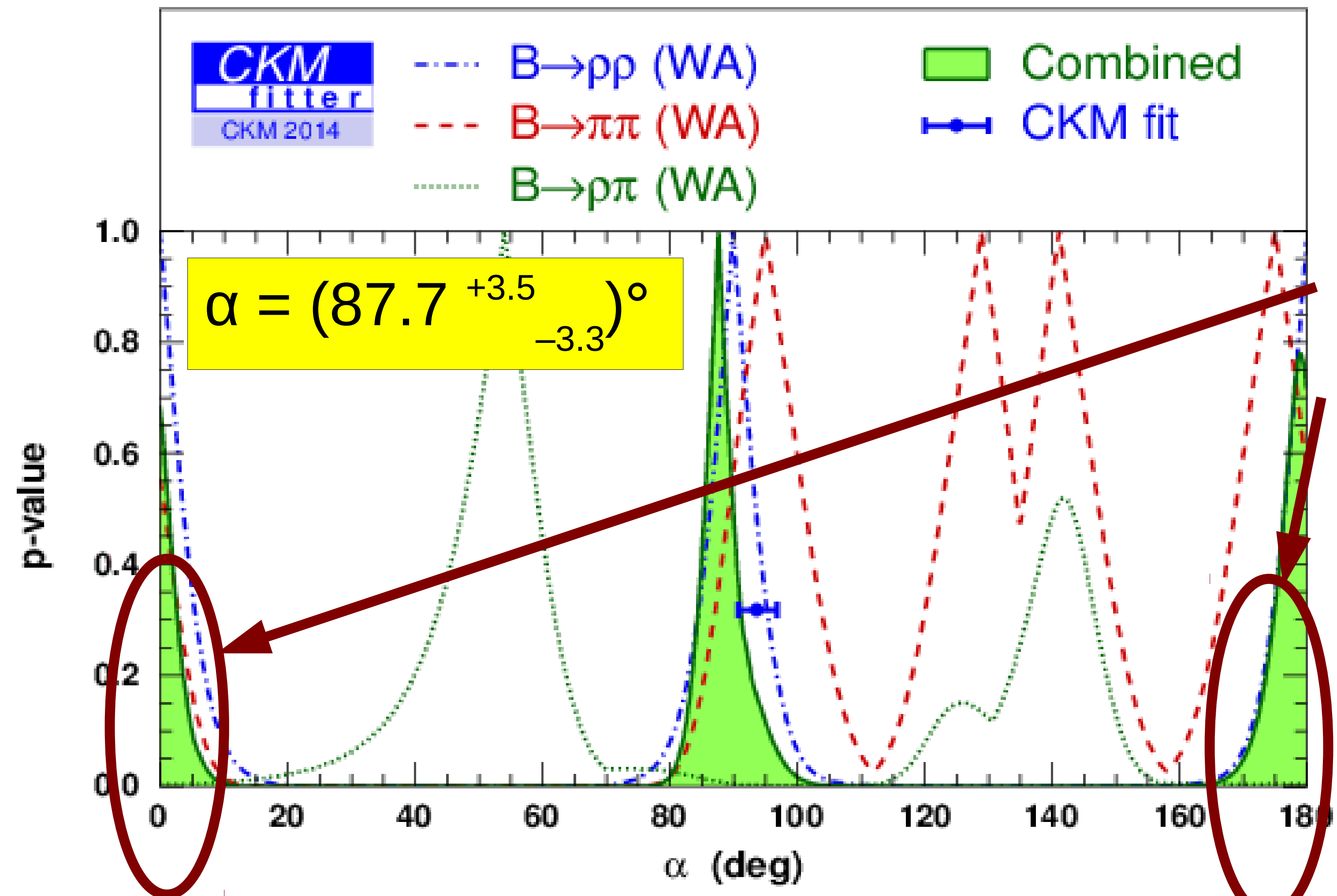
Experimental Situation





improved measurements needed!

Measurement of α



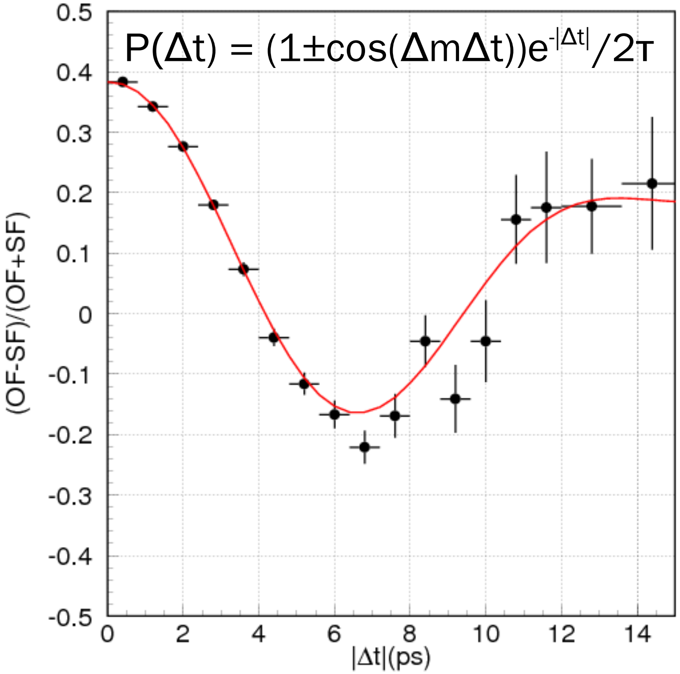
THESE SOLUTIONS RULED OUT BY OBSERVATION OF DIRECT CP VIOLATION IN $B^0 \to \pi^+\pi^-$

Is there any physical significance in the fact that α ≈ 90°?

R_t side from B^0–$\bar{B}^0$ mixing

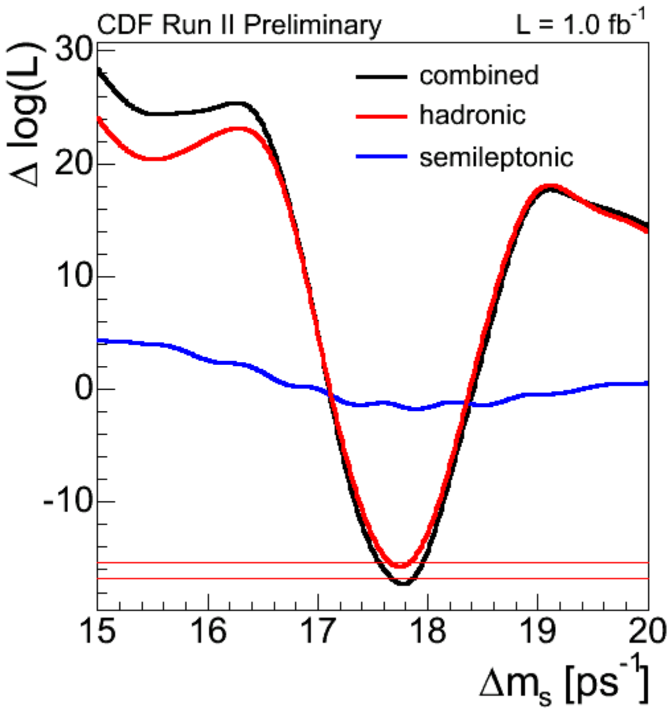
$$R_t = \left| \frac{V_{td} V_{tb}^*}{V_{cd} V_{cb}^*} \right| \quad \& \quad \frac{\Delta m_d}{\Delta m_s} = \frac{m_{B_d} f_{B_d}^2 \hat{B}_{B_d}}{m_{B_s} f_{B_s}^2 \hat{B}_{B_s}} \frac{|V_{td}|^2}{|V_{ts}|^2}$$

World average based on many measurements



$\Delta m_d = (0.511 \pm 0.005 \pm 0.006)\ \text{ps}^{-1}$

PRD 71, 072003 (2005)



$\Delta m_s = (17.77 \pm 0.10 \pm 0.07)\ \text{ps}^{-1}$

PRL 97, 242003 (2006)

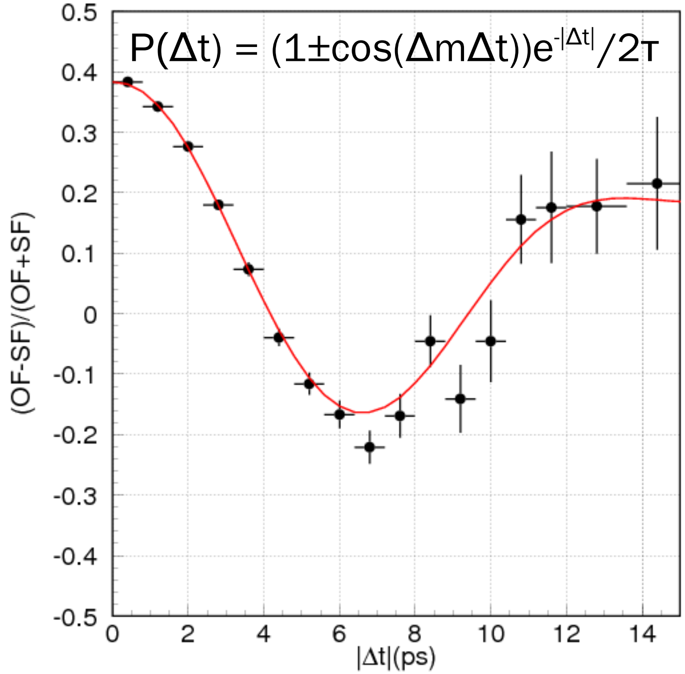
$$|V_{td}/V_{ts}| = 0.216 \pm 0.001 \pm 0.011$$

experimental uncertainty — theoretical uncertainty

R_t side from B^0–$\bar{B}^0$ mixing

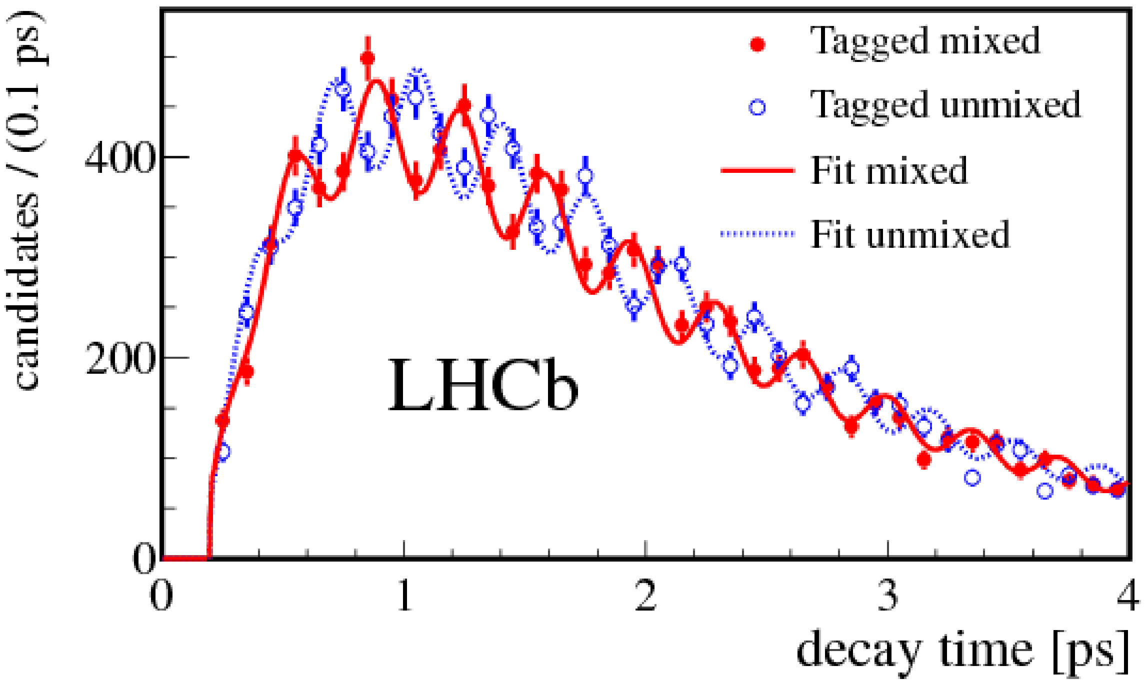
$$R_t = \left| \frac{V_{td} V_{tb}^*}{V_{cd} V_{cb}^*} \right| \quad \& \quad \frac{\Delta m_d}{\Delta m_s} = \frac{m_{B_d} f_{B_d}^2 \hat{B}_{B_d}}{m_{B_s} f_{B_s}^2 \hat{B}_{B_s}} \frac{|V_{td}|^2}{|V_{ts}|^2}$$

World average based on many measurements



$\Delta m_d = (0.511 \pm 0.005 \pm 0.006)\ \mathrm{ps}^{-1}$

PRD 71, 072003 (2005)



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

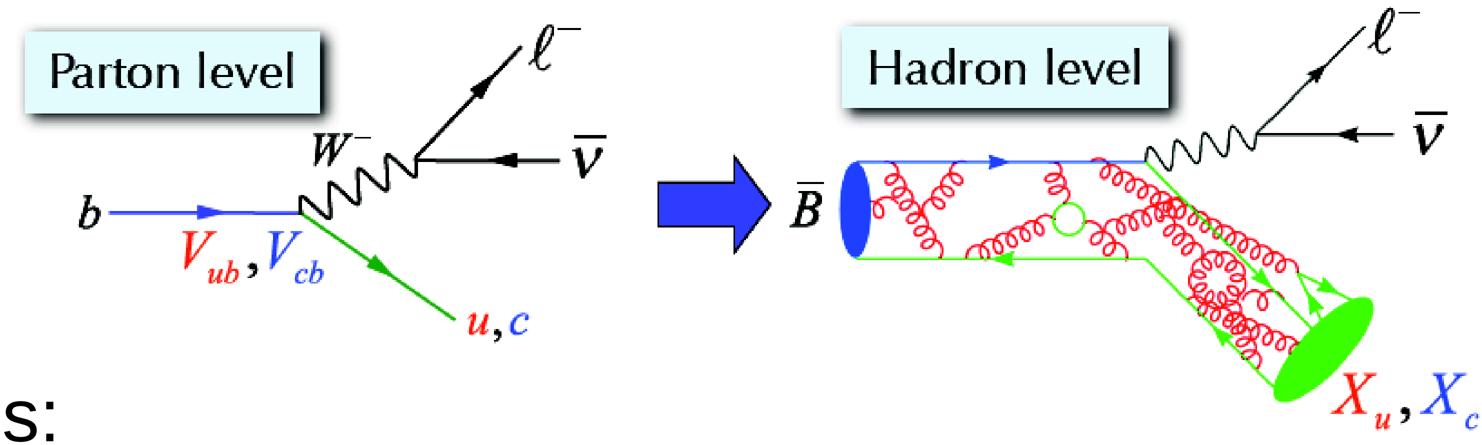
NJP 15 (2013) 053021

$$|V_{td}/V_{ts}| = 0.216 \pm 0.001 \pm 0.011$$

experimental uncertainty (first), theoretical uncertainty (second)

R_u side from semileptonic decays

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



- Approaches:
  - exclusive semileptonic B decays, eg. $B^0 \rightarrow \pi^- e^+ \nu$
    - require knowledge of form factors
      - can be calculated in lattice QCD at kinematical limit
  - inclusive semileptonic B decays, eg. $B \rightarrow X_u e^+ \nu$
    - clean theory, based on Operator Product Expansion
    - experimentally challenging:
      - need to reject $b \rightarrow c$ background
      - cuts re-introduce theoretical uncertainties

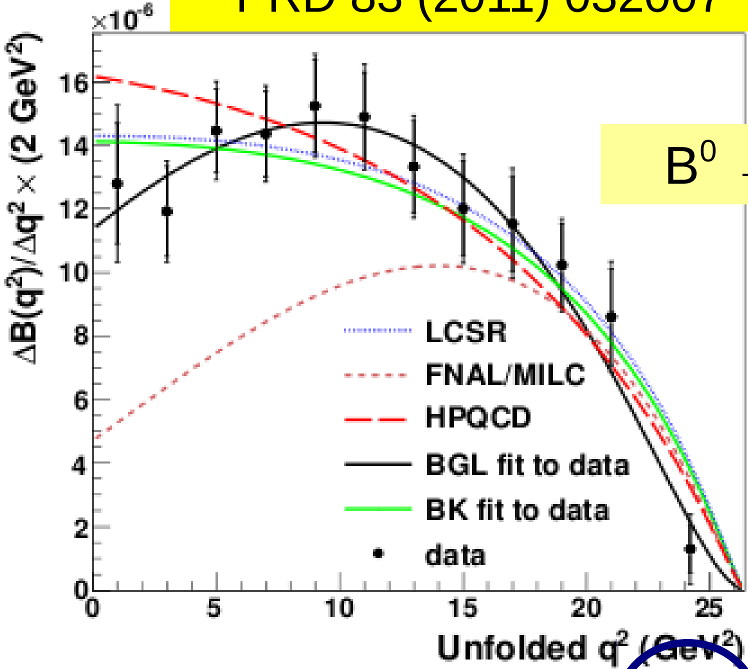
$|V_{ub}|$ from exclusive semileptonic decays

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

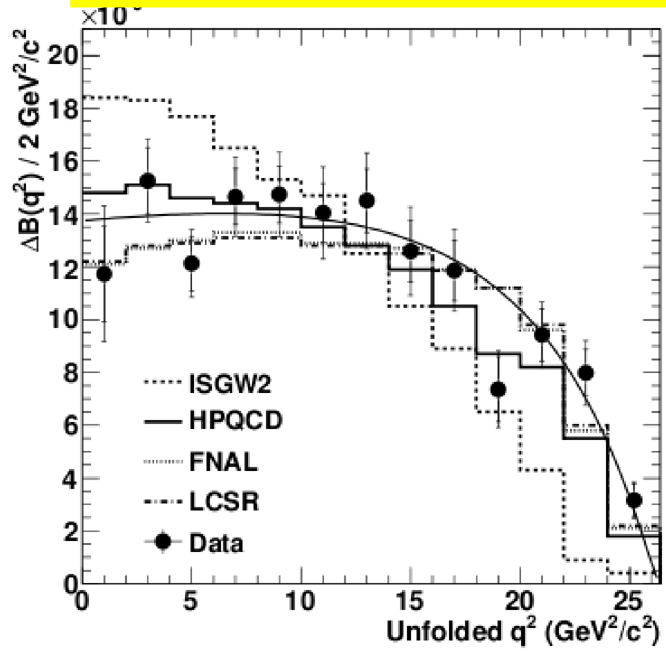
(recent competitive measurement form LHCb with $\Lambda_b \to p\mu\nu$)

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

Belle experiment
PRD 83 (2011) 071101(R)



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



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

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

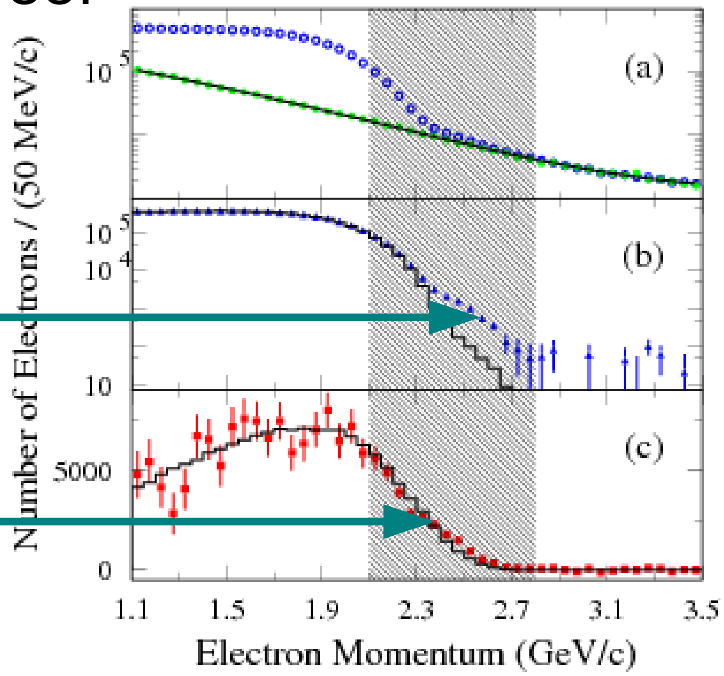
lattice uncertainty

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

- Main difficulty to measure inclusive $B \to X_u l^+ \nu$
  - background from $B \to X_c l^+ \nu$
- Approaches
  - cut on E_l (lepton endpoint), q^2 ($l\nu$ invariant mass squared), $M(X_u)$, or some combination thereof
- Example: endpoint analysis

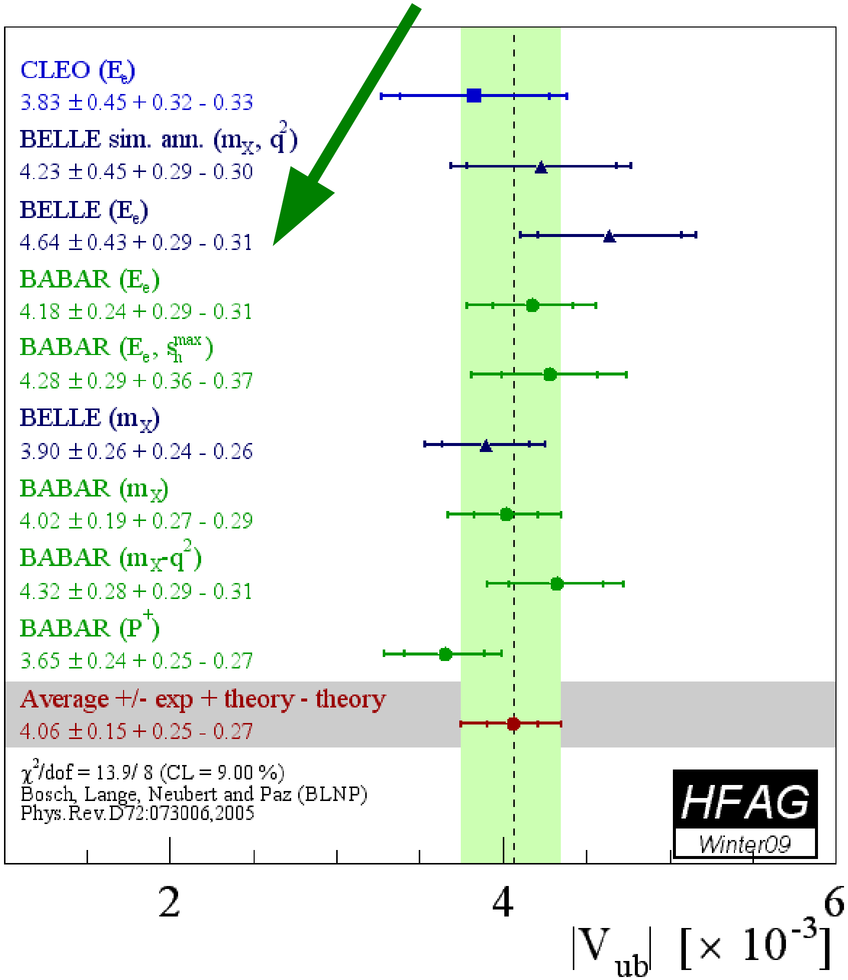
non $B\bar{B}$ background subtracted

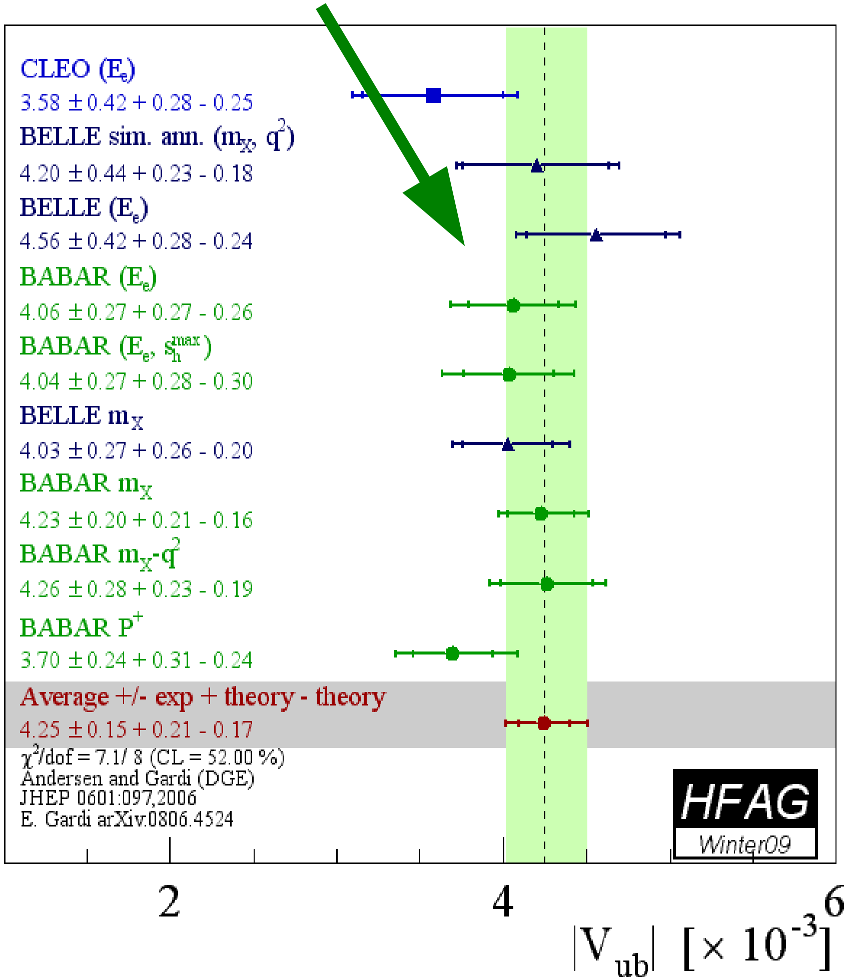
$X_c\ l^+ \nu$ background subtracted



$|V_{ub}|$ inclusive - compilation

Different theoretical approaches (2 of 4 used by HFAG)

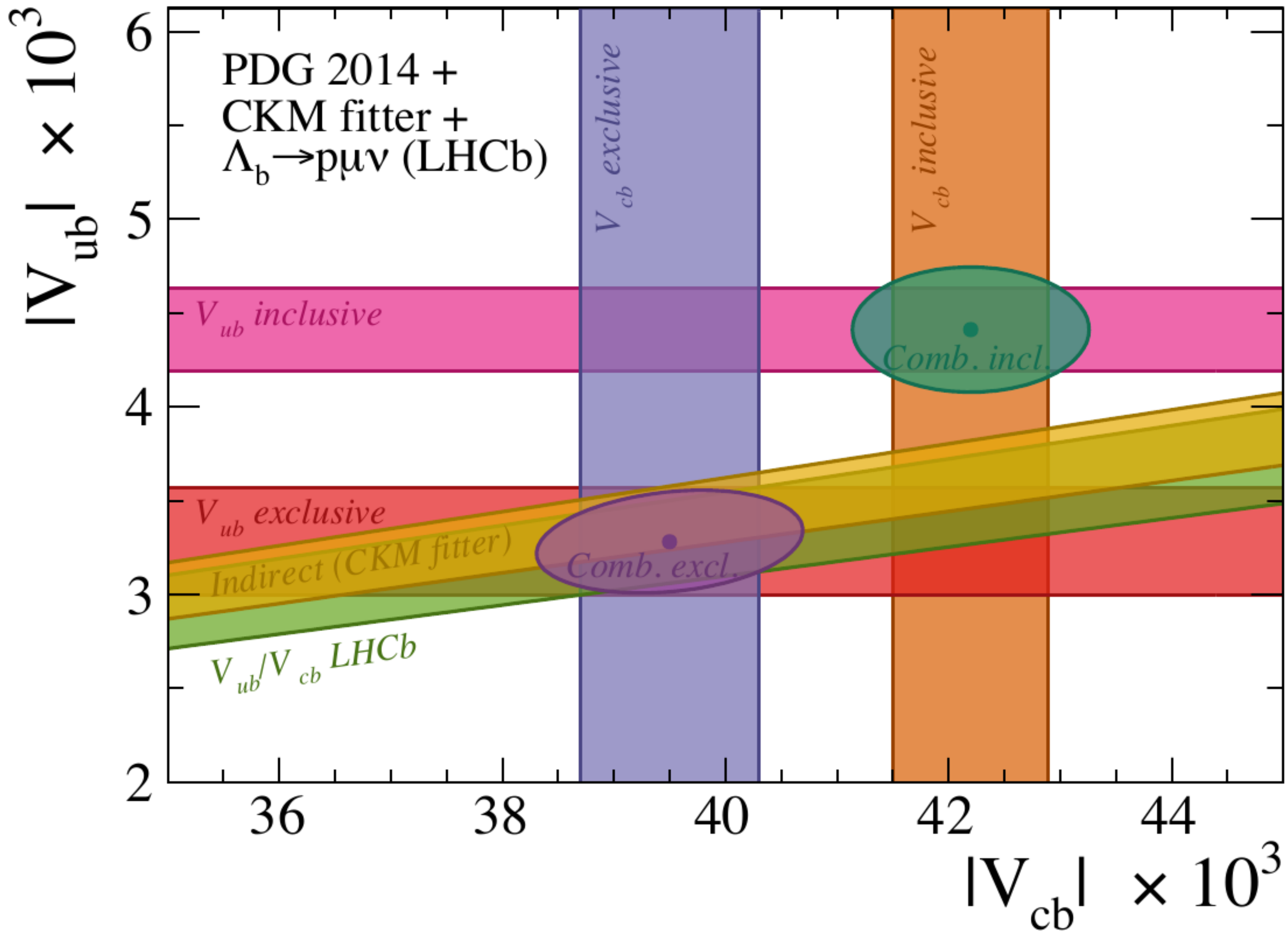




$|V_{ub}|$ average

- Averages on $|V_{ub}|$ from both exclusive and inclusive approaches
  - exclusive: $|V_{ub}| = (3.28 \pm 0.29) \times 10^{-3}$
  - inclusive: $|V_{ub}| = (4.41 \pm 0.15\,^{+0.15}_{-0.19}) \times 10^{-3}$
  - slight tension between these results
  - in both cases theoretical errors are dominant
    - but some “theory” errors can be improved with more data
  - PDG2014 does naïve average rescaling due to inconsistency to obtain $|V_{ub}| = (4.13 \pm 0.49) \times 10^{-3}$

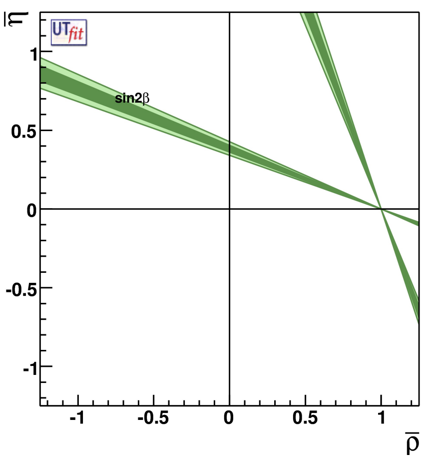
Inclusive vs. exclusive



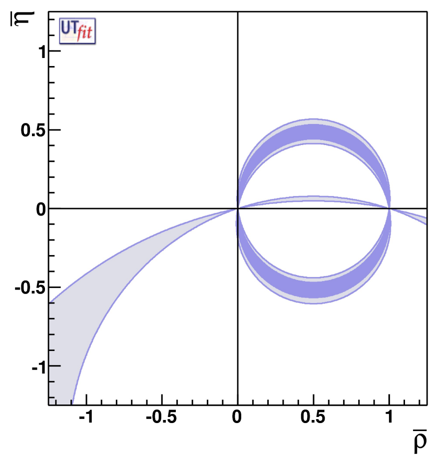
Discrepancies need to be understood!

Partial summary

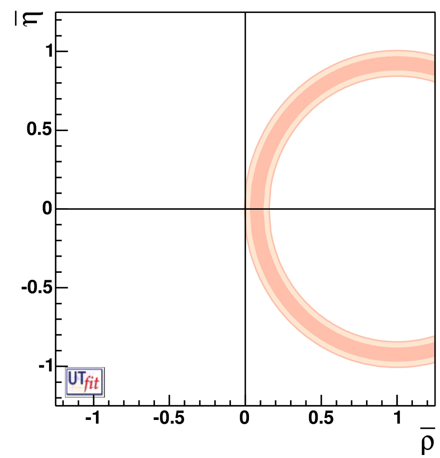
$\sin(2\beta)$



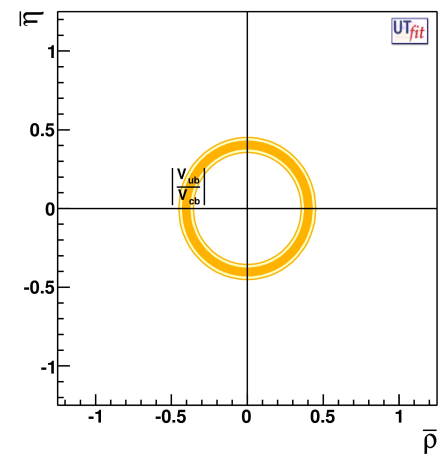
α



$|\Delta m_d / \Delta m_s|$

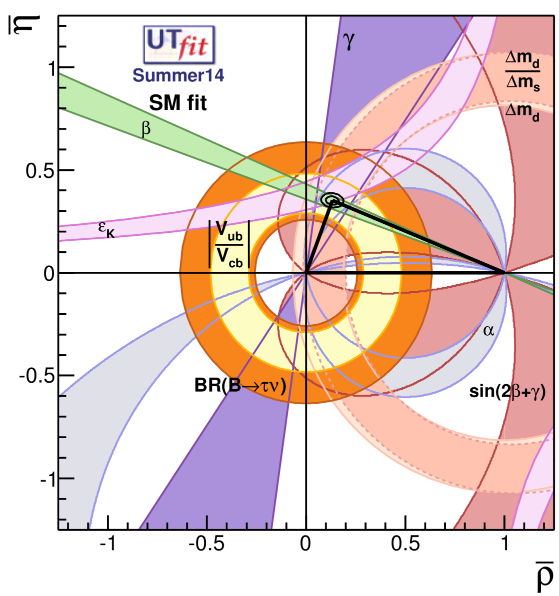


$|V_{ub}/V_{cb}|$



Adding a few other constraints we find

$$\bar{\rho} = 0.132 \pm 0.023$$
$$\bar{\eta} = 0.351 \pm 0.013$$



Consistent with Standard Model fit

- some “tensions”

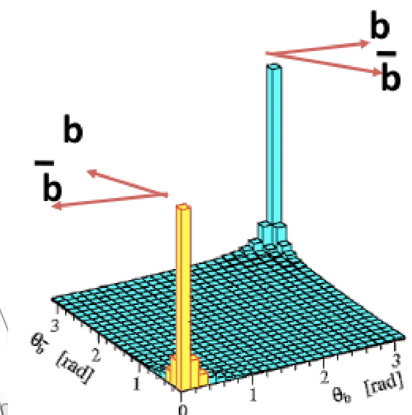
Still plenty of room for new physics

Flavour physics at hadron colliders

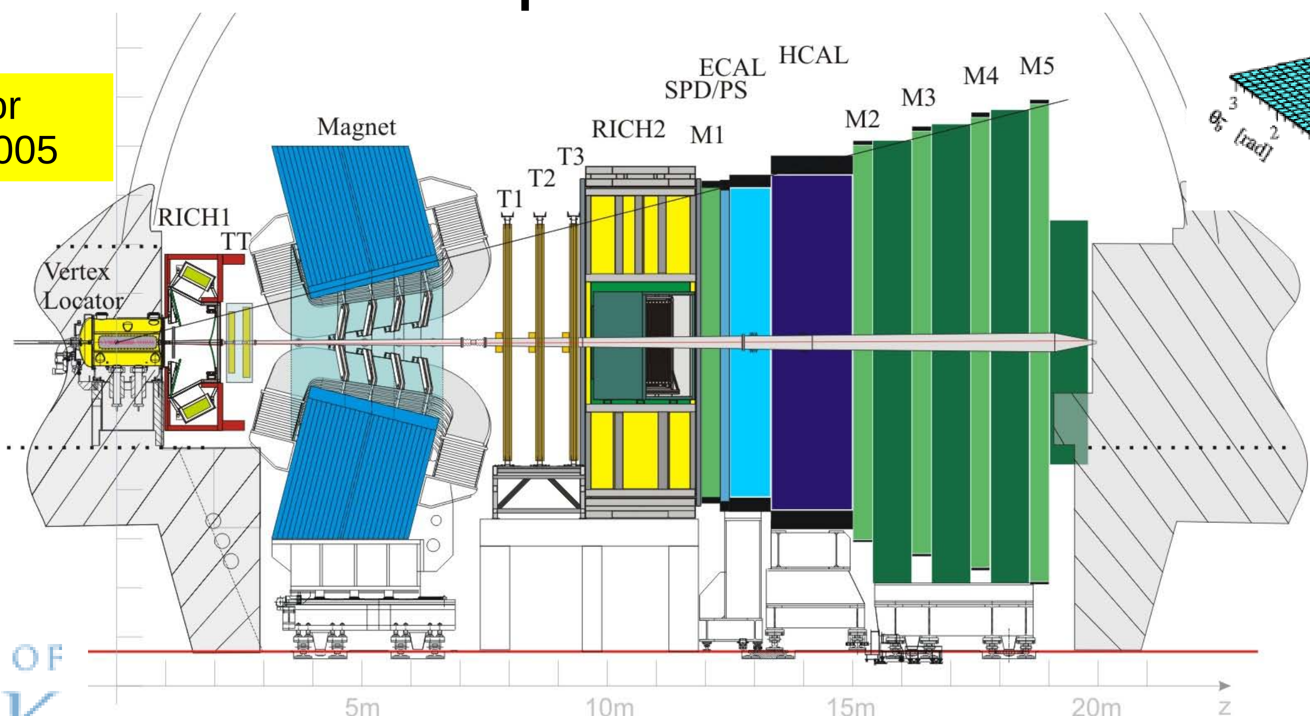
	$e^+e^- \to \Upsilon(4S) \to B\bar{B}$	$p\bar{p} \to b\bar{b}X$ ($\sqrt{s} = 2\,\mathrm{TeV}$)	$pp \to b\bar{b}X$ ($\sqrt{s} = 14\,\mathrm{TeV}$)
	PEP-II, KEKB	Tevatron	LHC
Production cross-section	$1\,\mathrm{nb}$	$\sim 100\,\mu\mathrm{b}$	$\sim 500\,\mu\mathrm{b}$
Typical $b\bar{b}$ rate	$10\,\mathrm{Hz}$	$\sim 100\,\mathrm{kHz}$	$\sim 500\,\mathrm{kHz}$
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	$\varepsilon D^2 \sim 30\%$	$\varepsilon D^2 \sim 5\%$	

Geometry

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

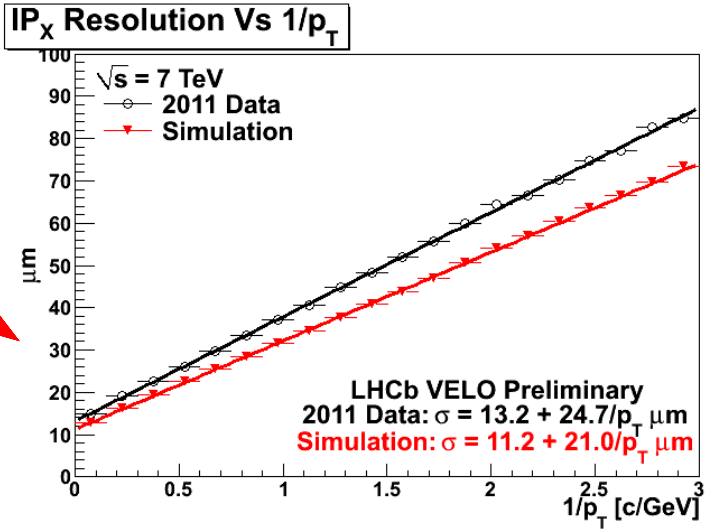


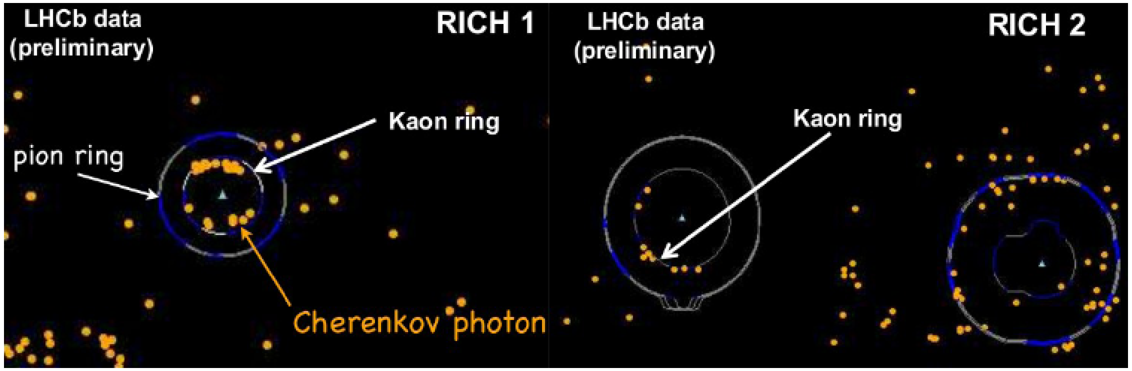
The LHCb Detector
JINST 3 (2008) S08005



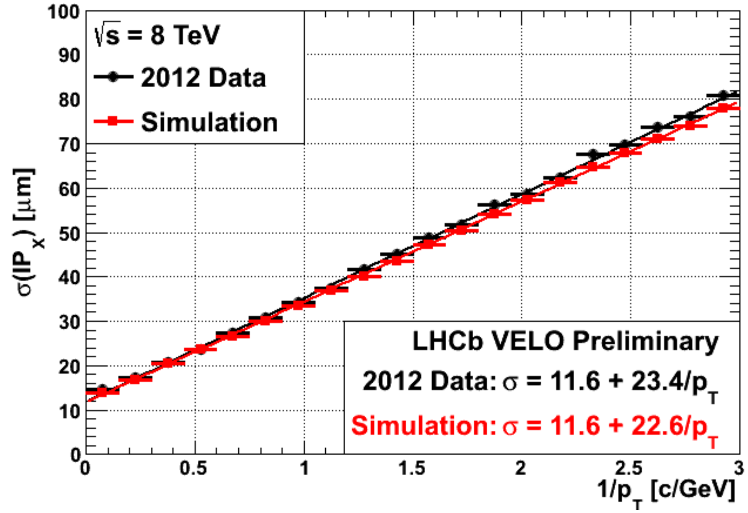
LHCb detector features

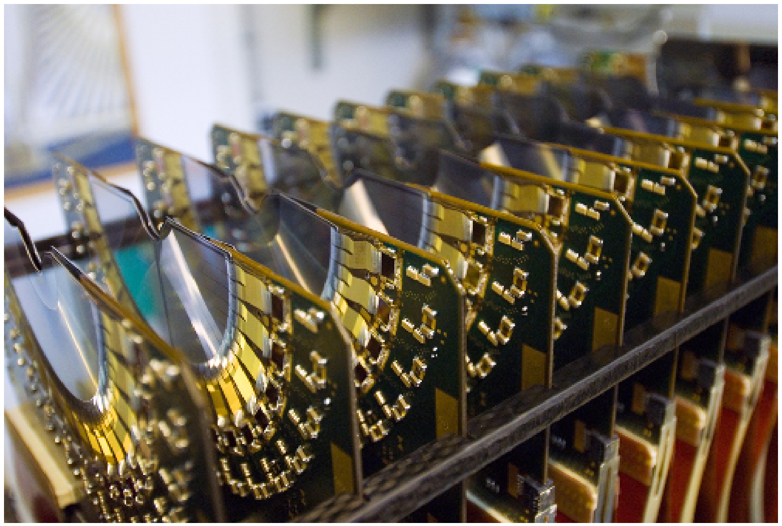
- Tracking and calorimetry
  - basic essentials of any collider experiment!
  - muon chambers
- VELO
  - reconstruct displaced vertices
- RICH
  - particle ID (K/π separation)
- Trigger
  - fast and efficient



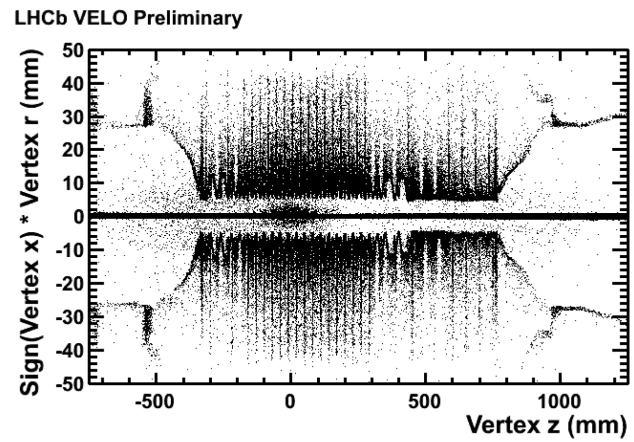


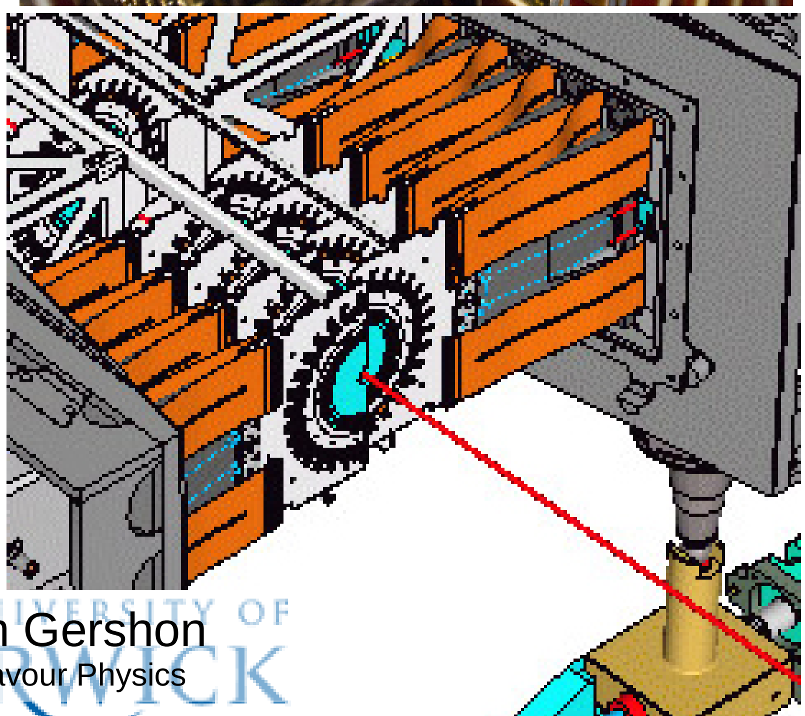
VELO

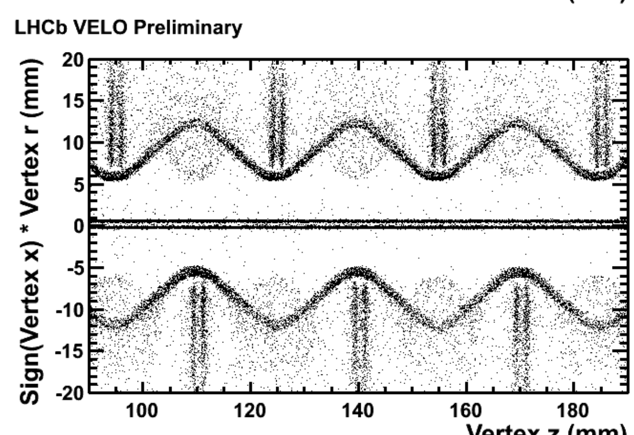




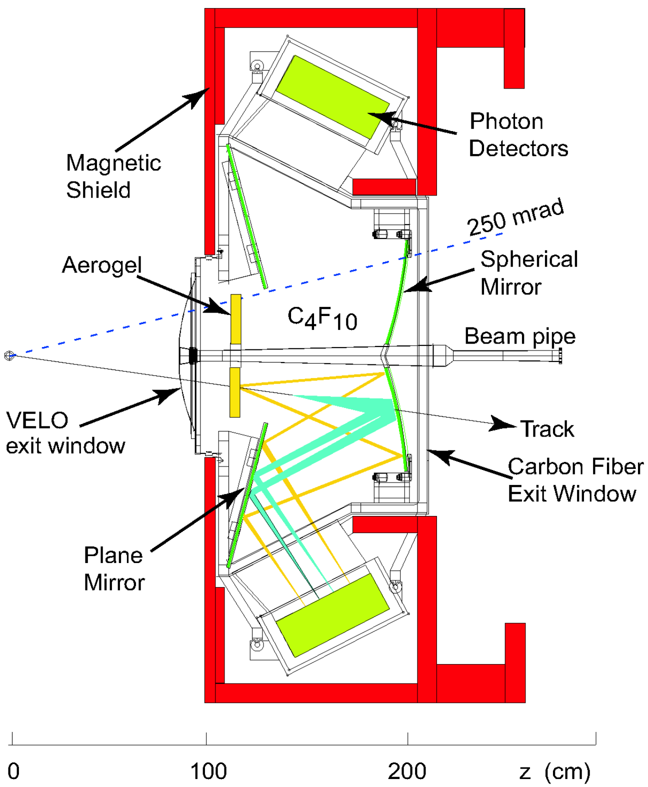
Material imaged used beam gas collisions

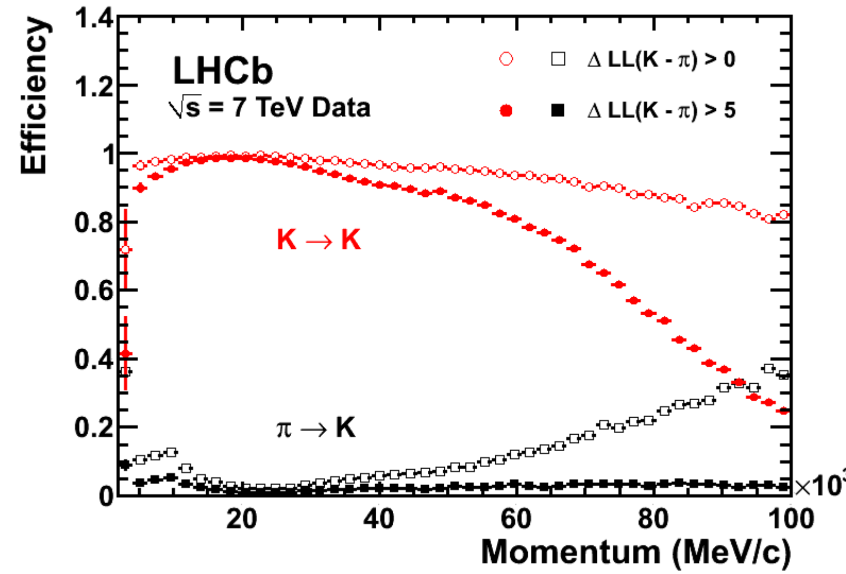


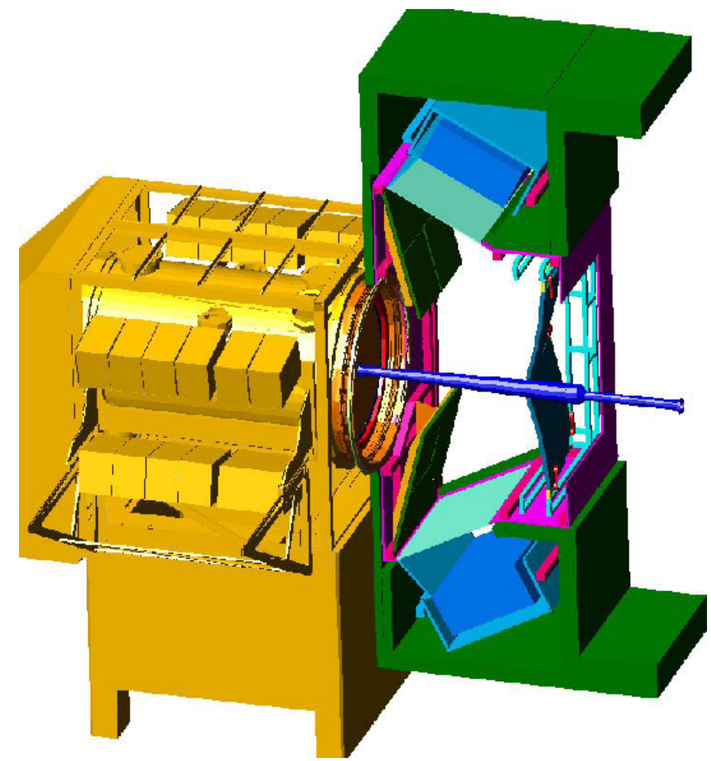




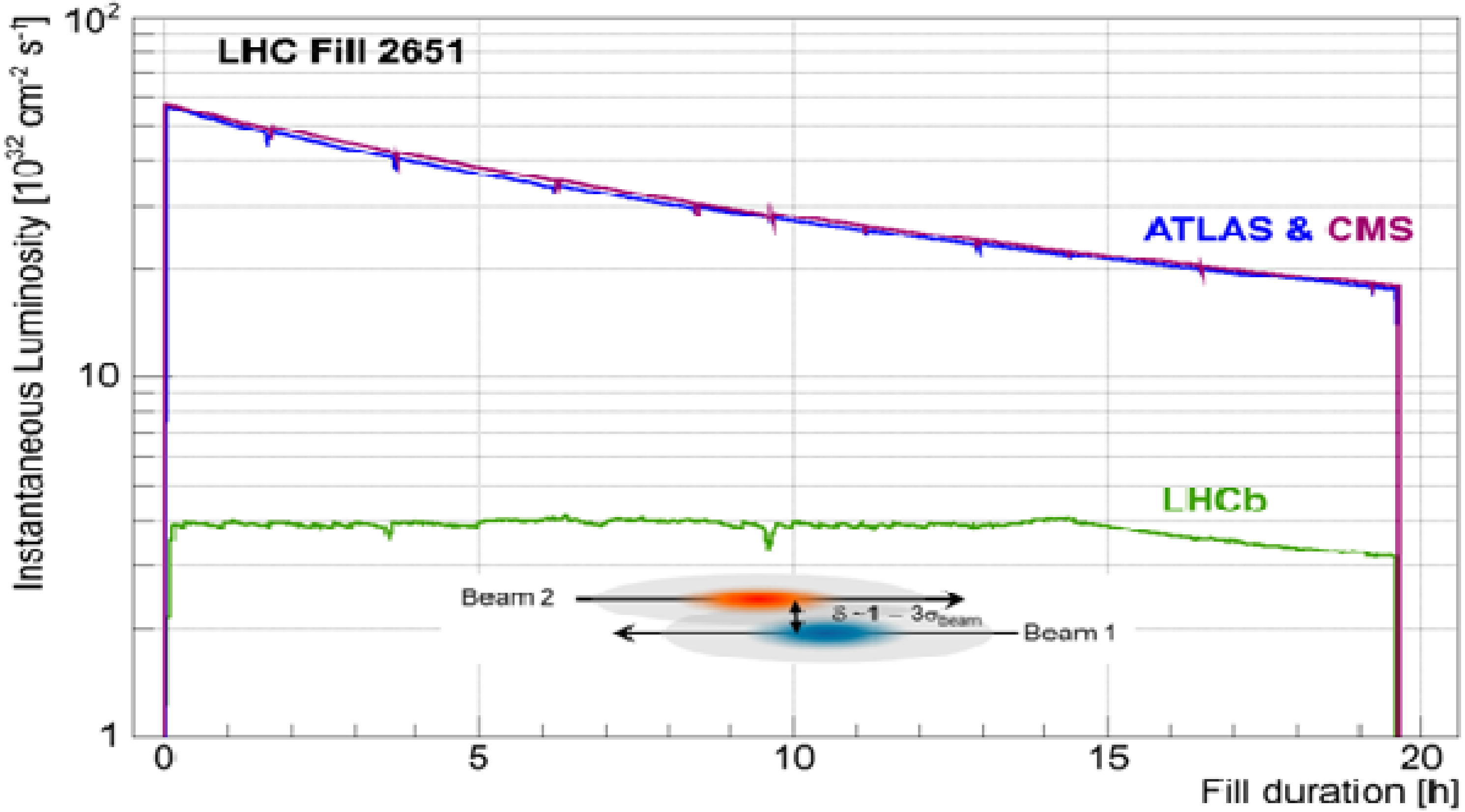
RICH


Magnetic Shield
Photon Detectors
250 mrad
Spherical Mirror
Aerogel
C_4F_{10}
Beam pipe
VELO exit window
Track
Carbon Fiber Exit Window
Plane Mirror
0
100
200
z (cm)


LHCb
$\sqrt{s}$ = 7 TeV Data
Δ LL(K - π) > 0
Δ LL(K - π) > 5
K → K
π → K
Efficiency
Momentum (MeV/c)
$\times 10^3$



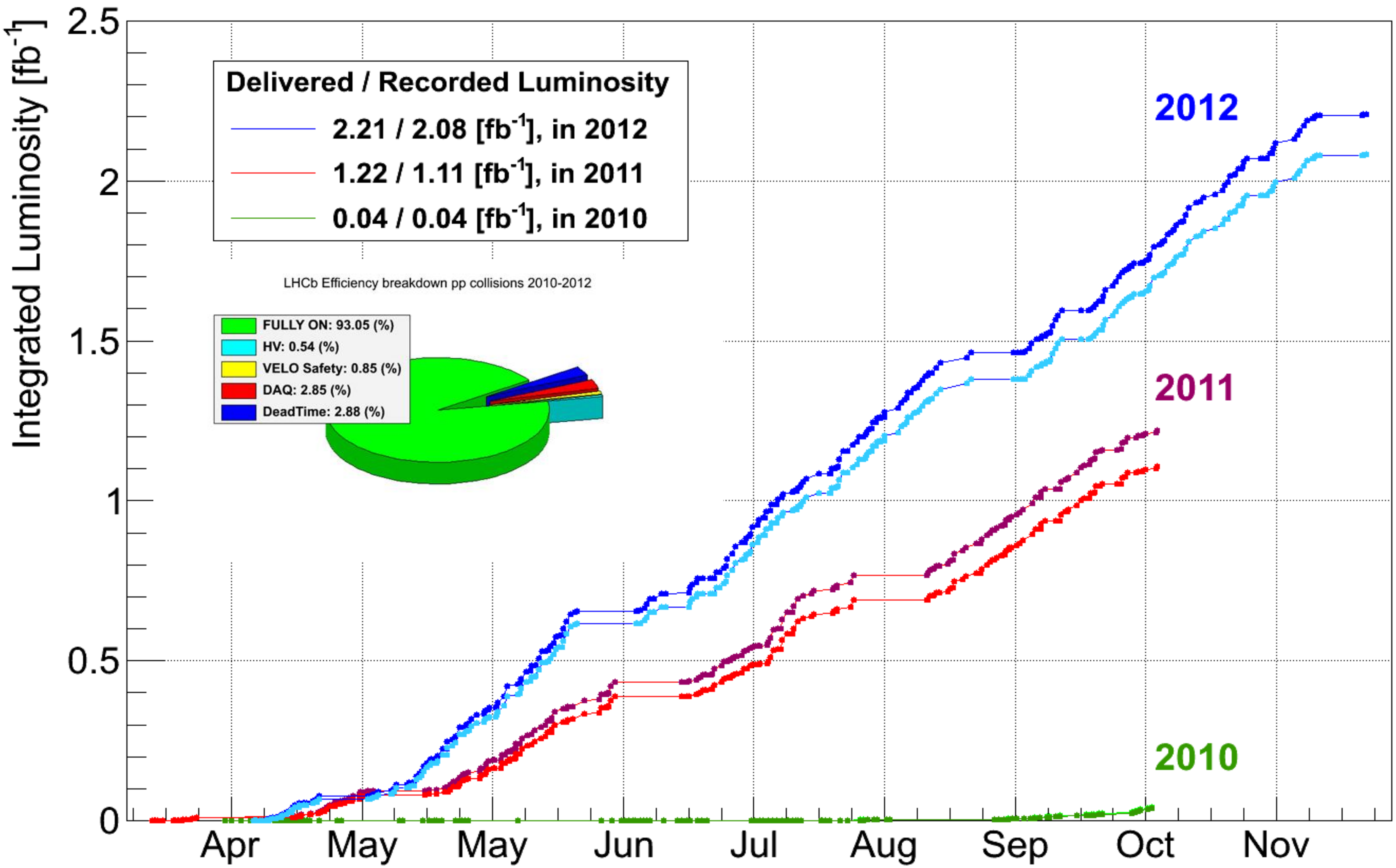
Luminosity levelling in LHCb



luminosity levelling at around 4×10^{32} cm^{-2}s^{-1} via transverse separation
(with tilted crossing angle)

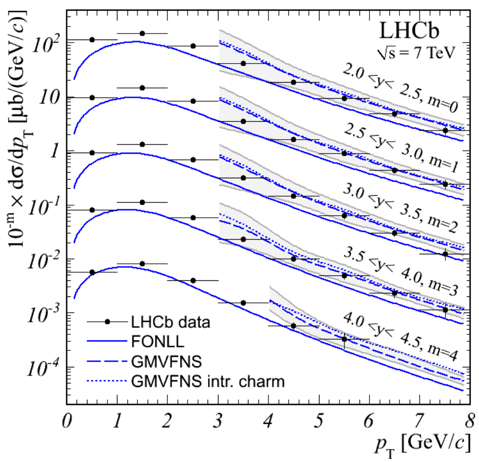
from C. Gaspar, via. F. Zimmerman

Run 1 data taking

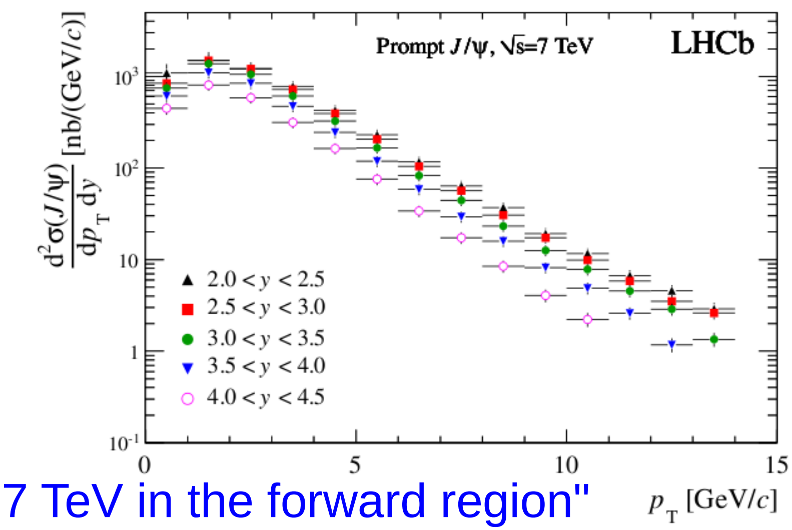


Heavy flavour production @ LHCb

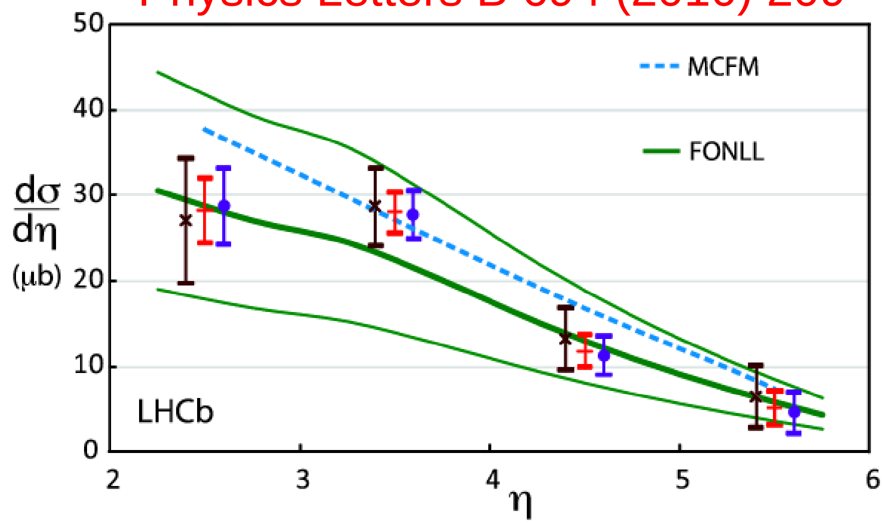
“Prompt charm production in pp collisions at √s = 7 TeV”
Nucl. Phys. B 871 (2013) 1



“Measurement of J/ψ production in pp collisions at √s = 7 TeV”
Eur. Phys. J. C 71 (2011) 1645



"Measurement of $\sigma(pp \to b\bar{b}X)$ at √s = 7 TeV in the forward region"
Physics Letters B 694 (2010) 209



What does $\int L\,dt$ = 1/fb mean?

- Measured cross-section, in LHCb acceptance

$$\sigma(pp \rightarrow b\bar{b}X) = (75.3 \pm 5.4 \pm 13.0)\ \mu b$$

PLB 694 (2010) 209

- So, number of $b\bar{b}$ pairs produced

$$10^{15} \times 75.3\ 10^{-6} \sim 10^{11}$$

- Compare to combined data sample of e^+e^- "B factories" BaBar and Belle of ~ 10^9 $B\bar{B}$ pairs

for any channel where the (trigger, reconstruction, stripping, offline) efficiency is not too small, LHCb has world's largest data sample

- p.s.: for charm, $\sigma(pp \rightarrow c\bar{c}X) = (6.10 \pm 0.93)$ mb

LHCb-CONF-2010-013

The all important trigger

JINST 8 (2013) P04022

Challenge is

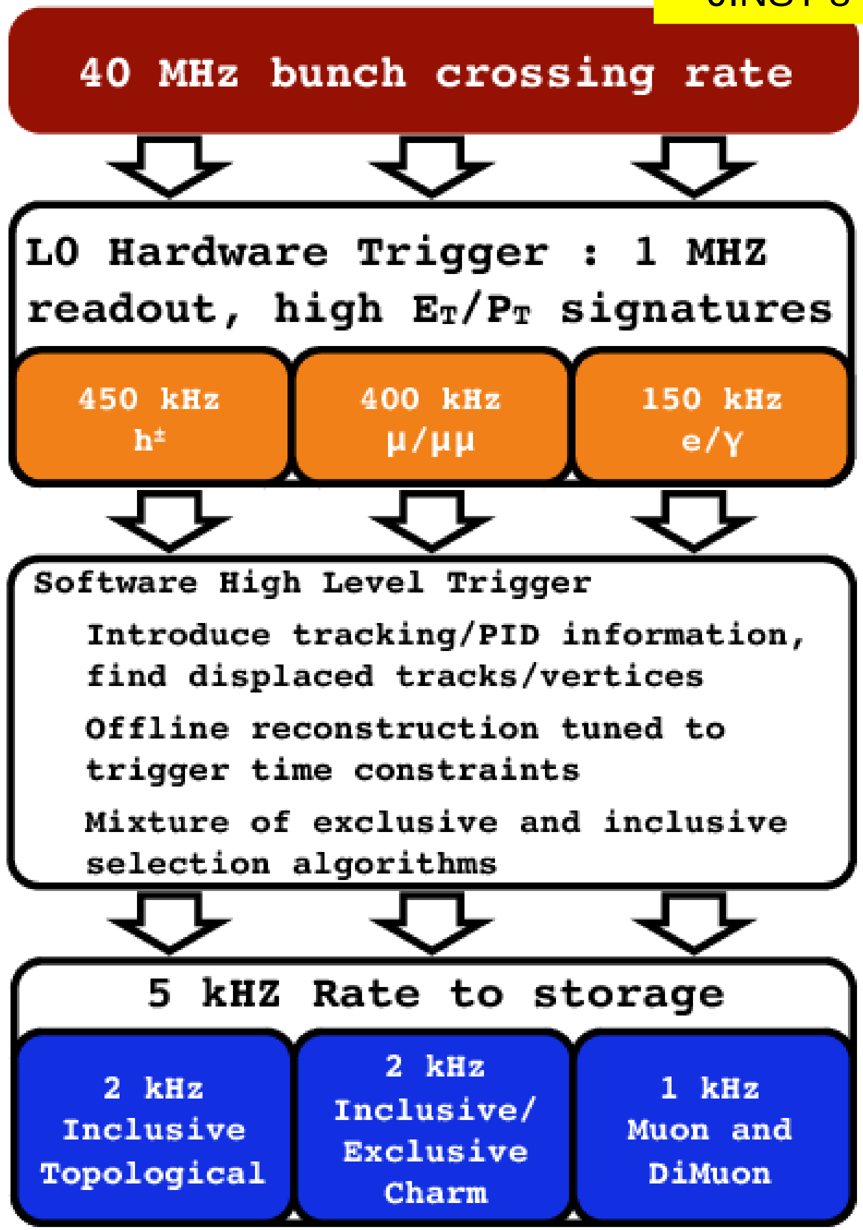
- to efficiently select most interesting B decays
- while maintaining manageable data rates

Main backgrounds

- “minimum bias” inelastic pp scattering
- other charm and beauty decays

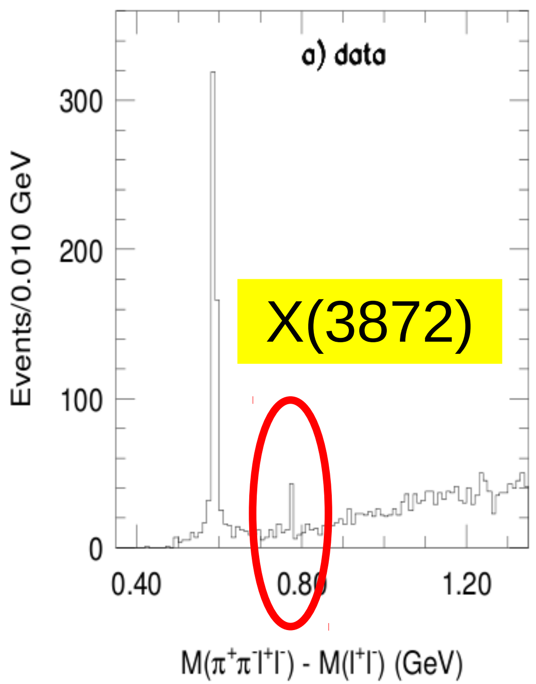
Handles

- high p_T signals (muons)
- displaced vertices



Spectroscopy

- I've talked about the headline items of flavour physics
  - CP violation, searches for new physics
  - what we tell the funding agencies, and the press
- But, much of the physics performed by flavour experiments is the study of properties of hadronic states
  - lifetimes, masses, decay channels, quantum numbers
  - and the discoveries of new ones



PRL 91 (2003) 262001
Most highly cited paper (>1000 citations)
from BaBar or Belle

Discovery of the lightest $b\bar{b}$ state – 2008

Selected for a Viewpoint in *Physics*
PRL 101, 071801 (2008) PHYSICAL REVIEW LETTERS week ending 15 AUGUST 2008

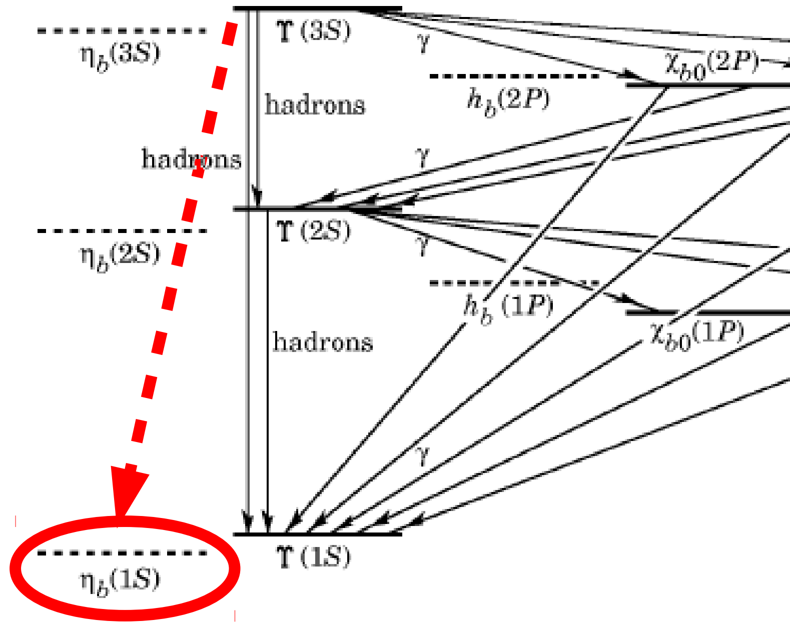
Observation of the Bottomonium Ground State in the Decay $\Upsilon(3S) \to \gamma\eta_b$

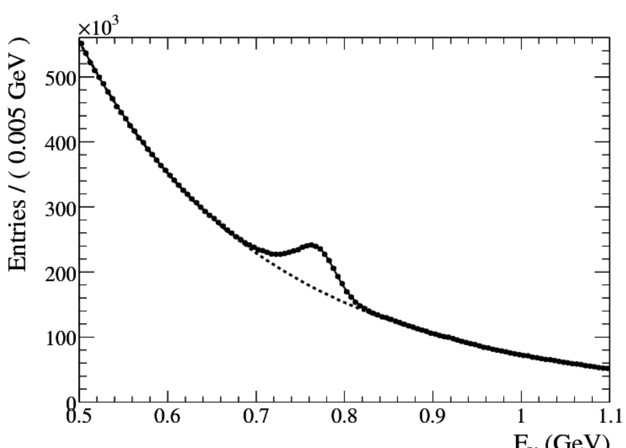
B. Aubert,[1] M. Bona,[1] Y. Karyotakis,[1] J. P. Lees,[1] V. Poireau,[1] E. Prencipe,[1] X. Prudent,[1] V. Tisserand,[1] J. Garra Tico,[2]
E. Grauges,[2] L. Lopez,[3] A. ... S. Abrams,[5] M. Battaglia,[5]

The BaBar Collaboration

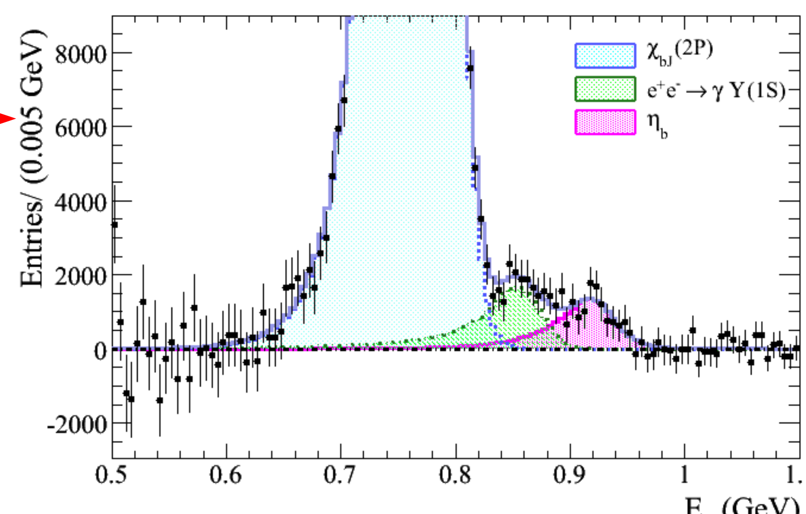
- Only recoil γ is reconstructed

$$m(\eta_b(1S)) = (9388.9\,^{+3.1}_{-2.3} \pm 2.7)\,\mathrm{MeV}/c^2$$
$$m(\Upsilon(1S)) - m(\eta_b(1S)) = (71.4\,^{+2.3}_{-3.1} \pm 2.7)\,\mathrm{MeV}/c^2$$
$$B(\Upsilon(3S) \to \gamma\eta_b(1S)) = (4.8 \pm 0.5 \pm 1.2)\times 10^{-4}$$





subtract smoothly varying background



Signal confirmed in Υ(2S) transitions by BaBar, and by CLEO

Why wasn't the η_b discovered at a hadronic experiment?

- Remember: Υ(1S) discovered at FNAL in 1977
  - fixed target experiment: p on Be

PRL 39 (1977) 252

- η_b is lighter
- Hadron collisions produce all types of b hadrons
- So why couldn't the η_b be discovered, e.g., at the Tevatron?

Why wasn't the η_b discovered at a hadronic experiment?

- Remember: Υ(1S) discovered at FNAL in 1977
  - fixed target experiment: p on Be

PRL 39 (1977) 252

- η_b is lighter
- Hadron collisions produce all types of b hadrons
- So why couldn't the η_b be discovered, e.g., at the Tevatron?
- It's all about the trigger!
  - need clean signature for trigger and reconstruction
  - CDF search used $\eta_b \rightarrow J/\psi J/\psi$ decay, with predicted BF ~ 0!

CDF note 8448

Digression on a digression: The "Oops Leon"

Observation of High-Mass Dilepton Pairs in Hadron Collisions at 400 GeV

D. C. Hom, L. M. Lederman, H. P. Paar, H. D. Snyder, J. M. Weiss, and J. K. Yoh
*Columbia University, New York, New York 10027**

and

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

and

D. M. Kaplan
*State University of New York at Stony Brook, Stony Brook, New York 11794**
(Received 28 January 1976)

We report preliminary results on the production of electron-positron pairs in the mass range 2.5 to 20 GeV in 400-GeV p-Be interactions. 27 high-mass events are observed in the mass range 5.5–10.0 GeV corresponding to $\sigma = (1.2 \pm 0.5) \times 10^{-35}$ cm² per nucleon. Clustering of 12 of these events between 5.8 and 6.2 GeV suggests that the data contain a new resonance at 6 GeV.

PRL 36 (1976) 1236

Homework exercise:
1. Read this paper
2. Do you find the "discovery" convincing?
3. Explain what's wrong

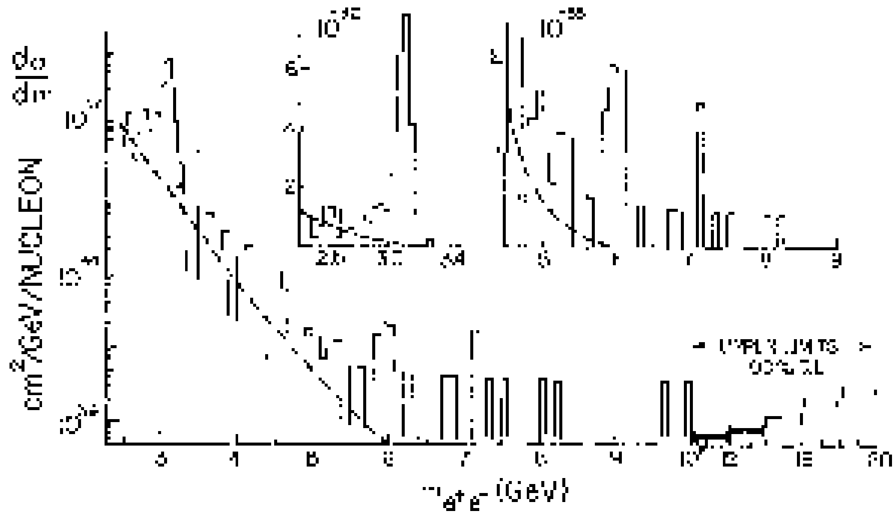
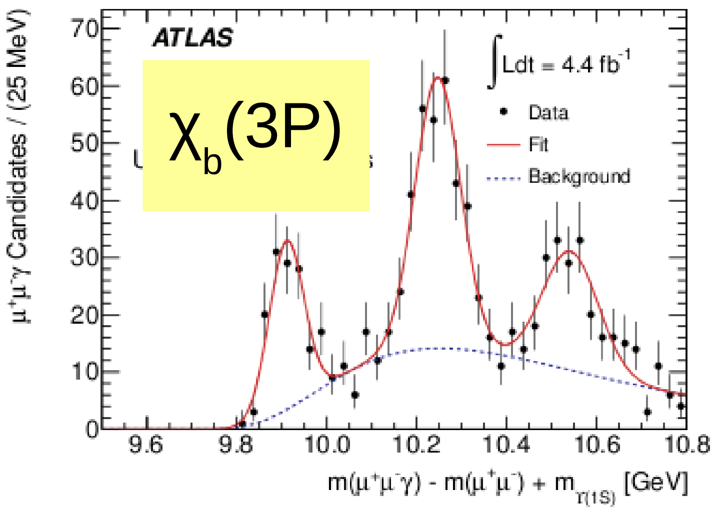


FIG. 2. Electron-positron mass spectrum: $d\sigma/dm$ per nucleon versus the effective mass. A linear A dependence is assumed. Note bin-width changes.

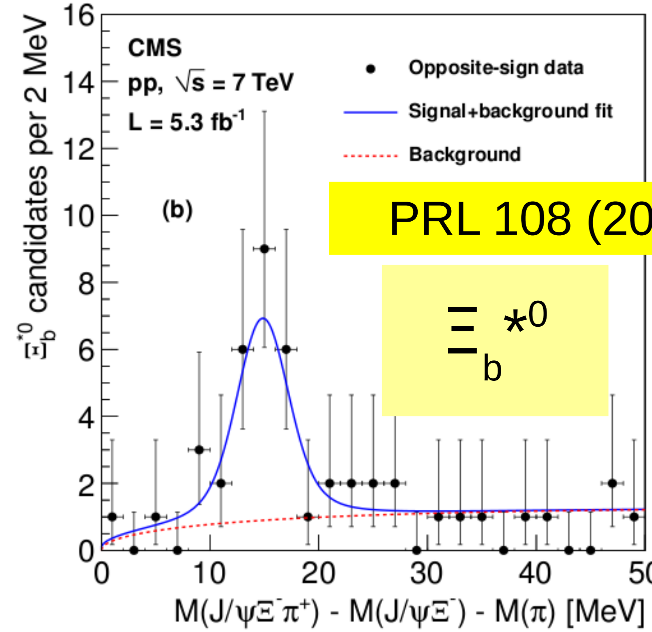
More new particles

PRL 108 (2012) 152001



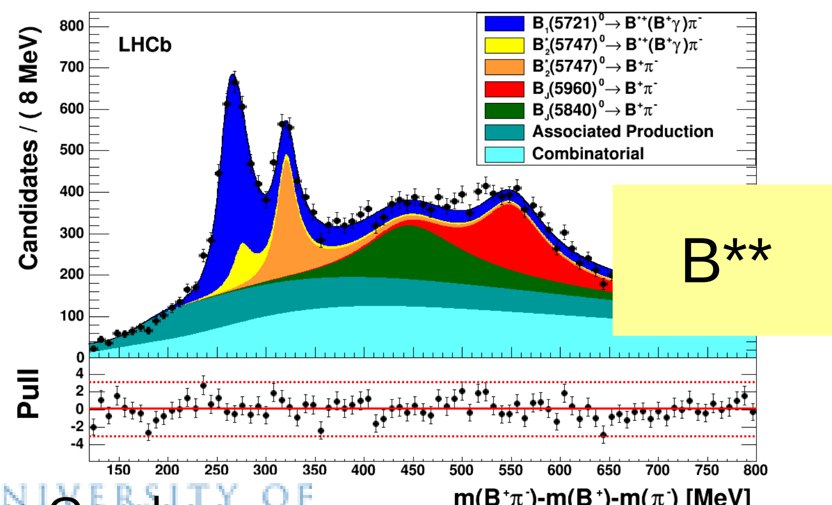
$\chi_b(3P)$

PRL 108 (2012) 252002



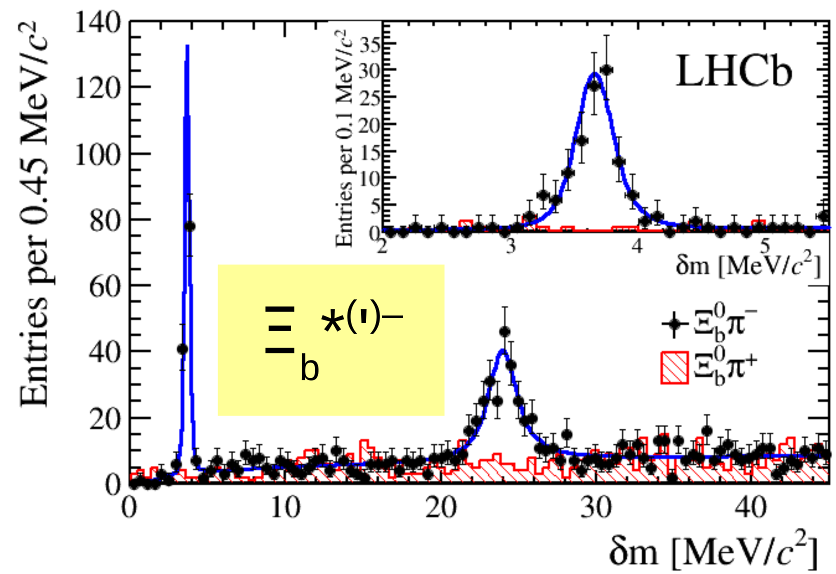
Ξ_b^{*0}

JHEP 04 (2015) 024



B**

PRL 114 (2015) 062004

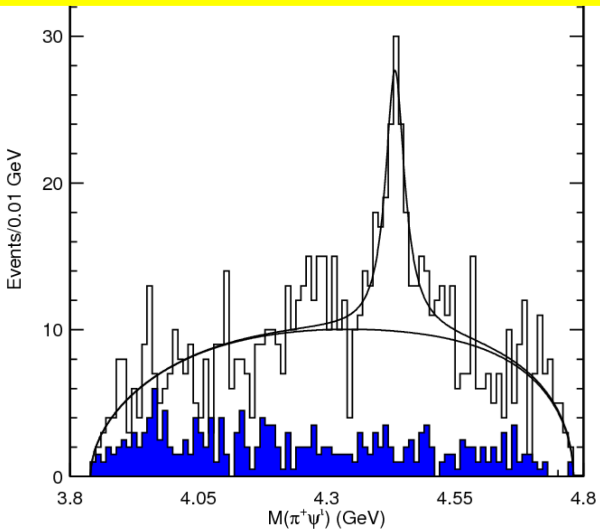


$\Xi_b^{*(\prime)-}$

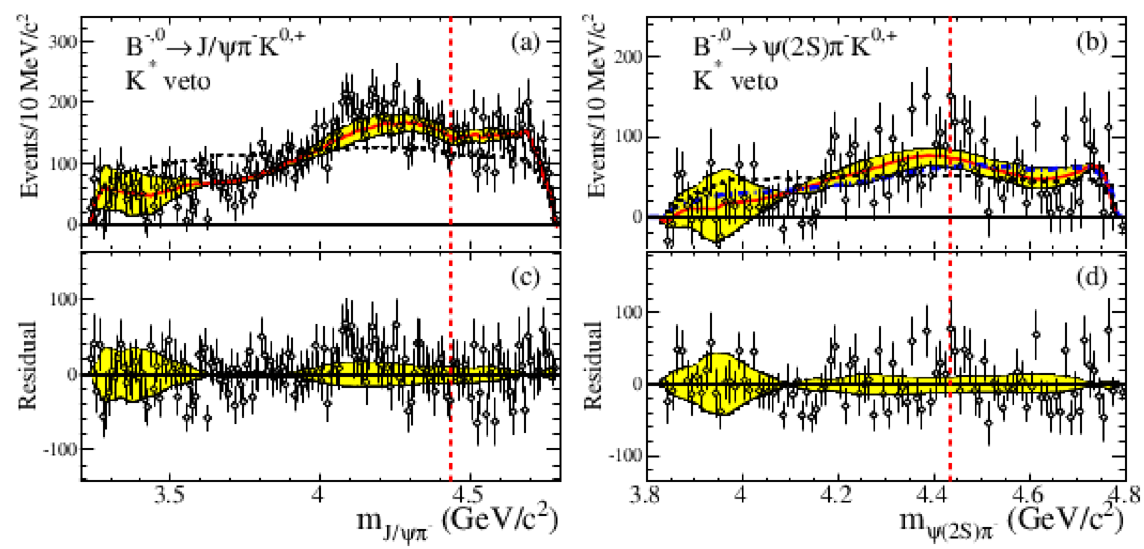
The smoking gun exotic hadron: A charged charmonium-like state

$B^0 \rightarrow Z(4430)^- K^+$, $Z(4430)^- \rightarrow \psi' \pi^-$

Belle PRL 100 (2008) 142001



BABAR PRD 79 (2009) 112001



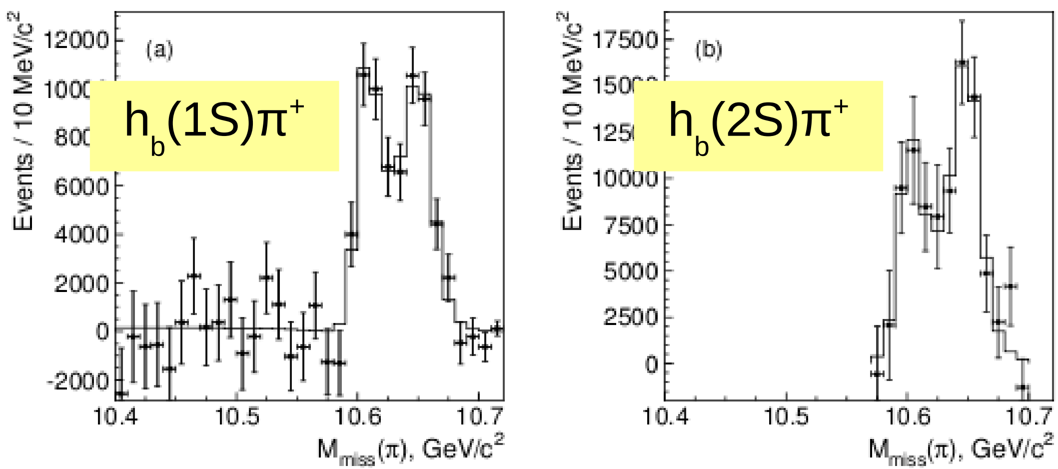
Clear peak
Still there in more detailed analysis
PRD 80 (2009) 031104

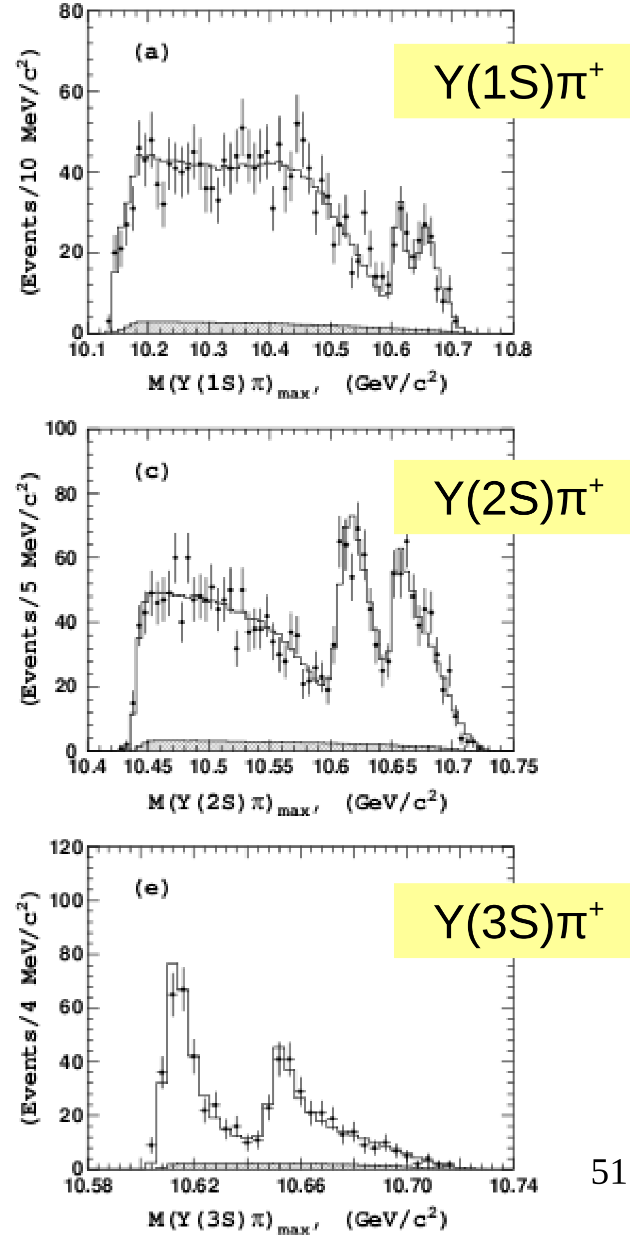
Data consistent with Kπ reflections
Slight peak but no evidence for new state
But also consistent with Belle

Need more experimental input
(CDF, D0, ATLAS, CMS or LHCb)

Charged bottomonium-like states

Belle
PRL 108 (2012) 122001





Final state	$\Upsilon(1S)\pi^+\pi^-$	$\Upsilon(2S)\pi^+\pi^-$	$\Upsilon(3S)\pi^+\pi^-$	$h_b(1P)\pi^+\pi^-$	$h_b(2P)\pi^+\pi^-$
$M[Z_b(10610)]$, MeV/c^2	$10611 \pm 4 \pm 3$	$10609 \pm 2 \pm 3$	$10608 \pm 2 \pm 3$	$10605 \pm 2^{+3}_{-1}$	10599^{+6+5}_{-3-4}
$\Gamma[Z_b(10610)]$, MeV	$22.3 \pm 7.7^{+3.0}_{-4.0}$	$24.2 \pm 3.1^{+2.0}_{-3.0}$	$17.6 \pm 3.0 \pm 3.0$	$11.4^{+4.5+2.1}_{-3.9-1.2}$	13^{+10+9}_{-8-7}
$M[Z_b(10650)]$, MeV/c^2	$10657 \pm 6 \pm 3$	$10651 \pm 2 \pm 3$	$10652 \pm 1 \pm 2$	$10654 \pm 3^{+1}_{-2}$	10651^{+2+3}_{-3-2}
$\Gamma[Z_b(10650)]$, MeV	$16.3 \pm 9.8^{+6.0}_{-2.0}$	$13.3 \pm 3.3^{+4.0}_{-3.0}$	$8.4 \pm 2.0 \pm 2.0$	$20.9^{+5.4+2.1}_{-4.7-5.7}$	$19 \pm 7^{+11}_{-7}$
Rel. normalization	$0.57 \pm 0.21^{+0.19}_{-0.04}$	$0.86 \pm 0.11^{+0.04}_{-0.10}$	$0.96 \pm 0.14^{+0.08}_{-0.05}$	$1.39 \pm 0.37^{+0.05}_{-0.15}$	$1.6^{+0.6+0.4}_{-0.4-0.6}$
Rel. phase, degrees	$58 \pm 43^{+4}_{-9}$	$-13 \pm 13^{+17}_{-8}$	$-9 \pm 19^{+11}_{-26}$	187^{+44+3}_{-57-12}	$181^{+65+74}_{-105-109}$